Corrosion Performance of Epoxy-Coated Reinforcement in Aggressive Environments

by

Enrique Vaca Cortés, B.S., M.S.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May, 1998

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Dedication

To my wife, Nancy, for her love and unconditional support throughout all these difficult and exciting years.

To my son, Enrique Alejandro, for the joy and happiness he brought to our lives.

To my parents for their love and encouragement throughout my life.

Acknowledgements

The financial support of the Texas Department of Transportation and the Federal Highway Administration, which made this research project possible, is greatly appreciated. A special recognition goes to Lloyd M. Wolf and Robert L. Sarcinella, with the Texas Department of Transportation. Their continuous support, cooperation, and feedback were instrumental for the success of this project.

I would like to express my most sincere gratitude to Dr. James O. Jirsa for the supervision and support of this research. Dr. Jirsa is not only an eminent professor and researcher, but he has also outstanding human qualities and a generous heart, and his unconditional support went always beyond the academic duties. I feel blessed and fortunate for the opportunity of having worked with him. I would like to recognize his wife, Mrs. Marion Jirsa, for all her fine and gracious attentions towards me and my family.

I would like to thank Dr. Ramón L. Carrasquillo for having co-supervised this project and for his always useful comments and suggestions. The help of Dr. Harovel G. Wheat is greatly acknowledged. Her expertise on corrosion provided a valuable guidance to achieve the project’s goals. The contribution of Dr. John E. Breen and Dr. David W. Fowler to this research is appreciated.

Many other people have made significant contributions to the execution and completion of this work. I would like to acknowledge Dr. Khaled Z. Kahhaleh, who started this project and constructed the concrete specimens for the durability studies. With his exceptional job, Khaled paved the way for a smooth, seamless transition of the project upon his departure. I am indebted to Reagan S. Herman and Miguel A. Lorenzo. Reagan conducted the portion of the study reported in Chapter 7 and always gave a helpful hand to the execution of other tasks. Above

all, Reagan’s friendship and sense of altruism makes her one of a kind. Miguel executed a portion of the adhesion study reported in Chapter 5. Miguel was an excellent coworker and a great friend too. Both Reagan’s and Miguel’s hard and smart work contributed to the success of this research. Special thanks to Dr. Hengching Chen for his assistance in conducting the EIS tests reported in Chapter 6. Our many chats and discussions on the topic of corrosion provided an invaluable source of knowledge.

Thanks to Rayhan Majid, Usnik Tuladhar, and Zarrar Sikander for their assistance during various stages of the project. My sincere thanks are extended to all the staff members at Ferguson Structural Engineering Laboratory and at the Construction Materials Research Group. This project could have not been completed without their cooperation. A sincere recognition goes to each of my friends here in Austin. In particular, the friendship of all students at Ferguson Lab is appreciated.

I am deeply thankful to my parents for their love and continuous encouragement throughout my life. Simply put, I would have not been successful in life without them. My sisters and brother occupy a special place in my heart too.

I am very glad and fortunate for having a lovely and wonderful wife who has been very supportive, understanding, and patient in putting up with a stressful graduate student. Nancy has been a wife, friend, partner, and lover all at once. She has celebrated my accomplishments and has encouraged me when I felt defeated.

Thanks to our son, Enrique Alejandro, for all the joy and happiness that he has brought to our lives. Nancy and Enrique Alejandro are the most important persons in my life.

Last but not least, I am thankful to God for all his generous gifts and for having blessed us with a healthy and beautiful son.

Austin, Texas

May, 1998 Enrique Vaca C.

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Publication No.______________

Enrique Vaca Cortés, Ph.D.
The University of Texas at Austin, 1998

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The objective of this research was to investigate the integrity and corrosion performance of epoxy-coated reinforcement in aggressive environments. A series of experimental studies were conducted: a) hot water immersion and knife adhesion testing for assessment of coating adhesion; b) materials and procedures for repairing coating damage; c) degree of mechanical damage caused during concrete placement when using metal head and rubber head vibrators; d) accelerated corrosion of coated bars embedded in macrocell and beam specimens placed in a corrosive environment for more than four years. The effects of coating condition and amount of damage, repaired vs. unrepaired damage, bar fabrication, and concrete cracking were studied.

Regardless of coating condition, the performance of epoxy-coated bars was better than that of uncoated bars. Unlike black bars, coated bars did not exhibit deep pitting or substantial loss of cross section at crack locations. **Damage to epoxy coating was the most significant factor affecting corrosion performance**. Bars with coating in good condition, without any visible damage, performed best. The greater the size and frequency of damage, the more severe and extensive the amount of corrosion. The performance of bars that were fabricated or bent after coating was worse than that of coated straight bars. Mixing coated and uncoated bars in the same concrete member led to undesirable performance. Patching damaged coating reduced but did not prevent corrosion, particularly at bar ends. The most important factor in coating repair was the type and properties of the patching material. Surface preparation prior to coating had little effect. The absence of cracks in the concrete delayed, but did not prevent the onset of corrosion of coated bars. During consolidation of concrete, rubber head vibrators caused less damage to epoxy-coated reinforcement than did comparable metal heads. Hot water and adhesion tests were useful and practical for evaluating coating adhesion after production. An adhesion test procedure was developed and is recommended for quality control. A set of recommendations for proper quality control, design, and construction practice of structures with epoxy-coated reinforcement was proposed.

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Corrosion Performance of Epoxy-Coated Reinforcement in Aggressive Environments

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Chapter 1. Introduction

1.1 BACKGROUND

1.1.1 Corrosion of Concrete Structures

Corrosion of reinforced concrete structures is a problem of great concern throughout the world. It causes gradual deterioration of structures and, consequently, a drastic reduction of their expected service life. In some cases, sudden collapses of concrete structures due to corrosion have been reported.[1] A great variety of concrete structures are experiencing the damaging effects of corrosion: Industrial facilities, water intake facilities, storage tanks, sewage treatment plants, highway bridges, parking garages, buildings, marine structures, and others exposed to highly corrosive environments.[2,3]

The extent and cost of corrosion damage to concrete structures are tremendous. For instance, the United States Federal Highway Administration (FHWA) has identified more than 240,000 highway bridges as deficient. The cost of repair of corroded steel reinforced concrete bridges was estimated at $20 billion.[2] If these bridges were permitted to corrode, the replacement cost would be over $112 billion.[4] Replacement costs of parking garages in North-America could be substantially higher. In the Middle-East, the extent and damage due to corrosion of concrete structures is even higher. It is estimated that more than 90% of concrete structures in the Arabian gulf area are suffering from chloride initiated corrosion. Cases of structures undergoing corrosion immediately after placing concrete have been reported.[5] Corrosion attack of concrete structures takes place whenever an aggressive corrosive medium is present.

The low durability of many concrete structures has aroused great concern because of the cost associated with replacing and maintaining the existing infrastructure and the potential hazard to the public if the problem is not corrected. Considerable research has been conducted in the following areas: Mechanisms of corrosion of steel embedded in concrete, parameters that influence the corrosion process, corrosion detection and rate determination, improvements in concrete quality, development of barrier systems to isolate the steel or both the steel and concrete, use of corrosion inhibitors, development of new deicing salts, use of non-corrosive reinforcement, galvanizing of reinforcement, and use of electrochemical procedures. These efforts have involved a number of organizations: Federal governments, state and municipal authorities, state agencies, professional organizations, academic institutions, research institutions, and others.[6] The multidisciplinary nature of the problem has been reflected in the participation of people from different areas: mechanical engineers, chemical engineers, civil engineers, materials engineers, environmental scientists, contractors, building officials, and owners.

Great advances have been achieved in the understanding of the factors influencing corrosion of steel in concrete, and in the development of preventive and corrective measures. Many questions remain to be answered and several remedial techniques are still in the testing stage.

1.1.2 Corrosion of Epoxy Coated Reinforcement

A coating is a protective barrier applied to the reinforcement and is intended to protect the passive film of the steel bars from the corrosive action of chlorides and water. Coatings can be organic or inorganic. The most commonly used organic coatings are fusion-bonded epoxy coatings. The use of coatings on the bars can be very effective as a preventive measure against corrosion.

Fusion-bonded epoxy coating consists of electrostatically applying finely divided epoxy powder to thoroughly cleaned and heated bars.[7] The technique is applied on new bars as a preventive measure. Application of epoxy coatings to steel reinforcement is the most popular method used today to protect embedded rebars in concrete against corrosion. However, the effectiveness of the epoxy coatings has been questioned lately and has been the center of controversy.[8] In general, most of the observed field performance of epoxy coatings in bridge decks has been reported as satisfactory.[9] The major problem of the epoxy coatings is that the coating can be damaged during transportation, handling, and placing of the bars at the job site, especially when bending the bars. In addition to damage, coating defects can be present in the form of small holidays and pinholes. At damaged areas and small defects, the corrosive action of chlorides can take place.[7] Nevertheless, in some cases where damage in the epoxy coating was detected, the corrosion performance of the bars was superior compared to that of the uncoated bars.[9]

1.2 RESEARCH OBJECTIVES

1.2.1 General

Epoxy-coated reinforcement has been extensively used to protect embedded rebars in concrete against corrosion. Any premature deterioration of concrete structures constructed the epoxy-coated bars will have a tremendous economic impact. The research work described in this study addresses the following issues:

- Determination of the performance of epoxy-coated reinforcement in corrosive environments.[10]
- Assessment of quality control methods for epoxy-coated bars.
- Evaluation of concreting operations with epoxy-coated reinforcement.
- Assessment of repair materials and techniques for damaged coating.

1.2.2 Objectives

The main objective of this research was to investigate the performance of epoxy-coated reinforcement in corrosive environments. The purpose was to identify the conditions that affect the performance of coated bars so that proper guidelines in design, construction, and maintenance can be implemented to maximize the service life of structure.[10] The main objective was divided in the following areas:

- Identifying conditions conducive to corrosion of epoxy-coated bars. An experimental program was implemented to evaluate performance of coated bars with different levels of coating damage and repair and under different loading conditions.[10]

- Identifying conditions that produce damage to epoxy coating during concreting practices.
- Development of quality control methods for assessing the quality and adhesion strength of the epoxy coating.
- Assessment of current patching materials and procedures to repair epoxy coating that has been damaged.
- Development of guidelines and recommendations for improving performance of epoxy-coated bars.

The findings of this study should benefit practitioners in the selection and detailing of coated bars, and should be helpful in improving procedures critical to performance of epoxy-coated bars. This study provides information that can be used to modify coated bar specifications.

1.2.3 Research Significance

Technical Concerns

Many concerns about long-term protection of epoxy-coated bars have been expressed. Some of these concerns are as follows:

- Specifications for coated bars are inadequate.
- Coated bars may be susceptible to excessive defects and damage from the production stage to embedment in concrete.
- Corrosion propagates beneath the film after corrosion starts on exposed steel at defects and damaged spots.

- Fabrication of coated bars may introduce damage to the coating and weaken adhesion to the steel substrate, compromising corrosion behavior.
- There are no specifications for adequate procedures to repair epoxy-coated bars.
- Coated bars may corrode at crack locations. Of particular concern is the fact that wider flexural cracks have been observed on concrete members reinforced with coated bars.
- Use of coated bars and uncoated bars in the same concrete member (bridge decks) may lead to macrocell corrosion if there is any incidental coupling between bar layers.
- The significance of coating adhesion and its role in the corrosion resistance of epoxy coatings is not completely understood. There is a lack of adequate test methods to reliably measure coating adhesion.

Early studies indicated that epoxy-coated reinforcement was a very promising corrosion protection material.[11, 12, 13] Later findings showed, however, that epoxy coating may be vulnerable to corrosion and its effectiveness came under siege.[8, 14, 15] Several studies showed very good performance[16, 17, 18, 19] while other studies concluded that the protection provided by the epoxy coating was questionable. [20, 21, 22, 23] The corrosion mechanism has been studied by several researchers but it is not completely understood. The construction industry and transportation agencies need to know the effectiveness of coated reinforcement in extending service life.

1.3 ORGANIZATION OF RESEARCH

The research was organized in five parts: I) Background, II) influence of coating operations, III) influence of concreting operations, IV) durability studies in concrete, and V) Synthesis. This study was part of a 7-year research project: Results from the first 3 years are reported elsewhere,[10] and those from the last four years are reported herein.

Part I: Literature Survey

A literature review on background information was conducted. Topics covered included background on corrosion of reinforcement in concrete, overview of epoxy coating materials and application processes, a brief review of the factors that influence performance of coated bars, a brief historical development of epoxy-coated bars, an extensive review of durability studies, and an overview of present status and future trends.

Part II: Influence of Coating Operations

The importance of coating quality and adhesion is discussed. Quality control measures, industry efforts to improve quality (CRSI Certification Program), and industry standards and specifications are reviewed and discussed. The nature and factors affecting coating adhesion, mechanisms of adhesion loss, available tests to evaluate coating adhesion, and prior research on coating adhesion evaluation are analyzed.

An experimental evaluation of hot water immersion and knife adhesion testing was conducted to determine the feasibility of these tests for coating adhesion evaluation. A pioneering experimental study of repair of coating damage was performed. In this research, the corrosion performance of several patching materials and procedures was investigated.

Part III: Influence of Concreting Operations

An experimental study was conducted to evaluate the degree of mechanical damage caused by concrete placement procedures. The effect of concrete consolidation on the epoxy coating using internal metal head vibrators and soft (rubber) head vibrators was determined. In addition, the degree and quality of consolidation obtained with a rubber head vibrator as compared to a metallic head vibrator were assessed in fresh and hardened concrete specimens.

Part IV: Durability Studies in Concrete

A two-part corrosion experimental program was established to study the performance of epoxy-coated bars in highly corrosive concrete environments. Triplicate, damaged, coated bent bars were embedded in concrete prisms exposed to chloride solution and were linked to uncoated bars. The corrosion currents were monitored and reported in the macrocell corrosion study. Straight bars and stirrups were placed in duplicate beam specimens that were partially irrigated with chloride solution. The beams were subjected to different loading conditions. The corrosion potential of each test bar was monitored. The effects of concrete cracking, loading condition, and coating condition on the performance of coated bars were examined. The results were reported in the beam corrosion study. In both macrocell and beam studies, the selection of the exposure procedure, test parameters, and specimen characteristics was intended to produce a very aggressive environment and to accelerate corrosion of the specimens.

Part V: Synthesis

The overall results and findings from the literature review and experimental research are put in perspective, analyzed, and synthesized. Emphasis was placed in analyzing the factors that affect the performance of epoxy coated reinforcement. A summary of the study, conclusions, and recommendations are presented. Guidelines for design and construction practice using epoxy-coated bars were prepared and included in a separate appendix.

Chapter 2. Background on Corrosion of Reinforcement in Concrete

2.1 CORROSION MECHANISM OF STEEL IN CONCRETE

The mechanism of deterioration of reinforced concrete structures due to corrosion of the reinforcing steel has been studied for several years and is generally well understood. However, there are some questions that remain unanswered and are still under investigation. It is beyond the scope of this study to analyze in depth the mechanism of steel corrosion in concrete. In this chapter, corrosion will be briefly described. The electrochemical principles of corrosion of steel in concrete will be discussed.

There are two forms in which corrosion attacks the reinforcing steel in concrete structures; these are chloride-induced corrosion, and carbonation of concrete. The vast majority of cases of distress caused by corrosion are due to chloride induced contamination; however, there have been several cases in which carbonation of concrete was the mechanism that triggered the corrosion of the reinforcing steel.

2.1.1 Basic Corrosion Cell

Corrosion can be defined as the destructive chemical reaction between a metal or metal alloy and its surrounding environment. In this process, the metal atoms tend to return to the state in which they are found in nature, that is, to a combined state in chemical compounds. Corrosion can be classified in different ways, but one distinction that is appropriate for this study is (1) aqueous corrosion, and (2) dry corrosion. The corrosion that takes place in steel embedded in concrete is an aqueous corrosion, which is electrochemical in nature. The term aqueous means that the corrosion process involves transfer of electrons in an aqueous environment. The aqueous environment in concrete structures is provided by the presence of free water in the pores of the concrete matrix.

Steel is an alloy formed by iron, carbon, and other components. When corrosion of steel in concrete takes place, iron reacts with water and oxygen. The chemical reaction that proceeds is as follows:[24]

$$Fe + 1/2\,O_2 + H_2O \longrightarrow Fe^{2+} + 2(OH)^- \longrightarrow Fe(OH)_2$$

(2.1)

The product of this reaction is constituted by iron hydroxides, which react with oxygen to form insoluble hydrated rust. Reaction (2.1) can be rewritten in an ionic form:

$$Fe \longrightarrow Fe^{2+} + 2e^- \qquad \textit{anodic reaction} \qquad (2.2)$$

$$1/2\,O_2 + H_2O + 2e^- \longrightarrow 2(OH)^- \qquad \textit{cathodic reaction} \qquad (2.3)$$

In reaction (2.2), metallic iron is oxidized to ferric ions and two electrons are liberated. In reaction (2.3), dissolved oxygen is reduced to hydroxide ions and in the process, the two electrons produced in reaction (2.2) are consumed. Reaction (2.2) is an anodic or oxidation reaction, and reaction (2.3) is a cathodic or reduction reaction. Both reactions must occur simultaneously due to the principle of conservation of charge. This characteristic leads to a fundamental principle of corrosion: The rate of oxidation is equal to the rate of reduction. Reaction (2.1), or reactions (2.2) and (2.3) are termed electrochemical, because they involve transfer of electrons.

Analysis of reactions (2.2) and (2.3) shows that the following conditions must be satisfied in the corrosion process of steel in concrete:

a) Metallic iron must be present on the surface of the steel in order for the anodic reaction to occur.
b) Oxygen and water must be available for the cathodic reaction
c) The electrical resistivity of the concrete must be low to permit electron flow and ionic diffusion between the anodic and cathodic areas.

These conditions clarify the role of oxygen and moisture in the corrosion mechanism. The presence of moisture will not only provide the water necessary for the reaction, but will also lower the electrical resistivity of the concrete. The presence of salt will further decrease this resistivity. Without oxygen, corrosion of steel is impossible.

2.1.2 Effect of Chlorides

Concrete provides a "friendly" environment for the steel because its high alkalinity makes the corrosion-protective passive gamma ferric oxide film formed on the steel surface stable. The concrete also insulates the reinforcing steel against the outside environment. Therefore, in normal conditions, steel embedded in concrete should not corrode.[7] If the concrete is very permeable or the cover over the steel is too thin, water solutions containing dissolved oxygen can penetrate and reach the steel surface creating the necessary conditions for corrosion to occur. The role of chlorides in this process is that they impair passivity by breaking down the protective passive oxide film, setting up the corrosion mechanism. Furthermore, chlorides react with the corrosion products forming an acid solution that lowers the alkalinity of the concrete, thus increasing the corrosion rate of the steel and making the process autocatalytic. [7, 25]

2.1.3 Distress Mechanism

The damaging effect of the corrosion of steel embedded in concrete will be spalling of the concrete cover, delamination, staining, and cracking. Such deterioration is the result of high pressures generated in the concrete due to the volume increase associated with the conversion of steel to corrosion products (Figure 2.1 – Ref. 27).[7, 26] Structural distress will occur due to the loss of steel and concrete cross section or loss of bond between the concrete and steel.[7]

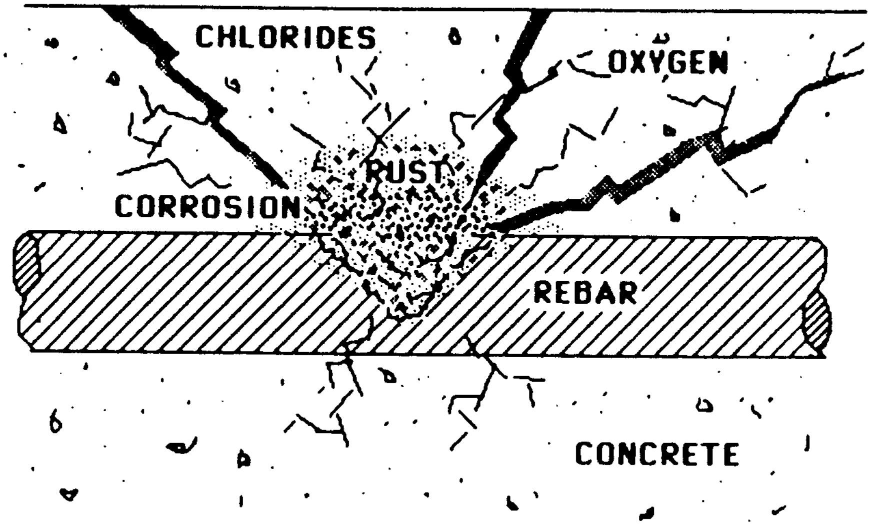


Fig. 2.1: The corrosion products occupy a volume much higher than the original steel, generating pressure-induced tensile stresses that crack the concrete cover.[27]

2.1.4 Form of Corrosion of Steel in Concrete

Corrosion can occur in several forms; the most common forms of corrosion are uniform corrosion, galvanic corrosion, crevice corrosion, pitting corrosion, environmentally induced cracking, hydrogen damage, intergranular corrosion, dealloying, and erosion corrosion.[24] Some forms of corrosion occur in steel corroding in concrete. Some have postulated that pits initially form at an early stage of corrosion of steel.[25] Stress corrosion cracking and corrosion fatigue cracking (environmentally induced cracking) are potential risks in prestressed concrete structures. Fretting corrosion, which is a form of erosion corrosion, has been observed in prestressed concrete structures.[28] Galvanic corrosion occurs when dissimilar metals are in contact with the steel. However, the type of corrosion that causes the most damage to concrete structures is the concentration cell corrosion. The term of galvanic corrosion has also been applied to this type of corrosion in the literature, because both types operate by similar principles.

Concentration cell corrosion occurs when differing solution concentrations are present on the surface of the same metal, setting up galvanic corrosive currents.[24] Concentration cells in bars embedded in concrete are formed by differences in concentrations of chlorides, moisture, oxygen, and metallic ions on different zones of the rebar surface. Even a temperature gradient in the steel can result in a concentration cell.[25] These differential concentrations create differences in potential due to the greater availability of reactive ions at some locations with respect to others. Electric currents are then set up between anodic and cathodic areas, and corrosion cells are thus established. The cells thus formed consist of anodic areas (typically with high chloride concentrations), cathodic areas (characterized by higher concentration of moisture and oxygen), a conductor (characterized by the rebars), and an electrolyte (the concrete).[29] A typical corrosion cell in reinforced concrete is shown in figure 2.2.

The establishment of corrosion cells in steel embedded in concrete can occur either in a micro or macro scale. In a micro scale, the anode and cathode are close to each other forming microcells. In a macro scale, the anode and cathode can be separated by a few centimeters or several meters, forming macrocells.[30] Figures 2.2 and 2.3 show two cases of corrosion cells in reinforced concrete structures. In the first case, a corrosion cell is formed with the anode and cathode on the same bar. In the second case, the top mat has an increased concentration of chlorides and moisture, and on the bottom mat, oxygen is available. The whole top mat then becomes an anode with respect to the bottom mat, which becomes a cathode. In general, corrosion in concrete structures is a complex combination and interaction of many microcells and macrocells.

2.2 VARIABLES AFFECTING THE CORROSION OF STEEL BAR

The corrosion of reinforcing steel in concrete is a complex mechanism that is influenced by several factors. In many cases, the role and interaction of these factors is either not completely understood or controversial. In this study, the factors have been classified in four broad categories: Exposure conditions, concrete quality and durability, design practices, and construction practices.

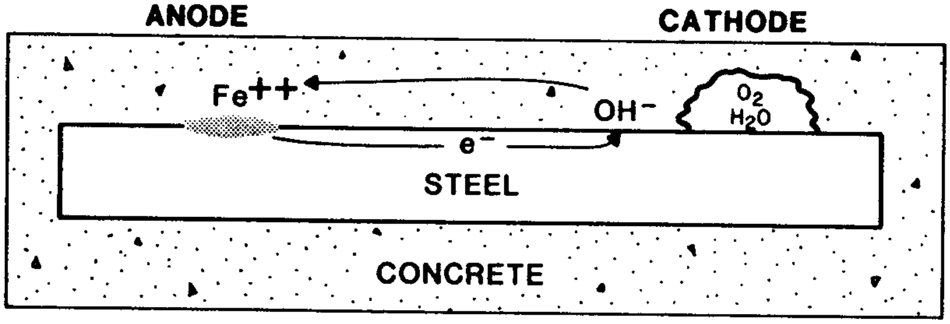


Fig. 2.2: Corrosion cell in reinforced concrete.[29]

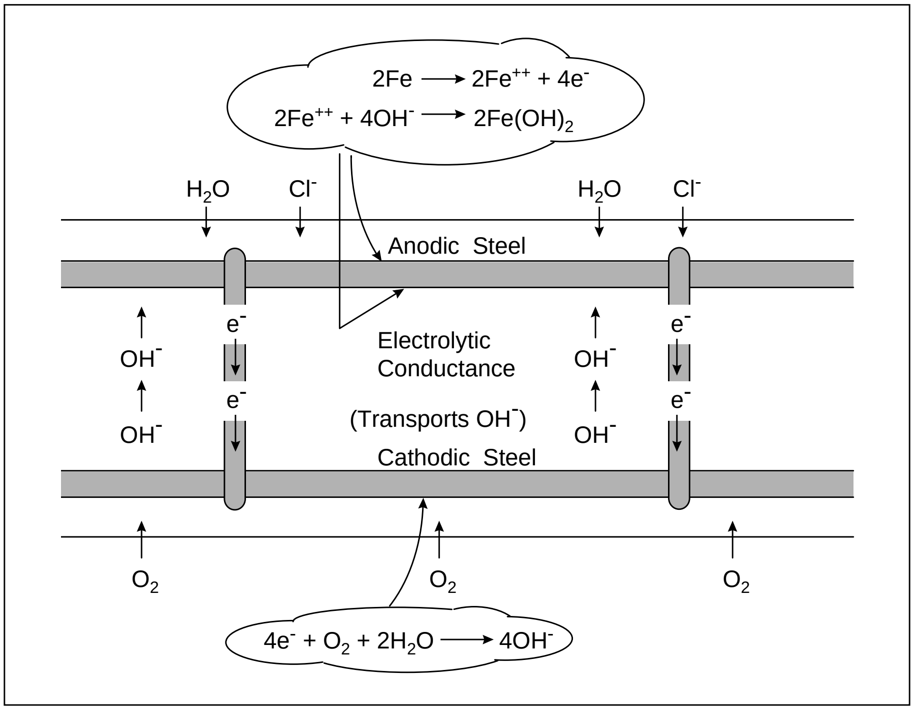


Fig. 2.3: Corrosion cell with top mat as an anode and bottom mat as cathode.[30]

2.2.1 Exposure Conditions

The severity of the environment surrounding a concrete structure is the most important factor influencing the corrosion process. Bad quality concrete and poor design and construction practices are factors conductive to corrosion of the reinforcing steel. However, if the exposure conditions are very mild, even the worst quality concrete structures will not corrode. Structures of relatively good quality may experience some degree of corrosion if exposed to a highly corrosive environment. The severity of the environment is also one of the most important factors in designing for service life and in designing a repair scheme. In other words, the exposure conditions will dictate the design approach.

Extremely corrosive conditions are those that furnish the concrete structure with the agents necessary for the corrosion process to occur; chloride ions, carbon dioxide, oxygen, water vapor, and others. If high temperatures are present, the corrosion rate will be accelerated. Examples of corrosive exposure conditions are salt spray in coastal zones, sea water, application of deicing salts, exposure to other types of salts, soils contaminated with chlorides, exposure to aggressive chemicals, presence of carbon dioxide in the atmosphere, industrial emissions containing carbon dioxide, and others.

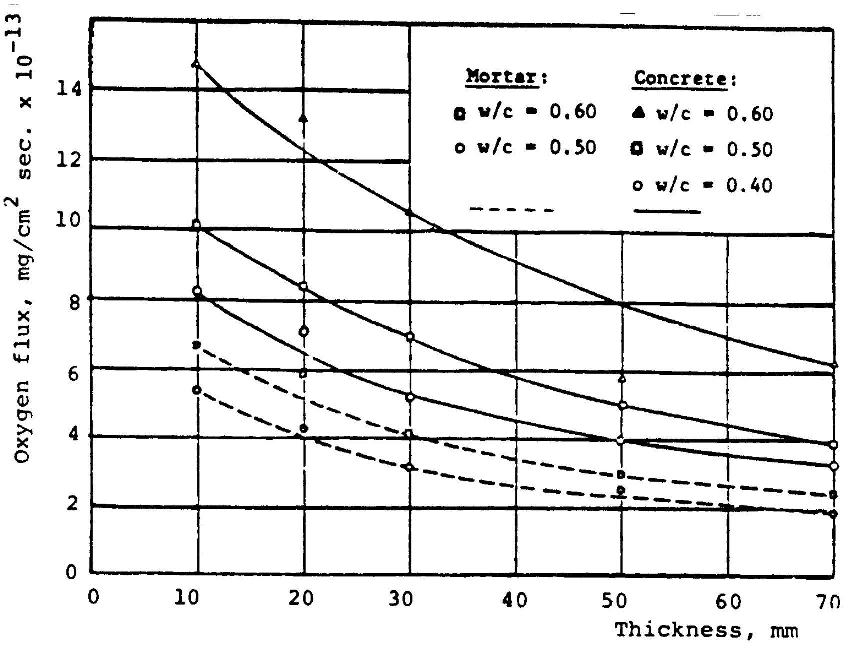
2.2.2 Concrete Quality and Durability

The vast majority of recommendations drawn from research conducted in the area establishes that the first line of defense of concrete structures against corrosion is high quality concrete.[7, 31] Therefore, it is important to understand the most important variables that affect the properties and characteristics of a corrosion-resistant, durable concrete.

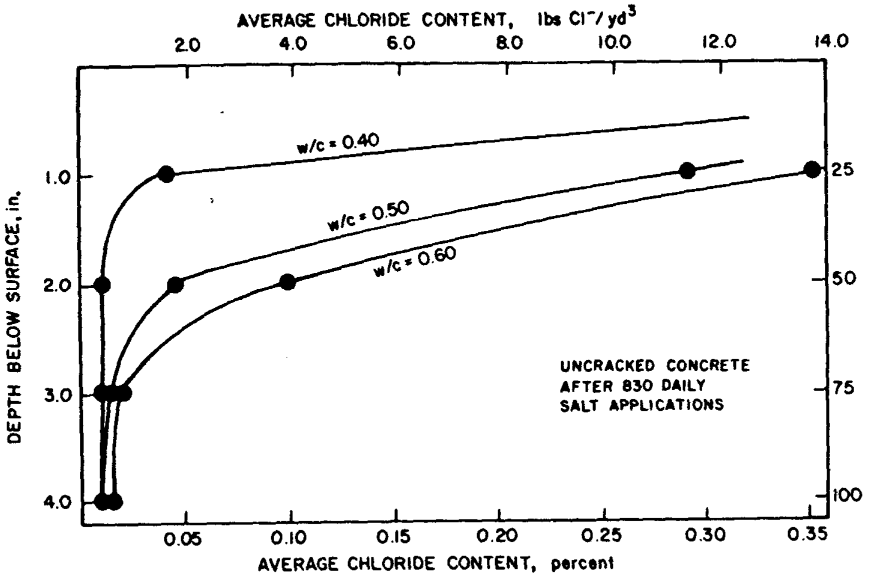
The most important property of a durable concrete is low permeability.[7, 31] The lower the permeability of the concrete, the lower the possibility of corrosive agents, i.e., oxygen, moisture, chlorides, and carbon dioxide, to penetrate through the concrete and reach the steel. Therefore, all the factors that affect the permeability of the concrete will affect its durability against corrosion. These factors are as follows:[7, 32]

a) *Water/cement ratio:* The lower the water/cement ratio, the lower the permeability of the concrete, and the more durable the concrete. A lower water/cement ratio will also increase the concrete strength, extending the time before corrosion-induced stresses cause cracking. See Fig. 2.4. Maximum water/cement ratios and minimum compressive strengths for various exposure conditions specified by the ACI 318-95 code are given in table 2.1.

b) *Concrete cover:* The thicker the concrete cover on reinforcing bars, the higher the protection provided to the bars against the intrusion of corrosive agents. Most researchers agree that a thick cover is one of the most important factors in preventing or delaying the onset of corrosion of the rebars. Figure 2.5 illustrates the effect of depth of cover and water/cement ratio on the time to corrosion. Values of concrete cover for corrosive environments recommended in the ACI 318R-95 Building Code Commentary are presented in table 2.2.



(a) Effect of water-cement ratio and thickness on the diffusion of oxygen through mortar and concrete.[7]



(b) Effect of water-cement ratio on salt penetration.[7]

Fig. 2.4: Effect of water-cement ratio.

Exposure condition	Maximum water-cement ratio, normal weight aggregate concrete	Minimum f'c, normal weight and lightweight aggregate concrete, psi
Concrete intended to have low permeability when exposed to water	0.50	4000
Concrete exposed to freezing and thawing in a moist condition or to deicing chemicals	0.45	4500
For corrosion protection for reinforced concrete exposed to deicing chemicals, salt, salt water, brackish water, seawater or spray from these sources	0.40	5000

Table 2.1: Required water-cement ratio by ACI 318-95 for special exposure conditions[33]

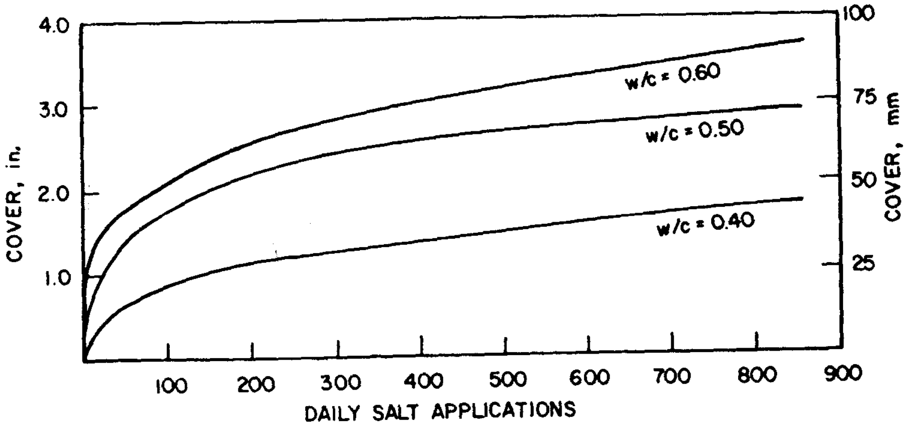


Fig. 2.5: Effect of water-cement ratio and depth of cover on relative time to corrosion.[7]

Type of element	**Minimum recommended cover, in**
Concrete walls and slabs (cast in place)	2
Other concrete members (cast in place)	2.5
Precast concrete walls and slabs*	1.5
Other precast concrete members*	2

*Manufactured under plant control conditions

Table 2.2: Minimum concrete cover for reinforcement recommended by ACI 318R-95 for elements exposed to corrosive environments[33]

c) *Curing:* Proper curing of the concrete will reduce the number and size of the capillary channels in the concrete matrix, decreasing the permeability of concrete.

d) *Consolidation:* The objective of consolidating the concrete is to reduce the air content of the concrete matrix in order to have a solid void-free mass. Consolidation will reduce the air voids that might form at the surface of the reinforcing bars. The voids provide a low alkaline medium to the concrete and serve as containers for moisture and oxygen. The effect of inadequate consolidation on chloride penetration is illustrated in Fig. 2.6. A side effect of the consolidation is that air and water move upwards in the structural element, creating a water/cement ratio gradient in the vertical direction and increased permeability in the top fiber. Difficulties in getting good consolidation in the perimeter of structural members will create a zone of poorer quality concrete precisely where the highest quality is most needed, that is, at the concrete cover.[32]

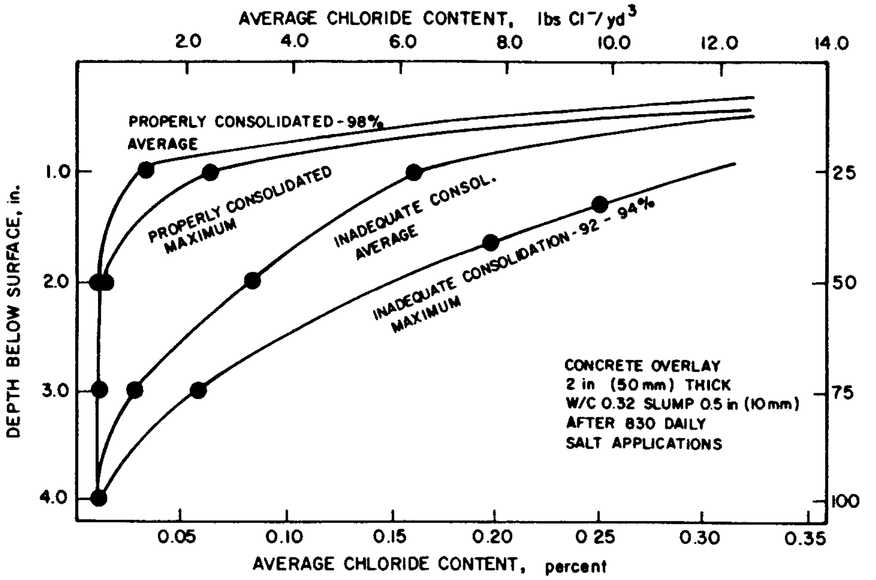


Fig. 2.6: Effect of inadequate consolidation in salt penetration.[7]

c) *Mix constituents:* The characteristics of the mix constituents affect the permeability and resistance to chloride attack of concrete. Some of these characteristics are cement type, cement content, quality of aggregates, quality of mixing water, chemical admixtures, mineral admixtures, concrete grade, and chloride content in the constituents. Corrosion resistance is enhanced with a large amount of cement, good quality and well-graded aggregates, use of pure water, use of admixtures without calcium chloride, and limiting the total amount of chloride content in the concrete constituents. Much research has been conducted in the last decades about the beneficial effect of silica fume, fly ash, and blast furnace slag in the corrosion performance of reinforced concrete and the results have been widely disseminated. Corrosion inhibitors have been used and added as an admixture. There has also been a great amount of research on the development of new constituents that reduce the permeability of the cement paste, such as polymer impregnation.

2.2.3 Design Practices

Design practices affect the durability of concrete structures. The occurrence and severity of deterioration and, in particular, corrosion of concrete structures have increased in the last few decades. One of the causes of this increase is that by optimizing member sizes and material quantities, structures are designed for higher stresses at service loads and with lower factors of safety than before. These changes are associated with the increase of strength of concrete and steel materials. The result is that concrete structures are lighter and less stiff, and may undergo greater deflections and cracking.[32, 34] Consequently, the durability of concrete structures is sensitive to errors in construction and design, to changes in the severity of the environment, and to occupancy or overloads.

An important design practice that has strongly influenced corrosion of concrete structures is the use of reduced concrete cover over the reinforcing steel for crack control.[35] For instance, the ACI 318-95 code in section 10.6.4 specifies the following:[33]

> when design yield strength f_y for tension reinforcement exceeds 40,000 psi, cross sections of maximum positive and negative moment shall be so proportioned that the quantity z given by

$$z = f_s \sqrt[3]{d_c A} \qquad (2.4)$$

[where:

f_S = calculated stress in reinforcement at service loads, ksi.

$\mathbf{d_C}$ = thickness of concrete cover measured from extreme tension fiber to center of bar or wire located closest thereto, in.

A = effective tension area of concrete surrounding the flexural tension reinforcement and having the same centroid as that reinforcement, divided by the number of bars or wires, sq. in.]

does not exceed 175 kips per in. for interior exposure and 145 kips per in. for exterior exposure.

Equation (2.4), based on the Gergely-Lutz expression for crack width, is intended to provide a distribution of flexural reinforcement that will reasonably control flexural cracking. The Gergely-Lutz expression was determined from laboratory tests whose results indicated that thickness of concrete cover and the area of concrete in the zone of maximum tension surrounding each bar are the main factors affecting crack width.[33] Therefore, Eq.(2.4) clearly indicates that a reduced concrete cover "d_C" will yield an adequate quantity "z" for crack control. However, the use of a small concrete cover is in contradiction with other research results that indicate the necessity of a sufficiently thick concrete cover for adequate corrosion protection of the reinforcement.[36, 37] Consequently, two schools of thought have originated concerning the influence of cracking and cover in the corrosion of reinforcing steel. The first one, is that the control of cracking will limit the access of deleterious agents that cause corrosion to the reinforcing bars. In order to limit cracking, a reduced concrete cover over the steel reinforcement is required. The second school says that corrosion resistance is enhanced by a greater cover over the steel bars although cracks will inevitably occur. In any instance, corrosion occurring in cracks would be very localized, whereas a very thin cover would expose the steel to a more widespread corrosion.[7, 35]

Which of the two philosophies is more accurate will be clarified only by continuous monitoring of the performance of actual concrete structures in relation to the factors discussed. Considering the electrochemical nature of the corrosion process of the steel bars and based on the evidence provided by research about the role of the concrete cover, the author favors the second philosophy. The ACI 318-95 code gives an important warning concerning the use of Eq.(2.1) that should always be kept in mind. Section 10.6.5 of the code states that:[33]

> Provisions of 10.6.4 are not sufficient for structures subject to very aggressive exposure or designed to be watertight. For such structures, special investigations and precautions are required.

In addition, the commentary to this section states that

> …clear experimental evidence is not available regarding the crack width beyond which a corrosion danger exists. Exposure tests indicate that concrete quality, adequate compaction, and ample concrete cover may be of greater importance for corrosion protection than crack width at the concrete surface.

Other design practices that have influenced the corrosion performance of concrete structures are the lack of complete, clear, and adequate design drawings and specifications. This aspect is to be analyzed in more depth in the next section due to its direct effect on the quality of the construction.

2.2.4 Construction Practices

Construction is now performed faster in order to reduce cost. The effect of this trend can be a reduction in the quality of the work performed. The lack of adequate and qualified supervision during the construction process will further aggravate this problem.[32, 34]

Another problem is that in many countries, design and construction tasks have been separated. The main repercussion of this practice is that the designer does not know how the structure will be constructed, and the constructor does not always understand the intention of the designer. Miscommunication has resulted in inadequate, insufficient, and unclear detailing drawings, plans, and specifications, and a consequent lower quality of the construction. Examples of poor construction details and procedures that affect the durability and corrosion-resistance of concrete structures are as follows:[38]

a) Lack of provisions for drainage and methods for removing drainage water.
b) Shape and dimensions of members that make the placing and consolidation of fresh concrete difficult.
c) Poor control of the water/cement ratio of the concrete.
d) Construction errors leading to inadequate cover.
e) Specification of tolerances leading to wide ranges of concrete cover.
f) Detailing of reinforcement leading to congestion of bars.
g) Badly performed vibration and compaction.
h) Concrete placed very fast.
i) Construction joints not clearly indicated and specified in the design drawings.

j) Concrete cover not clearly specified in the design drawings.
k) Reinforcing bars and tendons for a given portion not indicated in the same drawing.
l) Insufficient or deficient supervision and quality control.
m) Poor finishing and curing.
n) Absence of real-size drawings to check reinforcement detailing.
o) Use of inadequate or insufficient spacers for steel bars.
p) Metallic parts of form-ties left in concrete cover.
q) Low quality materials for post-filling holes in form-work from form ties.
r) Lack of specifications on the limits of chlorides in the concrete constituents.

2.3 IMPLICATIONS OF CONCRETE CORROSION

2.3.1 Effect on Structural Safety

It has been explained that when corrosion of steel bars in concrete structures takes place, deterioration arises due to loss of steel and concrete cross-sectional areas of structural members. If cracking is extensive and severe, loss of bond between the concrete and steel will occur. Both the reduction of cross-section area and debonding of steel in structural concrete members will reduce the capacity of the structural members and, in extreme cases, failure of members.

Several research efforts have been conducted to understand the effect of corrosion of steel reinforcement on the structural behavior of concrete members. In order to evaluate the effect of loss of steel area on the flexural behavior of reinforced concrete members, Ting and Nowak developed a mathematical algorithm.[39] It was found that the strength reduction due to the reinforcing steel area loss is a linear function of the loss of material. In pullout tests and beam tests conducted by Maslehuddin et al., it was observed that the ultimate bond strength increased at low levels of corrosion, but with further increase in corrosion, the bond strength decreased gradually.[40] One explanation of this behavior is that the roughness of the bars increases due to the growth of a firm layer of corrosion products. As corrosion continues, severe deterioration of the bar ribs occurs along with a lubricating effect of the flaky corroded metal on the bar surface. The problem is further increased by the occurrence of longitudinal cracks that reduce the concrete confinement. The bond stress was well below the ultimate value for all levels of corrosion in the tests performed, though. Perhaps the most interesting finding in these tests was that the reduction in strength with increase in the percentage of corrosion was attributable more to a reduction in the bar cross section than to a loss of bond between steel and concrete.

The reduction in ductility will be of great concern if the structure is situated in a seismic zone or is subjected to other types of dynamic loads. For instance, in reversed cyclic flexure tests on corroded and sound beams conducted by Okada et al., the strength of a corroded beam reduced more rapidly with repeated number of load reversals compared to a sound beam.[41]

The effect of corrosion of the reinforcement on structural safety is more dangerous in the case of prestressed concrete structures, because a reduction in the prestressing tendon and strand cross-sectional area would cause a decrease of the prestressing equilibrating force. There have been cases in which collapse of structures due to corrosion of the tendons occurred, such as a parking garage in Minneapolis in 1984[1] or the Berlin Congress Hall in 1980.[42]

2.3.2 Effect on Service Life

Corrosion of the reinforcement in concrete structures will cause a reduction of their service life, due to either a gradual decrease of the structural safety factor up to the point that the structure is inadequate to resist the applied loads, or to loss of serviceability because of excessive deterioration.

The main factor that relates the service life of a concrete structure with the corrosion of the steel reinforcing bars is the rate in which this process happens. Consequently, the factors that affect the rate of corrosion of the steel bars also influence the service life of the structure. The most important factors are availability and quantity of oxygen and moisture, diffusivity of the chloride ions, oxygen, and carbon dioxide through the concrete, and permeability of the concrete.

The loss of service life in concrete structures is creating a crisis as the infrastructure deteriorates and leads to big economic losses. The social and political implications are equally important because deficiencies in the infrastructure exacerbate other problems related to public policy.

2.4 PROTECTIVE CORROSION MEASURES

There are a number of different and varied methods to protect concrete from corrosion. Some methods are used as preventive measures and others can be used as corrective measures. In most of the cases, rehabilitation is performed using a combination of several methods. They can be classified as techniques that insulate the concrete, techniques that insulate the steel, corrosion inhibitors, use of non corrosive reinforcement, and electrochemical techniques. The adequacy and efficacy of each method depends on the factors described in the previous section.

2.4.1 Protective Barriers to the Concrete

One way of providing corrosion protection to the bars is by applying a protective barrier to the concrete surrounding the bars. In this manner, the penetration of corrosive contaminants through the concrete matrix is suppressed. The barriers can be concrete coatings, waterproofing membranes, concrete overlays, and polymer impregnation. The protective concrete barriers can not be used by themselves as repair procedures. Generally, they are applied as a complement of a more comprehensive repair method in order to prevent further penetration of corrosive agents. It is very important that the concrete is sufficiently dry before application of any barrier system. Otherwise, moisture will be prevented from leaving and, if the content is high enough, the corrosion process will continue. Selection of any method is based on its resistance to penetration of aggressive ions, its suitability or compatibility with service conditions, and its durability.

a) Concrete coatings or sealers

Organic or cementitious coatings or sealers can be applied to cured concrete to act as a barrier. These are considered thin films as opposed to waterproofing membranes. Coatings have the following constituents: the binder, fillers (sometimes), pigments, additives, dispersing agents, and solvents/diluents.

The most common types of sealers are epoxy resins, acrylic sealers, silanes, linseed oil emulsions, methyl methacrylate, chlorinated rubber, styrene-butadiene, urethanes, and others.

b) Waterproofing membranes

Waterproofing membranes are applied to the concrete surface. The main objective of these membranes is to suppress the ingress of moisture and chlorides inside the concrete. There are mainly two types of membranes: Preformed sheet systems and liquid-applied materials. Extreme caution must be taken during the application of the membranes to avoid the formation of blisters. The observed performance of waterproofing membranes varies from very good to poor.

c) Concrete overlays

Overlays made of concrete with low permeability are applied to the structure. The objective of these overlays is to reduce the penetration of chlorides and water inside the concrete. The most common types of overlays are portland cement concrete overlays, low-slump dense concrete overlays, latex-modified concrete overlays, polymer concrete overlays, and silica fume concrete overlays. Application of any of these overlays requires adequate surface preparation, and proper placing and curing.

d) Polymer impregnation

This method consists of filling the voids of the concrete matrix with a monomer and polymerizing in place. Preparation includes drying the concrete by heating and vacuuming. Monomer is then applied with pressure to saturate the voids and polymerization of the monomer is effected. Polymer impregnation is still in the experimental stage and there have been few applications to protect bars against corrosion. Some disadvantages are the high cost of the process, difficulty of achieving prolonged heating and vacuum saturation, and the tendency of concrete to crack during heat treatment.

2.4.2 Protective Barriers to the Steel Bars

A protective barrier applied to the reinforcement, also known as coating, will protect the passive film of the steel bars from the corrosive action of chlorides and water. Coatings can be organic or inorganic. The most commonly used organic coatings are epoxy coatings, which may be fusion-bonded or epoxy resins. Some inorganic coatings include ceramic, metallic, and metallic-clad coatings. Metallic coatings generally work as a sacrificial coating. The use of coatings on the rebars can be very effective as a preventive measure against corrosion. For repair purposes, coatings are applied after the damaged concrete has been removed and the rebars have been cleaned.

a) Fusion-bonded epoxy coatings

Fusion-bonded epoxy coating consists of electrostatically applying finely divided epoxy powder to thoroughly cleaned and heated bars.[7] The technique is applied on new bars as a preventive measure. Application of epoxy coatings to steel reinforcement is the most popular method used today to protect bars embedded in concrete against corrosion. A two-component liquid epoxy is generally used to repair damage in the epoxy.

A point of concern has been the effect of the epoxy coating on the bond between the bars and concrete. The coating gives a smooth surface to the bars, decreasing their adherence to the surrounding concrete. Bond strength tests have been conducted to determine this effect, and as a result, codes, like ACI 318-95, require an increase in the length of lap splices and anchorages when the reinforcement has been epoxy coated.[33] For instance, the ACI 318-95 building code specifies that the basic development length, l_{db}, of bars in tension shall be multiplied by a factor of 1.5 or 1.2, depending on the cover and spacing between bars, for epoxy coated reinforcement.

b) Epoxy resins

Epoxy resins can be applied as a paint to the steel bar to protect it against the intrusion of chlorides or moisture, and to electrically isolate the bar. This electrical isolation is helpful in stopping the growth of any existing pits that had not been cleaned up. Before application of the coating, the steel bar must be thoroughly cleaned in order to remove all the rust and corrosion products from the surface. Appropriate surface preparation methods include sandblasting, grit blasting, and high pressure water jetting. The products that have been most used are solvent-free or solvent-poor epoxy coatings. A zinc-rich epoxy resin has the additional advantage of the zinc acting as a sacrificial anode, thus giving galvanic protection to the steel bar.

c) Polymer modified cement coatings or polymer concrete coatings

The objective of these coatings is to provide an alkaline environment to the reinforcing steel bars. Repair concrete has good adherence to these coatings.

d) Sacrificial coatings

Sacrificial coatings are made of metals with electrochemical characteristics which have a tendency to corrode preferentially when coupled to the steel bars. The most commonly used sacrificial coating is zinc (galvanizing). Galvanizing is unsuitable as a rehabilitation measure because the technique can only be applied to new bars. Results of the performance of galvanized bars in new construction have been conflicting.

2.4.3 Corrosion Inhibitors

Corrosion inhibitors are chemicals that prevent the entry of chloride ions at the steel surface by stabilizing the passive layer chemically. Inhibitors can be added to the concrete or mortar mix as an admixture or they can be applied directly to the steel bar. The corrosion inhibitor admixture most commonly used is calcium nitrite. Figure 2.7 shows the effect of the addition of calcium nitrite to the concrete on the corrosion of the reinforcement.[43] The ratio of chloride ions to nitrite ions is important: As the dosage of calcium nitrite is increased, a greater chloride content is needed to produce corrosion. One difficulty in the application of calcium nitrite is the determination of the required dosage, since it depends on knowledge of the chloride exposure to which the structure will be exposed. Corrosion inhibitors applied directly to the bar surface are used in the form of coatings. The steel bars must be dried to ensure sufficient penetration of the inhibitor. A specially prepared urethane resin is an example of this type of corrosion inhibitors.

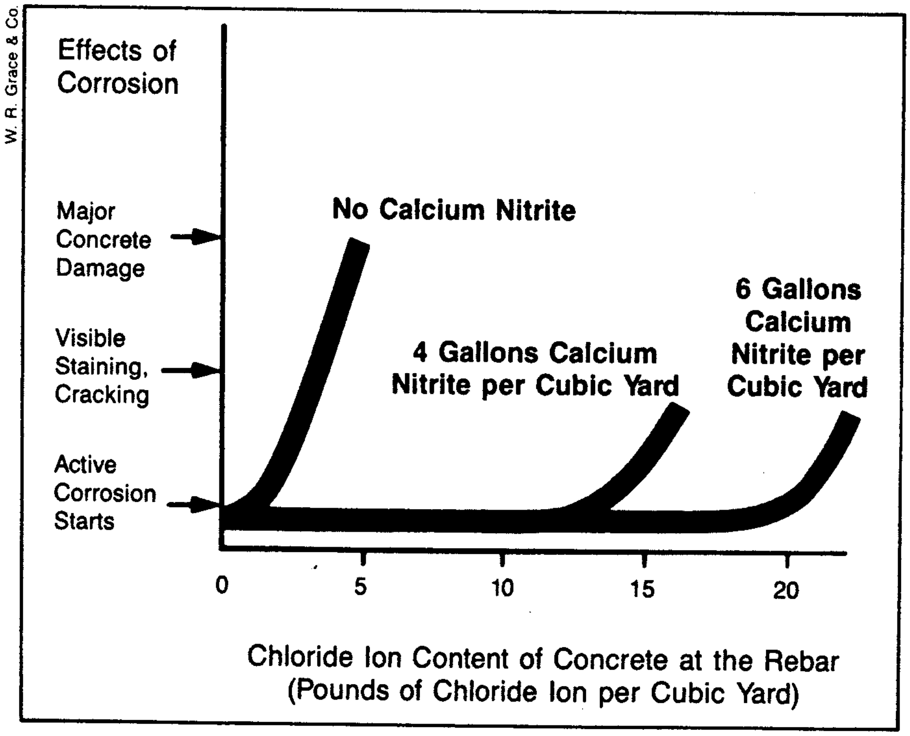


Fig. 2.7: Effect of addition of calcium nitrite admixture on the corrosion of the reinforcement.[43]

2.4.4 Non-corrosive Reinforcement

The use of reinforcement made of a material very resistant to corrosion is another alternative to prevent corrosion-induced deterioration in concrete structures. Stainless steel bars and glass-fiber-reinforced-plastic bars are examples of non corrosive reinforcement. The main disadvantage of stainless steel bars is that they are very expensive compared to conventional reinforcing steel bars. Glass-fiber-reinforced-plastic bars have a tensile strength ranging from 70 to 170 ksi but a modulus of elasticity that is very low, about one-forth that of the steel.

The above mentioned drawbacks have prevented the use of stainless steel or plastic bars as a reinforcement for concrete structures.

2.4.5 Electrochemical Techniques

The use of electrochemical techniques is one of the most innovative methods to protect the steel reinforcement against corrosion. Corrosion of steel in concrete is an electrochemical process. These techniques work on the basis of the electrochemical nature of corrosion. The two electrochemical methods actually available are cathodic protection and electrochemical chloride removal.

a) Cathodic protection

The objective of cathodic protection is to render harmless the corrosive effect of moisture, chlorides, carbon dioxide, or whatever corrosive agent, by means of electrochemically controlling the driving force that causes corrosion of the steel. The principle of cathodic protection and the different existing cathodic protection systems for concrete structures are analyzed in more depth in Reference 44. Cathodic protection is suitable both as a rehabilitation procedure and as a preventive measure.

b) Electrochemical chloride removal

This method consists of removing the chloride ions causing the corrosion of the reinforcing bars by means of an electrochemical procedure. Simply, the method is a desalination of the concrete. Electrochemical chloride removal is analyzed in depth in Reference 44. It can only be used when corrosion is caused by the presence of chlorides. Chloride removal is only applicable for rehabilitation.

Chapter 3. Literature Review of Epoxy Coated Reinforcement

3.1 INTRODUCTION

3.1.1 Corrosion Protection of Epoxy Coating

Epoxy coating provides corrosion protection to the steel substrate by means of two mechanisms: A barrier-type mechanism and an electrical resistance mechanism. In the first mechanism, the coating acts as barrier to prevent deleterious substances, such as chlorides, moisture, and oxygen, to reach the steel substrate.[45, 46, 7] The better the integrity of the epoxy, the more effective the barrier. Corrosion is then prevented or delayed by preventing or delaying the access of chlorides in the first place. In the second mechanism, the high electrical resistance of the epoxy coating has several protective effects: Increase in the macrocell corrosion path, and retardation of the cathodic reduction.[46, 47, 48] The corrosion current flow between adjacent anodic and cathodic locations is greatly reduced. Even if corrosion were to occur, the limited supply of oxygen beneath the epoxy film would be expected to keep the corrosion rate low, reducing the amount of metal loss and subsequent concrete disruption.

3.1.2 Usage of Organic Epoxy Coatings[49]

Organic epoxies have been successfully used in the coating of steel pipelines and tubing for the petroleum industry to achieve thin, but protective, barriers between the metal and the aggressive surrounding environment. When first used during the early 1970’s, most of the technology used to coat reinforcing bars was transferred from the steel pipe industry. The rationale was that steel pipelines were subjected to corrosive conditions similar to those in concrete structures where deicing salts or chlorides were present. The chemical formulation of the epoxy powders used for coating pipes and reinforcement was very similar. However, the lack of consideration of the effect of a concrete environment and other factors, such as bar fabrication and propensity to damage after coating, could have accounted for some of the observed failures. Epoxy resin formulations, which vary from manufacturer to manufacturer, have been improved as more knowledge of their performance in concrete has been gained.

In addition to reinforcing bars, other steel components used in reinforced concrete construction can be provided with an epoxy barrier to protect against corrosion. Some of these components include mechanical splice connectors, shearheads, casings and dowel bars for expansion joints, threaded plain bars for control and construction joints, and many others. Epoxy coated steel wire fabric has been introduced. Reinforcement supports such as steel chairs can be epoxy coated to isolate steel components electrically and to avoid macrocell corrosion.

3.1.3 Evolution of Epoxy-Coated Reinforcement[10]

Organic coatings were first used in the 1950's to protect the steel reinforcement against corrosion. The successful performance of epoxy coatings on underground transmission pipes encourage the investigation of epoxy resins for application in bridge deck reinforcement. In 1973, the National Bureau of Standards (NBS) and the Federal Highway Administration (FHWA) initiated the National Experimental and Evaluation Program (NEEP) Project No. 16, Epoxy-

Coated Reinforcing Steel. Tentative epoxy coatings were extensively researched and evaluated, and four epoxy products were pre-qualified. Highway agencies were then encouraged to construct experimental projects to evaluate the coated reinforcement.[12, 13, 50]

Companies applying epoxy coating to reinforcing bars were specialized in coating small diameter pipes used by utility companies and the petroleum industry, and they had to modify their equipment for reinforcing bar coating.[13, 51] The first epoxy powder formulation specifically for reinforcing bars was marketed in 1976.[52] By 1982, about 20 coating applicators were operating in the United States and Canada.[53]

The first application of epoxy-coated reinforcement in bridge decks was for a bridge in Pennsylvania (Route I-576 over the Schuytkill river). Four spans of the 15-span bridge were constructed with epoxy-coated reinforcement.[10] Subsequent bridge applications were conducted in states such as Florida, Idaho, Delaware, Iowa, and Texas.[54] By 1975, about 40 experimental bridges were constructed with epoxy-coated reinforcement.[55] In 1976, there were 10 pre-qualified coatings and the number of states participating in the NEEP survey increased to 19.[51] In 1977, 17 states specified epoxy-coated rebars for bridge decks, and nine more states were performing field evaluations.[56, 15] When the FHWA successfully concluded project NEEP 16 in 1978, most states included epoxy-coated reinforcement in their specifications.

In addition to field evaluations, FHWA conducted accelerated corrosion tests of coated bars in concrete slabs. In 1981, the FHWA concluded that epoxy-coated reinforcement was effective in providing long-term corrosion protection, its use was cost-effective, and recommended its adoption as the primary corrosion protection system for bridge decks. In the same year, ASTM published the first specification for epoxy-coated reinforcing steel bars. By 1982, 40 state highway agencies specified epoxy-coated reinforcement for new and replacement decks.[12] Some states, such as Florida, began to use epoxy-coated bars in marine structures. In 1987, 48 states specified epoxy-coated bars in bridge applications. By 1989, the number rose to 49 states.[15] Shipments of epoxy-coated reinforcement in the United States and Canada are summarized in Fig. 3.1.[51] Few other products have penetrated the highway market so rapidly. Main factors for this rapid growth were an urgent need to protect bridges, lack of confidence of alternative methods, ease of implementation, and availability at reasonable cost.[51] Use of epoxy-coated reinforcement rapidly extended to other types of structures, such as parking facilities, railroad stations,[57] cooling towers, naval facilities,[58] and others.

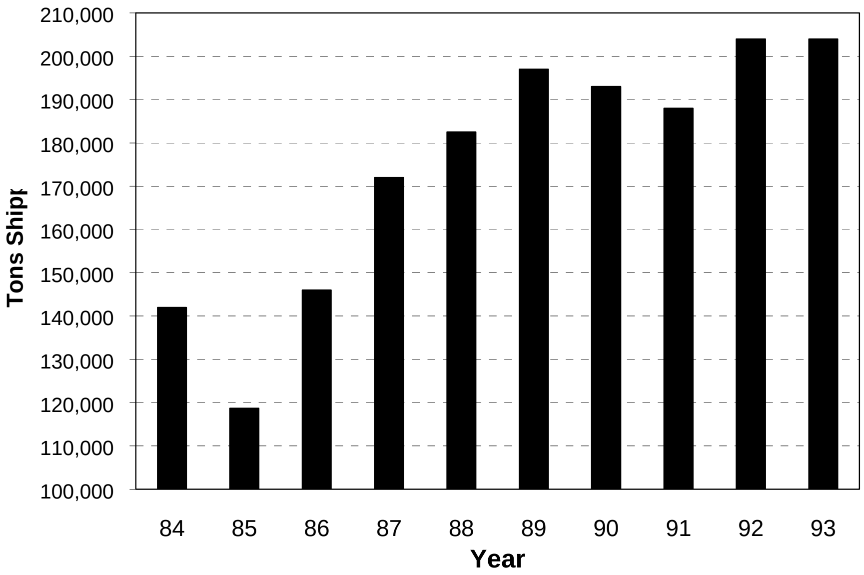


Fig. 3.1: Shipments of epoxy-coated reinforcement in North America, 1984-1993.[51]

Florida experience with epoxy-coated rebars has been unique and problematic. In 1986, corrosion-induced damage on a bridge with epoxy-coated reinforcement was observed in the Florida Keys. Subsequent investigations revealed four major bridges in the Keys with significant corrosion at the substructure. The bars met the specification requirements and no evidence of irregularities was found in the manufacturing process. Fabrication of coated bars and damage in the coating were identified as a major source of corrosion. Accordingly, the Florida Department of Transportation (FDOT) specified coating after fabrication for subsequent projects. However, based on further investigations, FDOT stopped specifying epoxy-coated bars in bridge substructures in December 1988. In 1992, FDOT discontinued the use of epoxy-coated reinforcement in all construction.[50] The agency concluded that epoxy coatings would not provide satisfactory long-term corrosion protection in a marine environment.

It should be pointed out that throughout this process, epoxy coatings have evolved. The first generation of fusion-bonded epoxy coatings were made with semi-flexible formulations that allowed the bar to be bent after coating. This usually resulted in hairline cracks and tears in the coating at outside bents, and rapid loss of adhesion that were associated with several of the corrosion failures in Florida. These coating formulations were particularly sensitive to degradation from ultraviolet (UV) exposure partly due to the curing agent used (MDA or methylene dianiline). The controversy stirred by poor performances in field structures increased the demand for coatings of improved properties and greater quality. First coatings were replaced by a second generation of epoxy coatings that were more UV resistant and more flexible. This was achieved primarily by replacing the curing agent MDA to a phenolic curing agent. More recently, chemical pretreatments have been used in some coating application processes to enhance adhesion and passivate the steel surface. The third generation consists of semi-rigid or non-bendable epoxy powder formulations that are applied after fabrication. These formulations are more resistant to cathodic disbondment and corrosion undercutting, are less permeable to water and aggressive species, and contain special fillers that block the UV radiation.[58, 59]

3.2 IMPORTANT ISSUES RELATED TO CORROSION PERFORMANCE OF EPOXY COATED REINFORCEMENT

3.2.1 Coating Damage

Continuity is a fundamental property for the epoxy coating to act as an effective barrier against the penetration of corrosion-inducing contaminants. The presence of bare areas exposing the steel surface may impair the effectiveness of the epoxy barrier. Exposed steel areas are vulnerable to corrosion in the presence of chlorides in the same fashion as the surface of uncoated bars. In addition, film undercutting may progress from corrosion initiating at exposed areas. Exposed bare areas are usually caused by damage to the epoxy coating during fabrication, handling, storage, transportation, and construction. Specifications for epoxy-coated bars set limits in the amount of permissible damage in the coating without repair. Specific requirements by AASHTO M284-87 and ASTM A775-97 will be discussed later.

3.2.2 Coating Quality

Quality of the epoxy coating material and of the application process is essential for satisfactory corrosion performance. Important coating properties that are affected by quality of the material and the application include continuity, adhesion to the steel substrate, thickness, flexibility, chemical resistance, degree of cure, permeability, and abrasion resistance, among others. Some aspects of coating quality, in particular coating adhesion to the steel substrate, will be addressed in more detail in the following chapter. Specifications for epoxy-coated bars describe qualification and quality control tests to verify different the properties of the epoxy coating.

3.2.3 Concrete Environment

As for any type of reinforcement, corrosion performance is affected by the concrete environment, namely the concrete quality. As was discussed in the preceding chapter, a concrete with high permeability will have poor durability. Thickness of concrete cover over the reinforcement is also important in delaying the penetration of chlorides. In the particular case of epoxy-coated bars, Kahhaleh found that the presence of concrete voids surrounding damaged areas in the coating provide pockets for the accumulation of deleterious substances leading to corrosion.[10] These findings were verified in the present research, as will be discussed in Chapter 8. Thus, proper consolidation of concrete is important to reduce the number of concrete voids forming around the reinforcement.

3.2.4 Coating Operations

The coating process is illustrated in Fig. 3.2.[10] The reinforcing bar goes through a conveyer line and is first cleaned and roughened by abrasive blasting (surface preparation). Then the bar is heated to a specified temperature before coating application. After coating, the bar is thermally treated (water quenching) to ensure full curing of the epoxy film. Each of these steps has been discussed in detail by Kahhaleh[10] and will not be repeated here. Instead, a shorter description of the coating stages will be included, highlighting the most relevant aspects of the coating process.

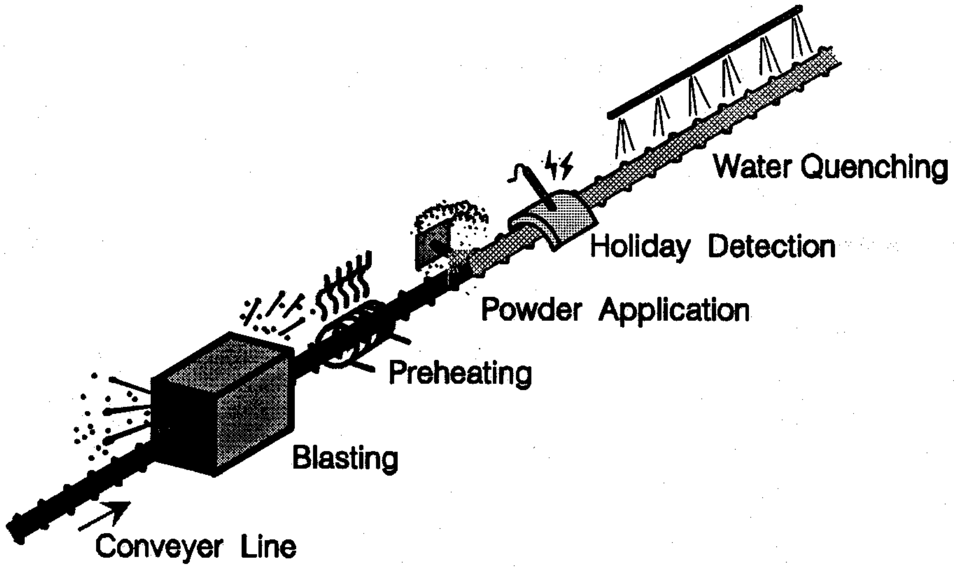


Fig. 3.2: Fusion-bonded epoxy coating process.[10]

Surface Preparation[10, 47]

Surface preparation consists of thoroughly cleaning and roughening the steel surface by blasting. Blasting removes mill scale and surface contaminants (rust, loosely adhering deposits, oil, grease, chlorides, and other foreign matter), and produces a rough surface with an optimum anchor pattern for stronger coating adhesion. Salts not removed from the surface before coating can promote corrosion.[60] An adequate surface profile (optimum number and depth of peaks and valleys) enables strong mechanical interlocking between the epoxy resin and the steel surface.

Various specifications, including ASTM, require that surfaces be blast-cleaned to “near-white” finish, according to the Steel Structure Painting Council

Surface Preparation Specification SSPC-SP10. Cleaning to “near-white” finish is not the most optimal cleaning method. The most thorough cleaning method that provides maximum coating performance is cleaning to “white” finish.

The type of abrasive for blasting is important to produce a proper anchor pattern. The height and frequency of peaks and the angularity of the surface profile is effected by the shape, size, and hardness of the abrasive. Grit blasting produces an angular shape that is more adequate for adhesion than the rounded profile of a shot blast.[47] ASTM requires an average blast profile maximum roughness of 1.5 to 4 mils as determined by replica tape measurements.

Bars should be coated as soon as possible after cleaning, because flash rust tends to appear on the surface soon after blasting. In no case should a clean bar remain outside for more than 4 hours before coating. Surface oxidation after blasting is known as “blueing” or “flash rust.”

The steel surface should be checked for defects, such as rolling laps or flaws, blowholes, fissures, slag inclusions, slivers, and scabs. Steel surface defects can impair coating adhesion. Also, excessively sharp and angular deformations can be difficult to coat properly. The coating tends to flow away at sharp edges, resulting in a very thin film. Sharp and angular deformations are usually produced when new dies are used at the mill.

Heating[10, 47]

The next step in the coating process is to heat the reinforcing bars. The steel surface needs to be at the specified temperature range for proper curing of the epoxy as it is applied to the bar surface. The optimum bar temperature at the entrance of the coating chamber depends on the epoxy type, but is generally between 232° and 246° C (450° and 475 F°). To heat the steel bars, ovens or electrical induction coils are often used. The applied temperature can be monitored through infra-red heat sensors, optical pyrometer, contact thermocouple, and temperature indicating crayons. For proper thermosetting action of the epoxy resin, a constant even temperature should be maintained. Some powders perform poorly if not applied within a 3° to 5° C (5° to 10° F) temperature range. To control the heat, the speed of bar travel and the heat generated need to be varied according to the bar mass. Larger bars require more heat and need to travel at a slower speed. Underheating will result in incomplete cure of the epoxy powder. Overheating can produce excessive foaming, poor bendability, lack of adhesion, blistering, and burning of the coating.

Coating Application[10, 47, 49]

The main methods of epoxy powder application to reinforcing bars are electrostatic spraying, tribostatic spraying, and fluidized powder bed dipping. The most common method of powder application is by electrostatic spray. The popularity of this method in the reinforcing steel coating industry is due to its applicability to in-line production. The powder is drawn from the container into spray guns. The powder is provided with an electric charge opposite to that of the base material by a small wire electrode at the tip of each nozzle. The electrostatic charge of epoxy powder enhances attraction to the grounded steel surface. The powder is sprayed from different directions to provide a uniform coat.

Several factors affect the thickness and uniformity of the coating. The physical characteristics of the powder control the amount of charge retained, and the resulting thickness and uniformity. Other factors include the speed at which bars move through the spray chamber and the orientation of the spray guns. Normally, the last 3 m (10 ft) of the bar is not well supported while being coated and the violent rotation of the end portion hinders uniform coating application.

Tribostatic spraying differs from electrostatic spraying in the method of charge induction. In tribostatic spraying, the powder is circulated in a spiral mode and the particles become charged by friction with the charged surfaces of the gun barrel.[14] This technique provides much more uniform charge, deposition, and thickness of the coating than that provided by electrostatic spraying, although more spray nozzles are required.[61]

In the fluidized powder bed dipping method, a tank is filled with the powder and when compressed air or other gases flow through, the contents of the bed are agitated and the powder resembles a fluid. Previously cleaned and preheated steel reinforcement is then "immersed" in the powder bath for a sufficient time to allow fusion of the epoxy, which is facilitated by the even flow of the powder.[62] This system is best suited for coating small pieces of reinforcement, or fabricated steel with complicated shapes, such as fittings, welded wire mesh cages, mechanical splice connectors, shearheads, casings and dowel bars for expansion joints, threaded plain bars for control and construction joints, steel chairs, and others.

Properties and physical attributes of epoxy powders used for electrostatic spray application must meet high standards. Many state transportation agencies, such as TxDOT, have a list of several pre-approved epoxy powders. Pre-approved powders meet the pre-qualification requirements specified by ASTM A775.[63] Requirements include storing the powder in original unopened containers and not using it if the shelf life has expired. If oversprayed powder is reused, it should be filtered and screened well to avoid coating defects.

Water Quenching[10, 47]

After coating, the bars are water quenched to cool the steel and coating to a temperature of around 95° C (203° F). This thermal treatment provides a fully cured coating. In a first cooling stage, the bars are moved on water-moistened, soft-covered rollers for about 30 seconds to allow slow curing. In a second cooling stage, water is directly sprayed to cool to a temperature that enables handling of the bars. The bars should not be cooled sooner than 28 seconds after coating application because cooling may stop the cure reaction before it is complete.

In the overall coating process, the time between melting to final cross-linking of the epoxy is known as the curing time. It usually takes about one minute for the bar to go from the powder spray chamber to the end of the water bath. Generally, slower curing results in better mechanical and chemical resistance properties. However, production speed would have to be slowed to achieve this goal.

3.2.5 Post-Coating Operations (Issues after Coating)

Fabrication [10]

For structural design requirements, coated bars must often be bent. Bending coated bars has two effects: a) Damage to the coating, and b) weakening of coating adhesion. Damage to the coating occurs primarily because of a) direct abrasion of the bar against the mandrels, and/or b) cracking of coating due to excessive stretching.

Damage caused by the mandrels usually appears as scraped or mashed spots on the transverse ribs at inside and outside of bends. Damage on the inside of bends is usually neglected during inspection. When the coating does not have adequate bendability or flexibility, the epoxy film may be stretched beyond its limit, and hairline cracks or micro-tears form at the bar rib bases. Weakening of coating adhesion may not always result in coating tearing or cracking, especially if coating has good flexibility.

Although the effect of speed of bending on the degree of damage is unclear, it is generally accepted that faster rates of bending produce more damage. To increase production, bars are often bent at a fast rate. Bending rates need to be modified if they produce damage to the coating. Normal rates of bending at the shop are between one to five seconds, but rates of 15 to 20 seconds may produce better results. The coating tends to crack when bending at lower temperatures. Likewise, thicker coatings have a greater tendency to crack during bending. Small radii of bending tend to produce more hairline cracking on the outer surfaces of bends.

Handling during Transportation and Construction[10, 47]

After production, epoxy-coated bars can be damaged if bars are not properly handled at different stages during transportation, storage, installation, and concrete placement. Coating damage and chipping generally results from any type of collision or violent rubbing with bars or other hard surfaces, such as:[10]

- scraping or skidding of bar bundles
- abrasion between bars when in a bundle sags during lifting
- dropping or dragging of bars
- use of unprotected contact areas on handling equipment
- dropping of heavy tools on bars
- walking and movement of heavy equipment on bars
- cutting action by tie wires
- cutting and welding of bars
- field bending or straightening of bars
- improper placing or dropping of concrete on bars
- abrasion by impact from internal concrete vibrators

Long periods of outside storage may affect performance of epoxy-coated bars. Of special concern is the exposure to ultra-violet rays and salt water spray for prolonged periods. The epoxy color may fade or chalk after exposure to sunlight for long periods. CRSI guidelines state that the discoloration does not harm the coating nor its properties.[64] Other studies have indicated that heating/cooling cycles and exposure to ultra-violet rays have resulted in deterioration of the coating.[65] Lee and Neville observed chemical changes in epoxy films from exposure to ultra-violet rays.[66] Exposure to chlorides and moisture can cause coating debonding and corrosion at holidays and damaged areas, even if the bars conformed to previous specifications.[50]

To avoid and minimize damage in the coating, good practice should be followed when handling the bars at the coating plant, during transportation, and at all subsequent stages after they arrive at the construction site.

3.3 CORROSION PERFORMANCE OF EPOXY COATED REBARS

3.3.1 Review of Durability Studies

A great deal of research has been conducted on the corrosion performance of epoxy-coated reinforcement in the last 20 years. Studies include both laboratory and field evaluations. Much of the present knowledge about epoxy-coated reinforcing bars has derived from the extensive research conducted. A summary of previous durability studies involving epoxy-coated bars is presented in the following sections. Kahhaleh has compiled and summarized a very extensive and complete list of previous durability studies.[10] The majority of such studies will not be described here and can be found in that reference. The studies included in this dissertation are either new studies not previously reported by Kahhaleh; studies reported by Kahhaleh where findings have been updated; or studies that are important and relevant for understanding the manner in which epoxy coatings function.

National Bureau of Standards, US, 1974[11, 45, 67]

Study. Sponsored by the Federal Highway Administration, the NBS performed an exploratory research of potential organic coatings for the protection of steel reinforcement in concrete. Forty-seven different coatings, of which 36 were epoxy coatings, were used in the tests, including liquid and powder epoxy, polyvinyl chloride powder, polyurethane liquid, polypropylene powder, phenolic nitrile liquid, and zinc rich liquid coatings.

Findings. *Chemical Resistance*. Bar specimens were immersed in 3M NaOH, saturated $Ca(OH)_2$, and 3.5% 0.7M NaCl for one year. Epoxy coatings applied on sandblasted surfaces were not affected by these chemicals. Absorption tests on epoxy coated disks showed the epoxies absorbed measurable amounts of water. Thin epoxy films, 50-250 μm (2-10 mils) thick, were not entirely impervious to moisture, as indicated by weight gains of 0.8 to 16% in tested specimens.

Chloride Permeability. Cured powder epoxy films, with thicknesses of 75 to 180 μm (3 to 7 mils), were practically impermeable to chloride ions after 37 weeks of exposure in special permeability cells. No clear interpretations were drawn from these tests, and it was concluded that epoxy films with low permeability values would probably provide satisfactory protection to reinforcing bars.

Film Integrity. Film integrity was assessed by visual examination, measurement of coating thickness, and holiday count per unit length of bar. Powder epoxy coatings produced films of moderate thickness 180 ± 50 μm (7 ± 2 mils) that were free of defects and holidays. Bar deformations were not concealed by this coating material. The electrostatic spray method of application produced coatings with improved integrity and covering characteristics than produced by the fluidized bed method.

Bend Test. Coated bars, 19 mm diameter (#6), were bent through an angle of 120° over a 75 mm (3 in) radius mandrel. Bent samples were checked visually for evidence of cracking or debonding of the coating. Powder epoxy coatings of moderate thicknesses performed well. Specimens with film thickness over 250 μm (10 mils) generally failed the test.

Abrasion and Impact Resistances. None of the powder epoxy coatings failed the abrasion resistance test in accordance with ASTM D1044-56. Powder epoxy coatings showed satisfactory impact resistance as per ASTM G14-69T. Damaged areas did not exceed a chosen limit of 95 mm^2 (0.15 in^2).

Applied Voltage Studies. A potential of two volts was applied between two 19-mm (#6) coated bars immersed in 7% NaCl electrolytic solution. Powder epoxy coatings thicker than 125 μm (5 mils) did not experience signs of corrosion after one month of testing. Subsequently, single holes of 6 mm (1/4 in) diameter were introduced in both bars and the test was continued for additional 24 hours. Significant undercutting was observed around the holes.

Electrical Potential and Resistance Measurements. Electrical potentials and resistances of epoxy films were measured on coated bars partially immersed in 3.5% NaCl solutions. Coatings with resistance below 500 ohms were considered to have many holidays or to be permeable to water and chlorides. Several corrosion sites were observed when potential readings fell below -600 mV with respect to a saturated calomel electrode (SCE). Properly applied powder epoxy coatings with thicknesses between 150 to 280 μm (6 to 11 mils) performed satisfactorily.

Bond and Creep Tests. Results from pullout tests revealed that bond strength of coated bars in concrete with film thicknesses below 250 μm (10 mils) were very similar to those of uncoated bars. Coatings with such thicknesses showed acceptable creep characteristics too. Very thick epoxy films (about 630 μm or 25 mils) developed bond strengths of only about 60% of those of uncoated bars.

Conclusions. Properly formulated and applied powder epoxy coatings should satisfactorily protect reinforcing steel bars against corrosion. The inert barrier provided by the epoxy coating can withstand stretching during bending of bars and impact or abrasion caused during normal construction practice. Coated bars with maximum film thickness of 250 μm (10 mils) can be safely used in concrete without risking structural performance. The optimum thickness in terms of corrosion protection, bond strength, creep characteristics, and flexibility was 180 ± 5 μm (7 ± 0.2 mils). Four epoxy resins were identified in this study as suitable for application in reinforcing bars. Pre-qualification requirements for epoxy coatings were developed. These requirements have changed little over the years and are used today to approve epoxy coating materials.[51]

Federal Highway Administration, US, 1981.[22, 48]

Study. A series of slabs were built in 1974 containing both coated and uncoated bars. Coated bars had two types of epoxy materials used in the first bridge deck constructed with epoxy-coated reinforcement. Coated bars were classified as either specification (two or less holidays per foot) or non-specification (more than two holidays per foot) bars. Various amounts of intentional coating damage were introduced in the bars. A 3% salt solution was ponded on the top surface of the slabs during the summer months for 4 years. Slabs were subsequently subjected to natural weathering at an outdoor exposure facility in northern Virginia. The top and bottom steel mats were not tied electrically and in most cases, top bars were not connected. A follow-up study on four slabs was performed after 7 years, consisting of demolition of slabs and examination of the embedded steel and coating. Finally, remaining slabs were examined after sixteen years of exposure, by extracting 34 cores from eight slabs.

<u>Findings</u>. Slabs with uncoated bars exhibited cracking after 0.7 year of exposure, and severe corrosion with section loss was evident after 7 years. Slabs with coated bars using epoxy material B started to experience cracking and delamination after about 4.2 years of exposure. Nevertheless, research results indicated that even non-specification epoxy-coated bars provided superior corrosion protection compared to uncoated bars.[22, 68] A progress report stated that the time to corrosion-induced cracking would be extended at least about 5 times. However, the report warned that some instances of coated bar corrosion and induced distress were observed, and that additional exposure time and screening tests were needed.[69]

Subsequent autopsies after 7 years of exposure revealed that non-specification bars underwent significant underfilm corrosion. Corrosion-induced cracking was observed on slabs where bars had bare areas and, in some cases, excessive holidays. Coating disbondment and undercutting were observed on bars with the two epoxy materials. For the 3 slabs with coated bars using epoxy material A, coated bars with excessive holidays and no bare areas were in better condition than bars with bare areas of 1.1% and 7.2% of the bar surface (in both cases, bar ends were uncoated). Coated bars with two or less holidays per foot, no bare areas, and patched bar ends experienced only light corrosion with no apparent undercutting. Coated bars with epoxy material B in the fourth slab had excessive holidays (more than 25 per foot), were spliced, and bar ends were uncoated. These bars experienced severe corrosion and undercutting. The coating could be easily removed from more than half of the coated bar area with a knife.[22]

Almost all slabs were badly cracked (due to both freeze-thaw and corrosion damage) after 16 years. The two slabs that showed slight cracking only (possibly freeze-thaw related) contained bars without intentional coating damage, two or less holidays per foot, and no bare areas. Bars with deliberate coating damage and/or uncoated bar ends were severely corroded, and the coating was blistered, cracked, brittle, and debonded. Bars with epoxy material A which had too many holidays to measure but no bare areas experienced less corrosion but the coating lost adhesion on all bars. Bars with two or less holidays per foot with no bare areas exhibited only light or spotty corrosion, but coating adhesion was poor on all bars. Apparently, bars with few holidays and no bare areas were experiencing the early stages of corrosion failure after 16 years of exposure. Interestingly, seven of the eight slabs displayed corrosion potentials more negative than -600 mV with respect to a copper sulfate electrode (CSE) [-525 mV with respect to a saturated calomel electrode (SCE)].[22]

Federal Highway Administration, US, 1981.[22, 69]

Study. This investigation, initiated in 1974, involved partial immersion of over 100 reinforced concrete beams with a single bar in a saturated sodium chloride solution for over 6.5 years. Testing variables included uncoated and coated bars, two types of epoxy coatings, bars conforming and not conforming to the specification (two holidays per foot or less, and up to 2% visible bare area).

Findings. Specification bars outperformed non-specification bars. Only 5% of the beams with specification epoxy-coated bars showed cracking, while 49% of the beams with non-specification bars (more than 25 holidays per foot and/or greater than 2% visible damaged area) showed cracking. All beams with uncoated bars were cracked after 2.8 years of exposure. All uncoated bars were much more severely corroded than coated bars; coated bars with epoxy material B were more corroded than those coated with material A; and bars coated with material A conforming to the specification exhibited the least corrosion, with no underfilm progression at intentionally damaged areas. While moist upon removal from the concrete, all coatings could be removed with varying degrees of ease with a knife.

Minnesota Department of Transportation, US, 1982.[70]

Study. A research program was established to evaluate different corrosion protection systems and repair procedures for bridge decks in Minnesota. The two basic approaches were (1) the use of special concrete overlays, deck sealers, and waterproof membranes to prevent chloride penetration, and (2) the use of galvanized or epoxy-coated bars after chlorides contaminate the concrete. Bridge decks were built or repaired from 1974 to 1978 and were tested annually through 1981. In this study, only three decks had epoxy-coated bars, one of them combined with a low slump dense concrete overlay. Field evaluation consisted of visual examination, corrosion potential surveys, depth of concrete cover measurements, delamination detection, and chloride content analysis.

Findings. Bridge decks with epoxy-coated bars experienced limited cracking and scaling. After four years of service, no corrosion-induced areas of deteriorated concrete were found. Chloride content at the level of reinforcement was below the threshold for corrosion initiation in all decks. There appeared to be some corrosion activity in one deck with coated bars in both top and bottom mats. The percentage of corrosion potentials more negative than -350 mV CSE (-273 mV SCE) increased with time. These readings were thought to reflect small areas of corrosion at coating discontinuities, instead of widespread corrosion. The majority of readings indicated absence of corrosion.

Federal Highway Administration, US, 1983. [22, 48, 68]

Study. Thirty-one concrete slabs with epoxy-coated bars not conforming to then-current specifications or with concrete containing calcium nitrite admixture with uncoated steel were subjected to outdoor exposure in 1980. Control slabs with uncoated bars in concrete without admixtures were prepared for evaluating the corrosion protection systems. Concrete was placed in two lifts: The bottom lift did not contain chlorides, and the top lift had 8.9 kg/m^3 (15 lb/yd^3) of chloride ions added to the concrete. A reinforcing steel mat was placed inside each lift. A poor quality concrete (w/c = 0.53), epoxy-coated bars with many holidays (more than 80 per meter) and failing the bend test, and intentional electrical coupling between the reinforcing mats accelerated corrosion. The epoxy-coated bars had been stored outdoors for over two years. Extent of damaged coating was 0.22 and 0.80% of bar surface area. The coating thickness was excessive and did not meet the specification. In some cases, bars for the bottom mat were epoxy-coated, and in other instances they were uncoated. The slabs were ponded with a 3% salt solution for 46 days and then exposed to natural weathering for the rest of exposure. Selected specimens were autopsied at about two years, and remaining specimens continued to be exposed. One slab was autopsied after 9 years of exposure. Corrosion was monitored by measuring corrosion current, open-circuit or instant polarized corrosion driving voltage, corrosion potentials of top and bottom mats, mat-to-mat electrical resistance, and slab temperature.

Findings. The corrosion rate was reduced by at least one order of magnitude with either epoxy-coated bars or calcium nitrite admixture. Slabs with uncoated bars only were cracked and the bars corroded extensively. No cracking was observed in slabs with epoxy-coated steel. No significant differences in performance were observed between coated bars with holidays only and those with holidays and visible damaged areas. When only the top mat was epoxy coated, it was estimated that it would take an average of 12 years to consume the same amount of iron consumed in one year when only uncoated steel was used.

When both mats were coated, it was estimated that it would take 46 years to consume equal amounts of iron. Light rusting was observed under the epoxy coating at certain locations. Inadequate bond between the coating and the steel allowed underfilm corrosion. Corrosion initiated at holes in the coating and progressed beneath the coating. It was concluded that epoxy-coated reinforcement should be many times more resistant to corrosion-induced damage than uncoated reinforcement even if the coated bars did not meet the specifications. It should be emphasized, however, that the levels of coating damage used in the study were not severe (below 1%). As will be shown in the study presented herein, levels of damage of 2% can result in significant amounts of corrosion.

Cracking of slabs with epoxy-coated bars was first noticed after 7 years, and after 9 years of exposure, all slabs were cracked as a result of corrosion. Time-to-cracking did not differ significantly between slabs with: 1) One mat vs. two mats with epoxy-coated bars, or 2) intentionally damaged bars vs. bars without intentional damage. In one slab, the top mat with coated bars showed significant corrosion and undercutting of the epoxy coating. A low pH liquid (less than 1) was found on the corroded coated bars. The coating of the bottom mat bars could be easily removed with a knife when the coating was either wet or dry.

Federal Highway Administration, US, 1987.[22]

Study. Slab specimens were subjected to 48 weeks of “southern exposure.” Cases with the top mat coated only and with both mats coated were studied. Macrocell currents and corrosion potentials were measured. Follow-up work consisted of testing of full-size reinforced concrete columns and beams subjected to saltwater exposure. About half of the bars contained one or two holidays per foot and the other half contained no holidays. Average coating thickness range from 8 to 10 mils.

Findings. Corrosion was minimized with epoxy-coated bars, even with 1 inch of cover, poor quality concrete (w/c = 0.51), and chloride levels around the bar 20 times greater than the threshold for corrosion of uncoated bar. No corrosion developed on coated bars, premarked holidays did not develop any corrosion, and specimens with coated bars developed high mat-to-mat electrical resistance. In contrast, control specimens with uncoated bars and 1-inch cover exhibited high corrosion rates.

Florida Department of Transportation, US, 1988.[10]

Study. Corrosion of concrete structures with epoxy-coated bars was first observed in 1986 on the substructure of the Long Key Bridge in the Florida Keys only six years after construction. A subsequent field survey by the Florida Department of Transportation (FDOT) unveiled significant corrosion of coated reinforcement in four of the five major bridge substructures in the Florida Keys. The fifth bridge , Channel Five Crossing, started to experience corrosion damage in March 1993.[20]

Findings. Corrosion occurred mainly at the splash zone of the substructures. Apparently, corrosion initiated in the fabricated bars at bends and progressed later to straight bars. An acidic solution (pH of 5) was frequently observed beneath the coating. A thin black, relatively dry corrosion product was observed on the steel substrate. Some bars experienced severe pitting. Concrete delamination and spalling occurred at zones of advanced corrosion. Corrosion spread to areas of sound concrete adjacent to the spalled areas. Although some spalls occurred in areas with shallow concrete cover and where concrete had poor quality, corrosion was mainly observed at areas with up to 10 cm (4 in) of sound concrete cover. Nevertheless, Kahhaleh observed that there was no agreement regarding in-situ concrete cover thickness, and it is possible that the cover was less than 10 cm in the corroded areas.[10]

Chloride concentrations at the rebar level were very high: 3 to 11 kg/m^3 (5 to 18.5 lb/yd^3) with a typical value of 9 kg/m^3 (15 lb/yd^3). In addition to the high salinity of seawater in the Florida Keys, a main contributing factor for the high chloride contents was early concrete cracking. Bar samples extracted from areas above the deteriorated splash zone showed complete loss of coating adhesion. The metallic surface beneath debonded coating was bright, dull, or slightly darkened. The quality of the coating was acceptable according to some references. Surface cleaning and anchor profile were marginal and the coating foam level was excessive, according to other references. Coating damage did not exceed the 2% limit in current specifications at time of construction.

Technical Research Centre of Finland, Finland, 1988 [71]

Study. The corrosion protection ability of one powder epoxy coating applied by electrostatic spraying and three liquid epoxy paints was studied. The corrosion testing program consisted of: a) tests on small concrete grout cylinders, and b) tests in cracked concrete beams under repeated tensile stress.

Concrete Grout Cylinders. Corrosion tests on small cylinders were planned to last 10 years and results after 2 years of exposure have been reported. A coated bar was embedded in each cylinder. Three groups of bars were tested: Bars with undamaged coating, bars with an intentional coating defect, and bars without coating. Some cylinders were prepared with 4% $CaCl_2$ added to the concrete mix, and some cylinders had a transverse crack crossing the embedded bar at the exact location of the coating defect. Cylinders were immersed in both tap water and synthetic seawater. Cyclic exposure consisted of raising and lowering the level of the solution every month so that for 50% of the time, the intentional coating defect was below the water, and the rest of the time above.

Cracked Concrete Beams. As with small cylinders, three groups of bars were tested: Bars with undamaged coating, bars with an intentional coating defect, and bars without coating. Beams were pre-cracked before the beginning of the test to produce a maximum crack width of 0.3 mm. During the test, each beam was loaded and unloaded about 7.5 times per minute. The peak load produce a tensile stress of approximately 200 N/mm^2 for the first two months, and subsequently about 150 N/mm^2 at each loading cycle. The beams were partly immersed in synthetic seawater at an inclination of 45°.

Findings. *Small Concrete Cylinders*. Powder epoxy coating and coal tar epoxy paint were effective in protecting against corrosion. However, corrosion was not completely hindered. Other liquid epoxies showed marginal or poor performance. The presence of a defect in the coating impaired corrosion prevention. Corrosion concentrated around the coating defect. Interestingly, some bars with a coating defect corroded more than uncoated bars. Bars in cracked concrete cylinders did not experience increased corrosion. The author stated that calcium hydroxide from the concrete leached into the cracks, producing a healing effect.

Cracked Concrete Beams. Only two beams with uncoated bars were examined after 1.5 and 3 years of exposure. Bars experience minor corrosion only, precisely at crack locations above the water level. No additional beams were examined. Eight beams remained under exposure at the time of the report.

Florida Department of Transportation, US, 1989 [22]

Study. In October 1979, FDOT began an investigation of different types of reinforced concrete piles at Matanzas Inlet on the east coast of Florida. Each pile was 6 in x 6 in by 10 ft and had 4 reinforcing bars held in place by insulated chairs. Placement of the piles was done by jetting to 5 ft. After 9 years, the piles were examined in the field and selected piles were removed and autopsied.

Findings. No changes were observed on any of the piles after about 2.5 years, although potential measurements in the tidal zone appeared to indicate active corrosion after about 5 months for both uncoated and epoxy-coated specimens. Potential differences along the length of the piles were much greater for piles with uncoated bars than for the piles with coated bars, indicating lack of macrocell action in the epoxy-coated case. At least one of the piles with uncoated bars showed corrosion-induced distress after 4 years. Extensive bar corrosion with rust products and damage in the surrounding concrete was observed in the pile with uncoated bars after 9 years of exposure. No corrosion-induced distress was observed in the pile with epoxy-coated bars. The coated bar was in excellent condition with minor corrosion at a holiday only. Corrosion did not progress beneath the coating.

Ontario Ministry of Transportation, Canada, 1989 [10, 51]

Study. A field investigation of barrier walls with epoxy-coated reinforcement was conducted by the Ontario Ministry of Transportation (MTO). The barrier walls were constructed in the late 1970's and were subjected to chloride contamination, which was facilitated by extensive shrinkage and plastic settlement cracks and voids. Two of the sections investigated had epoxy-coated reinforcement, while a third section had uncoated reinforcement for comparison. Crossing and overlapping bars were tested for electrical continuity, and corrosion potentials were measured along each bar. Corrosion rate was measured at the most active location with a three electrode linear polarization probe. From concrete cores extracted at critical locations, the chloride content in concrete and the bar condition were assessed. The concrete cover was removed at the area with most corrosion. Coated bars were visually inspected and results were correlated with corrosion measurements.

Findings. While the wall with uncoated bars experienced extensive rust staining, barrier walls with epoxy-coated bars were in good condition, without evidence of concrete deterioration. Minor surface corrosion at a small bare area was observed on only one bar in cored samples. Remaining coated bars from cores showed no evidence of corrosion activity. The coating condition was good with no evidence of adhesion loss. Uncoated bar samples experienced extensive and severe corrosion. In the wall section where concrete cover was removed, only superficial corrosion on a stirrup was observed. Corrosion was minor and localized, with no pitting or underfilm progression. Coating adhesion was stronger between the transverse ribs than on the ribs. Damage in the coating, apparently caused by bar-to bar abrasion and fabrication, was observed at the study area. Outer bends of stirrups presented extensive lateral hairline cracking and damaged ribs. Inner bends showed a few hairline longitudinal cracks and debonded areas.

University of South Florida, US, 1990 [10, 22, 50, 72, 73]

Several laboratory experiments were conducted to help explain the corrosion observed in the Florida Keys bridge substructures. Laboratory experiments included exposure to salt solution of straight and bent coated bars in concrete prisms, and immersion of coated bars in different solutions. The coating was intentionally damaged in some of the bars. Field studies included examination of bars at construction sites, a state-wide survey of bridges, and examination of test piles. Details of the studies can be found elsewhere.[72,73] Main findings indicated that corrosion of epoxy-coated bars was worsened by bending the bars, defects in the coating, and establishment of macrocells.[73] Bending of coated bars resulted in reduced coating adhesion and formation of cracks and holidays on the outer bends. Corrosion was evident at exposed steel areas. Adjacent steel surfaces were dark and the coating lost adhesion. It was found that several conditions led to disbondment of the coating, such as exposure of bars to salt water, mild levels of cathodic polarization, and anodic conditions while corrosion advances. It was observed that disbondment could occur in chloride-free concrete and that sodium ions, and perhaps potassium ions, played an important role. Coated bars removed from a test site at Matanzas Inlet after 9 years in service were found to be in good condition. The bars did not have damage or defects in the coating. Bars examined at construction sites showed corrosion at defects in the coating and poor coating adhesion. Complete disbondment of the coating was observed in all but one of the first 14 bridges examined, regardless of chloride levels.[50]

University of South Florida, US, 1991 [65]

Study. The main objectives of this study were to understand the mechanism of corrosion of epoxy-coated reinforcement in marine substructures, to determine the causes of coating debonding, to devise a model for corrosion prediction, and to evaluate a corrosion control method for corroded substructures.

To study coating debonding before placement of concrete, test bars were subjected to mechanical damage (1% of surface area) and immersed in 3.5% NaCl solution for four weeks (to simulate conditions at marine job sites). To study coating debonding after placing concrete but before chloride attack, test samples were subjected to exposure in synthetic concrete pore solutions, such as $Ca(OH)_2$ (specimens were previously exposed to 3.5% NaCl solution), and Na(OH) for 30 days. Test bars had about 0.25% damage to coating. To study coating debonding after chloride attack, test bars were first exposed to 3.5% NaCl solution and then submerged in Ca(OH)2 + NaCl solution. In all cases, bars from different source were used and the extent of coating debonding was determined using a sharp knife.

Eight concrete column specimens with coated bar segments placed at various levels were subjected to marine conditions by submerging the column bottoms in 5% salt water. In addition, 11.9 kg/m^3 (20 lb/yd^3) of chlorides were added to the concrete mix at the lower part of the columns. Tested bars had intentional damage in the coating of about 2% of surface area. The exposed steel areas in half of the bars were subjected to corrosion before the test.

Findings. The amount of coating debonding varied considerably from product to product. Debonding increased with time. Pre-existing corrosion did not worsen debonding in $Ca(OH)_2$ solution regardless of potential used. Similar debonding was observed at exposure to either Na(OH) or NaCl solutions at alike potentials. No corrosion products were observed under the coating in the case of Na(OH) solution, indicating cathodic debonding. In the cathodic potential range, debonding was probably an oxide dissolution mechanism at the steel/coating interface rather than alkaline degradation of the coating itself. Pre-existing corrosion significantly increased debonding upon exposure to an NaCl + $Ca(OH)_2$ under anodic conditions. Therefore, coated bars with pre-existing corrosion at damaged areas may produce more severe corrosion.

Pre-existing corrosion tended to ease cathodic reactions by debonding and exposing more surface to oxygen reduction. The increase in the rate of cathodic reactions resulted in overall larger corrosion activity. With longer exposure, cathodic debonding increased and resulted in similar macrocell currents for bars with both with or without pre-existing corrosion. In addition, in two columns with pre-corroded bars, only marginal anodic action was developed. At cathodic ends, complete coating debonding occurred without corrosion traces, while at the anodic ends, debonding of about 67% of the coating with underfilm corrosion was observed. A few small blisters were observed facing air voids in the concrete. An acidic liquid was frequently found in some of the blisters. Underfilm corrosion was relatively uniform without gross pitting.

Concrete Reinforcing Steel Institute, US, 1992 [22, 46, 47, 51, 74, 75]

The Concrete Reinforcing Steel Institute (CRSI) sponsored a long-term, 9-year study on the effectiveness of epoxy-coated reinforcement. The research, conducted by Kenneth C. Clear in Virginia, was divided in three areas:

Long-term Outdoor Exposure Study. Slabs with straight epoxy-coated, galvanized, and uncoated bars were subjected to macrocell corrosion by cyclically ponding 3% NaCl solution for 3.1 years. At the end of ponding, the slabs were exposed to normal weathering for 5.4 more years. The bars met applicable specifications.

Chloride content at the top bar level was very large after 3.1 years (more than 5.9 kg/m^3; 10 lb/yd^3). Slabs with epoxy-coated bars (at top mat or both mats) did not crack and exhibited very low or negligible corrosion currents. In contrast, slabs with uncoated bars cracked within 0.9 to 1.5 years and experienced corrosion currents more than 100 times greater than those of coated bars. Extensive corrosion products and section loss were seen in uncoated top bars. The best performance was achieved with both mats epoxy-coated. Typical corrosion in coated bars was minor, without significant metal consumption. Mat-to-mat resistance in slabs with coated bars did not decrease with time, indicating that the epoxy coating did not have a tendency to deteriorate after 6.5 years. Top and bottom bars experienced softening of the coating without underfilm corrosion.[75]

Macrocell Study. Straight and bent epoxy-coated bars from different suppliers were subjected to macrocell action in 60 concrete slab specimens. Bar sizes #4 (13 mm) and #5 (16 mm) were used in the study. Twenty test variables (three specimens per variable) were studied, including: Comparison with uncoated bar, thickness of coating, bend rate and temperature, patching damaged areas, coating before and after fabrication, and bend diameter. Except for one supplier, all bars met the specification, and most bars had high quality coating (no holidays or bare areas). Two slab specimens per variable were subjected to 70 weeks of cyclic ponding to 15% NaCl solution (4 days) and exposure to ultraviolet light (3 days), in the so called southern exposure. After the 70-week exposure, 25 slabs were ponded with tap water for 4.5 months or 10.5 months. The slabs were then moved outside and were exposed to natural weathering for 1.3 years. Twenty slabs not subjected to the southern exposure cycling were exposed to natural outdoor weathering for three years.

Slab specimens with epoxy-coated bars did not experience rust staining or cracking during cyclic ponding. Corrosion currents for most slabs were negligible. In contrast, slabs with uncoated bars experienced rust staining, cracking, and about 80 times more corrosion current on the average than that of coated bar slabs. Minor corrosion was observed at damaged areas and holidays on bent and straight coated bars. Performance of coated bar specimens changed during and after ponding with tap water. The majority of slabs experienced corrosion-induced cracking accompanied by high corrosion currents and significant reductions in mat-to-mat resistances. Source of the bars was the only variable that correlated with change in performance. It was theorized that the southern exposure had a drying effect in the concrete but, at the same time, had a deteriorating effect on the epoxy coating. Continuous wetting of previously chloride-laden concrete possibly created osmotic pressures and/or provided a highly moist environment that was conducive to corrosion. The slabs not exposed to the southern exposure were free from deterioration or loss of insulating properties.

Bridge Deck Field Study. Thirteen bridge decks with epoxy-coated reinforcement, built between 1974 and 1981 in the Eastern US, were evaluated. Bridges had been in service for 9 to 16 years. Eighty-five concrete cores from sound and unsound areas (including cracks) were taken and chloride content at the bar level was measured at a few uncracked locations. One hundred and seven segments of epoxy-coated bars were obtained.

Eighty-seven percent of coated bar samples from top mat cores had minimal or no corrosion. Some bars at crack locations experienced significant localized corrosion but without significant section loss. Some bar samples away from cracks showed some corrosion. Chloride content at bar level in half the cores did not exceed the threshold value for corrosion initiation. Chloride contents (water-soluble) between 0.6 to 4.7 kg/m^3 (1 to 8 lb/yd^3) were measured in the rest of the cores. Despite having many holidays and small damaged areas, coated bars in uncracked sections had good performance. Except at some cracks, the steel surface beneath the coating remained bright and shiny.

Peer Review by Wiss, Janney, Elstner Associates, Inc., 1993 [51, 76]

CRSI asked the engineering consulting firm Wiss, Janney, Elstner Associates, Inc (WJE) to conduct a peer review of this research, which was originally performed by Kenneth C. Clear, Inc. Their main finding was that the holiday count strongly influenced corrosion performance for both the long-term outdoor exposure test and the macrocell test on coated bars from different suppliers. Untested companion bars from different sources showed a large number of holidays in excess of specification limits. Electrical resistance was effective in assessing the corrosion protection capabilities of coated bars. Measured initial resistances correlated with number of holidays on companion retained bars. Thin films are prone to develop more holidays and, consequently, be more susceptible to corrosion. The following factors were not found to have a major influence on test results: Thickness of concrete cover, concrete water absorption, epoxy water absorption, surface roughness profile, film backside contamination, and curing of epoxy coating.

Clear disputed WJE’s conclusions because the correlation between holidays and performance was determined by measuring the number of holidays in the retained bars, without considering the measurements reported by Clear on the actual bars cast in the slabs. Clear claimed that deterioration of bars during storage and damage in previous shipping and handling resulted in more coating breaks shown in the WJE data. Similarly, WJE data included measurements near the ends of bars, which Clear excluded because they were not embedded in concrete. Clear also argued that the bars used in the slabs were selected carefully and were the highest quality bars received.[22, 51]

Testing on four slabs of the long-term exposure study was continued. Two slabs had been exposed to salt and showed hairline cracks above some bars. The other two slabs had never been exposed to salt. The slabs were cut transverse to the reinforcement to obtain two specimens. One specimen was ponded with salt solution and the other with tap water, and the bars were electrically connected. One slab ponded with salt solution was autopsied after 175 days of ponding. The bar beneath the hairline crack experienced blistering and cracking of the coating on about half of the surface, and the remaining coating surface was loosely adhered. In a second bar adjacent to a surface crack, adhesion was lost on two thirds of the surface and corrosion was taking place.[76]

Slab specimens retained by KCC Inc.

Several slab specimens for the long-term exposure study and the macrocell study were retained by KCC Inc. at the end of the contract with CRSI. Apparently, some slabs were incorporated for a study sponsored by C-SHRP, and other slabs were used for in-house research by KCC Inc. Results of the autopsy performed on one-half of one slab (part of the long-term study) are described in a subsequent section where the C-SHRP research is discussed. In February 1992, two specimens of the macrocell study were opened after 3.25 years of exposure. The concrete was cracked and delaminated, and bar corrosion was severe. The epoxy coating was brittle, blistered, cracked, and debonded in many areas on both straight and bent bars. A black product formed beneath the coating, with a pH in the range of 5-6.[22]

Canadian Strategic Highway Research Program (C-SHRP), Canada, 1992 [51, 77]

Study. The project “Effectiveness of epoxy-coated reinforcing steel,” conducted by Kenneth C. Clear, was divided in two phases. Phase I included documentation of the state-of-the-art; survey of producers; status of usage of epoxy-coated bars in Canada; a comprehensive account of the production and performance of epoxy-coated reinforcement; back to fundamentals regarding tests used in the pipeline and bar industries, and in other fields; and preparation of a work plan for Phase II.[47]

For Phase II, coated bars from 12 Canadian and US coating plants, 7 Canadian and US job sites, and 19 field structures built in Canada and the Northern US between 1974 and 1988 were acquired and tested. Cores taken from 13 bridges in the US as part of the CRSI study were available to the project. In addition, cores were obtained from two structures in each of the provinces of Alberta, Ontario, and Nova Scotia. Slabs from the long-term exposure study sponsored by CRSI were also available for this project. The project also included outdoor exposure of coated straight and bent bars in Toronto for six months to simulate the effects of job site storage. Laboratory examination of coated bars included detection of defects in the coating, underfilm contamination and foam in the coating, anchor pattern, coating hardness, coating adhesion, and electrical insulation of the coating. Coating adhesion was measured by the dry knife adhesion test, which consists of conditioning the bars in a desiccator for at least 7 days, and subsequently scoring and prying the coating with a sharp knife.

Two accelerated tests were conducted: A chemical immersion test consisting of 45-day immersion in aerated saturated limewater with 3.5% NaCl, and an accelerated corrosion test involving application of a two-volt potential to two bars immersed in the same type of solution used in the chemical immersion test. The objective of the accelerated tests was to predict future performance. Overall, more than 3,000 individual measurements were made on 317 epoxy-coated bars, 173 cores, and 93 concrete specimens under laboratory and outdoor exposure for Phase II.

Findings. The visual appearance of coated bars was generally good except for samples from cracked cores in structures more than 8 years old. In this case, corrosion varied from minor staining only at the crack to concrete deterioration and/or significant corrosion at crack locations and surrounding areas.[22] Extensive corrosion was also observed in shallow cover areas with high chloride. Bars from the 19 field structures had a greater number of coating defects than anticipated. The median number of holidays was 20 per meter and 79% of the bars had more than six holidays per meter. Ninety-four percent of the bars had 10 or more bare areas per meter and the median was 20 bare areas per meter. Underfilm contamination ranged from 10 to 70%, with a median of 25%. Therefore, half of the bars exceeded the 25% limit frequently accepted in the pipeline industry. Fifty-four percent of dry knife adhesion test results were rated as good, 14% moderate, and 32% were poor. In most cases, poor adhesion was observed in bars from older structures.[51] Median AC resistance ratio (resistance of the coated bar divided by that of an uncoated bar of equal size) was 130, which is less than the 300 minimum recommended by the NBS research. Low AC resistance ratios are generally associated with corroded bars, bars with high holiday and bare area densities, or bars with poor bonding.[22]

A noise barrier, built in 1981, showed evidence of corrosion in 1990. The wall was made of precast panels, and each panel had an epoxy-coated bar for transportation and erection. Several panels removed from the wall and shipped to the laboratory for investigation. Other panels that had been kept in storage were shipped as well. Corrosion occurred on the bar at the bottom of the wall but none was observed on the bars from the top wall panel and the panel from storage. Damage to the bars during compaction of the concrete, permeable concrete, low cover, and severe exposure were cited as important factors for corrosion initiation. The study emphasized that these circumstances were not unique to this structure and that similar condition could be present in other highway structures. Evidence of corrosion was subsequently found in 1991 and 1992 in two other bridge structures during the replacement of expansion joints (both bridges were built in 1979). The main concern was that there was no visible evidence of corrosion before the joint replacement was carried out.

The results of the six-month outdoor exposure of coated bars were somewhat inconclusive. The only significant change observed was an increase in the number of bare areas, from 7.9 to 24 per meter. There was no change in the number of holidays. The additional bare areas developed where the coating was very thin. The relevance of limiting outdoor storage in specifications could not be determined. Further investigation was initiated in August 1993 involving bars exposed at test sites in Alberta, Ontario, and in New Brunswick. One set of bars was coated with Scotchkote 213 (one of the earliest coatings used -- discontinued in 1993) and the other set of bars was coated using newer technology to improve coating adhesion. A final report on the study was to be published.

All slabs (retained from the CRSI long term exposure study) with epoxy-coated bars experienced cracking after 9 years of exposure. One of the cracked slabs with coated bars in the top layer only was autopsied after 9.3 years. The bar beneath the crack experienced significant corrosion, despite the fact that measured macrocell currents were low. The coating experienced blisters, cracks, and loss of adhesion. The pH beneath the coating was 4.5 to 5. The bar in uncracked concrete did not corrode and the coating on this bar was tightly adhered. It was projected that the epoxy-coated bars were experiencing the early stages of corrosion failure after 10 years of exposure[22, 51]

Many of the bars from field structures performed poorly in a seven-day accelerated corrosion test. Bars obtained from US and Canadian coaters experienced loss of dry coating adhesion at intentional bare areas in 45-day chemical immersion tests, even though most bars met specification requirements. An unexpected failure mechanism was identified from the accelerated tests. The mechanism involved progressive loss of coating adhesion and underfilm corrosion. Both straight and bent coated bars were susceptible to loss of adhesion and underfilm corrosion, although bent bars tended to have less initial adhesion, more coating cracks, more bare areas, and lower AC resistance than straight bars.

The report concluded that structures with epoxy-coated reinforcement would exceed the time-to-corrosion deterioration of uncoated reinforcement by only three to six years in bridges exposed to salt in Canada and the northern US. Time to corrosion damage of structures with coated bars could be extended by 8 to 11 years beyond that of uncoated bars if the number of defects in the coating were reduced. Field and laboratory testing suggested that epoxy coating would not provide long-term (50 years or more) corrosion protection to reinforcing steel in salt-contaminated concrete, even if new specifications were implemented and enforced. Because of this, the use of cathodic protection to extend the life of existing structures was investigated. Cathodic protection seemed feasible, and a method to provide electrical continuity to the epoxy-coated reinforcement was developed. A draft of the final report was received in 1992. Considering the controversy surrounding the report's findings, and the ongoing litigation between CRSI and Kenneth C. Clear at the time, the final report was reviewed in detail. An independent review was assigned to Prof. P. Schieβl. His report supported Clear's major conclusions.[78] The revised final report was published in 1994.

Ontario Ministry of Transportation, Canada, 1992 [51, 77]

Study. A field survey of 12 bridges built from 1978 to 1992 was conducted. This investigation was motivated by the discovery of two cases of corrosion (one noise barrier and one bridge during replacement of expansion joint) and the conclusions by Kenneth C. Clear about the corrosion mechanism of epoxy-coated bars [Letter to clients].

Findings. Several small spalls were observed in a barrier wall of one structure. Remaining structures appeared to be in good condition. However, loss of coating adhesion was found in the other structures regardless of the corrosion condition of the coated bars. A relationship existed between loss of adhesion and age of the structure. The study concluded that loss of adhesion during service conditions had serious implications. By the time chlorides reached the bar surface, adhesion has been lost and, since most bars have defects, rapid underfilm corrosion could be expected. The extension of service life would be short and repairs would be difficult.

Michigan Department of Transportation, US, 1993 [79]

Study. Thirty-eight slabs simulating bridge decks (3 ft x 4 ft x 7.5 in) containing uncoated, galvanized, and epoxy-coated reinforcement were cast. Three types of epoxy coatings, characterized by different pigmentation, were used. Three different surface preparation methods (commercial blast, near-white metal blast, and white metal blast) were applied for each type of epoxy coating. Both top and bottom mats had epoxy-coated bars or galvanized bars, and several slabs contained galvanized reinforcement in the top mat and uncoated reinforcement in the bottom mat. In all cases, top and bottom mats were not electrically connected. Depth of concrete cover was 1.25 inches. Three specimens had uncoated bar chairs.

All slabs were subjected to outdoor exposure for 13 years, and the top surfaces were ponded with salt solution during the winter months on a regular basis. Corrosion monitoring included visual inspection, corrosion potential measurements, delamination detection, macrocell corrosion current readings, mat-to-mat electrical resistance, and examination of reinforcement after autopsy. Bend tests were performed on epoxy coated bar samples soon after coating, after 3-month outdoor exposure, and after one-year storage in the laboratory.

Findings. The more extensive the degree of surface cleaning, the better the performance of epoxy coating in both the bend test and long-term corrosion study: White metal blast was slightly better than near-white metal blast, and these two were much better than commercial blast. Bars coated after commercial blast did not perform significantly better than uncoated reinforcement. Different types of epoxy coating performed significantly different. Bars with two types of coating performed better than uncoated reinforcement. However, bars with one type of epoxy coating performed worse than uncoated bars, with corrosion extending from one exposed end of the bar to the other, and only isolated regions of intact epoxy. Corrosion on bars with the best epoxy coating occurred mainly at areas adjacent to the exposed ends.

Interestingly, galvanized bars performed better than any of the epoxy coatings. This phenomenon was attributed to more susceptibility of epoxy-coated bars to corrosion at the exposed ends compared to galvanized bars (corrosion of epoxy-coated bars extended from exposed ends into the concrete greater distances than galvanized bars). Bar deformation pattern, which was not one of the test variables, had an effect on corrosion performance.

Georgia Department of Transportation, US, 1993 [21]

Study. A limited field evaluation was performed at a marine bridge substructure over the McKay River at Brunswick, Georgia. The structure was built in 1984 and was nine years old at the time of the evaluation. Six concrete cores were taken from the substructure in the tidal zone and in the splash zone. Coated bars from the cores were visually examined to assess their condition. Depth of concrete cover was measure from the cores. No corrosion monitoring techniques were used to evaluate the substructure. No chloride-ion content analysis was performed on the concrete.

Findings. In two cores obtained from a column base at the tidal and splash zones, the epoxy coating on extracted bars was not visibly damaged nor rust stained. The coating had a dull appearance and experienced some softening. The coating could be easily peeled with a pocket knife, evidence of loss of adhesion. The steel surface beneath the coating was bright and clean with no visible corrosion products. Measured concrete covers were 5.25 in, 7 in, and 7.25 in. Two cores were extracted from strut walls at two different bents at the splash zone. One of the cores was taken at a crack location. The crack was old, very fine, and formed when a barge bumped the wall during construction. The epoxy coating on the extracted bars retained its glossy appearance, hardness, and bond to the steel substrate, with no evidence of coating failure nor corrosion. The concrete in the walls did not appear wetted by the tide. Measured concrete cover was 5 inches.

A fifth core was taken at the base of a column in the tidal zone at a honeycombed concrete area. The honeycombed area appeared during construction. Concrete from the core experienced rust staining and accumulation of rust deposits. The epoxy coating at the extracted bar was ruptured at many points and a black product mixed with red rust was visible at coating breaks and underneath the coating. The sixth core was taken in the strut wall near unconsolidated concrete in the tidal zone. Epoxy coating from the extracted bar had a dull appearance and was easily removed with thumb pressure. A black liquid film of iron oxide formed underneath the coating. Wiping of the black substance revealed a shiny metallic surface. Concrete cover measured 6 inches.

The study concluded that the corrosion protection afforded by the epoxy coating was questionable after 9 years, especially at areas of poor construction and substandard concrete. The study made reference to other field surveys on bridge structures in Georgia showing that uncoated bars in bridge decks with 1.5 inches of concrete cover did not experience significant corrosion when quality concrete was used. The author has categorically stated that bars embedded in quality concrete with adequate cover does not corrode in the Georgia environment. The study recommended discontinuation of epoxy-coated reinforcement for highway bridges in the state of Georgia because of the danger of potential corrosion of reinforcement originated by debonding of the coating.

The report recommended improved concrete placement techniques, and strict quality control and enforcement of concrete cover instead.

Minnesota Department of Transportation, US, 1994 [16, 80, 81]

Study. A limited field survey of ten bridge decks located on I-35E south of St. Paul, Minnesota, was conducted to determine the extent of corrosion of epoxy-coated bars in bridge decks in Minnesota. The selected decks were all constructed in the late 1970's and early 1980's with epoxy-coated rebars in the top mat and uncoated rebars in the bottom mat. One core was taken from each deck to below the level of the top mat, at a crack location on the deck and centered over a rebar. Cores were examined visually for evidence of corrosion. No other evaluation techniques were used, including measurement of chloride content.

Findings. The first bridge deck built in Minnesota with epoxy-coated bars was examined visually and did not show any signs of distress after almost 20 years of service. The core of one bridge, constructed in 1964 but overlaid with 4 inches of concrete in 1980, contained an uncoated bar with a considerable accumulation of corrosion products and apparent loss of cross section. A core from another bridge deck showed a bar with a rust-covered area about one inch long. Upon removal of the surface rust, an area of about 3 mm in diameter showed corrosion damage at a holiday in the coating. The amount of metal loss seemed to be slight. No corrosion was observed in the bars of eight other cores. Although the limitations of the study were acknowledged, it was concluded that "the significant corrosion of epoxy coated rebars that has been observed in highway structures by other transportation agencies was not discovered by this survey." Depth of concrete cover measurements were not reported in the study.

West Virginia Department of Transportation, US, 1994 [82]

Study. A field investigation of 12 bridges with epoxy-coated reinforcement was conducted. The bridges were built between 1974 and 1976. Field investigations consisted of delamination surveys using the acoustic chain drag method, visual examination surveys, and chloride content testing. Chloride sampling had to be suspended because of inclement weather, and chloride contents were determined on three of the decks only. No concrete cores were taken for examination of reinforcement. To quantify differences in performance, previous surveys on decks with uncoated steel were reviewed.

Findings. With a few exceptions, decks exhibited transverse cracking on their surface. Nearly all cracking was related to expansion and contraction due to temperature changes rather than corrosion-related stress. No patch repairs were observed on any of the decks. Likewise, delamination was practically absent in all decks. In contrast, records of decks with uncoated reinforcement showed that delaminated areas were commonly between 5 to 20 percent of the deck surface, with some values as high as 60 to 80 percent. The study emphasized a comparison of four bridges located at different locations along Interstate 79. Two of the bridge decks had epoxy-coated bars and two of them did not. All four bridges were constructed at approximately the same time. Because of their proximity, they were assumed to have similar traffic loads, weather conditions, and exposure to deicing chemicals. The decks with epoxy-coated rebars experienced only one square foot of delamination in a total deck area of 92,400 ft^2, which corresponds to 0.001 percent. Meanwhile, the decks with uncoated steel exhibited an average of 8.5 percent delaminations. The average chloride content for all four decks was similar. The study concluded that "the use of epoxy coated reinforcement does result in a dramatic reduction of delamination in bridge decks and by inference an increase in the useful life expected of the deck."

Naval Facilities Engineering Service Center, US, 1994 [83]

Study. Small concrete specimens with epoxy-coated bars, zinc-coated (galvanized) bars, plain bars with calcium nitrite admixture, plain bars pretreated with calcium nitrite, and plain bars (control specimens) were evaluated in a marine exposure program at Key West, Florida. The specimens were suspended in a marine intertidal zone for about 6.3 years. The size of specimens was 15 cm (6 inches) in diameter by 60 cm (24 inches) in length. The concrete mix had a water/cement ratio of 0.60. Each specimen contained four 45-cm (18-inch) long #4 (13-mm-diameter) Grade 60 bars. The bars had various amounts of cover: 13 mm (0.5 inch), 25 mm (1 inch), 38 mm(1.5 inches), and 50 mm(2 inches). The specimens had no cracks or damage. At the age of 9 months, the specimens were suspended in nylon mesh nets in the intertidal zone at the Naval Air Station Trumbo Point Annex, Key West, Florida. Specimens were also tested in field exposure sites at Cutler, Maine, and Port Hueneme, California, but the report concentrated on specimens at the Florida test site.

Six specimens were prepared with epoxy-coated bar coated in accordance to ASTM A775 using 3M Scotchkote 213, which was the most commonly used epoxy powder at the time. Coated bars did not have any visible damage and had 1.5 holidays per linear foot. Bars were protected from exposure to weather, salt spray, and sunlight before use. In this respect, coated bars used in the specimens exceeded the ASTM specification and typical construction practices. The epoxy coating was cured by air cooling at ambient conditions, instead of water quenching. The bar coating in two of the six specimens was intentionally damaged by grinding 25 mm (1 inch) of the epoxy coating, 50 mm (2 inches) from each end. One of the damaged areas in each bar was repaired with a two-part epoxy patch material (100 to 500 μm; 4 to 20 mils thick), and the other damaged area was left unprotected. The specimens were inspected four times during the exposure period, and autopsied at the end of the exposure. Samples were tested for water soluble chloride content.

Findings. Specimens with plain bars pretreated with calcium nitrite exhibited visible surface staining and cracking after 3.5 years of exposure. Control specimens experienced a similar degree of surface distress after 6.3 years of exposure. None of the specimens with epoxy-coated bars, galvanized bars, and calcium nitrite admixture with plain bars showed signs of surface staining or cracking at the end of the study. Chloride contents at a depth of 50 mm ranged from 5.8 kg/m^3 (9.7 lb/yd^3) to 6.1 kg/m^3 (10.3 lb/yd^3). The measured amount of surface area affected by rust (in percentage of bar surface) at a depth of 2 inches was 14% for control specimen, 10% for plain bars pretreated with calcium nitrite, 6% for plain bars and calcium nitrite admixture, 0.5% for zinc-galvanized bars, and 0.5% for epoxy-coated bars. The galvanized bars were ranked second to the epoxy-coated bars because zinc oxide covered an additional 6% of the surface. Practically no changes in the amount of rusted area were observed on bars with different cover for plain bars plus calcium nitrite admixture, galvanized bars, and epoxy-coated bars. Plain bars and pretreated bars showed greater corrosion as the cover was reduced.

Corrosion in plain bars usually occurred at a location just below the high tide. Corrosion in coated bars was typically found at patched bar ends. Corrosion at intentionally damaged areas was similar to that observed on plain bars in control specimens. Damaged and patched areas performed similarly to undamaged areas. Coated bar with 13-mm (0.5-inch) cover showed signs of coating disbondment. It was concluded that the main factor for the excellent performance of epoxy-coated bars was the low number of defects in the coating. However, the disbondment observed in bars with shallow cover indicated that the coating was not suitable for a severe marine environment. The study recommended careful quality control to avoid damaging coated bars during construction, and suggested the investigation of other coating types with pretreatments that are less susceptible to disbondment.

University of South Florida, U.S., 1994 [20]

Study. A field and laboratory investigation was conducted to determine the present condition of Florida bridges built with coated bars and to establish a prognosis for the remaining life of these structures. About 30 bridges were selected for detailed examination, including a few bridges with uncoated bars for comparison. Portions of the substructure were examined in detail in the field.

Tests included covermeter surveys, concrete resistivity measurements, extraction of concrete cores and bar specimens, knife adhesion tests, corrosion potential readings of exposed bars at core holes, macrocell current measurements, bar-to-bar resistance readings, and polarization resistance measurements. Laboratory tests of field-collected samples included determination of chloride ion penetration rates, concrete characteristics (aggregate characterization, dry and wet concrete resistivity, weight change from dry to wet condition, evidence of fly ash), and the condition of the bar and the epoxy coating (coating breaks, coating thickness, corrosion on and under the coating, coating backside appearance, knife adhesion tests on desiccated specimens, and pull-off coating adhesion testing).

Additional laboratory tests involved coating disbondment tests of bars in a) concrete cylinder specimens partially immersed in tap water for nearly 2 years, and b) solutions representing the concrete moisture chemistry (simulated pore solutions) for 30 days. Simulated pore solutions had two levels of NaCl additions, and no NaCl addition. Specimens were tested at both open circuit potential condition and various levels of cathodic polarization. Pitting/crevice initiation potentials were determined in small steel prisms machined out of regular rebar and partially immersed in test solution. Time to cracking was determined on strain-gaged cylindrical concrete specimens with embedded uncoated and epoxy-coated bar segments and subjected to externally applied anodic currents. The objectives of these tests were to determine the susceptibility of the steel substrate to corrosion development when the coating was partially disbonded, and to establish whether the reduced mechanical bond between epoxy-coated bars and concrete could result in early cracking compared with similar corrosion in uncoated bars.

Findings. Except for the five Keys structures already showing corrosion, none of the structures with coated reinforcement examined exhibited signs of severe corrosion. The extent of chloride penetration in many structures was still too low to trigger corrosion. A significant reduction of coating adhesion to the steel substrate was observed in all structures five years or older, regardless of chloride contamination levels. The chemical composition of the concrete pore solution and the electrochemical service conditions of the bar in the concrete environment are conducive to extensive loss of adhesion, as revealed by the laboratory tests. The polarization experiments of pitting/crevice potentials evidenced that the presence of crevices under the disbonded coating contributed to aggravate corrosion propensity. The study concluded that coating adhesion loss was the first step in the degradation of the epoxy coating, leading to eventual corrosion of the steel substrate once enough chloride ions arrive. Laboratory tests suggested that the threshold chloride content for corrosion initiation under disbonded coatings is smaller than for uncoated steel. Laboratory tests also showed that concrete spalls could be created by both epoxy-coated and plain bar after exuding the same amount of corrosion products.

A computer model to predict the time to development of corrosion-induced spalls was devised, based on chloride penetration measurements and on the laboratory experimental results. The model consisted of a corrosion initiation period followed by a corrosion propagation period. The diffusivity of chloride ions in the concrete, obtained from the analysis of field-extracted cores, determined the length of the initiation period. The model could be validated with the structures showing corrosion presently, and served to categorize which structures are expected to have long service life, which structures would be expected to exhibit corrosion within the next decade, and which structures should be frequently monitored for the possibility of immediate repairs. The good performance of those structures with projected long service life was attributed to the concrete quality (FDOT 346 concrete with fly ash) and depth of concrete cover used, and not to the presence of the epoxy-coated reinforcement. Therefore, these measures were considered the most practical approach to attain long-term durability in Florida marine exposure. The use of cathodic protection with sprayed zinc anodes was suggested as the most cost-effective repair method for corroding ECR structures.

National Cooperative Highway Research Program, US, 1995 [22]

Study. This study was sponsored by the National Cooperative Highway Research Program (NCHRP) and conducted by Kenneth C. Clear Inc (Virginia), with Florida Atlantic University as a subcontractor. The project had two main objectives: 1) To determine the causes for unsatisfactory corrosion performance of epoxy coated reinforcement in highway bridges, and 2) to recommend improvements in current practice and specifications. The investigation was motivated by the observed instances of premature failure of substructure members in the Florida keys and at other places. Of special concern was the lack of performance-based qualification and quality control tests that can be correlated with long-term service performance. For the laboratory portion of the study, epoxy-coated bars were acquired from 11 different sources from the United Kingdom, Germany, Japan, and North America. Except for one source, bars were obtained directly from the coating plant, and shipped bars were specially packaged to avoid coating damage. The research approach consisted of the following tasks: 1) Definition of the state-of-knowledge and critical interpretation, 2) identification and development of techniques for evaluation of epoxy-coated bars, 3 and 4) development and performance of a work plan. Some of the tests included electrochemical impedance spectroscopy (EIS) combined with a) hot water testing, and 2) adhesion testing; ac resistance testing; solvent extraction weight loss; accelerated corrosion testing; chemical immersion testing; outdoor exposure; and field evaluation.

Findings.

Solvent extraction weight loss, and electrochemical impedance spectroscopy combined with hot water exposure were found appropriate for powder qualification and routine quality control in a production plant. A good correlation was found between degree of coating cure as measured by solvent extraction weight loss and electrochemical impedance after one day of hot water exposure. Impedance results also correlated with longer-term test exposures of concrete slabs. The main implication of these correlations was that coatings with a higher degree of cross-linking should be less porous, more moisture resistant, and hence less likely to experience premature deterioration than coatings with fewer cross links.

Bars that performed well in the study had a coating with no defects, a low solvent extraction weight loss, and exhibited a capacitive behavior as determined by EIS. Some bars with no initial defects developed coating defects and corrosion associated with those defects during testing. Therefore, long-term corrosion protection requires that the coating not develop conductive pathways and be defect-free. It was concluded that this level of quality cannot be achieved by present quality control methods nor by patching all visible or holiday-detected defects. Conventional holiday detection either does not reveal all coating defects and/or does not disclose sites that are predisposed for breakdown during service. Therefore, the quality control should be based on in-place coating impedance and in-place defect density of bars, using the ac resistance ratio test and/or the modified holiday detector test developed in the project. Since such requirements may be impractical to achieve in the field, it was suggested that other corrosion protection systems be used in conjunction with or in place of epoxy-coated reinforcement. Another suggested alternative would be to develop coating systems that in service, exhibit high resistance to cathodic disbondment and underfilm corrosion in association with defects.

Upon critical review of existing literature, coupled with findings of the NCHRP study, it was concluded that epoxy coating technology, as practiced, was not reliable in providing long-term (50-plus years) corrosion protection in aggressive environments. While the highest quality bars might perform satisfactorily in highway bridges, current production, storage, transportation, handling, and placement techniques and procedures result in bars which do not have the necessary quality. **The study stressed the importance of developing performance-based specifications through the establishment of a quantitative relationship between long-term performance in service and coating quality at the time of bar fabrication or construction, and accelerated tests results**.

Coated bars subjected to outdoor exposure did not exhibit coating degradation after 2 months, as indicated by HWT/EIS and adhesion measurements. However, coating degradation was apparent after 4 months, as evidenced by reduced adhesion, presence of holidays and rust spots, and a much lower impedance compared to that after 2 months. Degradation appeared to be independent of exposure site (coastal versus inland) and of exposure to ultraviolet radiation. Concrete slabs using 4-month outdoor-exposed coated bars experienced active corrosion potentials and high macrocell currents. Based on these findings, the study recommended a maximum of 2 months outdoor storage, regardless of whether epoxy-coated bars are covered or not.

State of California Department of Transportation (Caltrans), US, 1995 [18]

Study. A field survey of four bridge decks with epoxy-coated reinforcement located on Interstate 80 in the northern part of California was conducted. The four bridges were built from 1959 to 1969, but the decks were reconstructed from 1982 to 1985 with epoxy-coated bars. At the time of the study, the epoxy-coated bars had been in service for 7 to 10 years, among the longest time of service in the State of California. No previous investigations on bridge decks constructed with epoxy-coated bars had been performed in California. The field evaluation consisted of visual inspection, delamination survey, spot cover detection tests, and removal of cores from each traffic lane. Thirty-two 10 cm (4 in) diameter cores were removed from the four decks at various locations. Cores were taken over cracks, delaminated areas, and sound (non-cracked) locations. At the laboratory, cores were visually examined for assessment of concrete cover depth, extent of concrete cracking, and condition of epoxy-coated bar. Bar segments were examined for coating type, coating thickness, presence of coating damage, coating disbondment, and extent of rebar corrosion. Chloride contents near bar location were determined from extracted cores. Chloride profiles were determined for selected undamaged cores.

Findings. Corrosion of coated bar samples removed from cores was determined to be minor. Only eight out of thirty-two cores removed (25%) experienced corrosion. Corrosion consisted of superficial discoloration and/or minor loss of metal section. Bar segments from cores located at large cracks (extending from the deck surface to the bar) and areas with shallow cover (25 mm or less) experienced the most corrosion. Bars with coating defects had a higher propensity for corrosion. In contrast, no corrosion was observed at bars with no defects in the coating, despite the presence of high chloride concentrations (0.7 to 4.6 kg/m^3). Non-damaged epoxy coating provided an adequate barrier to chlorides. Various degrees of coating disbondment (at both corroded and non-corroded regions) were observed on eleven of the thirty-two bar segments (34%). In most cases, coating disbondment occurred around holidays and coating defects. Chloride content at the level of bars ranged from 0.2 to 5.5 kg/m^3 in three decks and from 0.4 to 15 kg/m^3 in one deck. The largest chloride contents were observed at crack locations with shallow concrete cover. The main conclusion of the study was that epoxy-coated reinforcement meeting Caltrans standard specifications provided effective corrosion protection to the bridge decks studied for 7 to 10 years in California's Northern mountain environment. Nevertheless, the study warned that drought conditions from 1985 to 1991 caused less-than-usual rainfall, snowfall, and associated de-icing application during that period, creating a less aggressive service environment than could be expected.

University of New South Wales (Australian Defense Force Academy), Australia, 1994 [19]

Study. The objective of this study was to compare the performance of epoxy-coated steel and galvanized steel reinforcement in concrete, with uncoated steel reinforcement being used as control. All specimens were concrete cylinders 150 mm by 300 mm. The concrete had a high water/cement ratio of 0.8. Two different sets of specimens were prepared. Type A specimens contained 150-mm lengths of reinforcement embedded vertically and 10 mm to 15 mm concrete cover. These specimens were used for corrosion potential surveys and metal loss determinations. Plastic-clad stainless steel screws were tapped into the embedded bars and the screw heads were level to the top cylinder surface. The screws served to connect the electrode to the reinforcement for potential measurements. Both cut ends of coated bars were repaired. Type B specimens, used for corrosion assessments, contained a vertical piece of reinforcement with no concrete cover at its ends and 4 lateral reinforcement pieces with end covers of 8 mm, 16 mm, 24 mm, and 32 mm. Only one cut end of each bar was repaired. All bars had a diameter of 16 mm.

Two accelerated corrosion environments were used: a) Cyclic wetting and drying by fully immersing the specimens in 3.5% NaCl solution at 40°C for 3 days followed by oven drying for 4 days at 60°C, and b) continuous salt fog exposure at 40°C and 100% relative humidity, using a 3.5% NaCl solution. Exposure period extended up to 132 days. Corrosion potential measurements were taken at regular intervals. Chloride measurements were taken on samples from plain concrete cylinders. At intervals, bars were removed from cylinders and weight loss was determined.

Findings. Provided the coating remained intact, epoxy coating provided excellent corrosion protection to reinforcing steel. However, at points of damage to the coating and at the unrepaired cut ends of bars, localized corrosion on the exposed steel occurred to a similar extent and over the same interval as for uncoated steel. In many cases, corrosion proceeded along the bar beneath the coating with subsequent disbondment of the coating. Patch repairs to bar cut ends did not delay corrosion of the steel substrate substantially. Corrosion potentials were unreliable to assess the corrosion of epoxy-coated reinforcement in concrete. Holidays and points of minor damage were responsible for the high negative corrosion potentials measured for epoxy-coated bars. Galvanized bars resisted chloride levels in concrete about 2.5 times that which caused corrosion of uncoated bars. Galvanizing provided sacrificial protection for a period of about 4 to 5 times that for the initiation of corrosion of uncoated steel in similar conditions. With further development, corrosion potentials may be useful in predicting the remaining life of the zinc coating in service.

University of Western Ontario, Canada, 1995 [51]

Study. The behavior of reinforcing steel prepared in a typical coating process was compared to that of steel panels prepared in the laboratory with different degrees of surface preparation and contamination. Testing consisted of hot water immersion followed by characterization of the chemistry of the epoxy-steel interface. Coated samples were also electrochemically analyzed after exposure in a simulated pore solution. Coated bar segments were removed from service and examined in a similar manner to the panels. The objectives of the study were to determine the mechanism of adhesion loss of epoxy coatings, and to determine the effect of adhesion loss in the corrosion performance of coated bars.

Findings. Coating adhesion was improved by increased surface roughness and decreased amount of contaminants. Water permeating the epoxy coating was identified as the main mechanism of adhesion loss. The epoxy coating was displaced from the steel surface by the water. No significant changes were observed in the chemistry of the epoxy. Electrochemical tests showed that in the absence of defects in the coating, loss of adhesion did not change the short-term corrosion behavior. If defects were present, though, poor coating adhesion resulted in high corrosion rates.

Purdue University, US, 1995 [17, 84, 85]

Study. Six bridge decks with epoxy-coated reinforcement were evaluated in Indiana. The first bridge in Indiana where epoxy-coated bars were used was included in the study. The bridges were built from 1976 to 1985, and were 6 to 18 years old at the time of the investigation. The field evaluation included:

Identification of delaminated and spalled areas, detailed crack survey, detection of concrete cover and bar location, core sampling with and without reinforcement, and concrete powder sampling for chloride analysis at several depths.

Findings. Epoxy-coated steel performed satisfactorily in the bridge decks surveyed. None of the bar samples extracted from cores in the six bridges showed signs of bar corrosion or debonding of coating. With the exception of two bridges, chloride concentrations at the level of the reinforcement were well above the accepted threshold value for corrosion initiation. Chloride content significantly decreased with increase in concrete cover. It was concluded that the combination of adequate concrete cover and epoxy-coated bars provided a good corrosion protection system in Indiana.

Minnesota Department of Transportation, US, 1996 [86]

Study. A thorough investigation of the condition of four bridge decks was conducted by WJE, Inc. for the Minnesota Department of Transportation.. The bridges were built between 1973 and 1978 and were about 17 to 22 years old at the time of the investigation. Two decks were constructed on steel girders and two built on precast concrete girders. Two decks had a 2-inch overlay of low slump concrete, one on steel girders and one on precast concrete girders. Deck reinforcement consisted of either both mats with epoxy-coated bars or a top mat with epoxy-coated bars and bottom mat with uncoated bars. Field examination included visual, crack, and delamination surveys; concrete cover measurements with pachometer; coring samples; corrosion potential, linear polarization, and electrochemical impedance spectroscopy measurements. Laboratory testing on extracted cores included photographs; measurement of concrete cover; inspection of the epoxy coating; holiday detection; coating thickness measurements; coating adhesion tests; coating back-side examination; concrete chloride content analysis; and corrosion potential, linear polarization, and electrochemical impedance spectroscopy measurements. A minimum of five cores was obtained from each deck.

Findings. The majority of bar samples from extracted cores were in good condition, with no visible corrosion. However, the effectiveness of the epoxy-coated steel could not be determined because the chloride content at the level of the steel was generally not sufficient to initiate corrosion. Corrosion at bare areas occurred when the chloride content exceeded the threshold for corrosion of uncoated steel (0.59 to 0.83 kg/m^3 or 1.0to 1.4 lb/yd^3). Extensive corrosion of epoxy-coated bars was only found at crack locations, and corrosion was sufficient to cause concrete delaminations. Nevertheless, the observed corrosion was expected to be lower than what could have occurred if uncoated bars had been used. Decks with black bars at the bottom mat were suspected to suffer significant corrosion at crack locations because of the rust products and staining observed at the underside of the deck at surface cracks. Unfortunately, no cores were extracted at the location of bottom mats. Interestingly, decks on precast, prestressed concrete girders experienced much less cracking than decks cast on steel girders, which developed many full-depth cracks. There was an evident advantage in terms of durability with the larger stiffness provided by prestressed concrete girders.

Patched bars performed well and had minimal corrosion. Although some bars had good coating adhesion, the overall coating adhesion to the bars was considered poor. A significant number of holidays and damage was found on the epoxy coating. The average number of holidays per meter (foot) was 101/m (31/foot). Although some damage was caused during the coring operation, the holiday count was well in excess of that allowed by ASTM specifications. These bridge decks may undergo extensive corrosion when chloride contents reach high levels in the future. Decks with an overlay had very low chloride levels at about 25 to 40 mm (1 to 1.5 inches) depth. Average concrete cover for all decks was over 76 mm (3 inches).

Canadian Strategic Highway Research Program, Canada, 1996 [77, 87]

Study. An outdoor exposure study of epoxy-coated bars was conducted to investigate the effect of storage conditions on the properties of coated bars before placement in concrete. Three sites were selected: One site was representative of dry conditions with cold temperatures, large temperature fluctuations, and high ultraviolet radiation (Alberta). The second site represented a marine environment (New Brunswick). The third site had a humid environment (Ontario). Specimens consisted of 15M bars one meter long with six 4-mm holes drilled into the epoxy coating. Bar ends and three of the holes were patched. Two different coatings were tested. One of the two coatings (coating B) used had a zinc chromate primer. Three bars were removed from each site after 1, 2, 3, 6, 9, and 12 months for testing (Coating thickness, holiday count, AC resistance, and adhesion testing).

Findings. Epoxy coating degraded over time: Bars performed well up to three months of exposure. Between three and nine months, performance of some bars decreased. By nine months, coatings degraded significantly. No corrosion or adhesion losses were observed in either coating [away from the holes]. The number of holidays increased after 6 months, and some bars were more susceptible to holiday formation than others. Thicker coatings with fewer discontinuities had improved performance. Corrosion was observed at unpatched holes after one month. The bars with coating B and primer did not show underfilm corrosion. The bars with coating A experienced underfilm corrosion and disbondment at six month exposure. Clearly, the chromate pretreatment significantly reduced the undercutting around coating discontinuities. Cathodic disbondment and salt spray tests also showed that chromate pretreatment substantially improved adhesion.

Patched holes in bars with coating A did not corrode. Some corrosion was observed on patched holes with coating B after six months. Apparently, the patches in the latter case did not cure properly. Patched ends showed minor rust stains that increased with time. A film of salt formed on top of bars stored in a marine environment at 12 months of exposure, and pitting corrosion was observed at some intentional defects and patched holes. For this reason, bars stored in marine environments should be washed with fresh water before placement in concrete. Changes in current practice for handling and storage of coated bars were proposed in the project report.

Federal Highway Administration, US, 1996 [88]

A five-year research project commissioned by the FHWA was conducted by WJE to investigate the corrosion resistance of a variety of coated and uncoated rebars. The main objective was to derive a corrosion resistant reinforcing bar that will endure a 75 to 100-year design life for concrete structures. An additional objective was to develop appropriate new short-term test procedures that can be incorporated into the ECR standard specifications. Over 52 different organic, inorganic, ceramic, and metallic coatings, as well as solid metallic bars were tested. The research was divided in the following tasks:

- Task 1. Tests on organic-coated bars
    - Phase I. Prescreening tests on 33 organic-coated bar types
    - Phase II. Screening tests on 10 organic-coated bar types
- Task 2. Tests on 14 different ceramic-, inorganic-, and metallic-clad bar types.
- Task 3. Tests on 10 different metallic bar types
- Task 4. Tests in concrete specimens

Task 1. Tests on organic-coated bars

Study.

Phase I. Twenty-two bendable and 11 nonbendable organic-coated bars were acquired from 15 plants in the United States, Canada, Japan, England, and Germany. New surface cleaning and/or chemical treatments were used in 17 of these 33 coating systems. Before testing, holiday-free bars with bendable coatings were bent 180° around a mandrel that had a diameter 4 times that of the bar (4D).

After bending, bars were examined for cracks, tears, holidays, and other defects in the coating. Straight and bent (4D) bar samples free of holidays were immersed in four different solutions at 55°C for 28 days. Each bar had a 6-mm hole drilled through the coating. The four solutions used were: a) Deionized water, b) 3% NaCl solution, c) 0.3 N KOH + 0.05 N NaOH, and d) 0.3 N KOH + 0.05 N NaOH + 3% NaCl. Bars were visually examined after 1, 3, 7, and 28 days for signs of cracks, coating damage, blistering, or corrosion. Knife-peel adhesion tests were then performed on the straight and bent sections of bars as discussed in ASTM G1. Knife-peel adhesion tests were conducted on the wet coating and after 1 and 7 days of air drying. Cathodic disbondment tests were performed on bent bars. AC impedance measurements were taken after 1 hour, 7 and 28 days of cathodic disbondment testing, and at the end of the 28-day period, knife-peel adhesion tests were conducted.

Phase II. Seven of the best performing coatings, 4 bendable and 3 nonbendable, were selected for testing in Phase II. In addition, an older bendable coating that was the most predominant in the US market for many years was used. Two more nonbendable coatings, one epoxy and one vinyl, were also selected and tested in this phase. Straight, and bent 8D, 6D, and 4D samples were prepared for solution immersion, knife-peel adhesion, and cathodic disbondment tests. Two solutions were used for immersion tests: a) Deionized water and b) 0.3 N KOH + 0.05 N NaOH + 9% NaCl. Tests were conducted similarly as in Phase I, but each sample had two 6-mm drilled holes instead of one.

<u>Findings</u>.

Phase I. Coating adhesion was reduced after the immersion tests. The best adhesion was observed on straight bars. Adhesion was generally low at the drilled hole and improved away from the hole (67 out of 88 straight bars tested in the 4 solutions did not experience adhesion loss in areas away from the hole). Adhesion of bent bars with bendable coatings (bent after coating) after immersion testing was generally poor. Wet coating adhesion of all bars with bendable coatings was poor. Bars with nonbendable coatings showed much better adhesion than bars with bendable coatings after cathodic disbondment testing. Pre-bent bars with nonbendable coatings had excellent adhesion. Nevertheless, none of the nonbendable coatings showed good to excellent adhesion ratings at the hole while wet. Good to excellent adhesion was produced by the same nonbendable coatings away from the hole under wet or air-dry conditions. A new test method was proposed to compare the performance of various organic coating types.

Phase II. No underfilm corrosion was observed, even if the coating was poorly bonded. Nonbendable coatings showed considerably better adhesion than bendable coatings. Straight bars retained significantly better adhesion than bent bars. Bent samples with bendable coating having 8D, 6D, and 4D bends exhibited consistently poor adhesion. Prebent bars with 4D, 6D, and 8D shapes coated with nonbendable coatings showed improved adhesion with minimal differences in rating. Adhesion was significantly improved away from the drilled hole with a dry coating compared to that at the drilled hole with a wet coating. Solution immersion and cathodic disbondment tests at the hole location had poor correlation, indicating that different adhesion loss mechanisms occurred in each test.

Task 2. Tests on ceramic-, inorganic-, and metallic-clad bars

Study. Fourteen different ceramic, inorganic, and metallic-clad bar types were acquired from the US, England, Canada, and France, and subjected to screening tests to identify bar types that are likely to show superior corrosion resistance in concrete. Submitted clad bars included: Nickel-clad, copper-clad, copper-based alloy clad, reactive copper in an organic coating, hot-dip galvanized, zinc coating using Delot process, inorganic zinc-silicate clad, several proprietary zinc rich claddings, ceramic-clad, 304 stainless steel clad, ceramic-clad, and galvalum. The bars were tested in three conditions: As-received, with a drilled hole in the cladding, and after abrasion. Both straight and bent bars were tested in two solutions: a) 3% NaCl and b) 0.3 N KOH + 0.05 N NaOH + 3% NaCl. Solution immersion was conducted for 28 days using the following cycling procedure: 1.25 hours wet and 4.75 hours dry, forming 6-hour cycles that were repeated continuously , providing a total of 112 cycles in 28 days. Quantitative analysis of corrosion activity was monitored by polarization resistance and corrosion potential measurements.

Findings. Zinc-rich clad, 304 stainless-clad, copper-clad, and ceramic-clad bars exhibited the best corrosion performance as measured by polarization resistance. These four clad-bar types were selected for additional testing in the more rigorous corrosion tests of Task 3.

Task 3. Tests on solid, metallic bar types and the best clad-bar types from Task 2

Study. The following solid, metallic bar types were included: Black; titanium; Type 304, Type 316, Type 317, Type 304N, Type XM-19, and Nitronic 33 stainless steels; a corrosion resistant steel alloy; and Type C613000 aluminum bronze. Bars were prepared in a manner similar to that for Task 2. Only bent bars were used. None of the solid bars were subjected to abrasion. Testing was performed in 3% NaCl solution for 90 days (360 cycles). Companion tests were conducted in 0.3N KOH + 0.05N NaOH + 3% NaCl solution for 56 days, followed by 56 days of testing in 0.3N KOH + 0.05N NaOH + 9% NaCl solution, and then 56 days of testing in 0.3N KOH + 0.05N NaOH + 15% NaCl solution. These tests amounted for a total of 168 days (672 cycles).

Findings. Black bars experienced very high corrosion current densities, in the order of those measured in 1- or 2-year-long accelerated corrosion tests in concrete slab specimens. Zinc-containing clad-bar types performed similar to black bars. Polarization resistance values of copper-clad bar was about 16 times larger than that of black bar in the 168-day test series. Stainless-clad, solid stainless, and titanium bars had polarization resistance values 50 to 750 times greater than those of black bar.

Task 4. Tests in concrete specimens

Study. The final stage of the multiyear study consisted of testing bars that performed satisfactorily in screening tests in concrete specimens. The following bars were selected: Two best bendable and two best nonbendable epoxies from Task1, Phase II; 3M Scotchkote 213, the most widely used coating until 1993; a post-baked epoxy from Task 1, Phase I; Type 304 stainless steel; galvanized bars; zinc-alloy clad bars; and copper-clad bars. Of the six epoxies chosen, three involved steel pretreatments prior to coating and three did not. In addition to their corrosion performance in the aggressive tests, clad and solid bars were selected based on other factors, such as feasibility of being manufactured economically, or widespread interest (galvanized bar).

Findings. Test results for Task 4 will be available in 1998.

University of New Brunswick, Canada, 1997 [89]

Study. An accelerated corrosion study was performed on U-shaped epoxy-coated and uncoated bars embedded in low grade concrete and high performance concrete, made with and without corrosion inhibitors. Seven concrete mixes with water/cement ratio of 0.6 and 0.25 were used. Types of corrosion inhibitors included organic corrosion inhibitor, calcium nitrite-based corrosion inhibitor, and migratory corrosion inhibitor. Concrete cover was 20 mm except for specimens with two types of corrosion inhibitors, where the cover was increased to 30 mm as per manufacturer request. Several specimens were pre-cracked by removing a rubber sheeting when the concrete reached a strength of 10 MPa, which created a pre-formed crack 0.4 mm wide transverse to the reinforcement. Three different types of epoxy-coated bars were used: Post-fabricated bars with flexible coating, post-fabricated bars with semi-flexible coating, and pre-fabricated bars with inflexible coating. Concrete specimens were placed in an accelerated testing chamber with simulated sea water. Exposure cycles consisted of two-hour wet followed by four-hour dry periods, to complete a total of four cycles per day. Results were presented for up to 2.4 years of exposure.

Findings. Epoxy-coated bars outperformed uncoated bars in all cases, for both water/cement ratios of 0.25 and 0.6, with or without corrosion inhibitor, with or without pre-cracking. The combination of epoxy-coated bars and corrosion inhibitors provided the best protection in concrete with w/c of 0.6. Pre-fabricated epoxy-coated bars performed better than post-fabricated bars in 0.6 w/c concrete. High performance concrete (w/c = 0.25) provided excellent protection for uncoated bars in uncracked specimens; however, significant pitting was observed in the preformed crack area. In contrast, all types of epoxy-coated bars in 0.25 w/c concrete showed negligible corrosion rates, and precracking of the specimen had no adverse effect.

Virginia Polytechnic Institute and State University, US, 1997 [23]

Study. Three bridge decks and three marine pile structures were inspected to assess the corrosion performance of the epoxy-coated reinforcing steel. The decks had an upper mat of epoxy-coated reinforcement and a lower mat of 50% uncoated and 50% epoxy-coated steel. Substructures consisted of prestressed driven piles 61 cm square with uncoated prestressing cable as main reinforcement and 9.5-mm diameter, smooth coated bars as transverse reinforcement. The concrete surface of all piles was coated with two layers of epoxy coating. The decks were 17 years old, two of the marine structures were 8 years old, and the remaining marine structure was 7 years old at the time of the study.

A visual crack survey on the right traffic lane and extraction of 12 cores randomly located in the lowest 12 percentile cover-meter depth readings were conducted as part of the investigation. Powder concrete samples for chloride analyses were obtained by drilling at various depths next to each core location. A single core from each pile was taken between high and low tides, from a total of 30 marine piles. Tests performed on extracted cores and coated bars included visual inspection; measurement of cover depth; AC impedance of combined cover concrete and coated bar; determination of moisture content, absorption, percent saturation, carbonation depth, and effective chloride diffusion constant of concrete; and assessment of physical damage, coating thickness, dry knife adhesion, corrosion at damaged sites, and underfilm corrosion of epoxy-coated bars.

<u>Findings</u>. Only one deck presented very small delaminated zones, with surface areas of 0.60 and 0.14 m^2. The chloride content on the coated bar trace of the cores from decks with surface cracks was not greater than that of cores without cracks (except for one core, all cracks were less than 0.3 mm wide). Corrosion at damaged areas of coated bars was observed on slightly over 50% of the cores from bridge decks. Only two bar segments had total coating damage greater than 2%. Underfilm corrosion was observed on 10 bar segments out of 36 specimens from bridge decks. Nine out of 23 bar segments from marine piles showed some degree of underfilm corrosion, despite that chloride contents were above the threshold in only two cores. Only two bar segments showed any visible

coating damage and 8 bar segments had one or more holidays (exceeding the specification of 2 per 30.5 cm).

Epoxy coating has debonded extensively from reinforcing bars in all structures. Coating disbondment occurred without the presence of chloride. The highest adhesion loss was associated with the highest concrete moisture content. It was estimated that epoxy coating loses adhesion in about 6 years in Virginia's marine environments and about 15 years in bridge decks. In 95% of the bridge decks, coating adhesion will be lost before the chlorides reach the depth of 12% of the epoxy-coated reinforcement. Thus, the service life of only 5% of the bridge decks in Virginia is being extended by epoxy-coated bars. When the chlorides arrive, underfilm corrosion in an acidic environment will take place because of the disbonded coating. The service life extension provided by the debonded coating is nil because the rate of underfilm corrosion is faster than that of the uncoated steel in concrete. Coated bars seemed to provide only up to 5 years of additional service life for only 5% of the bridge decks in Virginia, so the use of epoxy-coated reinforcement in Virginia may not be cost effective.

Other Studies [22, 51]

Concrete columns were exposed in the three zones (submerged, tidal, and atmospheric) at a sea location in Norway. Columns were loaded in three-point bending to 35-70 percent of yield reinforcement. Epoxy-coated bars showed good performance, as measured by the current demand of an external cathodic protection system. After three years, epoxy-coated reinforcement reduced the magnitude of the polarization current by more than 90% compared to the current recorded for uncoated steel. The epoxy coating acted as an effective barrier against oxygen diffusion to the reinforcing steel.[22]

The influence of sea water exposure and fatigue stressing on beams with both Australian and American coated and uncoated reinforcing bars was investigated by Roper. Despite improving the fatigue endurance of the concrete beams in the presence of sea water, corrosion was observed at areas adjacent to the bar lugs. The long-term efficiency of the epoxy coating was questioned because of general corrosion at the lug base. Corrosion attack appeared to advance under the epoxy coating. The author hypothesized that small access paths were created through the epoxy coating at points of high stress (rib bases), and the epoxy underwent creep because of its viscoelastic properties. This resulted in breakage of the epoxy coating. Coating adhesion was greatly reduced by the presence of moisture.[22]

Two poor quality bridge decks with epoxy coated bars were evaluated in Virginia in 1984. Corrosion potentials were relatively positive after 7 years. Except in an area with several transverse cracks, chloride contamination levels were below the threshold value. No delaminations were detected even in the cracked area.[22] The effectiveness of several bridge deck protective systems were investigated by the Pennsylvania Department of Transportation. Epoxy-coated bars remained in excellent condition despite high chloride concentrations around the bars.[51] In Oregon, a single test pile was examined after 9 years of exposure to a marine environment. Corrosion was observed on two of the #4 and several of the #3 coated hoop bars, while other bars showed no distress. No visible concrete damage was observed, but active corrosion potentials were recorded in the splash zone.[22]

In 1990, the New York Department of Transportation investigated the condition of 14 bridges that were 7 to 12 years old. Selected bridges had transverse cracks in the deck. Only three out of 54 cores taken contained bars with minor corrosion. Corrosion occurred as light rust coating breaks, without section loss or undercutting.[51] This investigation apparently originated after widespread delamination and spalling and severe bar corrosion was observed in 1990 on a bridge deck built in the mid 1970's. The coating used on the bars was one of the first four coatings approved in the NBS study. The epoxy coating was particularly prone to excessive holidays[22, 51] Another New York bridge deck constructed in 1981 exhibited horizontal cracking typical of corrosion-induced delamination, and the epoxy-coated bars were badly corroded after 9 years of service. Concrete cover varied from 2.0 to 2.4 inches.[22]

In 1993, the West Virginia Department of Transportation examined 12 bridge decks built in the period 1974-1976. The decks were in good condition and only one delamination of 0.1 m^2 was noticed. The study noted that decks of the same age with uncoated bars would have had 5 to 20% of the deck area delaminated.[22] In the same year, the condition of three coastal bridge substructures was examined by the North Carolina Department of Transportation. The bridges had been in service for about 8 years and the epoxy coating was in good condition, despite chloride contents above the threshold for corrosion initiation at bar locations.[51]

A group of researchers tested over 100 specimens containing bent "U" shaped epoxy-coated bars in a tidal marine environment at Treat's Island in Maine. The performance of these specimens was compared with that of laboratory specimens subjected to accelerated testing. Epoxy-coated bars performed significantly better than uncoated bars.[90] Coated bars were removed from three coastal bridges in North Carolina in 1985. The investigation consisted of visual inspection of the bridge bents and extraction of concrete cores in tidal, splash, and dry zones. Epoxy-coated bars were found to be providing adequate corrosion protection in spite of the harsh environment.[91] Deck ratings of 213 structures containing coated bars and built since 1978 were studied by the Kansas DOT. All of the structures were found to be in excellent condition.[92]

In 1990, a parking deck in the northern US constructed in 1982 experienced spalling and delamination. The structure had been exposed to large amounts of deicing salt and in some places, the cover was 13 mm. A study conducted in 1992 showed that the reinforcement corroded badly in two of four cores taken, and the coating experienced cracking, blistering, and disbondment.[22, 51] A field survey of parking structures in Canada did not reveal a correlation between the observed cracking and the use of epoxy-coated reinforcing steel.[51]

3.3.2 Failure Mechanisms

Failure Mechanism by Alberto Sagüés [65]

Coated bars produced according to existing specifications contain a small number of initial coating imperfections, as allowed by the acceptance criteria. During shipping, bars surface additional surface damage. Fabrication produces disbondment by mechanical means. At the construction site, bars are exposed to the environment for a period ranging from a few days to over a year. In coastal sites, salt water exposure creates additional disbondment. Heating/cooling cycles, ultraviolet exposure, and additional damage during handling results in further coating deterioration. Bar cage assembly, installation in concrete forms, and concrete pouring and vibration causes additional surface damage. Depending on the concrete permeability and position with respect to water level, coated bars are exposed to a low-chloride concrete environment for a period ranging from several months to years. During this time, concrete pore solution penetrates between coating and metal in regions where disbondment occurred during pre-service, aggravating coating delamination.

When enough chloride arrives, corrosion starts at the exposed metal at imperfections and in the crevices below the disbonded coating. Corrosion macrocells develop with cathodic regions where there is good oxygen availability. Cathodic areas include exposed metal at imperfections and the surrounding disbonded crevices. Macrocell action over large distances is produced by low concrete resistivity and electrical continuity of the rebar cage, which make for an unfavorable anode-to-cathode ratio. The intense current at the anode causes additional disbondment and corrosion at the crevices. The corrosion morphology eventually consists of extensive coating disbondment, accumulation of corrosion products and low pH liquid under the coating, and metal consumption characterized by spots of severe pitting on a background of more uniform corrosion.

Failure Mechanism by Kenneth C. Clear [77, 22]

Kenneth C. Clear postulated a failure mechanism primarily based on research he conducted for the Canadian Strategic Highway Research Program. He identified an unexpected loss of coating adhesion and underfilm corrosion in northern and southern field structures and in coated bars considered to have high quality in laboratory and outdoor exposure specimens. The mechanism involved debonding of the epoxy film and once significant chloride was present, the epoxy blistered, became brittle, and cracked. The disbondment occurred in concrete with or without chlorides when the coating was displaced by a thin layer of water (wet adhesion loss). Wet adhesion loss can set up local corrosion cells or facilitate the formation of osmotic blisters. Corrosion failure is the result of anodic activity under the coating, leading to further destruction of the coating-to-steel bond or production of hydroxides at cathodic regions, which dissolves the oxide film and/or reacts with the coating/oxide bond. Hydrogen evolution at cathodic sites beneath the coating could be involved.

Macrocell action, which results from electrically connecting different reinforcement layers, was another failure mechanism occurring on coated bars with holidays or visible bare areas, and on bars where the epoxy film broke as a result of significant underfilm corrosion. Macrocell action may contribute to adhesion loss even when corrosion current density is low.

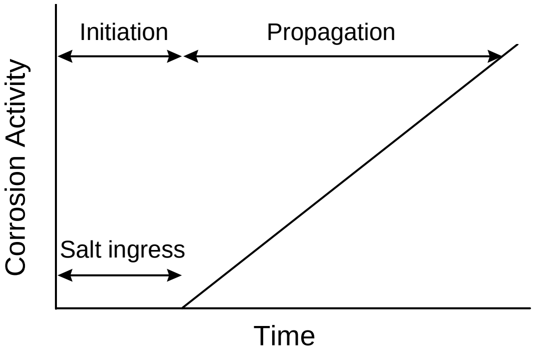
Failure Mechanism by Schieβl [78]

The failure mechanism of epoxy-coated bars is similar to known mechanisms of polymer coated steel surfaces exposed to outdoor environments.

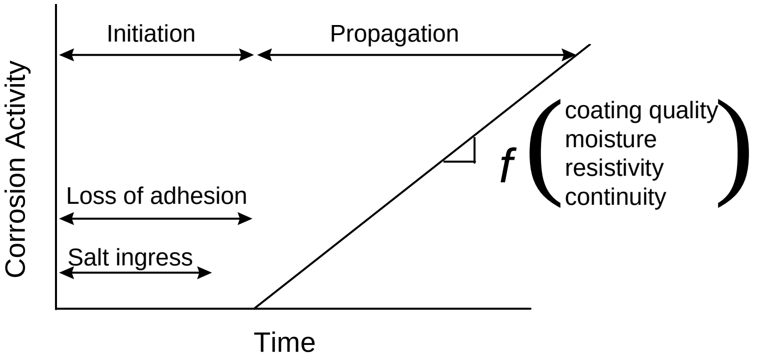
The mechanism is initiated when chloride levels at the bar surface reach critical values and bare areas start to corrode. The bare area becomes gradually covered by corrosion products and subsequently, a self polarization of the bare area occurs, which induces an opposite polarization in adjacent areas covered by the coating. A cathodic reaction may take place under the coating (because polymer coatings are permeable to moisture and oxygen), resulting in cathodic disbondment of the coating. Hydroxyl ions generated from the corrosion process may also undercut the coating around the defect. Even in the absence of defects in the coating, water, oxygen, and chloride ions may permeate through the film, causing a slow corrosion process, adhesion loss, and, eventually, blistering. As water and chlorides penetrate under the coating, the initially cathodic areas may become anodic and corrosion propagates. The enlarged anodic area causes additional disbondment at increasing rates. Moisture in the concrete accelerates degradation of the coating. The coating softens and its permeability increases when the film absorbs water. The film embrittles by alternate wetting and drying and by diffusion of substances through it.

Propagation Model by Manning[51]

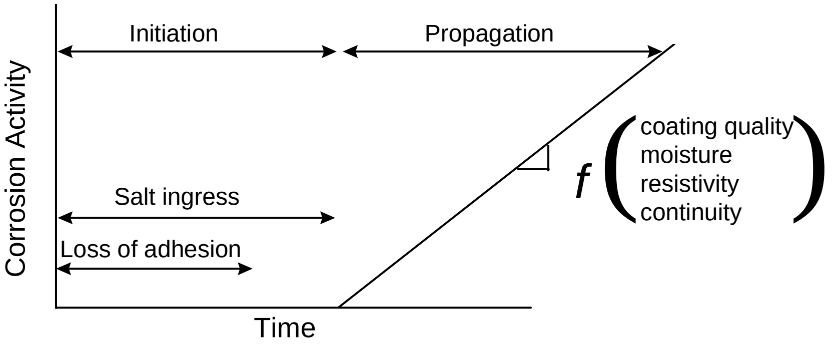
Manning proposed two models for the corrosion propagation of epoxy-coated bars in concrete. One model is for low quality concrete, and another model is for good quality concrete. As a reference, a model for the corrosion of uncoated bars in concrete in shown in Fig. 3.3(a). When epoxy-coated bars are embedded in poor quality concrete [Fig. 3.3(b)], chloride ions penetrate the concrete and reach the bar surface quickly, but corrosion will not start (except at bare areas) until the coating loses adhesion. The propagation phase begins when corrosion spreads beneath the film. When the concrete is of high quality, adhesion may be lost before the chloride ions reach the bar, as shown in Fig. 3.X(c). The propagation phase begins when enough chloride ions penetrate and accumulate at the bar surface. In both cases, corrosion accelerates in the propagation phase, and the corrosion rate is controlled by several factors, including moisture content and resistivity of concrete, electrical continuity of the reinforcement, presence of coating defects, and availability of oxygen at cathodic areas.



(a) Uncoated steel in average density concrete



(b) Epoxy-coated bars in poor quality concrete



(c) Epoxy-coated bars in good quality concrete

Fig. 3.3: Initiation-propagation models for uncoated and coated steel proposed by Manning.[51]

3.3.3 Controversial Issues

Early corrosion research seemed to indicate that epoxy-coated reinforcement was a reliable method to achieve satisfactory long term performance of concrete structures subjected to aggressive corrosive environments. The premature failures observed in the Florida Keys and other instances of corrosion problems in Florida, New York, Georgia, and Ontario have put epoxy-coated reinforcement under close scrutiny and focused attention on its quality. Although isolated cases of corrosion of coated reinforcement have been reported in the 1990's, many other field investigations have reported good performance. Laboratory studies have also been controversial, some predicting good performance, and others predicting only a short extension of service life. Some researchers have noted that the good performance observed in many structures can also be attributed to improvements in concrete quality and increased cover, measures that coincided with the introduction of epoxy-coated reinforcement.[51, 77] In other cases, periods of exposure were relatively short and levels of chlorides were low.[22] But even if it is accepted that epoxy-coated bars improve corrosion performance, some researchers stress that the real issue is to determine the extension of service life provided by coated bars.[51]

Florida Keys Experience

Field and laboratory investigations performed after the premature failure of the Florida Keys bridges led the Florida DOT to conclude that epoxy-coated bars were more susceptible to corrosion than uncoated steel in marine substructure applications. While coating quality was possibly a contributing factor, it was not the primary cause of deterioration.[22] Others disagree with these conclusions and believe that poor coating quality and/or field damage, or possibly an influence of Florida aggregates were the primary cause of the failures.[14] Others argue that an imperfection in the coating may create a small anode-large cathode condition, resulting in more severe local attack than in the case of uncoated bars.[22] Some have suggested that the Florida environment may be particularly aggressive and unique. Clear noted that corroded bars from the Florida Keys bridges were similar in appearance to the corroded non-specification bars removed from the FHWA outdoor exposure slabs in 1981 and in 1989. The FHWA slabs were exposed to a northern deicing salt environment, suggesting that the type of failure observed in Florida substructures was not unique to that particular environment.

Litigation by CRSI [51]

One of the most controversial aspects has been the apparent and sudden change of a researcher's views regarding the corrosion performance of epoxy-coated reinforcement. In previous research by Clear, he had stated that epoxy-coated bars were effective in reducing corrosion deterioration compared with uncoated bars. In an annual meeting of the Transportation Research Board in January 1992, Clear made a presentation where he stated his controversial opinions regarding the corrosion performance of epoxy-coated bars, reflecting an obvious change of his previous conclusions. Soon after, the Concrete Reinforcing Steel Institute (CRSI) filed a lawsuit against Clear. Although CRSI was shocked by Clear's change of opinion on the effectiveness of epoxy-coated reinforcement, and the negative impact of his views, the suit was not directly related to the performance of epoxy-coated bars, but about Clear's business practices. The actual charges were racketeering, fraud, breach of contract, and malpractice in relation to research that Clear had performed for CRSI in the period 1985-1991. The racketeering charges were dismissed at a preliminary hearing in May 1992.[93] In October 1992, the remaining charges were dismissed after the plaintiff rested its case and before the defense presented its evidence.[51]

Some of the issues stated by Clear that stirred controversy are as follows:[8]

- The technology for producing epoxy-coated bars is flawed. Therefore, bars coated with approved powders and meeting current specifications will not provide satisfactory long-term performance in aggressive corrosive environments.
- Projected performance based on dividing time-to-cracking for coated bar specimens by the corresponding life for uncoated bars used in previous research was an error. Subtraction, rather than division, is the correct approach. Thus, a life extension for epoxy-coated bar structures compared to uncoated bar structures of 6 to 8 years was projected, instead of original projections where life of ECR structures exceeded that of uncoated bars by more than a factor of five using the previous approach.[22]
- Properties of epoxy-coated bars affecting observed differences in corrosion performance have not been identified.

- Efforts to certify coating plants were futile and would not provide a significant benefit because the relationship between bar properties and field performance was not understood.
- The good performance observed in many structures was due primarily to the deep concrete cover and better quality concrete used by highway agencies, rather than the epoxy-coated reinforcing steel.[77]

Prior to the lawsuit, some friction between Clear and CRSI began to arise. The research that Clear conducted for CRSI, "Effectiveness of epoxy-coated reinforcing steel," apparently began to show deficiencies in the performance of epoxy-coated reinforcement late in 1990, and he made a proposal to CRSI to fund additional research. CRSI decided not to authorize additional work and requested a final report. After some differences over the scope of the remaining work, an agreement was reached under which Clear would provide specified data and test results. Clear submitted a draft final report in June 1991. Although CRSI acknowledged that the report met the requirements of the agreement, they gave Clear a list of comments in July 1991, many of which involved additional testing and analysis that CRSI would not fund. CRSI requested a peer review of Clear's work by Wiss Janney Elstner and Associates (WJE).[51] The findings of the peer review and Clear's opinions of the WJE review were discussed in earlier paragraphs.

In December 1991, Clear sent its final report to CRSI. CRSI demanded that Clear turn over all specimens in the CRSI project to WJE, but Clear refused these demands. An agreement between Clear and CRSI was reached in November

1991, under which a limited number of specimens would be turned over to WJE. In March 1992, CRSI demanded that Clear deliver all specimens and data collected during the project to CRSI. A few days later, Clear responded he would deliver only those items listed in their agreement.[51]

Manning cited two interesting comments from the Findings of Fact for the lawsuit. Manning quoted that the court documents stated that "From CRSI's standpoint, WJE was retained to criticize KCC's work because CRSI had begun to sense that KCC's scientific conclusions were not compatible with CRSI's business objectives." At the hearing where all charges were dismissed, the judge commented that "…there is an underlying undercurrent here, which I think the evidence supports, and that is that this case is less about money than it is about an attempted discrediting of the defendant."[51]

The controversy "muddied" the discussion and research on epoxy-coated bars and probably led many to the conclusion that epoxy coating was an unproven material and other types of corrosion protection were sought.

3.4 PRESENT STATUS

The debate on the effectiveness of epoxy-coated reinforcement originated by premature failures in Florida Keys substructures, the change in opinion by a top researcher, and other isolated cases of corrosion failures have forced state highway agencies in North America to evaluate the field performance of epoxy-coated bars and review their policies. Some agencies, like Florida Department of Transportation, decided to discontinue the use of epoxy-coated reinforcement because they judged that coated bars would not ensure adequate corrosion protection for their type of environment. The majority of users observed little or no corrosion deterioration of their infrastructure containing epoxy-coated bars and decided to continue using epoxy coatings. Surveys reported by CRSI indicate that there is still widespread acceptance of epoxy-coated reinforcement among owners, engineers, engineering management, parking garage developers, and others.[94, 95]

At present, epoxy coating is the most common corrosion protective system used by 48 state highway agencies in the US. To date, there are about 20,000 bridge decks with epoxy-coated reinforcement. This represents roughly 95% of new bridge construction since the early 1980's. The use of epoxy-coated reinforcement has been extended to other structures. Today, epoxy-coated rebar is used in parking garages, aquariums, nuclear power plants, coal plants, buildings, concrete pavements, and wastewater treatment tanks. Presently, epoxy-coated reinforcement has been used in approximately 100,000 structures.[96] The US uses nearly 300,000 tons of epoxy-coated bars per year.[86] There are about 35 coating plants in the US and Canada.[96]

In the following paragraphs, present policies and practices regarding epoxy-coated bars by several agencies are described.

3.4.1 Ontario Ministry of Transportation

The Ontario Ministry of Transportation in Canada deserves special mention. Several studies conducted by the Ministry, and those for C-SHRP, convinced the Ministry that although coated bars performed better than uncoated bars, coated bars would extend the service life of the structure for 3 to 6 years only in most cases. If specifications were tightly enforced, service life could be extended up to 8 to 11 years over uncoated bars. Neither case was compatible with the long-term objectives of the Ministry, which was seeking to provide 50 years of corrosion protection.[51]

Despite finding that epoxy-coated bars did not meet their expectations, the Ontario Ministry of Transportation decided to continue using coated bars but introduced some changes. In 1993, the Ministry held a meeting with the epoxy coating industry and came up with a very strong statement: Either significant improvements in the quality of the product were made, or the Ministry would no longer specify epoxy-coated bars. After visiting Europe, one of the producers proposed to improve coating adhesion with a new technology that incorporated the application of a primer between the epoxy coating and the steel bar. In addition, the Ministry established additional requirements for adhesion in the specifications and developed test procedures and acceptance criteria. To measure adhesion, three test methods were investigated: a hot water bath, cathodic disbondment, and salt spray exposure.[51] Coaters voluntarily produced and supplied coated bars with improved adhesion.

Other measures that were implemented consisted of: [51]

- Limiting maximum time of unprotected storage to 30 days, and of total on-site storage to 120 days
- Limiting maximum damage in the coating to 1% of surface area in any meter length (repair not allowed)

- Requiring repair of all visible coating damage (less than 1%) in accepted bars
- Requiring the use of plastic-covered vibrators for placing concrete in bridge decks, barrier walls, and end dams.

The above measures were targeted at reducing the number of defects in the coating. Although epoxy-coated reinforcement continued to be used in Ontario, the policy remained under review.

3.4.2 US Navy [58, 97]

The US Navy conducted research to evaluate long-term performance of epoxy-coated bars in marine environments. It was concluded that damage-free epoxy-coated rebar performed better than other protection measures. The bars used in the field exposure tests exceeded then-current industry standard specifications. However, it was recognized that the same coating did not have good long-term adhesion in marine environments, and that it would be unlikely to expect no defects in the coating of bars used in real life situations. Therefore, the Navy, through cooperative efforts with industry, focused on new technology using less flexible, non-bendable coatings; methods to prefabricate bars; and enhanced quality control measures. The Navy developed two new standard specifications for prefabricated epoxy-coated rebar: NFGS 03201 specifies procedures for manufacturing coated bar, and NFGS 03202 details procedures for correct handling, placement, and repair of coated bars. The Navy's goal was to specify a controlled process, from coating application through placement, that ensured high quality, coated prefabricated bar for Navy projects.

The new Navy specifications require that the bars be cut and bent to final size and shape before coating with a semi-rigid epoxy powder. That includes cutting straight bars to their final length at the fabricating plant so that the sheared ends are factory coated. The specifications also allow for the use of chemical pretreatment of the blasted surface prior to heating and coating to passivate the steel surface and to enhance adhesion of the coating. A procedure for product certification and acceptance was defined in NFGS 03201. First, the epoxy powder must be certified by an independent laboratory to a regime of prequalification tests. Second, the coating applicator must be certified by subjecting production run bars to prequalification tests. Third, production run epoxy-coated bars for each job must be tested at regular intervals. And fourth, some standard tests are recommended to assist the coating manufacturer in maintaining consistent quality production. Some prequalification tests are noteworthy: A 48-hour hot cathodic disbondment test (for powder certification only), a 168-hour ambient cathodic disbondment test, and an 800-hour salt spray test. Among other tests, a 24-hour hot cathodic disbondment test is used for regular testing of production run bars. Among recommended tests to assist the coating manufacturer, the screen analysis of the blasting abrasive and the detection of salt contamination tests stand out.

Specification NFGS 03202 has many of the recommended field practices set forth in other recommended procedures, such as those by CRSI. Some of the innovative requirements include: Rinsing of bars with fresh water before placing of concrete to remove salt contamination; use of nonmetallic or rubber vibrator heads to consolidate concrete; repair of all visible damage with patching material, where repaired areas should have a minimum coating thickness of 10 mils; spot grinding or blast cleaning surfaces at areas to be repaired to a near-white metal finish; avoid patching if precipitation is expected within 4 hours.

The constructibility of projects with the new Naval Facilities Guide Specifications (NFGS) was being evaluated in a plan termed PROSE (Prefabricated Epoxy-Coated Steel Reinforcement for Oceans and Other Severe Environments). Several technology demonstration projects were built at different naval locations: Construction of a submarine berthing pier in New London, CT; a submarine wharf and Ford Island Bridge project, both in Pearl Harbor; a pier and an aircraft carrier wharf in San Diego, CA. In addition, the Naval Facilities Engineering Service Center worked closely with the ASTM task group to develop ASTM Standard Specification for Epoxy-Coated Prefabricated Steel Reinforcing Bars, A 934/ A 934 M-95, which was approved in May 1995. The Navy is using these specifications for its new construction projects.

3.4.3 Texas Department of Transportation

The Texas Department of Transportation (TxDOT) uses approximately 18 million pounds of epoxy-coated reinforcement annually. The main use is in bridge structures with additional uses in concrete pavements and retaining walls.[98] TxDOT has been satisfied with research results of the present project and believes that epoxy-coated reinforcement can ensure satisfactory performance of highway structures in Texas. During the course of the present study, TxDOT has continually improved its Standard Specifications based on preliminary research findings. TxDOT specifications for epoxy-coated bars have been in some respects more stringent than ASTM specifications, especially before recent changes were introduced by ASTM. The specifications require coating applicators to be approved and “quality monitored” by the Materials and Test Division when furnishing epoxy-coated bars for TxDOT projects.[98] Although subjective, TxDOT has one of the few specifications that incorporated a knife adhesion test (termed “peel test”) for bar elements too small for the bend test.

TxDOT has a policy termed “belt and suspenders” approach for the corrosion protection of the Texas highway infrastructure where increased durability is desired, which consists of the use of multiple corrosion protection measures in addition to epoxy-coated reinforcement. Such measures include increased concrete cover, use of type II cement, high quality concrete with decreased permeability, penetrating concrete sealers, and the use of prestressed members. TxDOT estimates that the use of all these measures increases the total cost of the structure by approximately 5% for an anticipated 25 year increase in service life to 75 years.[98, 99] Based on research results that will be discussed in subsequent chapters, TxDOT encourages the use of epoxy-coated reinforcement throughout the same member. Epoxy coating increases the cost of the reinforcement by 25% to 50%. Epoxy-coated reinforcement was used throughout both the superstructure and substructure of the Redfish Bay and Morris and Cummings Cut bridges near Corpus Christi, Texas.[98, 99] The total bridge cost in these structures increased to about 1.8%.[98]

One of the main concerns of field engineers in Texas was the implementation of research findings in the field. This concern was frequently raised at the periodic project meetings where the status of the present project at different stages was reported. One of the worries stated by field engineers was that research findings are usually molded in a research report that few people read and seldom materialize in the field, where they matter most. With this in mind, TxDOT is developing a series of posters that contain the most relevant research recommendations in terms of field practice. The objective is to place these posters at visible locations in the job site, so that field workers, who are ultimately the ones who handle the epoxy-coated bars, can read them and become aware of the proper procedures to handle and repair coated bars. These posters are similar to those produced by the CRSI in technical content, but were artistically designed in a more appealing form using down-to-earth language so they attract attention of construction workers. Both English and Spanish version posters will be produced in recognition of the large presence of Spanish-speaking workers in the Texas labor force.[100]

3.4.4 Other Trends

Most bridge decks built in the 1970’s and 1980’s have epoxy-coated reinforcement in the top mat only, with the bottom mat uncoated. The rationale at the time was that the lower mat did not need to be coated because the bars would be protected by uncontaminated concrete without chlorides.[80] Research later showed that corrosion could be accelerated if any incidental electrical continuity between top coated and bottom uncoated bars was set up, and there were flaws and breaks in the coating.[10, 46, 47, 68] These convincing findings have caused several state highway agencies to change their design practices and are specifying now that all bridge deck bars be epoxy-coated.[80, 16] In addition, state agencies are taking provisions to avoid any incidental electrical continuity between steel mats, such as specifying the use of metallic or coated bar supports, used of coated tie wire, and coating all mechanical splices. In Texas, a bridge was recently built along the Gulf Coast near Corpus Christi where all the reinforcement for the foundation, substructure, and superstructure was epoxy-coated.[99] A cast-in-place reinforced concrete parking facility in Columbus, Ohio was built with epoxy-coated reinforcing steel throughout the structure.[101] In the future, it is expected that more and more state agencies will specify the use of epoxy-coated bars for all the reinforcement.

Another trend that State Departments of Transportation, City Departments of Public Works, and other agencies are taking consists of a multi-protection approach similar to that of TxDOT. Instead of relying on epoxy-coated reinforcement alone, other corrosion protection measures are taken. For instance, the Minneapolis Department of Public Works specifies, in addition to epoxy-coated reinforcement, the use of microsilica concrete with a water/cement ratio of 0.38, and 1.5 inches of cover over the steel for parking garages.[102]

The Great Belt Link, Denmark

The Great Belt Link project consists of three major structures that link the islands of Zealand and Funen in Denmark: A railway tunnel, a road bridge, and a combined road and railway bridge.[103] Because of the magnitude of the project, the structures were designed for a service life of 100 years. A multistage protection strategy was adopted to achieve the specified 100-year service life. It was reasoned that if one of the protective measures failed, others would take over.[104] The following protective measures were employed for the precast concrete lining segments of the bored tunnel:[104, 105]

- High quality concrete with low-alkali sulfate-resistant portland cement, fly ash, and microsilica, and with w/c ratio less than 0.40
- Epoxy-coated reinforcement
- Preparations for cathodic protection of welded reinforcement cage
- External grout with high fly ash content, microsilica, and admixtures, with maximum w/c ratio of 0.35
- Water-tight design using joints fully sealed with gaskets

The project was planned and executed in an innovative manner. The reinforcement for the concrete tunnel segments was fully assembled and welded before application of the epoxy coating.[104, 105] The complete reinforcement cages were blast cleaned, heated to 260°C (500°F), dipped in a fluidized bed for 4 seconds, cured, and stored. The cages were reported to have emerged from the fluidized bed with a very uniform coating. Application of the epoxy coating was optimized by dipping model cages in a series of trials before construction. It was believed that the fluidized bed technique had not been previously used for three-dimensional reinforcement cages.[105] Moreover, coating after manufacture of the reinforcement ensured the electrical continuity required for effective application of cathodic protection, should the need arise.[104] Structural tests on model segments showed that the epoxy coating did not have a significant effect on structural performance.[105]

An important aspect of the project was the high degree of automation employed in the fabrication of the concrete segments. The reinforcement was blast-cleaned, cut, bent, welded, and coated in an automatically or semi-automatically controlled operation. The chances for damaging the epoxy coating were minimized, thus ensuring a high standard of quality.[105] In addition, a quality assurance policy based on the international standard ISO 9001 was implemented in the contract specifications and the payment system.[103]

3.5 FUTURE DIRECTIONS

Future trends for the use of epoxy-coated reinforcement involve research and development in the following areas: [51, 58, 60, 97]

- *Materials:* Improvement in quality of epoxy coatings is expected to continue. This includes changes in the powder formulation, development of performance-based prequalification tests, reduction in the number of breaks in the coating, improvement of adhesion to the steel bar, use of semi-rigid or non-bendable coatings, proper selection of reinforcing steel, formulation of better patching materials, development of prequalification tests for patching materials.
- *Coating Application:* Improved techniques to ensure cleanliness and anchor pattern of the bar surface, use of primers or chemical pretreatments to passivate the steel surface and to improve adhesion, coating after fabrication, coating after bars are cut to final size so that bar cut ends are factory coated.

- *Corrosion Monitoring:* Development of new or refinement of existing techniques to monitor corrosion activity inside the concrete, verification of the precise corrosion mechanism in field structures.
- *Accelerated Laboratory Tests:* Development of standard tests to measure bar corrosion in concrete and coating adhesion, correlation of accelerated test results with long-term field performance.
- *Standard Specifications:* Use of more stringent specifications and rigorous test methods to measure coating properties, reduction in the amount of permissible coating damage, introduction of adhesion tests, development of acceptance criteria (especially for coating damage and adhesion) and correlation with long-term corrosion protection (performance-based specification).
- *Construction Practice:* Follow proper procedures to handle coated bars to minimize damage during construction, limit outdoor storage time, use of rubber-head vibrators to consolidate concrete, education and training of field workers.
- *Design Practice:* Specification of epoxy-coated bars for all reinforcement in the structure, specification of non-metallic reinforcement supports and chairs, design for crack width control during service, use of parallel corrosion protection measures in addition to epoxy-coated reinforcement.
- *Quality Control / Quality Assurance:* Voluntary or required plant certification programs (CRSI), inclusion of quality assurance testing of

samples from production runs in project specifications and/or standard specifications.

Chapter 4. Coating Quality and Adhesion

4.1 GENERAL

Some aspects regarding quality of coating application will be discussed in this chapter. Because of its relevance in the corrosion performance of epoxy-coated reinforcement, coating adhesion to the steel substrate will be discussed in more detail. Mechanisms of adhesion loss, factors affecting coating adhesion, and available tests to evaluate coating adhesion will be reviewed. In addition, standard specifications for epoxy-coated bars are examined, emphasizing recent changes and current trends in the specifications.

4.2 QUALITY CONTROL

As has been emphasized throughout the literature, coating quality is essential for satisfactory performance. To achieve that goal, suitable quality control of the coating application has to be implemented. Standard specifications usually contain pre-qualification tests for acceptance of the raw material (epoxy powder), quality control/quality assurance tests and acceptance criteria for verifying the adequacy of the finished product (epoxy-coated bar). Some of the quality control provisions will be discussed in the subsequent paragraphs. Specific acceptance criteria values by different specifications for some parameters are discussed in the section about standard specifications.

4.2.1 Coating Thickness

Specifications usually require a maximum and minimum coating thickness. A uniform coating layer of adequate thickness is needed. If the coating is too thin, it will not provide a satisfactory protective barrier against the intrusion of chlorides and other deleterious substances. If the coating is too thick, it may become brittle and could crack during fabrication. Films that are more than 500 mm (20 mils) may produce porous structures.[67] Coating thickness is usually measured with a calibrated magnetic gage. A more accurate (but less practical for quality control purposes) measurement can be obtained by direct microscopic measurement of the bar cross-section. As long as it meets the specification, coating thickness is usually not a critical factor for corrosion performance. Corrosion tests do not show differences in performance within these limits.[60]

4.2.2 Holiday Detection[10]

Specifications require a maximum number of holidays (i.e. coating discontinuities not visible to the unaided eye) per unit length of the bar. The objective is to ensure a continuous coating layer without defects, breaks, or imperfections that may impair its protective capability during service. The presence of holidays in the coating is noticed with a 67.5-volt DC, wet-sponge type holiday detector, which can be in-line or manual. The in-line detector is useful to the coating applicator for quality control purposes. A hand-held holiday detector is more suitable for acceptance purposes and to verify the accuracy of the in-line system. Caution should be exercised when using holiday detectors. Kahhaleh found that hand-held detectors are unreliable and test results varied significantly with changes in moisture of the sponge, speed of detection, and test operator.[10] In addition, the number of responses obtained only indicated possible defects in the coating, but the reading gave no indication of the location and size of such defects. Holiday detection should be accompanied by visual inspection. In general, thicker coatings tend to have less pinholes.

4.2.3 Coating Flexibility

Flexibility is the ability of the coating to stretch without getting damaged, tearing, or cracking. This property is important because reinforcing bars in structural members are usually fabricated or bent, as in stirrups or hoops, anchorage hooks, or transition from positive- to negative-moment reinforcement. Flexibility of the coating is measured by the bend test, which consists of bending a piece of bar around a mandrel of specified diameter (generally a function of the bar diameter) at a specified angle after rebound and at a specified bend rate. After the test, the bar is inspected and the coating must not have cracks, damage, or evidence of disbondment. The smaller the mandrel diameter, the larger the angle of bend, and the faster the rate of bend, the more severe the test. There is a concern that some coatings passing the bend test may exhibit delayed cracking some time after bending. Apparently, small tears develop after the stretched coating undergoes some relaxation.[106]

Some specifications incorrectly state that the bend test indicates adhesion of the coating. Although a poorly adhered coating with poor flexibility may debond from the steel substrate and crack after bending, a poorly adhered coating with excellent flexibility may debond from the substrate without cracking or getting damaged after bending. Likewise, an extremely well adhered coating with poor flexibility may crack or tear without visible signs of debonding after bending (although adhesion should theoretically be weakened).

4.2.4 Coating Adhesion

Some have argued that the epoxy film relies on adhesion to the steel substrate to protect the steel surface against corrosion. A well adhered coating acts as an effective physical barrier that slows down the arrival of corroding substances to the coating/steel interface. Poor coating adhesion may result in underfilm corrosion. Poor adhesion may also reveal a poor coating application process. Fundamental aspects of coating adhesion will be discussed in subsequent chapters. As will be seen, one of the main problems has been the lack of an adequate test to measure adhesion. As mentioned above, some standards incorrectly specify the bend test as an indicator of coating adhesion. Specimens which passed the bend test have experienced adhesion loss and undercutting at bent regions in past studies.[10, 107]

4.2.5 CRSI Certification Program [108, 109]

The Concrete Reinforcing Steel Institute (CRSI) launched an epoxy coating plant certification program in 1991. The goal of the program was to certify the procedures and techniques of coating applicators to establish a high level of quality in the production of epoxy-coated reinforcing bars. The program is a process certification, not a product quality guarantee, and supplements, but does not replace, the acceptance testing of materials. The plant certification program is industry-sponsored and voluntary. Approximately 75% of North

American epoxy coating plants have been certified at the end of 1996. As of April 1, 1997, 30 of the 35 plants in North America have been certified or are pending certification. These plants produce over 90% of epoxy-coated bar supplied. As of January 1, 1997, ten state Departments of Transportation and two Canadian Ministries of Transportation were requiring CRSI certification for suppliers of epoxy-coated bars.

The independent inspection agency for the program has noted significant quality improvements in all of the participating plants. Improvements in quality have been at little or no additional cost, according to CRSI. Before the initiation of the program, the cost of adding epoxy coating was $0.127 per pound of steel. In 1997, the average added cost was $0.087.

The program involves evaluating all aspects of the coating application process, including: Quality control policies, handling, storage of bars, surface preparation, heating, storage and handling of powder, powder application, curing, holiday testing, thickness measurement, and adhesion testing. In many cases, the certification standards are more stringent than standard specifications. An independent testing agency contracted by CRSI performs plant inspections as follows: Each plant is inspected at least once a year in an unannounced visit. A second unannounced inspection is conducted on 20% of the plants selected at random. A plant that is reported to be experiencing quality problems may be inspected more frequently. Plants are required to maintain detailed quality control records daily for each production shift. Such records are open for review by the independent testing agency.

Several new tests (not required by most standard specifications) introduced in the program are the following:

- *Backside contamination*. Measurement of the amount of dust, dirt, and other contaminants between the coating and the steel
- *Chloride detection*. Detection of salt contamination on the steel surface before coating application
- *Copper sulfate test*. Used to identify mill scale on the steel surface not removed by blast cleaning
- *Cathodic disbondment test*. Evaluation of coating adhesion
- *Bend Testing*. Pin diameters employed in bar fabrication are used in bend testing for routine quality control

The program has resulted in advancements in holiday detection equipment and thickness gage calibration, as well as the development of target blast media working gradations, installation of temperature alarms and recorders in powder storage rooms, and the use of wetting agents for manual holiday detectors.[86] The program has been constantly reviewed and updated, and quality control standards have been revised and tightened 7 times. Some of the reported improvements in product quality include:

- Certified plants average 0.23 holidays per foot of bar (ASTM limit is 1 holiday per foot)
- Average backside contamination is 15% for certified plants. Before 1991, best estimates indicated that the industry average was 40% to 50%

- Average cathodic disbondment tests is 4 mm of disbonded coating. Research results indicate that coated bars produced before 1991 typically had much poorer test results.

Results of the CRSI certification program have had an impact on ASTM standard specifications. ASTM requirements for holiday testing, bend testing, anchor profile, and powder prequalification were tightened based on the performance of coating applicators in the certification program. Future improvements in the certification program that are being contemplated include: Statistical process control concepts, new adhesion tests, and coverage of fabrication and field operations.

Clear et al. have been critical of the CRSI certification program.[22] The argument is that bent bar studies by KCC Inc. (from retained specimens of the "macrocell study" originally sponsored by CRSI) showed that no differences in performance were seen with different coating thicknesses, or between straight and bent bars; or that bars with no visible damage or very few holidays performed poorly. They also argued that the bend test is not relevant to long-term coating adhesion in the alkaline concrete environment. Clear et al. felt that the program was not measuring the properties that are most relevant to ensure long-term performance, and that there was an evident lack of tests (especially adhesion tests) aimed at predicting performance of the bars in concrete. Of special concern was the lack of tests to ensure that the epoxy coating will not disbond from the steel substrate. They concluded that the certification program was not expected to produce epoxy-coated bars that provided long-term corrosion protection to concrete structures in aggressive environments.[22]

The most recent literature from CRSI includes a cathodic disbondment test which has been recently introduced. Apparently, such a test was not available at the time of Clear et al.'s critique of the program (1995). The cathodic disbondment test has been used by the Ontario Ministry of Transportation in its epoxy-coated bar specifications. Evidently, the CRSI program has been updated as the technology changes and as new concerns are raised. Nevertheless, it should be pointed out that no adhesion test (hot water-knife peel tests, cathodic disbondment tests, chemical immersion-peel knife tests, etc.) has been correlated with field performance, i.e. disbondment of coating in alkaline concrete environments.

4.2.6 Inspection

An inspection plan has to be implemented to ensure the quality of coated bars and to verify that they meet the applicable specifications. An appropriate inspection plan includes:[10]

- Plant inspection for initial production approval
- Approved quality control plan on produced coated bars
- Transportation and job site control

The importance of a good inspection scheme cannot be overemphasized. Even the best and most stringent specifications will be futile if an unsatisfactory inspection fails to detect anomalies in the production process and at the job site.

4.3 DISCUSSION OF INDUSTRY STANDARDS AND SPECIFICATIONS

There are a number of standard specifications available that provide guidelines for quality control of epoxy coating for steel reinforcement. The specifications include information on pre-qualification tests, physical tests, corrosion performance tests, permissible coating thickness, continuity, and adhesion, as well as on the condition and preparation of the reinforcing bar before coating application.

4.3.1 ASTM Standards

The most current versions of ASTM standard specifications for epoxy-coated reinforcement are as follows:

- *ASTM A775-97. Standard Specification for Epoxy-Coated Reinforcing Steel Bars*. This is the most general guideline for epoxy-coated bars and covers all aspects from production to the point of shipment.
- *ASTM A934-96. Standard Specification for Prefabricated Epoxy-Coated Reinforcing Steel Bars*. These specifications were developed for rigid or semi-rigid coatings that are applied after steel fabrication.
- *ASTM D3963-96a. Standard Specification for the Fabrication and Jobsite Handling of Epoxy-Coated Reinforcing Steel Bars*. The standard is intended to cover all aspects after the coated bars after they are produced, from fabrication to final placement in the structure.
- *ASTM A884-96. Standard Specification for Epoxy-Coated Steel Wire and Welded Wire Fabric for Reinforcement*

- *ASTM A994-95. Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bar to Concrete Using Beam-End Specimens*

ASTM A775-97 and ASTM D3963-97 [110]

Since their issuance in 1981, both these standards have competed with one another and had essentially the same requirements during the 1980's. Differences between the two standards were gradually reduced in the 1990's as the responsible ASTM Task Groups responded to field and research data. Thus, ASTM completed a major reworking of ASTM D3963 / D3963M in 1996, revising its scope and title to "Standard Specification for Fabrication and Jobsite Handling of Epoxy-Coated Reinforcing Steel Bars." By reworking D3963, ASTM made A775 and D3963 complementary. A775 covers the criteria for producing epoxy-coated bar and D3963 covers the requirements from production to placement into the concrete.

In 1997, ASTM D3963 was issued with incorporated prequalification tests for patching material, an area not covered in past standards. D3963 now includes 400-hour salt spray and 28-day, elevated temperature, high-pH solution immersion as prescreening tests for potential patching materials. The tests are performed on repaired areas of coated flat panels.

4.3.2 Other US Standards and Recommended Procedures

- *AASHTO M284 / M284M-87, Standard Specification for Epoxy-Coated Reinforcing Bars*. This standard was designated by ASTM as D3963 / D3963M-87. A significant number of State DOT projects for reinforced concrete structures requiring coated bars request the use of

- *AASHTO M254, Standard Specification for Corrosion Resistant Coated Dowel Bars*
- *NACE RP0395-95, Standard Recommended Practice for Epoxy-Coated Steel Reinforcing Bars*. This standard was first developed in 1981 and went through a number of draft versions in the 1980's. After a major revision of the draft in the early 1990's, a draft was accepted by NACE International and, in 1995, RP0395 was issued. Further revisions were being prepared in 1997.[110]
- *TxDOT*. The specifications are a hybrid version of the ASTM and AASHTO specifications, and they cover the complete coating process, fabrication, and installation of the reinforcement.[98]
- *CRSI, Guidelines for Inspection and Acceptance of Epoxy-Coated Reinforcing Bars at the Job Site*. These non-mandatory guidelines are intended to determine whether the repair of individual damaged areas is required, and if the total amount of damage is permissible.
- *CRSI, Field Handling Techniques for Epoxy-Coated Rebar at the Job Site*. This document contains information about field handling procedures, including receiving, inspection, long and short term storage, placing with use of accessories, field repair, and guidelines for the concrete pour.

- *CRSI, Fabrication of Epoxy-Coated Rebar*. This document shows the approved method of receiving, storing, shearing, bending, repairing, handling, and shipping epoxy-coated rebar.

4.3.3 International Specifications

Some European countries, such as Norway and Denmark, have adopted ASTM A775, while others (Germany, Great Britain, and Switzerland) have developed their own specifications.[22] In 1987, an independent German expert group was formed at the Institute for Building Technology (IFBT) to develop guidelines for the manufacture and use of epoxy-coated bars. The guidelines were based on a review of the literature in Europe and North America, and on bar testing. The expert group concluded that the standard requirements should be the highest possible. Swiss, Dutch, and German experts initiated discussions in the late 1980's to harmonize guidelines and standards for epoxy-coated bars.[111] The Swiss and German guidelines were developed jointly and are very similar. The German document is termed GFORB (Guidelines for the Use of Epoxy-Resin Coated Steel Reinforcements) and was published in 1990.[22] The guidelines were similar to the ASTM A775 standard when first published but had generally stricter requirements.[111]

A proposal for Dutch specifications, which is similar to the British document, has been recently recommended.[22] In the United Kingdom, the specification used is the British Standard BS 7295 (Fusion Bonded Epoxy-Coated Carbon Steel Bars for the Reinforcement of Concrete), published in 1990. The Japanese specification JSCE EP10 was published in 1986.[60] In Canada, the

Ontario Ministry of Transportation (MTO) has issued Ontario Provincial Standard Specifications OPSS 1442, Material Specification for Epoxy-Coated Steel Reinforcing for Concrete, and OPSS 1443, Material Specification for Organic Coatings for Steel Reinforcement. The Ministry has also issued MTO Report EM-69, Guidelines for Inspection, Patching and Acceptance of Epoxy-Coated Reinforcing Bars at the Job Site .[47]

4.3.4 Evolution and Comparison of Standards on Epoxy Coated Rebars

Standard specifications for epoxy-coated bars have evolved in the last ten years. First specifications developed for epoxy-coated bars were adapted from the pipeline industry. Initial specifications were relatively lax because early research results showed that bars not conforming to specifications could still provide adequate protection. Premature corrosion failures in some structures and other research results showed this perception to be flawed. Bars meeting lax specifications could be subjected to corrosion problems. The knowledge and experience gained from premature failures and research has helped to pinpoint those areas that needed revision and change in the standards. The various specifications have evolved differently and some of them have been more expeditious in incorporating changes or innovations. Development of new materials and application processes, such as semi-rigid coatings applied to pre-fabricated bars, have made it necessary to issue new specifications. Recent changes in standard specifications for epoxy-coated bars and comparisons of the different standards are presented in the following paragraphs.

Comparison of US Standards [110]

Lampton and Schemberger have prepared an overview of the evolution of epoxy-coated bar standards in the last 10 years.[110] Some of the major changes were discussed, and a comparison of different standards for both prefabricated and post-fabricated bars were included. The main standards compared were AASHTO M284 / M284M-87 (-91I) with ASTM A775 / A775M-97 for post-fabricated bars, and ASTM A934 / A934M-95 for prefabricated bars with ASTM A775 / A775M-97. In this section, a summary of such work is presented.

Post-fabricated bars

AASHTO M284 / M284M-87 (-91I) standard is compared with ASTM A775 / A775M-97 at areas where major changes were made. For brevity, AASHTO M284 / M284M-87 (-91I) will be referred to as "M284" and ASTM A775 / A775M-97 will be noted as "A775."

Coating plant certification. A775 recommends that the coating application procedures and processes be audited by an independent certification program, such as that of CRSI, the Navy Facility Guide Specifications, or equivalent.

Powder storage. A775, in section 5.2.2, requires storage of the epoxy powder in a temperature-controlled environment prior to use and its consumption before its shelf life expires. The rationale is to keep the highly reactive epoxy powder in a cool environment for a relatively short time to prevent it from deteriorating to the point where it will not wet the steel surface during application, adversely affecting coating adhesion.

Bar condition. A775 stipulates inspection of bars to be coated for sharp edges on deformations, rolled-in slivers, and other surface imperfections that are difficult to coat. Such bar deficiencies result in areas of thin coating and holidays.

Dust removal. In section 6.2 of A775 requires the use of air knives after blast cleaning the bar surface to remove dust deposited during blast cleaning.

Salt removal. A775 (Note 7) recommends cleaning the bar surface when contaminated with salt before coating application (preferably prior to blast cleaning). The presence of salts may cause formation of blisters in the coating.

Pretreatment. A775 allows the coating applicator to apply a chemical pretreatment to the blast-cleaned bar before heating and coating application to improve coating adhesion and to passivate the steel surface. M284 does not state whether the use of pretreatment is permitted or not. As it is not referred to specifically, a few state Departments of Transportation have refused to prequalify epoxy coatings applied to pretreated surfaces.

Coating application interval. A775 specifies a maximum delay time between blast cleaning and coating application of 3 hours, while M284 allows a maximum delay of 8 hours.

Coating thickness. In 1987, the standards required a range of coating thickness of 125-300 μm (5-12 mils) for at least 90% of the measurements. AASHTO changed this requirement in 1991 to 250 ± 50 μm (10 ± 2 mils) on 90% of the measurements. A775 requires a range of 175-300 μm (7-12 mils) on 90% of the measurements taken. Lampton and Schemberger pointed that the AASHTO requirement was the better of the two provisions because it specifically targets a

250 μm (10 mils) thickness with a deviation due to coating processes.[110] With the ASTM provision, a coating applicator may theoretically shoot for a 175-200 μm (7-8 mils) range without worrying about the standard deviation. To counter this possibility, ASTM added the requirement that coating thickness measurements below 125 μm (5 mils) shall be considered cause for rejection of the coated bar.

Coating continuity. The average maximum number of holidays allowed in the coating is 3 per meter (one per foot) in A775, while the limit is 6 per meter (2 per foot) in M284. The stricter ASTM requirement has caused the coating applicators to be more careful in the selection of rebar for coating. To check for holidays, M284 permits the use of either in-line or hand-held holiday detection, while A775 recommends the use of in-line holiday detection of all bars with hand-held holiday detector checks to verify the accuracy of the in-line system.

Coating flexibility. A775 requires a bend of 180° (after rebound) around the appropriate mandrel while M284 requires a 120° bend with a much slower bend rate. A very important difference is that A775 no longer defines the test as an adhesion test (as still considered in M284) but as a coating flexibility test. The bend test does not always determine how well the coating is adhered to the steel surface nor does it indicate if such coating adhesion will be maintained in a chloride-contaminated concrete environment. The test is useful for quality assurance since failure of the test would indicate that something is significantly wrong with the coating process.

Coating adhesion. A775 has incorporated the requirement of conducting cathodic disbondment testing on a regular basis to measure coating adhesion.

ASTM recommends the coating applicator use the test data as part of the plant' statistical process control. There is no maximum limit specified for the coating disbondment in the test.

Testing frequency. A775 specifies the following test frequencies: For coating thickness, a minimum of 2 bars of each size for each 4 hours of production are to be tested; for flexibility, a minimum of one bar of each size for each 4 hours of production; for coating continuity, random tests; and for cathodic disbondment, at least one bar from every 8 production hours will be tested. M284 states that the purchaser may specify the test frequency for coating thickness, flexibility, and continuity.

Outdoor storage. The A775 standard requires protective covering of coated bars at the coating applicator's facility if the bar is to be stored outdoors for more than 2 months.

Coating repair. M284 states that hairline cracks without bond loss or other damage need not be repaired. Coating damage need not be repaired if the damaged area is 6.4 x 6.4 mm (¼ in x ¼ in) or smaller and the sum of all damaged areas in each 0.3-m (1-ft) length of bar does not exceed 2% of the bar surface. A775 requires all damage due to fabrication or handling (to the point of shipment) be repaired with an appropriate patching material. The repair area should have a minimum coating thickness of 175 μm (7 mils).

Prequalification tests. The chemical resistance test is the same for both M284 and A775. The weakness of the test is that except for indicating susceptibility of the coating to blistering, it does not determine whether the coating has softened, lost bond, or developed holidays from the immersion. The resistance to applied voltage test in M284 has been replaced by the cathodic disbondment test in A775. An 800-hour salt spray test was added in A775 and is not contained in M284. The test measures the adhesion of the coating in a hot, wet salty environment. Differences in the bend test are the same as indicated before. The bond strength test in M284 has been replaced in A775 by the "Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens." The creep test and Knoop hardness test contained in M284 were removed from A775.

Guidelines for job-site practices. A non-mandatory Appendix has been added to A775 covering guidelines for job-site practices when using epoxy-coated reinforcement. Some of the topics covered include handling, unloading, storing, placement, and repair of coated bars.

Prefabricated bars

Prefabrication of rebar prior to surface preparation and coating application was developed recently as a solution to the coating adhesion loss and damage caused by bending. ASTM prepared a standard for prefabricated bars and issued ASTM A934 / A934M in 1995. The standard was revised in 1996 and a 1997 version was being developed. A comparison of A934 with A775 is presented next.

Coating flexibility. For the bend test, A934 requires a bend angle of 6°-9° after rebound, depending on bar size, while the angle is 180° in A775. The difference in bend angles is due to the “less-flexible” coatings that are specified under A934.

Coating adhesion. A775 requires a 7-day, ambient-temperature cathodic disbondment test on a regular basis, with no specified acceptance criteria, but recommends the coating applicator use the data for statistical process control. A934 requires a 24-hour, 65°C (150°F) cathodic disbondment test with a 6-mm maximum coating disbondment radius as acceptance criterion of the bar lot.

Frequency of tests. For coating thickness, A934 requires measurements on a minimum of 2 straight and 2 bent bars of each size for each production hour, while A775 requires a minimum of 2 bars of each size for each 4 hours of production. The increased frequency of testing in A934 recognizes the fact that it is easier to uniformly coat straight bar. The frequency of bend tests is the same for both standards: A minimum of one bar of each size for each 4 hours of production. For coating continuity, A934 specifies 2 bars of each size from each production hour compared to random tests in A775. A relatively high testing frequency was adopted in A934 because holiday testing is not feasible in a prefabricated bar coating line, and the holiday testing must be done by hand. The testing frequency for cathodic disbondment is the same for both standards, but A934 includes a bent bar in addition to a straight bar section from each 8-hour production shift.

Prequalification tests. Prequalification tests for both standards are similar. A hot cathodic disbondment test is included in A934 in addition to the ambient-temperature cathodic disbondment test. The flexibility test has a reduced bend angle and the impact test has a reduced minimum value in A934.

Application process and product test procedures. A934 contains an Appendix of process and product parameters that should be regularly examined during the coating operation. The Appendix includes procedures on how to measure the parameters, such as analyzing the blast media, bar surface anchor profile, degree of bar surface residue, degree of salt contamination, degree of mill scale contamination, degree of coating porosity and interfacial contamination, 7-day cathodic disbondment test, and 800-hour salt spray test.

Comparison among International Standards

Schieβl and Reuter presented a comparison of requirements for epoxy-coated bars by German, British, and ASTM standards in tabular form and is shown in Table 4.1.[111] Note that the 1997 version of the ASTM A775 standard was included (the authors originally presented the 1990 version).

Requirement	***German Guideline IFBT-Rule 05-90***	***British Standard 09.90***	***ASTM A775-90***	***ASTM A775-97***
Diffusion	• H_2O-Diffusion • H_2O-Absorption		• Chloride Permeability	• Chloride Permeability
Chemical Resistance	• 10% NaOH • Bars Embedded in Concrete • Outdoor Exposure (Free)	• 3M $CaCl_2$** • 3M NaOH** • 3M $Ca(OH)_2$**	• Distilled Water** • 3M $CaCl_2$** • 3M $Ca(OH)_2$ **	• Distilled Water** • 3M $CaCl_2$** • 3M $Ca(OH)_2$**
Adhesion Quality	• Hot Water Test • MIBK Test • Cathodic Disbonding	• Cut Test** • Cathodic Disbonding	Bend Test (see Bendability)	Cathodic Disbonding
Coating Thickness	130 to 300 μm	200 ± 50 μm	130 to 300 μm	175 to 300 μm
Bendability d_{br} = mandrel diameter d_s = bar diameter	• <u>Testing</u> $d_{br}=4d_s$ ($d_s<20$ mm) $d_{br}=6d_s$ ($d_s\geq20$ mm) Additional bending after 6 months outdoor exposure Note: T = +5°C	• <u>Testing &Application</u> $d_{br} = 6d_s$ Note: $T \leq 15$°C	• <u>Testing &Application</u> $d_{br} = 8d_s$ (d_s < 43 mm) $d_{br} = 10d_s$ (d_s > 43 mm) Bend angle 120° Note: T = 20 to 30 °C	• <u>Testing &Application</u> $d_{br} = 8d_s$ (d_s < 43 mm) Bend angle 180° $d_{br} = 10d_s$ (d_s > 43 mm) Bend angle 90° Note: T = 20 to
Holiday Test	• Zero holidays: (powder and coating firms) • Maximum 6 holidays/m: Run production	Maximum 5 holidays / m	Maximum 6 holidays / m	Maximum 3 holidays / m

*Tests on resin films

**Tests on epoxy-coated steel plates

Table 4.1(a): Comparison of requirements for epoxy-coated bars in different standards and guidelines.[111]

Requirement	***German Guideline IFBT-Rule 05-***	***British Standard 09.90***	***ASTM A775-90***	***ASTM A775-97***
Damage	• < 25 mm2 • <0.5%: Coater • < 1% : Building site	< 10 mm2 / m and maximum 4 pieces / m	< 36 mm2 < 2% / ft	< 1% / ft (repaired to the point of shipment)
Corrosion Test	• Salt Spray Test • Cathodic Disbonding	• Salt Spray Test • Cathodic Disbonding	Current Test	• Salt Spray Test • Cathodic Disbonding
Mechanical Defects	• Impact Test** • Free-Fall Test	Impact Test**	Impact Test**	Impact Test**
Bond	Pull-Out Test (Short and long time)		Pull-Out Test	Beam End Specimens
Coating Tests		• Vickers Hardness** • Abrasion Test**	• Vickers Hardness** • Abrasion Test**	Abrasion Test**

*Tests on resin films
**Tests on epoxy-coated steel plates

Table 4.1(b): Comparison of requirements for epoxy-coated bars in different standards and guidelines.[111]

In 1995, Clear et al. also presented a comparison of different standards with respect to several requirements:[22]

- *Profile/Amplitude*: Qualitatively specified by ASTM D3963 and AASHTO M284, quantitatively specified by draft NACE spec. (1.5 to 4 mils), not specified by ASTM A775. GFORB references the ISO 8503 comparator and BS7295 specifies 50-70 microns (1.3-1.8 mils).
- Surface preparation: The ASTM and GFORB are very similar, and the British consider their requirement superior.
- *Coating thickness*: ASTM requires 90% at 5 to 12 mils with no specified min/max. BS7295 requires 6 to 10 mils for 95% and 5 to 12

mils for 100%. GFORB specifies 5 to 12 mils with minimum of 3 and maximum of 12 mils.

- *Surface defects*: BS7295 allows bare areas up to 0.016 in^2 with no more than four defects per bar length (length unspecified), while GFORB has a limit of bare areas of 0.04 in^2 and 0.5% of bar surface area.
- *Cure of coating*: GFORB specifies differential scanning calorimetry and infrared spectroscopy
- *Prequalification tests*: GFORB does not address abrasion resistance and hardness tests. However, the German testing includes preliminary, quality assurance, and external monitoring.

An interesting aspect is that the German and Swiss guidelines recommend the exclusive use of epoxy-coated reinforcement in any single structural member. If coated and uncoated reinforcement are combined, suitable tie wires and bar spacers must be used to avoid any electrical continuity between the two types of reinforcement. Electrical resistance measurements between coated and uncoated bars are prescribed in the Swiss guideline where mixed reinforcement systems are used.[111]

Differences in requirements of various specifications derive from differences in emphasis, perception and experience of the authors, construction practice, and are to some extent, arbitrary. Developers of European specifications claim that their national standards are more stringent than the ASTM counterpart. Clear et al. have argued that the main problem with present specifications for epoxy-coated bars is the lack of correlation of different specification criteria with service experience or projected service performance. The important parameters for assuring long-term corrosion resistance and parametric specification requirements to achieve this objective need to be defined and developed.[22]

4.4 COATING ADHESION

4.4.1 Nature of Epoxy Coating Adhesion to Steel [49]

The Condensed Chemical Dictionary defines adhesion as the "phenomenon of the sticking of two surfaces together due to molecular attraction for each other." The American College Dictionary states the definition as "the molecular force exerted across the surface of contact between unlike liquids and solids which resists their separation." In both definitions, a molecular force or interaction is referred as the fundamental nature of adhesion. Adhesion of epoxy compounds to metals is provided mainly by a) chemical or adsorption adhesion, and b) mechanical interlocking. Each of these components of coating adhesion is described below:

Chemical or Adsorption Adhesion

High polarity exists in the epoxy resin chain and the cured epoxy polymer due to the presence of aliphatic hydroxyl and ether groups. The presence of metal oxides in the treated steel surface causes a very strong electromagnetic attraction between both materials. The strength of coating adhesion to steel is directly proportional to the hydroxyl group content of the epoxy compound. The formation of chemical bonds between active hydrogen in the steel surface and epoxide groups in the coating provides additional contribution to coating adhesion.

Mechanical Interlocking

A roughened surface provided by preparation or pretreatment of the steel surface, or the presence of porous oxides on the surface, allows that prepolymeric epoxy resin and curing agents can penetrate into the crevices and pores provided by the pretreatment. Upon polymerization, the coating becomes mechanically embedded in the metal surface or the surface oxide structure. The cavities and pores formed during surface preparation provide a larger surface area for electrochemical reactions, further increasing the adhesive strength of the coating.

4.4.2 Factors Affecting Coating Adhesion [49]

Epoxy Coating Formulation

The formulation of the epoxy coating effects the chemistry of polymer chain formation and molecular weight. The ultimate form of the polymer chain, its length, shape, and configuration determines the properties and physical characteristics of the coating, such as flexibility, hardness, and adhesion. The viscosity of the epoxy during the transition from the wet to the cured state is particularly important. Adhesion develops as the coating is “wet-in” or absorbed into the substrate in a mechanism where the molecules of both materials are brought together in intimate contact. As the coating cures, its viscosity changes and increases, and its mobility or flow decreases. If the epoxy is not properly formulated, flow of the coating into the substrate microstructure may be hampered, adversely affecting adhesion and producing a number of voids and holidays in the film.[112]

Coating Process

Deficiencies in the following stages during the coating process may result in inadequate adhesion of epoxy coating to steel:[49]

a) Failure to provide an adequate surface profile (optimum number and depth of peaks and valleys) lessens the mechanical interlocking between the epoxy resin and the steel surface. Improper cleaning of the steel surface will result in mill scale and other surface contaminants (rust, loosely adhering deposits, oil, grease, chlorides, and other foreign matter) that can impair coating adhesion.

b) Improper heating of the bar causes incomplete reaction or degradation of the epoxy. On the one hand, if curing is incomplete as a result of underheating, the epoxy will not flow properly over the bar surface and fill in the cavities as needed for good mechanical interlock. On the other hand, overheating the steel degrades the epoxy and reduces the electrochemical bond by producing new oxide layers in the steel surface that will not react with hydroxyl groups in the epoxy.

c) A fast quenching of the coating can reduce the gel state time of the epoxy. A shorter gel time results in reduced time for the epoxy to flow and produce adequate mechanical bond. In addition, fast cooling may produce high internal stresses at the interface due to differences in coefficients of thermal expansion between the epoxy and the steel.

Moisture

The presence of moisture around the epoxy can be detrimental because water is one of the most destructive agents of metal/polymer adhesion. In the field, moisture around the reinforcement may come from water penetrating the concrete. Sources of water are rain, deicing, sea water, and ambient humidity. Moisture is also available as part of the pore solution in concrete. Depending on the length of exposure, adhesion failure tends to change from the resin to the epoxy/steel interfacial region. If exposure time is sufficiently prolonged, the presence of water in the interfacial region is believed to produce large reductions in adhesion strength. Water may cause loss of adhesion by breaking the hydrogen bonds at the epoxy/steel interface or by hydrating the metal oxide layer.[22] The mechanism of wet adhesion loss will be discussed further in a subsequent section.

Temperature

If a polymerized epoxy is exposed to temperatures close to the transition temperature, the coating will become soft and fluid, and will be susceptible to deterioration. If moisture is present, there can be permanent loss of adhesion. The presence of high temperature alone causes momentary loss of adhesion, but immediately after the epoxy cools down, adhesion can be regained. Therefore, high temperatures will only produce loss of adhesion when moisture is present. Conversely, moisture alone produces loss of adhesion over time, but high temperatures help to accelerate the disbondment process. This principle is the basis for the hot water tests reported in Chapter 5.

Coating Damage

Although not causing adhesion loss directly, discontinuities in the coating are a contributing factor. Deleterious agents, such as water, chlorides, or diluted chemical substances can enter the steel/epoxy interface through coating discontinuities as small as pinholes and produce loss of bond. Corrosion cells forming at sites of coating damage can produce adhesion loss by cathodic disbondment and/or corrosion progression under the film.

4.4.3 Adhesion Loss Mechanisms and Relevance

Most corrosion failure mechanisms of epoxy coating in concrete postulated in the literature involve the progressive loss of coating adhesion to the steel substrate. Adhesion is usually lost as a result of one or more of the following mechanisms: a) Wet adhesion loss, b) cathodic disbondment, c) anodic undercutting, and d) bar fabrication. A description of each mechanism is described below:

Wet Adhesion Loss.

It has been theorized and observed that coatings lose adhesion when subject to moist environments.[22, 23, 65] The mechanism under which this phenomenon occurs is still unclear. Water can reach the epoxy/steel interface by two ways: 1) Diffusion through the epoxy because of coating permeability to water, and/or 2) transport across the interface itself because of discontinuities in the coating. In process (1), moisture permeates the coating in a complex and only partially understood manner. Propelling forces consist of osmotic and electroendosmotic pressures with transport aided by thermally induced molecular movements and vibrations within the polymer.[113] Although not completely understood, the following theories regarding the mechanism by which water promotes loss of adhesion have been proposed:[49]

a) Displacement of epoxy by water: Electrochemical adhesion in epoxy/steel interfaces depends on strong hydrogen bonds. Since water molecules are very strong hydrogen bonding agents, they will break the bond between epoxy and metal, and produce new hydrogen bonds with the hydrated oxide surface of the metal.

b) Oxide layer deterioration by hydration: Water hydrates the oxide layer above the steel surface. Since metal oxide hydrates have poor adherence to their base metals, mechanical adhesion is reduced considerably by the presence of a weak layer of hydrates at the interface.

Wet adhesion loss is often recoverable upon drying, but can become permanent in the presence of stress, through substrate deformations, or by build-up of underfilm corrosion products.[22]

Cathodic disbondment.

The anodic reaction that occurs at a coating defect is usually coupled to a nearby cathodic reaction beneath the coating. Oxygen and water migrate through the coating and support the cathodic reaction $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. This is possible because epoxy coatings can be permeated by oxygen, water, and ions.[78] Cathodically generated alkalinity can react with the organic polymer to disbond the coating at a defect at the interface between coating and metal. Such reaction is termed saponification.[24] It has also been theorized that cathodic disbondment may proceed by dissolution of the oxide film by hydroxides rather than by alkaline degradation of the coating itself. This is based on the good stability of epoxy coatings in alkaline environments.[65] Cathodic disbondment may also occur at microscopic or smaller flaws in the coating to produce blisters, which do not require a physically obvious defect for initiation.[24]

Anodic undercutting.

This mechanism is also known as oxide lifting. Briefly, corrosion products that are generated by the anodic reaction are deposited under the epoxy film during subsequent periods of wetting and drying, and result in lifting or debonding of the coating from the substrate.[24] This mechanism will be thoroughly discussed in Chapter 8.

Bar fabrication.

During bending, shearing stresses generated at the coating/steel interface weaken the adhesion of the epoxy film by mechanical action. Regions that are particularly vulnerable are the base of transverse ribs at the outer bend, because the coating stretches at these regions. If the coating is of good quality and properly applied, adhesion will only be weakened, but not lost after bending. It is usually the combination of bar bending with one or all of the above mechanisms that produces extensive adhesion loss in bent areas embedded in chloride-contaminated concrete.

Generally, more than one of the above adhesion loss mechanisms occur during corrosion of epoxy-coated bars, although it is unclear which one precedes the others. If concrete is of poor quality, the coating will still be adhered to the steel surface when the chlorides arrive, and the prevalent mechanisms would be a combination of cathodic disbondment, anodic undercutting, and water displacement. If concrete is of good quality, chloride penetration will be delayed, but adhesion may be lost by water displacement before chlorides arrive at the bar surface.

Regardless of which adhesion loss mechanism predominates, it is expected that a higher degree of initial coating adhesion before exposure will prevent or significantly delay the loss of adhesion during service, and therefore, decrease the extent of underfilm corrosion.

Pencil hardness measurements in a study by Clear for C-SHRP showed that, except for the effects caused by steel corrosion, the epoxy coating did not undergo physical deterioration after accelerated corrosion tests or exposure to chlorides during service in field concrete. These findings, coupled with the variable, and often poor, dry knife adhesion test results, led to the conclusion that loss of adhesion and underfilm corrosion originated at the coating /steel interface.[77]

4.4.4 Tests for Evaluation of Coating Adhesion

Peel or Knife Tests

Knife adhesion tests have been used because of their simplicity. The test procedure involves the application of a shearing force through the interface between coating and substrate with a sharp knife and successive prying of the disbonded coating. Pre-cuts (usually an X or V cut) through the coating are made to define the test section and eliminate the effect of cohesive forces by the surrounding coating. During the application of the knife force, the coating will lift from the substrate until the adhesion strength is larger than the applied shear stress. At that point, the knife will not advance further under the coating or will cut through the epoxy coating itself. The use of a hand-held knife has practical advantages and disadvantages. The main advantage is the portability of the knife, which enables testing of bars at any location or position; job sites, bar storage areas, coating applicator plant, or laboratory. Disadvantages include susceptibility of the test to operator error and variability, and the subjectivity of adhesion ratings.

Peel or knife tests are frequently performed after a preceding test has been performed on the bar, such as solution immersion, hot water immersion, cathodic disbondment, bend test, outdoor exposure, UV exposure, or accelerated corrosion inside concrete. These tests are intended to simulate the service environment to which the bars will be exposed in an accelerated way, and the subsequent knife adhesion test is intended to give a measure of the coating adhesion during the service life of the bar. The chemical component of adhesion is usually affected after the accelerated tests and the subsequent knife force breaks the remaining mechanical component of adhesion. If knife tests are performed without any previous accelerated test and bars have not been exposed to the environment, the knife force has to overcome the combined chemical and mechanical adhesion. In this case, the knife test would give an indication of the coating adhesion as produced by the coating applicator.

A variation of peel adhesion test was conducted by McDonald et al.[107] After performing the two cuts through the coating, the coating was lifted and grasped with tweezers and then peeled back. The test was termed knife-peel adhesion test, perhaps because a knife was used to pre-cut through the epoxy. The authors referred to the ASTM G1 specification as the background for the test, but after reviewing the standard, no mention is made of any knife adhesion test.

Presently, there is a lack of uniformity in different specifications and research studies regarding test procedure and adhesion evaluation criteria. Knife adhesion tests have been performed at ambient temperature, after hot water solution immersion, after cathodic disbondment, and after bending of the bar. Other variables that have not been uniform or defined include angle of X or V pre-cuts, knife force application, knife angle, and type of knife blade. An evaluation of knife adhesion test variables is presented in the following chapter.

TxDOT Peel Test

The Materials and Test Division of the Texas Department of Transportation developed an adhesion test procedure for steel elements that are too short for the bend test. Such elements include mechanical couplers, dowel bars, steel chairs and supports, steel plates, and others. The test is performed in accordance with test method Tex-739-I: [114]

> Perform the Peel Test by cutting or prying with the edge of a stout knife, applied with a considerable pressure in a manner tending to remove a portion of the coating. Testing should not be carried out at edges or

> corners (points of lowest coating adhesion) to determine adhesion. Adhesion will be considered inadequate if the coating can be removed in the form of a layer or skin so as to expose the base metal in advance of the knife edge. Removal of small particles of coating by paring or whittling will not be cause for failure.

As with most knife adhesion tests, the TxDOT Peel Test is highly subjective. Lorenzo discussed some of the difficulties of this test method.[49] The correct placement of the knife at the beginning of the force application, the amount of force to be applied, and the acceptance criterion all depend on the operator's interpretation of the norm. Since no cuts are made through the epoxy to delimit the test area, the stiffness of the surrounding coating will tend to mask test results. An experimental evaluation of the Peel Test is presented in the following chapter.

Hot Water Immersion

The German and Swiss guidelines for epoxy-coated reinforcement have placed emphasis on hot water testing as a quality and performance indicator. Hot water testing has a historical basis within ASTM, per recommended practices C870-86, C868-85, and D870-92. The buried pipeline industry has also used hot water testing. The Ontario Ministry of Transportation developed some draft specifications for hot water testing of epoxy-coated bar samples.[22, 115]

The procedure involves immersion of samples in hot water at a specified temperature for given time. Different documents specify different water temperature and time of immersion. High osmotic pressures result in formation of blisters and cause vapor to migrate rapidly to the coating/steel interface at areas of marginal coating adhesion. As such, the procedure is an indicator of adhesion loss. Failure in water immersion may be caused by a number of factors, including deficiency in the coating itself, contamination of the substrate, or inadequate surface preparation. The test is particularly relevant to service performance because adhesion is considered a fundamental property for corrosion protection.[22]

Swiss and German guidelines specify a water temperature of about 10°C below the glass transition temperature of the epoxy coating. For typical coatings, that results in temperatures of 75°C to 80°C. The Ontario draft specified a temperature of about 73 ± 2°C. It is recognized that as long as the temperature is below that range, the elevated temperature serves only to accelerate the water permeability of the coating and to speed but not alter the degradation process. Test immersion time was 7 to 10 days for German and Swiss specifications, and 48 ± 2 hours for the Ontario draft. Interestingly, German and Swiss specifications do not include adhesion testing following hot water immersion and base the acceptance criteria on the lack or presence of blisters or coating damage after immersion. A knife adhesion test is incorporated in the Ontario draft specification.

Clear et al. incorporated electrochemical impedance spectroscopy (EIS) for the evaluation of samples following hot water immersion testing in a NCHRP study. EIS is particularly useful in providing mechanistic information and performance indications such as significance of defects and electrolyte take-up by the coating.[22] Direct tensile adhesion testing using a special test setup following hot water immersion was also evaluated in the NCHRP study.

McDonald et al. conducted knife-peel adhesion tests after immersing bar samples in four different solutions with and without chloride using a lower temperature (55°C) for a longer period (28 days).[107] Their rationale was that organic coating materials and steel have significantly different coefficients of thermal expansion and heat deflection temperatures. The 55°C was judged to provide a more reasonable in-service field temperature, yet provided a more aggressive condition than ASTM and AASHTO immersion tests at ambient temperatures. Two of the solutions contained sodium and potassium hydroxide and were intended to simulate the concrete pore solution environment. A summary of test parameters used in different specifications and research studies are included in Table 4.2.

An experimental evaluation of hot water testing was performed as part of the present research study and is presented in the following chapter.

Study or Specification	**Water Temperature**	**Time of Immersion**	**Evaluation**
Swiss and German	10°C below glass transition temp.	7 to 10 days	Visual examination
MTO (Canada) [115]	73°C ± 2°C	48 ± 2	Knife adhesion test
NCHRP Study [22]	80°C	Variable	• EIS • Direct tensile adhesion testing
FHWA Study [107]	55°C*	28 days	• Knife-peel adhesion test • Visual

			examination

* Four different solutions with and without chloride were used

Table 4.2. Test parameters for hot water test used in different specifications and research studies.

Cathodic Disbondment Tests

Cathodic disbondment tests consist of applying a cathodic potential to specimens immersed in an electrolyte solution for a specified period of time. The test subjects the coating to electrical stress in the highly conductive electrolyte. The coating is artificially perforated before starting the test. The test specimen is connected to the negative terminal of a source of direct current and an anode is connected to the positive terminal. At the end of the test, the extent of loosened or disbonded coating at the hole in the immersed area is compared with the extent of loosened or disbonded coating at a new test hole in the coating made in an area that was not immersed. A knife adhesion test is usually performed to determine the extent of disbondment.[116, 117]

The principle of the test is as follows: Water, ions, and oxygen are present at the steel surface by either permeating through the coating or moving along the coating/steel interface via a defect, and an electrochemical cell with anode and cathode is established. When a cathodic polarization is applied to a corroding metallic surface, the surplus or excess of electrons provided reduces the rate of the anodic reaction and increases the rate of the cathodic reaction

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

which increases the rate of oxygen reduction and OH^- production. The hydroxide ions will locally increase the pH at the coating/metal interface to as much as 14 or more. At very high pH levels, the polar bonds between the metal and the coating are significantly reduced.[24, 107]

Cathodic disbondment tests have been used in the pipeline industry to assess coating quality and to prequalify epoxy materials. There are numerous test procedures available for conducting cathodic disbondment tests, such as those described in AASHTO M284, ASTM A775, ASTM A934, ASTM G8, ASTM G42, MTO, and those performed by Schieβl and Reuter,[111] Sagüés and Powers,[118] and in the FHWA-RD-74-18[11] and FHWA-RD-94-103[107] studies. Different test methods will differ in their length of exposure time, applied potential, coating defects, temperature, and test solution. A reinforcing bar or a section of steel plate is used in the various procedures. For instance, the British Standard for cathodic disbondment is usually performed as a powder qualification test on plate samples.[60] In the FHWA-RD-94-103 study, cathodic disbondment tests were made particularly severe by testing bent bars instead of straight bars.[107] Table 4.3 summarizes parameters used in different tests procedures.

ASTM standards warn that although the ability to resist disbondment is a desired quality on a comparative basis, disbondment per se in the test is not necessarily an adverse indication. Although loosened coating and cathodic holidays may not result in corrosion, the accelerated condition for disbondment provided by the test gives a measure of resistance of coatings to this type of mechanism. According to ASTM, commonly used dielectric coatings will disbond to some degree and the test thus provides a means of comparing one coating with another. Adhesion strength may be more important for some coatings than others, and two different coating systems with the same measured disbondment may have not lost equivalent corrosion protection.[116, 117]

Test Method	***Time of Expos.***	***Temp***	***Potent (mV vs. SCE)***	***Intentional coating damage***	***Sample shape***	***Electrolyte solution***	***Accept Crit.***
ASTM G8	30 days	23°C	-1500	6-mm (¼ in) drilled hole	straight	3% NaCl* pH 7	No
ASTM G42	30 days	60°C	-1500	6-mm (¼ in) drilled hole	straight	3% NaCl* pH 7	No
ASTM A775	7 days	24°C	-1500	3-mm drilled hole	straight	3% NaCl pH 7	No
ASTM 934 (Test A) ***	24 hr	65°C	-3000	3-mm drilled hole	straight	3% NaCl pH 7	Yes
ASTM 934 (Test B)[IV]	7 days	23°C	-1500	3-mm drilled hole	straight	3% NaCl pH 7	Yes
AASHTO M284	30 days	23°C	-2000	none**	straight	7% NaCl	Yes

*The standard specifies a 1% by weight of each NaCl, NaSO4, and NaCO3 solution (pH 11.2) but the pipeline industry generally uses the 3% NaCl solution.

**If no holidays develop in 30 days, a 6-mm diameter hole is drilled into the coating of both the anode and cathode. The test is continued for 24 hr, in which time no undercutting shall occur.

***Used for coating application requirements and pre-qualification requirements

[IV] Used for pre-qualification requirements only

Table 4.3(a): Parameters for cathodic disbondment test from different standards and research studies [Adapted from Ref. 111].

Test Method	***Time of Expos.***	***Temp***	***Potent (mV vs. SCE)***	***Intentional coating damage***	***Sample shape***	***Electrolyte solution***	***Accept Crit.***
MTO	7 days	23°C	-1500	3-mm drilled hole	straight	3% NaCl	Yes
Schieβl and Reuter [111]	30 days	23°C	-1000	3, 2.5 x 10 mm cuts	straight	3.5% NaCl* pH 7	N/A
Schieβl and Reuter [111]	30 days	23°C	-1000	3, 2.5 x 10 mm cuts	straight	0.3N KOH + 0.05N NaOH pH 13.3	N/A
FHWA-RD-94-103 [107]	28 days	23°C	-1000 vs. rest potent.	6-mm (¼ in drilled hole)	bent	0.3N KOH + 0.05N NaOH pH 13.3	N/A

*The standard specifies a 1% by weight of each NaCl, NaSO4, and NaCO3 solution (pH 11.2) but the pipeline industry generally uses the 3% NaCl solution.

**If no holidays develop in 30 days, a 6-mm diameter hole is drilled into the coating of both the anode and cathode. The test is continued for 24 hr, in which time no undercutting shall occur.

***Used for coating application requirements and pre-qualification requirements

[IV] Used for pre-qualification requirements only

Table 4.3(b): Parameters for cathodic disbondment test from different standards and research studies [Adapted from Ref. 111].

Salt Spray Tests

Coated samples are placed inside a chamber and subjected to salt spray comprised of certain percentage of sodium chloride by mass dissolved in distilled water. A typical salt fog chamber contains an air saturator tower, a salt solution reservoir, atomizing nozzles, sample panel supports, and heat controls to maintain the conditions of test at the desired temperature, and a relative humidity of 95% to

98% (Fig. 4.1).[112] At the end of the spray, a knife adhesion test is usually performed to determine the extent of disbondment and underfilm corrosion. This test is described in several standards such as ASTM A775, ASTM A934, and MTO Draft 93-10-01. Different test procedures vary in concentration of salt solution, temperature, time of exposure, sample preparation, and acceptance criteria. For instance, both ASTM A775 and A934 specify 35°C ± 2°C salt spray of 5% NaCl solution for 800 ± 20 hours. Bars contain three intentional 3-mm diameter defects drilled through the coating evenly spaced along one side of the bar with the holes centered between deformations. The acceptance criterion is that the average coating disbondment radius should not exceed 3 mm from the edge of the intentional defect at 9 test sites.

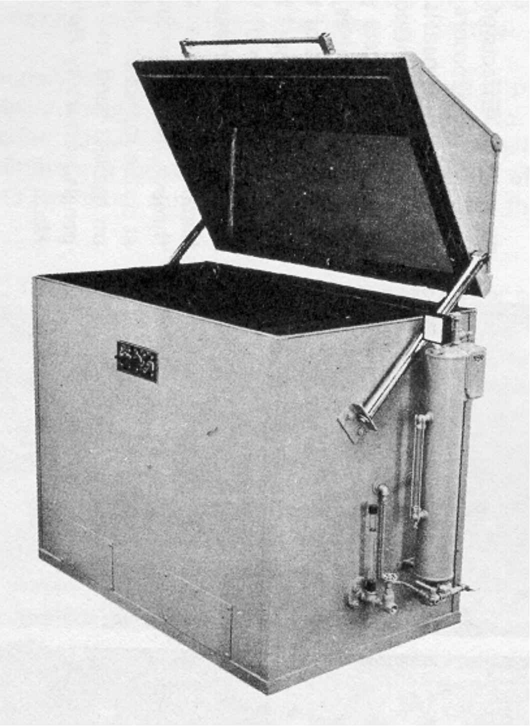


Fig. 4.1: Salt fog cabinet.[112]

In reality, the test is not an adhesion test but a corrosion test where adhesion loss occurs as a result of underfilm corrosion. Therefore, the mechanism of adhesion loss in a salt spray test is different from that in a cathodic disbondment test. While the latter test measures the amount of coating delamination that occurs because of cathodic reactions, the hot, wet conditions and high chloride concentration produced by the salt spray test will assay the adhesive strength of the coating and its ability to resist film undercutting in a hot, wet chloride environment. The ability of the coating to resist corrosion propagation initiated from damaged, bare areas is of utmost importance. Corrosion must be limited to the damaged areas by preventing film undercutting. The salt spray test is claimed to provide an excellent way to test these abilities. The test can be used as a screening test for material selection and/or as a quality control test to check coating at the plant.

Pull-Off Adhesion Tests

This test consists of pulling the coating off the steel substrate using a special adhesion test device. This procedure was developed and used in a NCHRP study.[22] In this study, the test procedure consisted of gluing the concave side of an aluminum pull-stub to the surface of the epoxy-coated bar using a two-part structural epoxy adhesive. To improve adhesion between the coating and the aluminum pull-stub, the coating surface was roughened with a rasp and subsequently cleaned with ethanol. Careful attention was given to properly align the pull-stub being placed on the bar using a specially designed alignment device.

The adhesive was allowed to cure for 24 hours before testing. The coating was then scored around the pull-stub to expose bare metal to isolate the coating test area and eliminate the influence of cohesive forces that could be exerted by the surrounding coating. The bar/pull-stub assembly was mounted on a specially designed loading frame. The test set-up is schematically shown in Fig. 4.2.

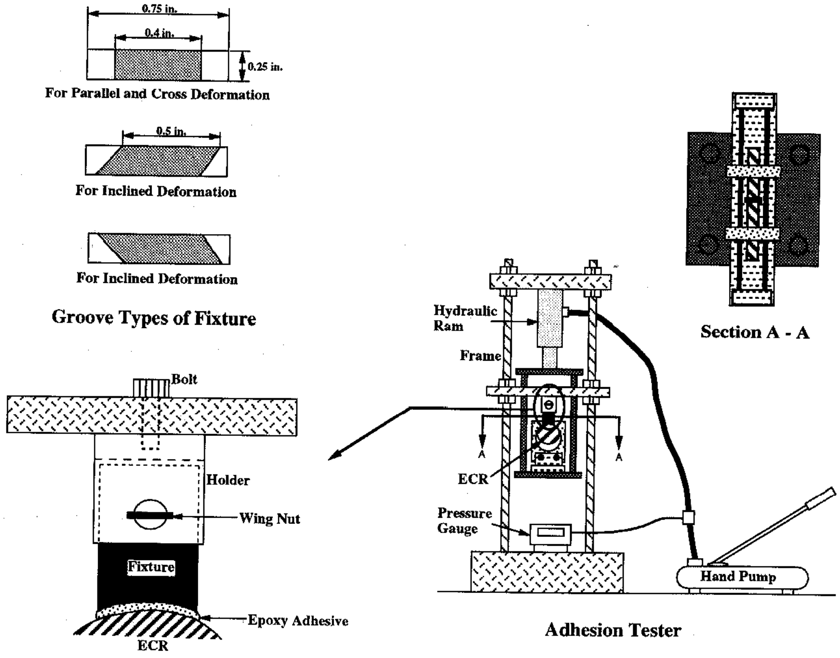


Fig. 4.2: Schematic of pull-off adhesion testing system used in the NCHRP 10-37 study.[22]

This procedure is possibly the less subjective and most accurate way to determine coating adhesion, because the maximum amount of pull-off force applied with the hydraulic ram can be measured and divided by the test area to give units of stress (psi or Pascals) for the nominal coating adhesion strength.

This procedure is mainly suitable for research studies but may not be as practical as knife adhesion tests for field or plant applications. It should be pointed out that several pull-stubs with varying geometry are needed to fit bars with different diameters and corrugation patterns.

Bend Tests

In reality, bend tests do not assess the adhesive strength of the coating and it is a misconception to use a bend test for that purpose, as stated in previous ASTM specifications. More accurately, bend tests provide an indication of the flexibility of the coating. Since epoxy-coated reinforcement in actual concrete structures has to be bent, it is important that the coating has enough flexibility without developing tears, cracks, or disbondment during bending. Epoxy coating must be formulated for adequate flexibility without sacrificing its corrosion protection properties.

4.4.5 Experience and Research on Coating Adhesion Evaluation

Experience by the Ontario Ministry of Transportation [51, 119]

In 1993, the Ontario Ministry of Transportation (MTO) asked coating applicators to significantly improve the quality of their product if the Ministry were going to continue to specify epoxy-coated bars. At the same time, the Ministry agreed to work with industry to develop test procedures and acceptance criteria. As a result of that work, three tests were investigated to measure coating adhesion: A hot water bath, cathodic disbondment, and salt spray exposure. The hot water test was found useful in discriminating and identifying bars with poor coating adhesion. However, knife adhesion ratings showed poor correlation when round-robin tests performed by different operators were compared. As a result, the hot water test was not incorporated into the 1994 specifications, and only cathodic disbondment and salt spray testing were introduced.

Experience in Europe

Test results by the German Institute for Building technology (IFBT) showed that high powder quality and adhesion of the coating film to the steel surface were the most important parameters for corrosion protection. In consequence, German and other European standards for epoxy-coated bars placed great emphasis on these parameters. Investigations in Germany showed that immersion of coated bars in 90°C demineralized water was an excellent test for quality of adhesion and, to a certain extent, the permeability of the coating film. This test is accepted in Germany and Switzerland as a quality criterion in the pipeline industry, and is one of the main quality control tests in both the German and Swiss guidelines for epoxy-coated bars. In addition to the hot water test, the cathodic disbondment test has been used in Europe to evaluate the quality of adhesion and the quality of application at the coating plant.[111]

Research by the US Federal Highway Administration [107]

The research project FHWA-RD-94-103 was already discussed in Chapter 3. Research results of Task 1 are discussed here in more detail. As was mentioned before, 22 bendable and 11 nonbendable organic coatings were tested for coating adhesion following 28-day immersion tests in four solutions at 55°C. The four selected solutions were considered representative of the environments that coated bars may experience in service. Adhesion was also tested after cathodic disbondment tests on bent bars. All bar specimens contained intentional holes in the coating. The main findings of Task 1 are summarized below:

In relation to hot solution immersion tests:

- Straight bars tested in hot deionized water can more easily pass the adhesion test than when tested in the other three hot solutions (NaCl, OH^-, and OH^- + NaCl). See Fig. 4.3
- The use of bent bars in hot NaCl and OH^- + NaCl solutions produced the greatest number of poor adhesion ratings, indicating that these solutions are more detrimental to adhesion (Fig. 4.3).

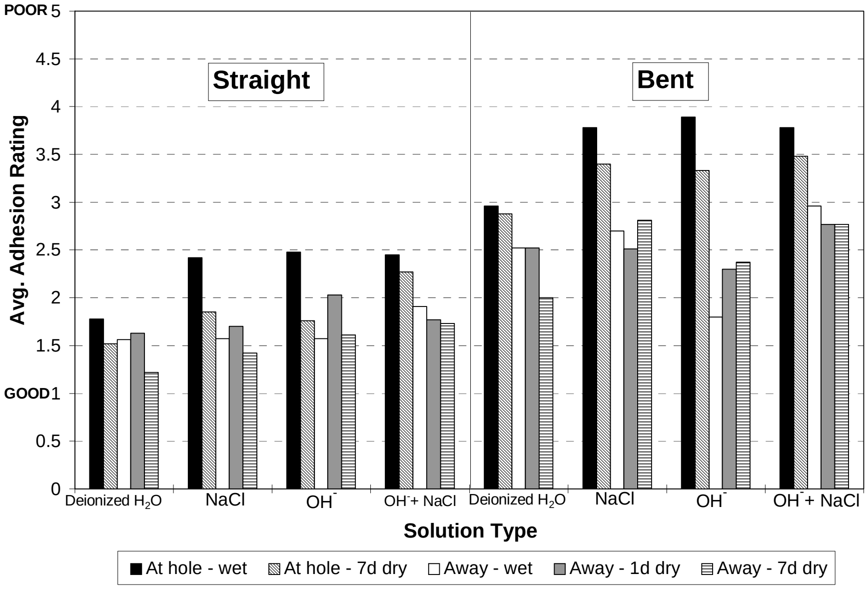


Fig. 4.3: Average overall adhesion ratings for all coatings under all test conditions [FHWA-RD-94-103].[107]

- For all types of solutions and conditions tested, bent bars experienced higher loss of adhesion (marginal to poor average adhesion) than straight bars after hot solution immersion (Fig. 4.3). None of the bent bars with either bendable or nonbendable coating achieved perfect adhesion ratings in all four solutions following the immersion tests.
- The adhesion at the hole immediately after removal from the solution provided the worst adhesion, while away from the hole after 7 days of drying provided the best adhesion. However, the improvement of adhesion observed due to drying was regarded as minimal (Fig. 4.4).
- Nonbendable coatings applied to straight bars exhibited the best overall performance, with more than 90% of nonbendable coatings on straight bars showing excellent adhesion ratings (Fig. 4.5).
- When nonbendable coatings were applied to prebent bars, the overall adhesion performance was poorer than when applied to straight bars (Fig. 4.5). This implies that it may be more difficult to coat and/or clean a prebent bar than a straight bar when applying nonbendable coatings.
- The poorest overall adhesion performance was achieved with bent bars using bendable coatings. Only 5% to 20% of the 20 or 21 bendable coatings on bent bars had excellent adhesion ratings (Fig. 4.5).

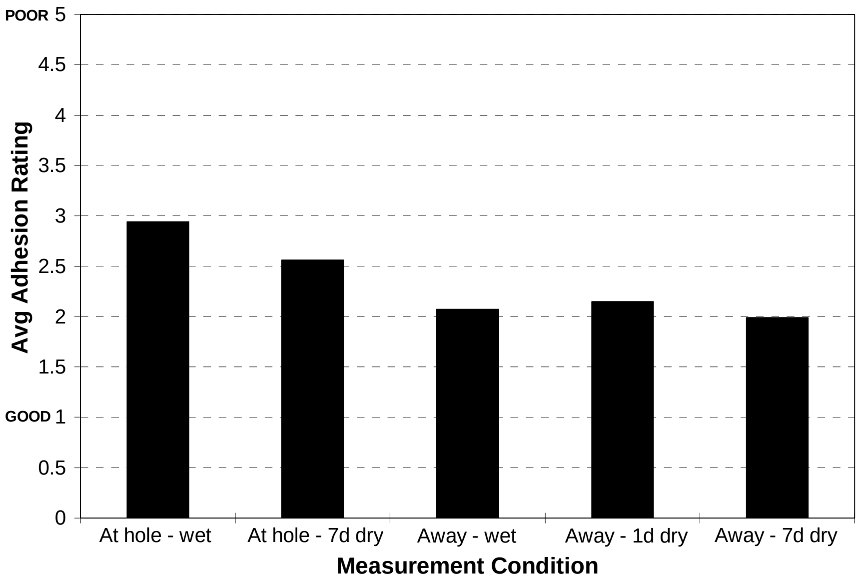


Fig. 4.4: Average overall adhesion ratings for bent and straight bars at all test locations for all four solutions [FHWA-RD-94-103].[107]

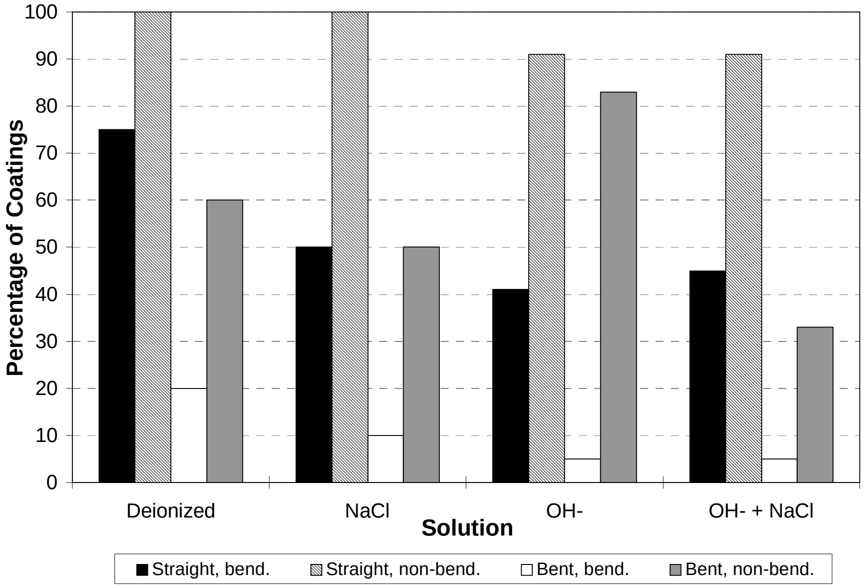


Fig. 4.5: Percentage of coatings with average adhesion rating of 1 to 1.5 in different solutions [FHWA-RD-94-103].[107]

- Nonbendable organic coatings provided better adhesion than the average organic coating systems that are considered bendable, as suggested by the better average adhesion achieved when nonbendable coatings were applied to straight bars compared to that of bendable coatings applied on straight bars (Fig. 4.5). The direct comparison of straight bars cancels out the added effects of bending on adhesion.

In relation to cathodic disbondment tests:

- Cathodic disbondment testing on bent coated bars, which was particularly severe in this study, showed that nonbendable coatings performed significantly better than bendable coatings (Fig. 4.6 and 4.7).
- Ninety-two percent of prebent specimens achieved excellent to good adhesion when tested away from the hole, either wet or after 7 days of air drying. In contrast, only one specimen achieved good adhesion when tested wet at the hole (Fig. 4.7). The increased adhesion away from the hole showed that adhesion loss is created by conditions at the hole.
- Excellent adhesion was achieved on 92% of prebent bars when tested away from the hole after 7 days of air drying (Fig. 4.7).
- If galvanized prebent bars are not considered, 100% of prebent bars had good to excellent adhesion away from the hole under either wet or dry test conditions.

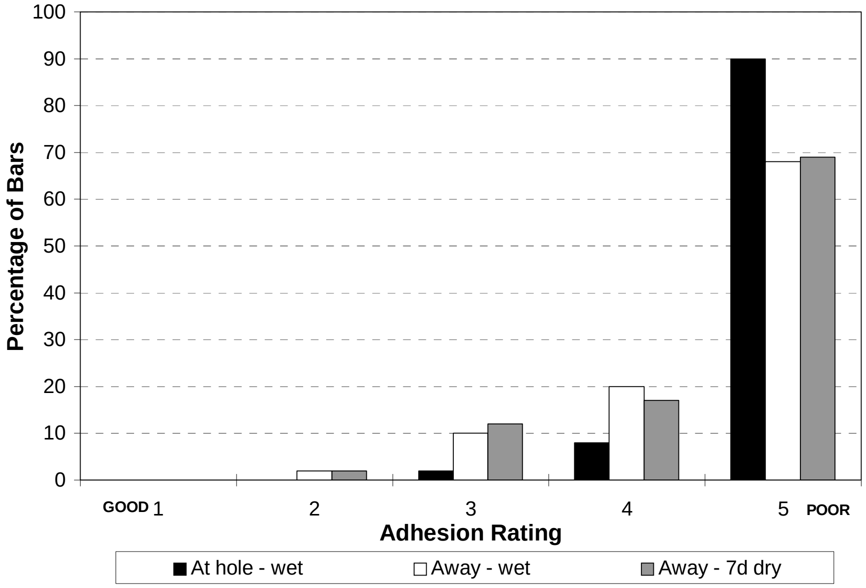


Fig. 4.6: Average overall adhesion ratings for bendable bars at all three test locations [FHWA-RD-94-103].[107]

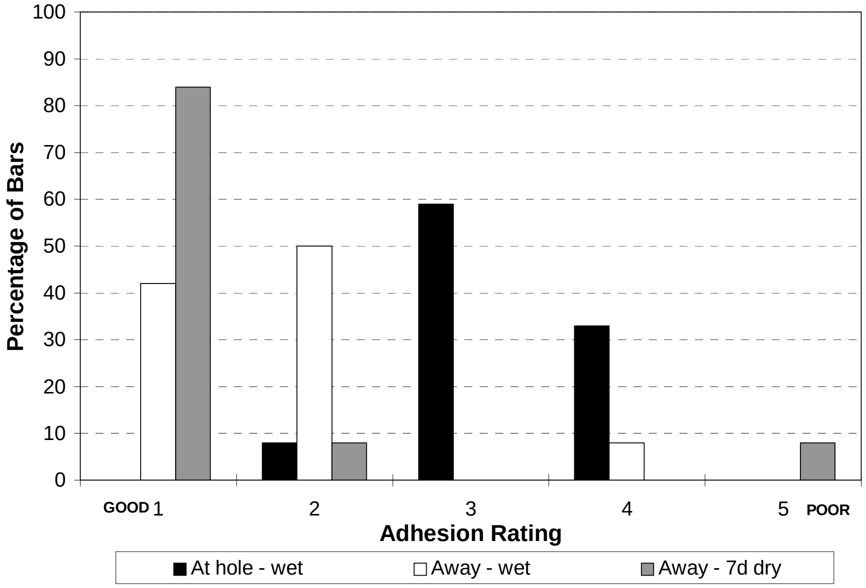


Fig. 4.7: Average overall adhesion ratings for nonbendable bars at all three test locations [FHWA-RD-94-103].[107]

- Bendable bars achieved poor adhesion on 98% of the specimens when tested wet at the hole, 88% when away from the hole wet, and 86% when away from the hole after 7 days of air drying. These data revealed that moderate to severe coating disbondment resulted from bending effects that overshadowed the electrical disbonding effects of the test.

In relation to adhesion performance in defect-free coatings:

- The reduction in adhesion for those particular coating systems that exhibited overall excellent adhesion generally occurs only at the hole in the coating. The adhesion away from the hole in defect-free coated areas, or areas with fewer than 2 holidays per foot for prebent bars, is not reduced or affected by either hot solution immersion or cathodic disbondment tests.

In relation to the testing procedures:

- Knife-peel adhesion testing performed after hot solution immersion and cathodic disbondment tests proved to be a very useful method to prescreen the overall quality of 22 bendable and 11 nonbendable organic coatings on steel reinforcing bars.

National Cooperative Highway Research Program [22]

The research project 10-37, sponsored by the NCHRP, was briefly discussed in Chapter 3. Research results from hot water immersion and adhesion tests, and their correlation with electrochemical impedance spectroscopy tests are discussed here in more detail.

Coated bar specimens were specially prepared and placed into immersion test cells, which were filled with the desired solution (distilled water or 3.5% NaCl solution) to a level just below the top of the bar specimen, as shown in Fig. 4.8. Multiple cell specimens were then placed inside a hot water bath (Fig. 4.9). Bath temperature was 80°C and time of immersion was 14 days. Electrochemical impedance scans were taken at intervals of 1, 3, 7, and 14 days. The bar specimens were examined daily for blister formation and rusting. At the end of immersion, adhesion testing was conducted using the special adhesion pull-off test device and procedure discussed earlier. Three test locations along the bar length were selected randomly per specimen. Adhesion tests were conducted after 1, 14, and 21 days of air drying.

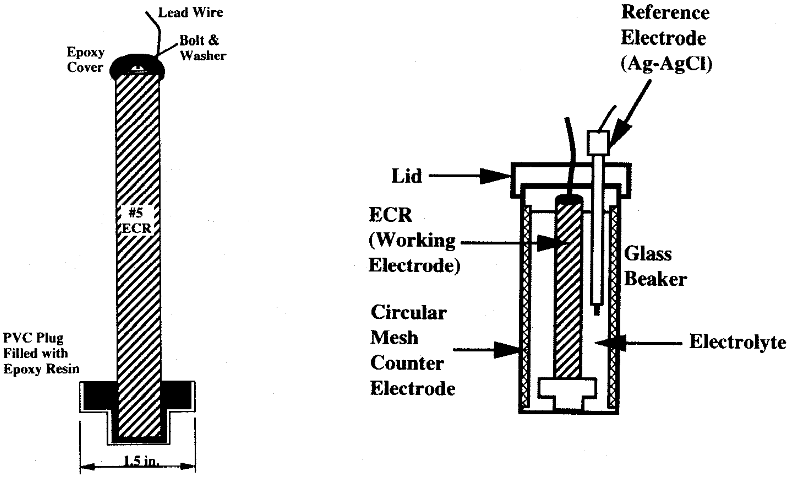
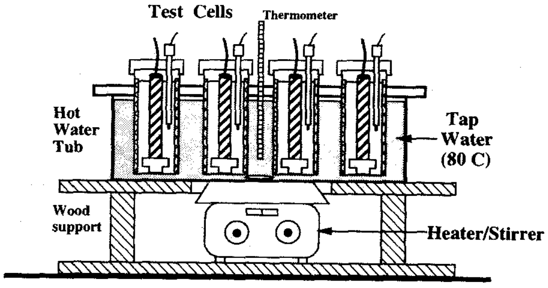
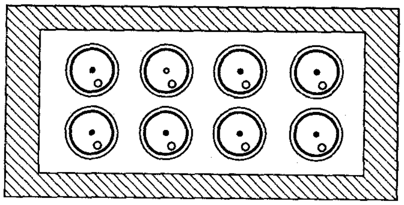


Fig. 4.8: Schematic of epoxy-coated bar specimen and of immersion test cell for hot water test of NCHRP 10-37 study.[22]



[Front View]



[Top View]

Fig. 4.9: Schematic of hot water test apparatus for NCHRP 10-37 study.[22]

Macrocell concrete slabs were prepared with coated bars from the same sources. In the upper mat, two coated bar specimens were embedded in chloride-contaminated concrete, while three uncoated bars were placed in the bottom chloride-free concrete. Slabs were cyclically ponded with tap water for 10 months. At the end of exposure, coated bars were removed, visually inspected, and tested for adhesion. The main research findings are as follows:

- The amount of underfilm corrosion and the post-immersion (drying) period affected coating adhesion strength. In general, adhesion strength increased with extended drying time (Fig. 4.10).

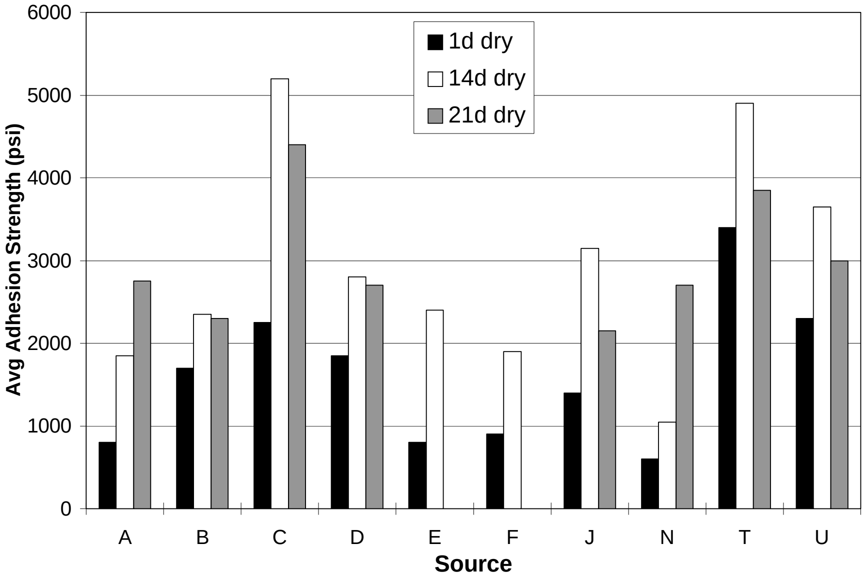


Fig. 4.10: Average adhesion strength of coated bars from various sources after 14 days of immersion in 80°C distilled water [NCHRP 10-37].[22]

- Specimens from most sources that showed high impedance during exposure also exhibited relatively high adhesion after hot water immersion and concrete exposure. However, there were specimens that exhibited low impedance and marginal to low adhesion after concrete exposure (due to corrosion) but high adhesion after hot water immersion. Therefore, the development of conductive pathways and presence of coating defects (low impedance) did not preclude good adhesion in distilled water.
- As a corollary of the above, while good wet adhesion is a desired property, it is not sufficient, in and of itself, to ensure good performance when excessive defects are present.
- When hot 3.5% NaCl solution was used for the specimen cells, adhesion test results correlated much better with electrochemical impedance spectroscopy scans as compared with distilled water. Therefore, hot water testing should be performed in an aqueous chloride environment because chloride ions promote more underfilm corrosion compared to distilled water.
- Hot water tests may not correlate well with epoxy-coated bar performance in more aggressive environments.
- Acceptance criterion of no blistering in 7-10 days of exposure to hot water as specified by the German procedure did not seem adequate to predict poor performance.

- Distilled water was more effective than aqueous 3.5% NaCl in promoting wet adhesion loss to specimens with no discernible initial defects.
- Adhesion strength for defect-free specimens in distilled water did not correlate well, in general, with impedance results. Some specimens were highly susceptible to coating breakdown in the presence of defects which developed during the hot water exposure, but the occurrence of such defects did not compromise adhesion.
- The most significant change in impedance response occurred within 24 hours after immersion in hot distilled water or aqueous 3.5% NaCl solution. Therefore, the hot water test can provide useful information in a single day.
- Unless a correlation between adhesion strength and long-term performance can be established, adhesion testing should not be included in a quality control protocol. EIS using single frequency measurements can provide a more reliable discrimination between “good” and “bad” epoxy coatings.

Chapter 5. Coating Adhesion Study

5.1 GENERAL

The quality of epoxy coating has been shown to be a key factor affecting the corrosion performance of fusion-bonded epoxy-coated rebars in chloride-contaminated concrete. One measure of quality is adhesion of the coating to the steel substrate. However, the role played by coating adhesion in the corrosion protection of steel reinforcement is not very well understood. It has been claimed that inadequate coating adhesion, along with the presence of discontinuities in the coating, may lead to film undercutting and early breakdown of the coating protection system.[20, 22, 51, 77] The application procedures for epoxy coating are based on the premise that good adhesion is crucial for satisfactory corrosion performance. Yet adhesion of epoxy-coatings is not satisfactorily addressed in current specifications on ECR. Quality of coating adhesion is determined by bending tests according to most specifications. Bending tests are more indicative of the coating flexibility than of the coating adhesion.

In the early 1990's, a hot water immersion test was developed and used in several European countries for evaluation of coating quality.[22, 111, 120] In these tests, an attempt was made to address quality by evaluating the amount of coating damage after the test. Corrosive action of hot water accelerates formation of rust spots at coating imperfections and defects. The earlier tests were not intended to evaluate epoxy coating adhesion. More recently, in Canada the Ontario Ministry of Transportation (MTO) incorporated a knife adhesion test after immersion in hot water.[51, 115] Epoxy coatings tend to lose adhesion in moist environments and hot water accelerates this phenomenon. Because of high variability of test results, the test was not incorporated in standard MTO specifications for quality assurance. Coaters in Ontario use this test for quality control at their plants.

Texas DOT specifications include a “peel test” for estimating coating adhesion.[114] This test is used for epoxy-coated elements that are too small to perform a bend test. Such elements include rebar couplers, plates, mechanical splices, etc. The test is performed by peeling the coating with a utility knife. The test has the disadvantage of being highly subjective and without sufficient background to support quantitative interpretation of test results.

Previous work on this project explored the feasibility of the hot water immersion test using Swiss specifications.[10, 121] The test was conducted on #4 and #8 bent, epoxy coated rebars, with both repaired and unrepaired damaged areas. The results showed that deterioration appeared at pinholes and cracks in areas deemed undamaged by visual inspection. Such damage was especially noted along the sides of the lugs. It was observed that the test was very effective in identifying pinholes in the coating on bent bars. The main conclusion was that the test was feasible for indicating the quality of coating application.

5.2 RESEARCH OBJECTIVES

In this study, the feasibility of hot water immersion and adhesion tests as a means for quality control of ECR was investigated. ECR samples from different coaters, with varying bar diameters, and both straight and bent samples were tested. Other variables that were evaluated include the temperature of the hot water bath, time of immersion, elapsed time between hot water immersion and adhesion test, different adhesion test operators, and different adhesion test procedures. Test results are discussed and analyzed. Different adhesion rating systems were devised and evaluated. The intent was to produce a test that could be easily and practically implemented without special or sophisticated equipment. With further research and refinement, this test may be incorporated in ECR specifications as an aid for quality assessment.

The main objectives of this research are the following:

- To develop and improve a hot water test that can be performed quickly and economically.
- To develop a reliable adhesion test that can be performed repetitively at the coating plant and which test results can be objectively interpreted.
- To determine the feasibility of incorporating hot water and adhesion tests in standard specifications for quality control of epoxy coated rebars.
- To understand the relationship between coating adhesion and corrosion protection.

5.3 ORGANIZATION OF STUDY

The adhesion study was divided in three phases. In the first phase, hot water tests were conducted following the Swiss and MTO procedures. The only modification that was introduced consisted of using an alternate adhesion rating system to evaluate test results by the MTO procedure. For the second phase, some modifications to the MTO hot water-adhesion test parameters were introduced and evaluated and the repeatability of the test was studied. In addition, a procedure to control the knife force was implemented. In the third phase, additional refinements in the test parameters and procedure were studied and evaluated. A self-calibrated knife was developed to measure and control the amount of force applied. Results from different adhesion test procedures were correlated. A short-term salt-solution immersion test was conducted in an attempt to understand the role of coating adhesion in corrosion protection. A proposed test procedure for hot water-adhesion is included in Appendix B.

5.4 FIRST PHASE: ADHESION STUDY FOLLOWING EXISTING GUIDELINES

5.4.1 Hot Water Test - Swiss Specification [120, 122]

The test consists of immersing bent and straight epoxy coated bars in a hot water bath at a water temperature of 10°C below the glass transition temperature of the epoxy coating (typically about 80°C) and length of immersion of seven days. The bar ends and damaged areas of about 25 mm^2 are patched. A maximum of 1 damaged spot (of up to 25 mm^2) per meter before immersion is admissible. The bars are evaluated by visual inspection. Assessment of coating damage is based on the classification shown in Table 5.1. Acceptance criteria are as follows:

- In previously undamaged coating, a maximum of 6 spots of damage type S2 per meter is allowed.
- A maximum of 5 damaged spots of type S2 may appear in bent bars.
- In the patched areas, deterioration such as the formation of blisters and damage visible to the unaided eye (damage type S3) is permissible.

Damage Type	**Description**
S0	No damage (evaluated with visual equipment)
S1	Microscopic damage that can be recognized only with visual equipment (magnifying glass, microscope)
S2	Damage that can be recognized by the eye without visual equipment
S3	Clear visual damage (0.1 - 1.0 mm)
S4	Clear visual damage of larger dimensions (> 1 mm)
S5	Surface failure of corrosion protective system (over 5 mm)

Table 5.1: Classification of damage of epoxy-coated reinforcement.

In all cases the assessment is done with respect to the effective size of damage on the coating, without any consideration of corrosion products that may be deposited underneath the coating.

Regarding the first two criteria, microscopic examination of a bar is very tedious, time-consuming, and difficult. There is no guidance for recognizing and identifying microscopic coating defects. These characteristics do not constitute a practical test. Also, it is desirable to examine the steel surface underneath the coating at rusted spots to give a better indication of the extent of coating degradation. Often, undercutting corrosion beneath the coating is more widespread than the corrosion observed on the coating surface.

Specimens from one coating applicator (*A*), one type of epoxy (*a*), two steel mills (*CH* and *NU*), two bar sizes (#10 and #4), and both straight and bent samples were used. A total of 8 group combinations and 31 samples (at least 3 samples per group) was considered. Specimens were immersed in their "as-received" condition without repairing coating damage. Bar ends were sealed with silicone. Length of specimens was 12.5 cm. The glass transition temperature of epoxy coating "*a*" was 87°C, which allowed a water temperature of 77°C for the test. Although not specified, samples were allowed to dry for 24 hours after immersion before visual examination.

Some of the major findings include: Black rust deposits appeared on previously damaged areas (coating damaged before water immersion) or on pinholes detected before the test. Coating defects and pinholes undetected before the test became visible as black dots or spots, dark-brown spots, or black or brown rusted cracks. Brown rust appeared much less frequently than black rust. About 90% of rusted areas appeared on or adjacent to bar deformations (longitudinal and transverse ribs). There were instances where large and small damaged areas did not experience any change in appearance nor did they exhibit rust formation.

On one hand, the hot water test following Swiss specifications seemed helpful in revealing coating defects such as pinholes, cracks, tears, thin coating, incipient damage, and other types of damage that were not evident to the unaided eye. On the other hand, the fact that no corrosion appeared at several locations with large and visible areas of damage raises questions about the reliability of the test. If large damaged areas withstand such test conditions, much smaller and less visible damaged areas could also undergo the test without corrosion attack. It may be possible for a bar with defective coating to pass the test.

For these reasons, the hot water test did not seem to be reliable for locating all possible defects and discontinuities in the coating. In addition, seven days of immersion and a very cumbersome microscopic examination process are not practical for a test intended to be completed quickly. With these factors in mind, no further tests using the Swiss specification were conducted in subsequent phases. Clear et al. also found the classification and acceptance criteria of the Swiss procedure to be inadequate.[22]

5.4.2 MTO Hot Water-Adhesion Test

MTO Draft Specification [115]

The Canadian draft specification requires submerging bar samples in a tap water bath at a temperature of 73 ± 2°C for a period of 48 ± 2 hr (Fig. 5.1). There should be a space of at least 25 mm between bar samples. The bars are then removed from the water bath and stored in air at 23 ± 3°C for 24 ± 2 hr. Subsequently, samples are prepared for adhesion testing as follows*:* With the specimen securely clamped on a vise, an X-cut is made through the coating at six locations between bar deformations, as shown in Fig. 5.2. Three test sites are located on each side of the bar. The cuts must extend through the coating so that the metal is visible. The cuts are made with a utility knife having a new, sharp blade for each specimen. The length of each cut should not be less than 10 mm or the distance between adjacent deformations. The two cuts forming the “X’ should intersect a an angle as close to 90° as possible. The “X” cut defines 4 flaps of coating and each one is tested. All test sites should be located at least 25 mm from the bar ends.

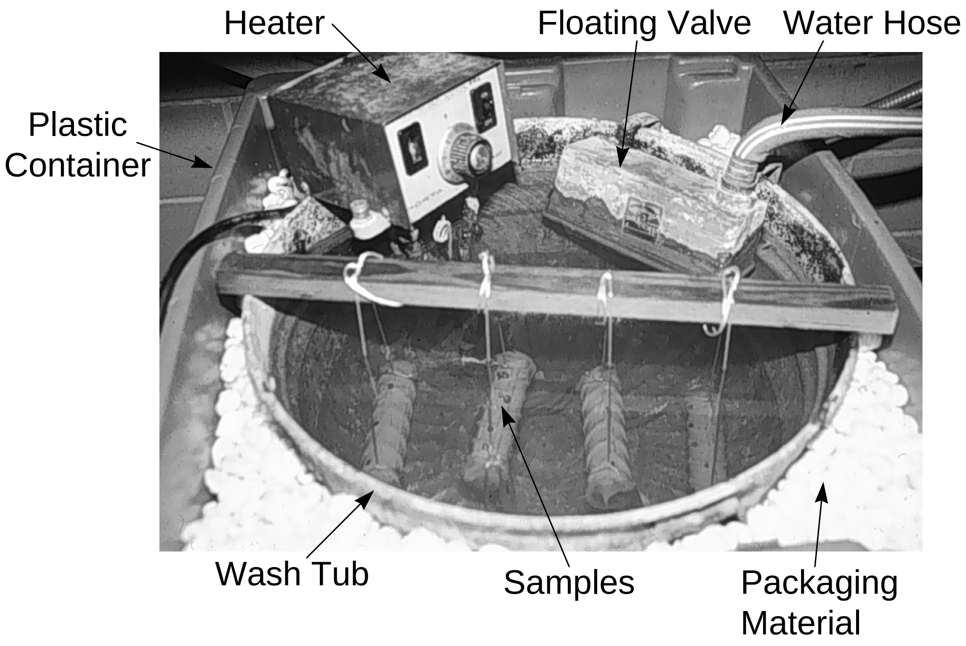


Figure 5.1: Hot water bath.

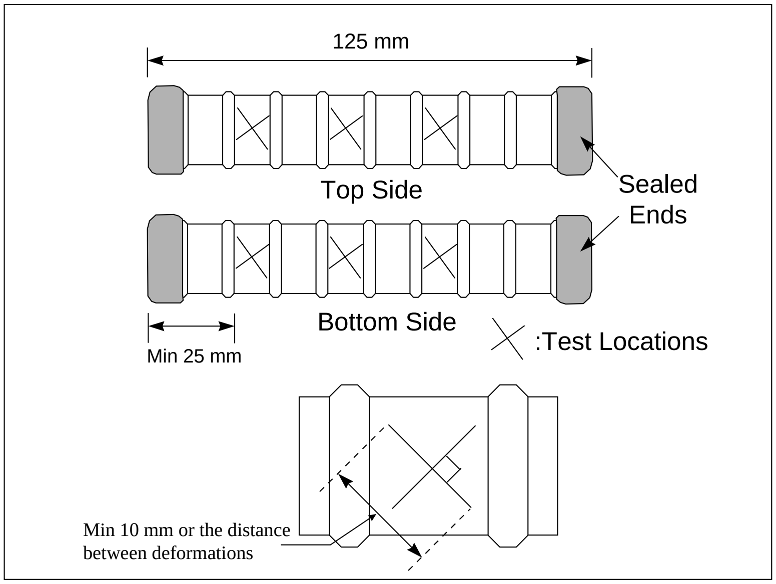


Figure 5.2: Test locations on rebar.

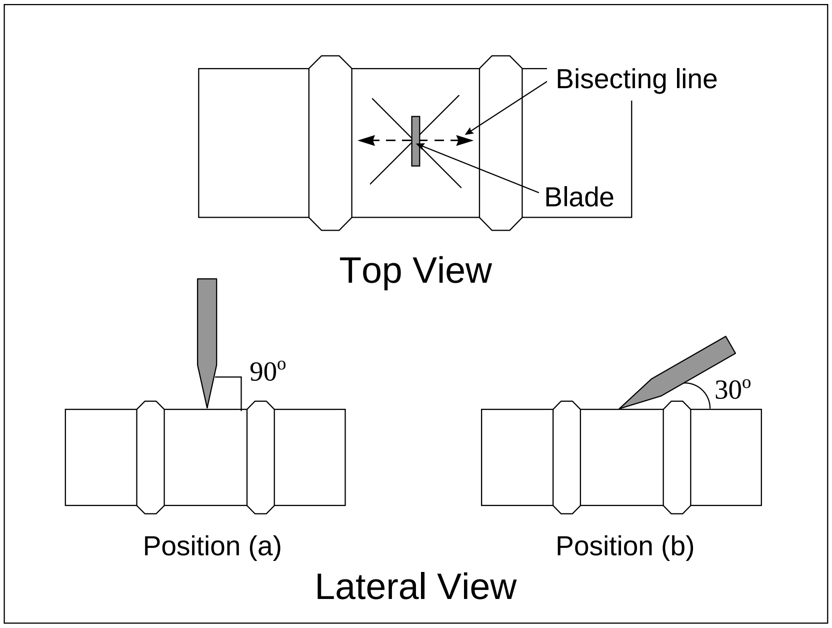


Figure 5.3: Position of knife and direction of force application.

Adhesion testing on each "X" is performed as follows: The knife is positioned vertically on the bar so that the tip of the blade makes contact with the intersection of the two cuts and the plane of the blade bisects the two cuts (the plane of the blade is perpendicular to a line bisecting the flap to be tested, as illustrated in Fig. 5.3). The blade is then rotated so that it makes a shallow (approximately 30°) angle with the bar while the tip of the blade remains in contact with the bar (Fig. 5.3). The blade is inserted under the coating and a constant pressure of approximately 3 kg is applied until the coating resists the insertion (Fig. 5.4). The pressure is maintained for at least 5 seconds. The knife blade should not cut through the coating. Any disbonded coating is removed by levering action of the blade. The procedure is repeated in all four flaps. An adhesion rating is assigned in accordance with Table 5.2.

Adhesion Rating	**Description**
1	Unable to insert blade tip under the coating at all four sections
3	Blade tip can be inserted under the coating. Levering action removes small chips of coating but cannot remove the entire coating at any section.
5	Blade tip slides easily under the coating and the entire coating can be removed at one or more sections.

Table 5.2: Adhesion rating of epoxy coating in Hot Water Test (MTO test procedure).

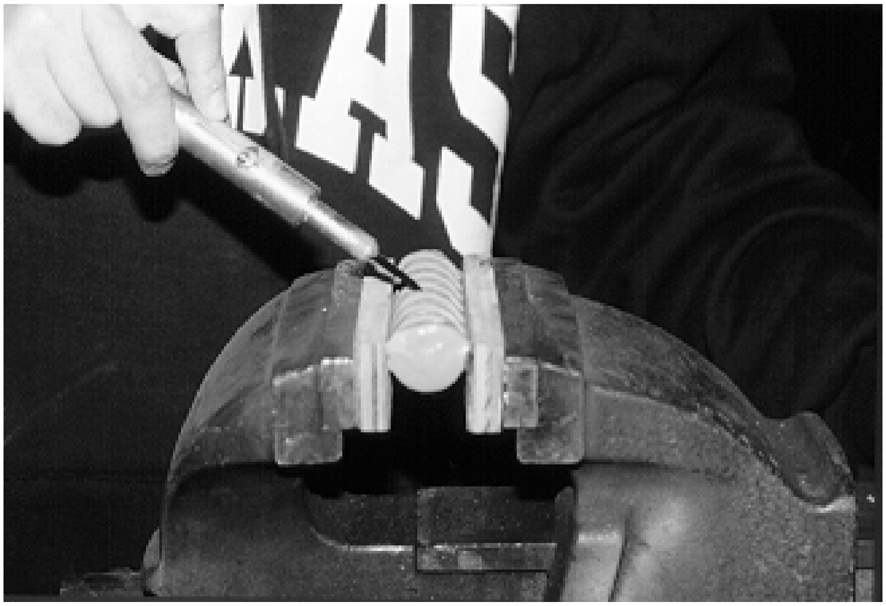


Figure 5.4: Adhesion testing of epoxy-coated bar specimen.

Refinements in Procedure

An interesting problem relates to the measurement and application of a constant knife force during the test. For this first phase, knife force was estimated very crudely. The procedure consisted of first pushing the knife against a digital scale until the desired amount of force was reached. The pressure on the scale was maintained for about 30 seconds so the operator would get a feel of the amount of force that has to be applied. The operator then tried to emulate that force during the test. Once the operator felt the desired force was reached, the knife pressure was maintained for at least 35 seconds (instead of the specified 5 seconds). This procedure is basically a calibration of the force applied by a human hand. Initially, the operator needed to calibrate his arm before testing every site. As the operator became more experienced, arm calibration was done at every 3 test sites. This approach to estimate the knife force was subjective and very susceptible to human error and was the first step towards developing a more reliable method for force calibration in subsequent phases.

Another problem involved positioning the knife to an angle of approximately 30° with respect to the bar surface. It is difficult for the operator to concentrate on both controlling his arm force and keeping the angle of the knife during the test. Obviously, human error is expected. Besides, the reference plane against which the angle of the knife should be estimated was not clearly defined. Possible reference planes could be: a) a plane containing the longitudinal bar axis, or b) a plane tangent to the bar perimeter at every point the blade tip makes contact with the bar as the knife moves. For this study, the angle of the knife was measured with respect to the tangential reference plane. In this manner, the knife would be positioned at an approximately constant angle with respect to the bar surface as the knife moves. This procedure should produce an approximately constant force at the coating-steel interface.

A utility knife with snap-off blades was used for adhesion testing. Such knife has the advantage of providing new blades handy for every test and it is economical. However, the knife blade design was not very suitable to perform adhesion testing on epoxy-coated bars. The problem is that the sharp edge of the blade runs in a longitudinal direction parallel to the knife axis. The blade is not symmetrical and does not have a very pointed sharp tip. During the test, the blade has to be held at an oblique angle with respect to the path that the blade has to follow (the line bisecting the flap of coating) so that the blade tip can be inserted under the coating. For the operator, this is an awkward and uncomfortable position.

Study Variables

Bars procured for this study had the following characteristics:

- Bars from three Texas DOT-approved coating plants (*A*, *B*, and *C*)
- Bars coated with two epoxy coating powders (*a* and *b*) pre-qualified by Texas DOT
- Bars from four steel mills (CH, NU, BI, and SM)
- Bent and straight bars
- Bars of three sizes (#10, #9, #4)
- Bars with two rib deformation (parallel, diagonal)

Bars from coating plants *A* and *B* were coated with epoxy material *"a"* and bars from coating plant *C* were coated with epoxy material *"b"*. Coating plant *A* acquired bars from two steel mills (CH and NU) and coating plants *B* from BI and *C* from SM. Coating plants *A* and *B* supplied #10 and #4 bars, and plant *C* supplied #9 and #4 bars. This yielded a total of 16 groups, each one representing a bent or straight bar, of given diameter, from a specific steel mill, coated with a particular epoxy at a certain coating plant. Determination of study variables had several limitations because all three coaters did not employ the same epoxy coatings, did not purchase bars from the same source, and did not provide bars of the same diameter. Main study variables included coating applicator, bent or straight bars, bar size, and steel mill.

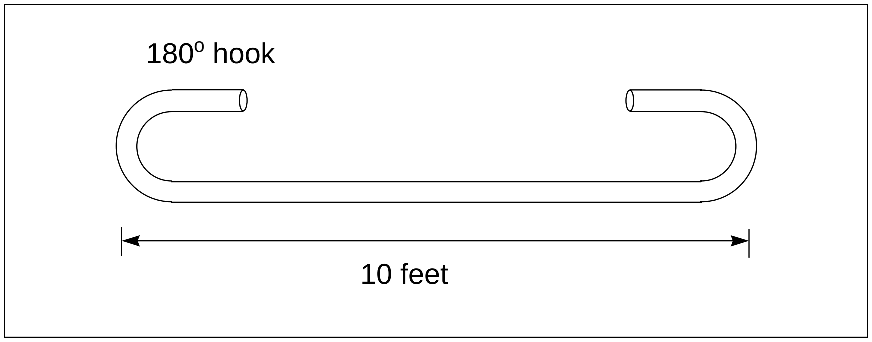


Fig. 5.5: Epoxy-coated bar dimensions as-received from coaters.

Shipped bars were 10 feet long and had a 180° hook at each end (Fig. 5.5). Bars from coater *C* were individually wrapped in soft styrofoam sleeves to protect the coating from damage during shipment. Bars from coaters *A* and *B* were not as carefully handled during shipment. Bars from coater A had the most damage. Samples 12.5 cm long were cut from both the straight and bent portions of the bars. A total of 51 bar samples were cut, including at least two samples from each group. Samples were selected from locations with the least damage. Bar ends were sealed with silicone. Specimens were immersed in their “as-received” condition without repairing coating damage.

MTO test procedures specify adhesion testing 24 hours after immersion. This requirement was followed at most test sites. However, adhesion tests were performed at selected test sites in 24 samples after varying post-immersion periods, ranging from 40 hours to 2 months after immersion.

Test Results and discussion

When the experiment was performed, the initial MTO rating system was different from that shown in Table 5.2. The earlier rating was based on measurement of the debonded coating area. A simplified system was developed for evaluation of test results and is described in Table 5.3. In this system, a “flap” rating was assigned to each individual flap and, depending on the combination of flap ratings, an adhesion rating was assigned to each test site. This alternative rating system has the advantage of not requiring any measurement. The final MTO rating system, which is considerably simpler than the one proposed in their first draft, became available during the course of the experiment.

Flap	**Description**

rating	
A	Unable to insert blade tip under the coating
B	Blade tip can be inserted under the coating. Levering action removes small chips of coating but cannot remove the entire coating
C	Blade tip slides easily under the coating and the entire coating can be removed

Adhesion Rating	**Description - Σ Flap ratings**
1	A at all 4 flaps (Good adhesion)
2	B at one flap, A at remaining flaps
3	B at 2 or 3 flaps, A at remaining flaps
4	B at all 4 flaps
5	C at one flap, A or B at remaining flaps
6	C at 2 or 3 flaps, A or B at remaining flaps
7	C at all 4 flaps (Poor adhesion)

Table 5.3: Alternative adhesion rating system.

Figure 5.6 shows average adhesion test results of specimens from all three coaters. A rating of 1 indicates good coating adhesion and a rating of 7 indicates poor coating adhesion. Specimens from coater *A* exhibited generally poor coating adhesion. In most cases, the coating could be easily peeled with almost no force. Frequently, the coating started to debond while making the “X” cuts. Straight bar specimens from coaters *B* and *C* showed better coating adhesion, with few test sites having adhesion rating of 7 and several test sites with ratings 1 and 2. On average, coating adhesion for straight bar specimens from coaters *B* and *C* was fair. A photograph showing typical adhesion results on several specimens from all coaters is included in Fig. 5.7.

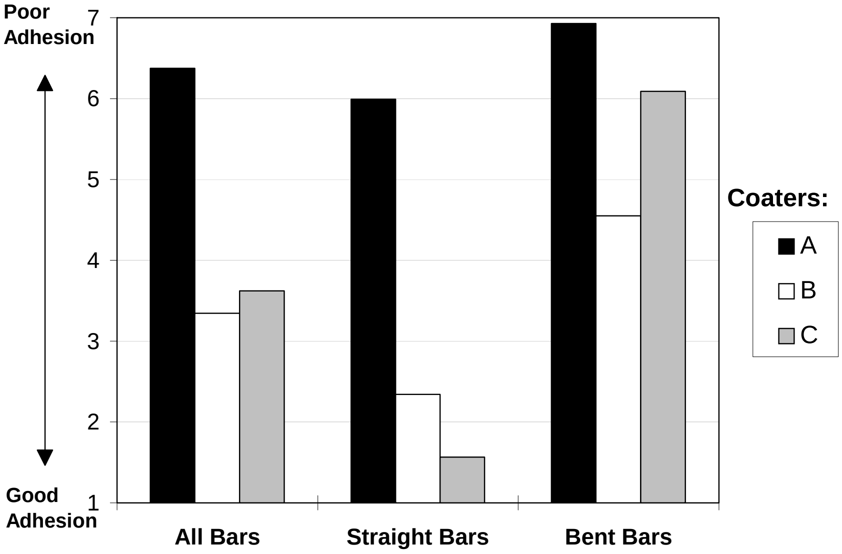


Figure 5.6: Average adhesion ratings of specimens grouped by coating plant and type of specimen (bent or straight).

Figure 5.6 also shows average adhesion test results of straight and bent samples for all coaters. Clearly, bent bars from all three coaters exhibited poor coating adhesion. Poor adhesion of bent bar specimens was expected. During bending, the epoxy coating is stretched and loses some adhesion to the bar surface. Bent samples start with marginal adhesion compared to straight specimens. After hot water immersion, the already marginal coating adhesion of bent samples was even worse. It seems that the test conditions may be too severe for bent bars. In several bent samples, coating on the outside of the bend was easier to peel than on the inside of the bend, even when adhesion ratings were the same on both the inside and outside of the bent. A possible reason is that during bending, coating on the outside stretches and coating on the inside compresses. Even if coating adhesion is poor, the compressed coating on the inside may offer some resistance to the knife blade.

If bent bars are not considered, the difference in coating adhesion between the three coaters becomes even more pronounced. Straight samples from coater *A* showed poor coating adhesion while straight samples from coaters B and C showed very good to excellent performance, as evidenced in Fig. 5.6.

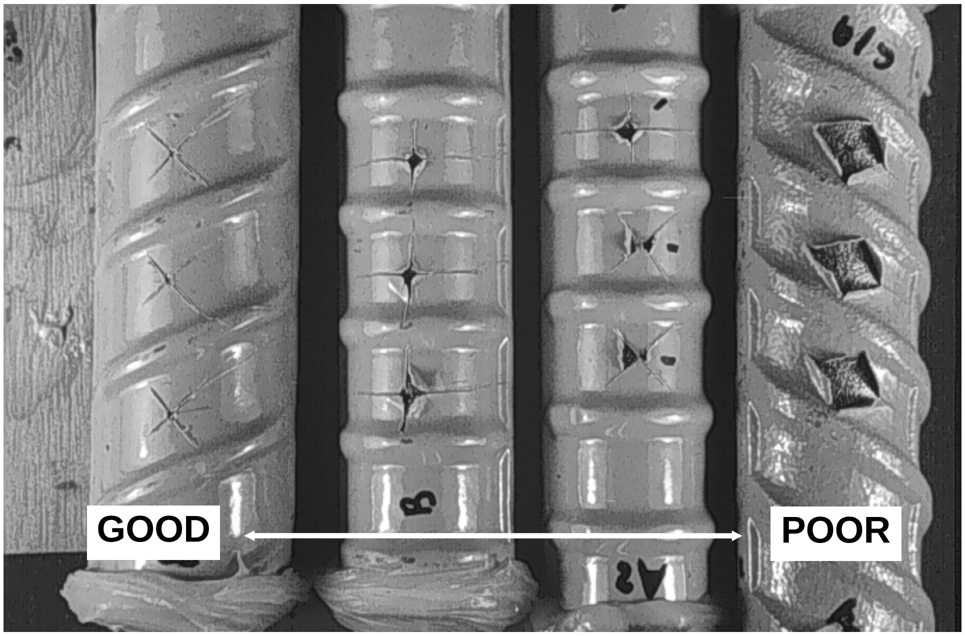


Figure 5.7: Typical adhesion test results of several specimens from all coaters.

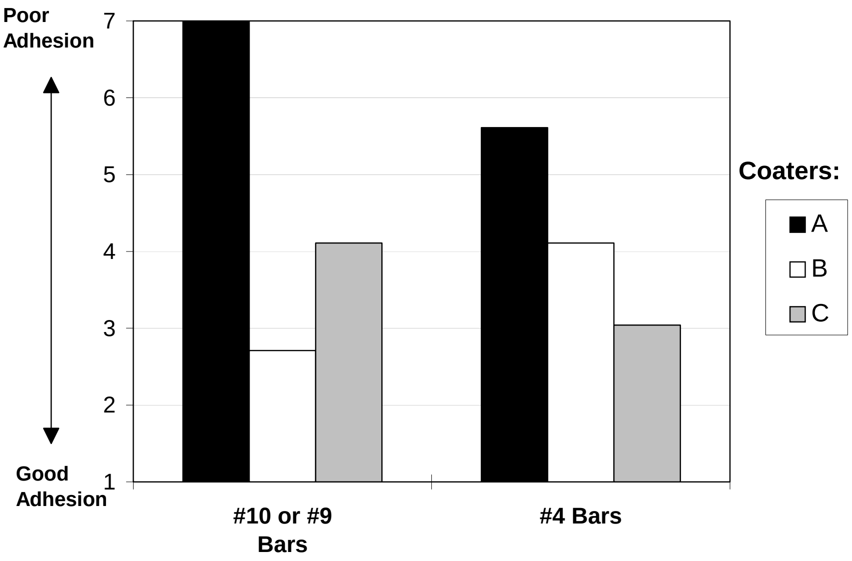


Figure 5.8: Average adhesion rating of specimens grouped by coater and bar size.

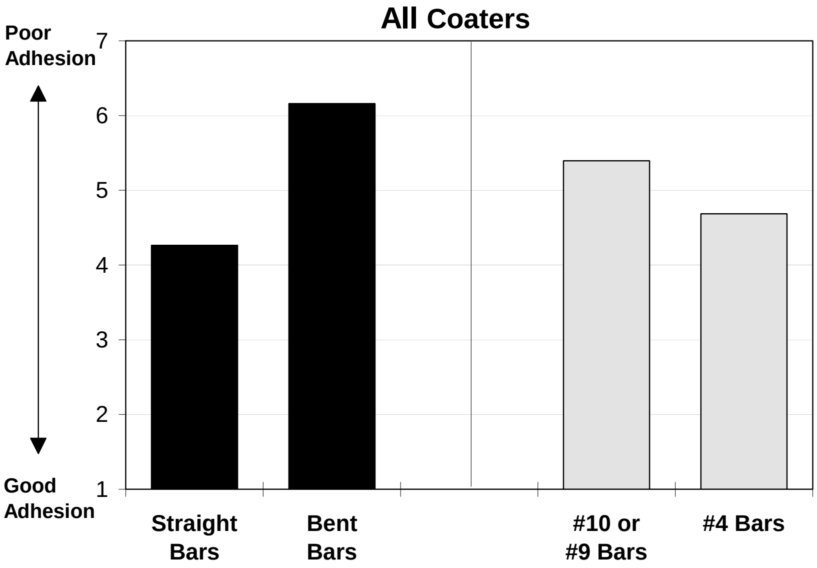


Figure 5.9: Average adhesion rating of specimens grouped by bar type and bar size.

In Fig.5.8, average adhesion ratings are categorized by bar size and coater. There is not a clear relationship between bar size and coating adhesion. Bars of smaller diameter from coating plants *A* and *C* performed better than bars of larger diameter. However, in the case of bars from plant *B*, larger bars showed better coating adhesion than smaller bars. Considering specimens from all coaters, smaller bars, with average rating of 4.7, tended to have slightly better coating adhesion than larger bars, with average rating of 5.4 (Fig. 5.9).

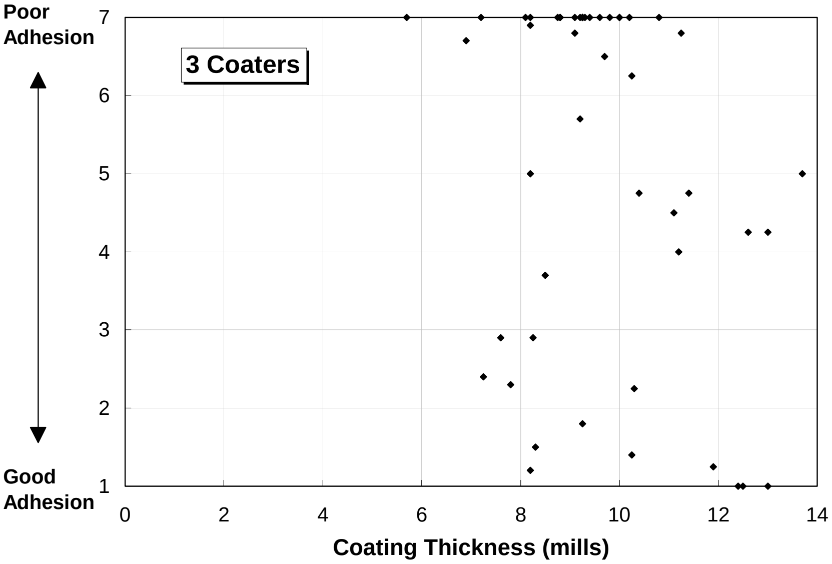


Figure 5.10: Adhesion rating vs. coating thickness of all specimens.

Adhesion rating and coating thickness of individual specimens are plotted in Fig. 5.10. The data points are widely scattered and there is no clear trend between coating adhesion and coating thickness. Coating thickness variability, which is a measure of the uniformity of coating thickness, and adhesion rating of each specimen are plotted in Fig. 5.11. Again, no clear relationship between these two coating characteristics was found.

As mentioned previously, bars were immersed in hot water in their as-received condition. About one third of the specimens had some degree of coating damage and remaining specimens were undamaged. Both Swiss and MTO test procedures specify the use of bars free from holidays and bare areas. Therefore, it was of interest to observe the performance of bars that did not meet specifications. Some field studies reported in the literature showed that bars with damaged coating prior to exposure underwent worse adhesion loss than undamaged bars.[18] Loss of adhesion was observed at an intentional hole in the coating after hot solution immersion tests by the FHWA.[107] Adhesion ratings of each individual specimen for coaters A, B, and C are plotted in Figures 5.12, 5.13, and 5.14. Data points are plotted in sequence and the horizontal axis only shows the sequence number of each sample. Black points represent specimens with coating damage and white points represent specimens with no damage in the coating. Figure 5.12 shows that most specimens from coater A were damaged and exhibited poor adhesion. One half of undamaged specimens showed poor adhesion and the other half showed better adhesion, with ratings between 2.4 and 3.7. Graphs for coaters B and C (Figures 5.13 and 5.14) showed more widespread scatter of data and no clear relationship between coating damage and coating adhesion. There were specimens with no coating damage and poor coating adhesion and specimens with damaged coating and excellent coating adhesion.

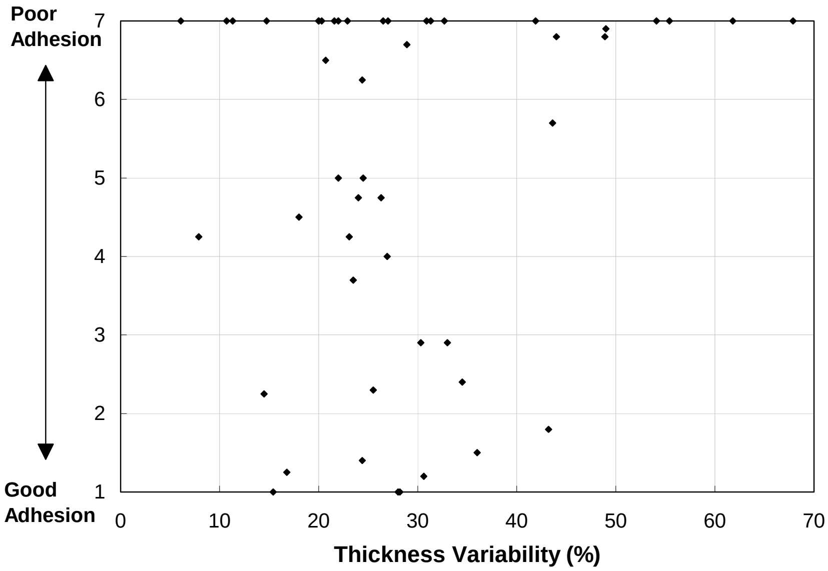


Figure 5.11: Adhesion rating vs. variability of coating thickness.

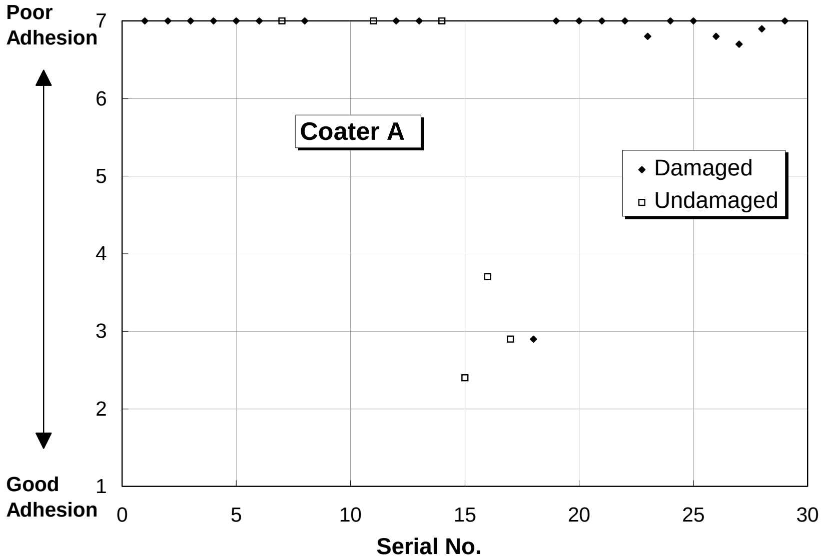


Figure 5.12: Effect of coating damage on coating adhesion (Coater A).

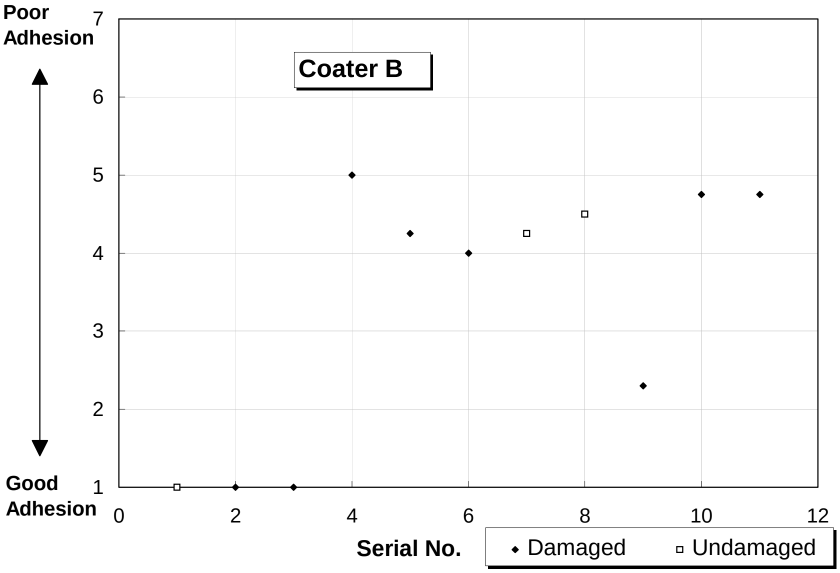


Figure 5.13: Effect of coating damage on coating adhesion (Coater B).

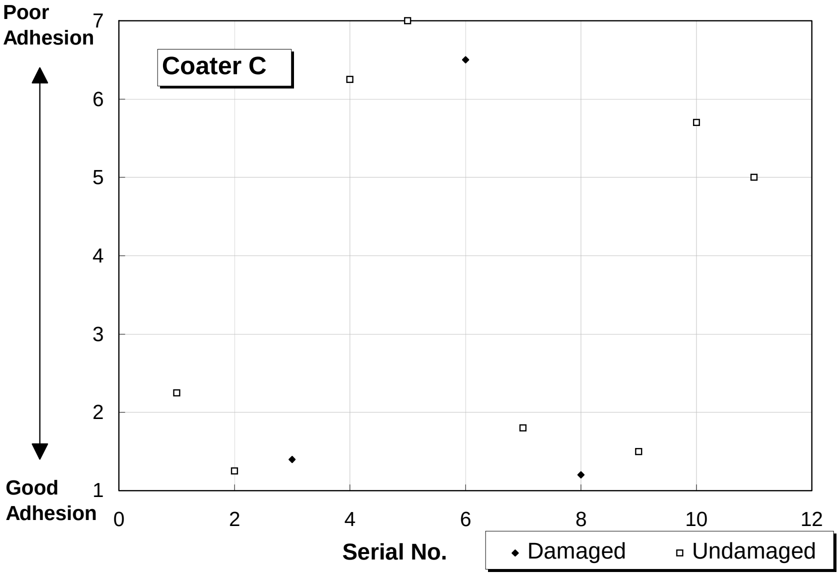


Figure 5.14: Effect of coating damage on coating adhesion (Coater C).

Tables 5.4, 5.5, and 5.6 contain adhesion ratings of specimens that were tested at different times after immersion in hot water. For each of those specimens, adhesion tests were performed typically 24 hours after immersion and either 40, 72, 90, 120 hours, or 2 months after immersion. In most cases, coating adhesion was either unchanged or slightly better when the test was performed at times longer than 24 hours after immersion. Examination of data from Tables 5.4, 5.5, and 5.6 reveals that most adhesion ratings were very similar and only in a few cases there was a drastic change (for the better or worse) in coating adhesion with respect to varying post-immersion times. Variability of adhesion ratings of tests conducted at varying post-immersion times was not significant and was similar to the variability of readings for tests conducted at a uniform post-immersion time of 24 hours.

Specimen	**24 hours**		**72 hours**		**90 hours**	
	NR	**Avg. Adh. Rating**	**NR**	**Avg. Adh. Rating**	**NR**	**Avg. Adh. Rating**
C23	4	7	2	6.5		
C24	4	7	2	7		
C25	4	7	2	7		
C26	4	7	2	6.5		
C27	4	7	3	6.3		
C28	5	7	2	6.5		
C29	6	7	2	7		
C32	3	1	2	1		
C33	2	6	1	4	1	4
C34	2	4.5	2	4		
C35	2	4			2	4
C36	2	3.5	2	5		
C37			2	5	2	4
C38	2	1.5			4	2.75
C39	2	4.5	2	5		
C40	2	4			2	5.5

NR: Number of readings.

Table 5.4: Adhesion ratings of tests conducted at varying post-immersion times.

Specimen	24 hours		40 hours		120 hours	
	NR	Avg. Adh. Rating	NR	Avg. Adh. Rating	NR	Avg. Adh. Rating
C41					4	2.25
C42	2	1.5			2	1
C43	2	1.5			3	1.3
C47			2	2	4	1.75
C48			2	1	4	1.25
C49			2	2.5	4	1

NR: Number of readings.

Table 5.5: Adhesion ratings of tests conducted at varying post-immersion times.

Specimen	24 hours		2 months	
	NR	Avg. Adh. Rating	NR	Avg. Adh. Rating
C6	6	7	2	7
C12	6	7	6	7

NR: Number of readings.

Table 5.6: Adhesion ratings of tests conducted at varying post-immersion times.

The knife force applied by an operator was not always constant. For instance, in samples with the best coating adhesion (ratings of 1 or 2), the actual applied force may have exceeded 4 kilograms. It is likely that the operator tended to push the knife strongly when the coating offered resistance to debonding. Despite the subjectivity of the procedure for estimation of knife force, the test seemed useful and produced some meaningful results. It should be emphasized, however, that only one test operator was involved. It may be expected that with more than one operator involved, applied knife force may vary significantly.

A common problem during the test was that of the coating ripping off as a result of: 1) high knife force, 2) slippage of knife, or 3) blade cutting through the coating. It was difficult to adequately interpret the results from these cases in terms of coating adhesion. Generally, only the area of coating lifted just before the coating tore was considered to have debonded. In cases where the knife slipped without tearing additional coating, the test force was re-applied at the position where the knife slipped. Any additional debonding was included in the test result. Such assessment was not always easy and required careful judgment. An interesting finding was that sometimes the blade could be inserted and advanced beneath the coating only for a short distance after maintaining the 3 kg force for 35 seconds; however, subsequent levering action of the blade would remove a larger portion of the coating. Another interesting phenomenon was that at some flaps whose adhesion was rated as “C,” the coating would initially offer certain resistance to the advancement of the blade, but after 20 to 30 seconds of maintaining the knife pressure, the coating would eventually yield and start peeling. This finding justified the procedure followed in this study for maintaining the knife pressure for at least 35 seconds. If this had not been done, some adhesion ratings may have been quite different.

The alternative adhesion rating system is compared to the MTO rating system in Fig. 5.15. The average adhesion rating of each representative group of specimens was calculated using both rating systems and plotted on the graph. Since each rating system has a different range, the values had to be normalized so they could be plotted on the same graph. Normalization was done by first dividing the readings of the alternative system by 7 (the largest value of that system) to produce a range from 0.14 to 1.0. Subsequently, the values of the MTO system were converted to the normalized system by interpolation. A normalized rating of 1.0 represents poor adhesion and a normalized rating of 0.14 indicates good adhesion. It can be seen that curves representing each system follow very similar trends. The largest difference between the two ratings was 0.18 and the average difference was 0.06. Consistently, the MTO rating system gave worse or equal adhesion ratings than the alternative system. This indicates that the MTO system tends to be more stringent and gives higher penalties in certain cases. As opposed to the system in the first MTO draft, the newer rating system was devised to be very simple and easy to use but, because of its simplicity, it would be expected to err on the safe side.

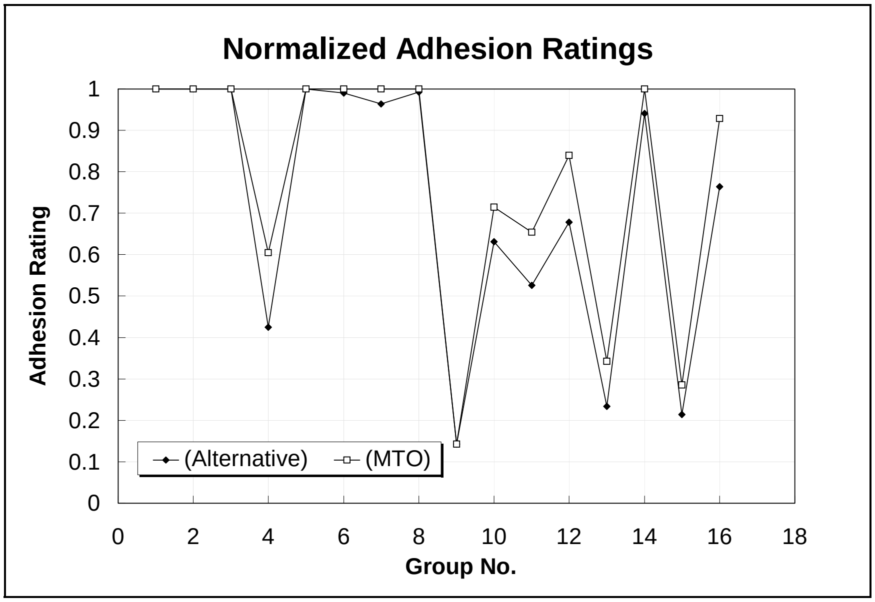


Figure 5.15: Comparison of adhesion rating systems.

5.4.3 Conclusions from First Phase

The main finding in the First Phase was that hot water-adhesion tests were useful in discriminating and differentiating good from bad coatings. The tests were relatively easy to perform and did not require special or sophisticated equipment. Test results were not significantly affected by changes in time of immersion, by adhesion test procedure, nor by adhesion test operator. Bar diameter did not influence test results. In all cases, straight bars performed better than bent bars. For the range studied, coating thickness and thickness variability did not correlate with adhesion performance. Adhesion test results did not have any correlation with original coating condition. Adhesion test results best correlated with sample source (coater). A rating to evaluate adhesion test results was devised based on ease of use and practicality. An important issue to address in the next phases was defining a limiting adhesion rating as acceptance criterion for quality assurance.

5.5 SECOND PHASE: HOT WATER-ADHESION TEST MODIFICATIONS

Work for the second phase was aimed at studying additional test variables and at improving the repeatability by eliminating or reducing factors that make the test subjective. Four major areas were addressed: 1) test repeatability, 2) effect of immersion time in hot water, 3) evaluation of knife blades and force calibration, and 4) effect of test operator.

Another important issue relates to the subjectivity of the procedure used in the First Phase for estimating and controlling the amount of force applied to the knife. It is important to develop a more reliable and objective procedure so that different operators apply approximately the same pressure to the knife.

5.5.1 Special Device to Control Knife Force

Adhesion tests reported in Section 5.5.2 were conducted using a special device to control the applied knife force. A device was manufactured for this study and consisted of a wooden assembly in which a long, thin, flexible plywood strip was mounted so that it could deflect in the horizontal direction. The ends of the strip were free to rotate (simply supported). The bar specimen was then fixed to the plywood strip with a hose clamp at each end. A short chamfer was fixed at the mid-length of the plywood strip to hold the bar in place. During testing, the operator applied sufficient knife pressure to the epoxy to deflect the plywood strip laterally until it touched a limit which was indicated using a nail. The device was calibrated so that the desired amount of knife force was reached when the plywood strip touched the nail. An sketch of this special device is shown in Fig. 5.16.

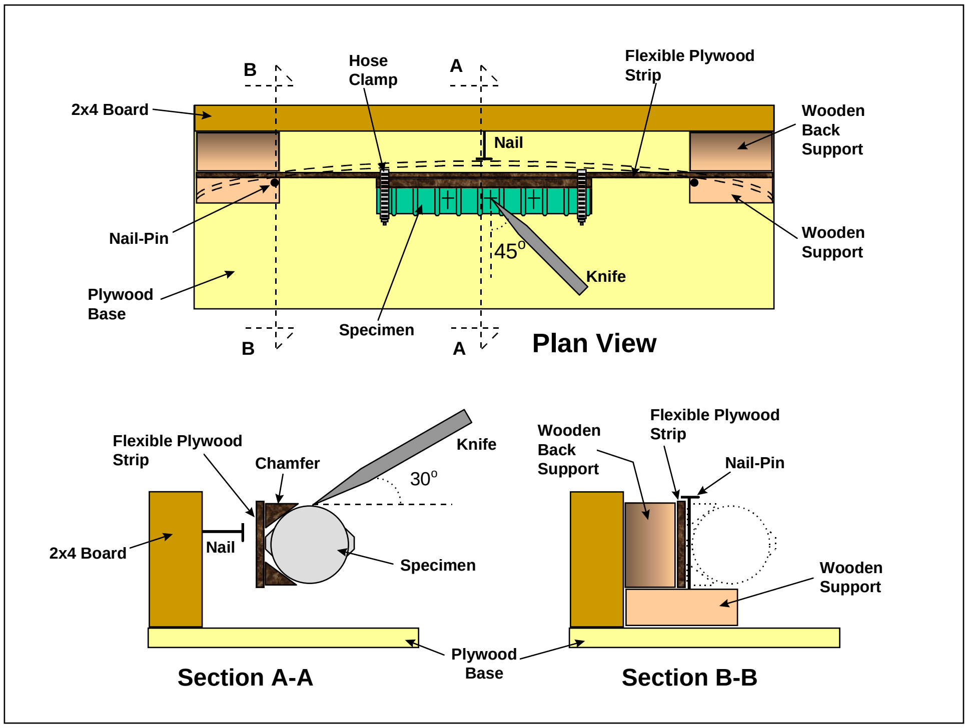


Figure 5.16: Special device to calibrate amount of knife force.

The procedure for calibrating the special device was as follows: The device was turned so that the plywood strip (with the specimen mounted to it) deflected downwards. A known weight was positioned above the specimen and the amount of deflection was measured. The nail head protruded to the desired point. The calibration process was performed for each specimen because clamping the bars stiffened the plywood strip and it was not possible to clamp each bar identically.

The weight selected for calibration was based on the following considerations: X cuts at each test site were oriented as illustrated in Fig. 5.16. The knife was positioned approximately 45° with respect to the bar axis in a horizontal plane, and at approximately 30° with respect to a tangential plane at the point of contact with the bar. When the knife is pushed against the bar, one of the three orthogonal components of the knife force produces lateral deflection of the plywood strip. The horizontal component is $F_{knife} \cos 30° \cos 45°$. For F_{knife}= 3.5 kg, the horizontal component is 2.14 kg.

5.5.2 Test Repeatability

One crucial question is how well an individual adhesion test represents the general properties of the coating application for a specific production run. The variability of coating adhesion throughout the length of a rebar is unknown. If adhesion test results from different portions of a rebar are available, variability may be due to the coating process itself, to inherent test errors, or to a combination of both.

Study Variables and Test Results

Main variables included bar source (coating plant) and location (Fig. 5.17) along bar from which the sample was obtained. Hot water and adhesion tests were conducted on straight epoxy coated bar samples from coating plants *B* (#10) and *C* (#9). For each coater, 8 specimens were cut from 2 rebars (eight feet long) at several locations along the rebar, typically 3 specimens from both bar ends and one specimen from the middle portion (Specimens 1, 2, 3, and 4 in Fig. 5.17). Six tests were conducted (three on each side) for each sample. Comparison of test results from different bar locations gave an indication of the variability of coating adhesion along an individual rebar. Test parameters included temperature of 75°C for water bath, 48 hours of immersion, 24 hours of post-immersion, and 3.5 kg of knife force.

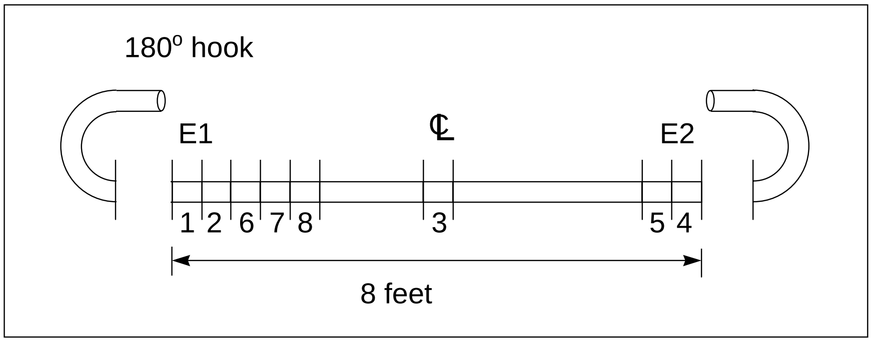


Figure 5.17: Location of specimens obtained from epoxy-coated bar.

A summary of adhesion ratings and average values for all specimens is included in Table 5.7. Statistical values based on all individual adhesion ratings are summarized in Table 5.8.

Specimens 1 and 2 were located at one end of the bar, specimen 3 was located at the middle portion of the bar, and specimen 4 was located at the other end of the bar (Fig 5.17). A first look at Tables 5.7 and 5.8 reveals that, on average, bars from coater *B* had better coating adhesion than bars from coater *C*. Also, all specimens from coater *B* performed better than those from coater *C*. The same is true when comparing bars I and II for each coater. For coater *B*, bar I had an average rating of 1.5 and bar II of 2.1 and nearly every specimen from bar II had worse average adhesion ratings than those from bar I. For coater *C*, bar I had an average rating of 5.4 and bar II of 2.9 and all specimens from bar I had worse average ratings than those from bar II. These observations indicate that coating adhesion tends to be relatively uniform for specimens cut from the same rebar at random locations.

Specimen	**Coater B**				**Coater C**			
	Bar I		**Bar II**		**Bar I**		**Bar II**	
	Side A	**Side B**	**Side A**	**Side B**	**Side A**	**Side B**	**Side A**	**Side B**
1	1 1 1	1 1 1	2 3 3	2 3 3	5 6 7	3 4 4	3 4 5	3 4 3
Average	1		2.7		4.8		3.7	
2	3 1 2	3 1 1	1 1 3	1 2 1	6 6 7	6 4 4	4 3 4	3 1 2
Average	1.8		1.5		5.5		2.8	
3	2 2 2	2 1 1	3 2 3	2 1 2	5 5 7	6 6 5	3 2 4	2 2 1
Average	1.7		2.2		5.7		2.3	
4	1 1 1	2 3 1	3 3 3	1 1 1	6 7 7	4 4 5	3 3 1	3 4 2
Average	1.5		2.0		5.5		2.7	

Table 5.7: Adhesion ratings for all specimens using rating system of Table 5.3.

Parameter	**Coater B**		**Coater C**	
	Bar I	**Bar II**	**Bar I**	**Bar II**
Mean	1.5	2.1	5.4	2.9
Median	1	2	5.5	3
σ	0.72	0.88	1.21	1.08
σ/Mean (%)	48	42	22.5	37
Range	2	2	4	4

A.D: Average deviation of all ratings
σ: Standard deviation of all ratings

Table 5.8: Statistical analysis of all individual ratings of Table 5.7.

The statistical values of Table 5.8 included some indicators of the variability of the data, such as the standard deviation, coefficient of variation, and range. Standard deviation values ranged from 0.72 to 1.21 and coefficient of variation values ranged from 22.5% to 48%. Standard deviations are greater for bars from coater *C,* that is, bars with greater adhesion ratings (lower adhesion). If standard deviation is divided by mean adhesion and expressed in percentage, the resulting value is the coefficient of variation. As opposed to standard deviations, coefficient of variations are greater for bars from coater *B.* The discrepancy comes from the fact that the magnitude of the mean significantly affects the coefficient of variation. The coefficient of variation is a relative measure of how large the standard deviation is with respect to the mean. The standard deviation is a measure of the dispersion of data in absolute terms and, therefore, provides a more better indication of the variability of the readings. Bars from coater *B* had a range of adhesion ratings of 2 and bars from coater *C* had a range of 4.

A statistical analysis indicates that bars with lower adhesion strength had greater variability. This is not surprising since low adhesion may be the result of an inadequate quality control in the coating process. The obvious exception would be a coating with very poor adhesion all along a rebar, in which case there is very little variability of adhesion ratings yet the quality is unacceptable. If adhesion ratings are to be used as quality indicators, both the mean rating and standard deviation of ratings have to be examined.

Examination of Table 5.7 shows that a lower number of tests per sample would have resulted in a less precise indication of the overall adhesion of a bar, especially for bars with greater dispersion of data. Small specimens seem to be representative of a long epoxy-coated bar, provided that several tests are performed on each specimen cut from that bar.

It should be noted that both bars from coater *C* came from the same production lot, yet the adhesion of bar I was worse than that of bar II. To properly evaluate a production lot, samples should be obtained from as many different bars as possible so that results are representative of a given lot.

Although average ratings per sample had low variability, Table 5.7 shows that individual ratings may vary significantly within the same specimen. Coating adhesion was not always uniform and usually varied along a bar. Variation of coating adhesion is affected by two factors:

a) Variability produced by the coating application because of inconsistencies of the coating material, uneven surface preparation, temperature differentials, uneven application, or improper curing.
b) Variability produced by adhesion testing because of human error, inaccuracy of the testing method, testing conditions, or sampling procedure.

It is extremely difficult to identify and separate the factors affecting the variability of coating adhesion, making the task of developing and improving adhesion test repeatability particularly complex. It is possible to assume, however, that coating application probably accounts for most of the variability if operator subjectivity is eliminated from the test.

The issue of test repeatability will be re-addressed in subsequent sections after more test results are presented.

5.5.3 Improved Special Device to Control Knife Force

For the series of tests reported in sections 5.5.4, 5.5.5, and 5.5.6, the adhesion test device previously used was further improved. The main disadvantage of the device was that very frequent calibration was required. The main change consisted of separating the specimen from the deflecting flexible strip so that the stiffness of the flexible strip was constant. The specimen was mounted and fixed inside a rigid, sturdy wooden assembly supported on metal rollers to allow translation (Fig. 5.18). The plywood strip was replaced by an acrylic strip. With the operator exerting pressure with the knife, the whole bar-assembly moves and pushes the flexible acrylic strip until it reaches the desired deflection. The end supports of the acrylic strip were fixed with clamps instead of being simply supported to make the test easier to control. Less deflection (and less translation of the bar-assembly) is needed to achieve the desired force. Calibration procedure was the same as before but the frequency of calibrations was greatly reduced. The improved device was calibrated once per working session.

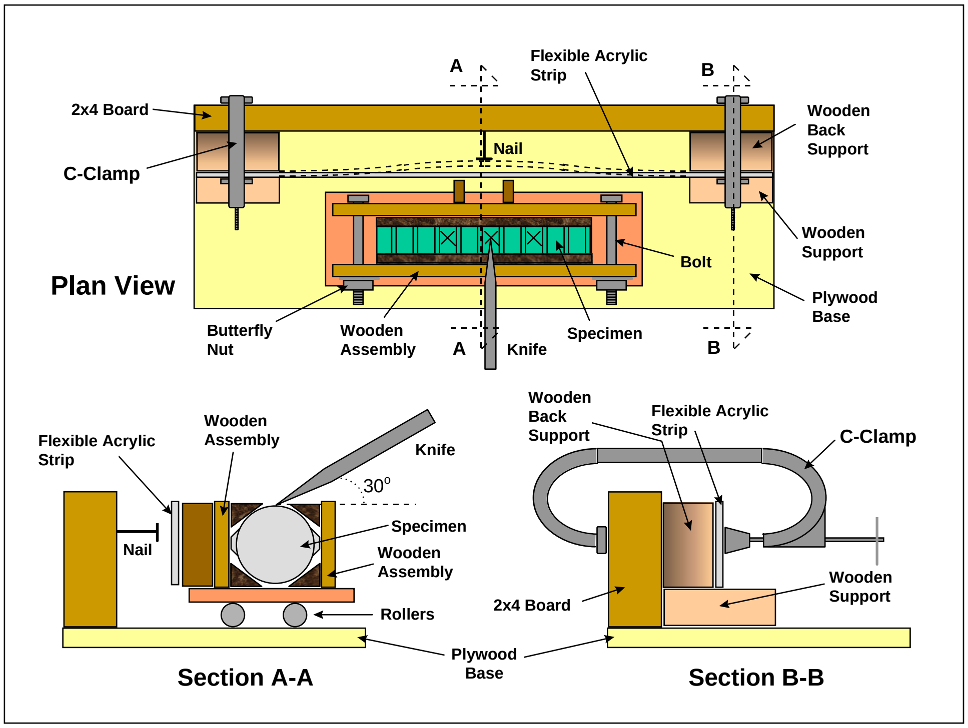


Figure 5.18: Improved device to calibrate knife force.

Another modification in the adhesion test procedure consisted of changing the orientation of the X cuts on the bar surface. The new orientation, illustrated in Fig. 5.18, allowed the knife force to be applied normal to the bar in the direction of deflection of the acrylic strip. With the earlier X orientation, the knife was aligned at an angle with respect to the deflection of the plywood strip (Fig. 5.16) and made the test more difficult to perform and control. The drawback of the new orientation of X cuts is that only two flaps (aligned perpendicular to the bar axis) can be tested. The other two flaps are aligned parallel to the bar axis and cannot be tested.

The modified device was calibrated for a knife force of 3.5 kg. With the knife oriented at 30° with respect to the direction of movement, a 3-kg weight (F_{knife} cos30° = 3.5 cos30° = 3 kg) was used for calibration.

5.5.4 Time of Immersion

Most hot water immersion tests have been conducted submerging the specimens for 48 hours. To determine the significance of immersion time, adhesion tests were conducted after several times of hot water immersion. A particular objective of this series of tests is to define an optimal time of immersion.

Study Variables and Test Results

Straight specimens from coaters *B* and *C* were submerged in hot water for the following periods of time: 2, 8, 24, and 48 hours. Specimens were obtained from the same two rebars from each coater as in the previous set of tests. Three samples were cut from one bar end and one sample from the opposite bar end (specimens 5, 6, 7, and 8 in Fig. 5.17). Previous test results were used for the 48-hour data and the new samples were immersed for 2, 8, and 24 hours.

The adhesion rating used in previous sections was based on the combination of results from four flaps. Since only two flaps per site were tested, the adhesion rating was modified as shown in Table 5.9 to give a rating based on the combination of results from two flaps.

Sub-rating	**Description**
A	Unable to insert blade tip under the coating
B	Blade tip can be inserted under the coating. Levering action removes small chips of coating but cannot remove the entire coating
C	Blade tip slides easily under the coating and the entire coating can be removed

Adhesion Rating	**Description**
1	Sub-rating A at 2 flaps (Good adhesion)
2	Sub-rating A at one flap and B at the other flap
3	Sub-rating B at 2 flaps
4	Sub-rating A at one flap and C at the other flap
5	Sub-rating B at one flap and C at the other flap
6	Sub-rating C 2 flaps (Poor adhesion)

Table 5.9: Modified adhesion rating system.

Since previous test results were used for the 48-hour data, their adhesion rating was re-evaluated according to the modified rating system. The sites were re-evaluated by arbitrarily considering every pair of directly opposite flaps as one test sub-site, resulting in two adhesion ratings per test location of four flaps (Fig. 5.19).

Adhesion test results for all specimens are summarized in Table 5.10 and a graph of average adhesion ratings versus time of immersion for each bar is shown in Fig. 5.20. Analysis of Fig. 5.20 indicates that there is no consistent trend in adhesion ratings with respect to time of immersion. Only bar I from coater *C* shows decreased coating adhesion with longer times of immersion. The remaining bars showed either no significant change or a slight improvement in coating adhesion with longer immersion times. In all specimens, there was little difference between adhesion ratings after 8, 24, and 48 hours of immersion. The large jump between 2 and 8 hours of immersion for bar I from coater *C* may indicate that 2 hours of immersion may not be sufficient exposure.

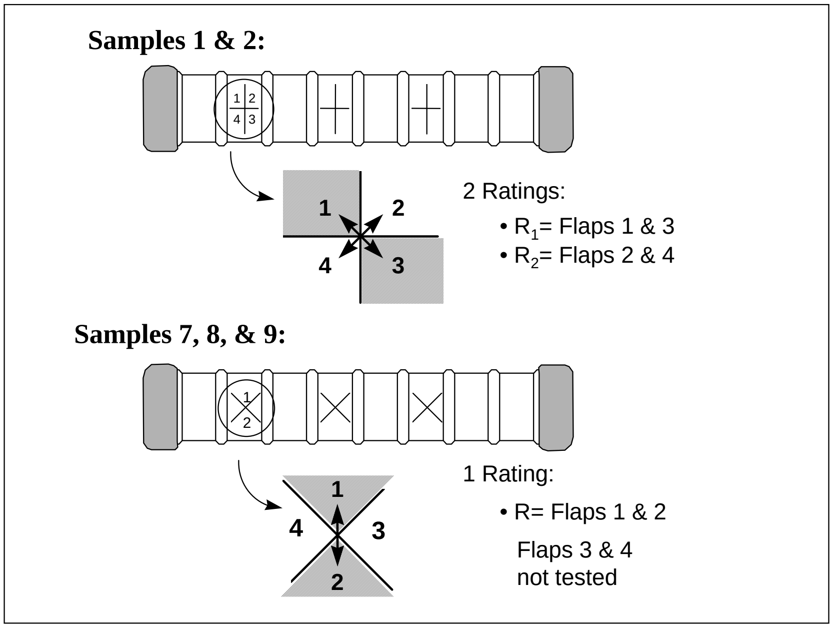


Figure 5.19: Convention for rating test sites using modified adhesion rating system from 1 to 6.

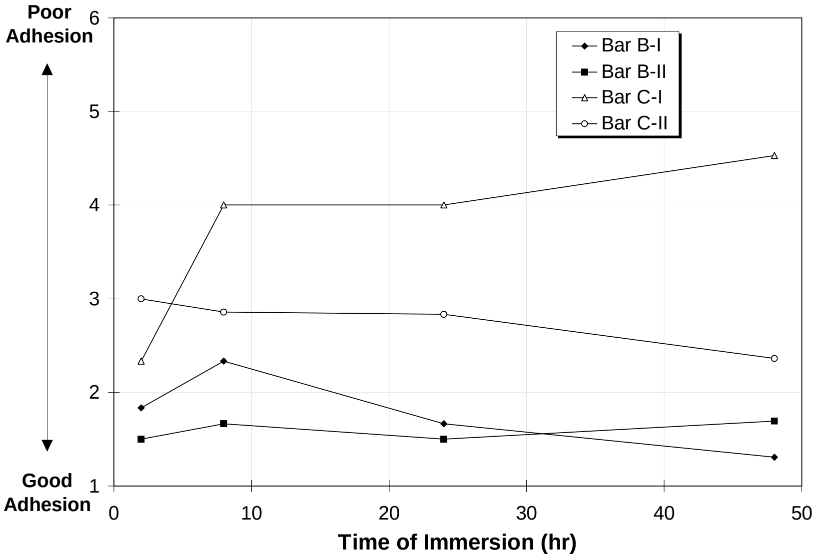


Figure 5.20: Effect of hot water immersion time in coating adhesion.

Sample	Coater B				Coater C				Time Immer
	Bar I		Bar II		Bar I		Bar II		
	Side A	Side B	Side A	Side B	Side A	Side B	Side A	Side B	
4	1 , 1 1 , 1 1 , 1	1 , 2 2 , 2 1 , 1	3 , 2 3 , 3 3 , 3	1 , 1 1 , 1 1 , 1	6 , 6 6 , 6 6 , 6	3 , 3 5 , 5 3 , 5	2 , 3 3 , 2 1 , 2	2 , 2 3 , 3 1 , 2	48 hr
Avg.	1.25		1.9		5		2.2		
5	1 1 1	2 2 3	2 2 2	1 1 1	5 5 6	2 3 3	2 3 3	3 3 3	24 hr
Avg.	1.7		1.5		4		2.8		
1	1 , 2 1 , 1 1 , 1	1 , 1 1 , 1 1 , 1	2 , 1 3 , 2 2 , 2	1 , 2 2 , 2 2 , 2	5 , 3 6 , 5 6 , 6	3 , 2 3 , 3 3 , 3	1 , 3 3 , 3 5 , 3	2 , 3 3 , 3 2 , 3	48 hr
Avg.	1.1		1.9		4		2.8		
2	2 , 3 1 , 1 2 , 1	2 , 3 1 , 1 1 , 1	1 , 1 1 , 1 2 , 2	1 , 1 2 , 1 1 , 1	5 , 5 5 , 5 6 , 6	5 , 6 3 , 3 3 , 3	3 , 3 2 , 2 3 , 3	2 , 2 1 , 1 1 , 2	48 hr
Avg.	1.6		1.25		4.6		2.1		
6	3 1 2	2 3 3	1 3 2	2 1 1	5 6 4	3 3 3			8 hr
Avg.	2.3		1.7		4				
7			2 2 2	1 1 1			2 3 3	3 3 3	2 hr
Avg.			1.5				2.8		
8	2 1 2	2 1 3			2 2 3	2 2 3	3 3 3	3 3 3	2 hr
Avg.	1.8				2.3		3		

Table 5.10: Adhesion ratings of specimens immersed at variable times.

Parameter	**Coater B**		**Coater C**	
	Bar I	**Bar II**	**Bar I**	**Bar II**
A.D.$_{\mathbf{M}}$	0.299	0.090	0.691	0.201
$\boldsymbol{\sigma}_{\mathbf{M}}$	0.370	0.091	0.826	0.241
Range$_{\mathbf{M}}$	1.03	0.19	2.19	0.64

A.D.$_M$: Average deviation of mean ratings
σ_M: Standard deviation of mean ratings

Table 5.11: Statistical analysis of mean ratings of samples -all times of immersion included.

Parameter	**Coater B**		**Coater C**	
	Bar I	**Bar II**	**Bar I**	**Bar II**
A.D.$_{\mathbf{M}}$	0.25	0.33	0.271	0.396
$\boldsymbol{\sigma}_{\mathbf{M}}$	0.312	0.417	0.32	0.491
Range$_{\mathbf{M}}$	0.83	1.167	0.83	1.33

A.D.$_M$: Average deviation of mean ratings
σ_M: Standard deviation of mean ratings

Table 5.12: Statistical analysis of mean ratings of samples tested after 48 hours of immersion.

In Table 5.11, a statistical analysis of mean adhesion ratings of samples with varying immersion times is presented (samples 1, 2, 4, 5, 6, 7, and 8 in Fig. 5.17). Table 5.12 includes a statistical analysis of mean adhesion ratings of samples tested after 48 hours of immersion (samples 1, 2, 3, and 4 in Fig. 5.17). Samples with different immersion times would be expected to have greater variability than samples with the same immersion time. A comparison of tables

5.11 and 5.12 shows that this was not always the case. There were cases where samples with the same immersion time (48 hours) had greater variability than samples from the same bar but with varying immersion times (bars “II” from both coaters).

Considering that there is little difference between adhesion ratings of specimens tested after 8 or more hours of hot water immersion, performing a hot water test with shorter immersion has the advantage of reducing the duration of the test compared with the specified MTO procedure. A 24-hour immersion period permits a convenient test schedule. Samples immersed early in the morning can be removed at the same time the next day. After an additional post-immersion period of 24 hours, samples can be tested the following day. This test variable will be re-addressed in the Third Phase after more test results are presented.

5.5.5 Evaluation of Knife Blades and Knife Force Calibration

Thus far adhesion tests have been performed with a utility knife with snap-off blades. As mentioned earlier, such blades are difficult to use because the knife has to be held in an oblique angle with respect to the direction of the path that the blade has to follow (along an imaginary line bisecting the flap of coating). For the test operator, this is an awkward and uncomfortable position. The search for a better knife design was an integral part of developing an improved adhesion test. A series of tests was conducted to evaluate several types of knife blades.

Another area of interest was to evaluate the procedure for calibrating the applied knife pressure. The subjective procedure used in the First Phase was compared with the procedure involving the modified test device. It was important to know if test results became less susceptible to human error with the use of the special device. Reducing the subjectivity of the test was of great importance for the adhesion test to become more universal and accepted.

Study Variables

A series of hot water-adhesion tests was conducted on six samples from 2 coating applicators. Specimens from each applicator came from the same batch. The two variables evaluated were the knife blades and knife force calibration procedures.

Description of knife blades

a) *Utility knife with snap-off blades*: A typical knife, shown in Fig. 5.21, consists of connected mini-blades. As a blade tip becomes blunt, a new sharp blade is available by breaking off the blade tip. The knife is economical and widely available.

b) *X-acto knife with # 11 blade*: X-acto knifes are widely used by architects and artists. They have the advantage that a wide variety of blades can be mounted. Blade # 11 is pointed with a triangular shape and has one sharp edge. A typical X-acto knife and a # 11 blade are shown in Fig. 5.21.

c) *X-acto knife with #17 blade*: A chisel blade with long rectangular shape. The blade is flat and has a sharp edge, as illustrated in Fig. 5.21.

d) *X-acto knife with #23 blade*: A pointed blade with a spade shape and two sharp edges, as shown in Fig. 5.21.

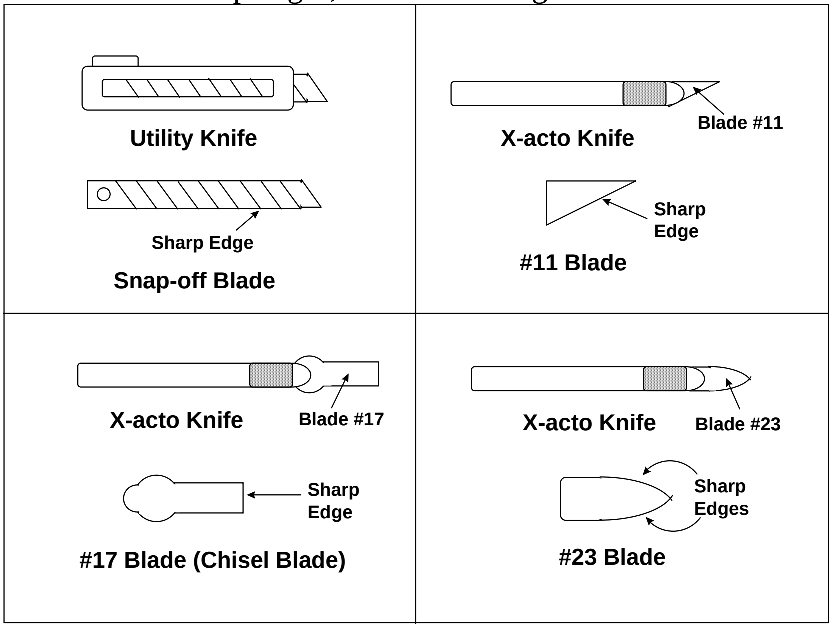


Figure 5.21: Types of knife blades used for adhesion study.

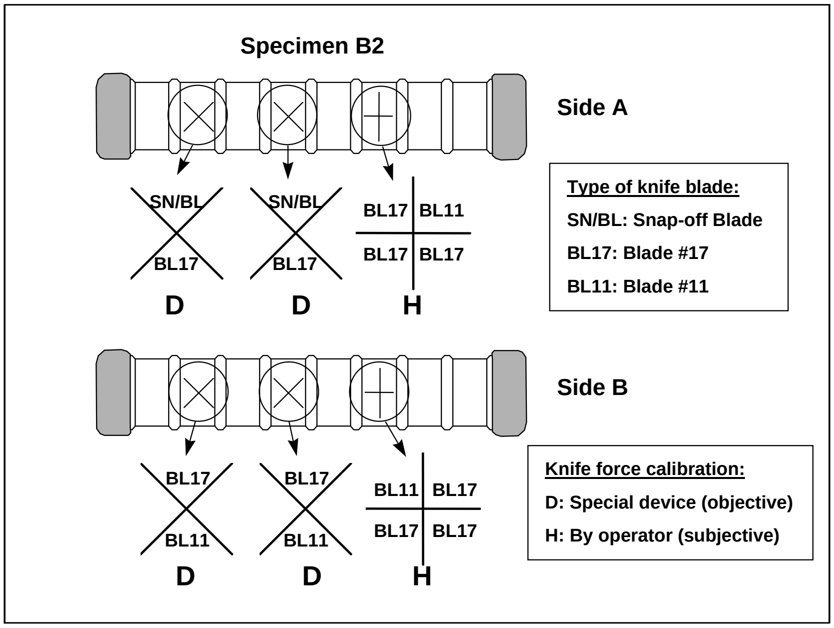


Figure 5.22: Typical specimen for adhesion test using several types of knife blades and force calibration procedures.

At most test sites, two types of blades were used (one blade type per flap), as illustrated in Fig. 5.22 to facilitate comparisons.

Procedures for knife force calibration

a) *Procedure H*: The operator calibrated the applied force by pushing the knife against a digital scale and then emulated that force for the test. The procedure was used before the introduction of the special device.

b) Procedure D: The procedure was used in the previous set of tests. The specimen was mounted on the improved special device and when the knife was pushed against the specimen, an acrylic strip was deflected to a predetermined amount.

The two procedures were used on each of the 6 specimens. On each specimen, four sites were tested following procedure *D* and two sites with procedure *H* (Figure 5.22). As shown in the sketch, the X cuts tested with procedure *D* were oriented differently than the X cuts tested with procedure *H*. As has been explained before, the orientation of X cuts shown for procedure *D* makes the test easier to perform because the knife moves more parallel to the deflection of the acrylic trip. The drawback is that only two flaps per site are tested. Procedure *H* is not affected by the X orientation and the four flaps can be tested. The reason the X cuts for procedure *H* were oriented differently was to facilitate their identification.

Test Results and Discussion

Knife Blades

Table 5.13 contains adhesion sub-ratings for individual coating flaps tested with several types of blades. The description of each sub-rating is included for reference. The #17 blade mounted on an X-acto knife seemed to produce more *B* and *C* sub-ratings than other blades on samples tested with calibration procedure *H*. It should be emphasized that variability of ratings produced by different blades was not greater than the variability observed when only one type of blade was used. No particular blade seemed to give consistently higher or lower ratings.

Evaluation of blades was based on ease of use and cost. The worst blade for adhesion testing was the #17 blade mounted on an X-acto knife. The chisel blade does not have a pointed tip, making it difficult to insert the blade under the coating and, consequently, has a propensity to tear or cut through the coating. The blade was very difficult to use and was expensive.

The #11 blade mounted on an X-acto knife was very long and was not stiff enough to adequately control the knife force. Besides, it only had one sharp edge and the triangular shape was not symmetrical. With such geometry, the knife has to be aligned at an angle with respect to the path that the blade has to follow under the coating (an imaginary line bisecting the flap of coating). The operator has to perform the test holding the knife in an awkward and uncomfortable position. The blade was also expensive.

Sample	Procedure *H*				Procedure *D*			
	SN/BL	**BL11**	**BL17**	**BL23**	**SN/BL**	**BL11**	**BL17**	**BL23**
B1					A A	A A		
B2		A A	B B B B B B		A A	B B	A B A B	
B3	A B			A A A A A B	A A			A A
C1	A A	A A			A A	A A		
C2	A B		B B		B C B C		B C C C	
C3	A A			A B	A B A			B B B

SN/BL: Snap-off blade BL17: Blade #17
BL11: Blade #11 Bl23: Blade #23

Sub-rating	Description
A	Unable to insert blade tip under the coating
B	Blade tip can be inserted under the coating. Levering action removes small chips of coating but cannot remove the entire coating
C	Blade tip slides easily under the coating and the entire coating can be removed

Table 5.13: Adhesion sub-ratings for individual flaps tested with different blades.

The plastic utility knife with snap-off blades, like blade #11, has to be positioned at an awkward angle with respect to the direction the blade has to follow. Its main advantage is that new sharp blades are readily available and it is economical.

The #23 blade on an X-acto knife was found very suitable for adhesion testing. Its symmetrical design with two curved, sharp edges makes it possible to position the knife parallel to the path that the blade has to follow. The blade is very stiff and robust, making it easy to control and maintain the knife force. The main drawback is that the blade is very expensive.

All tests in the first phase were conducted with the plastic utility knife with snap-off blades. Most of the tests in the second phase were performed with an X-acto knife with a #23 blade. The plastic knife with snap-off blades was found very suitable for making the X cuts through the coating and was used for that purpose in the second and third phases. The X-acto knife with blade #23 was the basis for a new test knife developed and used for adhesion tests in the third phase.

Procedure for Calibration of Knife Force

Figures 5.23, 5.24, and 5.25 show average adhesion ratings of specimens tested using procedures *H* and *D* for calibrating the knife force. For specimens from coating applicator *B*, there is little difference in adhesion ratings between procedure *H* and *D*. For specimens from coating applicator *C*, much higher ratings were obtained with procedure *D* on two specimens (especially on specimen C2). However, despite some large differences in some specimens, the difference in overall average adhesion ratings produced by procedures *D* and *H* is not significant (2.125 and 1.75 respectively). In fact, if specimen C2 is omitted, the overall average of adhesion ratings would be 1.55 for both procedures.

There was more dispersion of adhesion ratings when samples were tested following calibration procedure *D*, as evidenced by the higher standard deviation (Table 5.14). If specimen C2 is omitted, there is less difference in standard deviation: 0.67 for *H* versus 0.76 for *D*. The higher variability of results obtained with procedure *D* may reflect adhesion characteristics better than procedure *H*. It may be possible that with procedure *D*, areas of poor coating adhesion are more easily detected, resulting in a greater variability of adhesion ratings compared to procedure *H*. Therefore, bars with poor quality could be more readily identified by procedure *D*.

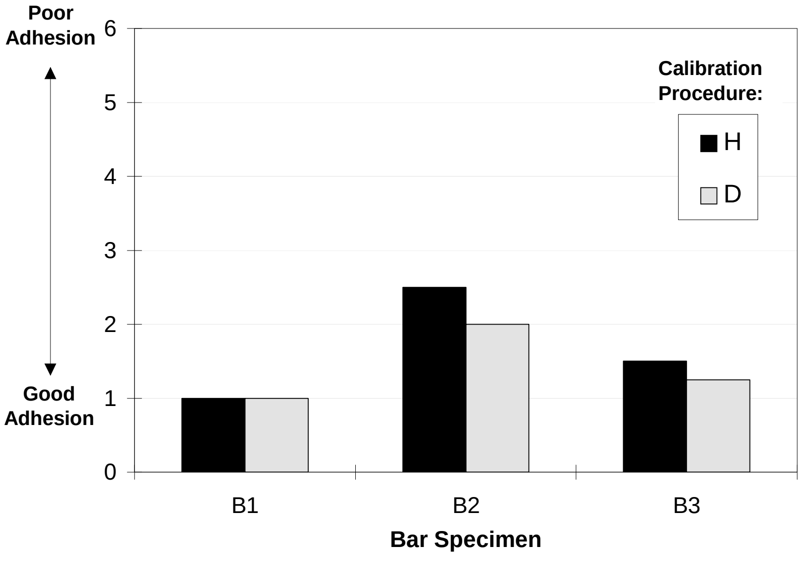


Figure 5.23: Effect of procedures to calibrate knife force on adhesion test results (samples from coater *B*).

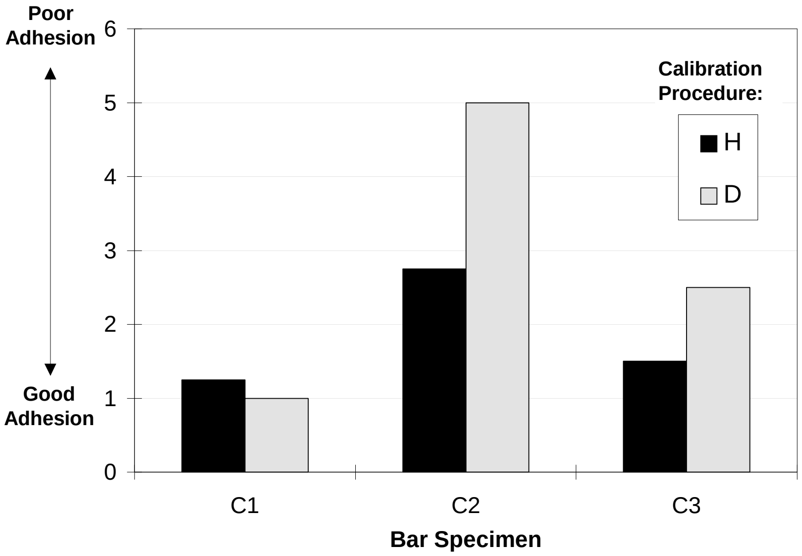


Figure 5.24: Effect of procedures to calibrate knife force on adhesion test results (samples from coater *C*).

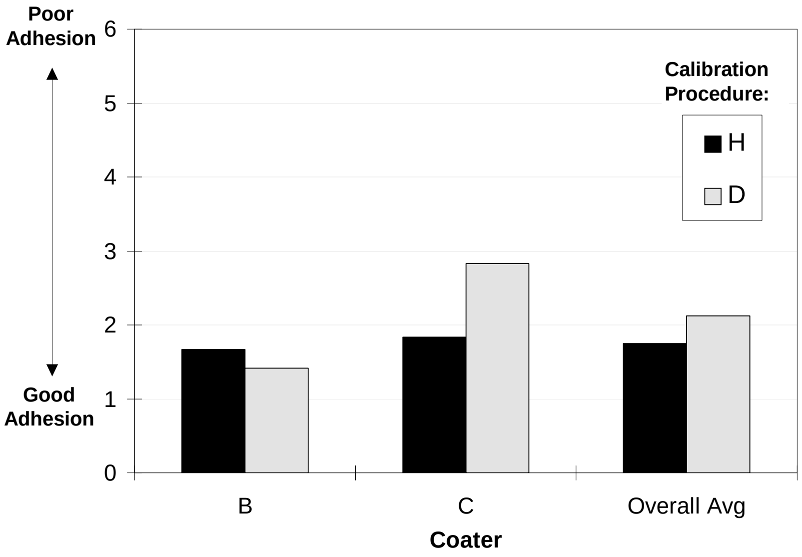


Figure 5.25: Effect of procedures to calibrate knife force on adhesion test results (all samples).

Coater	**Procedure H**	**Procedure D**
B	0.78	0.67
C	0.83	1.90
Overall	0.79	1.57

Table 5.14: Standard deviation of adhesion ratings on samples tested by calibrating the knife force with procedures *H* and *D*.

There have been many questions and doubts regarding the validity of adhesion tests, mainly because of the subjectivity involved in the test procedure. One subjective factor that has been widely pointed out is that the amount of pressure applied with the knife is judged by the operator, thus introducing human error. Despite the subjectivity involved in procedure *H* versus the more objective procedure *D*, the overall mean adhesion ratings were similar. Although the number of tests is small, the results seem to indicate that coating adhesion testing can be useful and meaningful if some subjectivity is involved. With practice, a test operator should be able to calibrate the force and produce reliable test results.

5.5.6 Effect of Test Operator

An important concern refers to the variability of results obtained by different test operators. If different operators produce widely different results, adhesion testing would be unreliable. An acceptable test should yield similar results regardless of the operator, especially if adhesion testing is to become a standard procedure in epoxy-coated bar specifications.

Study Variables

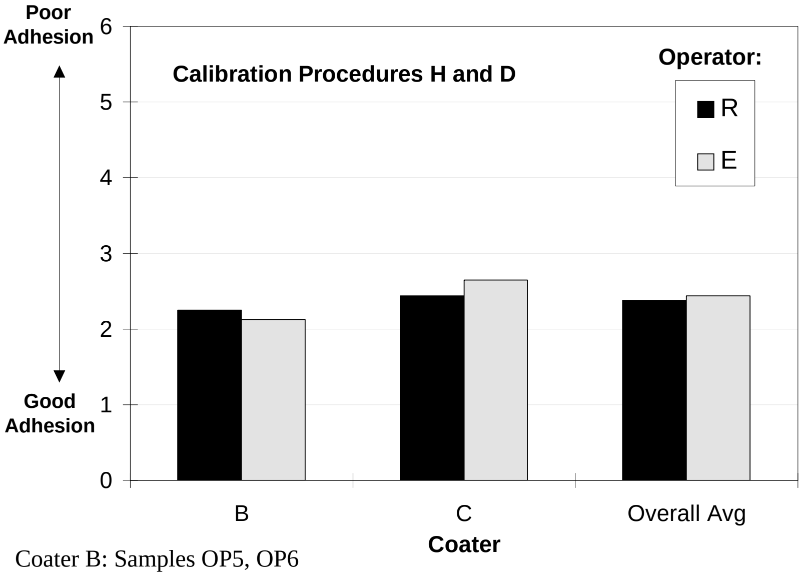
A set of hot water and adhesion tests was conducted on 6 epoxy-coated bar specimens from two coating applicators. Specimens from each coater were cut from the same rebar. Two operators performed adhesion tests on all specimens and each operator followed calibration procedures *H* and *D* to measure and control the amount of force applied with the knife. Adhesion test results were evaluated by each operator using the modified rating system from 1 to 6. It was of interest to verify that the system provides consistent ratings regardless of the person making the evaluation.

Test Results and Discussion

A summary of mean adhesion ratings produced by each operator for each sample is listed in Table 5.15. Mean ratings for both operators were very similar for all samples, with a highest difference of 0.58. In four out of six cases, mean adhesion ratings for operator *E* were higher (lower adhesion) than for operator *R*. As shown in Fig. 5.26, the overall difference in mean adhesion ratings between the two operators was only 0.06.

Specimen	Operator R	Operator E	Difference (E-R)
OP1	2	2.5	+0.5
OP2	3	2.5	-0.5
OP3	2	2.25	+0.25
OP4	2.75	3.33	+0.58
OP5	1.75	1.25	-0.5
OP6	2.75	3	+0.25

Table 5.15: Mean adhesion ratings for operators R and E.



Coater B: Samples OP5, OP6
Coater C: Samples OP1 through OP4

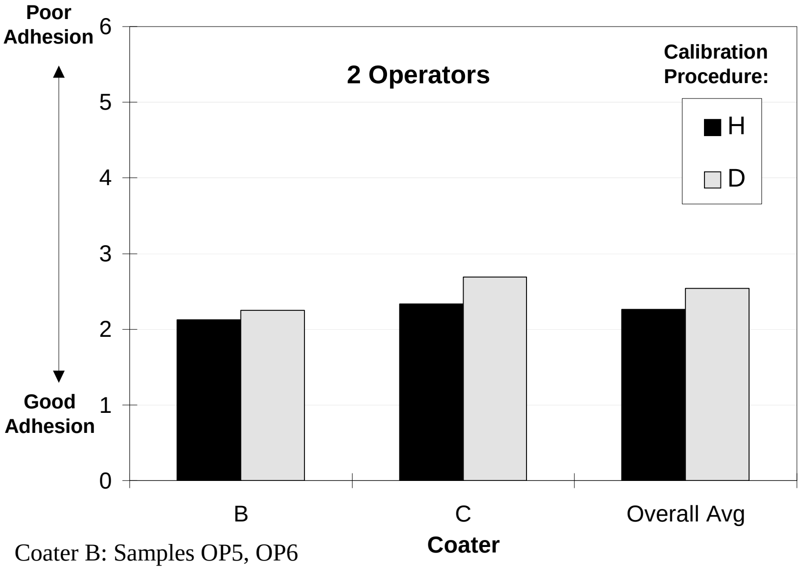
Figure 5.26: Overall mean adhesion ratings for test operators R and E.

Interestingly, operator *R* seemed to produce more consistent ratings than operator *E*. The overall standard deviation of ratings from operator *R* was 0.71 versus 0.90 of operator *E*. Specimen OP4 accounts for most of the difference. If specimen OP4 is not considered, standard deviation of adhesion ratings for both operators would be identical (0.73).

Adhesion test results performed by two operators are classified in Table 5.16 according to procedure for calibrating amount of knife force. The maximum difference in mean adhesion ratings on any specimen was 0.5. If all individual readings on all specimens are considered, the difference in mean adhesion ratings between the two calibration procedures is reduced to 0.28 (Fig. 5.27). Overall, there was no marked improvement in the variability of adhesion ratings by performing adhesion test using the special device to control the amount of knife force (procedure *D*). If test results are analyzed separately by operator, the variability of adhesion ratings by operator *R* was reduced by performing the test with the special device (procedure *D*). However, operator *E* experienced slightly higher variability of adhesion ratings by performing the test following calibrating procedure *D* (Table 5.17).

Specimen	Procedure H	Procedure D	Difference (H-D)
OP1	2	2.5	-0.5
OP2	2.75	2.75	0
OP3	2.25	2	+0.25
OP4	2.33	2.5	-0.167
OP5	1.25	1.75	-0.50
OP6	3	2.75	+0.25

Table 5.16: Mean adhesion ratings of calibration procedures *H* and *D* (tests performed by two operators).



Coater B: Samples OP5, OP6
Coater C: Samples OP1 through OP4

Figure 5.27: Overall mean adhesion ratings of calibration procedures *H* and *D* (tests performed by two operators).

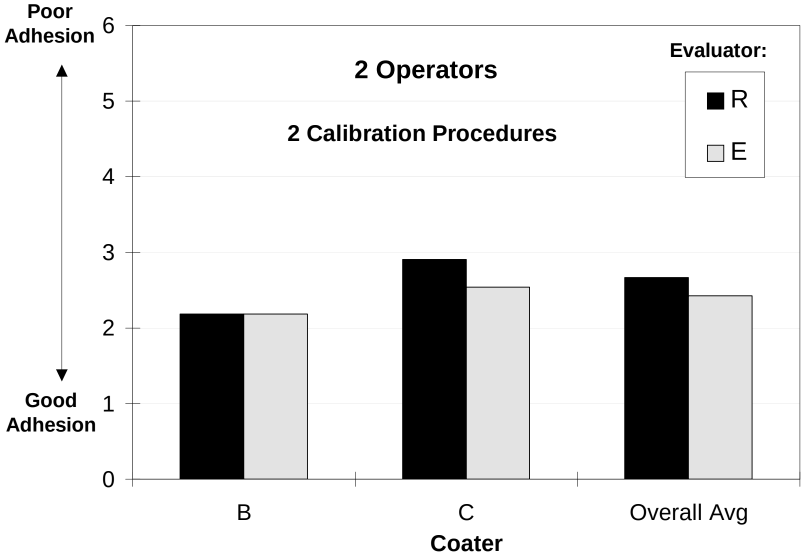
Parameter	Operator R		Operator E	
	Proced. H	**Proced. D**	**Proced. H**	**Proced. D**
Average	2.25	2.5	2.27	2.36
Avg. Dev.	0.73	0.43	0.66	0.69
Std. Dev.	0.83	0.50	0.75	0.95

Table 5.17: Statistical parameters of adhesion tests performed by two operators following two calibrating procedures to control knife force.

Average adhesion of specimens rated by two evaluators is listed in Table 5.18. Such specimens were tested by two operators following two procedures to calibrate knife force. The maximum difference in average adhesion ratings was 0.625. Evaluator *R* tended to give higher ratings (lower adhesion) than evaluator *E*. Evaluator *R* gave higher adhesion ratings on 4 out of 6 specimens. If all individual readings are considered, evaluator *R* gave an overall mean adhesion rating of 2.67 and evaluator *E* of 2.42 (Fig. 5.28). Variability of the adhesion ratings given by the two evaluators was very similar. Both evaluators had the same range, mode, and average deviation of adhesion ratings, and the standard deviations were similar (Table 5.19).

Specimen	**Evaluator R**	**Evaluator E**	**Difference (E-R)**
OP1	2.875	2.25	-0.625
OP2	2.875	2.75	-0.125
OP3	2.875	2.125	-0.75
OP4	3	3	0
OP5	1.875	1.5	-0.375
OP6	2.5	2.875	+0.375

Table 5.18: Average adhesion of specimens rated by two evaluators.



Coater B: Samples OP5, OP6
Coater C: Samples OP1 through OP4

Figure 5.28: Overall mean coating adhesion of specimens rated by two evaluators (specimens tested by two operators following two calibrating procedures to control knife force).

Parameter	**Evaluator R**	**Evaluator E**
Avg. Dev.	0.67	0.67
Std. Dev.	0.86	0.79
Range	4	4
Mode	3	3

Table 5.19: Statistical analysis of coating adhesion of samples rated by two evaluators.

Coating adhesion testing was not largely affected by test operator nor by calibrating procedure to estimate and control knife force. The adhesion rating system seemed to give consistent results regardless of coating adhesion evaluator.

5.5.7 Conclusions from Second Phase

Important findings in the second phase of the study are categorized and summarized below:

Regarding repeatability of adhesion test:

- There was small variation of average coating adhesion of specimens cut at different locations from the same rebar.
- Small specimens were representative of a long rebar.
- Small specimens were representative of a rebar lot if obtained from different bars in that lot.
- Bars with lower adhesion rates (better coating adhesion) tended to show less variability in adhesion values.

Regarding time of hot water immersion:

- There was no clear correlation between time of hot water immersion and adhesion rating.
- In some cases, specimens from a given lot tested with varying immersion times experienced less variability of ratings than specimens from the same lot subjected to the same time of immersion. In other words, variability of adhesion in a given lot is greater than the variability from varying time of immersion.
- Twenty-four hours of hot water immersion was adequate for practical considerations.

Regarding knife blades and calibrating procedure for determining knife force:

- Type of knife and blade did not affect adhesion test results.
- Knife and blade selection was based on ease of use and cost.
- Calibration procedures *H* (knife force subjectively determined) and *D* (knife force objectively determined with special device) yielded similar adhesion ratings and data dispersion.
- Calibration procedure *D* tended to produce a higher variability of ratings. This may indicate that bars with poor quality could be more easily identified with procedure *D*.
- Coating adhesion testing gave meaningful results even though subjective processes (procedure *H*) were used.

Regarding test operator and evaluator:

- Adhesion testing was not greatly affected by test operators.
    - Average adhesion ratings by two operators were similar.

    - Standard deviation of adhesion ratings by each operator was nearly the same.
- Adhesion ratings were not greatly affected by test evaluators
- Adhesion test results were not largely affected by procedure to calibrate knife force when two operators were involved

5.6 THIRD PHASE: REFINEMENT OF COATING ADHESION TEST

Tests from Phases One and Two showed that despite some subjective factors being involved, hot water and adhesion tests can be useful in assessing the overall quality of coating adhesion. Further development of the tests was warranted and was the major thrust for the third phase of the study. The main objective was to improve the reliability and practicality of the tests. Particular objectives included the following:

- To study the effect of additional test variables in hot water immersion (Water temperature, immersion times, post-immersion periods, test operator).
- To analyze the significance of some procedural modifications, such as pre-drilling a hole in the coating before immersion, making cuts in the coating that intersect at variable angles, making rectangular strip cuts in the epoxy coating (instead of X's) for adhesion testing, and performing adhesion tests with and without hot water immersion.
- To develop and test a self-calibrated knife that allows the operator to measure and control the amount of force applied.

- To improve the actual technique for peeling epoxy coating with calibrated knife.
- To continue developing a practical rating system for adhesion evaluation.
- To correlate several versions of adhesion tests developed.
- To correlate developed adhesion tests with existent TxDOT standard methods to evaluate coating adhesion (Bend test, peel test).

5.6.1 Bar Procurement for Adhesion Tests

Epoxy coated bars used for study phases 1 and 2 were obtained primarily from three coating applicators. For the third phase, epoxy-coated bars were requested from five coating applicators in order to have a wider spectrum of coating qualities. Each coater was identified with the following letters: *U, V, W, Y,* and *Z.* The requested bars from each coater included the following:

- One six feet long piece of deformed steel bar for each size: #4, #6, and #9
- One six feet long piece of plain steel bar for each size: #4, #6, and #9.
- Four bent bars from each of the original rebars where the above pieces were cut. Bars were bent according to TX DOT specification Tex 739-I.

In addition, bars with rigid, non-flexible coatings were requested when available. Details of supplied bars are listed in Reference 49.

Several quality control tests were performed to determine their compliance with ASTM and TxDOT standards. Such tests included visual examination of bent samples, coating thickness measurement, and holiday detection. Bars were divided in one-foot-long segments to record measurements from the above tests. The procedure followed for each of the above tests is described in more detail in Reference 49. Unlike bars for study phases 1 and 2, all visible coating damage and imperfections were patched. Although test results in Phase 1 were not greatly effected by the presence of coating damage, all bars were repaired so they had approximately the same initial coating condition. Holidays invisible to the unaided eye were not patched but the number of holidays occurring at various intervals along the bar was recorded.

Bend Test Observations

Of all bars tested, only the coating by applicator *Y* failed the bend test. All four bent segments from bar Y-2 showed some cracking and damage to the coating. Only one bent specimen from bar Y-5 passed the test and the remaining three showed the same type of coating flaws as bar Y-2.

As mentioned before, failure to pass the bend test may indicate either a) epoxy coating was too rigid or not flexible enough to pass the test, or b) epoxy coating had poor adhesion to the steel substrate. Most standards interpret reason (b) as the main factor for not passing the bend test. Correlation with adhesion tests in subsequent sections helped to clarify the validity of the bend test for determining coating adhesion.

Coating Thickness Measurement

The average coating thickness for each of the bars is shown in Fig. 5.29. Each data point represents the average of 24 thickness measurements taken at regular intervals along the bar.[49] According to TxDOT Standard Specification Item 440, thickness values must range between 7 to 12 mils.[123] TxDOT limiting values are plotted in the graph for comparison. Average thickness values ranged between 8.92 and 17.13 mils, with an average of 12.11 mils. Individual coating thicknesses ranged from 6.5 to 20 mils, with an overall average of 11.77 mils. These averages were at the upper limiting value allowed by specifications, which suggests that a large number of thickness measurements were above the maximum limit. Only a very few individual measurements were below the lower limit of 7 mils. All bars from coater W and bars V-3 and V-28 had average coating thicknesses higher than the upper limit allowed by the specifications.

Both ASTM and TxDOT standards also require that 90% of the coating thickness values fall within the range of 7 to 12 mils.[63, 123] Only two bars met this requirement: U-6 and Z-3, with 100% and 92%, respectively, of thickness measurements falling between 7 and 12 mils. Bars Z-1 and Y-5 almost met this requirement, with 88% of readings between 7 and 12 mils. All individual measurements from bars W-1, W-3, and W-17 were higher than 12 mills. If bars from all coaters are considered, 62% of the coating thickness measurements fell within the range of 7 and 12 mils.

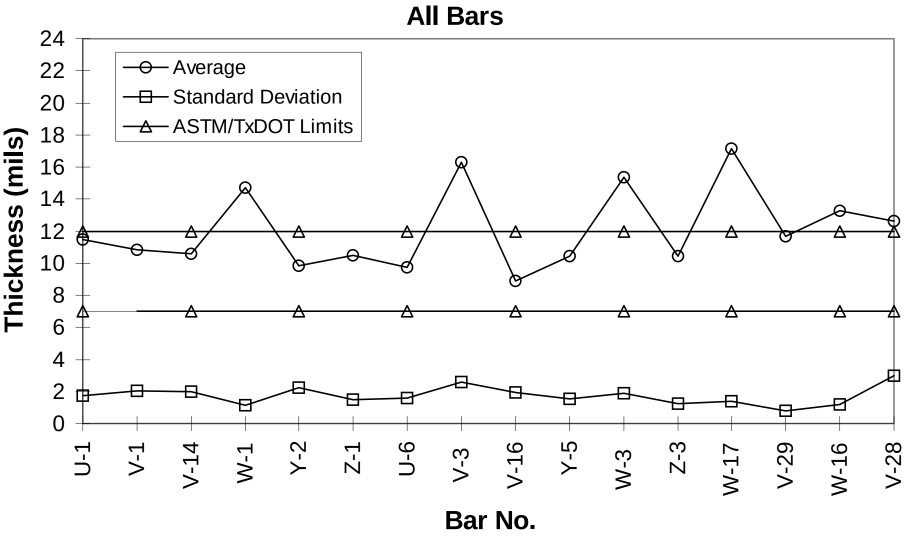


Figure 5.29: Average coating thickness of all bars from 5 coating applicators.

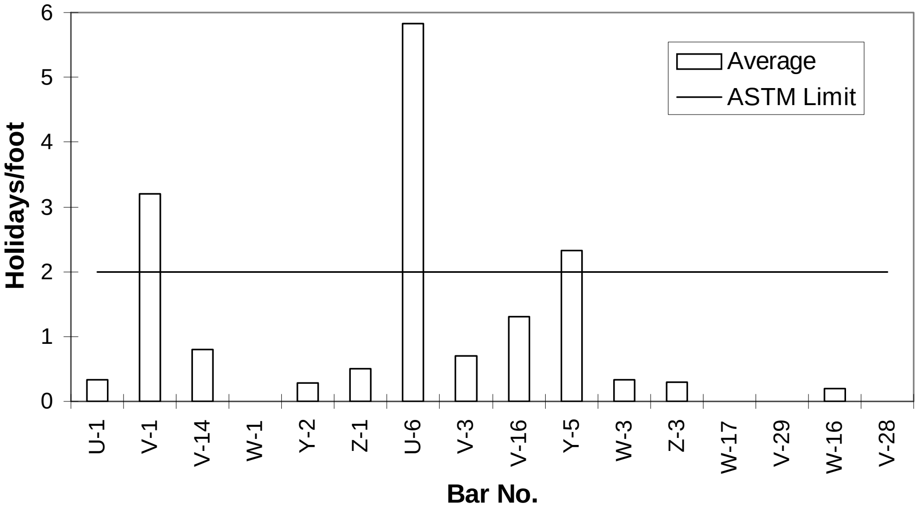


Figure 5.30: Average holiday count for all bars.

Holiday Detection

Figure 5.30 illustrates the average number of holidays detected per linear foot of rebar. The ASTM limit is plotted for comparison. The average number of holidays for all bars ranged from 0 to 5.8 per linear foot. Only three bars did not meet the ASTM standard: V-1, U-6, and Y-5. Bar V-1 had more than 3 holidays per foot and bars U-6 and Y-5 had extensive coating damage in areas close to mill marks. Such damage is not considered as part of the holiday count by ASTM specifications, which specify that such regions must be appropriately repaired.

5.6.2 Development of Calibrated Knife

The special device for calibrating and controlling the amount of force applied with the knife had several disadvantages. For TxDOT, adhesion tests could only be performed at the laboratory because it would be impractical to carry the device to coating plants. Another disadvantage is that the rigid assembly holding the bar specimen was built to fit certain bar sizes. To test a wider variety of bar sizes, several rigid assembly holders would have to be manufactured. Even though the device was improved so that calibration was needed only once per test session, the testing process is still time-consuming. Each specimen has to be positioned on the device four times to complete testing at all sites: 1) Specimen is positioned to test on one side, 2) Specimen is flipped horizontally and positioned to test in the opposite direction, 3) specimen is rotated about its axis and positioned to test the other side, and 4) specimen is flipped horizontally and positioned to test in the opposite direction. Clearly, this is very cumbersome and tedious, especially if many samples are tested.

Another disadvantage is that the test becomes more difficult to control as it progresses. As the knife advances around the bar perimeter, the horizontal component of the force decreases and the vertical component increases. This sometimes caused the whole assembly to slip and the operator had to re-adjust the knife force to continue the test. In a few cases, the blade slipped out or cut through the coating.

Finally, test results from second phase of the study showed that there was no remarkable difference in adhesion tests performed with and without the special device. If a better and more practical device cannot be developed, it may be easier and more practical to perform adhesion tests without the device.

With the above considerations in mind, it was desirable to design a better device to measure and control the force applied with the knife. The principle involved in the two previously used devices consisted of estimating the knife force externally. The deflecting acrylic strip can be considered an external “spring” element that reacts as the bar is pushed against it. Such an external “spring” has a constant stiffness and the amount of force is controlled by how much the spring deforms, that is, how much the acrylic strip deflects.

If an internal, real spring is implemented inside the testing knife, many of the difficulties associated with the external spring concept can be eliminated. A self-calibrating knife was developed using this principle. An aluminum shaft was machined to exactly encase an X-acto knife and a compression spring (Fig. 5.31). To avoid problems of lateral deflection of the spring, the inside diameter at the bottom of the shaft was machined to exactly encase the spring, whose diameter is much smaller then the diameter of the knife. The bottom portion of the X-acto knife was also machined to fit inside the narrow shaft area encasing the spring (Fig. 5.31). During the test, the base of the X-acto knife pushes and compresses the spring. Since the stiffness of the spring is known, the magnitude of the force is determined by measuring the spring compression. The knife surface was tapped to drive a screw and a slot was machined on the shaft surface around the screw area (Fig. 5.31). A screw is inserted through the slot into the knife. The screw served two purposes: 1) To keep the knife from sliding off the shaft, and 2) to hold a small indicator that measures the spring deformation.

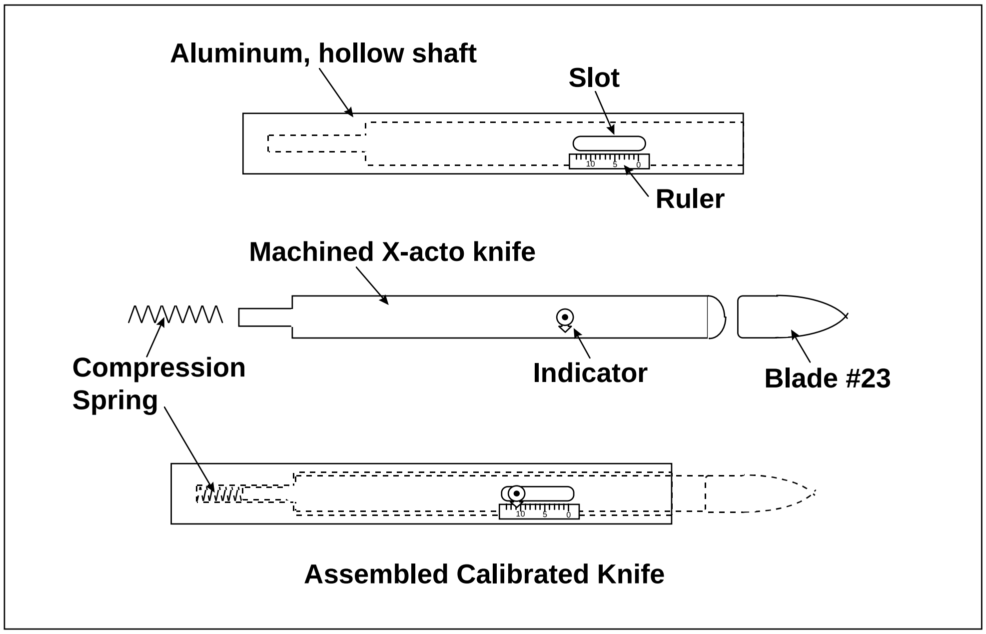


Figure 5.31: Calibrated Knife.

The indicator was secured to the screw above the shaft surface. A millimeter scale was pasted next to the slot (Fig. 5.31). When the knife is at the initial position (uncompressed spring), the indicator is zeroed. The target force is reached when the spring is compressed to a pre-determined amount.

The are several advantages associated with the calibrated test knife. It is a very simple device, easy to carry, and can be used anywhere (at the coating plant, in the field, at the laboratory). A wide variety of blade types can be fixed to the sliding X-acto knife. Replacement of blades is easy because the screw restrains the knife from rotating about its axis. The blade holder can be loosened or tightened by turning it in the appropriate direction while the rest of the knife remains gripped. The test knife is very easy to use and can be used on any rebar size. A major advantage is that the operator is much better able to control the amount of required force. Moreover, the magnitude of the force is no longer influenced by the angle of the knife.

It was not possible to incorporate a practical means to maintain a constant tangential angle in the calibrated knife. Although the knife angle does not effect the magnitude of the force applied, such angle determines the direction of the knife force. The two hypothetical extremes would be 1) 90° in which case all the force is transferred to the steel, and 2) 0° in which case all the force tends to penetrate the coating layer. An angle of approximately 30° seems adequate in directing most of the force to cut through the coating-steel interface. It is difficult to implement a practical method to control such angle because it must be measured with respect to the tangent of the bar at the point of contact with the blade tip. The knife angle with respect to an horizontal plane must be changed as the knife moves around the bar perimeter to maintain a constant angle with respect to the moving tangent (Fig. 5.32).

An X-acto No. 23 blade (determined previously to be the best choice) was mounted to the test knife and used for adhesion tests. The blade was replaced daily or when its tip became blunt.

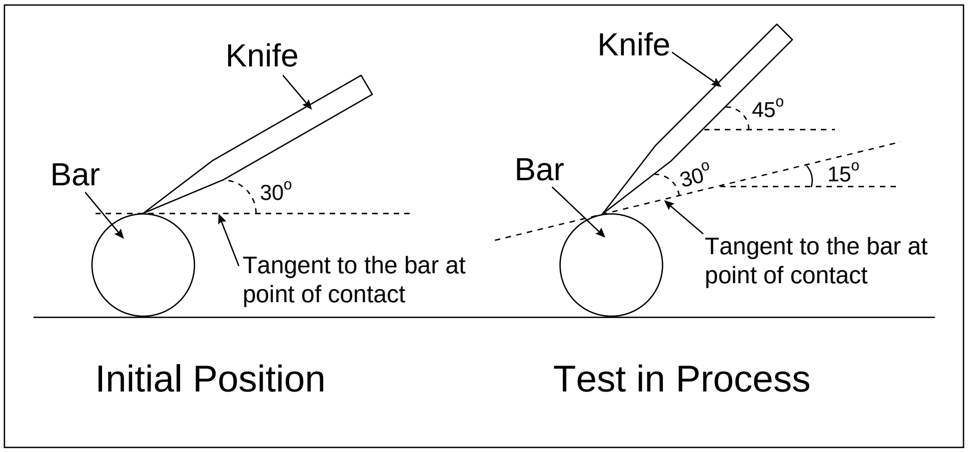


Figure 5.32: Angle of knife during adhesion testing.

5.6.3 Hot Water Test

Preliminary tests

A series of preliminary tests were performed in order to refine the test parameters to be used in the third phase of the study. Several of the variables were already addressed in the previous two phases of the study. It was recognized then that more tests were needed to validate some of the findings. Some of those variables were not as carefully controlled as they were in the preliminary tests of this phase. In addition, other new variables were studied and some procedural modifications in the test were introduced. A new adhesion rating system was devised for evaluating test results.

Samples were obtained from one #8 and one #9 epoxy-coated bars. Both bars were obtained from coating applicator *C*. Companion samples 5 inches long were cut from both bars to make a total of 16 samples from each bar. A total of 656 adhesion tests were performed, each test defined as the application of knife force to one of the flaps between two deformations.

Procedural Modifications

Each of the test locations consisted of 2 cuts in the coating that intersect a 45° angle to form an X. In all previous tests, the cuts forming the X intersected at a 90°. The angle was changed to make the test easier to perform. A more acute angle allows an easier insertion of the blade tip under the coating flap. Test results may also be simpler to interpret in flaps with an acute angle. It was observed that for several bar sizes and different deformation patterns, two diagonal cuts that extend from the top of one rib to the bottom of the next rib generally intersected at an angle of about 45° (Fig. 5.33). The main drawback is that only two flaps, instead of four, can be tested at each X location. As before, X-cuts were made with the plastic utility knife with sharp snap-off blades.

A second modification consisted of sealing the end of each specimen with a two part epoxy resin instead of silicone. This resin was much sturdier and more watertight than silicone and prevented water migration under the coating and corrosion of the exposed steel at the ends.

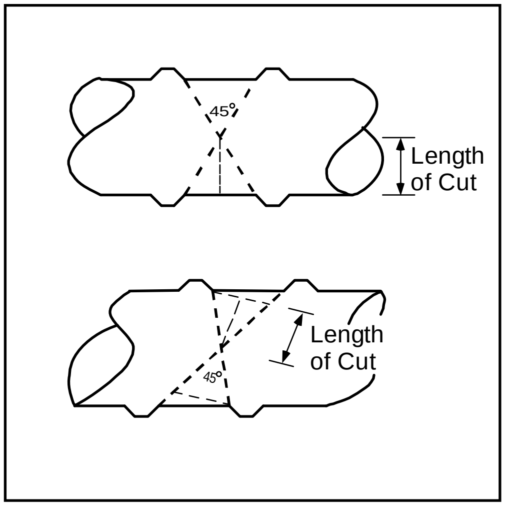


Figure 5.33: Length of cut for bamboo and diagonal deformation patterns.

Adhesion Index	Description
1	Difficult to insert blade under coating. Less than 5% of the length is removed.
2	Easier to insert blade under coating. 5% - 25% of length is removed.
3	25% - 50% of length is removed
4	50% - 75% of length is removed
5	More than 75 % of length is removed

Table 5.20: Adhesion rating system for preliminary tests of third phase.

The rating system adopted to evaluate coating adhesion was a function of the length of the line that bisects the triangular flap that is formed between the diagonal cuts (Fig. 5.33). A rating is assigned according to the average length of coating that is removed along the path of the bisecting line (Table 5.20). Measurement of areas of removed coating was not used as a rating criterion because it is easier to measure the length of the section of coating removed. An individual index is given to each flap (before, an individual index was given to each test location) and all indexes are averaged to yield a specimen adhesion rating. The previous two rating systems used in phases 1 and 2 did not involve any measurement of removed coating.

Study Variables

The following variables were used for the preliminary tests of third phase:

- *Water temperature:* 55°C and 75°C. Previous tests from first and second phases were performed at a temperature of 73°C. However, some researchers have used temperatures as low as 55°C when samples were immersed in aggressive media.[107] The objective was find an optimum combination of temperature-immersion time.
- *Time of immersion:* 0, 3, 6, 24, and 48 hours. Tests from second phase were performed with times of immersion of 2, 8, 24, and 48 hours. The most significant difference is that samples with no water immersion were included.

- *Post-immersion times:* 0, 3, 6, 24, and 48 hours. Some samples from first phase were tested after post-immersion times of 24, 40, 72, 90, 120 hours, and 2 months. However, these samples were not carefully controlled test variables.
- *Presence of initial damage:* A 1/8-in. hole was drilled through the epoxy coating into the bar to create an intentionally damaged area. The idea of drilling a hole was to create a more carefully controlled damaged area with the same size, shape, and location in all specimens. Samples from the first phase had damaged areas in the coating of different sizes and shapes and were randomly located. Such damage was present in the as-received bars and was produced during handling and transportation of the bars. Unlike samples from the first phase, adhesion tests were performed at the pre-drilled hole. Previous tests were not always performed at the location of the damaged areas.
- *Knife force:* 3 kg and 4 kg. The higher force was based on the maximum spring compression. The lower force was used to conform to specifications used in previous tests. Tests from the first and second phases used approximate knife forces of 3 and 3.5 kg.

Each side of the samples was tested at four locations using two knife forces and surface conditions (presence or absence of pre-drilled hole), as seen in Figure 5.34.

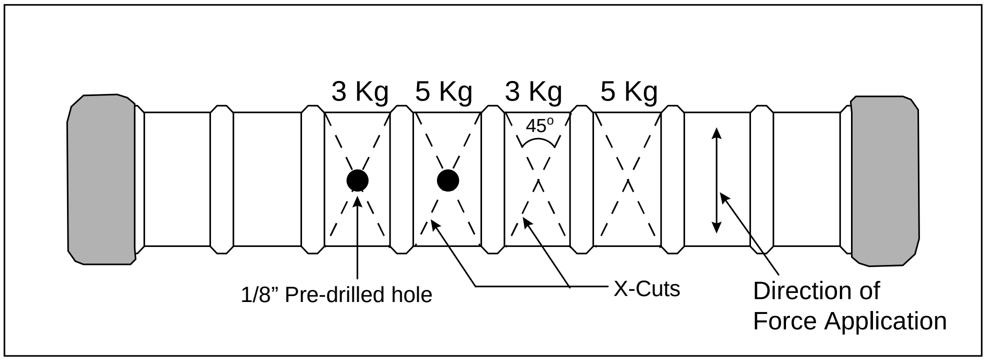


Figure 5.34: Test locations on 5-inch-long epoxy-coated bar specimens for preliminary adhesion tests.

Test Results

Time of immersion.

As the time of immersion increased, coating adhesion tended to decrease (adhesion ratings increased) regardless of the temperature of the hot water bath (Figures 5.35 and 5.36). These findings contrast with those of phase 2, where no consistent trend was found for most samples. Tests in phase 2 may be less reliable because the procedure used to test samples after 48 hours of immersion was not exactly the same as that for samples tested after other times of immersion (there were differences in the type of calibration device, orientation of X-cut, and number of tests per site). However, other factors might effect the difference of findings between phases 1 and 2, such as differences in the coating process, coating type, coating porosity, and adhesion test procedure (special device vs. calibrated knife, 90° vs. 45° angle of X-cuts).

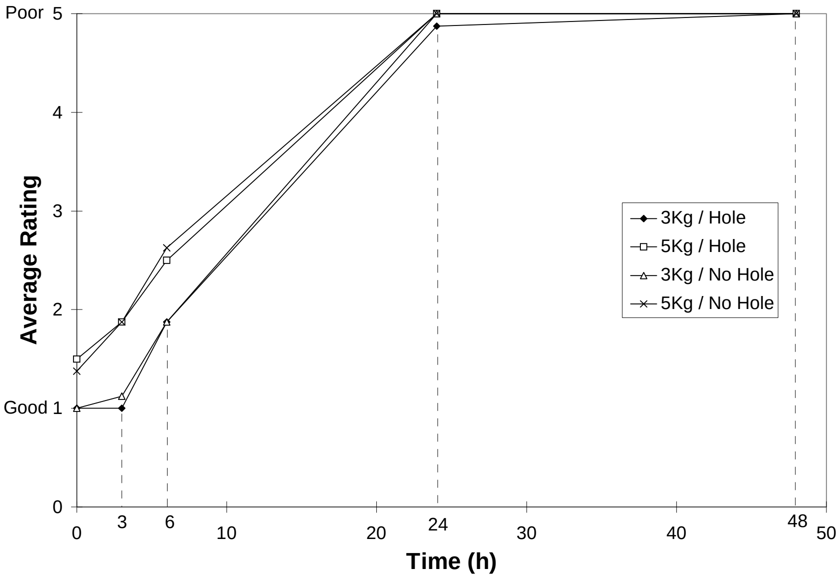


Figure 5.35: Effect of immersion time for bar No. A-1 exposed to 75°C water.

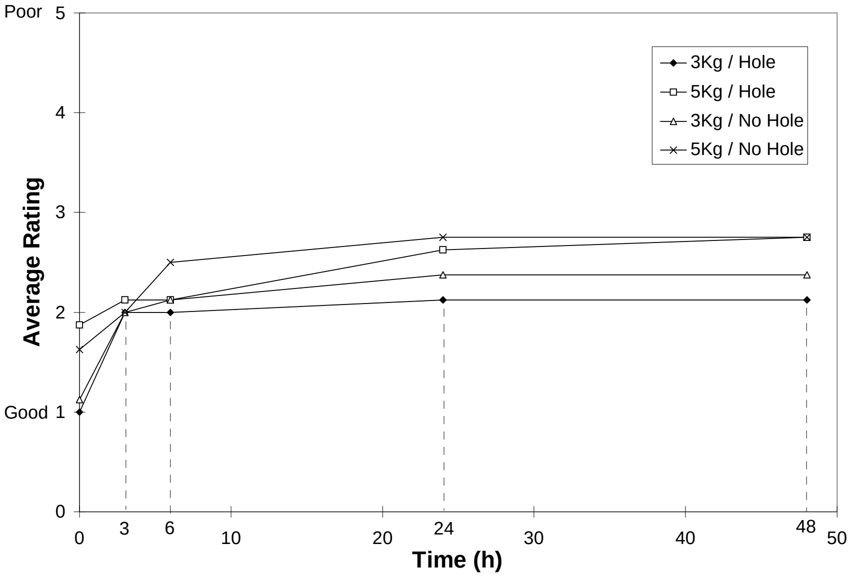


Figure 5.36: Effect of immersion time for bar No. S-1 exposed to 75°C water.

An important finding was that adhesion ratings remained fairly constant after times of immersion of 24 hours or longer (Figures 5.35 and 5.36). Tests from phase 2 revealed similar results. In practical terms, this is the most important finding because it confirms that hot water test duration can be effectively reduced from 48 hours (as proposed by MTO) to 24 hours. Times of immersion shorter than 24 hours are not recommended because of the discrepancies found.

Water temperature

As the temperature of the water bath increased, coating adhesion tended to decrease. A higher adhesion loss was always observed at higher temperatures. For bar A-1, there were samples that showed good coating adhesion at lower temperatures but experienced total loss of adhesion when immersed at 75° (Fig. 5.37). For bar S-1, there was little difference of adhesion between 55° and 75° (Fig. 5.38). In successive tests, the great majority of samples from five coating applicators experienced extensive adhesion loss at exposure to 75° water immersion.

Again, there are some discrepancies between results from previous two phases and third phase. A good number of samples from previous phases showed good or intermediate coating adhesion after immersion in 75° water. It may be that bars acquired for the third phase were of inferior quality than those from phases 1 and 2. Another factor may include differences in test procedure (special device vs. calibrated knife, 90° vs. 45° angle of X-cuts) but these are unlikely to cause such marked difference.

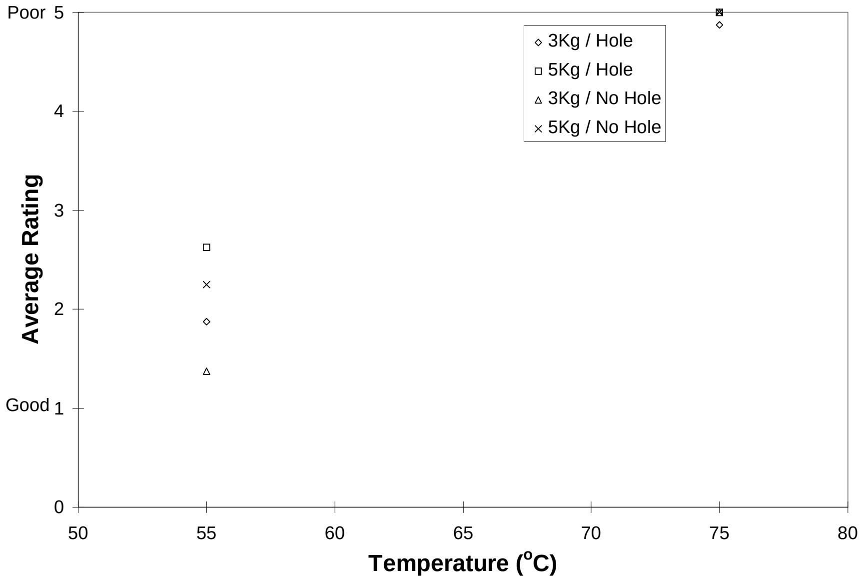


Figure 5.37: Effect of temperature on bar No. A-1 after 24 hours of immersion.

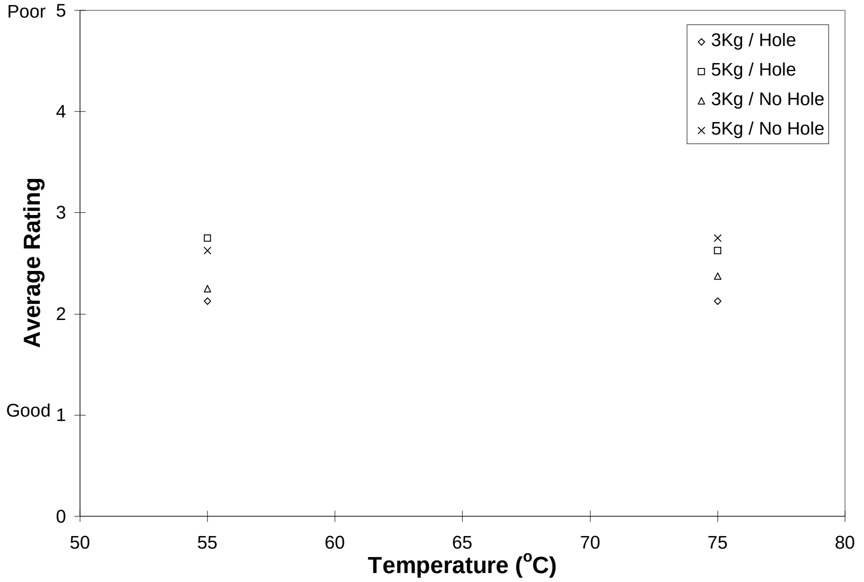


Figure 5.38: Effect of temperature on bar No. S-1 after 24 hours of immersion.

Hot water tests for phase 3 were conducted at a temperature of 55°. Immersion in 75° water may be too harsh for production bars to pass. More tests on bars from a wider variety of coating applicators would be needed to validate this hypothesis.

Presence of damage

Sections with pre-drilled holes experienced slightly higher adhesion loss than sections with undisturbed coating. The presence of the hole allowed migration of moisture and formation of corrosion products even at early stages. All samples exhibited corrosion products in the drilled hole after the hot water bath, even after short immersion times. However, the difference in adhesion ratings between the initial conditions (hole vs. no hole) was very small. In addition, specimens with pre-drilled holes were more difficult to test. No further samples were pre-drilled in future tests.

Despite differences in the type of damage and test procedure, results from phase 1 and preliminary tests of phase 3 indicated that coating damage before immersion does not greatly affect coating adhesion.

Knife force

Adhesion loss was found to be directly proportional to the applied force (Figures 5.35 through 5.38). In some cases, difference in adhesion ratings between the two forces was as high as one unit (Figures 5.35 and 5.36). Additional tests were performed with two knife forces to further evaluate this variable.

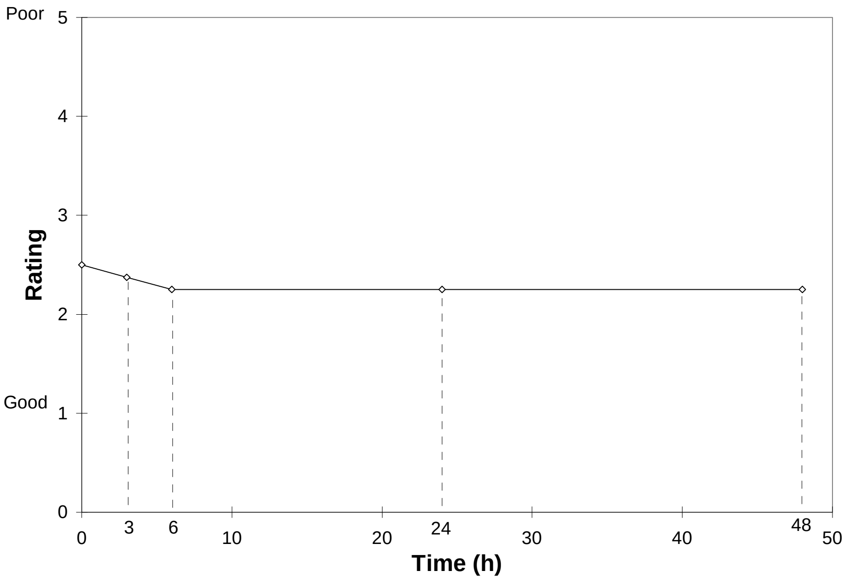


Figure 5.39: Effect of post-immersion period on coating adhesion for bar No. A-1.

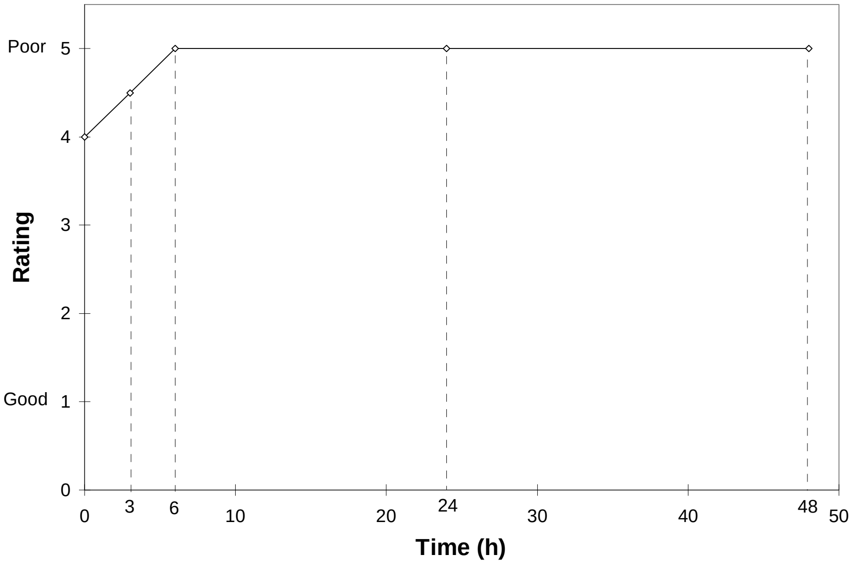


Figure 5.40: Effect of post-immersion period on coating adhesion for bar No. S-1.

Post-immersion time

With post-immersion periods longer than 6 hours, adhesion ratings tended to remain constant (Figures 5.39 and 5.40). Adhesion ratings from tests in the first phase at varying post-immersion times (equal or greater than 24 hours) did not vary significantly. Based on preliminary results, adhesion tests were performed after post-immersion times of 6 hours or greater.

Hot Water Test

Test Procedure and Variables

From preliminary tests and partial findings as tests progressed, the following variables were selected:

- Temperature of hot water bath:	55°C ± 2°C
- Time of immersion:	24 hours
- Post-immersion time:	6 hours or longer
- Knife force:	3 kg and 4 kg
- Initial coating condition:	Undamaged

Samples were obtained from 5 manufacturers as described in section 5.6.1. One sample was taken from every end and one sample was taken from the middle of the supplied bar. The procedure was intended to take into account possible variations of adhesion along the bar. At all three locations, companion samples were tested by a different operator.

Four 45° X-cuts were made on each side of the bar specimens. Two cuts were tested applying a force of 3 kg and the other two with a force of 4 kg, resulting in eight values of adhesion for every force in each sample. The eight adhesion values were averaged to obtain a mean adhesion rating for the sample. Tests were performed on #6 and #9 deformed bars and #6 and #10 plain bars.

Test Results

Table 5.21 contains adhesion ratings for each bar and each knife force, including the average rating, range, standard deviation, and coefficient of variation. Overall, there was little variability of test results. Although standard deviations measured for each bar ranged from 0 to 1.01, almost all values ranged from 0 to 0.55. Figure 5.41 is a graphical representation of values from Table 5.21 when 3 kg of knife pressure were applied. For reference, the mean of standard deviations is represented with a horizontal line. It can be seen that most standard deviations remained close to the 0.4 average regardless of the adhesion rating obtained, which means that there is similar dispersion of adhesion ratings for most coatings.

Neither the standard deviation nor the coefficient of variation correlated with average adhesion ratings. Results from Phase 2 seemed to indicate that bars with lower adhesion strength have greater variability of data, but this was not validated from the larger data base used in this phase. For instance, bar U-1 had very poor adhesion and standard deviation was zero. As stated in phase 2, if adhesion ratings are to be used as quality indicators, both the mean rating and standard deviation of ratings have to be considered.

Bar No.	Bar Size	Minimum Rating*	Maximum Rating*	Average Rating*	Standard Deviation*	Coeff. of Variation*
U-1	#6	5 (5)	5 (5)	5 (5)	0 (0)	0% (0%)
U-6	#9	1.5 (2.5)	4.5 (5)	2.8 (4)	1.01 (0.99)	36% (25%)
V-1	#6	1.5 (1.5)	2.5 (2.5)	2.1 (1.8)	0.42 (0.44)	20% (24%)
V-3	#9	1 (1)	1.5 (2)	1.2 (1.7)	0.25 (0.44)	21% (27%)
V-28	#6	2.5 (3)	4 (5)	3.4 (4.3)	0.55 (0.38)	16% (9%)
V-29	#10	1 (1)	2 (2)	1.3 (1.7)	0.40 (0.33)	31% (20%)
V-14	#6	3.5 (5)	5 (5)	4.5 (5)	0.52 (0)	12% (0%)
V-16	#9	4 (5)	5 (5)	4.9 (5)	0.31 (0)	6% (0%)
W-1	#6	4 (4.5)	5 (5)	4.8 (4.9)	0.34 (0.20)	7% (4%)
W-3	#9	3.5 (4)	5 (5)	4.3 (4.5)	0.45 (0.43)	11% (10%)
W-16	#6	4 (5)	5 (5)	4.9 (5)	0.29 (0)	6% (0%)
W-17	#10	4 (4)	5 (5)	4.8 (4.8)	0.33 (0.33)	7% (7%)
Y-2	#6	1.5 (1.5)	2.5 (3)	2.3 (2.1)	0.34 (0.38)	15% (18%)
Y-5	#9	1 (2)	2.5 (3)	1.6 (2.5)	0.52 (0.48)	33% (19%)
Z-1	#6	1.5 (2)	2 (2)	1.9 (2)	0.23 (0)	12% (0%)
Z-3	#9	1 (2)	3 (3)	1.5 (2.6)	0.54 (0.38)	37% (14%)

* Applied force = 3 Kg (4 Kg)

Table 5.21: Data obtained from hot water tests for each bar.

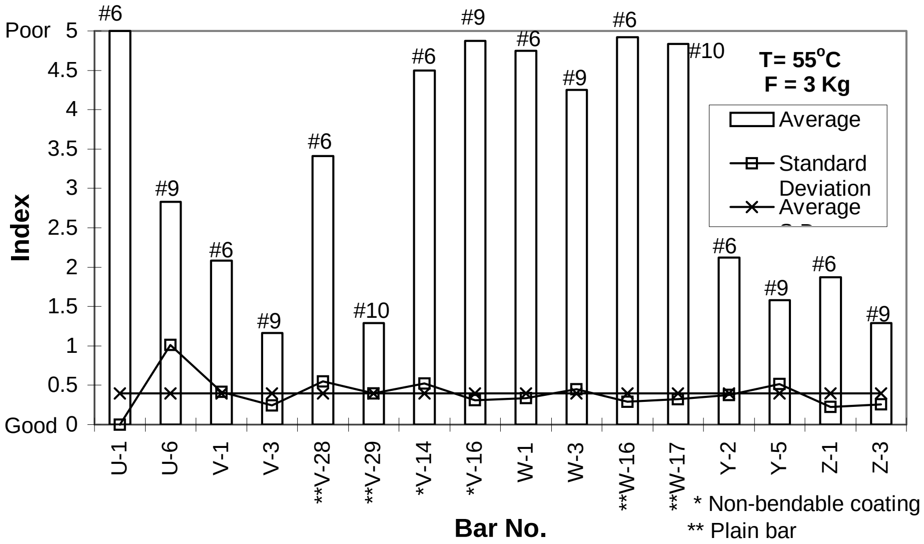


Figure 5.41: Average adhesion rating of all bars in hot water tests.

Although bars from the same coater but different lots generally had similar adhesion ratings, large discrepancies may occur. Bar V-28 had an average rating of 3.4, which is much greater than the average of 2.0 for all other bars coated by the same applicator and may suggest a less carefully controlled coating operation during production of that particular lot.

Table 5.22 shows values of average adhesion and standard deviation calculated at each location along the bars with a force of 3 kg. The force of 4 kg produced many failures involving tearing or slicing through the coating so calculations at each location are not tabulated. Regardless of the trend in standard deviations at a given location, the majority of adhesion mean values were similar among different bar locations. Average adhesion of most samples was representative of the overall adhesion of a rebar as indicated also in results from phase 2.

Bar No.	Bar Size	Left End		Middle		Right End	
		Avg.	σ	Avg.	σ	Avg.	σ
U-1	#6	5	0	5	0	5	0
U-6	#9	3	0.41	3.8	0.87	1.8	0.29
V-1	#6	2.4	0.25	2.1	0.48	1.8	0.29
V-3	#9	1.1	0.25	1.3	0.29	1.1	0.25
V-28 **	#6	3.3	0.65	3.8	0.29	3.3	0.65
V-29 **	#10	1.3	0.29	1.1	0.25	1.5	0.58
V-14 *	#6	4	0.41	4.6	0.48	4.9	0.25
V-16 *	#9	4.6	0.48	5	0	5	0
W-1	#6	4.6	0.48	4.9	0.25	4.8	0.29
W-3	#9	4.3	0.29	4.4	0.48	4.1	0.63
W-16 **	#6	5	0	4.8	0.5	5	0
W-17 **	#10	4.6	0.48	4.9	0.25	5	0
Y-2	#6	2.4	0.48	2.1	0.25	1.9	0.25
Y-5	#9	1.5	0.41	1.8	0.65	1.5	0.58
Z-1	#6	1.9	0.25	1.8	0.29	2	0
Z-3	#9	1.4	0.25	1.4	0.25	1.1	0.25

* Non-bendable   ** Plain bar

Table 5.22: Average and standard deviation of adhesion ratings at three locations along each bar. Applied force = 3kg.

Non bendable coatings performed poorly in hot water tests. For the two bars tested, there was almost total loss of adhesion after the hot water bath. This was a disappointing result because manufacturers claim that non bendable coatings are of superior quality. However, this finding is not conclusive because bars from only one applicator were obtained.

Figure 5.42 shows the overall average of all adhesion ratings for each coating applicator. As discussed earlier (first phase), such averages permit evaluation of the overall quality of different coating applicators. It is clear that adhesion correlated best with coating applicator even though other factors, such as coating operator, knife force, bar size, and adhesion within the same bar varied.

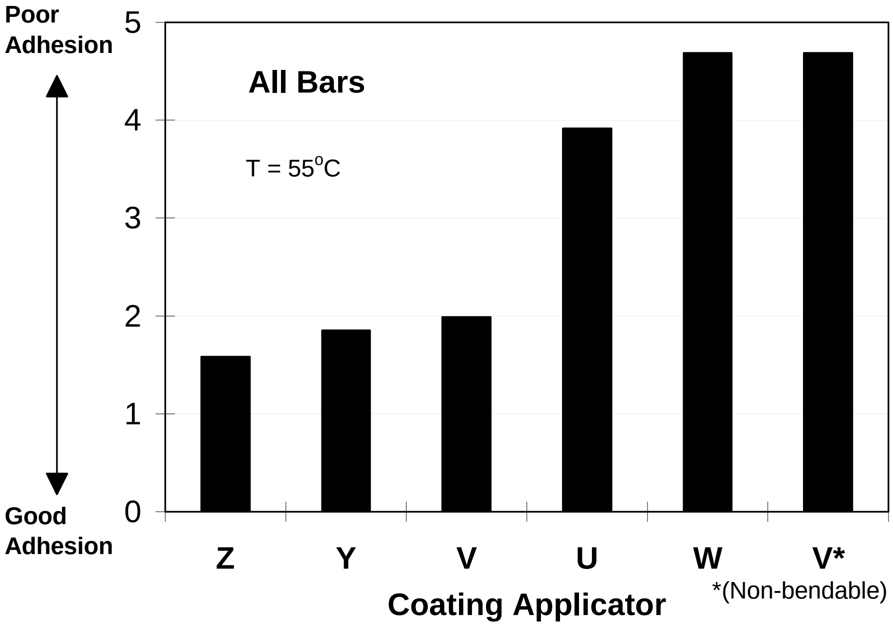


Figure 5.42: Coating applicator performance - Hot water tests.

Effect of Operator

Two operators performed adhesion tests on #9 bars after immersion in 75°C water only (because of time constrains, a second operator did not test bars after immersion in 55°C water). The second operator tested an additional sample from the end of the same bar. For each bar, only one of the samples tested by the main operator M is included in the comparison (the sample located at the same bar end as the sample tested by the second operator). Both operators performed 8 tests for each specimen, one half of the tests with a force of 3 Kg and the other half with a force of 4 Kg.

Test results are summarized in Figures 5.43 and 5.44. Except for bar U-5 tested with 3 Kg, specimens tested by operator M showed the same or slightly higher average rating (lower adhesion) than those tested by operator E. Average ratings of individual bars tested by both operators were very similar, with a maximum difference of 0.375. If mean ratings from all bars are averaged, the difference of results between the two operators is reduced to 0.06 (3 Kg) and 0.15 (4 Kg), as can be seen in Figures 5.43 and 5.44.

Finally, results from additional tests performed by two operators are shown in Fig. 5.45. The tests were performed on specimens from the same bar (P2) at different post-immersion times. Two ratings were higher for operator E (maximum difference of 0.5) and two were higher for operator M. Average ratings for each operator are very similar, with a difference of 0.16.

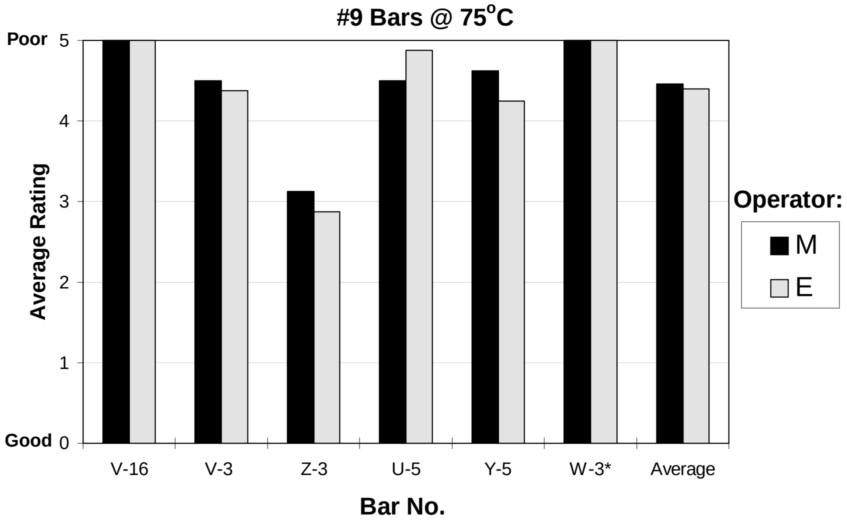


Figure 5.43: Effect of operator (Hot water test, F= 3Kg).

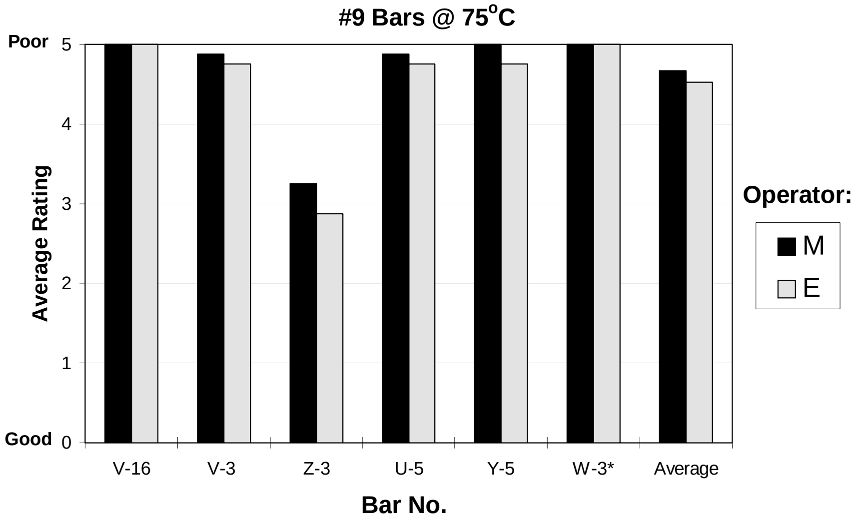


Figure 5.44: Effect of operator (Hot water test, F= 4Kg).

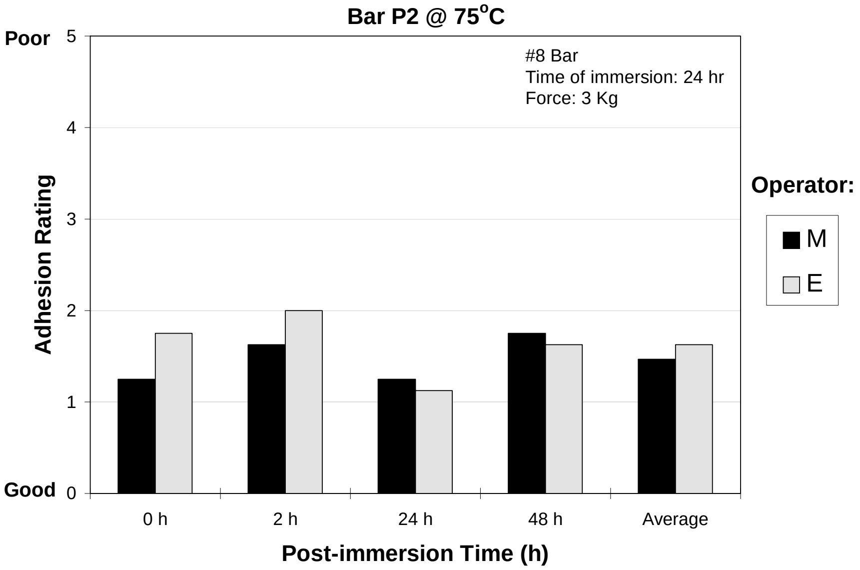


Figure 5.45: Effect of operator (Hot water test on bar P2).

5.6.4 Controlled Peel Tests

Adhesion tests in phases 1, 2, and 3 were performed after immersing specimens in a hot water bath. The purpose of the hot water immersion was to accelerate the electrochemical adhesion loss and to provide a measure of the coating adhesion in bars that have been in aggressive environments for an extended period. However, hot water immersion involves an elaborate, time-consuming sampling process.

TxDOT inspectors routinely perform peel tests at coating plants without any prior immersion. Such tests provide a measure of the total adhesion (electrochemical and mechanical) immediately after the bar is coated. At that stage, adhesion is a function of the quality of the coating process and handling at the plant.

The feasibility of performing adhesion tests directly on rebars without conducting hot water immersion was of interest to TxDOT because a simple, quick, and reliable quality control method that could be performed “in-situ” (coating plant) was desired. There are several advantages associated with testing at the production line: No laboratory testing is required, results are obtained much faster, and the costs are reduced. Since the test can be performed directly on the coated bar, there is no need to cut samples.

Two test procedures were developed and evaluated: (1) Strip method, and (2) X-cut method. The difference between the two methods lies in the definition of the test area. Evaluation of coating adhesion was not based on a conventional rating system but on direct estimates or measurements, which were different for each method.

A major breakthrough was the technique for peeling the coating during the test. So far, adhesion tests have been performed by applying a shearing force through the coating-steel interface with a knife blade. There are several disadvantages associated with this technique. Inevitably, a portion of the knife force (depending on the actual knife angle) is transferred to the epoxy coating layer and to the metallic surface. Local rugged areas on the steel surface and thick coatings may resist the forward motion of the blade. When such resistance is overcome, the blade may suddenly slip off and tear the coating.

The new technique consisted of applying a simultaneous combination of shearing and prying action with the blade. Previously, prying was only used to remove coating that had already been debonded by the shearing action of the blade. For controlled peel tests, prying would become a substantial component of the blade debonding action. Prying of coating was achieved by applying a rotating motion to the testing knife, resulting in an uplifting stress that effectively debonded the coating from the substrate. The magnitude of the shearing force needed to keep the forward motion of the blade was smaller than in previous tests.

Strip Method

Test Procedure

Four cuts were made through the coating to form a 2 x 25 mm rectangular strip at each test location. The strip was parallel to the circumference of the bar. The 2 mm width was determined based on preliminary trials. Narrower strips resulted in debonding of the strip of coating, and wider strips could not be peeled at all. The tip of a utility knife was used to lift the coating at one end of the strip. The tip of the calibrated knife was than inserted under the coating and the knife was positioned at an angle of approximately 30° tangent to the curvature of the bar. A constant force (1 to 2 kg) was applied to the knife maintaining the tip of the blade in the center of the strip. Simultaneously, the knife blade was rotated about its axis as the knife blade moved forward. The amplitude of the rotating motion is illustrated in Fig. 5.46. The blade was continuously rotated 30° on each direction from the initial position. The test was stopped when the calibrated knife traversed along the whole length of the strip.

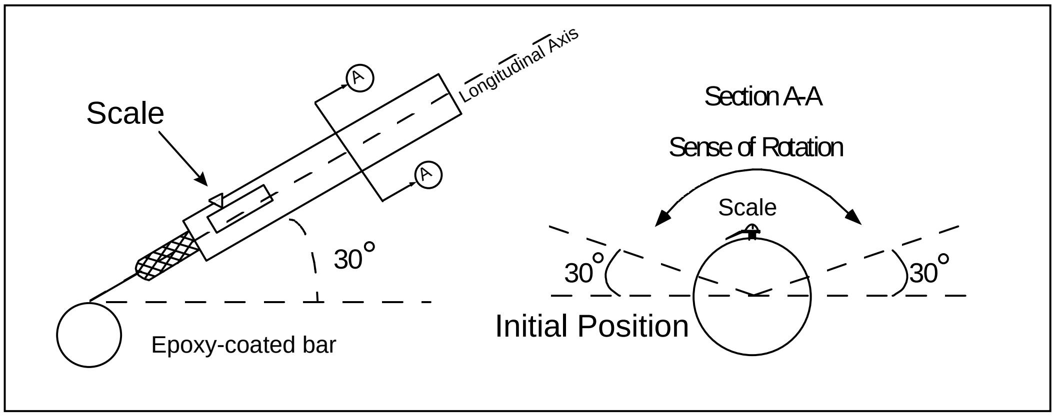


Figure 5.46: Position of testing knife and rotating motion.

At the end of the test, all loose and debonded material was removed and the surface was examined. The recorded adhesion index consisted of the approximate percentage of coating that remained adhered to the steel. Such values were estimated visually to the nearest 10%. The greater the index, the better the adhesion. Adhesion indexes ranged from 0% (No adhesion) to 70% (good adhesion). The maximum index cannot be 100% because the blade tip removes a very thin strip of epoxy even in the best adhered coating. The maximum index of 70% is based on the actual dimensions of such strips (roughly equal to the width of the blade tip).

The main disadvantage of the strip method is that the initial rectangular cut is very difficult to make and is time-consuming. Once the cut is made, the test is easy to perform. As in previous adhesion tests, the rectangular cut has to be made through the whole coating thickness to the bare steel. Likewise, the blade should be advancing through the coating-steel interface and not through the coating itself. This was verified by a small trail of metal visible through the coating left along the strip.

Adhesion tests were performed at both ends of the rebar and at the middle portion. In each location, two tests were conducted on each side of the bar. A test is defined by the application of knife force to one pre-cut rectangular area or strip. Four adhesion indexes were obtained at each location.

Test Results

Table 5.23 summarizes the test results on bars from five coaters using the same bars as in hot water tests. Some bars presented very high coefficients of variation, especially bars with poor adhesion. Average adhesion values were lower than the standard deviation, indicating that coefficients of variation are not meaningful indicators of the dispersion of data. For example, coefficient of variations for bars W-16 and V-29 were 346% and 4%, respectively. Examination of all individual readings reveals that for bar W-16, there were eleven 0% readings and only one 10% reading. For bar V-29, there were eleven 70% readings and only one 60% reading. Obviously, both bars had identical standard deviation of 2.9%. What increased the coefficient of variation for bar W-16 was that the standard deviation is divided by its much smaller average adhesion value (1% vs. 69% for bar V-29).

Bar No.	Bar Size	Max. (%)	Minim. (%)	Average (%)	σ (%)	C.V. (%)
U-1	#6	10	0	4	5.2	124
U-6	#9	60	0	37	22.3	61
U-3	#4	70	60	66	5.1	8
V-1	#6	50	10	22	11.2	51
V-3	#9	70	60	68	3.9	6
V-2	#4	70	50	63	7.8	12
V-14*	#6	30	0	14	7.9	56
V-16*	#9	20	0	12	7.2	62
V-28**	#6	50	0	18	16.4	90
V-29**	#10	70	60	69	2.9	4
W-1	#6	0	0	0	0.0	0
W-3	#9	20	0	8	7.5	101
W-2	#4	10	0	2	3.9	234
W-16**	#6	10	0	1	2.9	346
W-17**	#10	10	0	1	2.9	346
Y-2	#6	50	20	41	10.0	24
Y-5	#9	70	50	61	9.0	15
Y-3	#4	70	50	63	8.7	14
Z-1	#6	70	50	63	6.5	10
Z-3	#9	70	40	55	8.0	15
Z-2	#4	70	50	67	6.5	10

* Non bendable coating ** Plain bar

Table 5.23: Adhesion indexes from strip tests for all bars in percentage of remained coating.

Bars with poor adhesion tended to have high coefficients of variation in strip tests and low coefficients of variation in hot water tests. Different interpretations in the rating system for each method produced this discrepancy. In hot water tests, a high rating indicates a poorly adhered coating, while in peel tests by the strip method, a high index indicates good coating adhesion. A higher adhesion index (regardless of whether it represents good or bad adhesion) results in a lower coefficient of variation. As opposed to the coefficient of variation, the standard deviation was not affected by differences in rating systems.

Standard deviation in peel tests by the strip method varied more than in hot water tests. This situation was created by the inherent inaccuracy in reporting the results to the nearest 10% and that values were estimated visually. A more accurate system would involve measuring the width of the strip at several sections along the strip and calculating an average.

Figure 5.47 shows the average adhesion index and standard deviation of values for each bar. The average of standard deviations is plotted for reference. As in hot water tests, bars from coating applicator U had the largest dispersion of adhesion indexes along the bar. The strip method produced more variation of adhesion strengths among bars from different lots from the same coater than the hot water test.

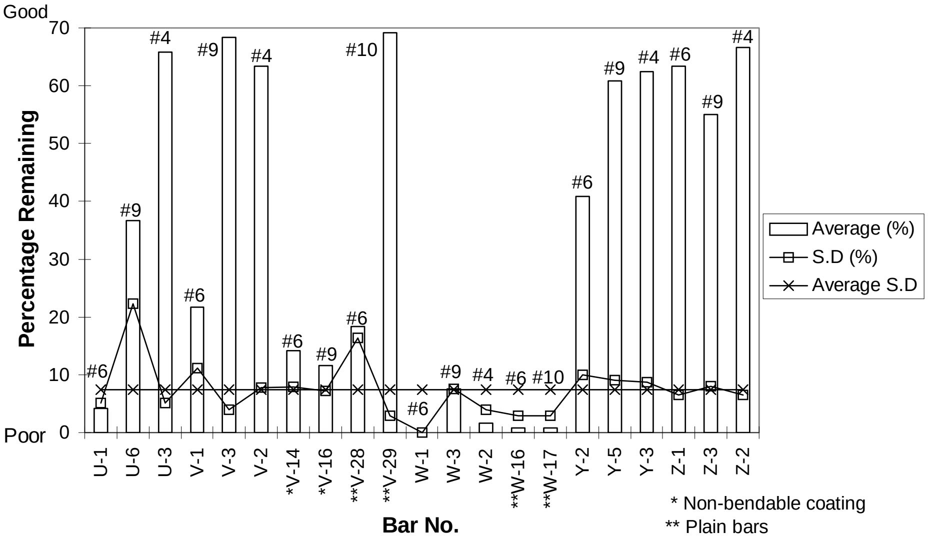


Figure 5.47: Average adhesion index of all bars in strip tests.

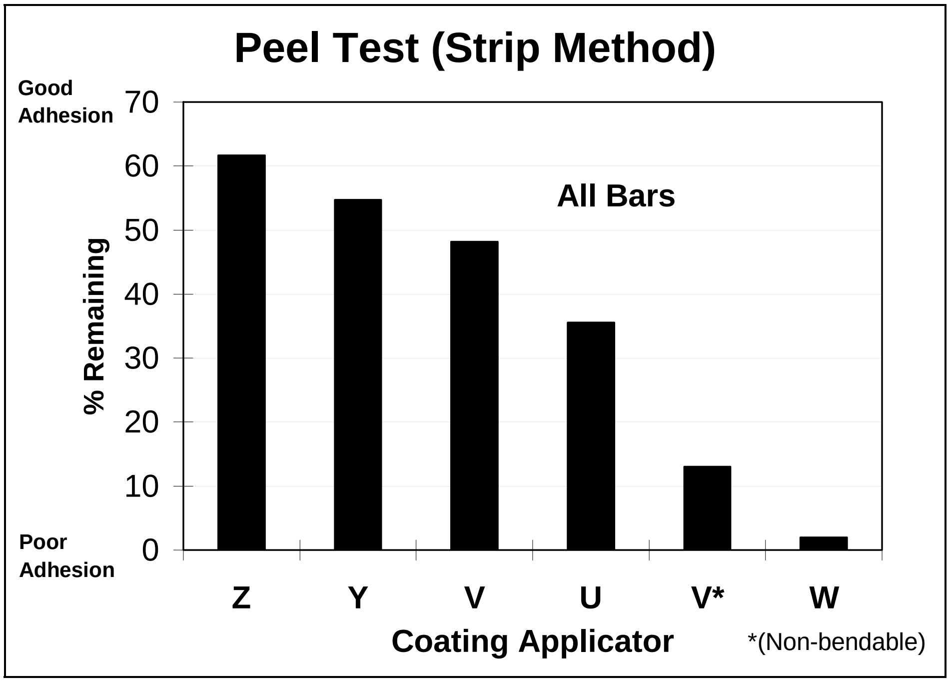


Figure 5.48: Coating applicator performance - Peel tests (strip method).

All bars from coater W had very poor coating adhesion, in all cases less than 10% of coating remained adhered after the test. Visual examination of these samples disclosed a very dark and scaly residue, possibly the product of improper surface preparation. Again, non-bendable coatings performed poorly compared to bars with flexible coating from the same applicator V. Interestingly and in contrast to bars from coater W, visual examination of non-bendable samples revealed a very clean steel surface, suggesting that factors other than surface preparation may produce loss of coating adhesion.

For most applicators, #6 bars tended to have poorer coating adhesion than larger (#9 or #10) or smaller (#4) bars.

Figure 5.48 shows the overall average of all adhesion ratings for each coating applicator. The adhesion performance among different coaters was practically the same as in the hot water test, with only a slight difference in the order of the two worst performers.

X-Cut Method

Test Procedure

This test method combines some of the features of the previous two tests. An X-cut, similar to that for adhesion testing after hot water immersion, is made. Peel tests are performed using opposite flaps of the X-cuts. As in the strip method, the calibrated knife is used to apply a combination of shearing force and prying action.

Unlike adhesion tests after hot water immersion, the interior angle of the X-cut was not restricted. After trials on many bars, it was found that when several tests were performed at the same location using the shearing-prying technique, the width of the section where coating broke remained constant, regardless of the angle of the X-cut (Fig. 5.49). The uplifting stress applied by rotating the knife tends to break the bond of the epoxy to the steel until the resistance provided by adhesion is larger than uplifting forces. When that point is reached, the coating breaks off or rips apart. The weaker the adhesion, the wider the section at which the coating breaks, regardless of the X-cut interior angle. Therefore, measuring the width of the section where the coating breaks provides an indication of the adhesion strength at that location.

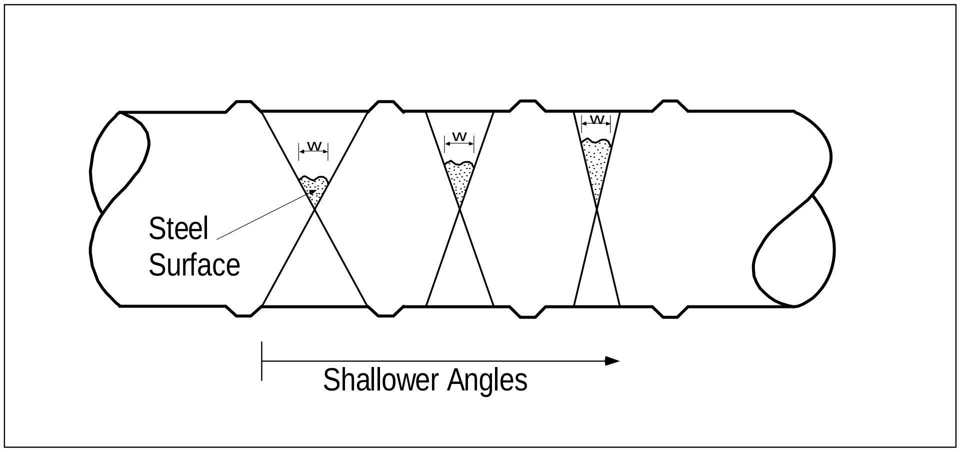


Figure 5.49: Width of final section remains roughly equal as the angle of the X-cut becomes shallower.

The angle of the X-cut can be can be increased or decreased to obtain debonded areas that are easier to measure. If the coating has strong adhesion resulting in very small widths at coating breakage, the next X-cut should have a smaller angle. If adhesion is so weak that the width of section at coating breakage is large, subsequent X-cuts can be made with a larger angle. Cuts with a 45° angle should be tried first.

As in the strip method, adhesion tests were performed at both ends of the bar and at the middle portion. At each location, two tests were conducted on each side of the bar to obtain the same number of readings as in the strip method. A test is defined by the application of knife force on one flap of the cut.

For #4 bars, a “V” cut instead of an “X” cut was used because of the small area between ribs. Twice as many “V” cuts as “X” cuts were made.

Test Results

Results from X-cut tests performed on bars supplied by all coaters are listed in Table 5.24. Adhesion values were based on measurements of the failure zone and ranged from 1.0 mm to 5.0 mm or more. A reading of 5 mm was recorded for all measurements equal to or greater than 5 mm. The rationale was that when section widths larger than 5 mm are reached, the uplifting force of the knife is not effectively transferred to the whole width of the cut and the sharp edges of the blade start shearing or cutting through the coating. Measurements larger than 5 mm become unreliable. Obviously, coating thickness affects this phenomenon. Nevertheless, a 5-mm reading indicated a very low adhesion regardless of coating thickness.

Bar No.	Bar Size	Max. (mm)	Minim. (mm)	Average (mm)	σ (mm)	C.V. (%)
U-1	#6	4.0	2.75	3.3	0.3	10
U-6	#9	4.5	1.75	2.9	1.0	33
U-3	#4	2.0	1.0	1.5	0.3	18
V-1	#6	2.5	1.25	1.8	0.4	25
V-3	#9	1.75	1.0	1.4	0.3	18
V-2	#4	2.25	1.0	1.4	0.4	27
V-14*	#6	5.0	4.0	4.8	0.5	10
V-16*	#9	5.0	4.0	4.8	0.5	10
V-28**	#6	5.0	3.0	4.1	0.7	17
V-29**	#10	1.5	0.5	1.0	0.2	22
W-1	#6	5.0	4.0	4.9	0.3	6
W-3	#9	5.0	3.5	4.1	0.4	11
W-2	#4	5.0	3.0	4.4	0.7	16
W-16**	#6	5.0	4.5	4.9	0.2	4
W-17**	#10	5.0	4.0	4.9	0.3	6
Y-2	#6	1.5	1.0	1.3	0.1	11
Y-5	#9	2.0	1.0	1.8	0.3	19
Y-3	#4	2.25	1.0	1.5	0.4	26
Z-1	#6	1.75	1.0	1.4	0.3	18
Z-3	#9	2.25	1.25	1.6	0.3	17
Z-2	#4	2.0	1.0	1.5	0.3	20

* Non bendable coating   ** Plain bar

Table 5.24: Adhesion measurements from X-cut tests for all bars in millimeters (width of section at coating breakage).

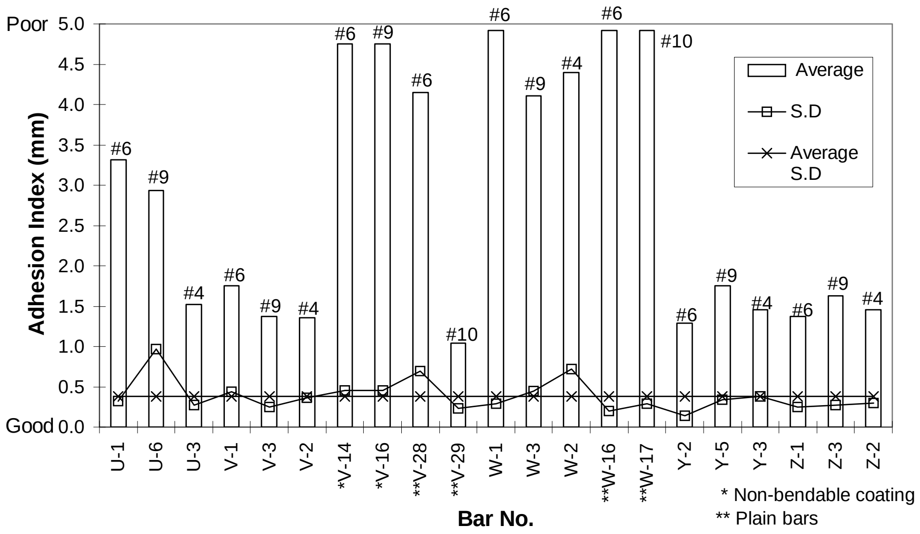


Figure 5.50: Average adhesion index of all bars in X-cut tests.

Average adhesion index and standard deviation for each bar are plotted in Fig. 5.50. Most bars had standard deviations 15% or less over their average, except bars U-6, V-28, and W-2. All bars from the same coater were within one standard deviation from each other, except bars V-28 and U-3. In general, dispersion of adhesion ratings were less variable than in the strip method and were similar to those from the hot water test. Figure 5.51 illustrates the average adhesion readings obtained on all bars from each coating applicator. Performance of coaters followed the same order as in hot water tests. Among flexible coatings, those of coater W performed the worst and those of coaters Z and Y performed the best. Non-flexible coatings showed the worst adhesion.

It was evident in Fig. 5.50 that no bar size consistently performed better or worse. Comparing performances as rated by hot water test, strip peel test, and X-cut peel test, no particular bar size performed better than others. The data seemed to validate findings from Phase 1, where no consistent trend was found between bar size and coating adhesion.

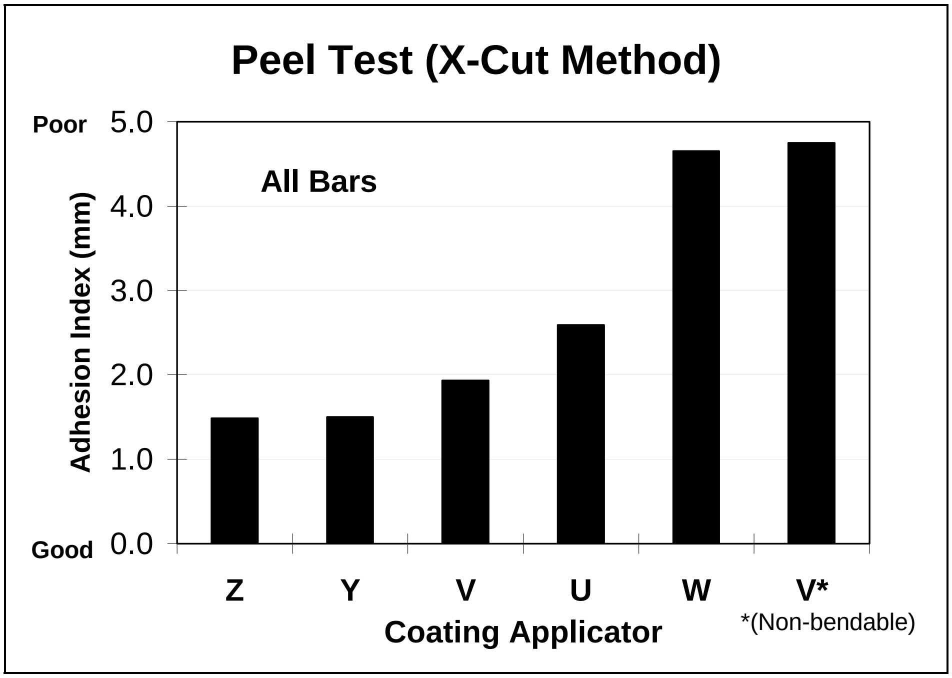


Figure 5.51: Coating applicator performance - Peel tests (X-cut method).

5.6.5 TxDOT Peel Test

The three test methods performed in Phase 3 provide a rating or index that is indicative of the coating adhesion of a bar. None of the methods defines a limiting value for acceptance criterion. Such a value will have to be defined and based on field calibrations. Adhesion ratings will be useful mainly for quality control.

TxDOT Peel Test is a subjective adhesion test that does not provide adhesion rating values, it only determines if a coating passes or fails the test. Test results from the three test methods described above were correlated with results from TxDOT Peel Test. Such correlation may give an approximate acceptance criterion until more definitive evidence is available.

Test procedure

The test was performed following the procedure described in TxDOT test method Tex 739-I presented in Chapter 4. Tests were conducted at the same locations as for the previous three methods, namely the two bar ends and the middle portion, on both sides of the bar. Only one operator performed all tests to reduce possible variations and subjectivity. An “OK” or “NG” (not good) rating was given to all test location but an overall pass/fail criterion was assigned to the whole bar. If poor adhesion (NG) is found in any of the three tested locations, the bar fails.

Test Results

In Table 5.25, results of TxDOT test method Tex 739-I are given. As expected, all bars from coater W failed the test. Bars with non-bendable coatings failed the peel test too. Rigid, non-bendable coatings were brittle and tended to break during the test instead of being lifted from the steel surface as a whole. Careful judgment had to be exercised to properly evaluate coating adhesion of rigid coatings.

Bar No.	Adhesion Rating
U-1	FAIL
V-1	PASS
V-14	FAIL
W-1	FAIL
Y-2	PASS
Z-1	PASS
U-6	FAIL
V-3	PASS
V-16	FAIL
Y-5	PASS
W-3	FAIL
Z-3	PASS
W-17	FAIL
V-29	PASS
W-16	FAIL
V-28	FAIL

Table 5.25: Adhesion performance of all bars - Tex 739-I peel test.

5.6.6 Analysis and Correlation of Adhesion Test Results

The three methods for adhesion testing in phase 3 are compared and analyzed in this section. Each of the three methods has a different rating system. Adhesion values were normalized to a common scale to allow comparisons of results from different procedures. In the rating for strip tests, a low index meant poor adhesion. The opposite was true for hot water and X-cut ratings. Results in strip tests were presented as percentage of coating remaining after the test and had a maximum value of 70%. The values were subtracted from 70% to transform them to a percentage of epoxy coating that is removed in the test so that a high value indicates poor adhesion and a low value, good adhesion, as in the other 2 rating systems.

The values were normalized in two steps. The first step involved dividing all readings by the maximum value for each system. This produced a rating system ranging from 0.2 to 1.0 for the hot water and X-cut tests and from 0 to 1.0 for strip tests (before normalization, strip tests had minimum values of 0 while hot water and X-cut tests had minimum values of 1.0). The second step consisted of re-adjusting the normalized values of hot water and X-cut tests to a common scale from 0 to 1.0 by linear interpolation. Normalized index values approaching unity indicate very poor coating adhesion.

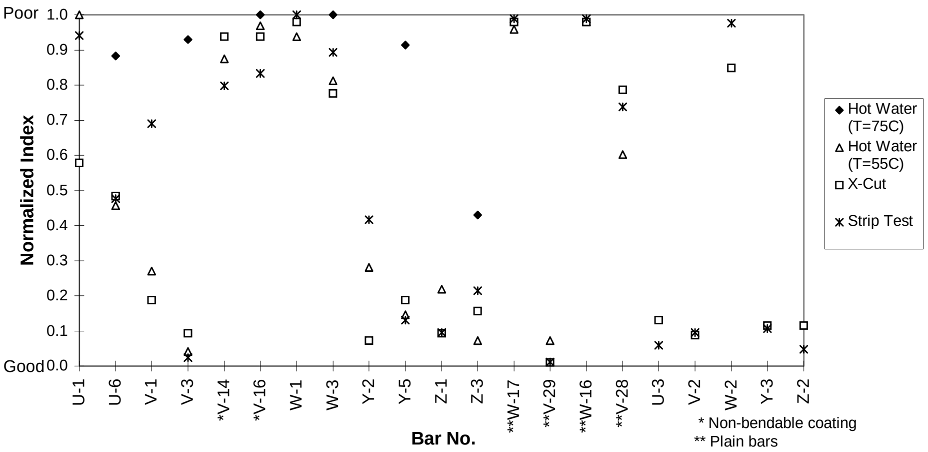


Figure 5.52: Relative adhesion values between all tests.

Average normalized adhesion ratings for all bars and all test procedures are plotted in Fig. 5.52. The few results of hot water test at 75°C on #9 bars are also included. Except for hot water tests at 75°C, the three test methods followed the same general trend. Adhesion ratings given by the three test procedures were similar for most bars. The largest discrepancies were found for bars U-1, V-1, and Y-2. Even though X-cut and strip tests differed the most in terms of average difference of mean ratings, their mean values were closer to each other than to those for the hot water test in seven out of sixteen bars. No test method consistently gave higher or lower adhesion ratings, although there was a slight tendency for the strip test to give higher values (lower adhesion) more frequently (seven out of sixteen bars). Statistical analysis showed that dispersion of ratings between different test methods was not greater than the dispersion of individual ratings along the bar by one test procedure.

Of the three test procedures, the X-cut method seems to be the most practical. It is easier to perform than the strip method and does not require hot water immersion. There is no practical advantage in immersing samples in 55°C water before adhesion testing. If a more severe test is desired, a hot water test with water temperature of 75°C can be conducted. For adhesion testing after immersion, the X-cut method (shearing and prying) is recommended over the method that employs shearing only.

The three test procedures were correlated with test results from test method Tex 739-I (Peel Test). In Fig. 5.53, the results of the TxDOT Peel Test are plotted with the average adhesion index values obtained for each bar. Good correlation is shown between results from the Peel Test and other tests developed in this study. Bars that failed the TxDOT Peel Test generally exhibited poor coating adhesion by all methods. Only one case (bar V-1) passed the Peel Test but displayed poor coating adhesion by the strip method. Bar V-1 can be considered an outlying value.

In Table 5.26, limiting values for the three test methods above which bars failed by the Peel Test are listed. Test ratings are presented and normalized for comparison. As noted from the table and from Fig. 5.53, there seems to be a well defined adhesion index above which epoxy coatings can be considered to fail the peel tests. The normalized limiting values as given by the three test methods were very close to each other and to their average of 0.47. Of course, a much larger data base would be needed to determine limiting values for use as acceptance criteria.

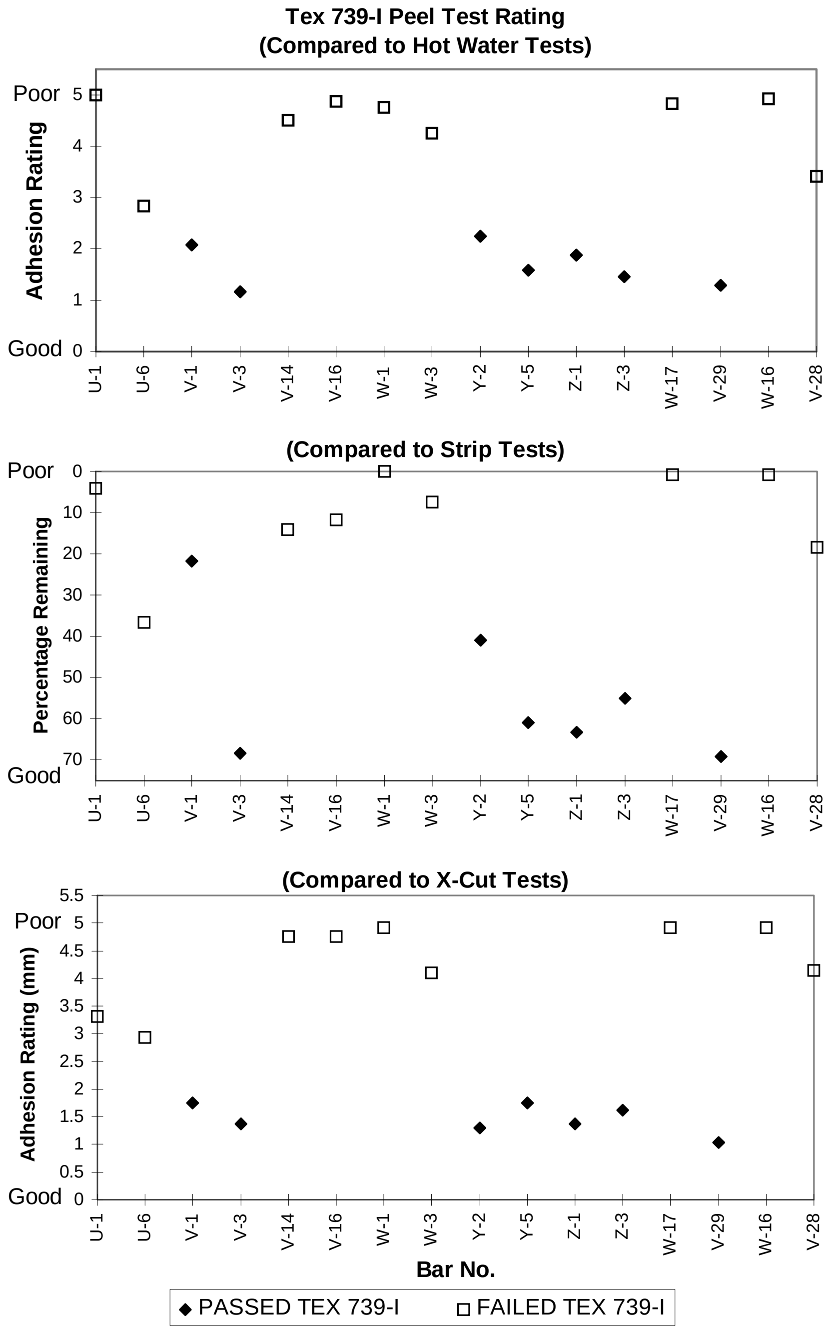


Figure 5.53: Adhesion test results from three test methods compared to TxDOT peel test.

	Hot Water Test	**Strip Test**	**X-Cut Test**	**Average**
Test Rating	2.83 (Bar U-6)	36.67% (Bar U-6)	2.94 mm (Bar U-6)	N/A
Normalized Rating	0.46	0.48	0.49	0.47

Table 5.26: Limiting values of all adhesion tests with respect to TxDOT Peel Test.

In Fig. 5.54, the results of the bend test performed by the coating applicator (Section 5.6.1) are plotted with average adhesion index values obtained for each bar using the X-cut test. Clearly, there is poor correlation between the bend test and adhesion. All bars with poor adhesion passed the bend test. The only two bars that failed the bend test showed relatively good adhesion. Bend tests were not reliable indicators of coating adhesion in this study, yet they are often the only tests specified to evaluate coating adhesion.

In Fig. 5.55, the average normalized adhesion index from the three test procedures is plotted against the coating thickness at the test location. As in phase 1 of the study, no clear relationship was found between coating thickness and adhesion strength for the three tests performed, as evidenced by the large scatter of data in Fig. 5.55. There was some tendency for coatings thicker than 14 mils to have poor coating adhesion.

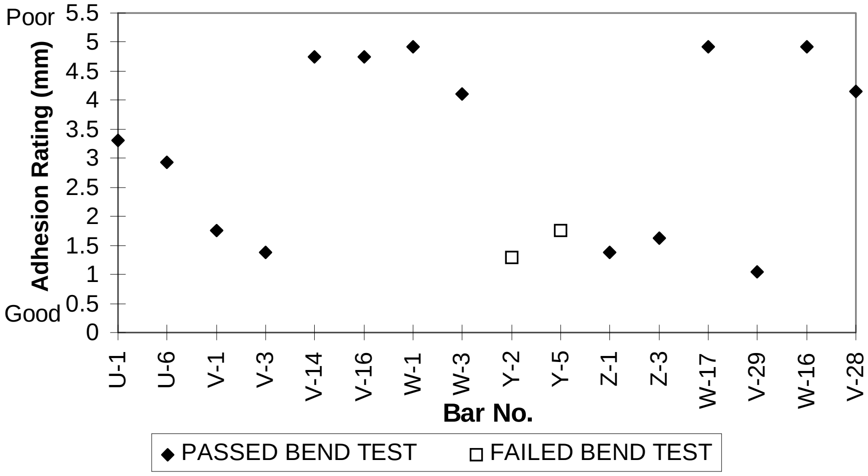


Figure 5.54: Adhesion test results from X-cut method compared to bend test.

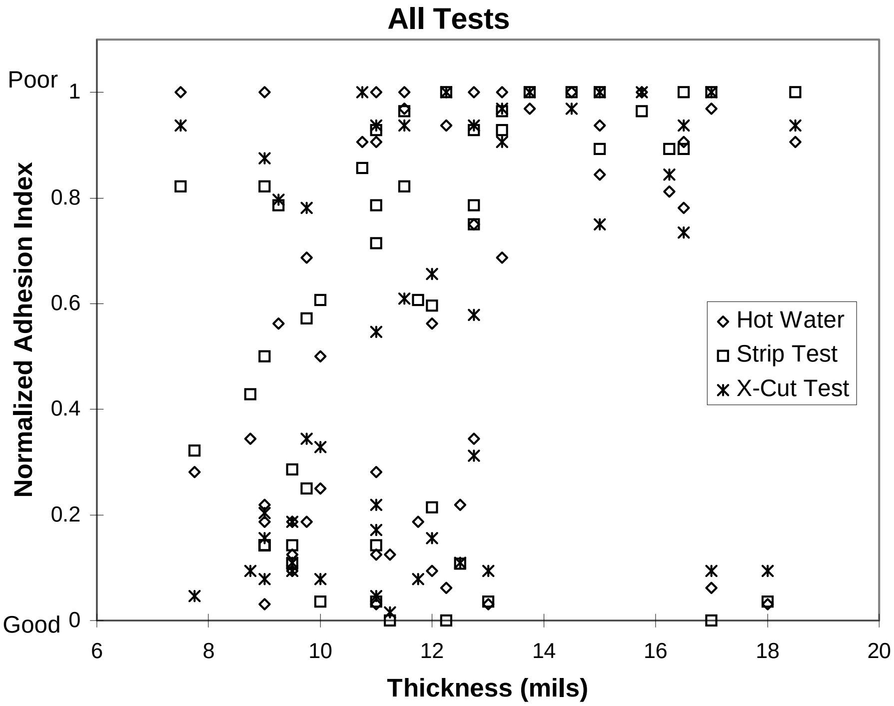


Figure 5.55: Coating thickness -vs- normalized adhesion index.

5.6.7 NaCl Immersion Test

The role of coating adhesion in the corrosion protection of epoxy-coated bars is not completely understood. In an effort to gain some insight in this subject, a short exposure study was conducted. The study consisted of immersing epoxy-coated bar samples in 3.5% NaCl solution. It should be emphasized that the exposure study does not reflect the real corrosive environment of epoxy-coated bars in concrete but provides a way to subject different epoxy coatings to the same chloride environment in a short period.

Test Procedure and Evaluation

Five-inch samples were obtained from the same three locations as for adhesion tests for every supplied bar. Ends of the specimens were sealed with a two-part epoxy resin. Samples were carefully inspected for the presence of defects or holidays. Any coating discontinuity was repaired with a two-part patching material. A 1/8-inch-diameter hole was drilled through the coating on both sides of the bar to expose the steel surface. This intentional discontinuity provided the same initial condition for all specimens and a place for corrosion to initiate.

Exposure consisted of 12 wet/dry immersion cycles; each cycle was 4 days wet and 3 days dry. At the end of the exposure period, specimens were allowed to air dry for 2 weeks before inspection.

Assessment of specimens after exposure consisted of (1) Visual examination of surface condition, (2) adhesion testing using the X-cut peel test at least one inch away from the pre-drilled hole (to test adhesion on a surface free from corrosion products), and (3) peeling of coating around the hole area to inspect the corroded area and to estimate coating adhesion in the zone of chloride attack.

Test Results

Coating adhesion was completely lost in the vicinity of the pre-drilled hole, which corresponded to the corroded area under the coating. A mix of dark brown and dark gray corrosion products filled the pre-drilled hole and the surrounding epoxy coating was rust-stained (Fig. 5.56). A radial corroded area under the coating changed in appearance. Closer to the hole, dark gray corrosion products, sometimes with small brown rust areas, were prevalent. Farther away from the hole, corrosion products were dark to light brown. The appearance of the surface away from the pre-drilled hole in bars with good adhesion was shiny and clean, whereas in bars with low adhesion the surface was scaly and dull.

Average adhesion indexes from X-cut tests performed (at least one inch away from the hole) on all bars are plotted in Fig. 5.57. Adhesion indexes for specimens without immersion are also plotted for comparison. In all cases, there was a slight decrease in adhesion as a result of NaCl immersion. This was expected because moisture promoted loss of adhesion in organic epoxy coatings.

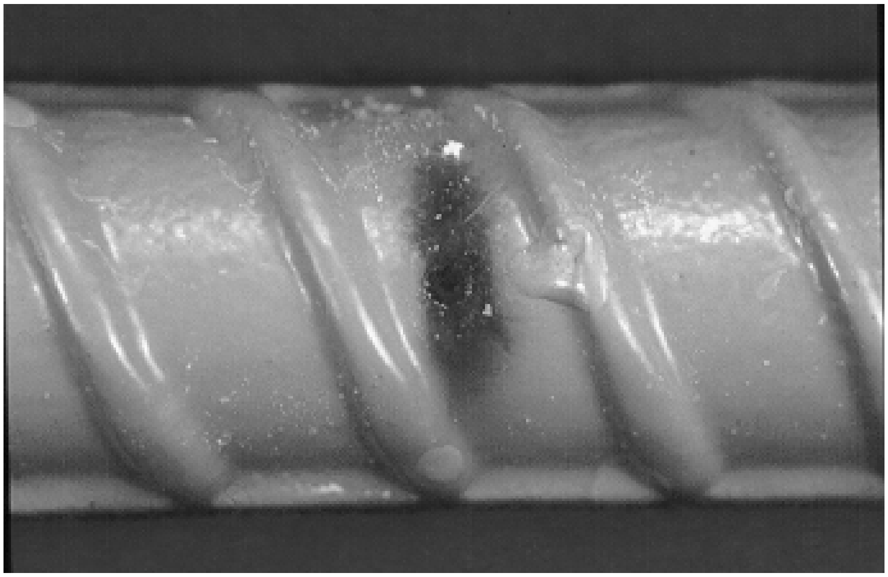


Figure 5.56: General aspect of specimens after immersion.

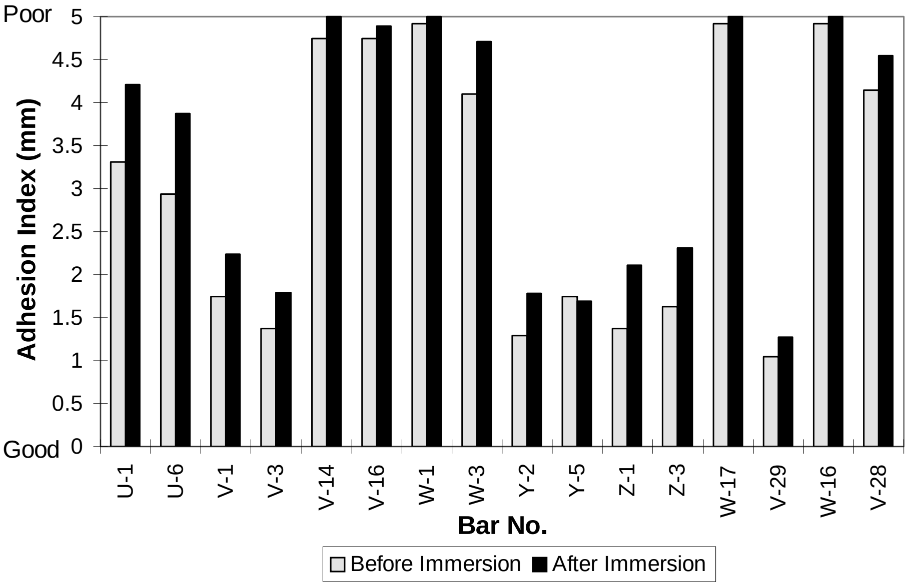


Figure 5.57: Adhesion index before and after immersion for all bars.

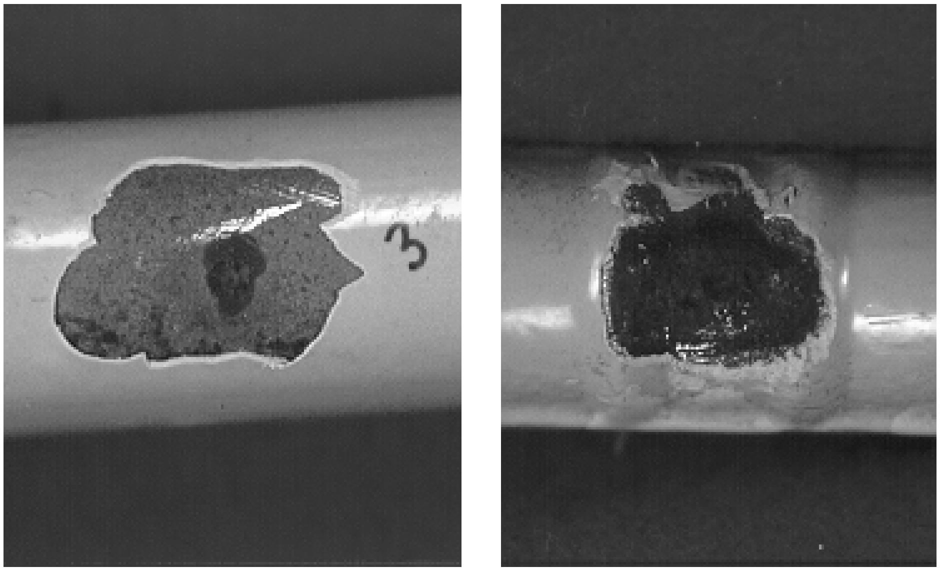


Figure 5.58: Damaged area in samples with good (right) and poor (left) coating adhesion. Note that the dark corroded area on the sample with good adhesion is larger than that on the sample with poor adhesion.

It was astonishing that most bars with low adhesion before immersion showed less localized corrosion after immersion than those with better adhesion (Fig. 5.58). A satisfactory explanation for this phenomenon could not be found. One hypothesis is that bars with varying adhesion strengths developed different anode/cathode area ratios. Very likely, salt solution penetrated easily under the coating in bars with low initial adhesion and made contact with a large portion of the steel surface, resulting in a greater anodic area compared to bars with better adhesion. For similar cathodic areas, the greater the anode the slower the corrosion. However, this hypothesis would be true only if the cathodic areas were of similar size in both cases. The larger steel area available for anodic reactions is also available for cathodic reactions in bars with poor adhesion, resulting in a larger cathode compared to bars with better adhesion. In addition, exposure conditions would tend to become similar with time in both cases because of progressive adhesion loss by moisture. A longer exposure could have produced different results.

Size of corroded area is plotted against adhesion index for all samples in Fig. 5.59. There is wide scatter of the data and no clear correlation can be found. Nevertheless, there was a slight trend for bars with lower adhesion to have smaller corroded areas. As adhesion improved, data scatter spread more.

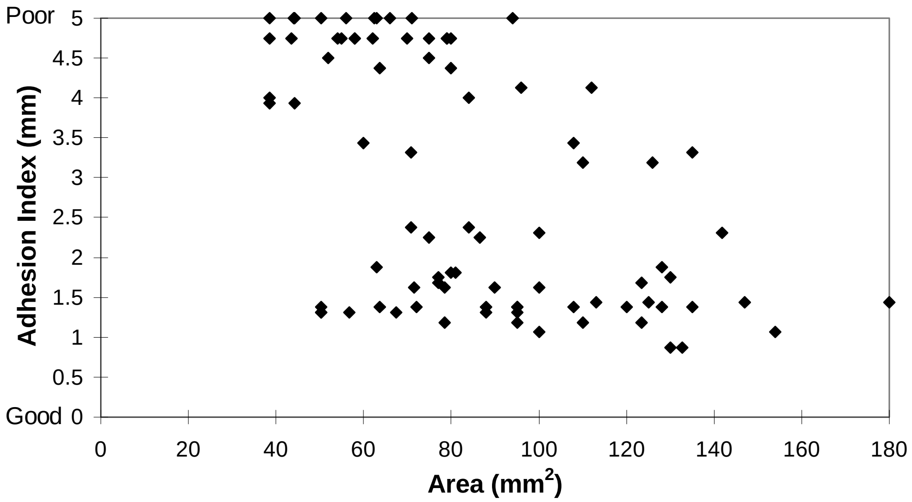


Figure 5.59: Size of corroded area in relation to X-cut adhesion index.

5.7 SYNTHESIS OF COATING ADHESION STUDY

5.7.1 Summary

The role played by coating adhesion in the corrosion protection of steel reinforcement is not well understood. It has been claimed that inadequate coating adhesion may lead to early failure of the coating protection system. It has also been asserted that adhesion is a measure of quality of the coating application to the steel substrate. The main objective of this study was to develop a reliable, quick, and practical method to evaluate adhesion strength of epoxy coatings. Hot water and adhesion tests were performed on epoxy-coated bars from several coating applicators at three different stages. A wide variety of variables was studied, aimed at both the development of the tests and at the assessment of their viability for quality control. Practicality and repeatability of tests were especially emphasized.

5.7.2 Conclusions

The main conclusions are categorized and summarized as follows:

Test usefulness

- The tests developed in this study are a valuable tool for quality control and in-depth studies of coating adhesion. Hot water and adhesion tests were very useful in discriminating and identifying good from bad quality coatings. Most of the subjectivity involved in earlier tests was eliminated or reduced. The tests were relatively easy to perform and did not require special or sophisticated equipment.

Test procedure

- Coating adhesion can be reliably evaluated by different methods. Test results were not significantly affected by changes in the testing procedure. Adhesion testing proved useful and meaningful even if performed in a subjective way.
- Adhesion testing using the X-cut method combining shearing and prying action with the knife was very practical and reliable.
- Hot water testing at a temperature of 75°C was severe for the bars received. Nevertheless, there were several bars that performed satisfactorily.
- Adhesion testing without immersion provided a measure of minimum quality, and adhesion testing combined with 75°C water immersion provide a measure of optimum quality.

Test parameters

In relation to hot water immersion:

- Temperature of the water bath was the most influential test parameter. A water temperature of 75°C proved to be more severe than 55°C.
- There was little effect of time of immersion for periods longer than 24 hours, of the presence of pre-drilled holes, and changes in post-immersion periods longer than 6 hours.

In relation to adhesion testing:

- There was little effect of knife force calibration procedures, adhesion test method, test operator, type of knife and blade, and test evaluator.

- Adhesion loss was found to be directly proportional to the applied force of 3 and 4 kg.

Influencing factors

- The following factors had little effect on adhesion test results: Bar diameter, coating thickness and thickness variability, and original coating condition (damaged or undamaged).
- In all cases, straight bars performed better than bent bars.
- Visual examination of the steel surface in samples with poor adhesion revealed, in several cases, a very dark and scaly residue, possibly the product of improper surface preparation. However, in other cases a very clean steel surface was found, suggesting that factors other than surface preparation may produce loss of adhesion.
- Adhesion test results correlated best with sample source (coater).

Test repeatability

- There was a small variation in average adhesion at different locations on the same bar. Despite local variations in adhesion at different portions of a bar, average adhesion of samples may be representative of the overall adhesion of a rebar.
- Small specimens were representative of the quality of a coating applicator if obtained from many bar lots. Bars from the same coater but from different lots may have similar adhesion ratings, but large discrepancies may occur during the production of certain lots.

- Dispersion and variability of data were independent of adhesion strength. If adhesion ratings are to be used as quality indicators, both the mean rating and standard deviation of ratings must be examined.
- Coefficients of variation may not be meaningful indicators of the dispersion of data. The higher the adhesion index (regardless of whether it represents good or bad adhesion), the lower the coefficient of variation.
- Standard deviation in peel tests by the strip method varied more than those from hot water and X-cut tests. Likewise, peel tests using the strip method produced more variation of adhesion strengths for different lots from the same coater.

Correlation between tests

- There was good agreement between results from hot water-adhesion tests and those from the TxDOT peel test.
- From correlation between adhesion tests and TxDOT peel tests, a limiting normalized adhesion rating separating good and poor adhesion was defined in the range of about 0.5 (1.0 indicates poor adhesion, 0 indicates good adhesion). A much larger data base would be needed to define a limiting value as acceptance criterion for quality assurance.
- There was poor correlation between adhesion tests and bend tests. Bend tests were not reliable indicators of coating adhesion and were more a measure of the coating flexibility.

- Test results from immersion in salt solution were inconclusive. No clear correlation was found between adhesion strength and size of corroded area.

Miscellaneous

- Non-bendable or rigid coatings were difficult to evaluate because of their high stiffness. Rigid coatings tended to break and tear when subjected to the shearing action of the knife.

5.7.3 Recommendations

1. Implementation of methods developed in this study to evaluate coating adhesion will reduce the subjectivity inherent in prior tests and can be useful for quality control.
2. Of the test methods developed in this study, the X-cut method using a combination of shearing and prying action with a calibrated knife is highly recommended. The only resources needed are a calibrated knife, a utility knife, and a properly trained operator. If more resources and time are available, the test can be made more stringent by immersing samples in a 75°C water bath for 24 hours before adhesion testing. If hot water immersion is selected, pre-screening could be conducted at the coating plant by testing bars with the X-cut method.
3. The TxDOT peel test is simple and quick to perform and is recommended, especially if a calibrated knife is not available.
4. Additional long-term research is needed to determine the effect of adhesion strength on corrosion protection of epoxy-coated

reinforcement. Presently, there is no clear understanding of the relationship between these two properties. The effect of coating adhesion on corrosion protection must be established. Acceptance criteria based on adhesion strength alone will not suffice.

5. The use of bend tests as the only method of testing epoxy coating adhesion is discouraged.
6. More adhesion tests of non-bendable epoxy coatings are needed to gain a better understanding of their properties and to adjust testing procedures as necessary. Rigid coatings were found to be very brittle and had poor adhesion, but only a few bars were tested in this study.

Chapter 6. Repair of Coating Damage

6.1 PROBLEM STATEMENT

As was previously mentioned, coating damage to epoxy-coated rebars in chloride-contaminated concrete may lead to failure of the coating protection system. Damage to epoxy coating can occur during the stages of coating application, handling, storage, transportation, fabrication, assemblage, and/or concrete placement. In addition, rebar ends are left uncoated during the coating process or when rebars are cut. Epoxy patching materials are manufactured to repair coating damage and touch-up rebar ends.

In earlier corrosion studies in this project, performance of patched damaged areas in chloride contaminated concrete specimens and in ECR samples submersed in NaCl solution was marginal.[10] After 2 years of exposure, macrocell specimens where coating damaged was repaired experienced rust staining on the patched surface. Nevertheless, they exhibited less corrosion than those specimens where coating damaged was not repaired. The overall conclusion was that patching delayed but did not prevent the onset of corrosion.

Most specifications now require that all coating damage be repaired with patching material. However, existing ECR specifications do not adequately specify procedures for using patching materials. Repair of coating damage with a suitable patching material compatible with the epoxy coating and following the manufacturer's recommendations is the main guideline provided in all ECR specifications. No systematic study of the efficacy of patching materials and repair procedures has been reported.

6.2 REPAIR MATERIALS AND PROCEDURES

6.2.1 Patching Materials

Patching materials used for repairing damaged epoxy coated rebars consist of two-component, thermosetting, liquid or viscous epoxy resins. The two components are the epoxy resin (part A) and the curing agent or hardener (part B). The two parts are thoroughly mixed together in order for the polymerization of the epoxy resin to take place. Mixing of the two components in incorrect proportions or incomplete mixing of the components will cause improper curing of the coating and will remain tacky. Thoroughness of the mixing is achieved until a uniform color is obtained.

Some manufacturers provide the two parts in separate cans of the same size and, therefore, mixing of the two parts is done in a separate container. To accurately measure the right amounts of each material before pouring and mixing them in a separate container may not be very practical in a job site. Other manufacturers distribute or sell patching materials with the correct mixing proportions in two cans of different size. This is a more practical solution since it only requires that the component inside the smaller can be poured into the larger can containing the other part, and then mixing the epoxy materials. The only drawback is that the amount of the produced material may in some cases be much greater than needed for a specific application.

Patching materials or compounds are produced by epoxy coating manufacturers so that there are as many patching materials available as there are manufacturers. Patching materials have different characteristics including uncured consistency and viscosity, pot life, color, drying time, curing time, and cured consistency and thickness. Some formulations can be applied right after mixing the two parts or components while other formulations require a standing time period after mixing before application. As with any epoxy, the higher the ambient temperature, the shorter the pot life and drying time. Manufacturers generally specify a minimum ambient temperature for application.

Some trends in the characteristics of different patching material were found during the course of this research. The greater the viscosity of uncured epoxy, the shorter the curing time and pot life. The greater the viscosity, the thicker the coating layer of the patched area. The greater the viscosity, the harder the cured surface. The greater the viscosity, the fewer air voids formed in the patch.

Some ECR specifications mention that patching material should be compatible with epoxy coating on the rebar and should not be harmful to the concrete. In addition, the patch material should conform to the same pre-qualification requirements of all organic coatings.

6.2.2 Repair Procedures

Epoxy coated rebar specifications require that repair of coating damage be done in accordance with the manufacturer's recommendations. A typical set of manufacturer recommendations includes the following:

1. *Surface preparation*: Clean and remove loose and deleterious materials such as moisture, oil, grease, dust, scale, rust, and damaged coating from the area to be repaired,.
2. *Patch application*: Patching material may be applied by brush, roller, or spray. For spray application, follow guidelines regarding tip orifice opening and air supply pressure. Special care should be taken to apply the product before its pot life ends. As with all chemical products, special safety precautions should be observed during application of the patching compound.
3. *Post-application handling*: Allow the patching material to dry before handling and storage of repaired epoxy coated rebars.

There are some practical issues related to surface preparation of a damaged area. Patching manufacturers recommend cleaning of the area to be repaired but do not mention how that task can be accomplished, what specific procedures or tools should be used for adequate cleaning. Options include a wire or wheel brush, sand paper or other types of abrasive paper, or sandblasting. It is also not clearly mentioned the degree of surface cleanliness that should be obtained. Degree of cleanliness range from removing only loose dirt and materials to thorough cleaning to a bright metal surface or “near white” surface. There is no guidance regarding tolerance in the degree of surface cleanliness.

Damage to epoxy coating on steel rebars usually consists of chipped areas of small size. Most damage occurs due to mishandling of the epoxy coated bars during the various stages from production to placement in the structure. Bars may be abused, dragged, hit, pounded, dropped, stepped on, or scratched. Most of the damage occurs on the bar corrugations but some damage occurs on the valleys between corrugations. Such abuse may produce small chipped off areas, scratches, nicks, tears, and abrasion. Damaged areas are usually of very small size, generally less than 1 cm^2. It is very difficult to clean the metallic surface of such small area. If a wire brush is used, the relatively large size and bristle spacing of the brush compared to the small area to be cleaned makes it difficult to achieve good surface cleaning of the exposed metal. In addition, the metallic bristles of the brush rub against the epoxy coating around the damaged area and cause abrasion of the coating. Even though a wire brush may not be the most suitable tool for cleaning of damaged areas in epoxy coated rebars, it is the tool typically employed by contractors when surface cleaning is attempted.

The touch up of bar cut ends presents an interesting problem. When a bar is cut, either with shears or with a chop saw, the edges of the bar at the perimeter of the cut section will be sharp. Patching around sharp edges is very difficult. The patching material will tend to flow away from sharp edges in its uncured state, resulting in a very thin layer of coating when the epoxy completely cures. If the epoxy has a very thin consistency, it may be possible that no material is left on some of the sharp edges, mainly at top edges because the material flows down from those edges. The problem may be aggravated if bars are cut with a torch. The high temperatures needed to cut steel with a flame will leave a thick layer of slag at the cut section. The slag layer has a very irregular, rough surface with many sharp edges all throughout.

Several manufacturer's recommendations mention that patching materials can be applied by brush, roller, or spray. From the above discussion related to the difficulty in cleaning small areas of coating damage, it is evident that applying epoxy materials by roller or spray would be extremely difficult and impractical, and would result in too much material being wasted. Application with a paint brush is easiest and most practical for epoxies with liquid-like consistency. Spreading patch material with a spatula, tongue depressor, or wood stick is the most viable method for epoxies with very thick consistency.

6.3 RESEARCH OBJECTIVES

As previously mentioned, there is no information about the in-situ effectiveness of different patching materials and repair procedures. There are no specifications for testing procedures to evaluate the effectiveness of a patch on an epoxy coated bar. The objective of this research was to determine the effectiveness of the patching and repair materials and procedures presently approved by the Texas DOT and to develop improved guidelines for repairing damaged epoxy coated bars.

In this research, the corrosion performance of several patching materials was investigated. The effect of different rebar surface conditions and application procedures was examined. The effectiveness of patching rebar cut ends was of particular interest. In addition to examining repair procedures following manufacturers recommendations, other repair procedures were evaluated. Of special interest was a study of procedures that are currently practiced in the field. From several field visits it was noted that in many instances, contractors did not follow all the manufacturer's recommendations. Most commonly, repair materials were applied without any surface preparation. In one case, epoxy coated rebars were cut using a torch and the cut ends were immediately touched up without any cleaning (Figure 6.1). Flame cutting leaves a very rough end and burns the epoxy coating, making it very difficult to patch the damage.

Figure 6.1: Improper field practice: Epoxy coated bars were flame cut and, immediately thereafter, bar ends are being touched up by hand.

6.4 TEST PROGRAM

To evaluate the effectiveness of patching materials and procedures to repair epoxy coated rebar, three major series of experiments were conducted: a) Cyclic immersion in NaCl solution, b) electrochemical impedance and polarization resistance, and c) Hot water immersion-adhesion tests. In cyclic immersion and electrochemical tests, the corrosion performance of repair materials is studied. In hot water test, the adhesion quality of patching materials is examined.

6.4.1 Cyclic Immersion Test

6.4.1.1 Test Procedure

Cyclic immersion in a 3.5% NaCl solution was conducted on 80 epoxy-coated rebar samples containing 524 patched areas. Samples were subjected to 200 days of exposure in cycles of 7 days (4 days wet, 3 days dry). Samples were cut from epoxy coated bars as follows:

Type of Damaged Area	Sample Length	Bar Size	ECR Coating
I	16.5 cm to 17.5 cm	#11	a
II	16.5 cm to 18.4 cm	#11	a
III	14 cm 16.5 cm	#10 #11	b a
IV	30 cm	#10 #11	b a

Table 6.1: ECR samples for cyclic immersion test.

Samples were prepared and patched using a variety of repair materials and procedures as described in the next section. Once cured, patch thicknesses at repaired locations were measured with a Mikrotest thickness gage for each specimen. Average patch thickness for different types of repaired area and patching material are listed in Table 6.2. No attempt was made to control patch thickness for all specimens because it is extremely difficult to achieve a specified thickness. The finished thickness of patched areas was a result of the viscosity of each epoxy material.

Patch thickness at rough flame-cut ends was often impossible to measure. The irregular, ridged slag surface was barely covered by a thin film of epoxy at protruding ridge edges. Similarly, attempting to measure patch thickness of small patched areas (few mm^2 in size) was futile. In several cases, thickness of rebar ends patched with epoxy materials *C* and *D* was probably underestimated. The finished coating was thicker than the maximum value of the gage scale (40 mills).

Patching Material	**Types of Damaged Area**				
	I	**II**	**III**	**IV**	**V**
A	7.5	3.9	2.9	3.7	
B	14.3	7.1	8.4	12.9	
C	26.3	24.8	41.9	43.4	38.9
D			43.2		

Table 6.2: Average patching thickness (mills) of different types of repaired area and patching material.

Samples were hung with nylon strings from wooden racks. All rebar specimens were enclosed inside large plastic containers holding the 3.5% salt solution. Wooden supports for the racks were built to permit specimens to be immersed in the solution during wet cycles by lowering the racks. The saline solution was periodically changed when it became contaminated by significant amounts of rust. A view of all rebar samples in the immersion test set-up is shown in Figure 6.2.

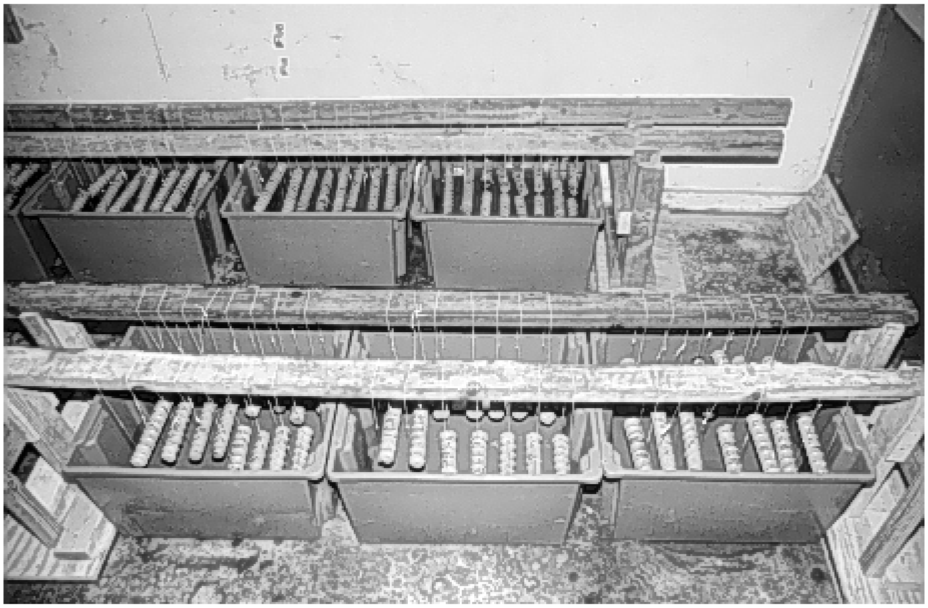


Figure 6.2: Salt immersion test set-up for patched epoxy coated rebar specimens.

Observations of the rebar surface condition at repaired or patched areas were taken every other month. Photographs were taken at different stages to record significant changes. Detailed observations taken throughout the exposure experiment are not included because of space limitations. Instead, the most important events are summarized.

Patching material at repaired areas was removed to uncover and examine the steel surface underneath. Patch materials *A* and *B* were removed with a sharp utility knife. Epoxy materials *C* and *D* were so hard that chiseling (using a hammer) was required to remove the patch. Fusion bonded epoxy coating in the vicinity of patched areas was peeled to inspect the extent of corrosion beyond the repaired zone.

6.4.1.2 Study Variables

The following variables were used for cyclic immersion in NaCl solution:

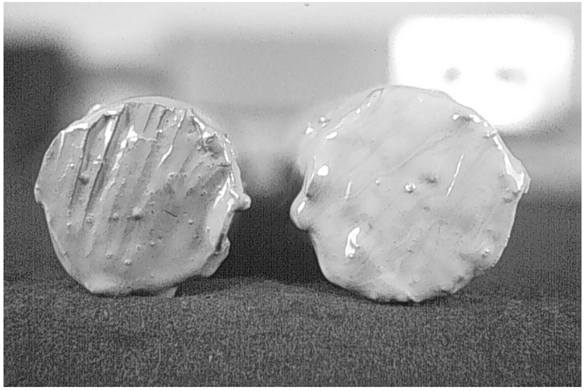
<u>*Patching Materials:*</u>

Three patching materials (*A*, *B*, and *C*) from different manufacturers were evaluated. The feasibility of an industrial coating (material *D*) for repair of coating damage was also explored. The characteristics of each repair material were as follows:

A. Material of very thin consistency in its liquid state. Dried at touch at about 5 hours in a small 2 oz. cup at a temperature of approximately 19°C. Its color was light green. Could be applied by brush, roller, or spray.

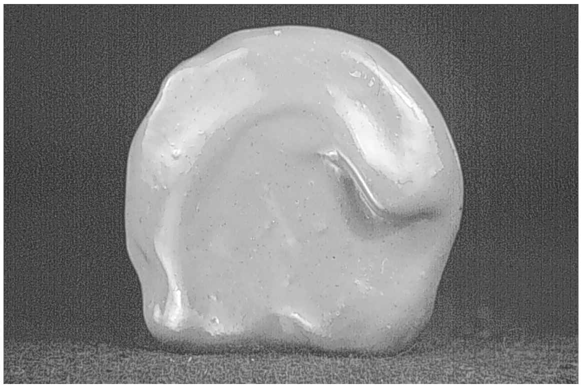
B. Material of viscous consistency in its liquid state. Dried at touch at about 3 hours in a small 2 oz. cup at a temperature of approximately 19°C. Its color was grayish green. Could be applied by brush or roller.

C. Material of very thick consistency in its uncured state. Dried at touch at about 10 minutes in a small 2 oz. cup at a temperature of approximately 19°C. Its color was bright green. Due to its thick consistency, could not be applied by brush, roller, nor spray. Could be applied by spreading with a spatula, tongue depressor, or wooden stick.



(a): Patching materials *A* (left specimen) and *B* (right specimen).

(b): Patching material *C*.



(c): Epoxy material *D*.

Figure 6.3: Specimens patched with different patching materials.

D. Material of very thick consistency in its uncured state. Dried at touch at about 10 minutes in a small 2 oz. cup at a temperature of approximately 19°C. Its color was gray. Due to thick consistency, could not be applied by brush, roller, nor spray. Could be applied by spreading it with a spatula, tongue depressor, wooden stick, etc.

General properties of all four epoxy materials are included in Appendix C. Figure 6.3 shows bar ends patched with materials *A*, *B*, *C*, and *D*.

Damaged Areas:

I. *Areas between Bar Deformations*: Rectangular incisions of 11 x 16 mm and 6 x 6 mm were made through the coating with a sharp utility knife. Coating inside the rectangular incision was removed with a chisel blade mounted on an X-acto knife. Figure 6.4 shows rectangular damaged areas on a typical ECR sample. The objective of this type of damage was to have controlled areas of the same size. In this manner, performance of patched areas could be evaluated by size.

II. *Areas on Bar Deformations*: Intentional damage of irregular shape was created by subjecting ECR to different types of action, such as dragging, dropping, or hammering, which resulted in damage mainly at rebar ribs (both transverse and longitudinal). In many instances, damaged areas were enlarged by chipping with a utility knife. This type of coating damage is similar to that produced in the field. Size of damaged areas ranged from barely visible areas of less than 1 mm^2 up to large areas (90 mm^2). The average damaged area was 13.09 mm^2 and the median value was 2 mm^2. Figure 6.5 illustrates two typical samples with irregular shaped coating damage on bar ribs.

III. *Saw-Cut Rebar Ends*: Epoxy coated rebar samples were cut with a chop saw and bar ends were patched. See Fig. 6.6 for a typical sample.

IV. *Flame-Cut Rebar Ends*: Epoxy coated rebar samples were cut with a torch and bar ends were patched. Samples with flame-cut ends were about twice as long as those samples with saw-cut ends because the torch cutting operation burned a good amount of the epoxy coating. Although flame cutting epoxy coated rebars is not recommended, it is done in the field and it was felt important to investigate the possible repercussions of such practice. Figure 6.7 (a, b, and c) shows samples with torch cut ends.

V. *As-Received, Patched, Shear-Cut Rebar Ends*: Samples in which touching up of bar ends was done by the coating applicator. The use of these samples allowed to compare the performance of samples patched by the coating applicator against that of samples patched in the laboratory. A bar end patched by the coating applicator is shown in Figure 6.7 (d).

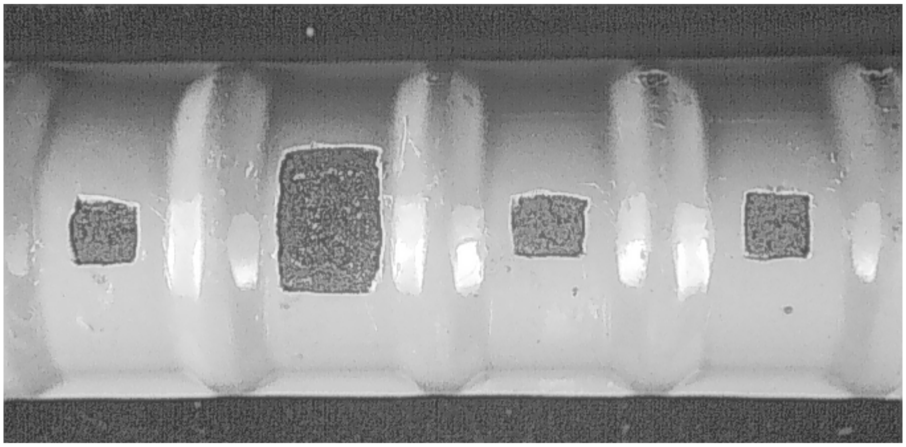
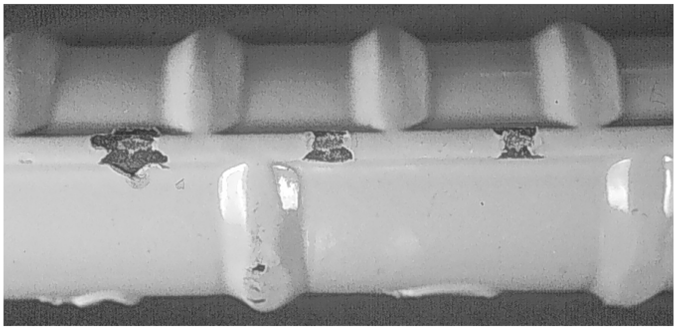
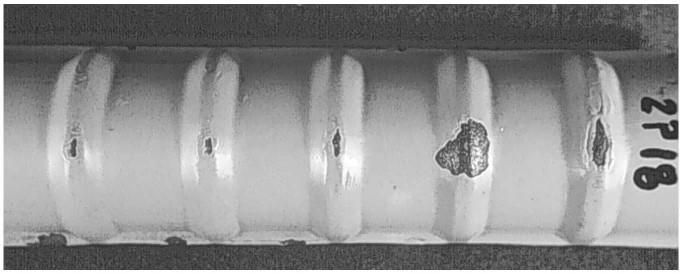


Figure 6.4: Damaged areas between bar deformations

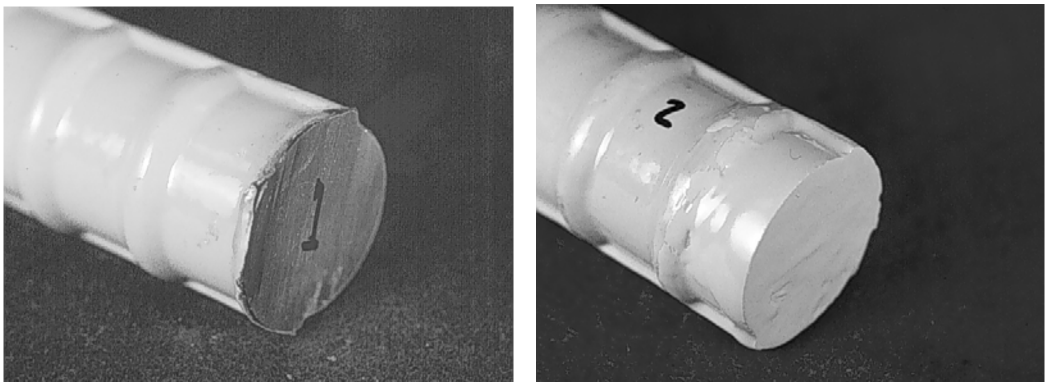


(a): Coating damage on longitudinal rib.



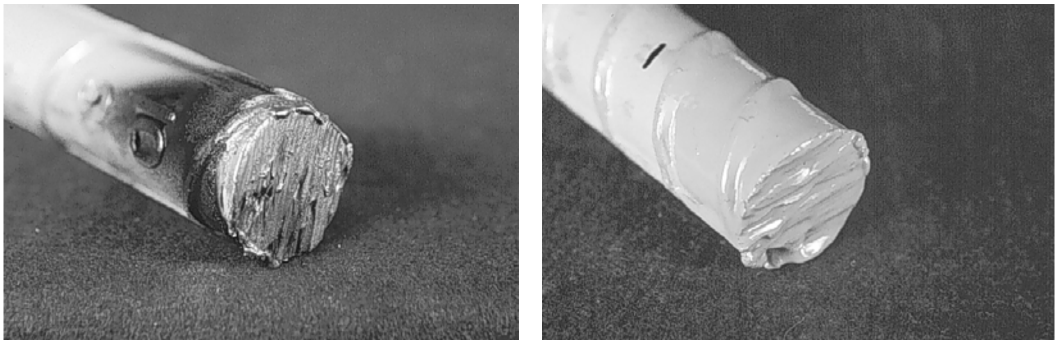
(b): Coating damage on transverse ribs.

Figure 6.5: Damaged areas on bar deformations.

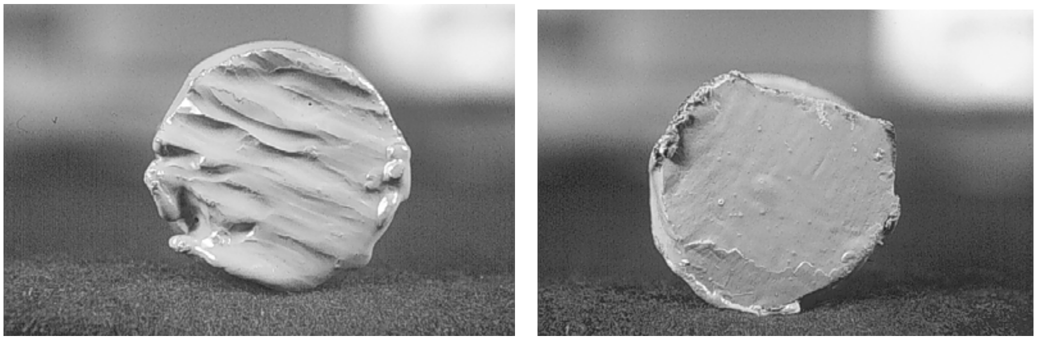


(a): Saw-cut bar end. (b): Patched bar end (saw-cut).

Figure 6.6: Specimens with saw-cut bar ends



(a): Torch-cut bar end. (b): Patched bar end (torch-cut).



(c): Patched bar end (torch-cut) (d): Shear-cut bar end patched by coating applicator

Figure 6.7: Specimens with torch-cut ends patched at the laboratory (a, b, and c) and specimen with shear-cut end patched by coating applicator (d).

<u>*Repair Procedures:*</u>

a. Patching immediately applied after laboratory-type surface cleaning

b. Patching immediately applied after damage and surface cleaning (wire brush)

c. Patching applied on smoothed and cleaned (wheel grinder/brush) rebar end (no outdoor exposure)

d. Patching applied on wheel brush-cleaned rebar end (no outdoor exposure)

e. Patching applied on surface cleaned (wire brush) after outdoor exposure

f. Patching applied after short outdoor exposure of previously cleaned surface (wire brush)

g. Patching applied on smoothed and cleaned (wheel grinder/brush) rebar end after outdoor exposure

h. Patching applied after short outdoor exposure of previously smoothed and cleaned rebar end (wheel grinder/brush)

i. Brush-applied patching on untreated surface after outdoor exposure

j. Spatula-applied patching on untreated surface after outdoor exposure

k. Hand-applied patching on untreated surface after outdoor exposure

l. Brush-applied patching on untreated surface immediately after saw or torch cutting

m. Hand-applied patching on untreated surface immediately after saw or torch cutting

n. Touch-up of as-received patch

A description of each of the above procedures is included in Appendix C.

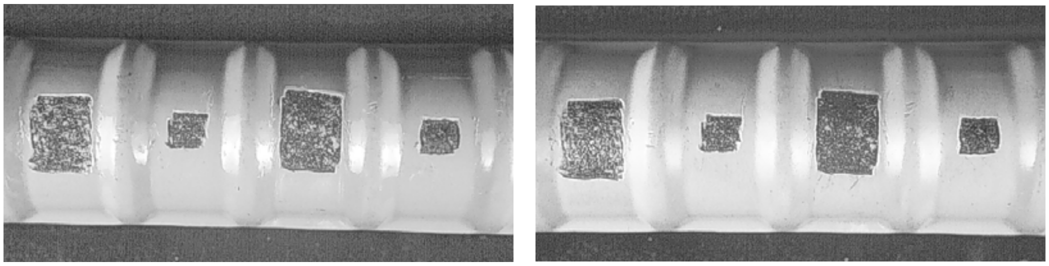
For facility, repair procedures can be categorized as follows:

i) *Specimens with no surface preparation*: The exposed metallic surface at damaged areas and rebar cut ends was not cleaned at all before patching. In several cases, bar samples were subjected to outdoor exposure for 1 or 2 weeks until rust developed on the steel surface. In other cases, patching material was applied on hot rebar cut ends immediately after torch or saw cutting. Patching material was applied with a small paint brush, spread with spatula, or spread with glove-covered finger. Procedures *i, j, k, l, m,* and *n* are included in this category. Specimens with no surface preparation are illustrated in Fig. 6.8 (a, c, and e).

ii) *Specimens with surface preparation*: The exposed metallic surface at damaged areas and rebar cut ends was cleaned either with a wire brush or wheel brush before patching. Some rebar cut ends were rounded and smoothed with a wheel grinder. In several cases, bar samples were subjected to outdoor exposure for 1 or 2 weeks before surface cleaning until rust developed on the steel surface. Some specimens were subjected to additional 24 to 48 hours of outdoor exposure after surface cleaning and before patching application. Patching material was applied with a small paint brush or spread with spatula. Procedures *b, c, d, e, f, g,* and *h* are included in this category. Figure 6.8 (b and d) shows various specimens with surface preparation.

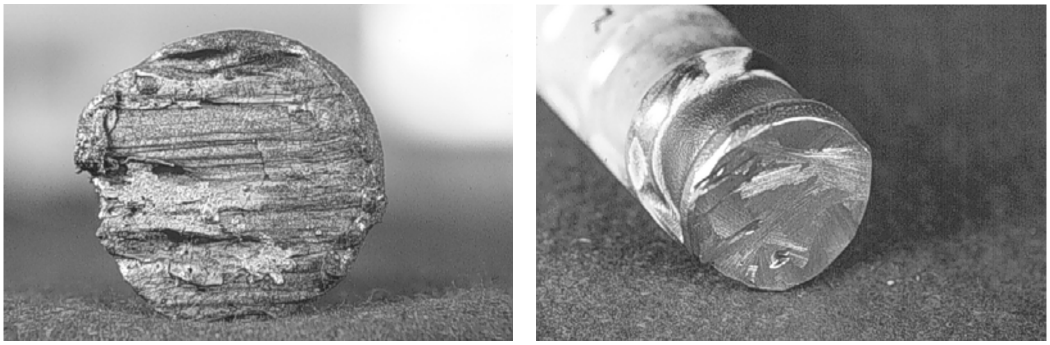
(a) Unclean bar end surface after 2 weeks of exterior exposure.

(b): Surface preparation with wheel grinder and wheel brush.



(c): Appearance of damaged areas after two weeks of outside exposure.

(d): Appearance of damaged areas after cleaning with a wire brush.



(e): Appearance of torch-cut end after two weeks of exterior exposure.

(f): Appearance of torch-cut end after wheel grinding and wheel brushing.

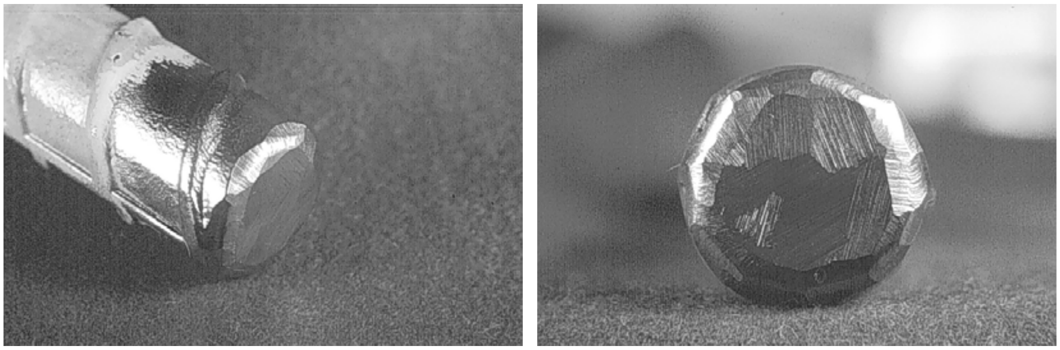
Figure 6.8: Specimen with no surface preparation (a); appearance of specimens before and after surface preparation (b through f).

i) *Control Specimens (Procedure a)-* Patching material applied to specially prepared bar surface for following two cases:

- Rebar cut ends [Figure 6.9 (a) and (b)]: Sharp edges at perimeter of rebar cut sections were cleaned from burrs, rounded, and smoothed using a wheel grinder and wheel brush. The sharply ridged slag surface in flame-cut rebars was smoothed and rounded as much as possible. The metallic surface was cleaned to a near-white, polished finish with the aid of a wheel brush. All dirt, slag, burrs, rust, coating, and other contaminants were thoroughly removed.
- Bar surface [Figure 6.9 (c) and (d)]: On an undamaged epoxy coated rebar sample, portions of the coating were removed with a wheel brush at the following locations: a) bar surface between ribs (1.4 cm x 2.2 cm), and b) bar deformations or ribs (2.5 cm x 3.0 cm). The uncovered metallic surface was cleaned to a near white, polished finish with the wheel brush. An effort was made to get rid of as many coating remains as possible.

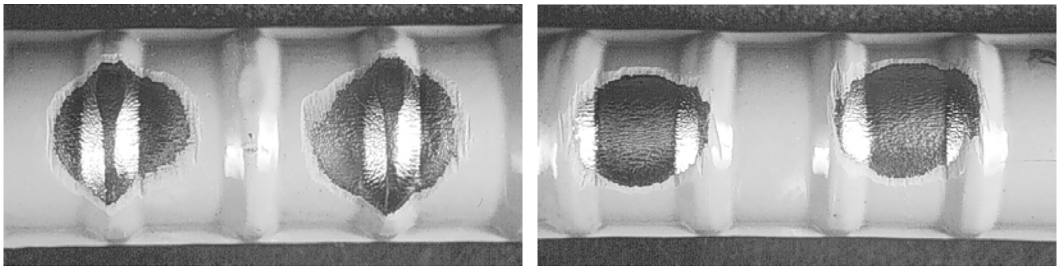
Prior to patching, any remaining grease and dirt on the surface was removed with acetone to produce a shinning, bright metallic surface.

In all repair procedures, patching material was allowed to cure overnight before any further handling of patched samples. In samples where areas were patched on both rebar sides, patching was applied first on one side, then was allowed to completely dry, then sample was turned over and patching was applied on the other side.



(a): Aspect of specially cleaned bar end.

(b): Front view of specially cleaned bar end.



(d): Specially cleaned surfaces on bar deformations.

(c): Specially cleaned areas between bar deformations

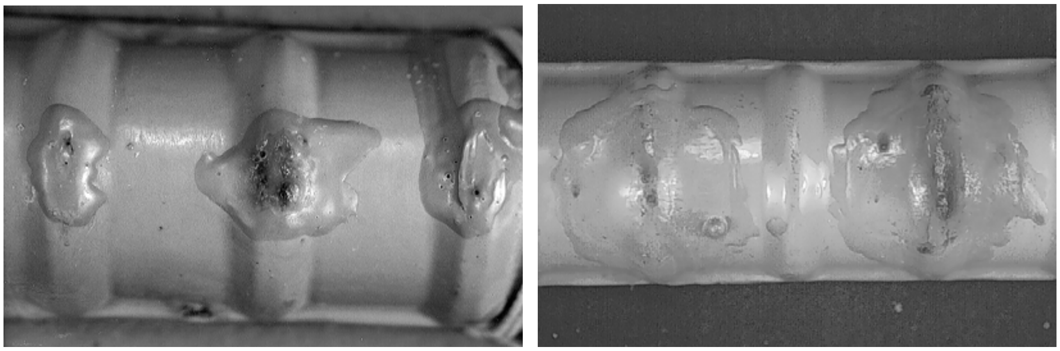
Figure 6.9: Specially cleaned surfaces before patching application (control specimens).

6.4.1.3 Test Results and Discussion

Corrosion of Specimens

Corrosion on patched surfaces occurred in the form of coating blisters, patch softening and debonding, rust spotting and staining, fine rust exudation, and breakage and delamination of patch at perimeter of bar end section. Rust staining spread beyond patched end section into adjacent bar side surface. A few photos illustrating corrosion on patched surfaces and ends are shown in Figures 6.10 and

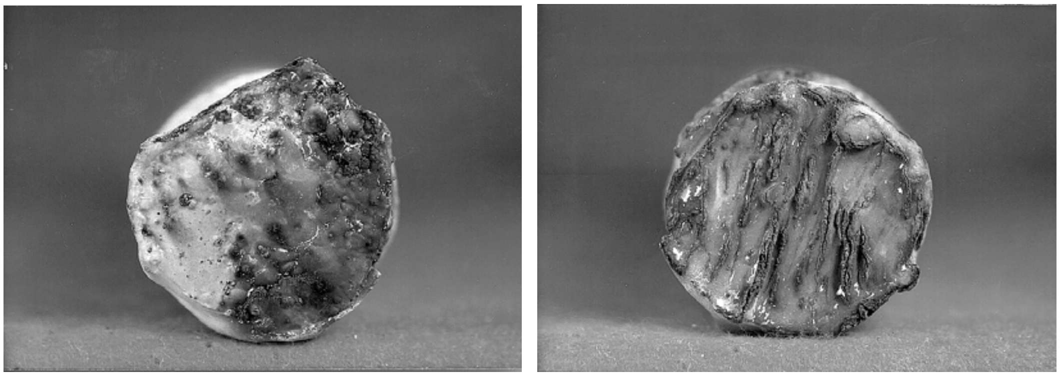
6.11. Corrosion on the steel surface beneath the patch produced a uniform black or dark rusted surface combined with areas of reddish-brown (or other tones of brown) rust. There were zones with accumulation of black, reddish-brown, or other tones of brown, fine rust products, especially underneath areas with softened or debonded patches and blisters. Mounds or bulges made of accumulated, hardened rust (black or reddish-brown) formed underneath patching blisters. In several bar ends, the dark rusted surface could be removed in large, thick (0.5 mm), flat layers or flakes with a utility knife, leaving behind a uniform layer of fine black rust with scattered reddish-brown rust spots. In cases of most severe corrosion, several shallow pits developed. Steel surface at adjacent non-corroded portions looked dull. A few photos illustrating corrosion on steel surfaces beneath patch are shown in Figures 6.12 and 6.13.



(a): Corrosion of patched area on bar deformation.

(b): Rust stains on repaired areas on bar deformations.

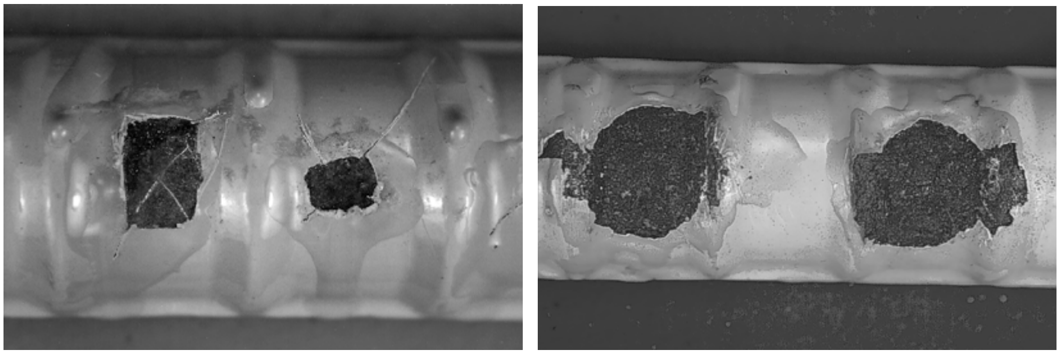
Figure 6.10: Corrosion of patched areas on bar surface after 200 days of immersion in salt solution.



(a): Corrosion of patched end (shear-cut).

(b): Corrosion of patched end (torch-cut).

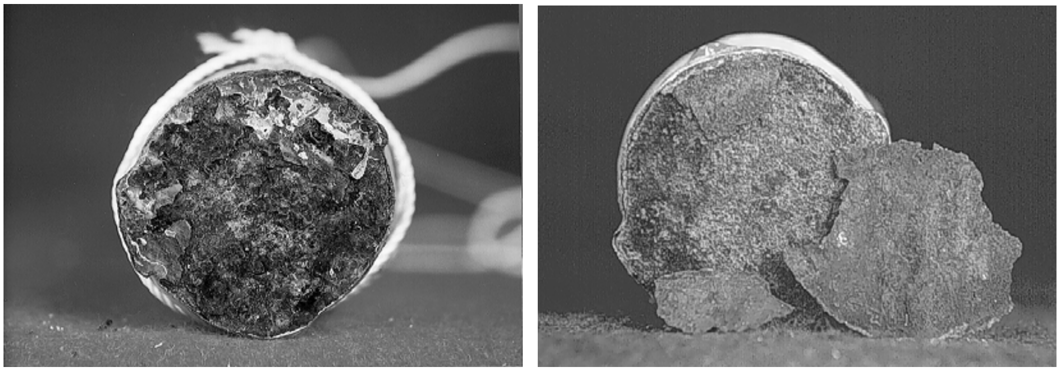
Figure 6.11: Corrosion of patched bar ends after 200 days of immersion in salt solution.



(a): Corrosion of steel surface underneath patch on damaged areas.

(b): Corrosion of steel surface beneath patched areas.

Figure 6.12: Aspect of corroded steel surfaces underneath patched areas after 200 days of exposure.



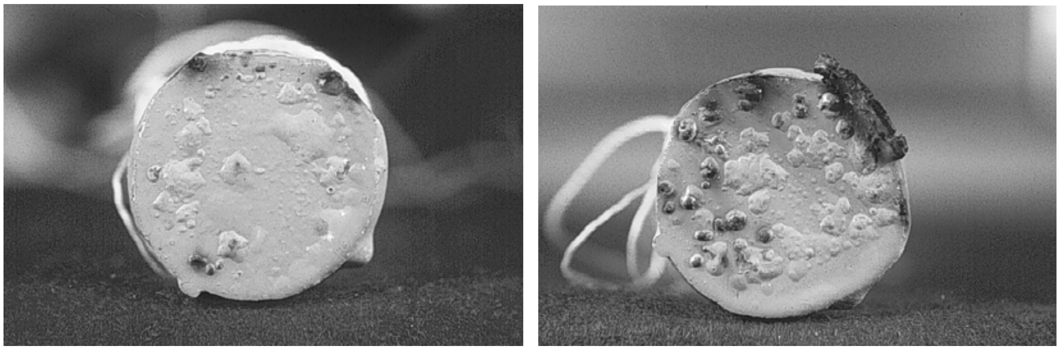
(a): Corrosion of bar end surface underneath the patch.

(b): Rust layer came off corroded bar end surface beneath the patch.

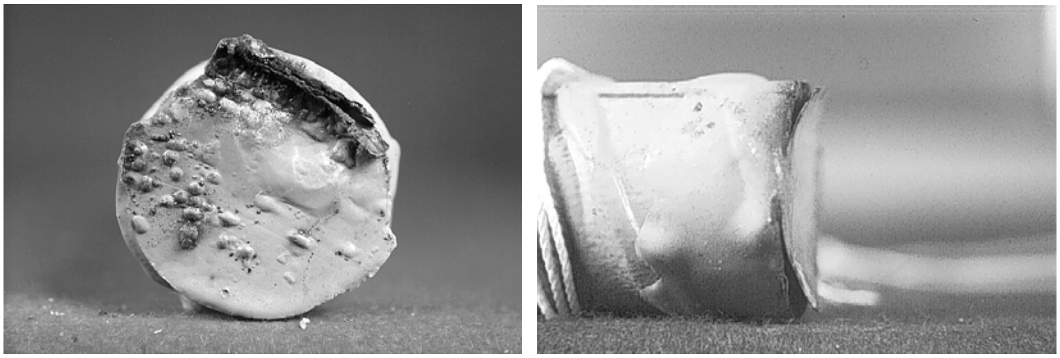
Figure 6.13: Appearance of corroded bar end surfaces underneath the patch after 200 days of exposure.

From periodic examination of specimens, various corrosion stages for patched, repaired areas were observed:

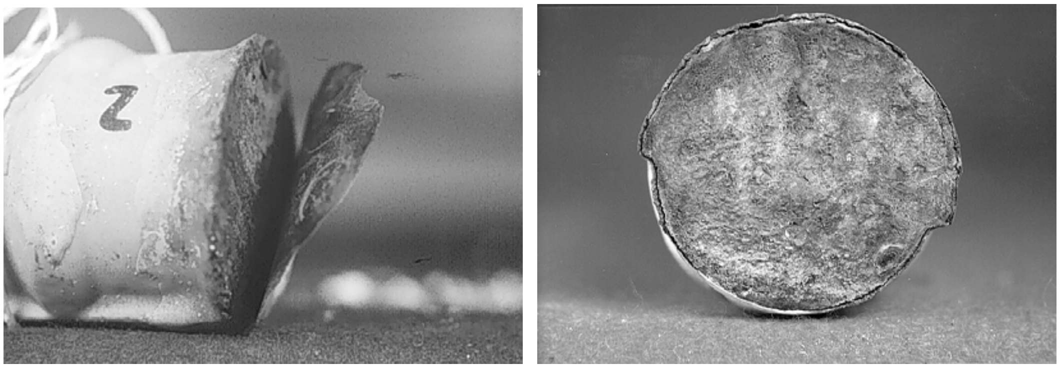
1) Salt solution permeates through patch layer until patch eventually loses adhesion and slightly bulges at certain areas of small to medium size [Fig. 6.14 (a)]. Solution seems trapped underneath patch at such areas. This phenomenon is called patch softening in this discussion because the patch feels soft at these areas. Small to medium size blisters develop on patched surface. At patched areas on bar sides, rust spotting or staining of small size may form anywhere on the patch surface (around blisters, at patch boundaries, on pinholes, etc.). On patched ends, rust spotting or staining of small or medium size forms preferentially around perimeter of rebar end section, at burrs, at slag ridges, and around blisters [Fig. 6.14(a)].



(a): Corrosion stage 1. (b): Corrosion stage 2



(c): Corrosion stage 3. (d): Corrosion stage 4.



(e): Corrosion stage 4. (f): Corrosion stage 4.

Figure 6.14: Corrosion progression of patched bar ends.

2) Corrosion progresses with subsequent wet-dry cycles. Debonded, softened patch areas increase in size. More blisters form and existent blisters enlarge and bulge further. Already present rust spots and stains gradually increase in size and additional rust spotting may appear, especially around perimeter on bar ends [Fig. 6.14 (b)].

3) Patch breaks and rust exudes at blister edges (all patched areas) and perimeter edges (bar ends) [Fig. 6.14(c)]. More salt solution and oxygen is accessible to steel surface through small zones of patch breakage. Areas of debonded patch material have medium or large size. Presence of medium size to large rust stains. Widespread rust staining around perimeter of bar ends and at sharp, projecting burrs and slag ridges [Fig. 6.14(c)]. Rust staining and blistering spreads beyond patched end section into adjacent bar side surface.

4) Widespread rust staining over the whole patch surface on bar ends (less extensive on other patched areas). Patch continues to break and separate from steel surface at perimeter of bar ends [Fig. 6.14(d)]. In a few samples, patch material completely separated and lifted from the steel surface [Fig. 6.14(e)]. Uniform corrosion (black or dark with spots of brown rust) develops on steel surface underneath the patch. Extent of uniform corrosion is variable: It ranged from a portion of repaired area to full, complete patched area and spreading a few millimeters (centimeters on bar ends) into adjacent surface underneath epoxy coating [Fig. 6.14(f)]. Fine reddish-brown (or other tones of brown) rust accumulates at areas where more salt solution is

concentrated (softened or debonded patch and blisters). At blistered patch locations, corrosion products accumulate and form hard mounds or protrusions. In some cases, shallow pits developed.

In the corrosion process described, penetration or diffusion of chlorides through the layer of patching material is the necessary first step for corrosion initiation and progression. Therefore, thickness of the patch layer is an important feature for a repair material and procedure to be successful. The thicker the patch layer, the slower the chloride diffusion, and the more delayed the corrosion initiation.

Rust spotting and staining may occur anywhere within the patched area but appear more frequently at blisters and near boundaries of patched area and seem to indicate vulnerable zones for corrosion attack. As the patch swells to form a blister, the coating eventually breaks at the perimeter of blister. Breakage zones are of small, microscopic size. More chlorides and oxygen enter under patch and rust products exude at the breaks. At boundaries of patched area, there may be microscopic gaps between the patching material and epoxy coating. Chlorides and oxygen access the steel surface through those gaps and the patch debonds and blisters close to the boundary. Rust exudes through the broken patch at blisters and/or through gaps at boundary of the patched areas.

On bar ends, the perimeter is the most vulnerable zone for corrosion attack. Other vulnerable areas are projecting or protruding burrs and slag ridges. These vulnerable zones have one characteristic in common -sharp edges. If the patching material has thin, very liquid consistency, it will have the tendency to flow away from sharp edges, resulting in a very thin coating layer. The patch layer was so thin at the perimeter edge of some end surfaces that the steel could be seen (Fig. 6.15). It was very difficult to coat sharp edges at rebar ends with patching materials of thin consistency, despite the fact that liberal amounts of epoxy were applied. Chlorides diffused easily to the steel surface through zones of very thin patch thickness. As corrosion progressed, thinner patches offered less resistance to debonding and blistering. Once enough rust accumulated, the increase in volume exerted an outward pressure on the patch layer and easily tore the coating at its weakest zone: sharp edges, where the patch was very thin. Once the patch was broken, chlorides and oxygen directly accessed the steel surface and corrosion accelerated. Therefore, the adverse effect of thinly covered areas was threefold: Initially, it allowed easy diffusion of chlorides; subsequently, as corrosion progressed, it was the weak link for patch tearing; and finally, when the patch tore, chlorides and oxygen had direct access to the steel surface.

Touched-up surfaces cut with a chop saw behaved differently than those surfaces cut with torch. Saw-cut surfaces were more prone to patch softening and blistering than torch-cut surfaces. Surfaces cut with a chop saw were level and smooth. Once chloride solution permeated, surface smoothness facilitated corrosion undercutting, patch debonding, and patch blistering. Torch-cut surfaces did not show extensive patch debonding and blistering. Instead, they experienced breakage and extensive rust staining at multiple locations along slag ridges (Fig. 6.16). Both torch-cut and saw-cut surfaces experienced rusting and patch tearing around perimeter of section. However, patch material separated and lifted from steel surface only at saw-cut surfaces. Surface smoothness preserved the integrity of the debonded patch.

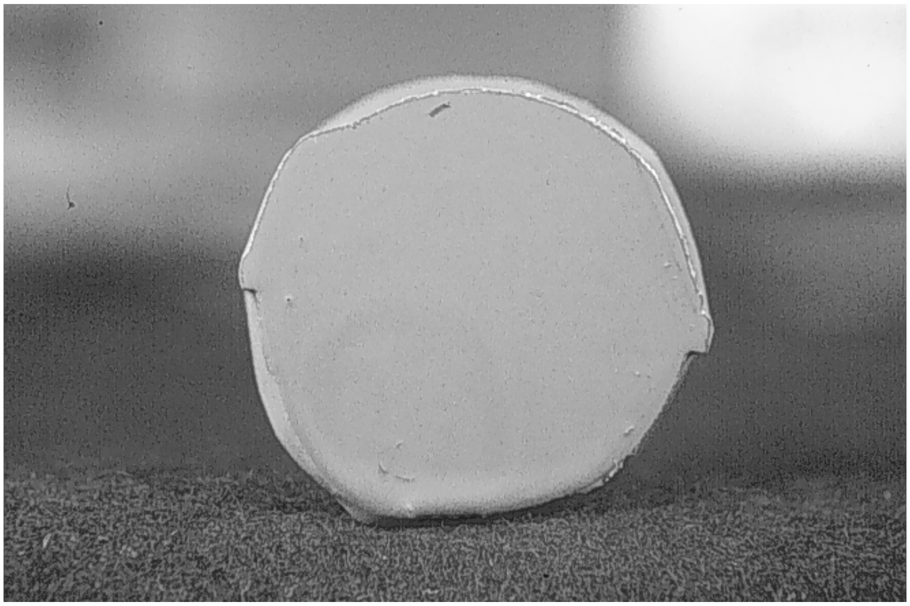
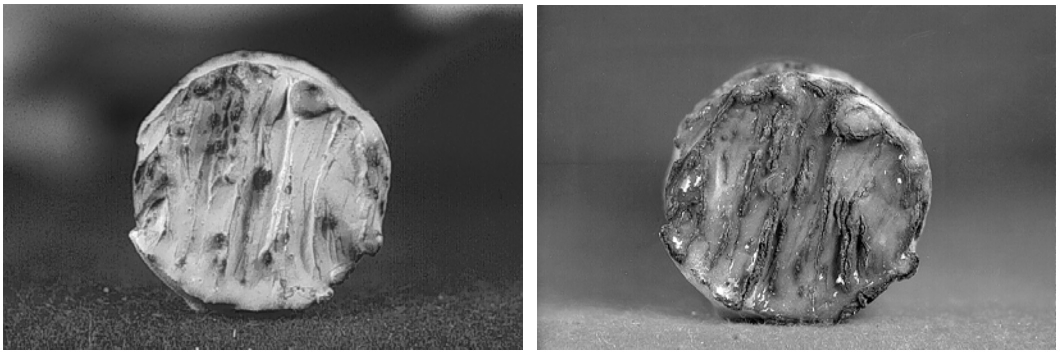


Figure 6.15: Visible steel due to very thin patch around perimeter edge on bar end.



(a): Appearance after 53 days of immersion in 3.5% salt solution.

(b): Appearance after 200 days of immersion.

Figure 6.16: Corrosion of flame-cut and patched bar ends.

Depending on the patching material used, several patched areas exhibited relatively good corrosion performance. When corrosion occurred, it was confined to a limited area and was rather superficial, with no appreciable amount of metal loss or pitting. Many specimens with good performance did not experience corrosion at all and the steel surface maintained its original condition (either cleaned or unclean). The assessment of “no corrosion attack” on unclean, patched areas (atmospherically rusted steel surface not cleaned before touching-up) was made when only the pre-existent, thin layer of rust appeared on the steel surface and no evidence of chloride-induced corrosion (dark or black corroded metal combined with reddish-brown rust) was found (fig. 6.17). In fact, the amount of atmospheric rust was less at the end of the exposure study than at the beginning. Most of the original rust was blended with the patching material. Upon removal of the coating, there was only a very superficial layer of old rust left.

Patch adhesion to steel surface was lost in corroded areas. Patching material could be easily peeled off and be lifted in large portions with a sharp utility knife. In many cases, rust adhered well to the patch and removal involved cutting through the rust layer. At non-corroded areas, there was inconsistent patch adhesion. In most cases, patch adhesion to steel remained intact and the patch material could only be removed in small chips. Many small chips of patching material remained stuck to the steel surface. However, there were several cases where adhesion to the steel was marginal or poor but no corrosion occurred (Fig. 6.18). Patch adhesion seems to always be lost because of steel corrosion; however, adhesion may not be crucial for corrosion protection.

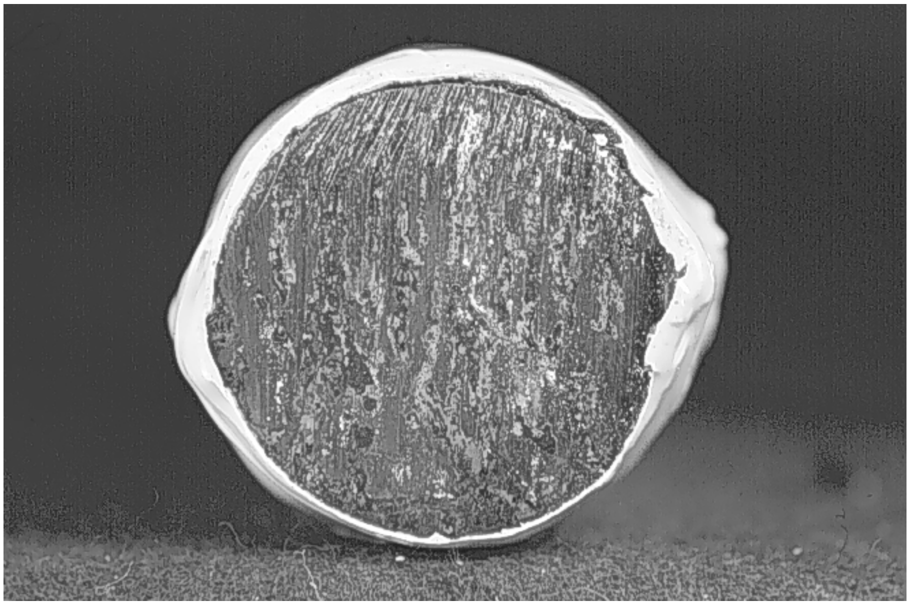
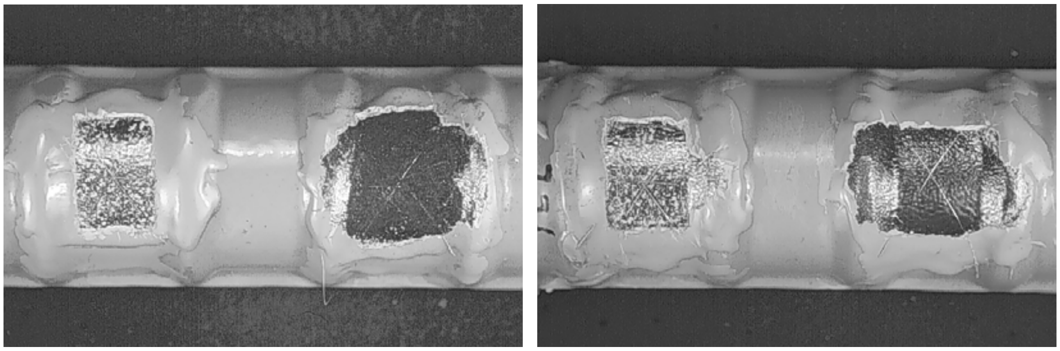


Figure 6.17: Appearance of bar end surface after 200 days of exposure to 3.5% NaCl solution. Surface was not cleaned before patching. This specimen exhibited good corrosion performance.



(a): Good adhesion and no corrosion on left area. Poor adhesion with surface corrosion on right area.

(b): Uncorroded areas with good adhesion (left area) and poor adhesion (right area).

Figure 6.18: Patch adhesion after 200 days of exposure to 3.5% NaCl solution of specimens with varying degrees of corrosion.

Corrosion Evaluation

To compare corrosion performance of different coating repair materials, a rating system was developed to evaluate corrosion activity of each patched specimen as described below:

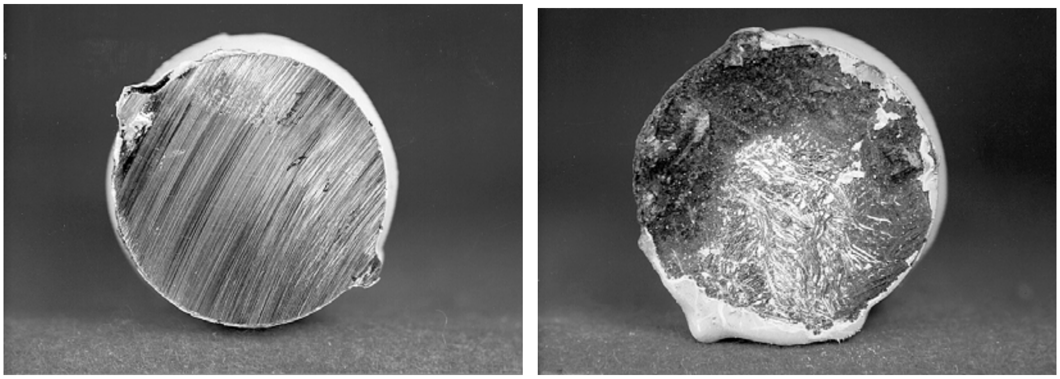
1. None
2. Slight
3. Moderate
4. Moderate to Severe
5. Extensive

Specimens were evaluated both before and after peeling of patching material. A detailed description of each of the above indexes is explained in subsequent paragraphs.

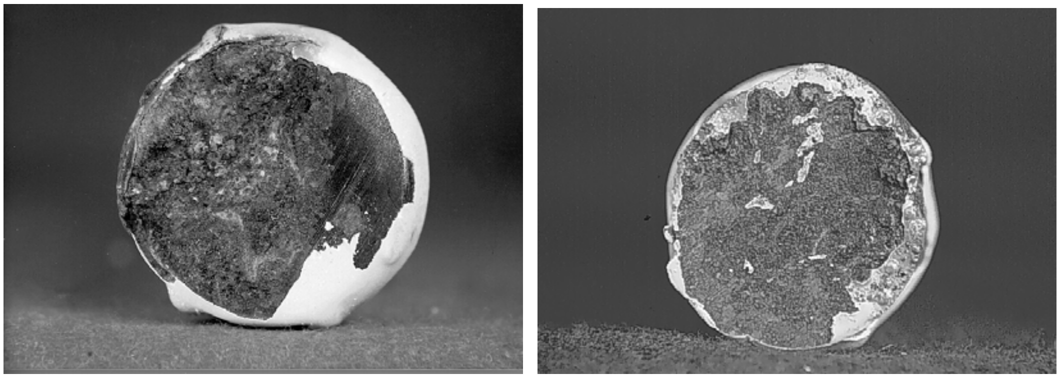
Corrosion rating of patched areas

1: None

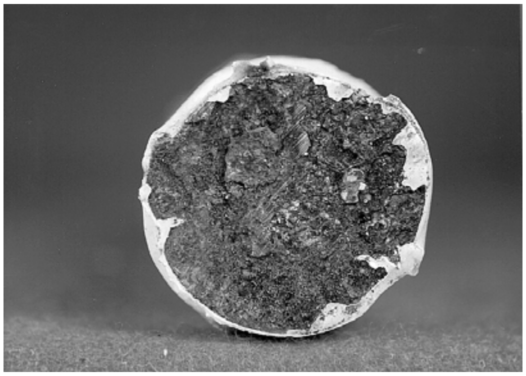
Patch surface was clean without rust staining, patch softening, or patch blistering. Steel surface underneath the patch remained in the condition noted before patching, that is: a) bright, shiny steel for surfaces thoroughly cleaned before patching, and b) no change in appearance of rust for surfaces not cleaned prior to patching. Patch adhesion ranged from good to poor. See Fig. 6.19(a) for an example of a rated 1 specimen.



(a): Rating 1. (b): Rating 2.



(c): Rating 3. (d): Rating 4.



(e): Rating 5.

Figure 6.19: Corrosion rating of patched specimens.

<u>**2:** Slight</u>

Corrosion was observed on one third or less of steel surface area beneath the patch. Surface no longer appeared smooth and showed generally superficial rusting. On patched ends, the corroded portion may have spread on bar side surface several centimeters beyond the cut end section. Adhesion of patch to steel surface was marginal. A few tiny, small rust deposits were present on the patch surface. Thirty percent or less of the patch surface area exhibited rust staining. Some blisters were formed. There was partial patch softening and debonding. See Fig. 6.19(b) for an example of a rating level 2.

<u>**3:** Moderate</u>

Corrosion spread on one third to two thirds of steel surface area underneath the patch. Corrosion ranged from superficial to loss of smooth appearance. On patched ends, the corroded portion spread on bar side surface several centimeters beyond the cut end section. Several large and small rust deposits were present on the patch surface. Rust staining was observed on 30% to 60% of the patch surface area. There was extensive blistering and patch softening and debonding. Patch started to crack at patch boundaries or sharp surface edges. Patch adhesion to steel surface was marginal to poor. See Fig. 6.19(c) for an example of a level 3 rating.

<u>**4:** Moderate to severe</u>

Corrosion spread over more than two thirds of steel surface area beneath the patch. Mostly superficial rusting but some pitting and accumulation of rust was observed. On patched ends, corrosion spread on the bar side surface several centimeters beyond the cut end section. At other repaired areas, corrosion extended a few millimeters beyond the patched area. Several to many large rust deposits were present on the patch surface. Overall rust staining ranged from 60% to 90% of patch surface area. Patch clearly delaminated and may have broken at sharp edges. Patch adhesion to steel surface was marginal to poor. See Fig. 6.19(d) for an example of a rating level 4.

5: Extensive

Corrosion was uniform over the whole steel surface area underneath the patch. Shallow pitting and accumulation of rust layers were observed. On patched ends, corrosion spread on bar side surface several centimeters beyond the cut end section. At other repaired areas, corrosion spread well beyond the patched area. The patch completely debonded from steel surface. Overall rust staining was observed over more than 90% of patch surface area. Patch adhesion to steel surface was poor. See Fig. 6.19(e) for an example of extensive corrosion.

Evaluation Results and Discussion

Average and standard deviation of corrosion ratings for different types of damaged areas and patching materials are summarized in Table 6.3.

Most patched areas on the bar surface exhibited relatively good corrosion performance with an average corrosion rating of 1.7 (Type I) and 1.6 (Type II) (Fig. 6.20). When corrosion occurred, it was rather superficial, with no appreciable amount of metal loss or pitting. Many specimens did not experience corrosion at all and the steel surface maintained its original condition (either cleaned or unclean). However, more specimens with patched ends experienced extensive corrosion, with an average corrosion rating for saw-cut ends of 2.8 and 3.4 for flame-cut ends. Shear-cut ends patched at the coating plant performed very poorly, with an average corrosion rating of 4.3 (Fig. 6.20). Poor performance of patched rebar ends was due to the vulnerability of sharp edges as discussed earlier.

Patching Material	Type of Damaged Area											
	I			II			III			IV		
	N	Avg	σ	N	Avg	σ	N	Avg	σ	N	Avg	σ
A	44	2.6	1.3	99	2.4	1.8	27	4.7	0.4	20	5	0
B	45	1.1	0.6	119	1.2	0.8	19	2.3	1.3	21	3.1	1.2
C	22	1.0	0	37	1.01	0.08	25	1.06	0.2	10	1.01	0.03
D							30	1.0	0.02			

No: Number of readings
Avg: Average
σ: Standard Deviation

Table 6.3: Average and standard deviation of corrosion ratings of patched areas after 200 days of exposure.

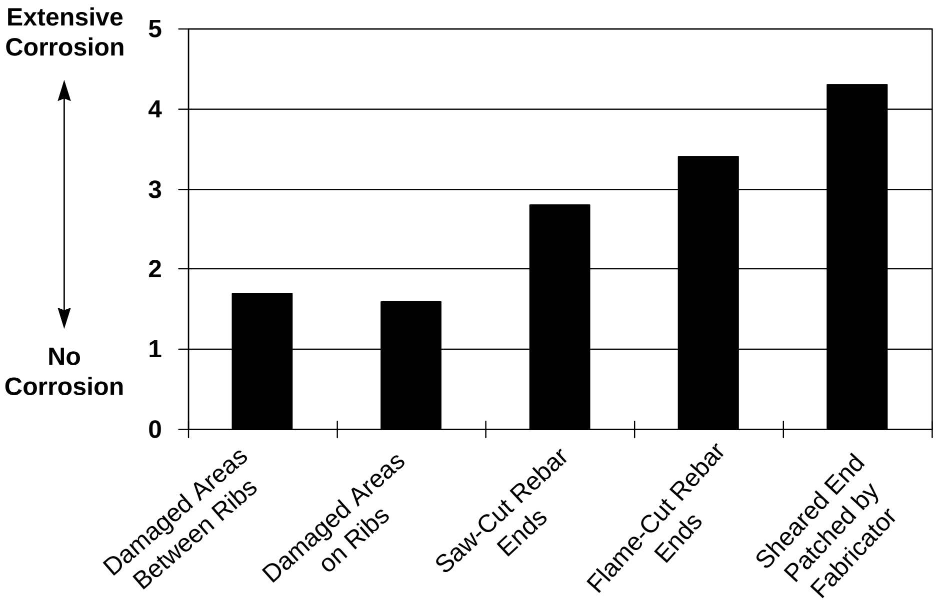


Figure 6.20: Corrosion rating of different damaged areas.

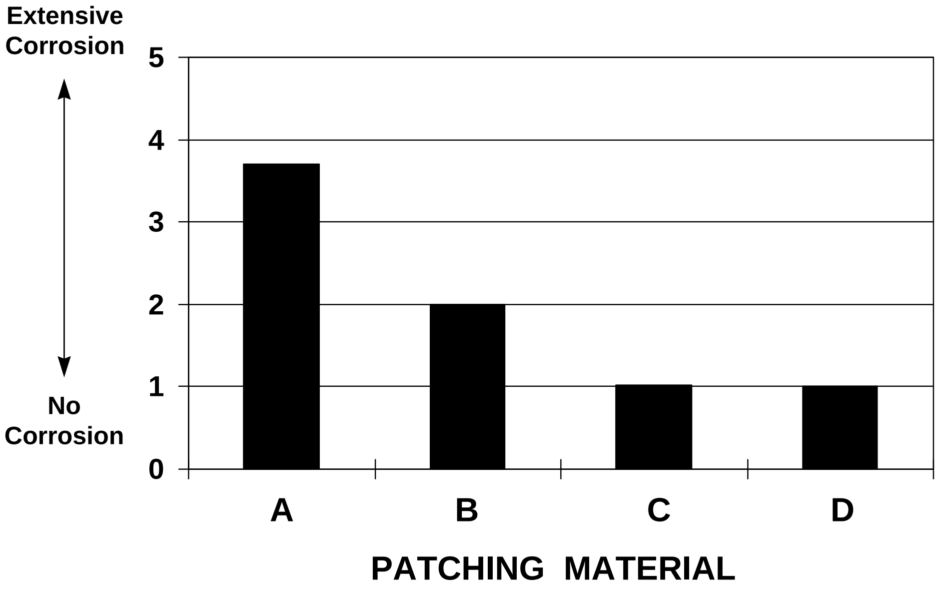


Figure 6.21: Corrosion performance of different patching materials.

There was a clear trend in the relative performance of specimens repaired with different patching materials (Fig. 6.21). Consistently, specimens patched with materials *C* and *D* showed excellent corrosion performance. Specimens repaired with material *B* exhibited more corrosion than those specimens patched with materials *C* and *D*. Specimens patched with material *A* underwent the greatest corrosion attack. Figure 6.22 illustrates the performance of repaired areas type I (patched damage between ribs) and III (saw-cut and patched rebar ends) with different patching materials. Likewise, Fig. 6.23 shows corrosion ratings for repaired areas II (patched damage on ribs) and IV (flame-cut and patched rebar ends). For all cases, patching material *C* performed best and material *A* worst. The average thickness obtained with each patching material is plotted at the top of both figures. Clearly, as patch thickness increased, corrosion performance improved.

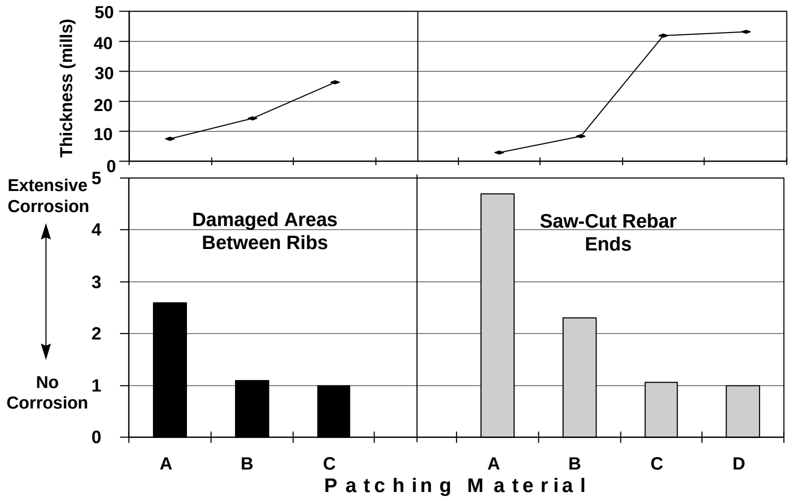


Figure 6.22: Comparative performance between 2 types of specimens repaired with different patching materials.

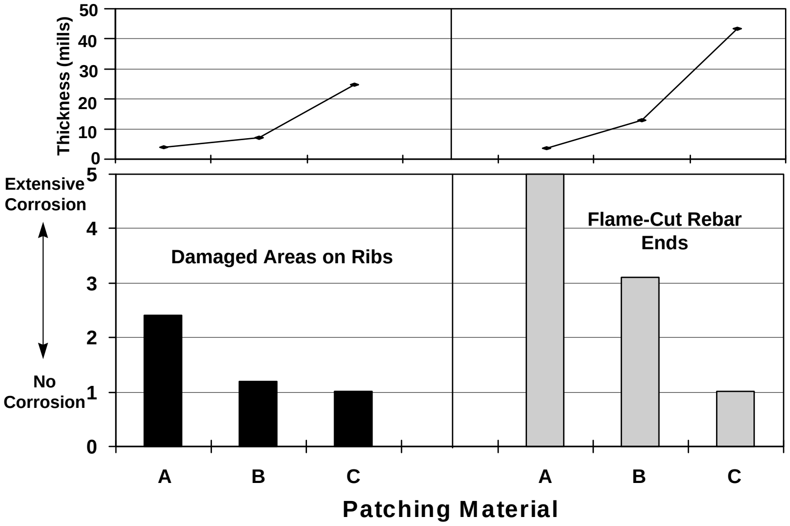


Figure 6.23: Comparative performance between 2 types of specimens repaired with different patching materials.

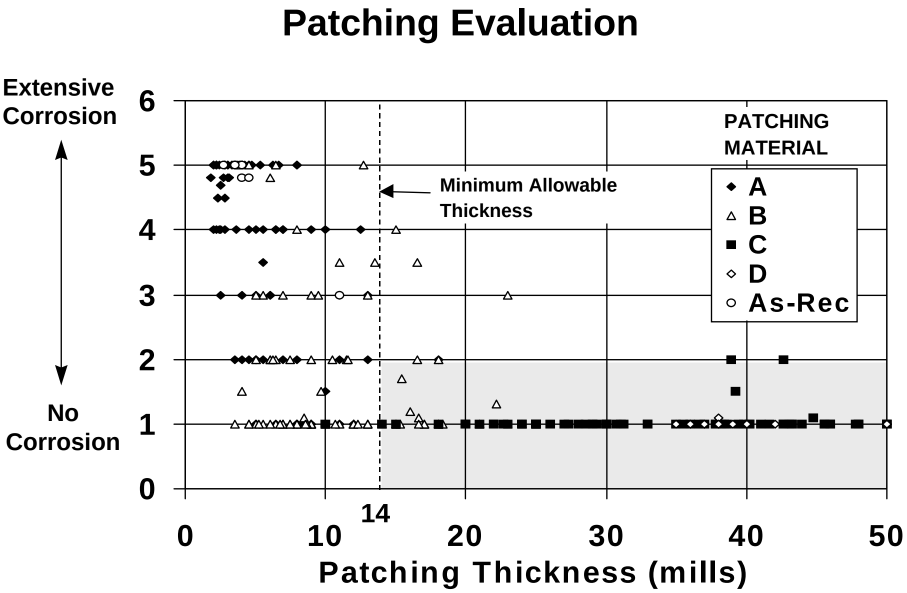


Figure 6.24: Corrosion rating vs. patch thickness of all specimens.

In Fig. 6.24, thickness and corrosion performance are plotted for all individually patched areas. Although data points show scatter, some trend in behavior can be observed. More specimens patched with material *A* lie in the high corrosion region and smaller patch thickness of the graph than specimens patched with other materials. For specimens patched with material *B*, more data points are in the low corrosion region and have greater thickness than specimens patched with material *A*. Finally, specimens patched with materials *C* and *D* are prevalent in the region of greatest patch thickness and little to negligible corrosion. Again, performance improved with increasing patch thickness. Diffusion of chlorides through the patch was significantly delayed as patch thickness increased. Thicker patches provided good protection at vulnerable areas such as sharp edges of rebar ends, as shown in Fig. 6.25.

A statistical evaluation of the data in Fig. 6.24 may help determine minimum patch thickness. If ratings of 1 and 2 are considered acceptable (little to no corrosion) and ratings above 2 are unacceptable (moderate to extensive corrosion), analysis of the latter group of points shows that a thickness of 14 mils roughly corresponds to the 95 percentile of points with ratings greater than 2. In other words, 95% of data points with ratings above 2 (unacceptable performance) had thicknesses lower than 14 mils. Similarly, only 5% of data points with ratings above 2 had thicknesses greater than 14 mils (Fig. 6.24). If it is assumed that the data constitutes a representative sample and 14 mils is established as the minimum effective patch thickness, material *A* would not be acceptable, material *B* would not be acceptable in most instances (only about one third of samples patched with material *B* had a thickness equal or greater than 14 mils), and materials *C* and *D* would be acceptable. The region containing data points with thicknesses greater than 14 mils and acceptable performance (ratings lower than 2) is shaded in the graph (Fig. 6.24).

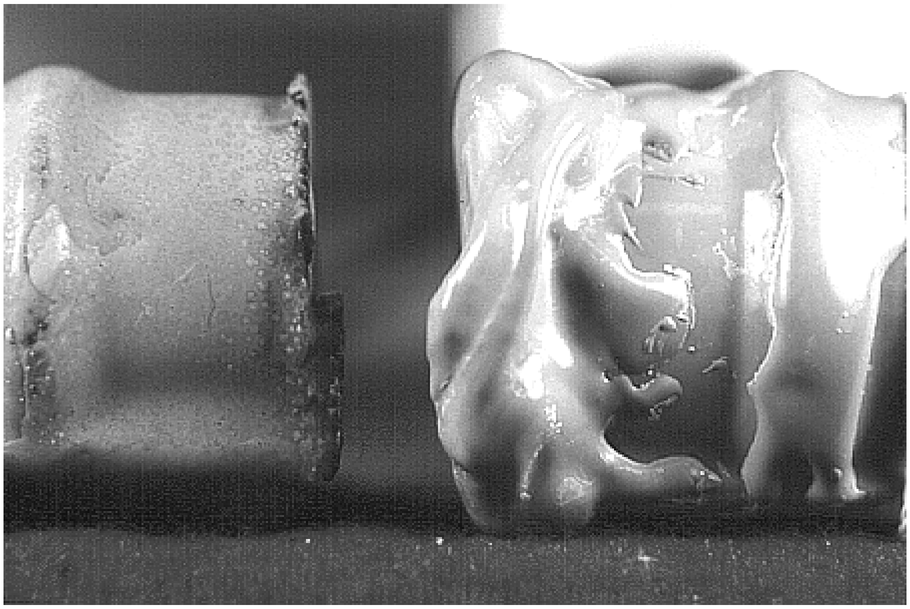


Figure 6.25: Patching material *A* (left side specimen) performed worse than material *C* (right side specimen).

The thickness of a cured patch layer is largely dependent on the properties of the patching material. The greater the viscosity of uncured epoxy, the thicker the coating layer of the patched area. Also, with greater viscosity, fewer air voids (and possible discontinuities) formed in the patch and the cured surface was harder. In addition, as viscosity increased, drying and curing times became shorter. In terms of corrosion protection, materials *C* and *D* appear to be the best patching materials. However, some disadvantages are associated with their properties. Because of their thick consistency, the resins have poor workability and are difficult to prepare, mix, and apply. Unlike patching materials *A* and *B*, epoxy repair materials *C* and *D* cannot be applied by brush. A short, stiff rod, such as a spatula or tongue depressor is needed to thoroughly and vigorously mix the resin and to apply it to the damaged coating. In addition, these materials had a short pot life. Epoxy material suppliers need to continue developing new materials that provide excellent corrosion protection and are easy to use. Of the materials considered here, material *B* provides good corrosion protection and is relatively easy to use.

Although thickness of the patch was identified as an important factor, it remains unclear what specific properties make a patching material perform well. One property seemed to be the viscosity, which had a direct effect on the thickness of the patch. There may be a series of properties, such as rheology, flow, percent of solids, modulus of elasticity, flexibility, hardness, and permeability, which may be interrelated and act together to give the material desirable characteristics. For instance, a viscous epoxy that has a greater content of solids may be less permeable to chloride diffusion. In addition to provide a thicker patch, materials *C* and *D* may be less permeable than materials *A* and *B*. It is important to keep the differences between thickness and permeability in mind because it could be wrong to assume that a very thick application of material *A* will provide adequate protection. In fact, it was not possible to obtain thicker patches by adding layers while material *A* remained fluid because the added material simply flowed away. Successive applications might be possible after each layer has cured or is dry to the touch; however, time and cost rule out such successive applications. On the other hand, materials *C* and *D* provided thick patches in one application.

No clear trend was observed in terms of surface preparation. No improvement in performance was observed with surface cleaning before patching, as can be seen in Figures 6.26, 6.27, and 6.28. Rounding and smoothing sharp edges at bar ends did not prove successful. Even some control specimens where the surface was specially cleaned showed poor performance (Fig. 6.29). Manufacturers' application procedures indicate that proper surface preparation is important for satisfactory performance but this correlation is not supported by results obtained in this study. No correlation was found between size of patched areas and corrosion performance, as illustrated in Fig. 6.30.

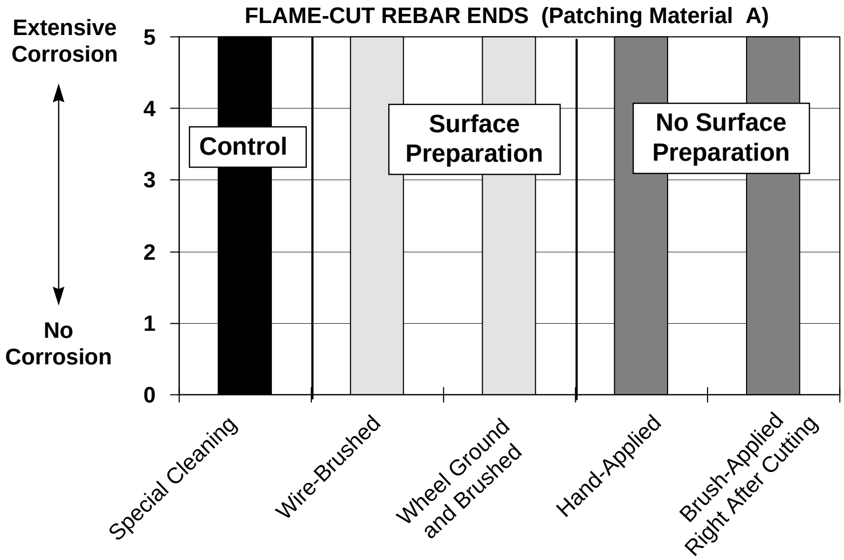


Figure 6.26: Corrosion rating of several coating repair procedures on bar surface.

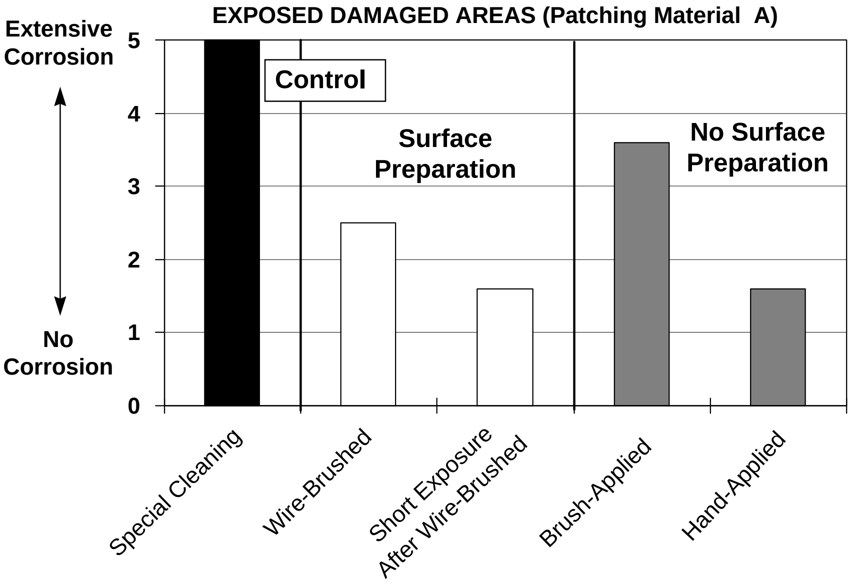


Figure 6.27: Corrosion rating of several coating repair procedures on flame-cut bar ends (Patching material A).

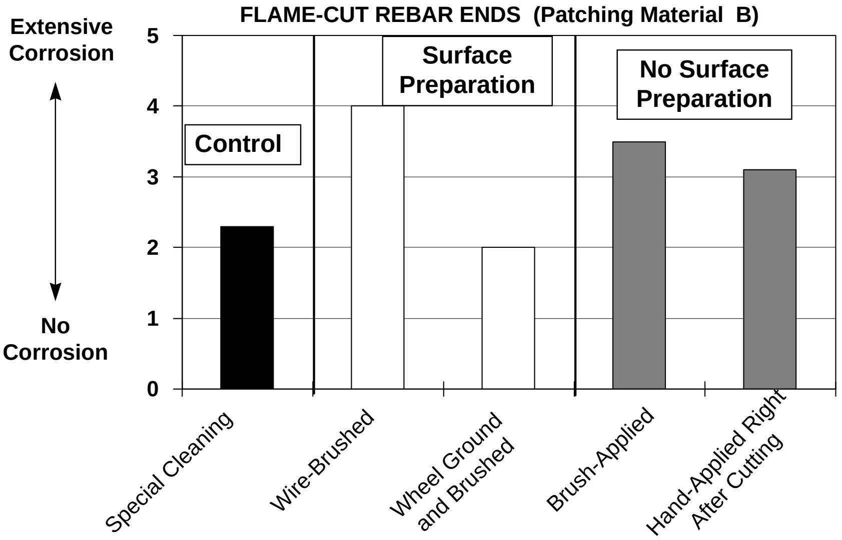


Figure 6.28: Corrosion rating of several coating repair procedures on flame-cut bar ends (Patching material B).

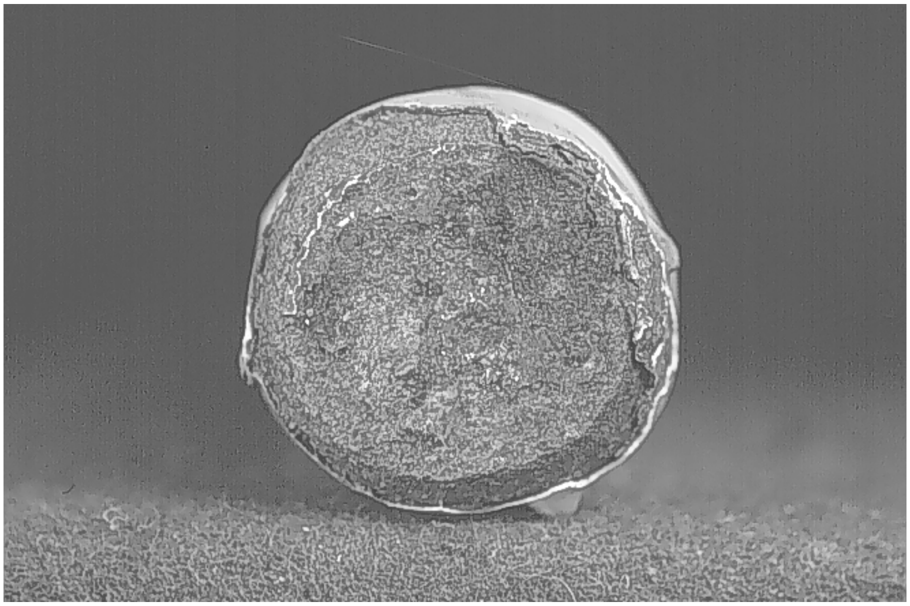


Figure 6.29: Corrosion of bar end surface that was specially cleaned before patch application.

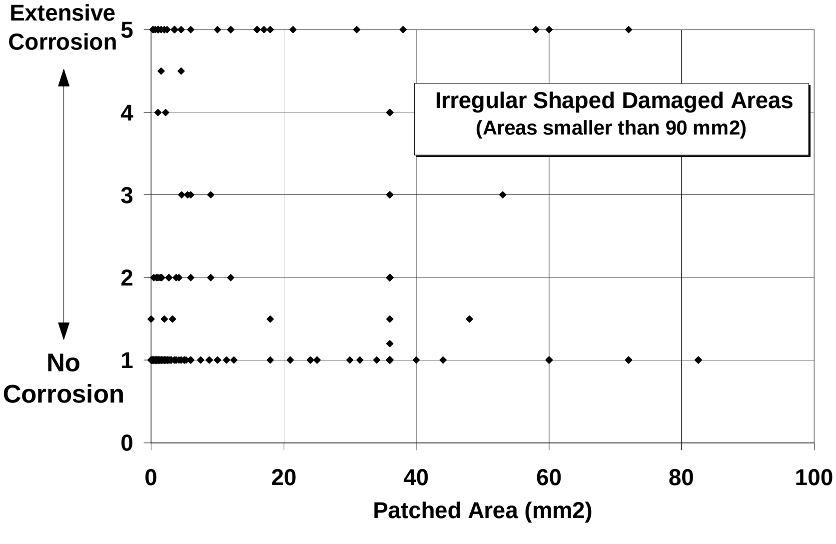


Figure 6.30: Corrosion rating vs. size of patched area.

6.4.2 Electrochemical Impedance Spectroscopy and Polarization Resistance

Electrochemical impedance spectroscopy and polarization resistance tests were conducted on 9 rebar samples immersed in 3.5% NaCl solution during 100 days. Sample preparation involved removing all the epoxy coating with a wheel brush, preparing the metallic surface, and coating the bar with patching material. Electrochemical measurements were intended to monitor the behavior of patching materials only. If patched ECR samples had been used, the effect of epoxy coating and the patch material would have been measured but the relative contribution of each could not have been attained. The decision of removing coating from epoxy-coated bars instead of using plain samples was based on the fact that ECR are subjected to a special surface preparation prior to coating. Patching materials are intended to touch-up damaged surfaces which are pre-treated before the coating is first applied.

6.4.2.1 Test Procedure and Evaluation

At one bar end, a hole was drilled and tapped to insert a screw for electrical connection. The other bar end was sealed with a plastic cap filled with epoxy cold mount resin. Bar specimens were immersed individually in one-liter plastic containers filled with 3.5% NaCl solution up to a height of 8 cm. Two graphite counter electrodes and a calomel reference electrode with Luggin probe were placed around the specimens using a special apparatus (Fig. 6.31). The bar samples and electrodes were wired to the measuring equipment

(Potentiostat/Galvanostat, Lock-In Amplifier, and IBM PC-XT). Bar specimens were immersed for about 100 days and measurements were taken at 12 hours, 2, 4, 7, 10, 14 days and at subsequent week intervals until 98 days after immersion. More frequent measurements were conducted in the first week to attempt to monitor the coating pore resistance and the initiation of corrosion. The electrolyte levels of the immersion cells were checked every three days and when necessary, replenished with solution at the fixed level. The screws securing the electric wires were periodically inspected for signs of corrosion and replaced when necessary.

Figure 6.31: Test setup for EIS and polarization resistance tests.

Corrosion potential (E_{corr}), polarization resistance, and impedance measurements were performed in that order on each specimen at the scheduled time. There was a fifteen minute delay period between the polarization resistance and the impedance measurement to allow the specimen to return from the polarized condition back to its rest state. The polarization resistance measurement was run between ± 20 mV with respect to E_{corr} using a scan rate of 0.1 mV/sec. An impedance measurement consisted of three independent readings to cover a wide frequency range. One measurement, based on the Lock-in Amplifier (single-sine wave) technique, was set to cover the range from 10 hertz to 100 kilo-hertz, with 8 data points obtained per decade of frequency. The other two measurements were based on the Fast Fourier Transform (multi-sine wave) technique: One measurement was run using a base frequency of 0.1 hertz to cover the range from 0.1 hertz to 10 hertz. The other measurement was performed with a base frequency of 0.001 hertz to cover the range from 0.001 hertz to0.1 hertz. Two data acquisition cycles were used for both measurements. All three measurements used sinusoidal voltage excitations with amplitudes of 15 mV and were run at the specimen's open circuit potential. Data obtained from the three measurements were merged in one curve for analysis. Frequencies lower than 0.001 hertz were not used because of the long times to complete the testing and of the potentially serious problems that might occur during data acquisition.

At the end of the experiment, specimens were removed from solution and air dried. Assessment and photographs of the patch-coating condition were performed. The coating was then removed with a utility knife and by chiseling. The steel surface condition was examined visually and photographed.

6.4.2.2 Study Variables

Three patching materials and three surface preparation conditions were evaluated. As in the immersion test, patching materials *A*, *B,* and *C* were used (Fig. 6.32). Types of surface preparation were as follows:

1) No surface preparation: Specimens were subjected to two weeks of outdoor exposure until rust developed on steel surfaces. Water was poured on the specimens during dry days to simulate rain. Unclean, rusted steel surfaces were then coated with patching materials.
2) Wire-brushed surface: Specimens were subjected to two weeks of outdoor exposure until rust developed on steel surfaces. Water was poured on the specimens during dry days to simulate rain. Surfaces were then thoroughly cleaned with a wire brush before coating with patching materials.
3) Control: The surface was thoroughly cleaned with a wheel brush until a polished, near-white finish was achieved. Remaining grease and dirt was removed with acetone to produce a shiny, bright metallic surface. Immediately after cleaning, patching material was applied.

The three steel surface conditions can be seen in Fig. 6.33. After samples were prepared, coated, and cured, coating thickness was measured with a Mikrotest thickness gage. Average coating thickness for each specimen is listed in Table 6.4. As before, no attempt was made to control coating thickness for all specimens and it was related to the viscosity of each epoxy material.

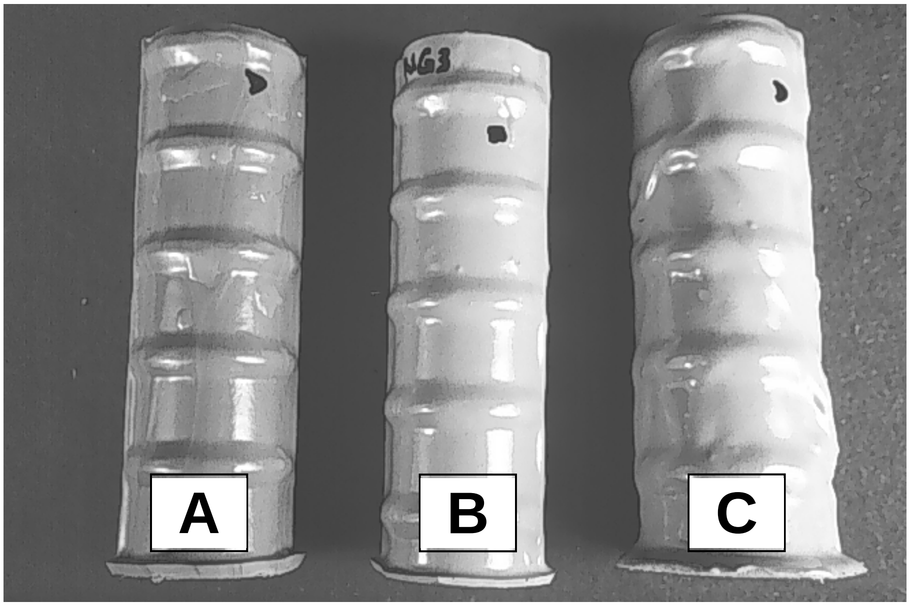


Figure 6.32: Specimens coated with patching materials *A*, *B*, and *C*.

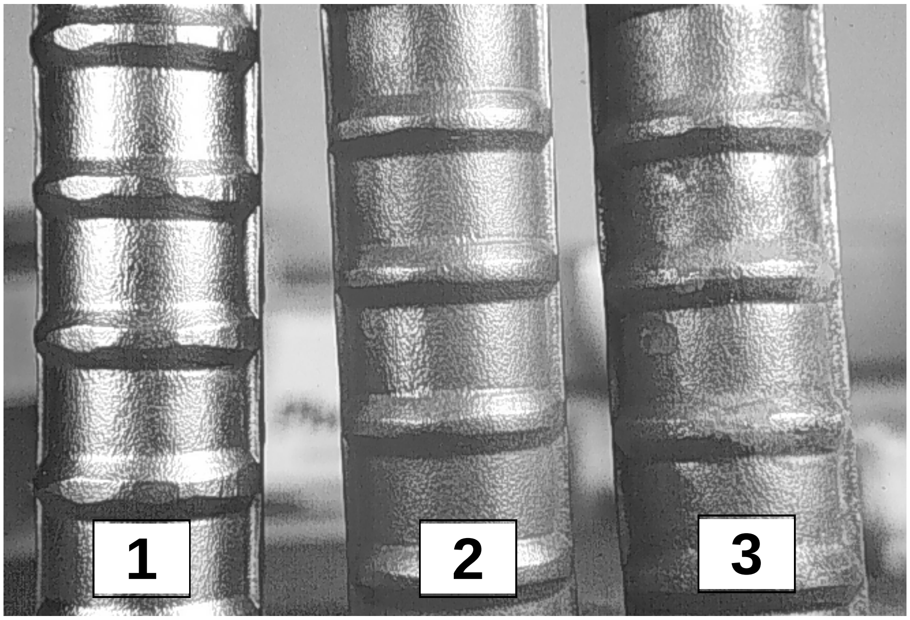


Figure 6.33: Steel surface conditions on specimens: (1) No surface preparation, (2) wire brushed, and (3) control.

Patching Material	**Surface Preparation**		
	1	**2**	**3**
A	6.8	6.4	5.2
B	8.5	12.3	11
C	34	36.8	32.2

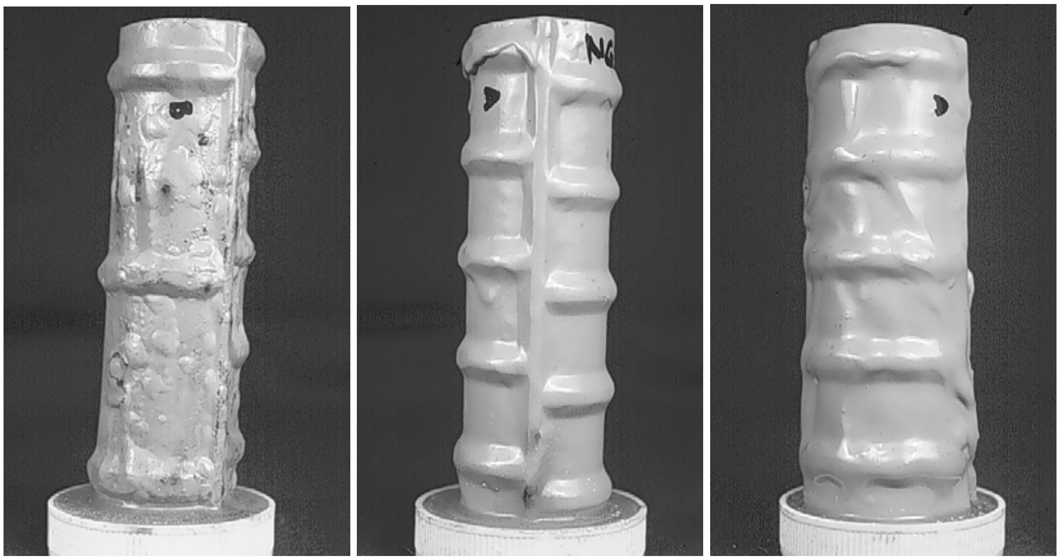
Table 6.4: Average coating thickness (mills) of specimens for EIS and polarization resistance.

6.4.2.3 Corrosion of Specimens

Specimens patched with material *A* developed extensive blistering with formation of many small rust spots, mainly on ribs and mill marks [Fig. 6.34(a)]. After several weeks of drying, coating cracked along longitudinal ribs. The steel surface underneath the coating had a uniformly dark rusted appearance with extensive accumulation of fine orange-brown rust, especially beneath blistered areas (Fig. 6.35). The coating had poor adhesion and was easy to peel with a utility knife. Specimens patched with material *B* showed a few large, medium, and small rust spots or stains. Coating material did not blister [Fig. 6.34(b)]. Two of the specimens had some cracking in the coating along longitudinal corrugation. Outside localized rust spots, the coating remained in good condition. A few isolated, hardened dark and reddish-brown rust spots formed at sides of ribs on the bar surface beneath the coating. The degree of corrosion at such spots looked superficial, with no accumulation of loose, fine reddish or orange-brown rust. The rest of the steel surface appeared to be in very good, non-corroded condition (Fig. 6.35). Patch adhesion was poor at corroded areas, and ranged from good to poor at non-corroded areas in all specimens. Finally, specimens coated with patching material *C* did not exhibit any rust spots or staining on the coating surface. The patch was clean and shiny [Fig. 6.34(c)]. The steel surface underneath the coating was in extremely good condition (Fig. 6.35). Coating removal required chiseling but practically no coating residues were left on the metallic surface. Observed corrosion agreed with EIS and polarization resistance measurements.

6.4.2.3 Test Results and Discussion

Electrochemical impedance results for all specimens are plotted in Bode format in Fig. 6.36. There is a clear difference in behavior among the three patching materials. For the lower frequency region, the magnitude of impedance for patching material *C* is the greatest, followed by material *B*, and then by material *A*, regardless of surface preparation. The greater the impedance, the greater the corrosion resistance of the specimen. Therefore, patching material *C* showed the best corrosion performance, followed by *B* and *A*. Material *C* showed a linear behavior with slope of -1 throughout almost all frequencies. This represents purely capacitive behavior, which is indicative of a high quality coating with no defects. Curves for material *B* deviated from linearity and flattened at frequencies lower than 10^3 hertz. This is characteristic of a corrosion process largely controlled by diffusion of corrosive ions and oxygen to the steel surface. Curves for material *A* have small impedance magnitudes and are flat throughout the whole frequency range. The corrosion process is largely controlled by charge transfer reaction and is indicative of a coating with poor pore resistance (the coating does not retard the ingress of corrosive elements).



(a): Patch material A. (b): Patch material B. (c): Patch material C.

Figure 6.34: Surface condition of specimens coated with patching materials A, B, and C after 100 days in 3.5% NaCl solution.

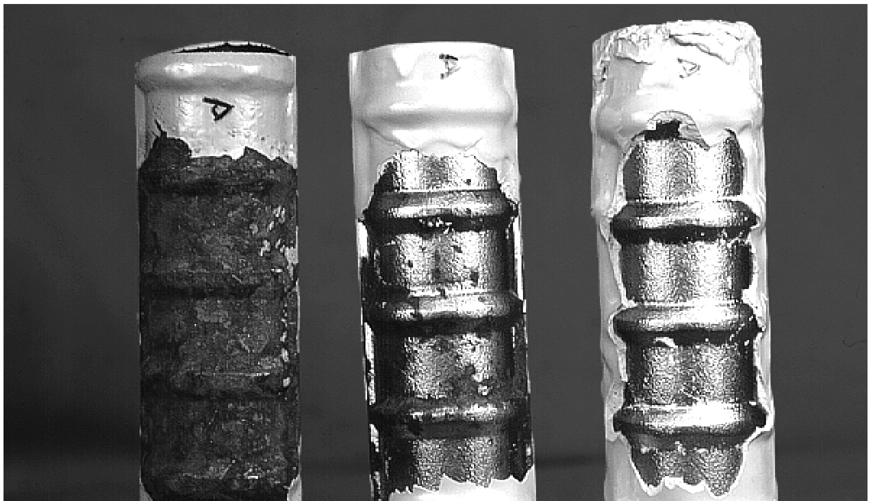


Figure 6.35: Steel surface condition underneath patching materials A, B, and C after 100 days in 3.5% NaCl solution.

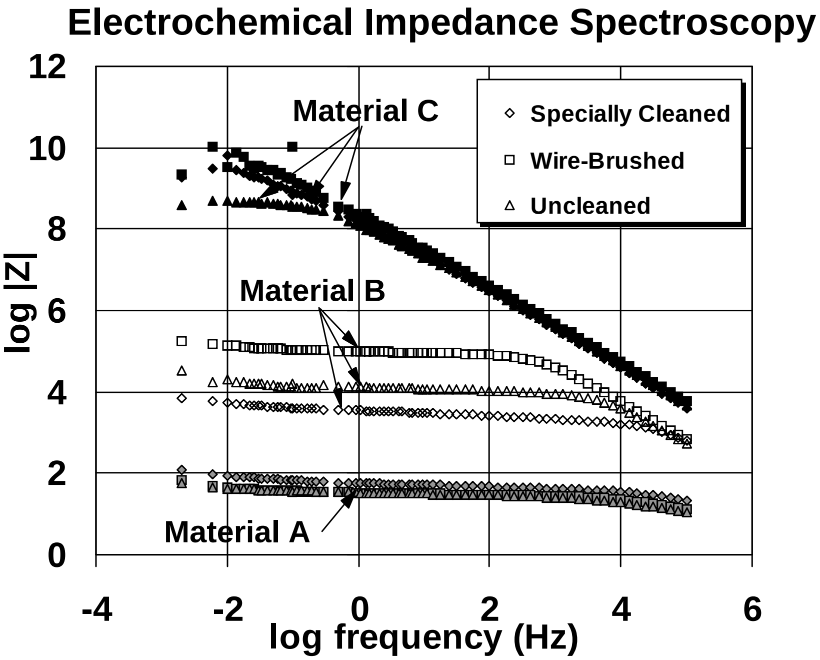


Figure 6.36: EIS results in Bode format (3 patching materials and 3 repair procedures) after 100 days in NaCl solution.

From Fig. 6.36, it is clear that the effect of surface preparation on the corrosion performance of coated specimens is negligible when compared to the effect of patching material type. In addition, no surface preparation procedure was consistently better or worse. These results were in complete agreement with results from the cyclic immersion tests.

Corrosion currents after 100 days as measured by polarization resistance are summarized in Table 6.5. Again, specimens coated with material *A* experienced much greater corrosion currents than specimens patched with materials *B* and *C*. Specimens coated with material *B* showed small corrosion current. No stable values could be measured for specimens coated with material *C*, an indication of the absence of corrosion activity.

Patching Material	**Surface Preparation**		
	1	**2**	**3**
A	226.5	451.2	475.6
B	3.16	0.13	0.65
C	-	0.01	-

Table 6.5: Corrosion current (μA) as measured by polarization resistance after 100 days of immersion.

6.4.3 Hot Water Immersion-Adhesion Test

A hot water immersion-adhesion test was conducted on patched ECR specimens. The objective was to determine the feasibility of the test to evaluate coating repair materials and techniques quickly and reliably.

6.4.3.1 Test Procedure and Evaluation

Seventeen epoxy-coated rebar samples containing 68 patched areas were tested. Samples 17 cm long were cut from epoxy coated bars #10 and #11. Samples were prepared and patched using several repair materials and procedures as described in the next section. Once cured, patch thickness at repaired locations were measured with a Mikrotest thickness gage for each specimen. Samples were subjected to 24 hours of hot water immersion at a temperature of 75°C. Specimens were allowed to dry for 24 hours at room temperature. Adhesion tests were then conducted at the patched areas following the procedure described in Section 5.4.2.

6.4.3.2 Study Variables

The following variables were used for hot water immersion-adhesion tests:

Patching Materials:

Four patching materials were used. In addition to previously mentioned materials *A* and *B*, materials *E* and *F* were tested. The characteristics of such repair material are as follows:

E. Material of very thin consistency in its liquid state. Dried at touch at about 6 hours in a small 2 oz. cup at a temperature of approximately 21°C. Bright green color. It can be applied by brush, roller, or spray.

F. Material of viscous consistency in its liquid state. Dried at touch at about 3 hours in a small 2 oz. cup at a temperature of approximately 21°C. Grayish green color. It can be applied by brush or roller.

Patching materials “E” and “F” are no longer manufactured. For this reason, they were not included in the immersion and EIS studies.

Damaged Areas:

Coating damage was caused at areas between bar deformations. Rectangular incisions of 11 x 16 mm and 6 x 6 mm were made through the coating with a sharp utility knife. Coating inside the rectangular incision was removed with a chisel blade mounted on an X-acto knife.

Repair Procedures:

b. Patching Immediately Applied after Damage and Surface Cleaning (Wire Brush)

e. Patching Applied on Surface Cleaned (Wire Brush) after Outdoor Exposure

f. Patching Applied after Short Outdoor Exposure of Previously Cleaned Surface (Wire Brush)

i. Brush-Applied Patching on Untreated Surface after Outdoor Exposure

k. Hand-Applied Patching on Untreated Surface after Outdoor Exposure

A description of each of the above procedures is included in Appendix C.

6.4.3.3 Test Results and Discussion

The majority of patching materials *A* and *E* showed poor adhesion to the steel surface. The patch was easily removed by cutting and prying with the blade. The integrity of the patch was mostly preserved after the test, except when patch was very thin. Larger patched areas were easier to peel than smaller areas.

Areas patched with materials *B* and *F* showed more varied behavior. Patches had a tendency to either break, disintegrate, chip off, or tear apart. In several cases, the blade cut a narrow strip of patch only, and remaining patch area was intact. Adhesion ranged from relatively good to poor, but in most cases was difficult to assess. Larger patched areas were easier to peel than smaller areas. Patching materials *B* and *F* were more brittle and patching materials *A* and *E* were more flexible.

No attempt was made to rate patch adhesion of specimens because of the difficulty to adequately interpret test results when the patch was broken, disintegrated, or chipped off during the test. Clearly, patching materials *A* and *E* showed poor adhesion to the steel surface. Patching materials *B* and *F* seemed to have better adhesion to the steel surface than materials *A* and *E*. However, it was not possible to precisely assess their overall adhesion performance. In all cases, adhesion of the patch to steel surface was much lower than the adhesion of the original epoxy coating to the steel surface.

In conclusion, the hot water immersion-adhesion test was not found adequate to assess patching materials and procedures because of the difficulty in satisfactorily interpreting test results. Besides, there seems to be little correlation between patch material adhesion and corrosion resistance.

6.5 CONCLUSIONS AND RECOMMENDATIONS

6.5.1 Conclusions

Corrosion performance was mostly affected by the patching material consistency and texture. Materials of greater viscosity and shorter curing time produced patches of greater thickness. Thicker patches performed better than thinner patches. However, patching materials that provided the best performance had poor workability and were difficult to use. Patched rebar ends were very vulnerable because of difficulty in patching sharp rebar end edges. Presence of burrs and slag also impaired patch effectiveness. Flame-cut and patched rebar ends had the worst corrosion performance. Rebar ends patched by coating applicator showed very poor performance too. Damaged and patched areas on rebar sides experienced less corrosion than patched rebar ends. There was not clear effect by cleaning and application procedure and size of damaged area.

There was excellent agreement of test results between cyclic immersion testing and electrochemical experiments. Hot water immersion-adhesion test proved unsuccessful to assess coating repair quality.

Corrosion of patched areas was in the form of coating blisters, patch softening and debonding, rust spotting and staining, fine rust exudation, and breakage and delamination of patch at perimeter of bar end section. Corrosion on steel surface beneath patches was in the form of uniform black or dark rusted surface combined with areas of reddish-brown (or other tones of brown) rust.

6.5.2 Recommendations

Recommended Practice

Coating damage should be repaired with patching materials that provide a uniformly thick coating layer, especially at sharp edges at perimeter and slag ridges on rebar cut ends, and up-side-down surfaces. The minimum thickness of a patch should be 14 mils. Discontinuities on the patch surface should be avoided. Slag and burrs should be removed from rebar cut ends. Preferably, epoxy coated rebar should not be flame-cut and patched. Patching materials of high viscosity and thick texture provide excellent protection but are difficult to use. Additional research is needed to develop repair materials with good workability and acceptable corrosion performance. Of the materials considered here, material “B” provides good corrosion protection and is relatively easy to use. Although surface preparation is not necessary for most cases, careful cleaning is still encouraged, especially under extreme field conditions which differ considerably from those used in this research (mud- or oil-covered surface).

Future Research

Future research efforts should be directed at a) defining the specific engineering properties that make a patching material perform well, and b) developing an improved patch formulation that will be easy to apply and still provide adequate corrosion protection. The relevant properties must be identified in order to develop a satisfactory and practical patch formulation.

Chapter 7. Consolidation of Concrete with Epoxy-Coated Reinforcement

7.1 DAMAGE TO EPOXY COATING DURING CONCRETE PLACEMENT AND VIBRATION

7.1.1 Problem Statement

The adverse effects of damaging the epoxy coating have been discussed in preceding chapters. As was discussed, epoxy coating on reinforcing bars can be damaged during any of the stages from production to construction: handling, fabrication, and storage at the plant; transportation; handling and storage at the job site; assembly and installation; and concrete placement. This chapter will concentrate on the damage that is incurred to the epoxy coating during concrete placement.

Concrete placement is the last procedure during which the epoxy coating may be damaged before the reinforcing bar is put into service. Any damage during concrete placement cannot be seen nor repaired. During placement of concrete, an internal vibrator is frequently used to consolidate the concrete. During vibration, the steel vibrator head and aggregate particles physically impact the coated bar repeatedly. The head usually rebounds from the sides of the formwork and violently contacts the rebar cage. The extent of coating damage that results from concrete placement and consolidation is not known and has not been widely investigated.

Vibrators with “soft” (rubber) head have been manufactured. Marketing literature for soft head vibrators indicated that they will “not damage epoxy coatings."[124] Furthermore, the soft head was reported to be more "effective" than the steel head in consolidating the concrete. Given the potential benefits, the performance of the soft head vibrator with respect to both coating damage and consolidation was worth investigating.

7.1.2 Prior Research on Coating Damage due to Concrete Vibration

A field study was conducted by Allied Bar Coaters to investigate the level of damage to their coated bars during construction.[125] A typical foundation element (approximately 2.0 x 1.0 x 0.50 m) with epoxy-coated reinforcement was built alongside existing works. The amount of coating damage had been recorded during previous stages before concrete placement. Concrete was placed and consolidated with a spud vibrator. After consolidation, the reinforcing cage was lifted out of the formwork and washed to remove excess concrete. The cage was disassembled and the bars were returned to the factory for detailed examination. It was found that the vast majority of damage to the coating occurred during the concrete placing and consolidation stages of construction. On average, 75% of all defects were observed during this stage, accounting for 88% of the total surface area damaged during construction. The average coating damage was 0.099% of bar surface area, and the maximum damage was 0.621% of surface area.[125] Similar findings were observed in a previous research by the Building Research Establishment on the reinforcing cage of a specially designed panel (2.0 x 0.80 x 0.80 m) after the compacted concrete had been washed out.[126]

A laboratory investigation of steel head and plastic head vibrators was conducted by the Ontario Ministry of Transportation.[51] Concrete was placed in a form and consolidated using both types of vibrators following standard field procedures. It was noted that when the steel head vibrator was held against the bar, the coating could be removed from all the bar deformations. The plastic head vibrator could be forced to penetrate the coating but, in normal conditions, the coating was scuffed but not broken. From the results of this investigation, the Ministry required the use of plastic head vibrators for placing concrete in bridge decks, barrier walls, and end dams. The limitation of the requirement to these structural members was a concession to the limited availability of vibrators in 1993 and 1994. These components were thought to present the worst conditions in terms of dragging the vibrator across the reinforcement. In January 1995, plastic head vibrators were required wherever epoxy-coated reinforcement was specified.[51]

7.1.3 Research Objectives

A preliminary experimental study (Phase 1) was conducted to evaluate the degree of mechanical damage caused by concrete placement procedures. Based on the amount of damage that resulted from the preliminary study, it was decided that additional damage tests be conducted in a second phase study using soft (rubber) head vibrators in addition to steel head vibrators. A comprehensive summary of the test procedure and results from study phases 1 and 2 is presented in this Dissertation. References 10 and 127 contain more detailed information of study phases 1 and 2, respectively.

The specific objectives of Phase 2 testing are as follows:[127]

- Assess the damage introduced to epoxy coated bars by metallic head and rubber head vibrators through a visual examination of the bars.
- Assess the quality of consolidation obtained with a rubber head vibrator as compared to a metallic head vibrator based on measurements in fresh concrete during vibration.
- Determine the degree and quality of consolidation obtained with the rubber head vibrator as compared to metallic head vibrator through both a visual examination and density of cores from vibrated specimens.
- Make recommendations on the appropriate type of internal vibrator to be used in conjunction with epoxy-coated reinforcement.

7.1.4 Test Specimens and Procedure

Phase 1 [10, 121]

One column base and two slab specimens were prepared. The column base had two mats of epoxy-coated bars. The top mat consisted of 25-mm (#8) bars and the bottom mat consisted of 13-mm (#4) bars. Each slab specimen had one top mat of coated bars. In one slab, the mat consisted of 13-mm (#4) bars, and in the other slab, the mat consisted of 25-mm (#8) bars. Bars with both parallel and cross deformation were used for both mats. All the reinforcement was carefully examined and damage in the coating was marked before placement of concrete.

A 50-mm (2-in) immersion-type, metallic head vibrator was used. Concrete vibration was started at the middle of the form and the vibrator was gradually moved around to consolidate the entire volume of concrete. Concrete was placed and vibrated in several lifts in the column base specimen. Vibration of concrete lasted a few minutes in the slab specimens and about 15 minutes in the column base specimen. The concrete was removed quickly and the bars were washed carefully. The bars were thoroughly inspected to document the coating damage caused by vibration.

Phase 2 [127]

The purpose of the tests conducted in this phase was to examine and compare the damage to the coating during placement of concrete with steel and rubber head vibrators. Three types of test specimens were constructed, representing a column or bridge pier, a footing, and a deck slab. Two identical forms and reinforcement cages were constructed for each type of specimen: One for use with the metal head vibrator, and the other for the rubber head vibrator. All reinforcement in the test specimens was epoxy-coated. The vertical reinforcement in the columns consisted of 36-mm (#11 bars), and the stirrups were 13-mm (#4) bars. Black bars were welded near the top on each of the four sides of the cage to lift the cage from the concrete after the vibration test. Each footing specimen was reinforced with two mats of coated bars. The top mat of reinforcement in each specimen consisted of 13-mm (#4) bars. The lower mat was made up of 19-mm (#6) bars. Deck reinforcement consisted of 13-mm (#4) and 16-mm (#5) bars. The reinforcing cages were tied with plastic coated tie wire to minimize assembly damage. Ropes were attached to both the upper and lower reinforcing mats in each footing and deck specimen during construction. These ropes were used to pull the reinforcing mats out of the concrete after vibration was completed. The epoxy-coated reinforcement was carefully examined and existing coating damage was marked prior to placement of concrete. All details of the specimen design and dimensions and concrete mix used can be found in reference 127.

The metal head used in the column and footing tests was 4.4 cm (1 3/4 in) in diameter and 35.5 cm (14 in) in length. The rubber head was 4.8 cm (1 7/8 in) in diameter and 35.5 cm (14 in) in length. Figure 7.1 shows the two types of vibrator heads used. The concrete was placed in the form in three equal lifts and the vibrator was inserted at sixteen points in each lift. During each column test, the head of the vibrator was purposely inserted between the formwork and the stirrup at eight locations to simulate the damage that results when the vibrating head is forced to operate in a very confined area. At each insertion point the concrete was vibrated for 4-5 seconds.

The metal head used in the slab test was 4.4 cm (1 3/4 in) in diameter and the rubber head was 7.0 cm (2 3/4 in) in diameter. Both heads were 22.9 cm (9 in) in length. Concrete was placed in the slab forms in one lift directly from the ready-mix truck. The vibrator was inserted at thirty-six points in each slab form and the concrete was vibrated for 4-5 seconds at each insertion point. The head of the vibrator was purposely inserted at an angle at several points throughout each form, to closely model typical field vibration procedures.

Fig. 7.1: Metal (top) and rubber head vibrators.

Fig. 7.2: Consolidating column specimen.

The same operator consolidated the concrete with both the metal and rubber head vibrators to eliminate differences that might occur between operators. The same procedure and schedule of insertion points was followed with each type of vibrator head. Figure 7.2 shows the vibration of concrete in a column specimen. After vibration, and before the concrete reached initial set, the reinforcing cages were pulled from each form (Fig. 7.3). After the cages were removed from the concrete, they were carefully washed to remove all concrete from the bars before it hardened (Fig. 7.4). The coating on the reinforcement was carefully inspected after the test and the damage induced with each head was documented.

Fig. 7.3: Lifting column reinforcement cage from concrete.

Fig. 7.4: Washing column cages after vibration.

7.1.5 Test Results

First Phase [10, 121]

Damage caused by the vibrator during concrete placement was generally characterized by rough, abraded surfaces of the coating. In the areas with worst damage, the bare steel surface had been exposed. Individual bars from the column base specimen had a total damaged area ranging from 0.1% to 3.0% of the bar surface area. For both reinforcing mats, bars next to the sides of the forms had more damage than bars in the middle. The largest damaged spots measured more than 6 x 6 mm (¼ x ¼ in) and were found near the corners.

For the slab specimen with 13-mm (#4) bars, the total damaged area on each bar ranged from 0.1% to 1.1% of the bar surface area, with maximum damage per linear 0.3 m (1 ft) ranging from 0.2% to 1.7%. The largest damaged spot did not exceed 6 x 6 mm (¼ x ¼ in). Although there was not much difference in coating damage between bars on the side and bars in the middle, the most damaged lineal 0.3 m (1 ft) of each bar occurred near the end.

For the slab specimen with 25-mm (#8) bars, the side bars had the worst damage in general, especially near the ends. Damage on 25-mm (#8) bars was larger and more frequent than damage on 13-mm (#4) bars. The upper bars in the mat were, generally, more damaged than the lower bars. The total damaged area on each bar ranged from 0.3% to 1.7% of the bar surface area, with maximum damage per linear 0.3 m (1 ft) ranging from 0.4% to 2.2%. The largest damaged spot was a little less than 13 x 6 mm (½ x ¼ in) and occurred on a side bar.

Second Phase [127]

Most of the damage from concrete placement appeared to have been caused by abrasion between the vibrator head and the reinforcing bars. Depending on the length of time the head was in contact with the reinforcement, and the degree to which the vibration of the head was constrained, the condition of the coating ranged from slightly roughened to severely abraded. Bars located close to the edge of the form, where the vibrating head was most tightly confined, were subject to the largest amount of damage. Abrasion of the coating was seen with both the rubber and metal vibrator heads, but the severity of the abrasions was worse with the metal head. Under severe conditions, the metal head completely removed some areas of coating, exposing the bare steel surface, while the rubber head abraded and scuffed the coating more superficially and did not expose large bare steel surfaces. Typically, only the coating on the ribs was removed, especially on the smaller diameter bars. However, there were areas where the metal head removed the coating from the ribs and from the area between the ribs.

In addition to direct contact with the vibrator head, some roughening of the epoxy coating was seen from contact with the concrete. Some abrasion was caused as the concrete was placed into the form and over the bars. The coating was also marred from aggregate particles that are propelled by the vibrating head. Damage was also seen at several locations where reinforcing bars were in contact with each other. In the column specimens, large damage spots on both the stirrup and the vertical bar were observed where the stirrup was in contact with the vertical reinforcement (Fig. 7.5). When the vibrator head was inserted between the edge of the cage and the form, the stirrups were violently shaken and rubbed against the vertical bars, removing coating from both the stirrup and the vertical reinforcement. This type of damage was seen in specimens consolidated with both metal and rubber head vibrators.

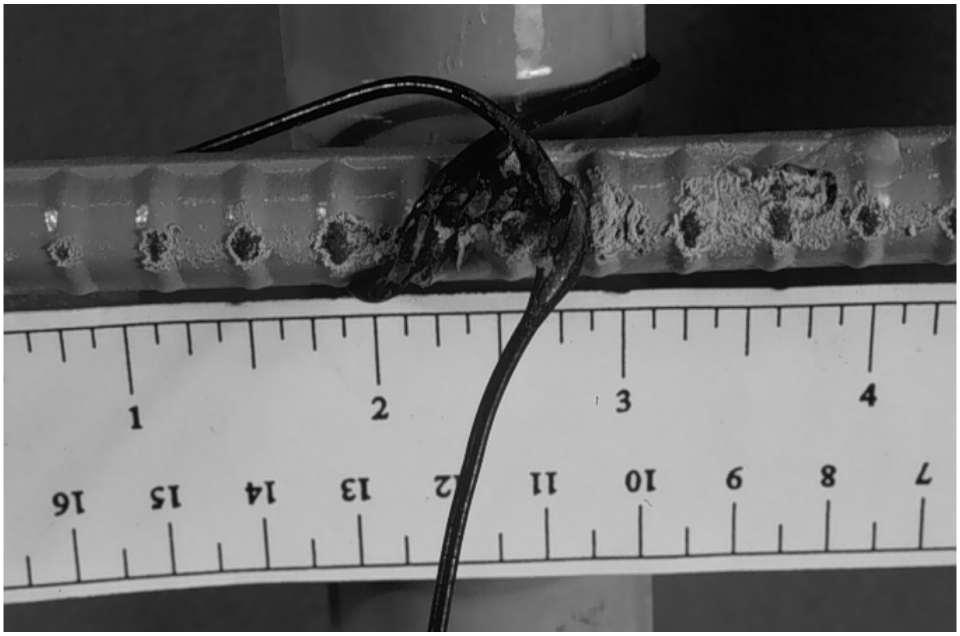


Fig. 7.5: Damage to stirrup coating and coated tie caused by metal head vibrator.

In the following sections, the percentages of damaged annotated refer to the percentage of damage in a 0.3 m (1 foot) length of bar.

Column Specimens

In general, the difference between the rubber head and metal head vibrators was more noticeable, and significant, on stirrups and cross-ties than on vertical bars. The percentage of damage for the stirrups was much more significant than that for the vertical bars.

<u>Vertical Bars</u>

The average damage with the metal head (0.064%) was about 20% greater than that with the rubber head (0.052%). The largest percentage of damage in any 0.3 m (1 ft) length was 0.21% for the metal and 0.16% for the rubber head.

Stirrups

The average percentage damage for all sections of stirrups examined was 0.96% with the metal head and 0.30% with the rubber head. At stirrups where the vibrator head was inserted between the stirrup and the form, the average percentage of damage was 1.49% with the metal head and 0.43% with the rubber head. Comparing the single worse side for the stirrups, there was 2.58% damage with the metal head and 0.43% with the rubber head. In this instance the metal head did over five times as much damage as the rubber head.

The maximum size of damaged area produced with the metal head was 6 x 38 mm (¼ x 1½ in) in size. The largest single damage spot with the rubber head was 6 x 13 mm (½ x ¼ in). In addition to producing the largest damage spot, the metal head also produced more large damage spots on the stirrups than did the rubber head. The metal head thus produced greater percentages of damage, and damage spots of larger size on average than that produced with the rubber head.

Cross Ties

The average percent damage was 0.64% with the metal head, almost five times the 0.13% damage with the rubber head.

Footing Specimens

Based on both the percentage of damage and size of individual damaged areas, there was relatively little difference between the two heads for the upper mat with the 13 mm (#4) bars. On the lower mat with the 19 mm (#6) bars, the metal vibrator head produced worse damage based on the overall percentage of damage, the size of damaged spots, and the single worst damaged 0.3 m (1 ft) length. With regard to the single worst damaged 0.3 m (1 ft) of bar, there was one bar that had 2.0% damage due to vibration with the metal head. The worst case with the rubber head had only 0.38% damage, less than one-fifth of that done with the metal head.

The fact that more damage was produced on lower mats than upper mats is possibly due to the relative large depth of the specimens. When the vibrator head was inserted to consolidate concrete in the vicinity of the lower mat, the vibrator operator had less control over the action of the head than when the concrete near the upper mat was vibrated.

Slab Specimens

Greater amounts of damage were seen on the upper mat than on the lower mat. This fact was in contrast with the results in the footing specimen, and can probably best be attributed to the shallow depth of the deck member. Since the two reinforcing mats of the deck were so close together, the upper mat provided a significant degree of protection to the mat below it. Particularly, when the vibrator head was dragged through the specimen, the upper mat received most, if not all, of the abuse.

The average percentage of damage on the upper mat was 0.51% with the metal head, over two and a half times the 0.20% damage with the rubber head. The 16 mm (#5) bars in the lower mat showed average damage of 0.20% with the metal head vibrator, and 0.12% with the rubber head.

7.1.6 Discussion of Results

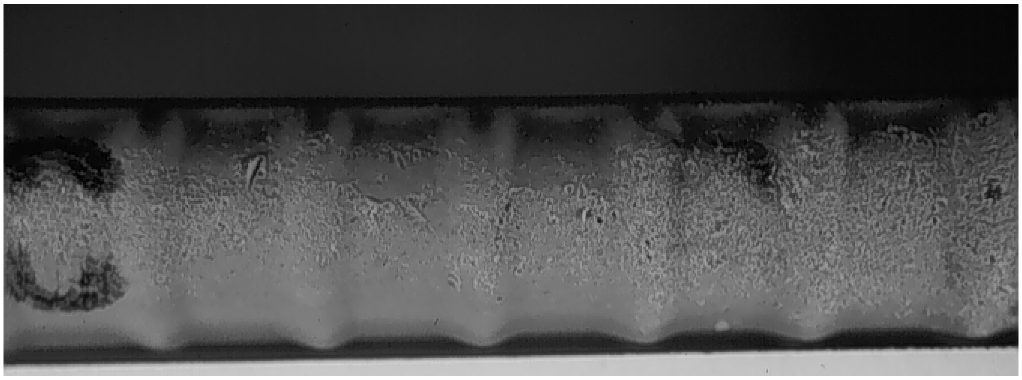
The investigation in Phase 1 showed that the use of the steel head vibrator to consolidate the concrete resulted in substantial amounts of damage when it came into contact with the coating. Typical damage caused by the vibrator head was in the form of abrasion and roughening of the coating surface. The steel surface was exposed at the most heavily damaged spots. Damage was generally limited to the bar deformations, as they were more likely to come in contact with the vibrator head. Damage was the worst where there was limited space for motion of the vibrator, such as sides of bars adjacent to form sides or form corners. Damage to some of the bars was greater than 2% of the surface area in their worst damaged 0.3 m (1 ft) or contained damaged spots greater than 6 x 6 mm (¼ x ¼ in). Larger diameter bars had more propensity to damage than smaller bars. An example of damaged coating due to vibration in a test bar from Phase 1 study is shown in Fig. 7.6.

Test results from Phase 2 confirmed the main trends found in Phase 1. Vibration of concrete during placement can produce significant damage to coated bars. Typical damage resulted from the abrasion of the vibrator head against the coating on the bar. Vibrator damage was generally located on bar deformations since they protrude from the bar surface and are most readily contacted. However, the coating was completely removed from the surface of the ribs and from the area between them at severely damaged locations. Coating damage was worst where the space available for the vibrator head was limited. In confined areas, the head of the vibrator was forced to contact the coated bars repeatedly. A trend not mentioned or found in Phase 1 was that damage also resulted at places where reinforcing bars crossed each other and abraded each other during vibration.

Fig. 7.6: Damage to coating caused by metal head vibrator on test bar from Phase 1 study.

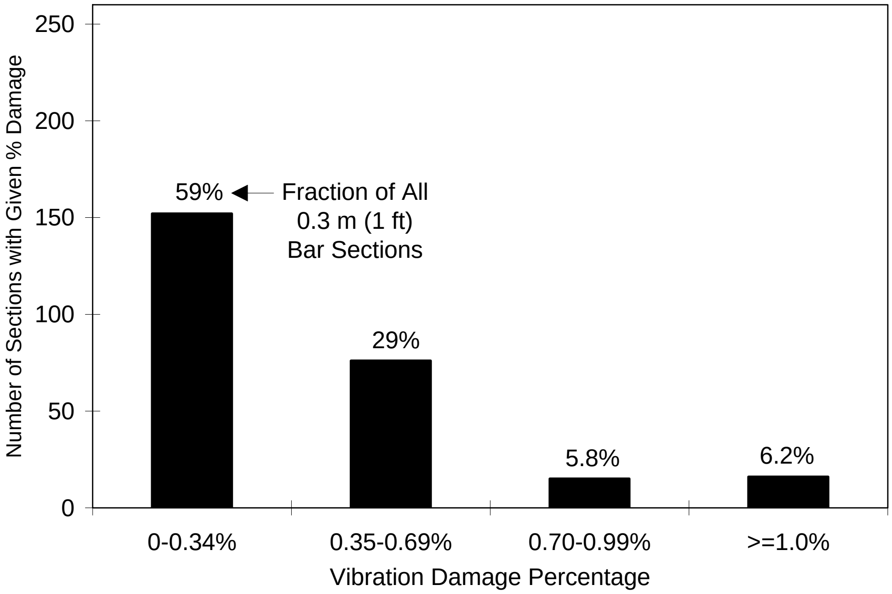
The rubber head vibrator produced less damage and removed less coating during concrete vibration than the metallic head vibrator. Figure 7.7 shows two cases of coating damage on a coated stirrup produced by the metal head and the rubber head. If the average damage from the three specimens for horizontal bars (reinforcement in all test specimens except vertical bars in columns) is combined, the metal head produced an average damage percentage of 0.64%, and the rubber head produced 0.22%. Thus, the metal head did almost three times as much damage, overall, as did the rubber head. The histogram of Fig. 7.8 shows that larger numbers of bars from the rubber head test were grouped in the very low damage ranges than were bars from the metal head specimens. In contrast, a larger proportion of bars from the metal head test were grouped in the higher damage ranges than were bars from the rubber head tests. With the metal head, vibrator damage alone was greater than the current 1% total acceptable damage limit of ASTM A775 for 6.2% of the test sections evaluated. With the rubber head, this number dropped to 1.5%. If the vibrator procedure had been more careless, or if the time of vibration was lengthened, the disparity could have been greater.

(a) Metal head vibrator.

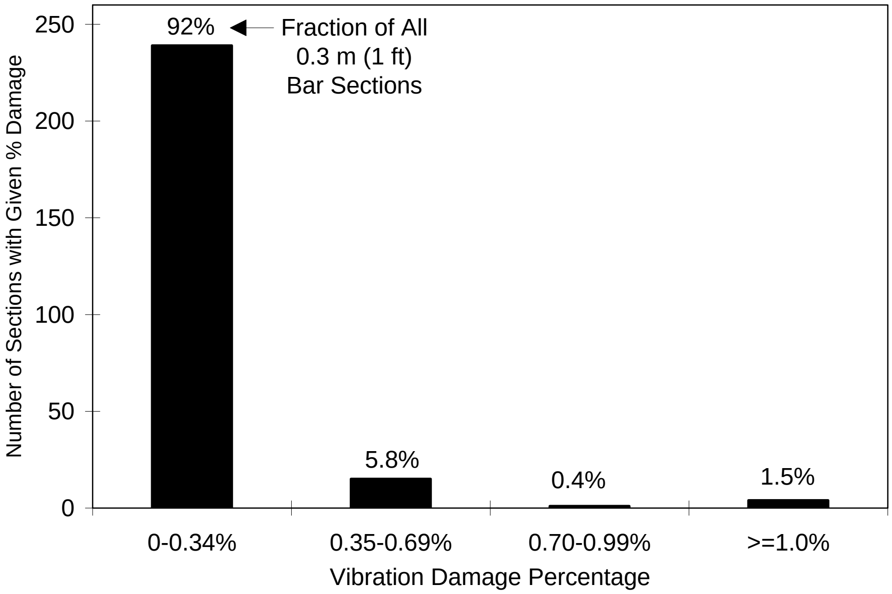


(b) Rubber head vibrator.

Fig. 7.7: Vibration damage to epoxy coating (Phase 2 study).



(a) Metal head.



(b) Rubber head.

Fig. 7.8: Histogram of damage percentages for 0.3 m (1 ft) horizontal bar sections from column, footing, and slab specimens.

7.2 CONSOLIDATION OF CONCRETE AROUND EPOXY COATED REBARS

7.2.1 Problem Statement

Earlier work on this project showed that corrosion activity is of great concern at locations where damaged spots are adjacent to voids in the concrete.[10] Concrete voids provide a space for the concentration of deleterious agents such as oxygen, water, and chlorides. When a damaged spot facing a concrete void is exposed to corrosive agents and the chloride concentration is large enough, the localized area of steel depassivates and the corrosion process starts. Corrosion progresses with periodic wetting and drying cycles. Corrosion may be particularly extensive on the bottom of a coated bar, where voids have more propensity to form adjacent to the bar surface. Since the degree and quality of concrete consolidation determine the void content of the concrete, the ability of concrete vibrators to reduce voids was of great interest in this study. Concrete consolidation, particularly in the area surrounding reinforcing bars, plays a significant role in the corrosion performance of coated bars, so the ability of rubber vibrator heads to adequately consolidate concrete specimens and remove as many air voids as possible warranted investigation.

7.2.2 Evaluation in Fresh Concrete

The objective of this study was to assess the quality of consolidation obtained with a rubber head vibrator as compared to a metallic head vibrator based on measurements in fresh concrete during vibration.

Test Specimens and Procedure

Vibration tests were conducted in two unreinforced, freshly placed concrete blocks. Two electrical receptacle boxes were suspended from the top with a wooden assembly and immersed in the concrete approximately 4.5 cm (1.75 in.). The metal boxes were used to house small size, high sensitivity, high frequency accelerometers. The boxes protected the accelerometers from the concrete, while permitting measurement of the wave motion in the concrete during vibration. Another receptacle box with an accelerometer was attached on one side of each form. The accelerometers were attached with magnets to the receptacle boxes during the tests. The two receptacle boxes partly immersed in the concrete were positioned at 10 cm (4 in.) and 20 cm (8 in.) respectively from the vibrator's point of insertion. The accelerometers were connected to a data acquisition system. A view of an accelerometer inside a receptacle box is shown in Fig. 7.9. Specific details of the specimen design and concrete mix used are included in reference 127.

The concrete in each of the two forms was vibrated with a flexible shaft type internal vibrator with the same electric 2.4 amp motor used in previous vibration tests. The same operator vibrated the concrete in each of the tests to minimize any effect the operator might have on the results. In the first set of tests, the concrete in the first form was vibrated with a rubber vibrator head. While the concrete was being vibrated, measurements were taken with the accelerometers at different stations and in different orientations. The data acquisition system used in this experiment could monitor only 2 channels, so it was necessary to move the accelerometers during the test to take readings at all desired positions. The next test utilized a metal vibrator head in the second form. The same schedule of accelerometer placements and orientations was used in this test. The final test involved the use of the rubber vibrator head in the second form.

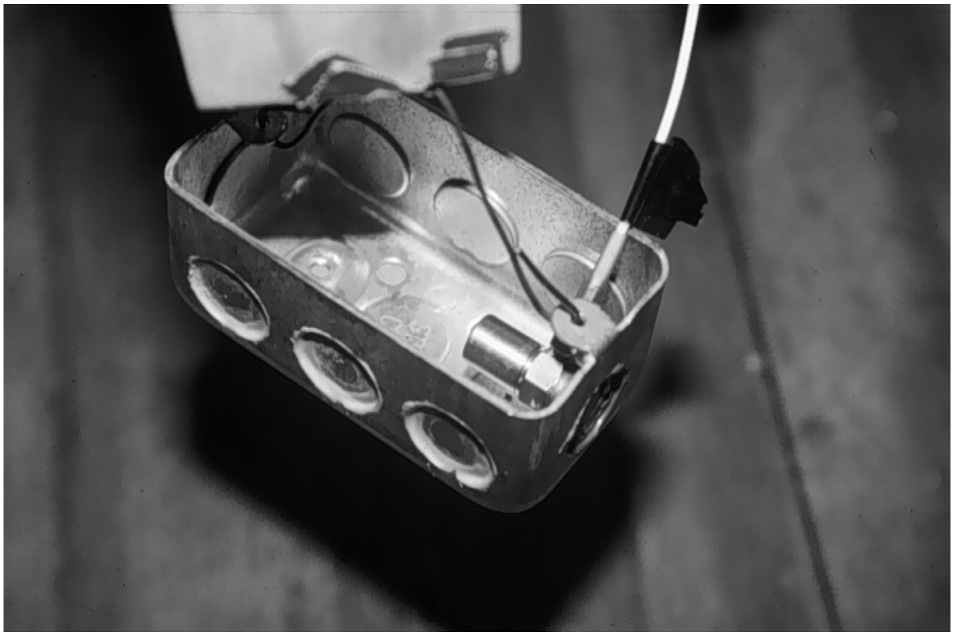


Fig. 7.9: Accelerometer in receptacle box.

Vibration tests could not be conducted in both forms simultaneously due to equipment limitations. The concrete was in the second form for at least 20 minutes before the metal head vibrator was inserted for consolidation. Even though the metal head was tested in concrete from the same batch, the concrete was less workable than that used with the rubber head. Therefore, the metal head was tested in a more severe environment than that of the rubber head. Observations of the fresh concrete surface during the vibration test confirmed that all data stations were within the area of influence of the vibrator. Thus, the data recorded at each station is representative of vibratory motion within the radius of action of the vibrator.

Discussion of Results

The average peak frequency was 10,200 vibrations per minute (vpm) with the rubber head vibrator in the first box tested and 11,800 vpm with the metal head in the second box. The final test frequency with the rubber head in the second box was 10,600 vpm. These results indicate that the frequency in the concrete when vibrating with the rubber head is about 10% less than that obtained with the metal vibrator head. In addition, the range of peak frequencies over the successive tests is less with the rubber head than the metal head. The use of the rubber head vibrator results in a lower peak frequency than that obtained with the metal head.

The time records from the vibration tests show that the horizontal particle acceleration induced in the concrete with the metal vibrator head is greater than that obtained with the rubber head at all test stations. The difference in both maximum and average horizontal acceleration was larger at the station located farther away from the vibrator head, with the metal head having the larger accelerations. The percent difference between the rubber and metal heads at the farther station was twice that at the nearer station. The increased difference between the two heads suggests that the area of influence for the rubber vibrator head is less than that of the metal head. At increasing distances from the point of vibrator insertion, the rubber head produced increasingly smaller accelerations.

The rubber head vibrator was further compared to the metal head by revibrating the concrete in the second form with the rubber head vibrator. The horizontal accelerations in the concrete were drastically reduced with the rubber head as compared to the metal head. The metal head produced substantially more vibratory force than did the rubber head in relatively similar conditions of dense concrete.

Concrete vibrators also induce vertical accelerations in the concrete. This component of acceleration arises from the operator moving the vibrator head up and down during consolidation of the concrete, from the rise of entrapped air bubbles, and the general settling of the concrete during vibration. Unlike the horizontal accelerations in the concrete, the vertical accelerations were generally greater with the rubber head than with the metal vibrator head. The increase in vertical accelerations with the rubber head was attributed to the physical design of the rubber vibrator head.

7.2.3 Evaluation in Hardened Concrete

The objective of this study was to determine the degree and quality of consolidation obtained with the rubber head vibrator as compared to metallic head vibrator through both a visual examination and density of cores from vibrated specimens.

Test Specimens and Procedures

A total of eight concrete block specimens was constructed for this test. There were four pairs of blocks of varying size, three pairs were companion specimens with identical volume and size and amount of reinforcement. One companion specimen was vibrated with a metal head and the other with a rubber head. Block specimens in the fourth pair were not companion and had different volume and amount of reinforcement. Both specimens were vibrated with a rubber head vibrator. The plan size of the specimen was selected so that the area of the concrete block was located just inside the reported radius of influence of the vibrator heads used to consolidate the specimen. Both epoxy-coated and uncoated bars were used in each specimen to attempt to identify any differences in concrete consolidation around coated versus uncoated bars. The density and permeable void content of extracted cores and the amount of air voids underneath reinforcing bars in each specimen were used to evaluate the quality of concrete consolidation.

All of the specimens were cast at the laboratory with concrete from the same ready-mix truck. Three different rubber head and two different metal head vibrators were used during the consolidation of the test specimens. Companion specimens in the first pair were 20.5 cm (8 in) high. Concrete was placed in a single lift and vibrated with short vibrator heads [23 cm (9 in) long]. The rubber head was 7 cm (2¾ in) in diameter and the metal head was 4.4 cm (1¾ in) in diameter. Companion specimens in the second pair were 43 cm (17 in) high. Concrete was placed in two lifts and vibrated with common-size vibrator heads

[36 cm (14 in) long]. The rubber head was 4.8 cm (17/8 in) in diameter and the metal head was 4.4 cm (1¾ in) in diameter. Companion specimens in the third pair were 71 cm (28 in) high and concrete was placed in three lifts. Vibrator heads used were the same as those for the 43 cm (17 in) tall specimens. The fourth pair of specimens was consolidated with a large rubber head vibrator. The rubber head was 7 cm (2 3/4 in) in diameter, and 38 cm (15 in) in length. The concrete in the shorter, 45.5 cm (18 in) tall block, was placed in two equal lifts. The concrete in the 76 cm (30 in) tall block was placed in three equal lifts. Size of reinforcement for different specimens consisted of 13-mm (#4), 16-mm (#5), 19-mm (#6), and 25-mm (#8) bars.

Fig. 7.10: Consolidation of specimen 20.5 cm (8 in) high.

In all specimens the concrete vibrator was inserted at a single point in the plan center of the block and the concrete was vibrated for a specified period, after which the vibrator was removed. The length of vibration time for each pair of specimens was selected by observation of the concrete surface during vibration. First, a rubber head vibrator was inserted into one of the specimens, and the length of vibration was timed. The concrete was vibrated until the rapid escape of air bubbles subsided. The companion specimen was vibrated with the metal head for the same length of time. This procedure resulted in times of vibration of 8 seconds for each lift of concrete in all 3 pairs of companion specimens, and 15 seconds per lift of concrete for the fourth pair of specimens. Figure 7.10 illustrates the vibration of concrete in one of the specimens.

The surface of the specimens was then finished, and the blocks were allowed to cure for at least five days before coring began. A total of thirty-seven cores were taken from the eight consolidation specimens (Fig. 7.11). All but two of the cores were taken through specimen reinforcement. Nineteen of the cores were taken from the shallowest specimens (20.5 cm deep). A smaller number of core samples were taken from each of the other specimens. All cores were split open at the level of reinforcement and bar sections were removed from the core for a detailed evaluation of the concrete surface above and below each exposed reinforcing bar. The number and size of air voids under each bar section were recorded. Sections were cut from cores of each specimen for density and void analysis. The density and void content of the hardened concrete was determined in accordance with ASTM C642 procedures. Details of the specimen dimensions and identification; concrete mix used; coring locations, depths, and identification; and reinforcement layout are included in Reference 127.

Fig. 7.11: Coring reinforced concrete test specimen.

Discussion of Results

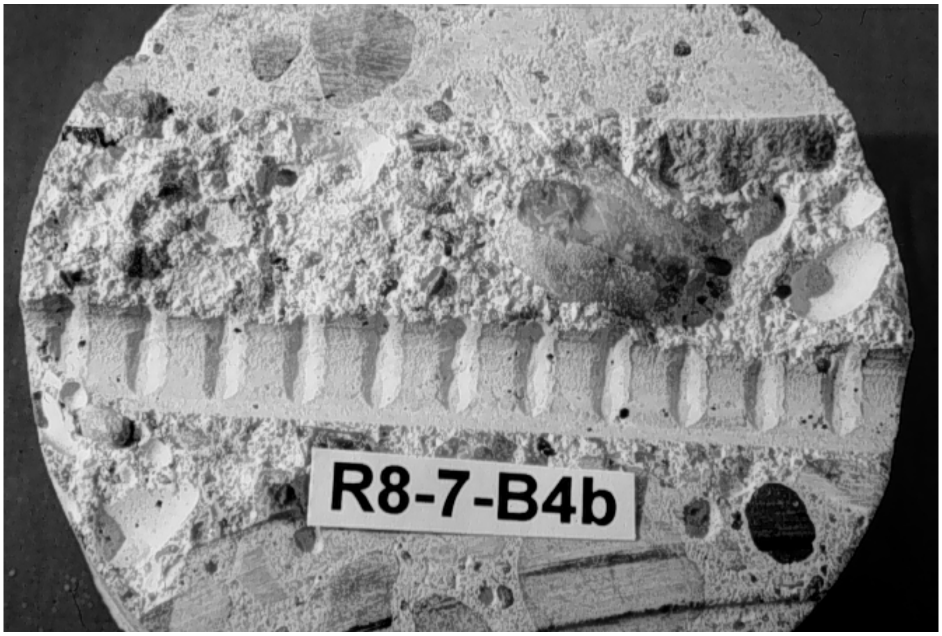
The most important trend identified with both vibrator heads was the variation in void area under reinforcing bars with distance from the point of vibrator insertion. In general, the area of voids under the reinforcement increases with distance from the point of vibrator insertion. This trend was observed on reinforcing bars at both upper and lower mats. The average area of voids under reinforcing bars close to the point of insertion was as high as 70% of and as low as 5% of the void area under bars farther from the point of insertion. Figure 7.12 shows the voids under a bar close to and farther from the vibrator at the bottom mat of specimen R8.

Most voids in the concrete were located beside and beneath the reinforcing bars, especially those farther from the point of vibrator insertion. In nearly all cases, there were no air voids adjacent to the top surface of reinforcing bars.

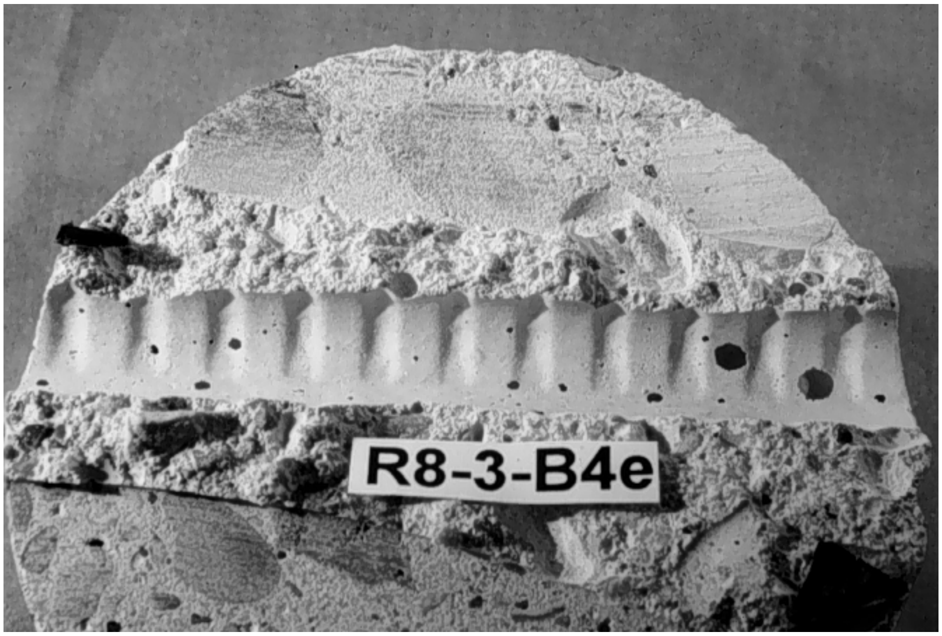
There was more void area located under bars in the upper mats of a specimen than in lower mats. The average void area under bars in the top mat varied from 1.6 to 4.8 times the void area under bars in the lower mats. During vibration of concrete, entrapped air rises towards the top surface of a specimen. At the end of vibration, there are air voids that do not escape the concrete and are trapped under the bars closer to the top surface. Another contributing factor was the placement of concrete in lifts. During the vibration of the upper lifts, the head of the vibrator was inserted several centimeters (a few inches) into the preceding lower lifts, which received additional consolidation as compared to upper lifts.

Analysis of the air void distribution showed that larger void areas were located below larger bars. This phenomenon was expected, since larger diameter bars would tend to interfere with the escape of entrained air bubbles more than smaller diameter bars would.

After examining the void area under reinforcing bars in all of the specimens, no conclusive difference could be identified between the rubber and metal head vibrators. At certain locations, use of the metal head vibrator resulted in the production of less void area under the bars than did the companion rubber head. However, at other locations, there was less void area with the rubber head.



(a) Air voids close to point of vibrator insertion.



(b) Air voids farther away from point of vibrator insertion.

Fig. 7.12: Voids under bars from specimen 20.5 cm (8 in) high consolidated with rubber head vibrator.

No appreciable difference was seen between the void area beneath uncoated bars versus that beneath coated bars. At some locations, the area of voids beneath uncoated bars was less than that beneath epoxy coated bars, but the opposite situation was observed at other places. Small and large voids were found under both epoxy-coated and uncoated bars from each specimen.

The density and permeable void content of the rubber and metal head specimens were very similar. The difference between the largest and smallest test section densities was only 2.3%. Overall, vibration with metal heads seemed to produce a slightly lower amount of permeable void space than did vibration with rubber heads. Based on the small difference between the two heads and the limited test database, a conclusive difference in the relative performance of the two vibrator heads was not found.

7.3 CONCLUSIONS AND RECOMMENDATIONS

7.3.1 Conclusions

Rubber head vibrators caused less damage to epoxy-coated reinforcement than did comparable metal heads. Under similar conditions and with the same time of vibration, metal heads produced significantly greater percentages of damage and larger damaged spots on a coated bar than rubber head vibrators. With both metal and rubber heads, longer periods of vibration and restricted clearances will result in the production of more damage to the coated bars. Direct contact between either head and a coated bar for even very short periods can result in significant damage to the epoxy coating.

The metal head vibrator imparted more energy to the surrounding concrete than did the rubber head. The frequency in the concrete during vibration was about 10% less with the rubber head than with the metal head. Metal head vibrators produced more significant horizontal accelerations than did companion rubber heads, especially at larger distances from the point of insertion. The area of influence with a metal head vibrator was larger than that of a comparable rubber head. The higher particle frequencies and horizontal accelerations observed with the metal head indicate that the metal head will consolidate concrete more rapidly and efficiently than the rubber head. Longer periods of vibration will likely be required to consolidate a specimen with a rubber head vibrator than with a metal head. However, with sufficient periods of vibration and appropriate spacing of insertion points, a rubber head vibrator can satisfactorily consolidate concrete.

From consolidation tests with both metal and rubber heads, it was found that the amount of voids located under reinforcing bars was greater farther from the point of vibration insertion than closer to the insertion point, even when the concrete at both locations was adequately consolidated. The radius of influence for adequate consolidation of concrete thus may be larger than the radius of influence for removal of air voids beneath reinforcing bars. Herman suggests to take the area of influence for removal of void area beneath bars as 75% of that required for concrete consolidation.[127] A closer schedule of insertions seems to be required to ensure adequate removal of air voids from beneath reinforcing bars than is required for consolidation of the concrete. A reduction in air voids under bars should improve corrosion performance, as there will be fewer places for water and corrosive elements to collect in close proximity to the reinforcement.

Based on test results from permeable pore space and concrete density, both metal and rubber heads produced specimens which were consolidated to about the same degree. Both heads removed the large entrapped air bubbles from the concrete. The rubber head vibrator was able to produce adequately consolidated concrete with a density comparable to that produced using a metal head.

7.3.2 Recommended Practice for Concrete Placement

Rubber head vibrators should be specified for consolidation of concrete with epoxy-coated reinforcement. The use of rubber heads will reduce the amount of damage to coated reinforcement, while observance of proper vibration procedures will ensure the concrete is adequately consolidated.

It is recommended to increase the schedule of vibration insertions to ensure that a greater amount of air voids beneath bars be removed and that the concrete is well consolidated. Such a schedule can be based on Herman's suggestion of taking the area of influence for removing air voids as 75% of that required for consolidation.[127] Since there are generally more voids located beneath the top layer of reinforcement, it is recommended that the top lift of the concrete, or the whole depth if the concrete is cast in one lift, be vibrated for longer periods to ensure air bubbles have sufficient time to escape. It is not realistic, however, to attempt to remove all entrapped air, since excessive vibration may cause segregation of the concrete. If the operator follows proper procedures and is careful to avoid overvibrating the concrete, the reduction in insertion point spacings should not have adverse affects. With the use of rubber head vibrators, the level of damage to the coated bars should not be significantly worsened because of the increased schedule of insertion points.

As with all reinforced concrete construction, vibrator operators should be well trained in proper consolidation procedures, especially when the concrete is reinforced with epoxy-coated bars. Operators should not deliberately contact coated reinforcement with either metal or rubber heads, and they should avoid incidental contact between the vibrating head and reinforcing bars. The vibrator should not be dragged over coated bars, nor should the head be forced into restricted areas between a coated reinforcement cage and formwork. Operators should be instructed on proper spacings of insertion points for concrete vibrators with rubber heads, and special care should be taken to ensure concrete reinforced with epoxy-coated reinforcement is adequately consolidated.

It is very important to limit vibrator-induced damage by all possible means. Concrete placement is the last possible procedure during which the coating on reinforcement can be damaged before it is put into service, and damage during concrete placement cannot be inspected nor repaired. In addition, since the quality of concrete consolidation has a significant effect on the corrosion performance of epoxy-coated reinforcement, it is also important to ensure that the concrete is well consolidated. These two goals can be successfully achieved by properly using rubber head vibrators with a sufficient schedule of insertion points.

Chapter 8. Macrocell Corrosion Study

8.1 GENERAL

Corrosive cells are set up in concrete structures by differences in concentration of chlorides, alkalies, moisture, oxygen, and metallic ions on different zones of the steel reinforcement.[24, 128] Depending on the size and location of the anodic and cathodic areas, corrosion cells may occur in a micro and/or macro scale. In a macro scale, the anode and cathode can be separated by a few centimeters or by several meters, forming macrocells. A typical case of macrocell corrosion occurs in a bridge deck exposed to de-icing salts (Fig. 8.1). The top mat, which is closer to the road surface, is subjected to increased concentration of chlorides and moisture, and oxygen is available at the bottom mat. The top mat becomes an anode and the bottom mat a cathode.[30] Macrocell corrosion is particularly severe because of the availability of a large cathodic area with respect to the smaller anodic areas. The smaller the anode/cathode ratio, the more severe the corrosion.[24, 129]

In concrete structures with epoxy-coated reinforcement, macrocell corrosion was originally thought to be unlikely. The rationale was that the epoxy coating would provide not only a physical barrier to the ingress of chlorides to the rebar surface, but would also electrically isolate the protected rebar from other portions of the reinforcement because of its dielectric properties. Because of this assumption, in early applications in which bridge decks were reinforced with epoxy-coated reinforcement, only the top mat was coated (Fig. 8.2).

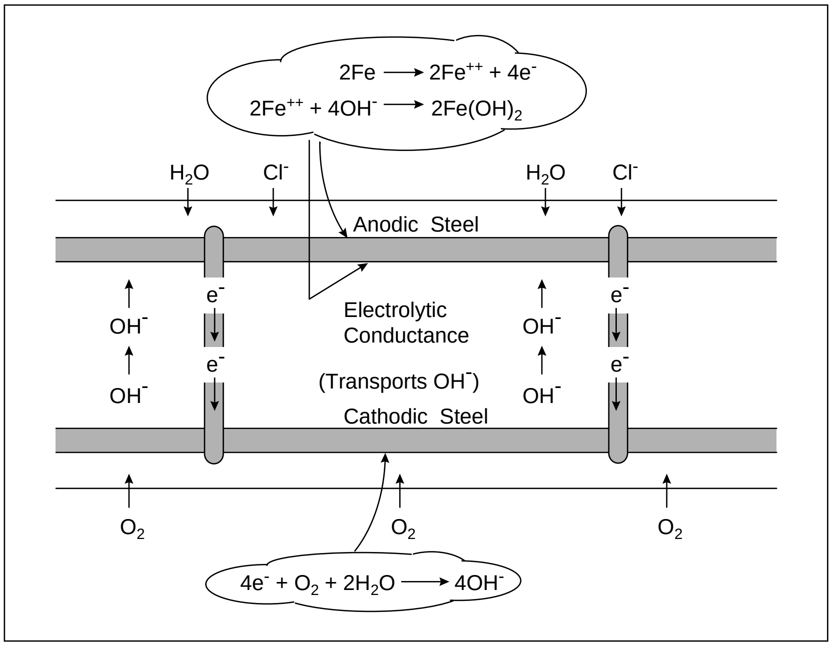


Fig. 8.1: Macrocell corrosion cell in bridge deck.

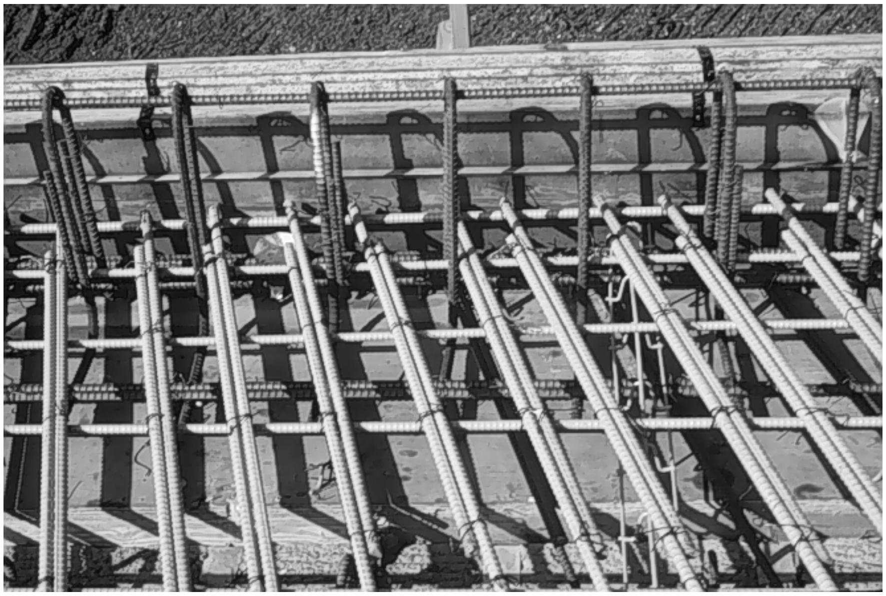


Fig. 8.2: Bridge deck construction showing mix of coated and black bars.

As mentioned earlier, damage to coating at various stages following coating and before the concrete is placed is almost inevitable and leaves the steel exposed. Any incidental contact between exposed, damaged areas of epoxy coated bars with uncoated bars may lead to macrocell corrosion. It is not unusual that uncoated tie wires connecting epoxy-coated to black bars indent and damage the coating, thus effectively bridging the metallic surface of the two bars. A considerable degree of electrical contact between epoxy-coated bars has been observed in one structure.[20] Although damaged areas on straight and fabricated bars are repaired with patching materials supplied by manufacturers, use of improper materials will not provide adequate corrosion protection as was discussed earlier.

Another concern regarding the performance of epoxy-coated rebars is damage caused by fabrication of the bars. During bending, the coating may not only be damaged (cracks, small fissures, or holidays) but also debonded from the steel substrate. Coating damage and debonding may coexist, especially where coated bars are bent to very tight radii. Damage to coating and loss of adhesion are detrimental to corrosion performance, as was noticed in Florida bridge substructures, where the first signs of corrosion of epoxy-coated reinforcement were observed on fabricated bars.[47, 72]

In this part of the study, the factors noted above were considered in the design of test program which included the following parameters:

- Use of epoxy-coated and black bars in the same specimen
- Debonded coating in tightly bent bars
- Level of coating damage
- Repair of damage
- Bar size
- Bar deformation pattern

8.2 TEST SETUP AND PROCEDURE

Test specimens consisted of small concrete blocks with a fabricated epoxy-coated bar (bar bent 180°) in the top layer and uncoated bars in the bottom layer (Fig. 8.3). In control specimens, black bars were used for the top and bottom layers. The top bar was electrically connected to the bottom bars through a resistor. Several degrees of coating damage (based on specification limits current at the time) were introduced in the specimens and the damage was patched on some of the specimens. Intentional damage was introduced on the outside of the bend to reach required damage levels. Damage caused by mandrels during fabrication was not patched. Two bar diameters, #4 and #8, and two deformation patterns, parallel and cross ribs, were selected. Variables are summarized in Table 8.1.

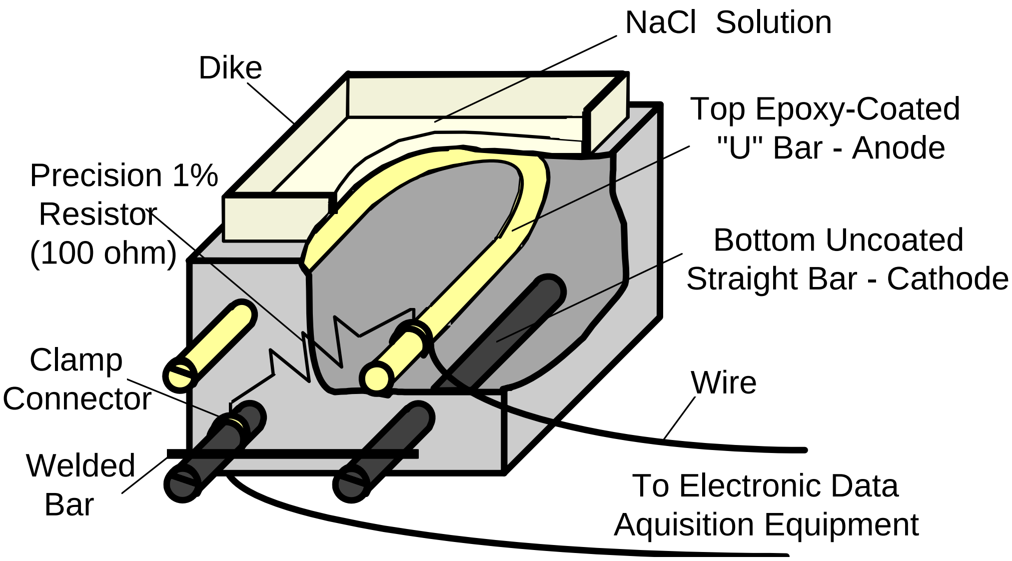


Fig. 8.3: Macrocell specimen model.

An acrylic dike was built on the top surface to pond a salt solution. Bars were connected to a data acquisition system for corrosion monitoring. All details of the test, such as test variables, steel preparation, material characteristics, specimen design and preparation, specimen dimensions, test set-up, routine monitoring, and post-mortem examination procedure are described in reference 10.

Several elements were considered in the design of the specimens to accelerate exposure testing:[10]

- Concrete with a water-cement ratio of 0.57 was used to make the concrete more permeable to the corrosive solution.
- A concrete cover of 1 inch was selected to reduce the time of chloride penetration to the bars.

- A large cathodic (bottom) steel area was coupled to a small anodic (top) steel area to produce a large corrosion driving force.
- The distance between anode and cathode was reduced to facilitate the ionic flow.

Group No.	Deformation Pattern		Epoxy Coating Damage Level[a]					Damage Condition	
	Parallel Ribs	Cross Ribs	Spots >6x6mm	Spots > 2%	Cracks < 1%[b]	Spots < 2%	Pinholes < 1%[c]	Patched	Not Patched
1	●		Control Specimens - Uncoated Bars						
2	●		●					●	
3	●		●						●
4	●			●				●	
5	●			●					●
6	●				●				●
7	●					●			●
8		●	Control Specimens - Uncoated Bars						
9		●	●					●	
10		●	●						●
11		●					●		●

a: Refer to either the size of damaged spots or percentage of damaged area to bar surface area embedded in concrete.
b: Hairline cracks along the transverse ribs on the outside of bends.
c: Fine intermittent tears or pinholes along the rib bases on the outside of bends.
Groups 1 through 7: Parallel Ribs
Groups 8 through 11: Cross Ribs

Table 8.1: Summary of Macrocell Study Variables, Series A (#4 bent bars) and B (#8 bent bars).

The test represents an artificial situation that may not accurately represent field conditions. The difference between test and field conditions should be kept in mind when analyzing and interpreting the data. It should also be emphasized that the epoxy coating material used for the bars was produced in the early 1990's. Epoxy coatings have been continuously developed since then and today's materials have improved properties compared to earlier formulations. Test results reported herein may not necessarily reflect the potential performance of materials more recently developed.

The test program consisted of 11 groups of macrocell specimens with triplicates in each group of variables for both series A (#4 bars) and B (#8 bars). The exposure conditions consisted of cycles of ponding a 3.5% NaCl solution on top of the specimen followed by removal of the solution to let the specimen dry. Twenty-eight day cycles, wet for two weeks and dry for two weeks, were imposed. The layers were connected via a known resistance to enable monitoring of the corrosion activity. The voltage drop across the resistor was measured every week and converted to current using Ohm's Law. Periodic visual examinations were conducted to detect signs of surface corrosion and concrete deterioration and cracking. One specimen from each group of triplicates was opened after a certain time period to examine the condition of the bars. Figure 8.4 illustrates the convention for identifying the portions of a bar that was used to describe the bar condition after exposure.

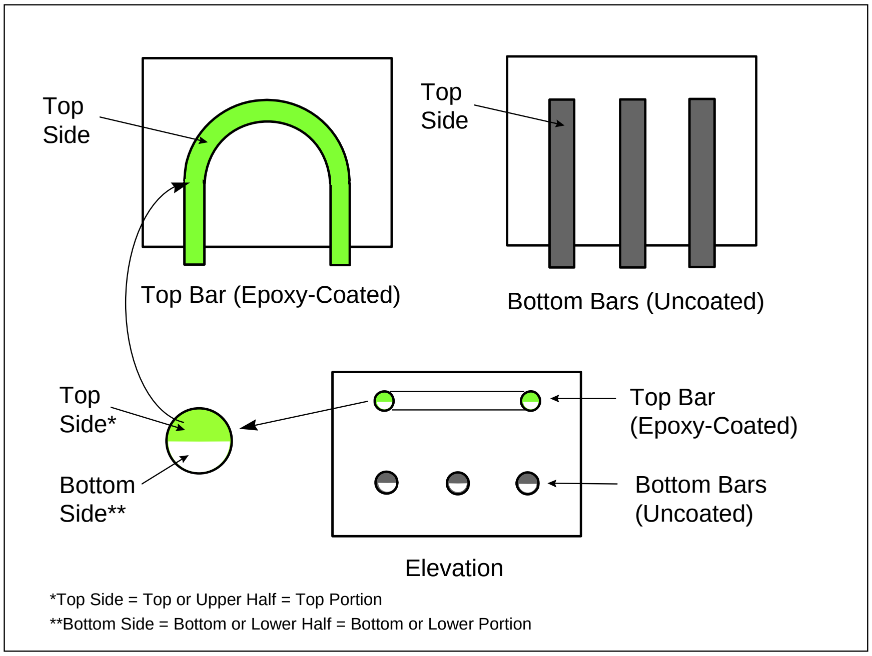


Fig. 8.4: Convention for identifying bar locations.

8.3 OVERVIEW OF FINDINGS AFTER 1 AND 2 YEARS

One-third of the triplicate specimens were opened at the end of 14 cycles of exposure (one year) and the second third were opened at the end of 26 cycles of exposure (2 years). Exposure testing of the last third, originally scheduled to last 39 cycles (3 years), was lengthened to 60 cycles of exposure (4.5 years). Test results from the autopsies at the end of 1 and 2 years are thoroughly presented and discussed in reference 10. In order to have a background for the discussion of results from the specimens autopsied at 4.5 years, a comprehensive summary of the findings after 1 and 2 years is presented. Since there were many similarities at the end of 1 and 2 years, the findings from both autopsies are summarized together as follows:

- Corrosion of epoxy-coated reinforcement was delayed and started at chloride concentrations about twice those associated with the onset of corrosion of uncoated steel.
- Epoxy coating was able to reduce the amount of macrocell corrosion even with the presence of damage. As the percentage of coating damage was reduced, corrosion performance improved.
- Patching reduced but did not prevent corrosion. Patching on the outside of the bend proved insufficient because corrosion spread from damaged areas on both sides of the bend.
- No corrosion-induced cracks were observed at the concrete surface when epoxy-coated bars were used. Corrosion products were at a very low enough state of oxidation that concrete distress was not evident.
- Epoxy-coated bars seemed to deteriorate as the period of exposure increased. The rate of metal consumption of the most corroded bars was increasing and approaching that of uncoated bars.
- Smaller diameter bars corroded less than large diameter bars. No clear trend was observed in relation to bar deformation pattern.
- The quality of concrete next to the rebar surface had a large effect on corrosion protection. Corrosion spots and blisters were numerous at locations with concrete voids, especially voids near damaged areas.
- Coated bars showed more propensity to develop plastic settlement cracks, gaps below the bar, and corrosion products under the bar. The lack of adherence between epoxy-coated bars and concrete and

different concrete consolidation above and below the coated bars were considered to cause the increase in corrosion activity.

- Epoxy coating debonded from the steel substrate after 2 years of exposure to chlorides. Coating adhesion was already marginal at the beginning of the experiment due to bar fabrication and was further diminished by exposure to moisture and subsequent underfilm corrosion. No relationship was found between the degree of coating debonding and the amount and severity of corrosion.

The following corrosion mechanism was postulated: Corrosion originated at exposed steel areas where the chloride concentration reached a threshold level and spread to adjacent areas by undercutting the epoxy coating. Debonding and undercutting progressed at the coating/metal interface and corrosion products built up at exposed areas. Acidic solution accumulated and was trapped under the coating and in blisters. Corrosion products were mostly black and non-expansive, an indication of limited oxygen availability beneath the coating. Corrosion spread more under the bar than on the top, preventing the formation of concrete cracks.

8.4 TEST RESULTS AFTER 4.5 YEARS

Exposure testing of the last group of the triplicate specimens was terminated after sixty 28-day cycles of exposure (4.5 years). The specimens were observed periodically, about every 2 to 4 months (every 6 months in the last 1.5 years). Special emphasis was placed in detecting signs of concrete cracking and surface corrosion. Corrosion currents were monitored throughout. In addition, corrosion potentials were monitored on the top surface for the last 10 months of the exposure for the last group only.

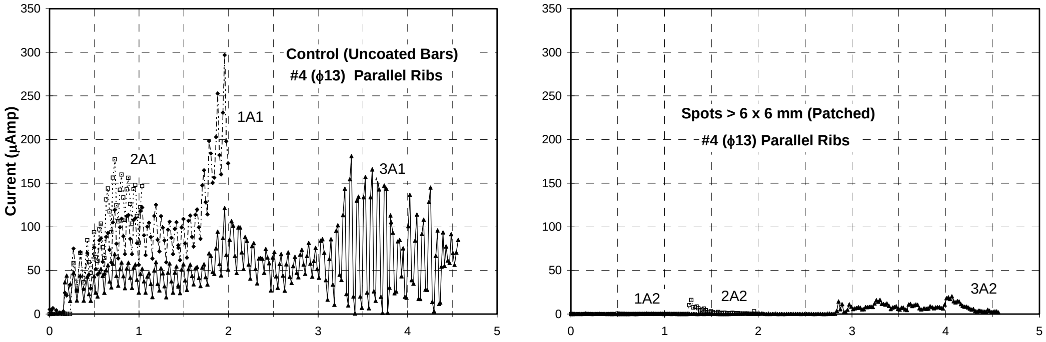
8.4.1 Measured Macrocell Currents

Graphs showing the trend of corrosion current data over time for all specimens are included in Fig. 8.5 and 8.6. Monitored currents were useful in assessing the relative performance of specimens before autopsy and complemented the findings after the autopsies. Current plots were generally jagged curves with a series of low and high peaks. Such peaks corresponded to the end of the wet (high values) and dry (low values) periods.

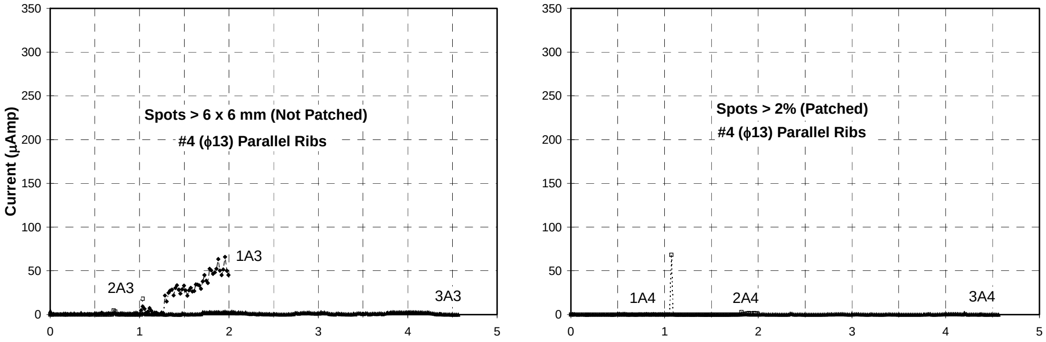
Control Bar Specimens

Uncoated bars showed higher currents than epoxy-coated bars. All bars showed more scattered and erratic behavior after 2 and 3 years of exposure. The jumps between high and low peaks became significantly larger. This was especially noticeable in the #4 bar with parallel ribs. Larger bars experienced higher corrosion currents than smaller bars.

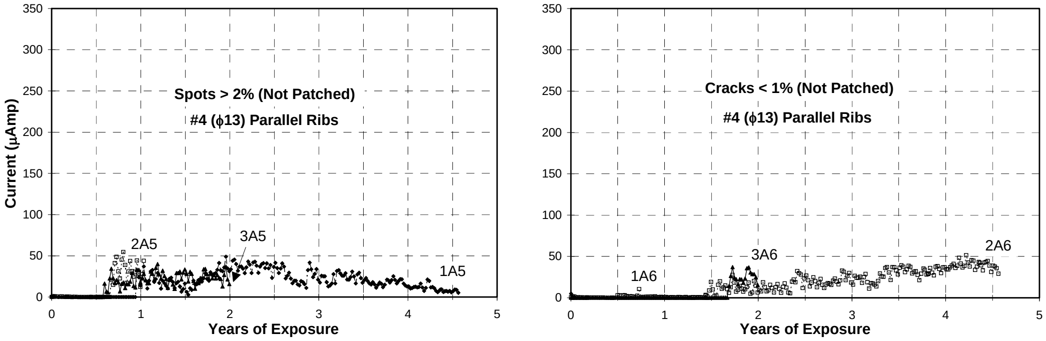
Interestingly, macrocell currents for #4 bars with parallel ribs [Fig. 8.5(a)] were not very high (in the range of 60-90 μA) despite the evident surface deterioration and cracking of the specimen. At about 2.5 years, #4 bar with cross ribs [Fig. 8.5(h)] started to show a continuous drop with wide jumps between high and low peaks after reaching maximum currents (200 to 250 μA) between 2 and 2.5 years. However, at about 3.5 years the current continuously increased again until the end of the exposure (range of 150 to 230 μA).



(a) Group A1 (control specimens) (b) Group A2

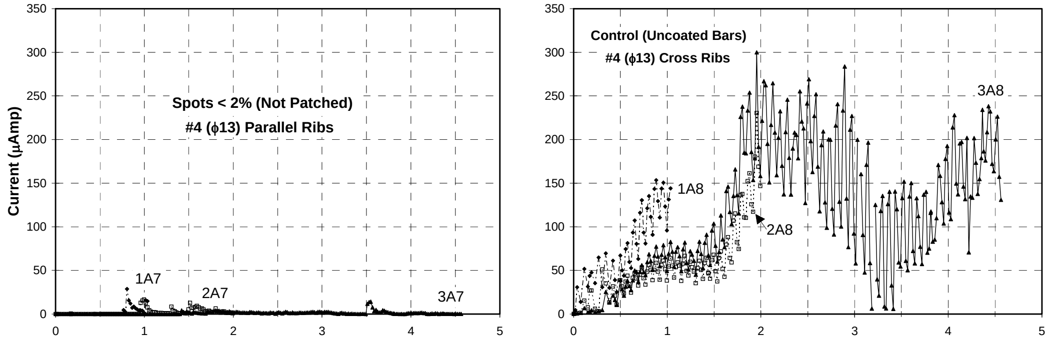


(c) Group A3 (d) Group A4

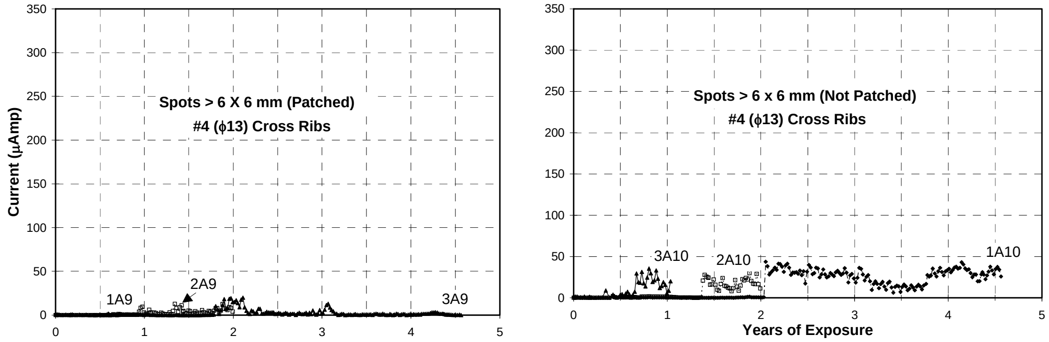


(e) Group A5 (f) Group A6

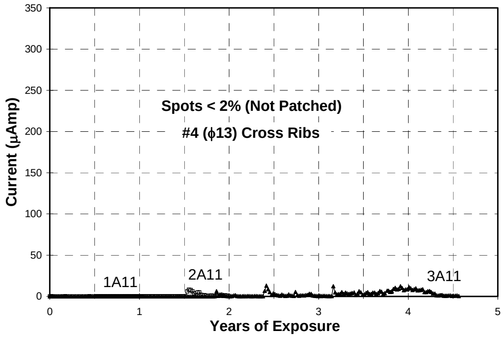
Fig. 8.5: Current vs. time of series A (#4 bars).



(g) Group A7 (h) Group A8 (control specimens)

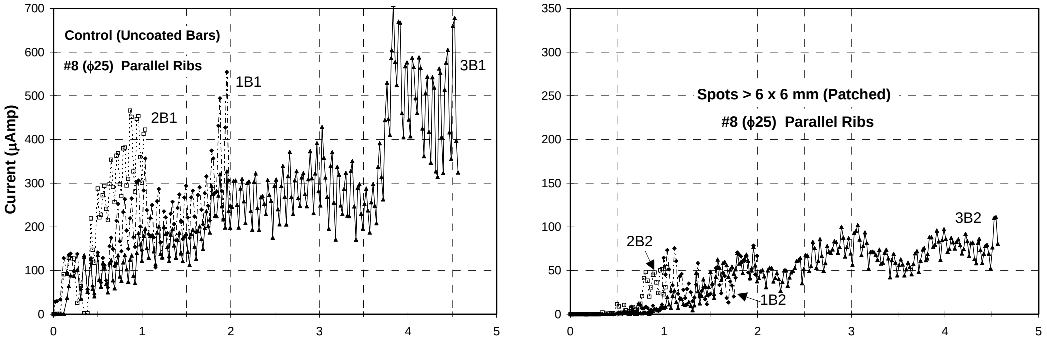


(i) Group A9 (j) Group A10

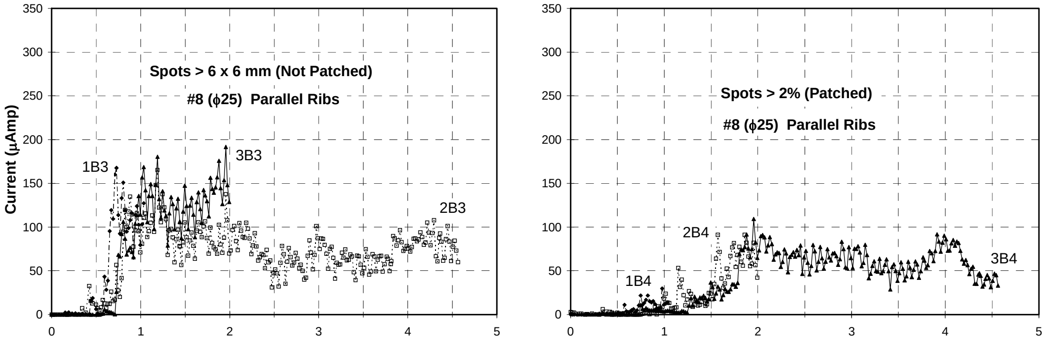


(k) Group A11

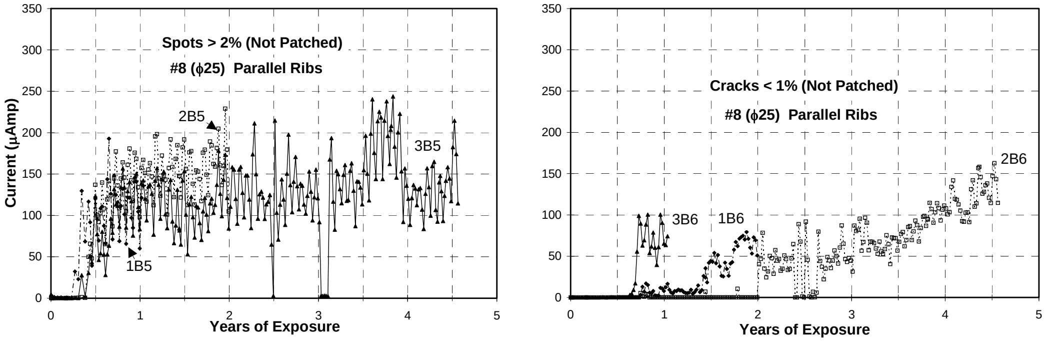
Fig. 8.5: Current vs. time of series A (#4 bars).



(a) Group B1 (control specimens) (b) Group B2

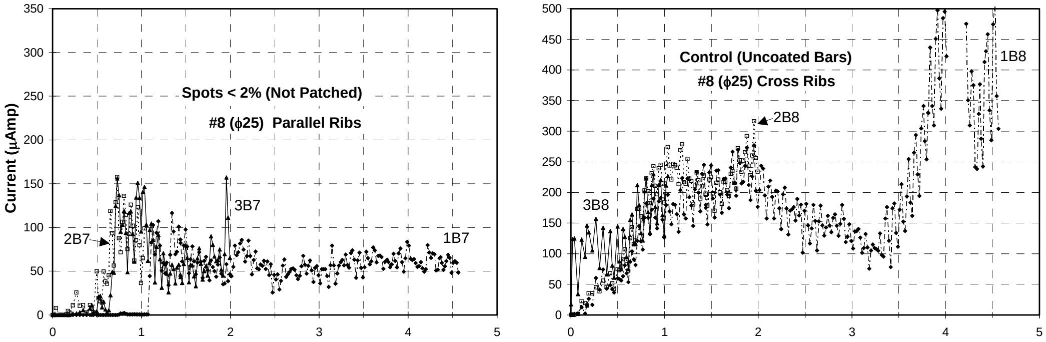


(c) Group B3 (d) Group B4

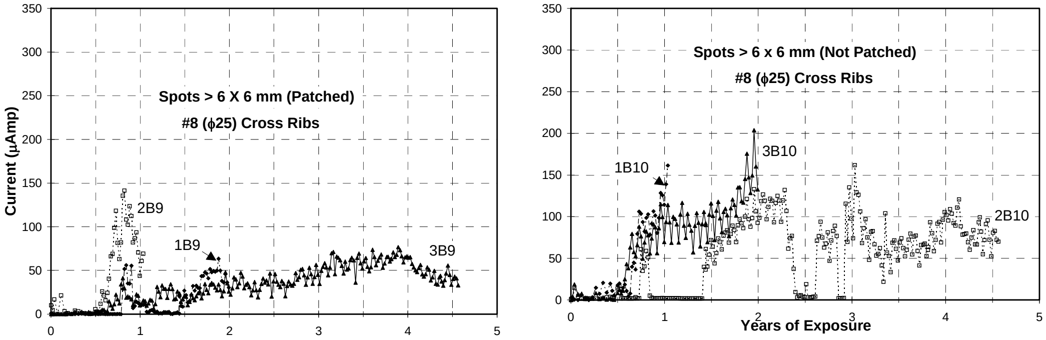


(e) Group B5 (f) Group B6

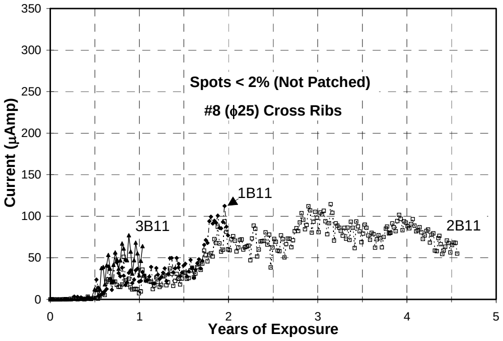
Fig. 8.6: Current vs. time of series B (#8 bars).



(g) Group B7 (h) Group B8 (control specimens)



(i) Group B9 (j) Group B10



(k) Group B11

Fig. 8.6: Current vs. time of series B (#8 bars).

Jumps between high and low peaks tended to be less pronounced in #8 bars but the specimens experienced relatively sudden, large increments of activity at certain periods. The specimen with parallel ribs [Fig. 8.6(a)] reached a steady-state behavior (between 200 and 300 μA) at about 3.5 years when there was an abrupt increase in current (up to 700 μA). Thereafter, the behavior showed wide variations between high and low values (range of 400 to 600 μA). The specimen with cross ribs [Fig. 8.6(h)] showed declining currents from 2 to 3 years, but after 3.5 years the currents suddenly increased about 200% in a 9-month period and remained high until the end.

Epoxy-Coated Bar Specimens

Plots of corrosion currents for epoxy coated bars did not show as large variations between high and low readings as those for uncoated bars, possibly due to the smaller current levels. From Fig. 8.5 and 8.6, clearly, the specimens with larger bars developed much higher current levels than specimens with smaller bars. If corrosion rate is defined as the increment of corrosion per unit time (the slope of the curves), most specimens showed small corrosion rates and seemed to have reached a steady-state behavior. The few specimens that were showing increasing corrosion rates at the end of the exposure were #4 and #8 bars with cracks in the coating of less than 1% (coating is cracked alongside the ribs and the amount of exposed steel is less than 1 %).

Bars with damage greater than 2% experienced the highest current. Repaired specimens tended to develop less current than unpatched specimens, but there were a few cases where patched bars had similar or higher currents than damaged bars. No. 4 bars with cross ribs showed slightly higher currents than bars with parallel ribs. No difference was found in #8 bars with different bar deformation.

8.4.2 Corrosion Potentials

Corrosion potentials of specimens were monitored for the last 10 months of exposure. Corrosion potentials were measured on the top surface by placing a saturated calomel electrode probe on the top surface of the specimens. The probe was located at three points: above the middle of straight bar legs and above the center of the bent portion, as indicated in Fig. 8.7. The probe was connected to a voltmeter and the circuit was completed by connecting the other terminal to the top bar. During initial potential measurements, the continuity between top and bottom bars was temporarily interrupted to isolate the top bar and reflect its true potentials. This practice was later abandoned because only a small difference was observed in the potentials depending on continuity between bar layers.

A few, typical plots of corrosion potentials measured over time of exposure are shown in Fig. 8.8 and 8.9. For the majority of specimens, there was little variation between readings and potential curves had reached steady-state behavior. Any corrosion process (large or small) is expected to be well established by the time measurements were first taken (after 3.5 years of exposure).

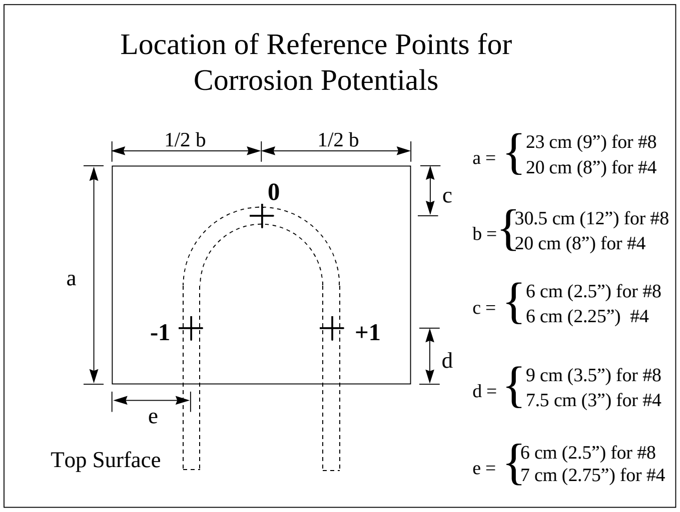


Fig. 8.7: Top surface of macrocell with points for corrosion potentials.

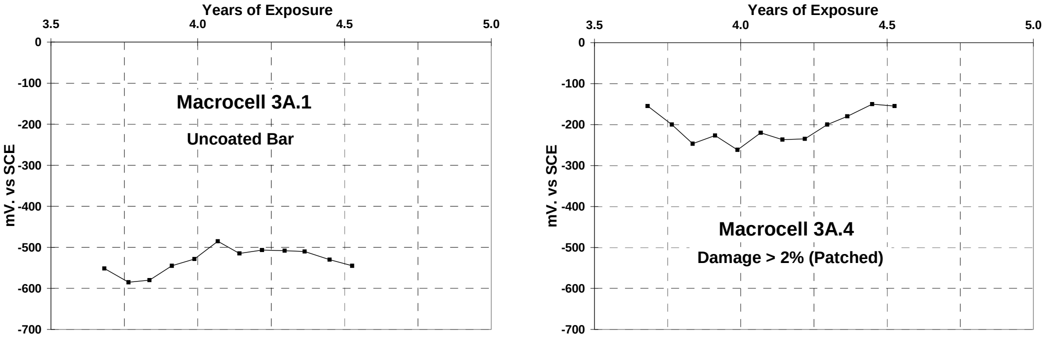


Fig 8.8: Average corrosion potentials vs. time of typical specimens A (#4 bars).

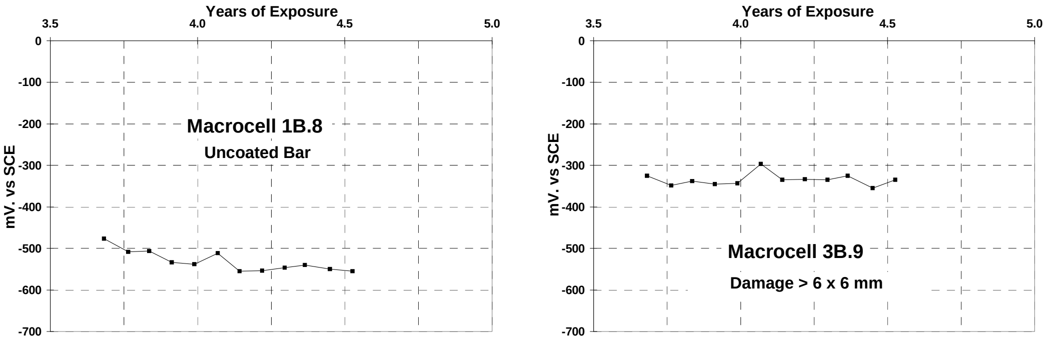


Fig. 8.9: Average corrosion potentials vs. time of typical specimens B (#8 bars).

Figures 8.10 and 8.11 show average corrosion potentials for all specimens from series A and B. All uncoated bars (#4 and #8) had more negative average potentials than coated bars (from -530 to -565 mV vs. SCE). Corrosion potentials were similar for both #4 and #8 black bars. For coated bars in series A (#4 bars), average corrosion potentials ranged from -205 mV to -480 mV vs. SCE. For coated bars in series B (#8 bars), average potentials ranged from -325 mV to -425 mV vs. SCE. Clearly, larger bars developed more negative and more uniform average potentials than smaller bars.

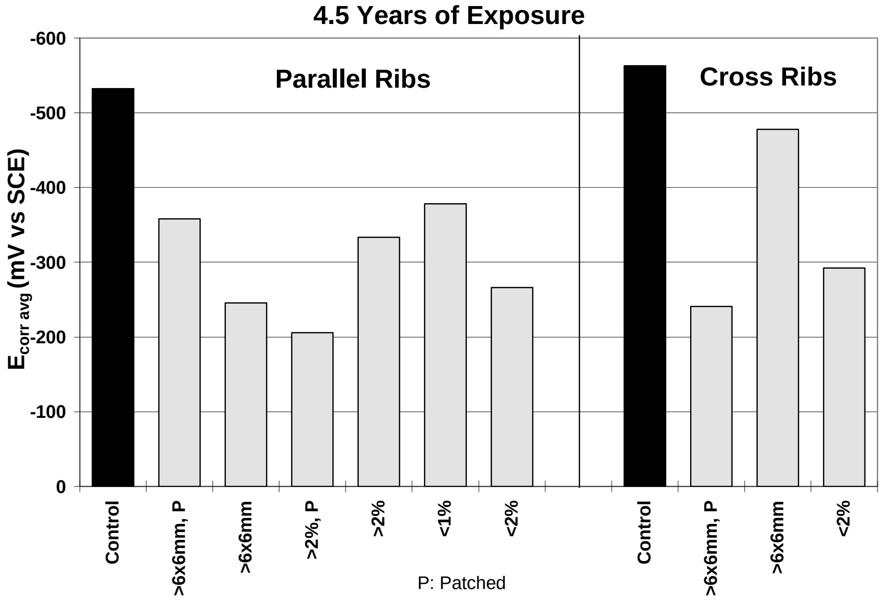


Fig. 8.10: Avg. corrosion potentials of all specimens A (#4 bars).

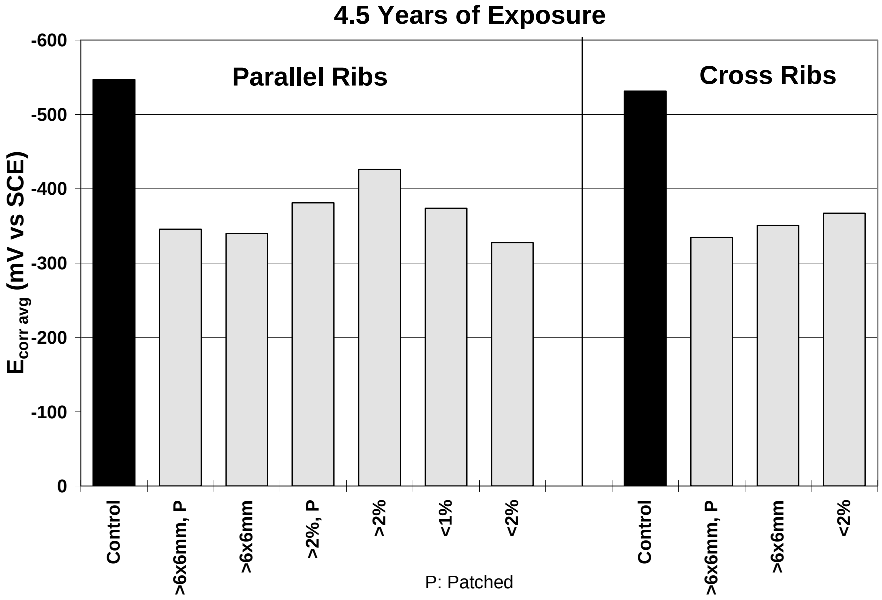


Fig. 8.11: Avg. corrosion potentials of all specimens B (#8 bars).

8.4.3 Specimen Surface Condition

Control Bar Specimens

All specimens with uncoated bars underwent extensive deterioration, including concrete cracking, rust staining, and surface scaling, as shown in Figures 8.12 and 8.13. Three of the specimens (2 #4 bars and 1 #8 bar with cross ribs) started to crack between 7.5 months and 1.4 years, and one specimen (#8 bar with parallel ribs) first cracked within the first 7.5 months of exposure. None of the specimens developed early cracking due to plastic shrinkage. Cracking generally occurred along the path of the top bar, starting at the straight regions of the bar next to the front face and later extending towards the bent zone of the bar.

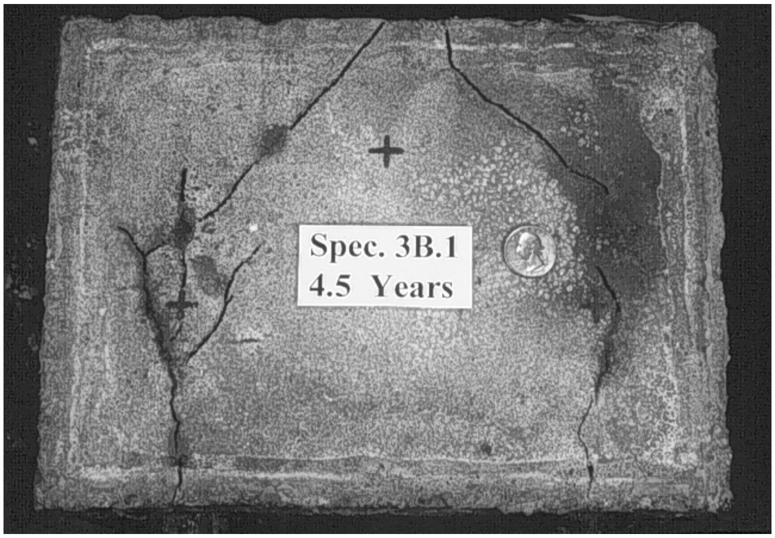


Fig. 8.12: Specimen surface condition of specimen with uncoated bar.

Fig. 8.13: Specimen surface condition of specimen with uncoated bar.

In all cases, cracks propagated towards the front face above the protruding bar legs. In specimen 3A1 (#4 bar with parallel ribs) horizontal cracking developed on the front face between the 2 bar legs. In specimen 3A8 (#4 bar with cross ribs), the crack above the left bar leg propagated on the front face all the way down to the bottom of the specimen and was visible at the bottom surface, along the left cathodic bar (Fig. 8.13). Horizontal cracks appeared on the two lateral surfaces of specimen 3B1 (#8 bar with parallel ribs) at a section slightly below the top bar location. The maximum crack width was 1.0 mm in specimens with #4 bars and 1.25 mm in specimens with #8 bars.

Concrete scaling on the lateral surfaces developed mostly during the third year and worsened during the fourth year of exposure. Scaling was always worse and more extensive on the lateral surface closer to the zone of more extensive cracking on the top surface. Scaling was so severe at some surfaces that concrete aggregate particles were exposed. Fine granules of salt exuded on scaled areas at different depths, indicating that solution permeated to a considerable depth from the top surface.

In specimens with larger bars, rust stains appeared on the top surface after 7.5 months to 1.4 years of exposure, and occurred earlier than in specimens with smaller bars. The #4 bar with cross ribs started to show rust stains between 1.7 and 2.1 years, and #4 bar with parallel ribs between 2.1 and 2.4 years. A rust solution oozed down the front face of two of the specimens (one small and one large bar) after 1.7 years. Rust stains were of different sizes and colors (light to dark brown, reddish and orange brown) and generally formed along cracks on the top surface. Their appearance constantly changed during exposure. At different periods during the third and fourth years, fine orange brown rust powder exuded on the surface, especially on cracks. The top surface of all control specimens had an overall yellowish appearance, probably due to contamination by dissolved rust products in the solution. Rust stains also formed on the front face, mainly around protruding bar legs.

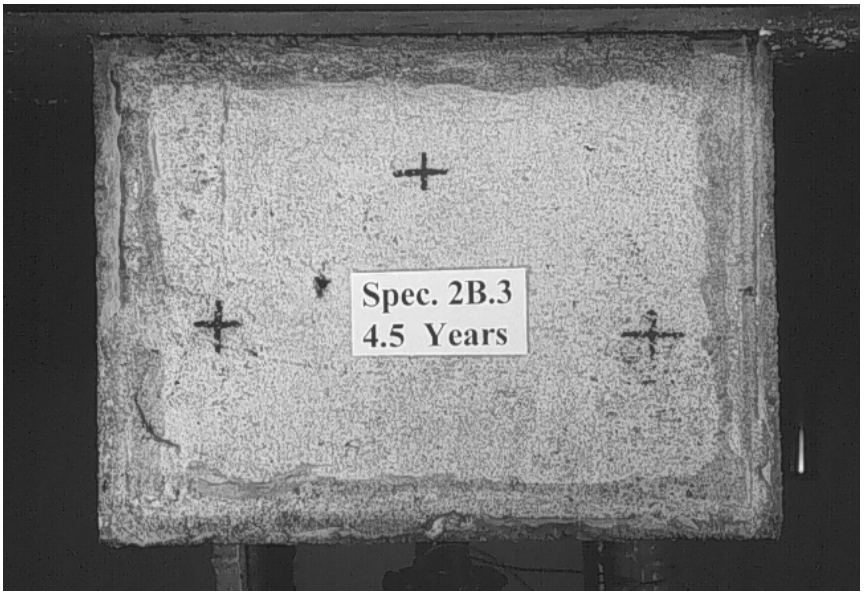
After the first signs of concrete cracking and rust staining, deterioration of the specimens progressed gradually during the first two years of exposure and worsened noticeably during the third and fourth years. Rust staining seemed to have reached its peak during the third year of exposure, and concrete cracking and scaling continuously progressed until the end of exposure.

Epoxy-Coated Bar Specimens

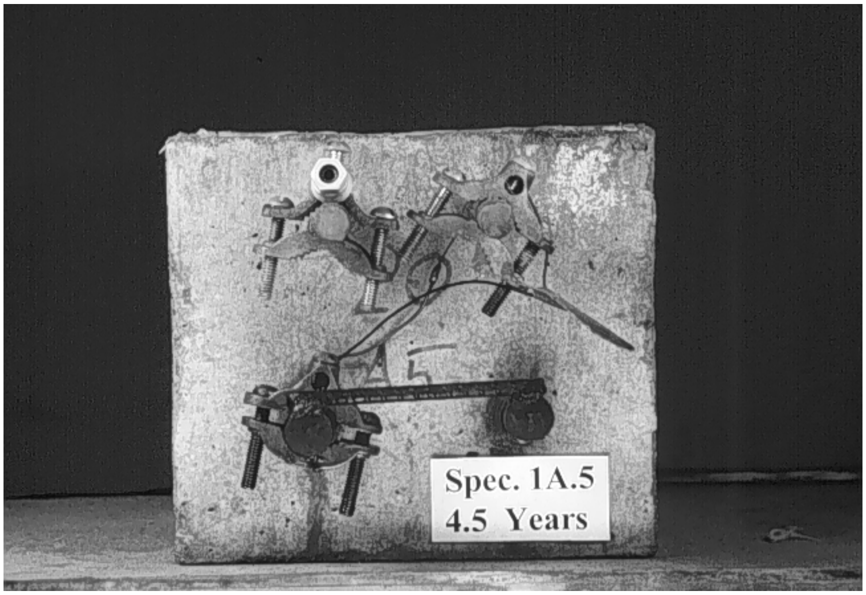
Unlike specimens with uncoated bars, specimens with coated bars maintained very good surface conditions (Fig. 8.14). Some specimens cracked but widths were narrower than in control specimens. Twenty percent of specimens with #4 bars and 80% of specimens with #8 bars developed cracking. In the first two years of exposure, no specimen with coated bars cracked. Crack formation is summarized below:

For series A (#4 bars):

- Specimen 2A6 (bar with exposed damaged area less than 1%): Plastic settlement cracks were noted before the first day of exposure. Cracking progressed after 3 years of exposure.
- Specimen 3A9 (bar with exposed damage greater than 6x6 mm): Cracking initiated after 3.5 years.



(a): Top surface



(b): Front surface

Fig. 8.14: Surface condition of specimens with coated bars.

For series B (#8 bars):

- The two specimens with damage greater than 2% (patched and not-patched) had plastic settlement cracks. In specimen with unrepaired damage, cracking progressed after 2.5 years.
- Two specimens started to crack at the end of 3 years (bars with damage less than 2%, both parallel and cross ribs).
- Three specimens cracked during the last 10 months of exposure (bar with parallel ribs and patched damage greater than 6x6 mm; bar with damage less than 1%; and bar with cross ribs and damage greater than 6x6 mm).

Most coated bar specimens cracked between the end of the third year and the fourth year of exposure. In 2 specimens with plastic settlement cracks, cracks progressed after about 3.5 years. Maximum crack width was 0.20 mm, but most cracks had widths of 0.08 mm (hairline cracks). In fact, among cracked specimens with coated bars, only two specimens had the maximum crack width of 0.20 mm (bar #8 with damage > 2% and bar #4 with cracks < 1%). The rest of specimens had very fine, hairline cracks with a maximum width of 0.08 mm.

Concrete scaling was mostly superficial, not severe, and not widespread on the surface of specimens with coated bars. Scaled areas were hardly noticeable and of small size on most specimens with #4 bars. Scaling was a little bit more severe and scaled areas were larger on specimens with #8 bars. Scaling was first observed on a specimen with #8 bar after about 2.8 years of exposure.

Specimens with coated bars did not develop significant rust stains on their top surface. The largest manifestation of rust staining occurred on the front face of specimens with #8 bars. Solution with rust products exuded on the exterior surface of protruding bars near the concrete face (Fig. 8.15). When the solution dried, a formation of very brittle rust products was noted. Frequently, some of the solution oozed down the concrete face. Almost all specimens with #8 bars exhibited this phenomenon which was first observed after about 1.5 years of exposure in one specimen, and after 2.5 to 3.5 years of exposure in others. The solution had a pH between 3 and 4. A small sample of solution was obtained for chemical analysis. Such analysis disclosed the presence of hydrochloric acid in the solution.

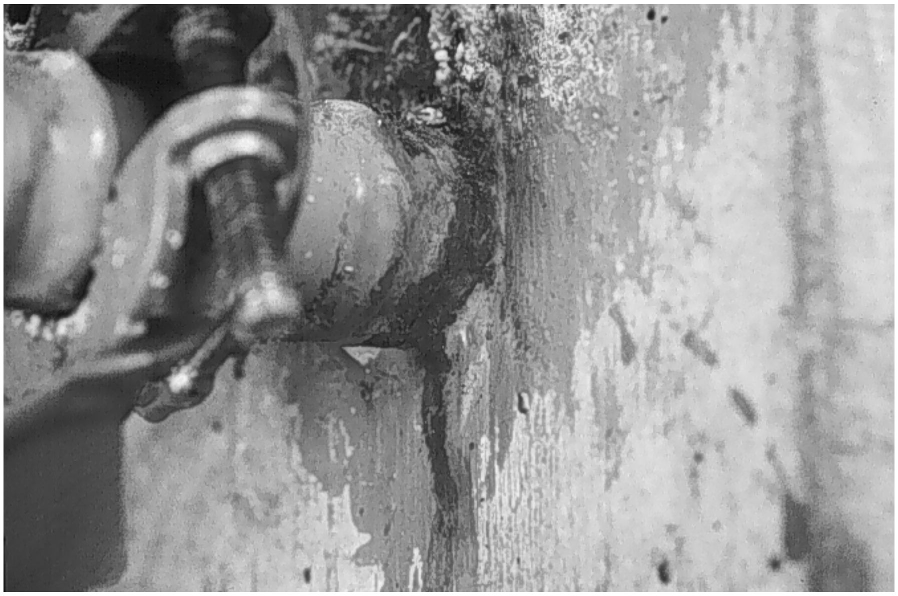


Fig. 8.15: Brown solution exuding from protruding bar at front face of specimen.

Overall, there was good correlation between crack width and concrete deterioration with measured corrosion currents. Most specimens with #4 coated bars did not develop cracks, maintained excellent surface condition, and exhibited very low corrosion currents. Most specimens with #8 coated bars developed fine cracks, experienced exudation of acidic solution with rust on the front face, underwent light to moderate concrete scaling, and had medium corrosion currents. Specimens with uncoated bars experienced extensive concrete scaling and cracking, developed extensive rust staining, and exhibited larger corrosion currents.

8.4.4 Chloride Content

Chloride penetration in concrete over time was monitored by measuring the acid-soluble chloride content in companion concrete prisms at different depths. Companion prisms were made from the same concrete used in the specimens. Concrete powder samples from different depths were obtained by drilling through the blocks at the centroid of the top surface. Two samples were obtained for each representative depth. A portable chloride test kit was used for rapid measuring of chlorides on site.

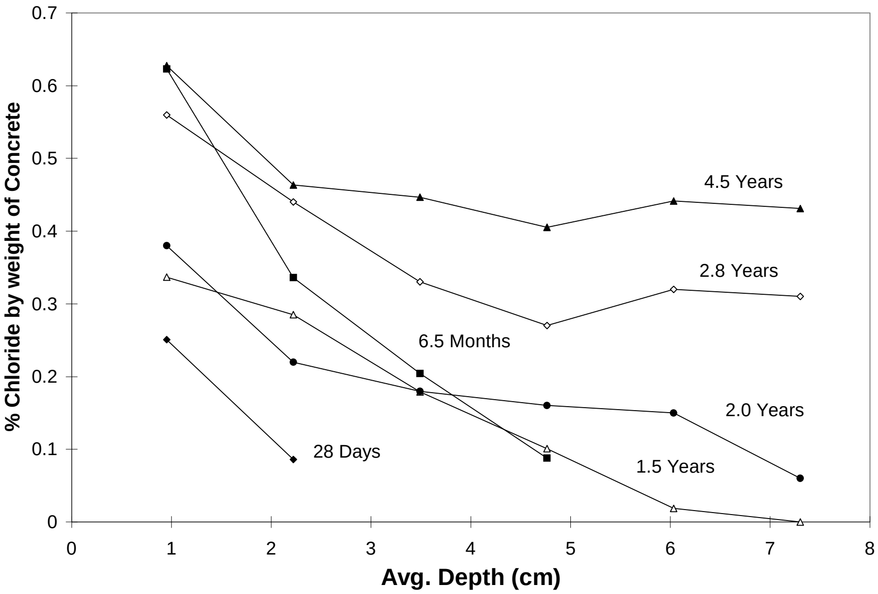
During the first two year of exposure, samples were obtained at the end of every complete exposure cycle. Because of the limited number of prisms available for the last 2.5 years of exposure, samples were obtained much less often during that period.

A graph showing the history of chloride profiles for selected years of exposure is included in Fig. 8.16(a). Chloride content at a depth of 3.5 cm (1.375

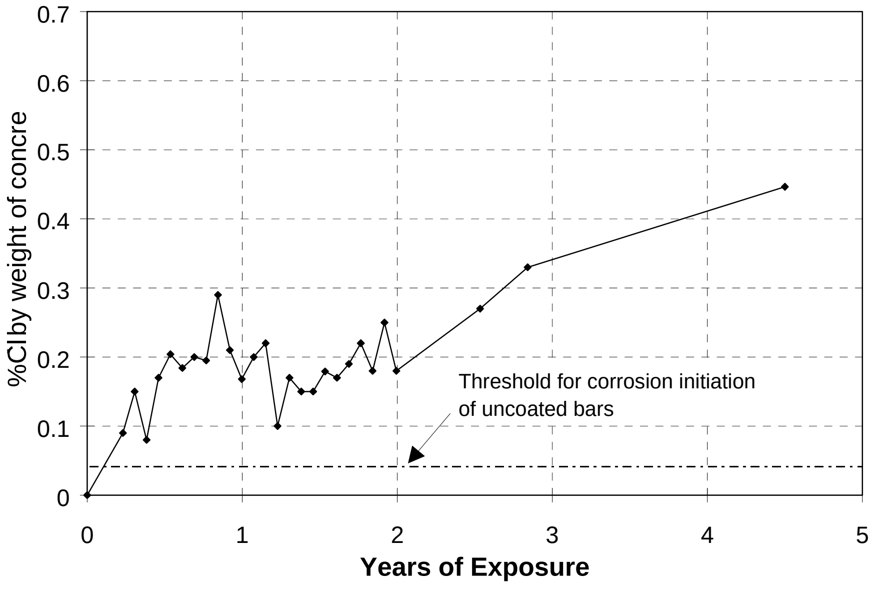
in) vs. time is plotted in Fig 8.16(b). The chloride contents shown are not the chloride contents in the actual specimens, but give a good indication of chloride penetration with time because the samples were made from the same concrete mix used for the specimens and the exposure cycles were the same. Chloride penetration increased with time, and the penetration was accelerated in the last 2.5 years of exposure. The increase was significant deeper into the concrete. Note in Fig. 8.16(a) that the chloride content at a depth of 7 cm (2 7/8 in.) after 4.5 years was higher than that at a depth of 1 cm (3/8 in.) after 2 years. The chloride content at the level of the coated bars was quite high towards the end of the exposure period.

By comparing the trends of chloride contents and corrosion currents, Kahhaleh estimated that chloride concentrations associated with the onset of corrosion of uncoated bars ranged from 0.08 to 0.12% by weight of concrete. [10] The corresponding average chloride content for onset of corrosion of epoxy-coated bars was estimated at about 0.18%. In general, it was difficult to find a clear relationship between increases of chloride content and spikes in the corrosion current. The following two observations illustrate this point:

1) The chloride content remained relatively constant from 6 months to 2 years of accelerated exposure [Fig. 8.16(b)]. Within that period, a number of specimens experienced a gradual increase of current (Fig. 8.5 and 8.6). Apparently, the presence of a steady level of chloride ions had a corrosive effect over time.



(a) Chloride profiles at different times of exposure.



(b) Chloride content at the bar location vs. time of exposure.

Fig. 8.16: Chloride measurements over time on concrete blocks cast with same concrete mix as in macrocells.

2) The steady increase of chloride content observed in the last 2.5 years of exposure was not associated with an increase in the amount of current for the majority of the specimens.

8.4.5 Forensic Examination

General

The last triplicates in each group were autopsied after 4.5 years of exposure to chloride solution. The method used to open the specimens was similar to that used for the first two triplicates. The main difference was that instead of using a jackhammer, a deep slot was saw-cut around the specimens (along with other shallower cuts on the top surface) at a section below the top bar. Concrete was removed by chiseling with a hammer. In this way, larger pieces of concrete could be removed and damage to epoxy coating was minimized. Four specimens with #8 bars (cross ribs) were not autopsied because they were diverted to another corrosion experiment for exposure for an additional year.

Concrete Delamination

Before breaking open the specimens, signs of concrete delamination were detected by tapping the surface with a hammer. Three of the control specimens developed concrete delamination: The two specimens with #4 bars and the specimen with #8 bars (parallel ribs). Delaminated areas were confined and generally coincided with lateral surfaces and wide cracks. Delamination was localized. None of the specimens with coated bars developed concrete delamination.

Chloride Content

As for previously autopsied specimens, the content of chlorides per unit weight of concrete was measured at different depths. Concrete powder samples from different depths were obtained by drilling through the specimens at the centroid of the top surface before performing autopsy of the specimens. Two samples for each representative depth were obtained.

A summary of measured chloride content for all specimens is included in Table 8.2. Average chloride percents by weight of concrete are plotted in Figures 8.17 and 8.18. The curves corresponding to the average chloride content of specimens autopsied after 1 and 2 years are also shown for reference. There was a slight increase in the amount of chlorides from 1 to 2 years of exposure for both #4 and #8 bar specimens, but from 2 to 4.5 years, there was a significant increase for all specimens. At the end of 4.5 years, the average chloride content by weight of concrete at the top bar location was 0.34% for series A specimens and 0.33% for series B specimens. This contrasts with 0.23% and 0.21% of chlorides at the top bar location for series A and B, respectively, at the end of 2 years. At a depth of 8 cm (3 ¼ in.), the average amount of chloride after 4.5 years was similar to that at the level of the top bar after 2 years.

There is no agreement as to the chloride threshold level that triggers corrosion of steel in concrete.[130, 131] For reference, reported chloride thresholds for corrosion initiation fall in the range of 0.02-0.05% by weight of concrete.[10] These numbers indicate that the exposure conditions were particularly severe for the top bars, especially during the last 2.5 years of exposure.

Specimen	**Sampling Depth Ranges (mm)**			
	19-32	**32-38**	**38-51**	**76-89**
3A1	0.30	0.30	-	0.19
3A2	0.40	0.38	-	0.19
3A3	0.30	0.29	-	0.14
3A4	0.31	0.30	-	0.12
1A5	0.37	0.33	-	0.18
2A6	0.30	0.23	-	0.18
3A7	0.35	0.26	-	0.13
3A8	0.43	0.36	-	0.29
3A9	0.34	0.38	-	0.21
1A10	0.41	0.45	-	0.19
3A11	*	*	-	*
3B1	0.33	-	0.27	0.23
3B2	0.41	-	0.25	0.21
2B3	0.41	-	0.31	0.19
3B4	0.41	-	0.37	0.24
3B5	0.55	-	0.32	0.17
2B6	0.47	-	0.31	0.23
1B7	0.30	-	0.21	0.16
1B8	0.36	-	0.24	0.20
3B9	0.41	-	0.27	0.20
2B10	0.37	-	0.31	0.22
2B11	0.43	-	0.32	0.30

* Lost data

Table 8.2: Acid-soluble chloride concentrations in autopsied macrocell specimens after 4.5 years of exposure (Percentage by weight of concrete).

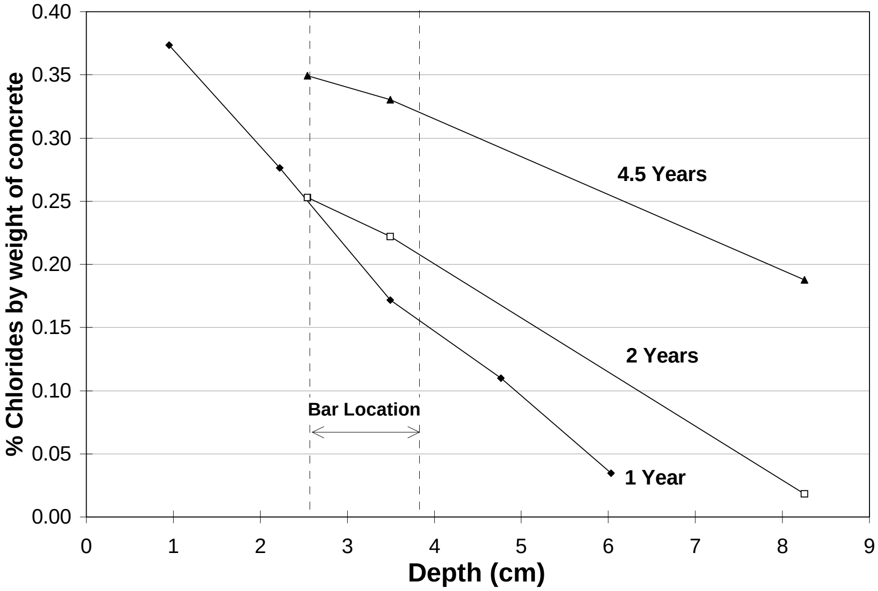


Fig. 8.17: Average chloride profiles for A specimens (#4 bars).

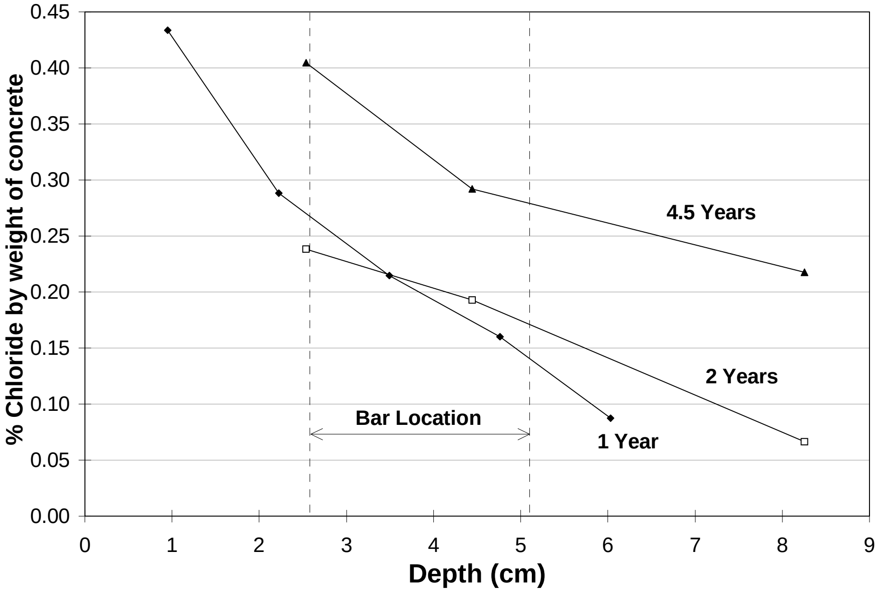


Fig. 8.18: Average chloride profiles for B specimens (#8 bars).

Appearance at Removal from Concrete

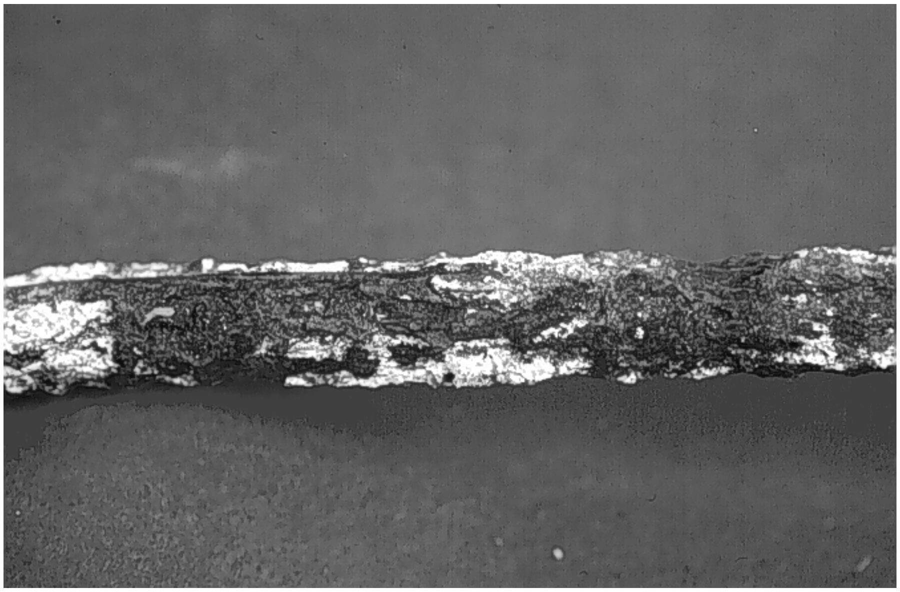
Control Bars

Figure 8.19 shows the top and bottom sides of one uncoated bar after removal. Uncoated bars exhibited extensive corrosion after 4.5 years. Immediately after opening the specimens, corroded metal had a black or dark appearance with randomly distributed areas of reddish-brown rust and several smaller areas of dark-green and bluish-green rust. After being exposed to oxygen, all dark- and bluish-green areas changed to bright orange-brown or yellowish-brown rust. Corrosion was more extensive and severe on straight bar legs than on the bent zone, and spread more on the bottom side than on the top side of the bars. On bent areas, a relatively clean, non-corroded metallic surface was visible over most of the top half of the bar and over a portion of the bottom side. The accumulation and build-up of rust products was evident in the most corroded areas. Loss of metal and pitting was appreciable on the straight bar legs (Fig. 8.20). Several large pits, ranging from 0.5 to 2.0 mm deep, developed on the straight legs of both #4 bars [(Fig. 8.20(a)], outside of the bent portion on a #4 bar with cross ribs, and on the right side of the bent portion in a #8 bar with parallel ribs. A large, deep pit on the top side of a #4 bar with parallel ribs caused a significant reduction in bar area at that location.

(a) Top side

(b) Bottom side

Fig. 8.19: Uncoated bars after autopsy.



(a) Severe metal loss and pitting at straight leg of #4 uncoated bar.

(b) Pitting at straight leg of #8 uncoated bar.

Fig. 8.20: Loss of metal and pitting of uncoated bars.

On specimen 3A1 (#4 bar with parallel ribs), a series of brown drops of acidic solution (pH = 3) appeared on the straight portion. The solution was very similar to the solution oozing from the front faces of specimens with #8 coated bars. An interesting phenomenon that occurred on most specimens was that about 24 hours after removal from the concrete, drops of brown, acidic solution, similar to the drops found on specimen 3A1 after autopsy, formed on the bar surfaces.

Interestingly, #4 bars with parallel ribs showed somewhat more severe and widespread corrosion than #4 bars with cross ribs. The opposite situation was expected because of the much higher average current density measured for #4 bars with cross ribs.

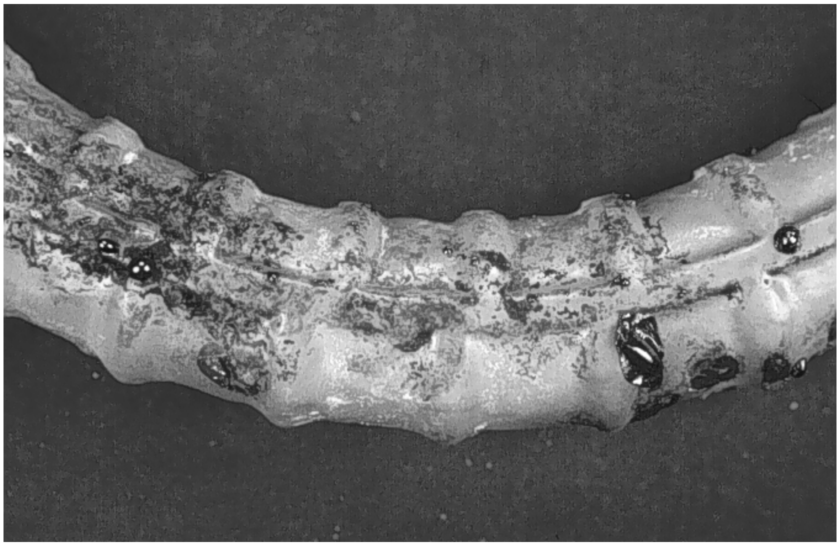
Fragments of concrete of different size remained adhered to several portions of bar surfaces, evidence of good adherence between concrete and uncoated steel.

Epoxy-Coated Bars

The following observations pertain to the appearance of the epoxy-coated bars before peeling the coating to uncover the metallic surface underneath. Results from such examination are shown later. Here, the condition of the coating surface and of the damaged areas is described. As was found later, the condition of the coating surface usually differed from the condition of the metallic surface beneath the coating.

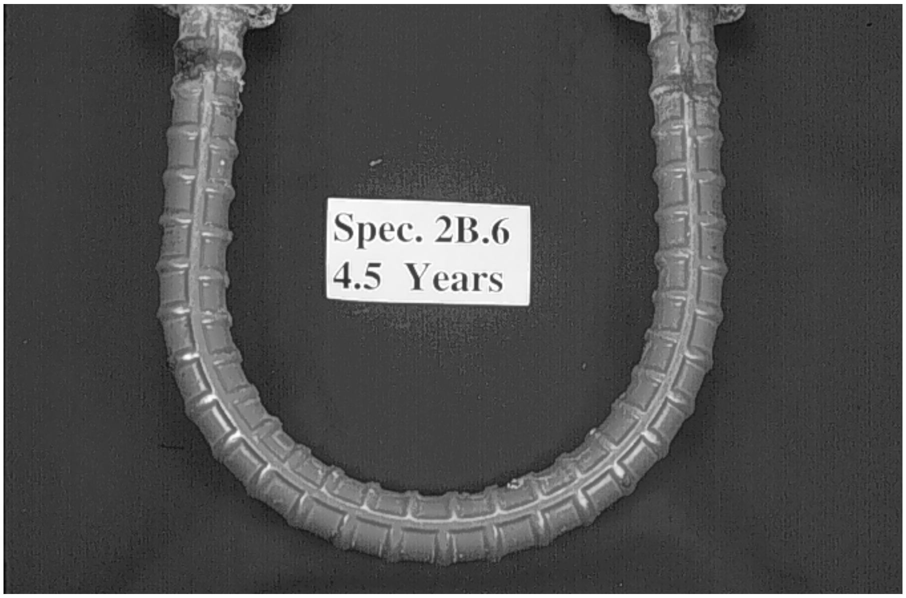
After examining all bars, it was evident that smaller bars corroded less than large bars. Rust staining, coating blistering, and corrosion of exposed areas were noted (Fig. 8.21). The color of rust stains ranged from dark to light brown, and their appearance varied from dense to tenuous. Blisters of different sizes formed but small ones were prevalent. Corrosion did not always occur at the damaged, exposed areas of smaller bars. In contrast, all exposed areas of larger bars corroded severely. Generally minor corrosion was observed on patched areas. Except for bar 3B.5 (#8 bar with damage greater than 2%), all bars experienced more rust staining or spotting and blistering on the bottom surface than on the top (Fig. 8.22). In most cases, more corrosion developed on the bent area than on the straight portions. Most damaged areas on the inside of the bend (produced by the mandrel during fabrication) did not show much corrosion, only superficial rusting. There was almost always a void in the concrete where a blister formed. However, corrosion did not occur at all voids. A common phenomenon was that a few days after the bars were removed from the concrete, a series of drops of brownish, acidic solution (pH between 3 and 4) formed on the surface of the bars (Fig. 8.23). In several cases the drops dried and formed beads of brittle rust. An unsuccessful attempt was made to obtain samples of the acidic solution for analysis, but the amount of liquid in the drops was too small to be sampled. In most bars, remains of whitish concrete paste adhered to the bottom side of the bars while the coating remained cleaner and glossy on the top portion.

(a) Rust staining and blistering on epoxy-coated bar.

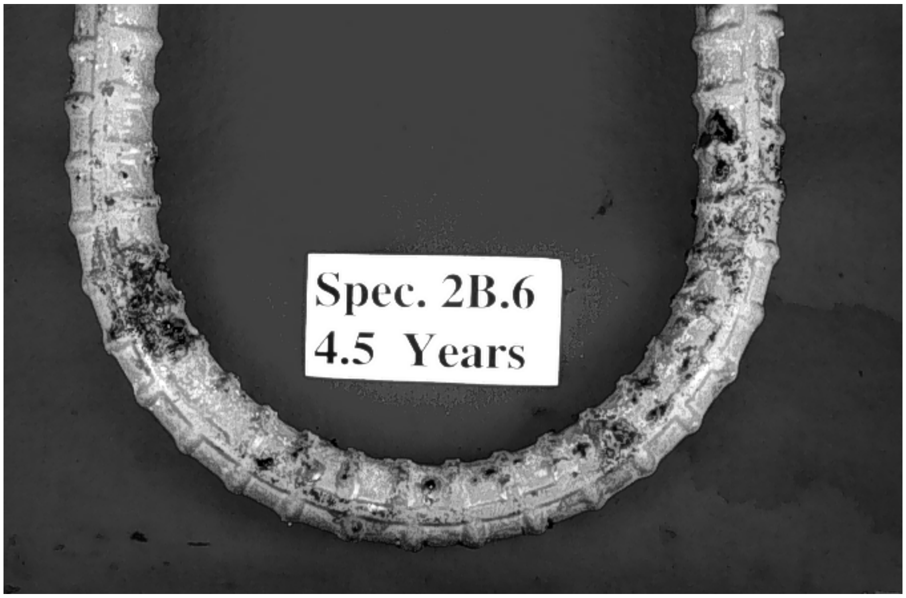


(b) Rust staining and exudation of brown liquid on epoxy-coated bar.

Fig. 8.21: Corrosion of epoxy-coated bars after 4.5 years of exposure.



(a) Top side.



(b) Bottom side.

Fig. 8.22: Comparative performance between top and bottom sides of epoxy-coated bars.

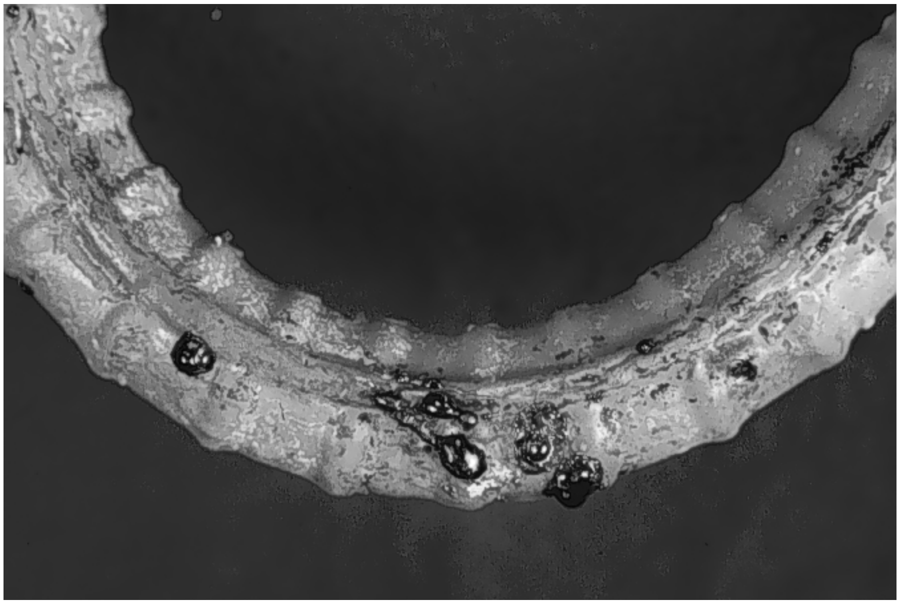


Fig. 8.23: Brownish, liquid solution exuded on surface of epoxy-coated bars.

Series A Specimens

Bars 1A.5 (damage >2%), 2A.6 (cracks with damage <1%), and 1A.10 (damage > 6x6mm) showed the most corrosion. The coating condition on remaining bars was good with few rust stains and blisters. The bars with the best appearance were 3A.3 (damage > 6x6 mm) and 3A.7 (damage <2%). A description of the coating condition of a few bars follows.

Bar 1A.5 (damage >2%) experienced the most corrosion among bars from series A. On the bottom side, rust staining occurred as a series of diluted, tenuous brownish stains or spots which were more prominent on the bent area and on the portion of straight bar close to the front face of the specimen. There were a few small blisters on the straight legs and several more on the bent zone. There was a zone where the coating appearance changed to a brighter green at the large rust spot on one leg. The top of bar 1A.5 was in good condition. There was no visible rust staining and there were only a few blisters on the legs. Mandrel-induced damaged areas on the inside of the bend showed only superficial rust if any. Rust at damaged spots on the outside of the bend was uniformly dark. There were traces of bright or dull reddish-brown rust inside the darkly rusted damaged areas. Traces of acidic (pH = 3) brown solution were found on two damaged areas.

Condition of bar 2A.6 (cracks with damage <1%) was as follows: Extensive blistering along with a series of many small brownish stains (mainly alongside the longitudinal rib) formed on the bottom side. On the contrary, the top side was in a good, clean condition, with only 2 blisters and limited, diluted black staining on the bent zone. More rust staining and blisters formed on the bent zone than on the straight bar legs. Mandrel-induced damaged areas at the inside of the bend had only superficial rust if any. There were traces of dark rust along coating cracks. A similar appearance was noted for bar 1A.10 (damage > 6x6 mm).

Corrosion of patched areas was generally minor. Dark or brownish, generally diluted staining (from medium size to tiny spots) and very small, microscopic blisters formed on the surface of patched areas (Figure 8.24). In bar 3A.2, a few small cracks developed in the coating near patched areas and next to the parallel ribs on the outside of the bend. It was a significant contrast to find that the exposed steel areas at damaged spots in specimens 3A.3 (damage > 6x6mm) and 3A.7 (damage <2%) were completely free of corrosion after 4.5 years of exposure and displayed a shiny, bright surface (Figures 8.25. and 8.26). No voids were visible in the concrete adjacent to the exposed areas. The overall condition of bars 3A.3 and 3A.7 away from the damaged areas was good, with only a few blisters and small brown stains.

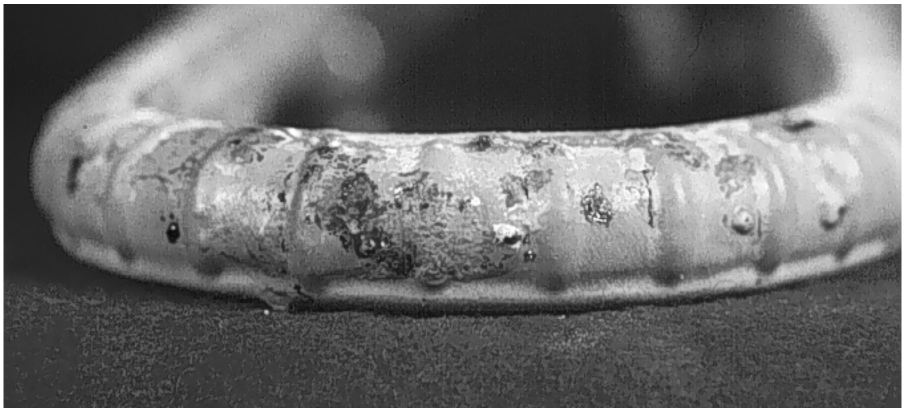


Fig. 8.24: Corrosion of patched area of #4 epoxy-coated bar (Bar 3A.2).

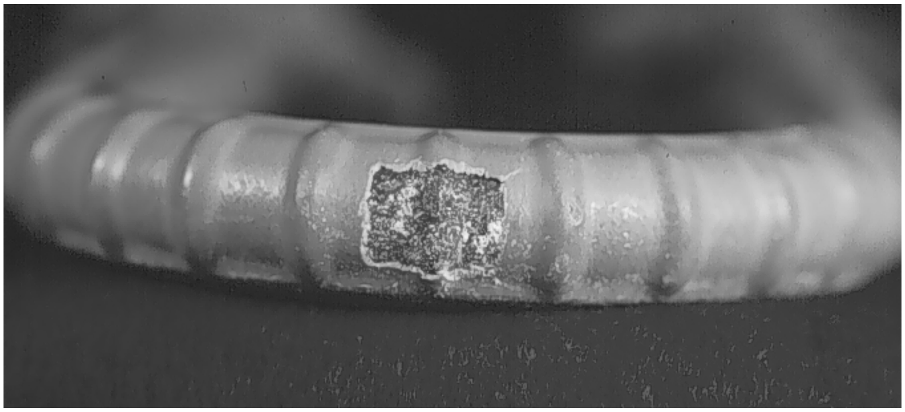


Fig. 8.25: Clean, uncorroded damaged area after 4.5 years of exposure (Bar 3A.3).

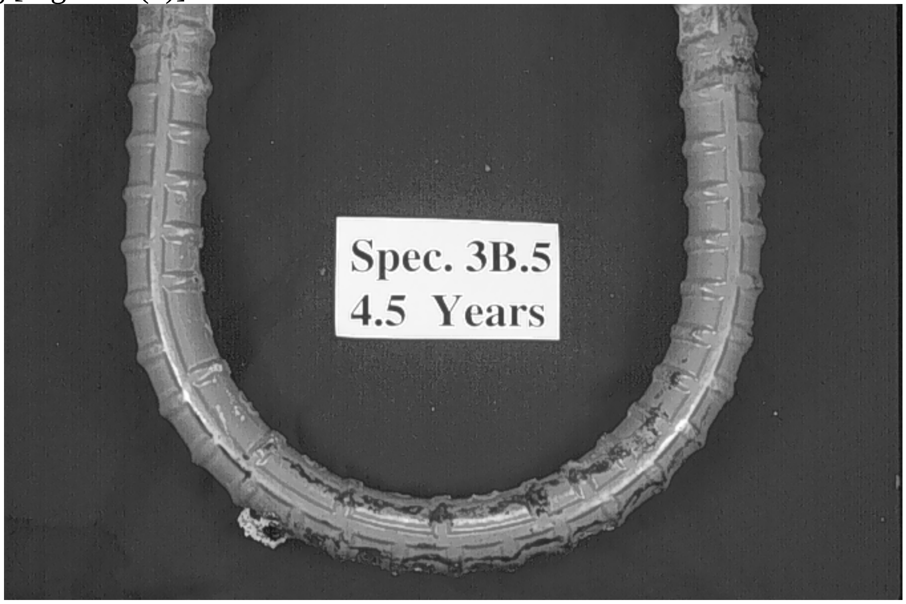
Fig. 8.26: Clean, uncorroded damaged areas after 4.5 years of exposure.

Series B Specimens

As already pointed out, larger bars underwent more corrosion than smaller bars. Evidence of corrosion was similar to that of smaller bars. Bars 2B.3

(damage > 6x6 mm), 3B.5 (damage >2%), and 1B.7 (damage <2%) exhibited the highest corrosion. The remaining three bars had a similar appearance. A description of the coating condition of a few bars follows.

Figure 8.27 shows the top and bottom sides of bar 3B.5 (damage >2%). More corrosion occurred on the bent area than on straight legs. Similar or perhaps more rust staining developed on the top side compared to the bottom side. Dark, dense stains formed on the top portion of the bar [Fig. 8.27(a)]. Diluted, dark and brownish stains appeared at the bottom side around the bent zone and on one bar leg [Fig. 8.27(b)]. A number of small to medium sized blisters formed on both the



(a) Top side.

(b) Bottom side.

Fig. 8.27: Bar 3B.5 after 4.5 years of exposure.

top and bottom sides. Mandrel-induced damaged spots on ribs and mill marks inside the bend had a dull grayish appearance, but only a few showed rust. Damaged areas at the outside of the bend had a dark rust accumulation (Fig 8.28).

Several localized reddish-brown and black rust stains of tenuous appearance were visible on the bottom side of bar 2B.3. Several medium-sized and small blisters were found at the top and bottom sides, especially on the bent zone (A few large blisters formed at the top side of bent area). A few small stain lines with dull appearance were detected on the top side next to longitudinal lugs. Mandrel damage imprints at the inside of the bend showed some dark and dull rusting but corrosion was not severe. Damaged areas at the outside of the bend exhibited extensive corrosion, with a very dark, uniform rust formation on the surface. At one of the damaged spots, metal depletion was evident.

A good example of contrasting aspects of top and bottom sides is given by bar 2B.6, included in Fig. 8.22. The coating on the top side was clean and in good condition (with only a few blisters and rust small stains), but extensive blistering developed throughout the bottom side. Brown and dark staining was also visible, mainly alongside longitudinal lug. Very light rust stains were observed on mandrel-induced marks at the inside of the bend.

As in smaller bars, corrosion of patched areas was not significant. Corrosion manifestation was similar to that of smaller bars, as can be seen in Fig. 8.29. Patched areas at the outside of the bend of bar 3B.4 were discolored and had medium-sized to small dark-brown or reddish-brown rust spotting (Fig. 8.29). In addition to the diluted dark and brown staining and presence of tiny blisters, fine reddish-brown rust products (in small amounts) were visible at several damaged spots.

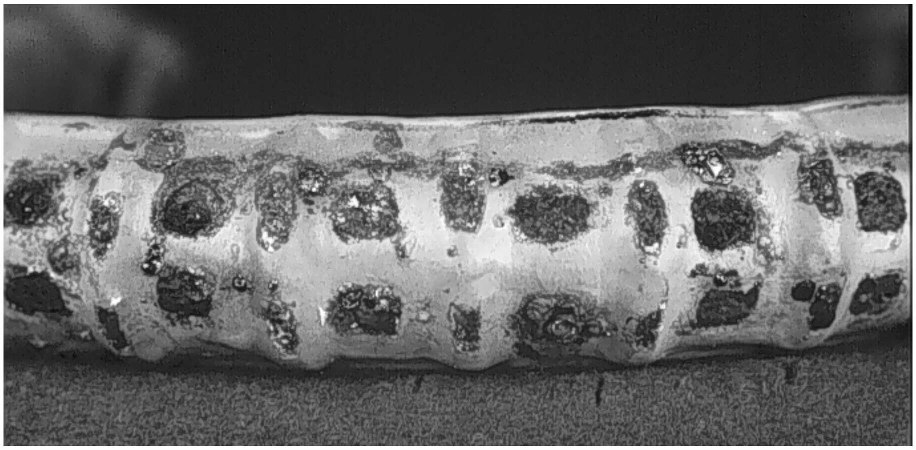


Fig. 8.28: Corrosion of damaged areas at outside bend on bar 3B.5.

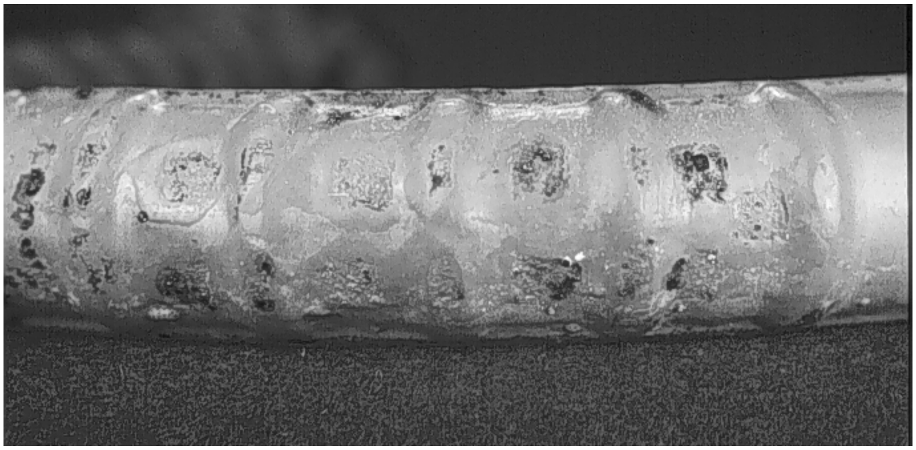


Fig. 8.29: Corrosion of patched areas at outside bend on bar 3B.4.

Cathodic Bars

Cathodic bars were removed from a few selected specimens and their condition was examined. Selected specimens were 3A.1 (control), 3A.3 (damage > 6x6 mm), 1A.5 (damage >2%), 3A.8 (control), 3B.1 (control), 2B.3 (damage > 6x6 mm), 3B.5 (damage >2%), and 1B.7 (damage <2%). The appearance of the cathodic bar trace in concrete was also examined.

Most cathodic bars from control specimens experienced corrosion. Corrosion tended to be more severe and extensive on one of the bars for each specimen. For instance, the left bar of specimen 3A.1 had a clean, uncorroded surface. Bar trace in concrete above and below the bar was clean, with a grayish appearance. In contrast, the right bar experienced reddish-brown rusting mainly on its right and bottom sides. Two medium-sized pits were observed: One pit was located at the top side close to the front face of the specimen and was 36 mm^2 big, 1.5 mm deep. The other pit was located at the bottom side close to the back end of the bar and measured 16 mm^2 of area, 0.9 mm of depth.

The left bar in specimen 3A.8 underwent very extensive and severe corrosion, characterized by uniform dark or black rust with large areas of evident rust volume accumulation, causing cracking of concrete at the bottom of the specimen (Fig. 8.30). Corrosion was slightly more severe below than above the bar. The right bar experienced more limited corrosion, with a dark rust area at the back portion of the bar, and another rust area relatively close to the front face. The rest of the bar surface was non-corroded, with a dark grayish aspect, especially at the bottom side. Concrete adjacent to uncorroded areas had a grayish appearance.

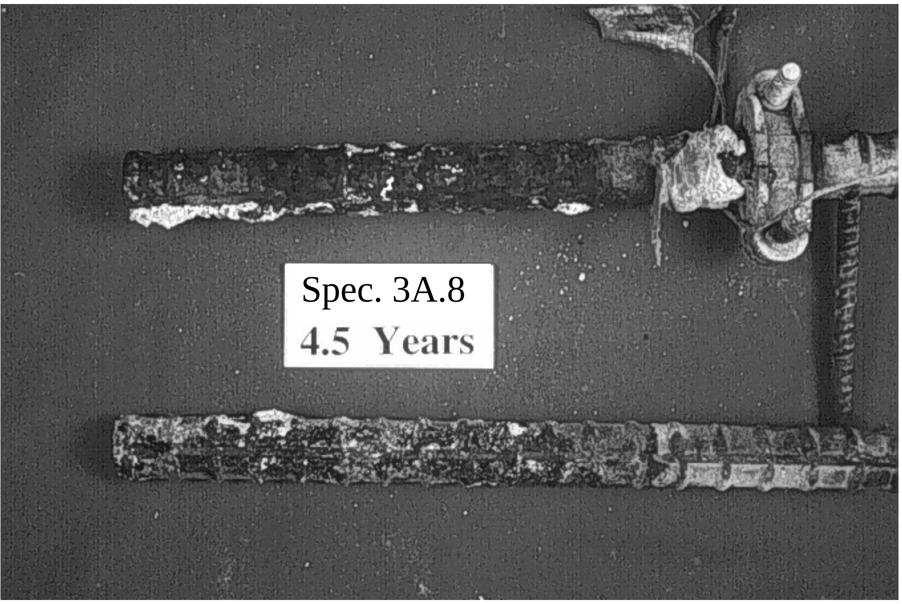


Fig. 8.30: Corrosion at bottom side of cathodic, bottom bars of specimen 3A.8.

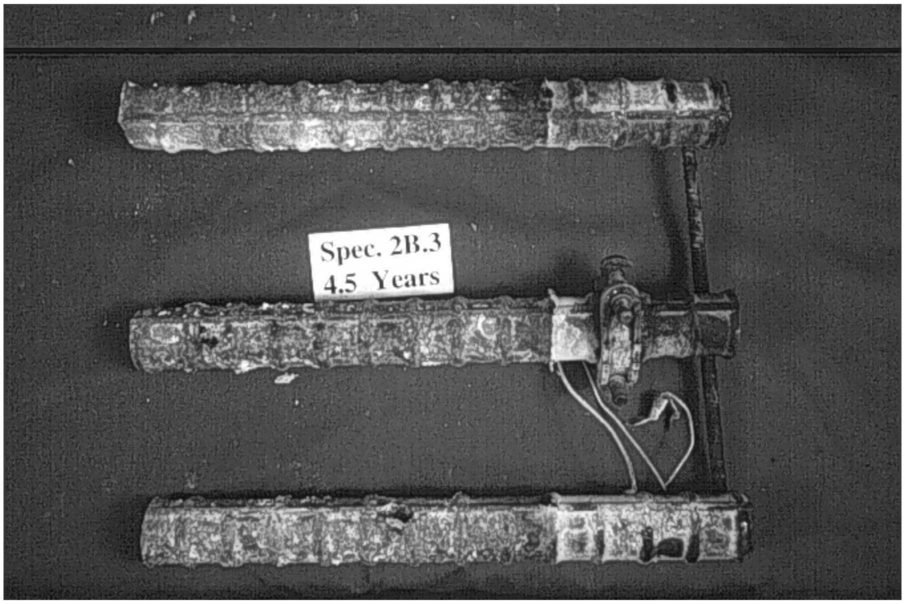


Fig. 8.31: Appearance of bottom side of cathodic, bottom bars of specimen 2B.3.

Cathodic bars from specimen 3B.1 showed widespread black or dark and reddish-brown rusting on their surface. More corrosion was found at the left side of the left bar and at the bottom of the right bar. Several sizable pits formed on the right bar: One medium-sized (24 mm^2) and several small, shallow pits (0.4 mm deep) were observed on the top side. One large, deep pit (0.84 cm^2, 1.3 mm deep) and two large, shallow (0.2 or 0.3 mm deep maximum) pitted areas were observed on the bottom. The trace of corroded bars in concrete showed extensive dark and reddish-brown rust staining, similar to the corrosion observed on the bars. Sites adjacent to pitted locations in the bars showed accumulation of solid rust products, usually inside concrete voids.

Most cathodic bars from specimens with epoxy-coated bars had a clean metallic surface without corrosion (Fig. 8.31). Most bars experienced slight surface darkening within 1.0 to 2.0 cm from the front face of the specimen. At some portions of the bottom side of two bars (specimen 1A.5), dark-grayish stains giving the appearance of solution trace were observed. Small concrete paste residues remained adhered to the bottom side of the bars. One of the cathodic bars in three specimens with top epoxy-coated bars experienced corrosion: The left bar of specimen 3A.3, the right bar of specimen 2B.3, and the middle bar of specimen 3B.5. The left bar of specimen 3A.3 experienced light but widespread dark-brown rust staining at the bottom side. No pitting was observed. The right bar of specimen 2B.3 had a relatively large, dark rust spot exactly at the point of contact with the bar chair. Examination of the adjacent bar trace under the bar showed that the bar chair was visibly rusted. It is possible that localized galvanic corrosion took place at the contact zone between the two metals.

The middle bar of specimen 3B.5 experience the largest corrosion among cathodic bars in coated specimens. The bar exhibited dark and reddish-brown rusting on the bottom, on a 6.0 cm-stretch from the embedded end of the bar, including the embedded cut end surface. One medium-sized, shallow pit (25 mm^2, 0.7 mm deep) was observed at the bottom side close to the back end. Interestingly, grayish and darks stains appeared at the uncorroded portion on the bottom side (a 11.5-cm long zone closer to the front face of the specimen). Laitance was present at the adjacent bar trace in concrete, suggesting that something occurred at the metallic surface (ions that were generated by the cathode may have reacted with concrete). Macrocell currents in specimen 3B.5

experienced incidental large drops between cyclic high and low peaks after 2 years. This suggests that corrosion of the cathodic bar started to affect the currents measured.

The trace of uncorroded bars in concrete had a grayish-like appearance, with a darker gray within 1.0 to 2.0 cm from the front face. Concrete at the top side of the bar was smoother with few concrete voids. Concrete on the bottom of the bars was more porous with much more voids.

Coating Removal

The steel surface was examined by peeling the epoxy coating with an X-acto knife. A precut was made with a utility knife alongside one longitudinal rib (generally the rib located at the more corroded bottom side). The coating was then lifted by inserting the blade tip of the X-acto knife under the coating at the precut sections and applying prying action. The removal process provided a rough indication of the remaining adhesion of the coating to the steel substrate.

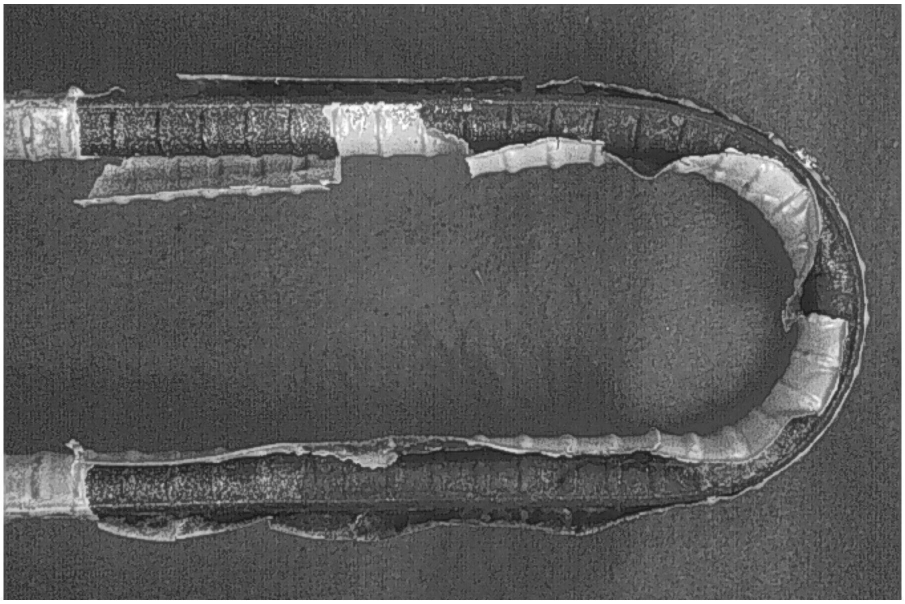


Fig. 8.32: Coating debonding on #4 bar.

As expected, the coating was extremely easy to peel at the bent area of all bars, evidencing complete loss of coating adhesion (Fig. 8.32). Coating debonding progressed from the bent areas towards the straight bar legs. Extensive adhesion loss was observed more frequently on large bars than on small bars. Four small bars developed complete coating debonding throughout their whole length (bent and straight zones). At the remaining small bars, debonded areas included the bent zone and an adjacent portion of the straight bar legs. Coating adhesion was preserved in the portion of straight bar legs closer to the protruding ends, away from the bent zone (a 4- to 7.5-cm stretch extending from the front face). In contrast, all large bars experienced complete loss of adhesion throughout their length. Only in bar 1B.7, a short piece of coating (about 2.5 cm long) adjacent to the protruding end of one leg remained adhered to the steel substrate.

In areas where coating adhesion was preserved, the steel surface beneath the coating maintained its original condition (bright, shiny surface) without corrosion. The steel surface beneath the coating at debonded areas changed appearance and corrosion was observed, as will be discussed in the following section.

Underfilm Corrosion

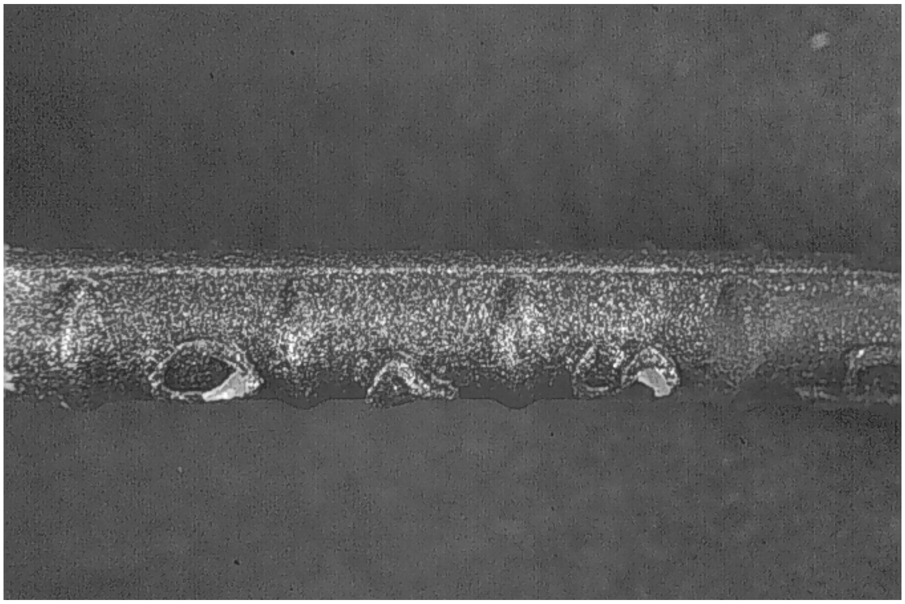
It was observed that the greater the amount of rust staining on the epoxy coating, the greater the degree of corrosion on the steel surface beneath the coating. However, the amount of staining on the coating surface was not always indicative of the severity of corrosion of the metal substrate. Corrosion of the steel surface was generally more severe and extensive than was apparent from the coating surface.

Examination of steel surfaces indicated trends similar to those found upon examination of coating surfaces. Larger bars corroded more extensively and severely than smaller bars. Corrosion was more severe on the outside than inside of the bend. Corrosion at the bend zone tended to be worse than along straight bar legs. In small bars, bottom sides corroded more than top sides but the difference in corrosion severity between top and bottom sides was less pronounced than indicated by the coating surface appearance. In large bars, corrosion at top and bottom sides tended to be similar (the bottom sides corroded slightly worse than the top sides in most cases) and in one specimen (3B.5), corrosion seemed to be worse at the top side. Corrosion beneath patched areas was rather superficial and not severe. Corrosion spread and tended to be worse at portions adjacent to repaired areas.

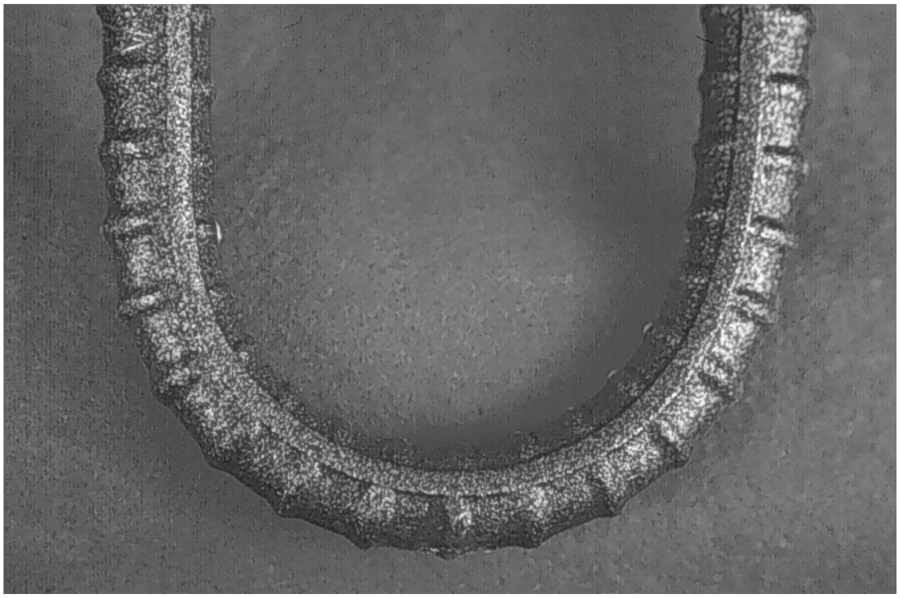
The appearance of the steel surface varied depending on the severity of corrosion and will be classified as: 1) Debonded, non-corroded surfaces, and 2) Corroded surfaces.

Debonded, non-corroded surfaces

The designation of “non-corroded” is possibly a misnomer because corrosion may be in an initial stage. The steel surface showed a very unique characteristic: A sort of a mottled, glittery or twinkling appearance with a golden-brown or similar brownish color. An example of such a surface is illustrated in Fig. 8.33. The condition of such steel surfaces was very good, with no discernible pitting or metal attack. The term “non-corroded” was used to describe the good condition of the steel. The loss of coating adhesion, though, may indicate that corrosion may already be in early stages. Mottled surfaces were found mainly in the less corroded small bars and occurred more often at straight bar legs than at bent zones. Debonded areas with mottled surfaces underneath were suspected to have undergone cathodic disbondment, as will be explained later.



(a) Left leg of bar 3A.2.



(b) Top side of bar 3A.3.

Fig. 8.33: Mottled, glittery surface with golden-brown (or similar brownish) appearance under the coating.

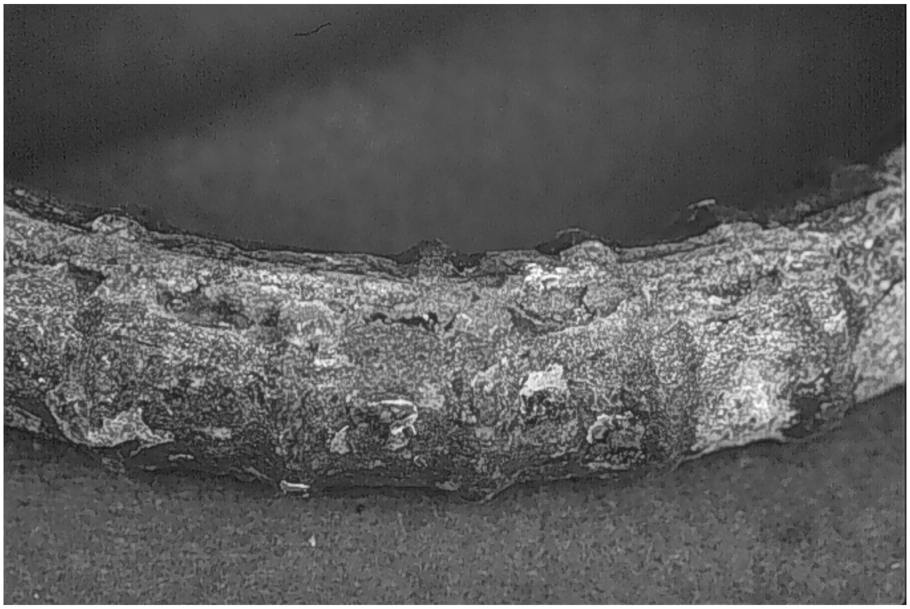


Fig. 8.34: Shallow pitting and accumulation of rust products on steel surface under the coating (outside bend).

Corroded surfaces

The appearance of corroded surfaces varied from bar to bar. Some of the main characteristics shown by such surfaces will be described. In most cases, a uniformly black or dark rusted surfaces developed. The degree of darkness varied from specimen to specimen and it also changed with time for the same specimen. In several bars, the corroded surface looked darker one or two days after the coating was removed. Depending on the severity of corrosion, shallow pitting and metal depletion, rust volume increase, and blistering may have developed in varying degrees (Fig. 8.34). No severe, localized, deep pits were found in any bar. The largest pits were less than 0.5 mm deep. No drastic reduction of cross-sectional area was found in any coated bar. The volume increase (due to rust formation) appeared to be less than for uncoated bars. Variable amounts of dark rust powder came off during removal of the coating, more noticeably in larger bars. Smaller blisters were more abundant than larger blisters. Blistered areas had a very hard, solid consistency.

In many specimens, spots of whitish matter with pasty consistency, sometimes combined with brownish rust, were observed. Whitish products would turn yellowish-brown, orange-brown, light-brown, and reddish-brown after several hours of being exposed to air. In one case (bar 3B.5), a silver-colored stain was detected (top side of bar between bent zone and right straight leg) immediately after removing the coating. One hour later its color changed to whitish, and 2 days later changed to dull-brown and orange-brown. At the bottom side of bar 1A.5, a whitish substance found alongside a longitudinal lug (bent zone and straight right leg) turned yellowish-brown a few hours after coating removal. Such matter was deposited along a strip, giving the appearance of a solution trace (Fig. 8.35).

Areas with rust deposits or pockets of varying size, shape, appearance, color, and amount were usually present along the bar surface above the uniform black rusted surface (Figures 8.36 and 8.37). The size of such rust spots ranged from very large, occupying large areas of the bar surface, to small flecks. Appearance of rust spots was dependent on rust concentration, varying from a light film of rust, similar to a stain, to thicker layers of rust deposits. Rust layers at some spots were bulky enough to cause a bulge in the coating, but in most instances, rust amounts in such areas were light. At the time of autopsy, whitish products were the most prevalent. After a few days of being exposed to air, more

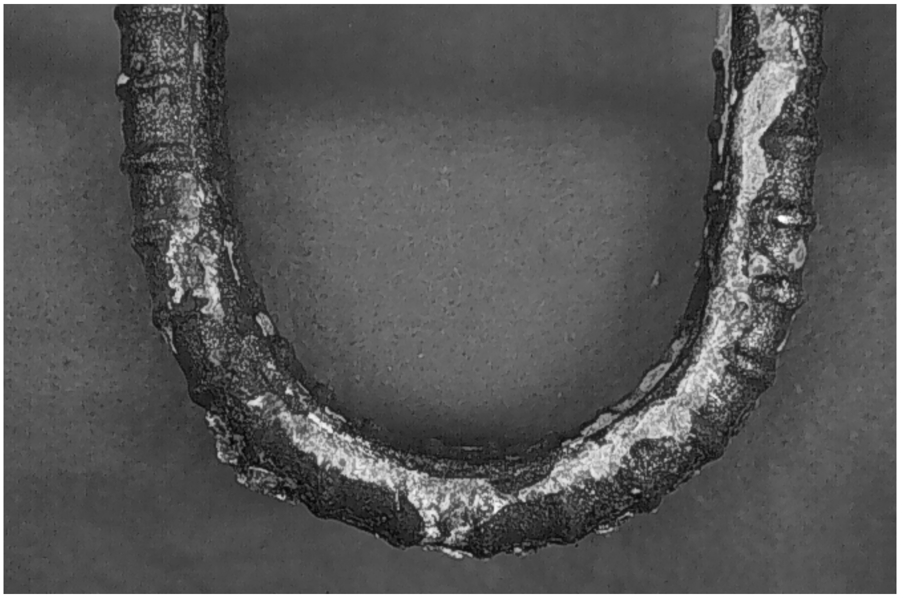
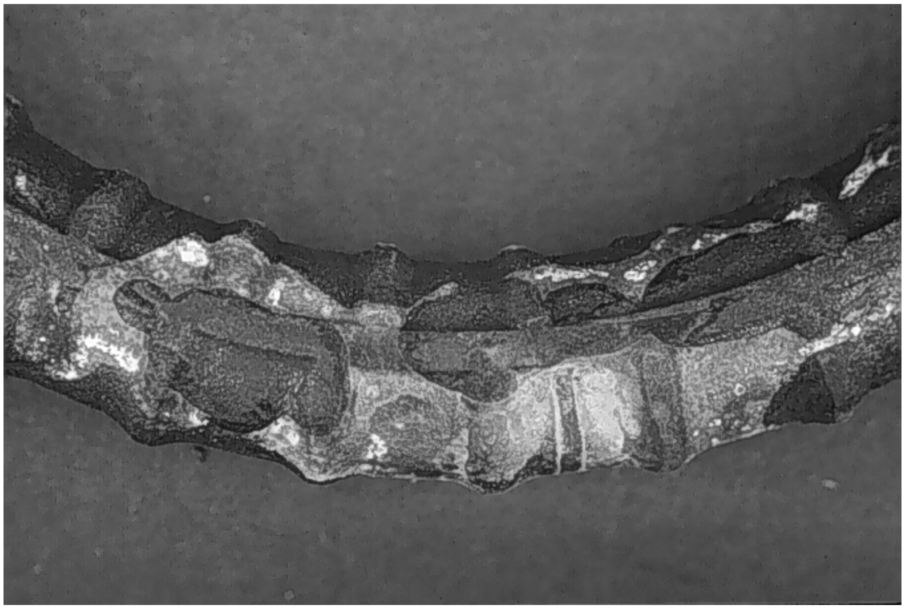


Fig. 8.35: Whitish products alongside longitudinal lug at bottom side of bar 1A.5.

Fig. 8.36: Various rust products above uniformly black corroded surface under the coating.



(a) Top side of bar 1B.7

(b) Outside bend of bar 1B.7

Fig. 8.37: Rust products or stains with clearly delineated boundaries, with the appearance of solution trace.

commonly found colors were light-brown, reddish-brown, orange-brown, and yellowish-brown. Many of the larger and medium-sized rust stains often had shapes with clearly delineated boundaries, giving the appearance of traces or remains of a solution (Fig. 8.37). Several rust spots or stains appeared to be wet.

Wet areas and drops of brownish, liquid solution formed on the surface of most bars, similar to those found above the coating. This phenomenon occurred in more bars as days after coating removal passed. As before, some of the drops had dried and formed driblets or beads of brittle rust with wet consistency. The measured pH was between 3 and 4, indicating that the solution was acidic. This phenomenon was more common in larger bars.

In the following paragraphs, the condition of the metallic surface of a few small and large bars is described.

Series A Specimens

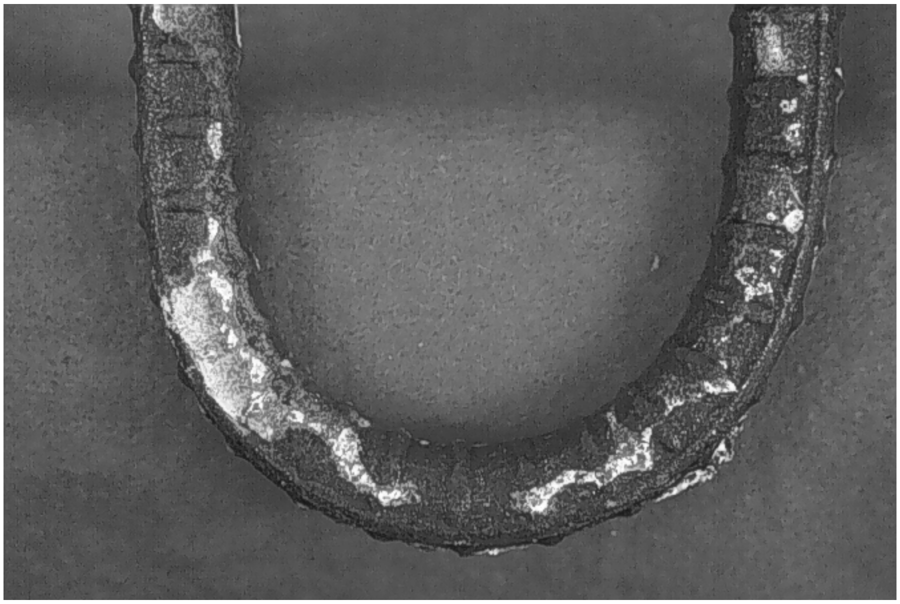
Specimen 1A.5 (damage >2%) suffered the worst corrosion, followed by bars 2A.6 (cracks with damage <1%) and 1A.10 (damage > 6x6 mm). The bar with best condition was, amazingly, 3A.3 (damage > 6x6 mm), followed by bar 3A.7 (damage <2%).

A view of top and bottom sides of bar 1A.5 is shown in Fig. 8.38. The overall bar surface was uniformly dark with a few very shallow pits and light metal consumption. There was accumulation of whitish and yellowish-brown matter along a strip on both sides of the bar. The whitish matter turned yellowish-brown a few hours after coating removal. The strip shape seemed to indicate that such products were trails of a solution formerly present. There were other spots with whitish and brown stains, especially on the top side. A small amount of acidic solution (pH = 5) was found at the longitudinal lug on right portion of the bent zone (top side). Mottled surfaces with a glittering golden-brown appearance were visible along the straight legs closer to protruding bar ends, mainly at the top side. Dark-brown, orange-brown, and black rust accumulated at damaged areas on the outside of the bend.

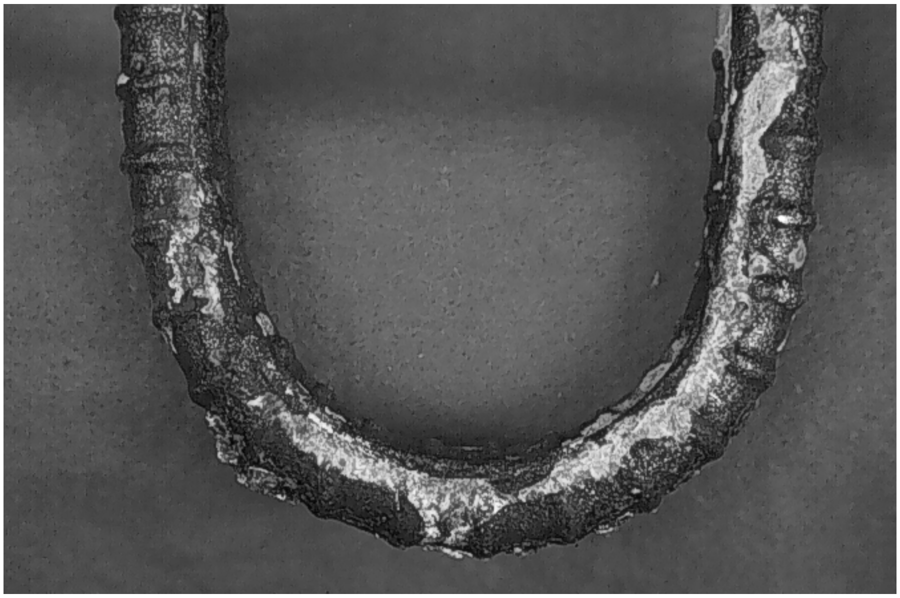
Figure 8.39 shows the top and bottom sides of bar 3A.3. As previously indicated, no corrosion occurred at the damaged site on the outside of the bend. The only corrosion activity occurred far away from the damaged area, at the outside of the straight right bar leg. A thin film of dull-brown and black staining was observed. The black stained portion turned dull reddish-brown minutes after coating removal. The remaining debonded surface had a mottled surface with glittering golden-brown appearance. Coating adhered along a short portion of both straight legs next to the protruding bar ends. The steel surface beneath the adhered coating was in its original condition, with a shiny, bright appearance.

Series B Specimens

Specimen 3B.5 (damage >2%) suffered the worst corrosion, followed closely by bar 3B.4 (damage >2%, patched). The extent and severity of corrosion was similar for the remaining bars. Interestingly, in bars with damage greater than 6x6 mm, corrosion spread much more on the repaired bar (3B.2) than on the unrepaired bar (2B.3).

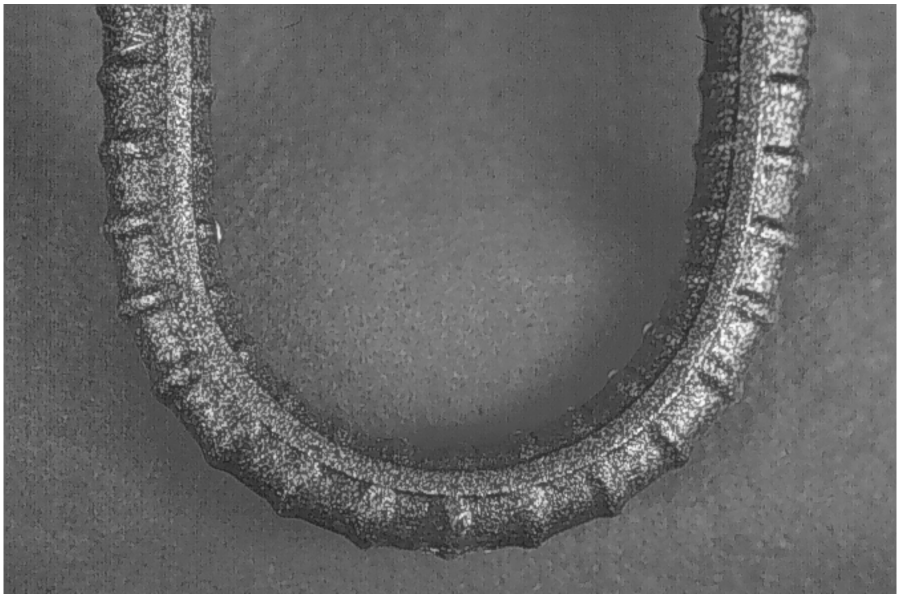


(a) Top side.

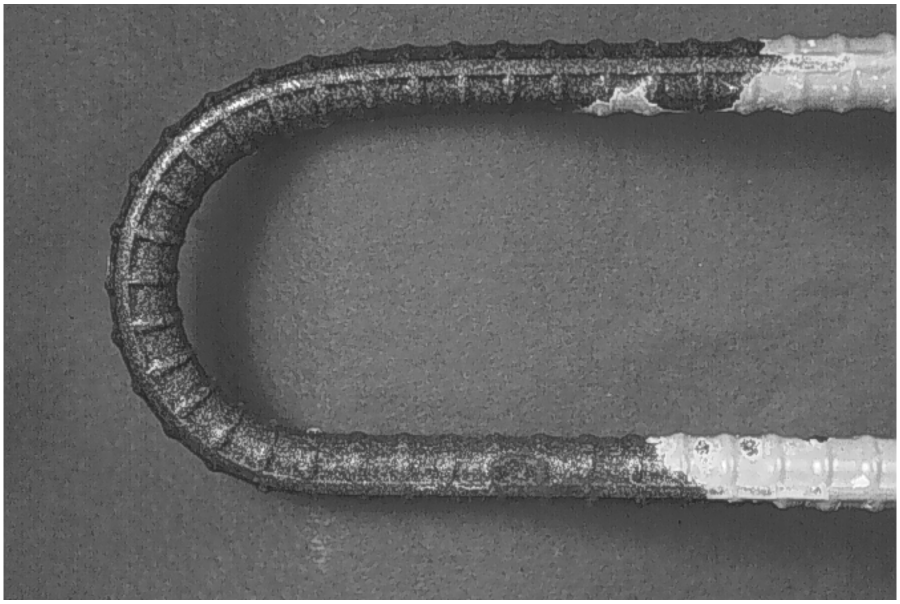


(b) Bottom side.

Fig. 8.38: Whitish and yellowish-brown corrosion products on bar 1A.5.



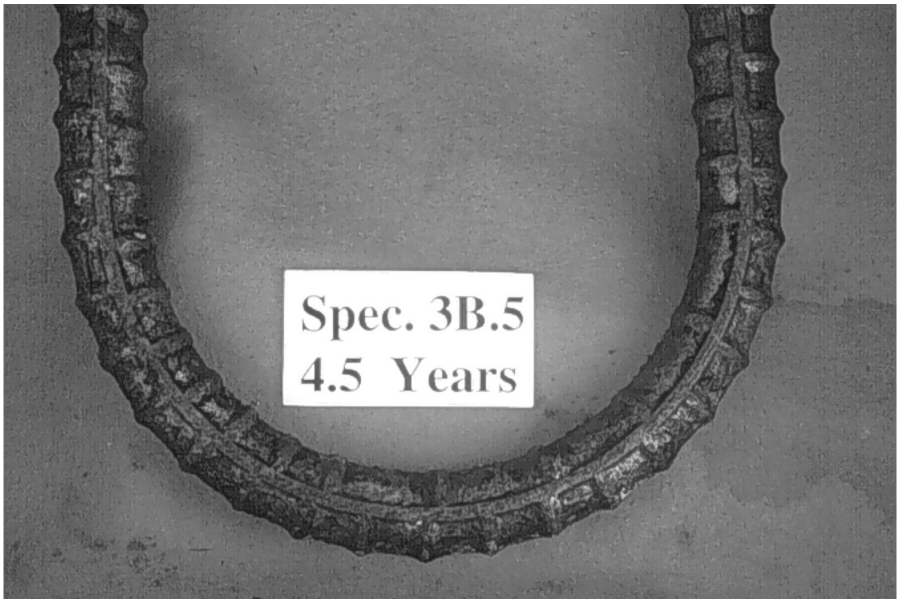
(a) Top side.



(b) Bottom side.

Fig. 8.39: Steel surface condition beneath the coating of bar 3A.3.

(a) Top side.



(b) Bottom side.

Fig. 8.40: Steel surface condition under the coating of bar 3B.5.

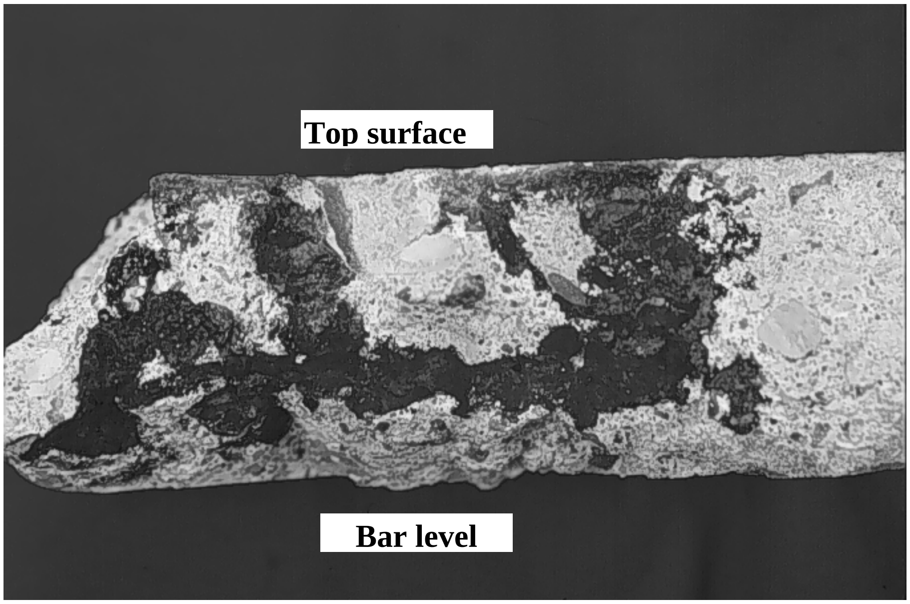
An aspect of top and bottom sides of bar 3B.5 can be seen in Fig. 8.40. Most of the surface was a uniform black rust. Shallow pitting, loss of metal, and accumulation of orange-brown and reddish-brown rust was evident at longitudinal lug at top side of bent zone. A few days after coating removal, orange-brown rust turned dull-brown with some smaller orange-brown spots. At other portions of top and bottom sides, there were dull-brown rust stains or spots, scattered reddish- or orange-brown rust flecks. Damaged sites at the outside of the bend experienced accumulation of orange- and reddish-brown rust. Such rust products were more brittle at some spots. Surrounding area had shallow pitting and loss of metal. There were several blisters, mainly at the bottom side of the bent zone. Many drops of brown, acidic (pH = 3) solution formed on the bottom of the bent area. Corrosion was more severe on the outside than on the inside of the bend. Corrosion seemed worse at the top side of the bar than at the bottom side.

Bar Trace in Concrete

Control Bars

Concrete surrounding the top bar (above and below the bar) was extensively rust stained (Fig. 8.41). Rust stains were very large, mostly black or dark and reddish-brown colored. Sometimes, reddish-brown stains had a black rim. Other observed stains were bluish, bright orange, brownish, yellowish-brown, and whitish. In specimen 3B.1, a few dark-greenish spots were observed immediately after autopsy, and hours later turned bluish or dark. In specimens with small bars, concrete around straight bar legs experienced more rust staining than concrete around the bend zone. Black and reddish-brown rust usually accumulated and hardened in concrete above straight bar legs. Staining distribution seemed more uniform in concrete around large bars. Rust staining was more extensive in concrete above smaller bars, especially in the portion closer to the front face of the specimen, where stains penetrated the concrete far beyond the bar location at either side or both sides of bar legs (Fig. 8.41). Rust staining was more extensive in concrete below large bars. In general, rust stains penetrated the concrete far beyond the bar location along different portions of the bar. Stains penetrated cracks and expanded towards the top concrete surface (Fig. 8.42). Rust staining was mostly reddish-brown and orange-brown at areas closer to the upper surface while it tended to be dark or black at the rebar level. Reddish-brown and dark rust was also observed inside large concrete voids above and below the bar.

Fig. 8.41: Rust staining on surrounding concrete under uncoated bar 3A.8.



(a) Rust inside crack surfaces in concrete cover.

(b) Another aspect of rust inside crack surface.

Fig. 8.42: Rust products penetrated through cracks and rose to the upper surface in specimens with uncoated bars.

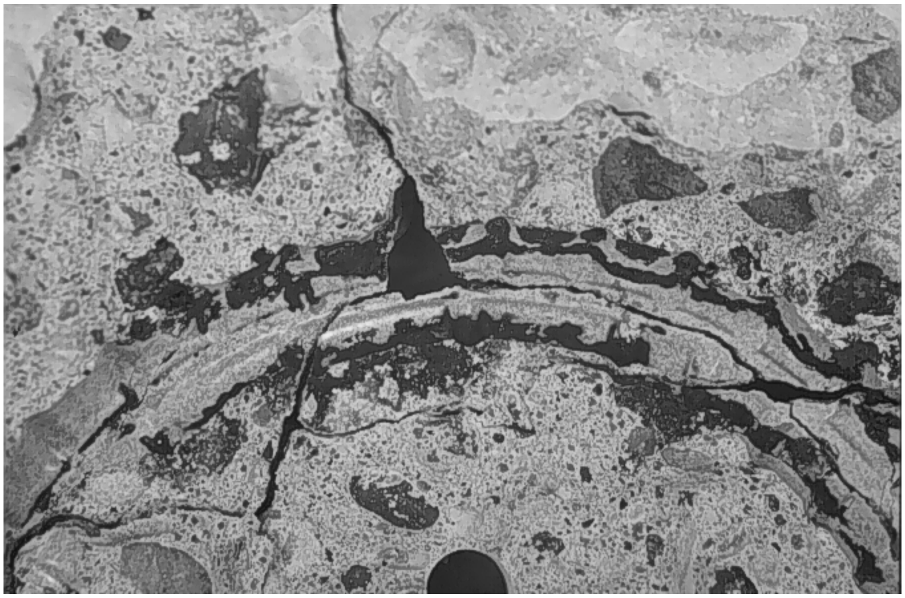
In non-stained areas, the bar trace in concrete above the bar looked porous with a grayish-like appearance, the rib imprints were not clearly defined, and there were few voids. The bar trace in concrete below the bar had also a grayish-like appearance, but looked more porous with the presence of laitance and more voids of different size. Concrete adhered well to black bars as evidenced by the chunks of concrete that remained stuck to the bar surface.

Epoxy-Coated Bars

Concrete surrounding epoxy-coated bars showed much less rust staining than specimens with uncoated bars. Rust staining was generally confined to the concrete-bar interface and did not spread inside the concrete beyond the bar location. Among specimens with coated bars, concrete around #8 bars experienced more extensive rust staining than concrete around #4 bars. In all specimens, rust staining was more extensive in concrete below the bars than in concrete above the bars. In most specimens, rust staining in concrete spread more around the bend than along straight bar legs. Distribution of staining in concrete tended to be more uniform in specimens with larger bars.

The size of rust stains ranged from large to very small. The largest stains were in the bend zone. Color and appearance of stains varied widely. Very often, colors of stains were combined: brown or reddish-brown areas inside black stains, brown or reddish-brown with a black rim, black with reddish rim, stain ranging from dark reddish-brown to light brown, and stain ranging from black to reddish-brown. The most common stains were dark or black, reddish-brown, and black with reddish-brown areas. Dark-greenish stains were found mainly in specimens with #8 bars: Only one specimen with #4 bars had a dark-greenish stain versus four specimens with #8 bars. The appearance of dark-greenish stains changed within minutes or hours after specimen autopsy, i.e. after being exposed to the atmosphere. The color of dark greenish stains changed to one of the following colors: Reddish-brown, brown, reddish-brown combined with dark or black, and light-brown. In specimen 2B.6, one dark-greenish spot turned brown within minutes, then gradually turned reddish-brown within a day. Another greenish spot in the same specimen turned yellowish-brown within minutes and then reddish-brown within a day.

Rust stains in concrete in most cases were at the following locations: At and near concrete voids, next to coating imperfections and discontinuities (intentionally damaged spots, patched areas, as-received damage, cracks in the coating, pinholes, and mandrel-induced nicks), and alongside the path of the longitudinal lug on the bottom of the bar (Figure 8.43). Rust staining below the bar sometimes extended along a strip. Stains at other locations were more sporadic, such as at straight bar legs (above and below the bar). There was almost always a blister in the coating next to a rust-stained void in the concrete. However, there were many concrete voids, large and small, which were free of any rust products or staining.



(a) Concrete above the bar.

(b) Concrete below the bar.

Fig. 8.43: Bar trace in concrete of specimens 3B.5.

The bar trace in concrete above epoxy-coated bars consisted of a smooth, shiny, glossy surface with a grayish-like appearance, the rib imprints were clearly defined, and there were few voids. The bar trace in concrete below epoxy-coated bars had a whitish-like appearance, looked more dusty and porous with presence of laitance, and had much more voids of different size. Chemical adhesion to concrete was lost, as evidenced by the ease with which the bar was removed from the concrete and lack of concrete adhering to the bar. Only a film of white dust from the concrete paste adhered to the bottom of the bars.

8.5 DISCUSSION OF RESULTS AFTER 4.5 YEARS

8.5.1 General

Results from corrosion monitoring, visual examinations, chloride analysis, and post-mortem examination are analyzed and discussed. Special emphasis is placed in comparing the results after 4.5 years of exposure with the results after 1 and 2 years of exposure. Special mention will be made of factors that are apparent after long-term corrosion and differ from previous findings and conclusions.

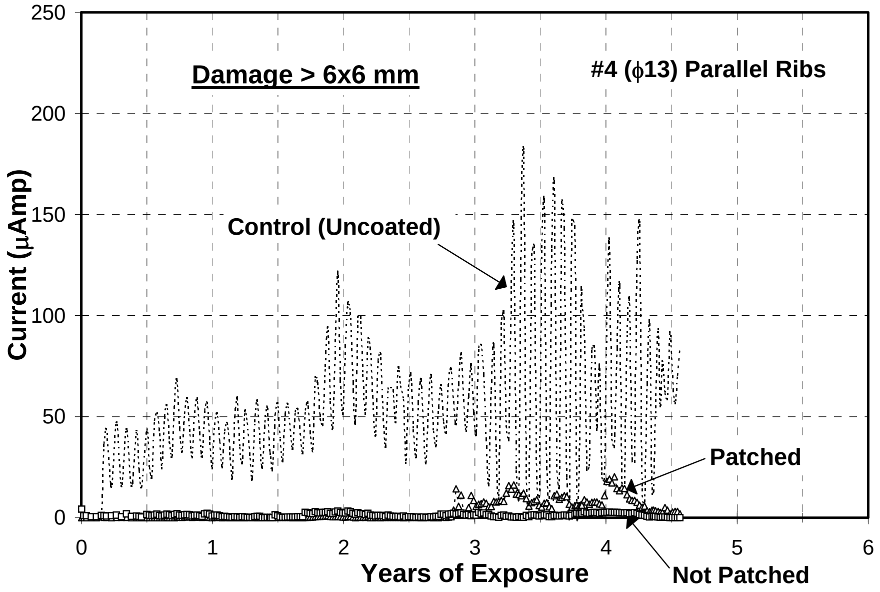
8.5.2 Corrosion Activity

Macrocell Current and Corrosion Potentials

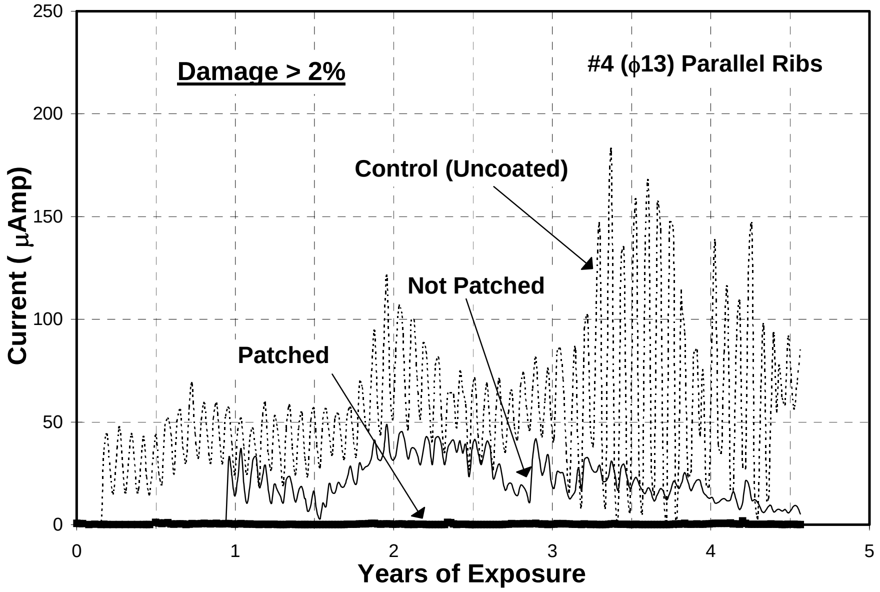
Figures 8.44 through 8.49 show graphs of macrocell currents comparing relative performances of different damage conditions for specimens with both #4 and #8 coated bars. Among #4 bars with parallel ribs, specimens with damage greater than 2% and specimens with coating cracks and damage less than 1%

underwent the highest corrosion currents. Interestingly, the specimen with cracks in the coating and damage less than 1% tended to have increasing currents at the end of the exposure, while the specimen with damage greater than 2% had lower, declining currents at the end of 4.5 years (Fig. 8.46). Specimens with parallel ribs and damage greater than 6x6 mm had very low currents and, paradoxically, the repaired specimen showed slightly greater currents [(Fig. 8.44(a)]. This agreed well with the observed lack of corrosion at damaged spots noted previously. For #4 bars with cross ribs, specimen with damage greater than 6x6 mm experienced the greatest current, as expected.

Among #8 bars with parallel ribs, the specimen with damage greater than 2% and the specimen with cracks less than 1% experienced the highest currents, as was the case for #4 bars (Fig. 8.49). Again, the specimen with cracks and damage less than 1% experienced increasing macrocell current at the end of 4.5 years while other damaged specimens seemed to have reached a steady-state behavior. Apparently, when there are cracks in the coating, the corrosion mechanism may differ from that for other types of damage. Among #8 bars with cross ribs, the specimen with damage less than 1%, which met previous specifications in terms of limiting damage, showed currents very similar to the specimen with damage greater than 6x6 mm. Among all #8 bars (parallel and cross ribs), except for damage greater than 2% [Fig. 8.47(b)], patched specimens underwent macrocell currents similar to unrepaired specimens after 4.5 years of exposure (Figures 8.47(a) and 8.48). It seemed that patching provided some initial protection during the first 2.5 years but currents for both patched and non-patched specimens were similar thereafter.



(a) Damaged areas larger than 6x6 mm.



(b) Damage greater than 2% of bar surface.

Fig. 8.44: Current vs. time of various combinations of A specimens (#4 bars) with parallel ribs.

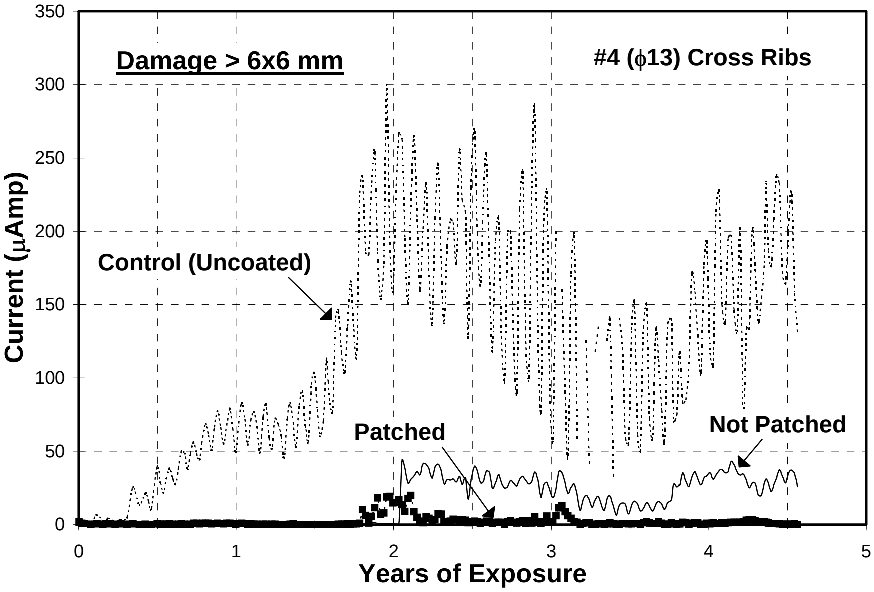


Fig. 8.45: Current vs. time of A specimens (#4 bars) with cross ribs and damaged areas larger than 6x6 mm.

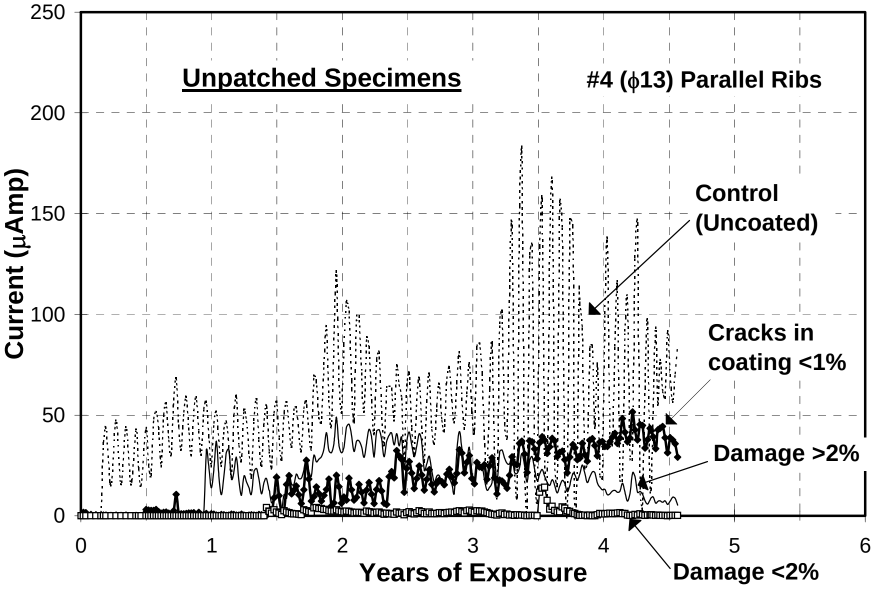
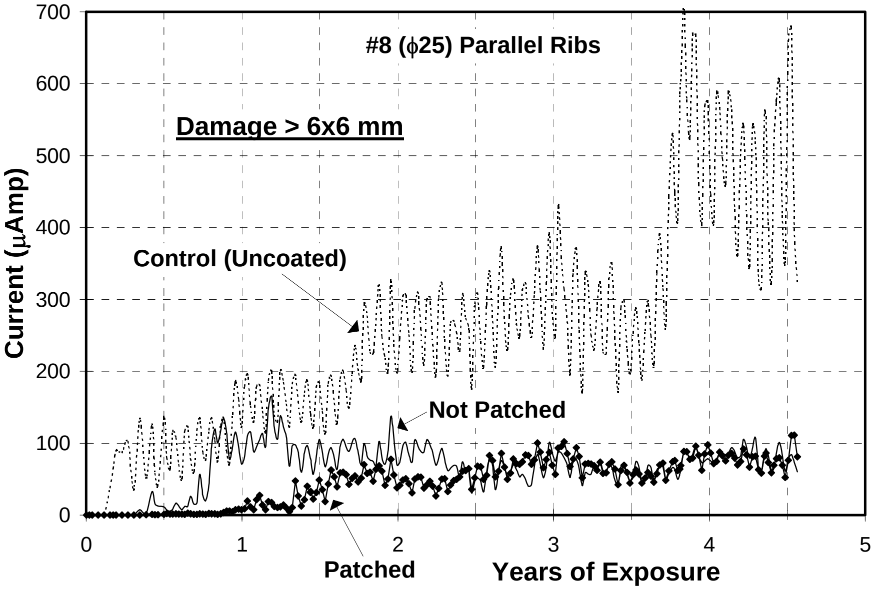
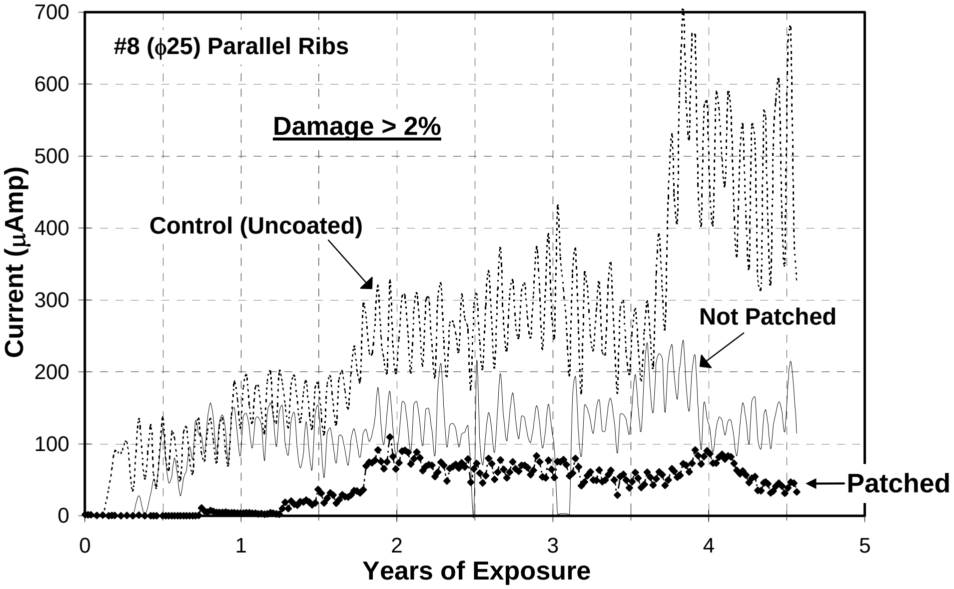


Fig. 8.46: Current vs. time of A specimens (#4 bars) with different damage frequency or cracks in the coating.



(a) Damaged areas larger than 6x6 mm.



(b) Damage greater than 2% of the bar surface.

Fig. 8.47: Current vs. time of various combinations of B specimens (#8 bars) with parallel ribs.

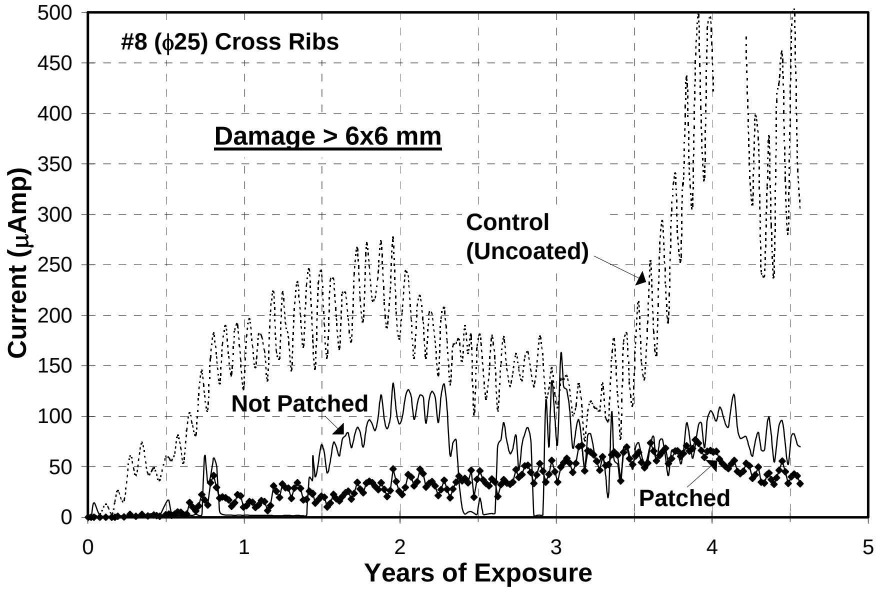


Fig. 8.48: Current vs. time of B specimens (#8 bars) with cross ribs and damaged areas larger than 6x6 mm.

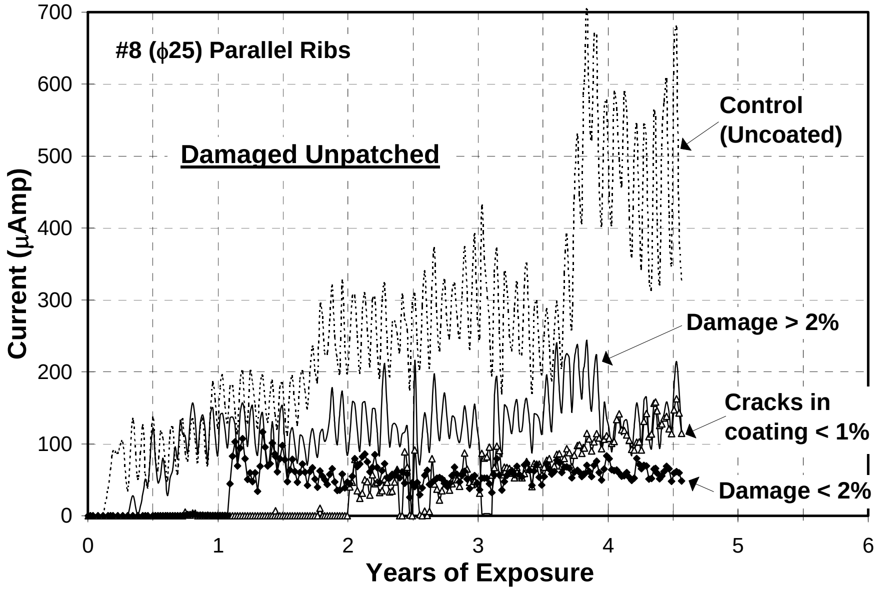


Fig. 8.49: Current vs. time of B specimens (#8 bars) with different damage frequency or cracks in the coating.

Corrosion potentials correlated well with measured currents in terms of the relative performance of different groups with the same bar type and damage. Plots of corrosion potentials over time of bars with the same type of damage and of the respective control bar are shown in figures 8.50 and 8.51. A comparison of these graphs with those of figures 8.44, 8.45, 8.47, and 8.48 indicates that the order of relative performance among specimens is the same for both potential and current measurements. The average corrosion potential of each specimen is plotted in figures 8.52 and 8.53. In the same graphs, the average current density (calculation of this parameter is explained in subsequent sections) of each specimen is also plotted for comparison. Both corrosion potential and current density curves have very similar shapes, indicating comparable trends. With a few exceptions, more negative corrosion potentials correlated with higher current densities for a given set of bars with the same type of damage.

Average current densities versus average corrosion potentials for all specimens are plotted in Fig. 8.54. All specimens with potentials between -200 and -300 mV vs. SCE had average current densities smaller than 0.015 $\mu A/cm^2$. Bars with corrosion potentials between -300 and -400 mV vs. SCE had average current densities between 0.025 $\mu A/cm^2$ and 0.194 $\mu A/cm^2$. Corrosion potentials in the range of -400 to -500 mV vs. SCE correlated with average current densities of 0.115 $\mu A/cm^2$ and 0.315 $\mu A/cm^2$. Finally, control specimens, which had corrosion potentials between -500 to -550 mV vs. SCE, experienced average current densities between 0.418 $\mu A/cm^2$ and 1.02 $\mu A/cm^2$. With this limited data,

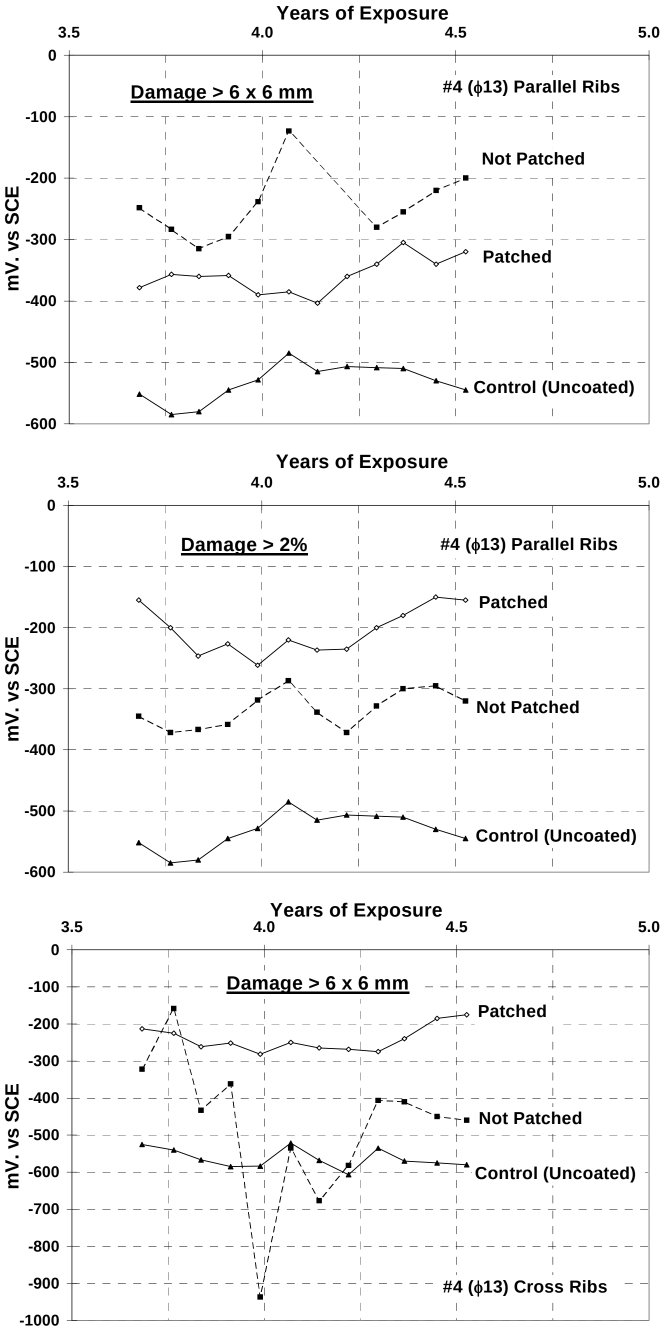


Fig. 8.50: Three graphs of corrosion potential vs. time of various combinations of A specimens (#4 bars).

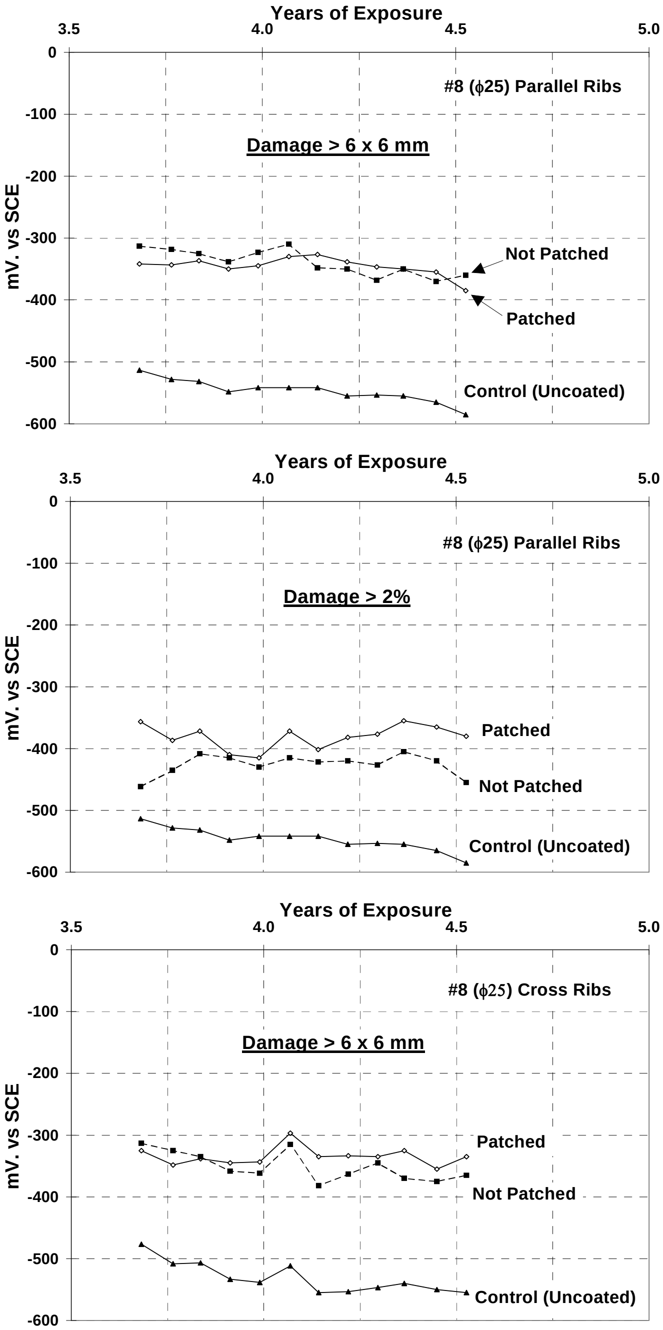


Fig. 8.51: Three graphs of corrosion potential vs. time of various combinations of B specimens (#8 bars).

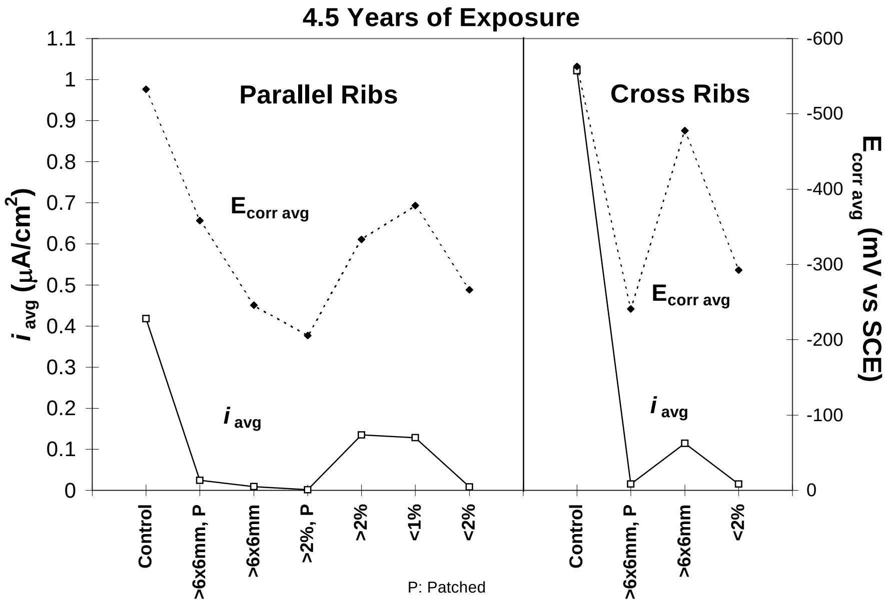


Fig. 8.52: Graphs of average corrosion potentials and current densities of all A specimens (#4 bars).

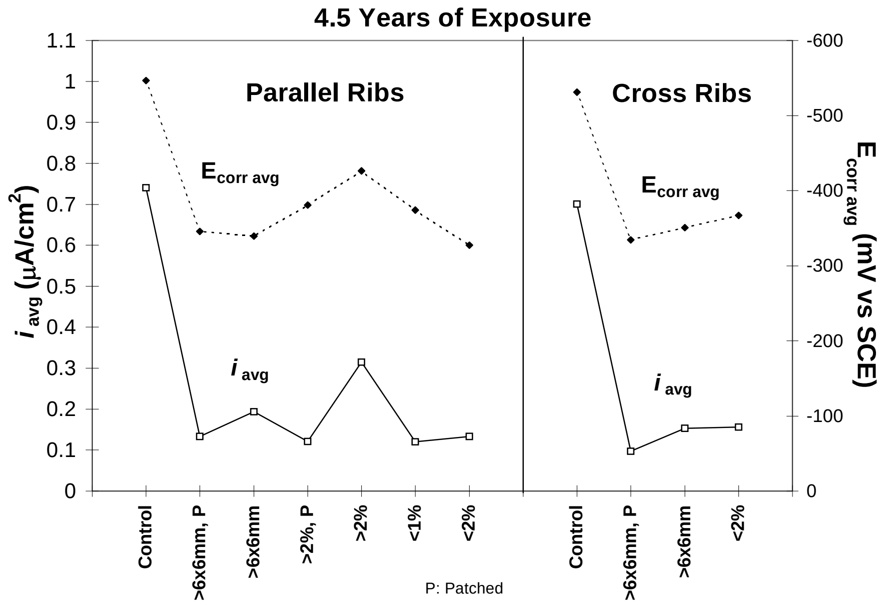


Fig. 8.53: Graphs of average corrosion potentials and current densities of all B specimens (#8 bars).

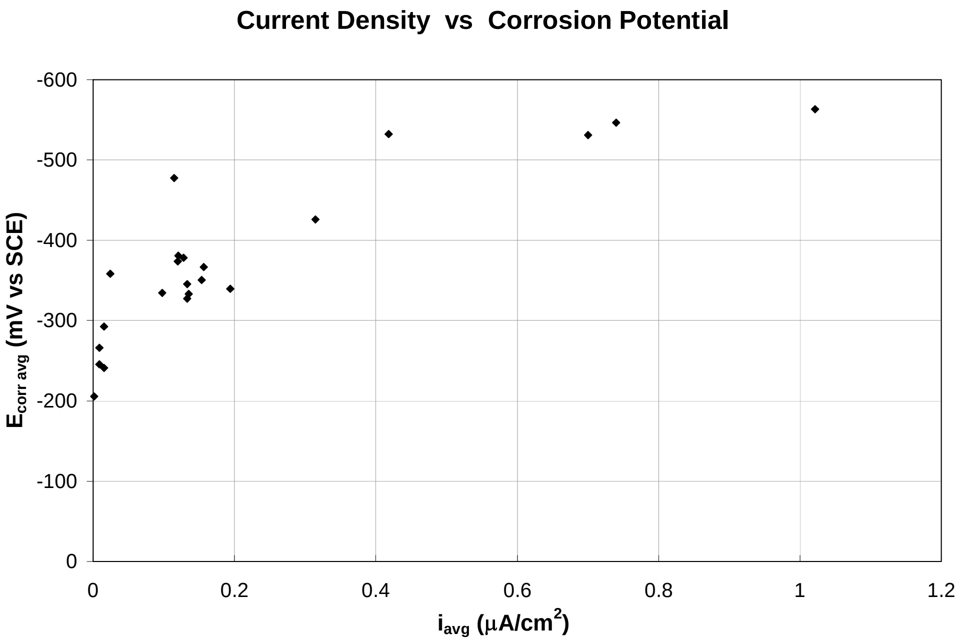


Fig. 8.54: Average current densities vs average corrosion potentials for all specimens.

corrosion potentials between -200 and -300 mV vs. SCE correlated with negligible corrosion, potentials from -300 to -500 mV vs. SCE related to low to moderate corrosion, and potentials more negative than -500 mV vs. SCE correlated with severe corrosion.

Other researchers have measured similar corrosion potentials. Wheat and Eliezer found that loss of passivity and general corrosion of uncoated bars occurred at a potential range of -450 to -600 mV SCE.[132] Sagüés measured potentials in the range of -350 to -475 mV SCE on coated bars in uncracked columns after 300 days of exposure.[65] Zayed et al. observed potentials in the order of -400 mV SCE in damaged epoxy-coated bars in uncracked specimens.[72]

Weighted Average Current

The weighted average current for any specimen can be calculated using the following equation:

Iwa = **Error! Bookmark not defined.**$\Sigma I_{ai}/\Sigma T_i \quad i = 1,n$

where, I_{ai} = average current in time interval i,
T_i = time interval i,
n = total number of time periods of measurements.

The weighted average current gives an indication of the severity of macrocell corrosion over the time of exposure. The calculated values of weighted average current at one, two, and 4.5 years are listed in Table 8.3. These values were calculated using currents from the last triplicate specimen only. Currents from companion specimens were not used to calculate weighted averages at 1 and 2 years. The weighted average currents were very similar to the average currents because the time intervals for measuring currents were practically the same throughout the test.

Values in the table show that uncoated bars developed very high average currents. Among uncoated bars, bar #4 with cross ribs had the largest increase by far in average current. Larger bars had greater average currents than smaller bars. Average currents tended to increase with time of exposure. Specimens with cracks less than 1 % showed greater activity in the last 2.5 years of exposure: Bar #4 had the second largest weighted average current among #4 coated bars, and bar #8 had the largest increase in average current in the last 2.5 years of all specimens. For both #4 and #8 bars, specimens with damage greater than 2% exhibited the largest average currents.

Group No.	Damage Category and Condition	Series A (#4)			Series B (#8)		
		1 Yr	2 Yr	4.5 Yr	1 Yr	2 Yr	4.5 Yr
1	Control (Uncoated Bars)	32	40	55	82	134	255
2	Spots > 6x6 mm, Patched	0.16	0.19	3.21	1.37	19	46
3	Spots > 6x6 mm, Exposed	1.11	1.08	1.18	29	62	67
4	Spots > 2%, Patched	0.27	0.21	0.21	1.67	16	42
5	Spots > 2%, Exposed	1.24	11.3	17.7	56	74	108
6	Cracks < 1%, Exposed	1.16	3.90	16.8	0.29	0.28	41
7	Spots < 2%, Exposed	0.01	0.67	1.15	0.25	30	46
8	Control (Uncoated Bars)	30	71	134	76	140	241
9	Spots > 6x6 mm, Patched	0.40	1.37	2.03	7.70	15.4	34
10	Spots > 6x6 mm, Exposed	0.30	0.29	15	7.5	27	53
11	Pinholes < 1%	0.06	0.21	2.02	8.2	23	54

Table 8.3: Weighted average corrosion current for macrocell specimens (μAmp).

Except in one case, patched specimens had much smaller average currents than damaged specimens among #4 bars. The exception was bar #4 with parallel ribs and damage greater than 6x6 mm, but even in this case the average current for the damaged specimen was not significant (3.21 μAmp). Among #8 coated bars, patched specimens had smaller average currents than damaged specimens, but the amount of current reduction was not as large as in #4 coated bars. It should be noted that among coated specimens, #8 bar with pinholes less than 1% had the third largest average current. No clear trend is discernible for different rib patterns: Among series A, bars with cross ribs tended to have larger average currents, and among series B, bars with parallel ribs tended to show slightly higher average currents.

Corrosion Current Density

Corrosion current density was calculated by dividing the weighted average current by the nominal surface area of the anodic bar. From other studies, Kahhaleh reported that values of current density below 0.1 μA/cm2 indicated a negligible corrosion rate, current densities between 0.1 and 0.2 μA/cm2 denoted a low corrosion rate, and values between 0.2 and 0.5 μA/cm2 represented a shift to moderate corrosion rate.[10] Figures 8.55 and 8.56 graphically display corrosion current densities for #4 and # 8 bars, respectively.

Obviously, current densities showed the same trends as weighted average currents because the values are proportional. The graphical representation makes the already observed trends easier to see. The uncoated #4 bar with cross ribs had the largest current density of all specimens (#8 bars included). In general, a number of coated bars (especially #8 bars) showed a tendency to develop increasing current density with time. Current densities in three specimens with #4 coated bars (damage greater than 2%, cracks with damage less than 1%, and cross ribs with damage greater than 6x6 mm) entered the region of low corrosion rate. The rest of #4 coated bars still had current densities in the negligible range. Almost all #8 bars had current densities at least in the low corrosion rate region and one specimen (damage greater than 2%) had current density in the moderate corrosion region.

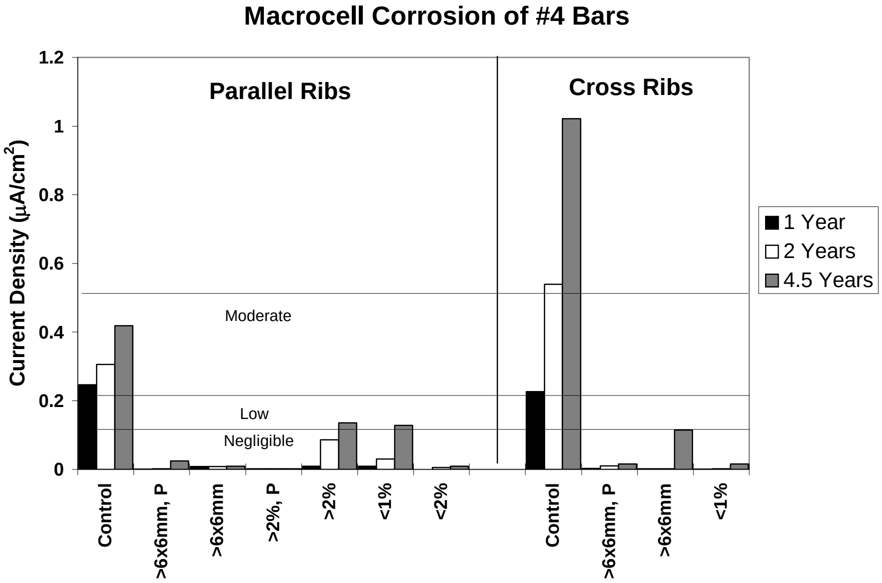


Fig. 8.55: Corrosion current densities for all A specimens (#4 bars).

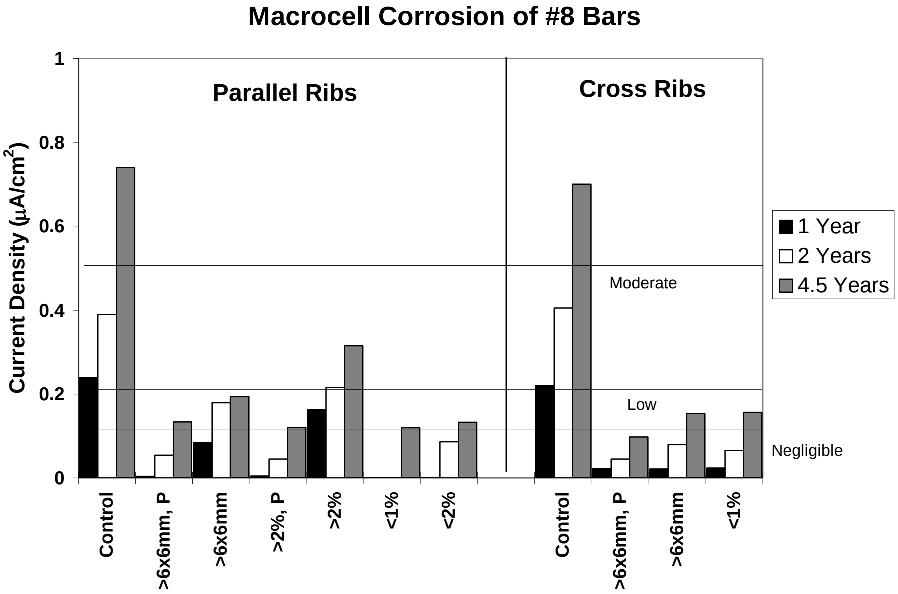


Fig. 8.56: Corrosion current densities for all B specimens (#8 Bars).

Metal Loss

The area under the current vs. time curve represents the amount of electrical charge (flux) exchanged in a certain period of time.[10] The amount of charge, that is, the number of electrons exchanged, is proportional to the amount of metal consumed. For this reason, charge flux is a reliable indicator of corrosion severity. The amount of charge flux passed in 4.5 years for specimens from series A and B is plotted in Figures 8.57 and 8.58. In these figures, the amounts of charge of the coated bars are indicated as a percentage of the companion uncoated bars.

Analysis from charge flux graphs confirms the previous observations. For series A, the coated bars with worst corrosion (damage > 2% and cracks with damage < 1%) passed slightly over 30% of the charge passed by the uncoated bar. The specimen with cross ribs and damage greater than 6x6 mm passed slightly less charge than the specimen with most charge passed (2164 Coulombs vs. 2548 Coulombs), but a low percentage of 11% is shown because of the excessively high amount of charge passed by the respective control specimen. Two thirds of the specimens passed 6% or less of the charge passed by their respective control specimens.

For series B, the coated bar with worst corrosion (damage > 2%) passed 43% of the charge passed by the uncoated bar. It should be pointed out that although the charge flux for that specimen increased from 4,677 Coulombs at 2 years to 15,614 Coulombs at 4.5 years, the percentage of charge flux passed with respect to that of the uncoated bar decreased from 55% to 43% in the same period.

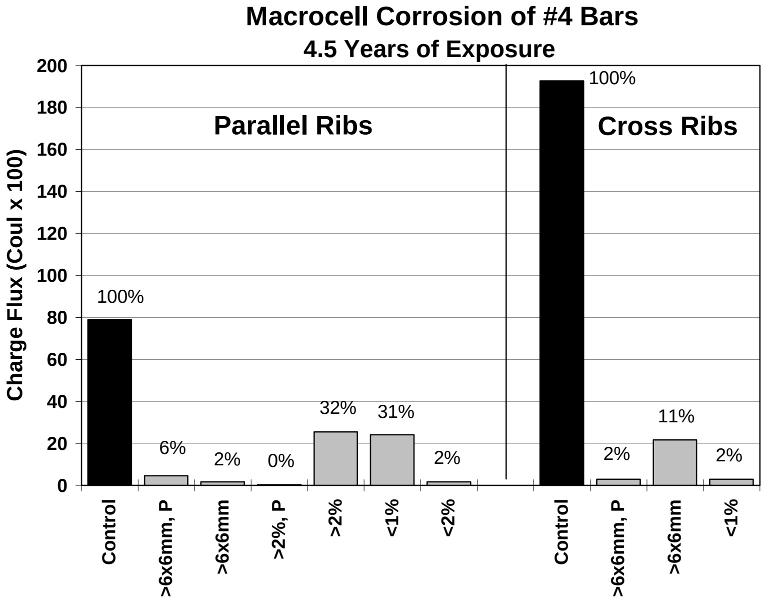


Fig. 8.57: Charge flux for all A specimens (#4 bars).

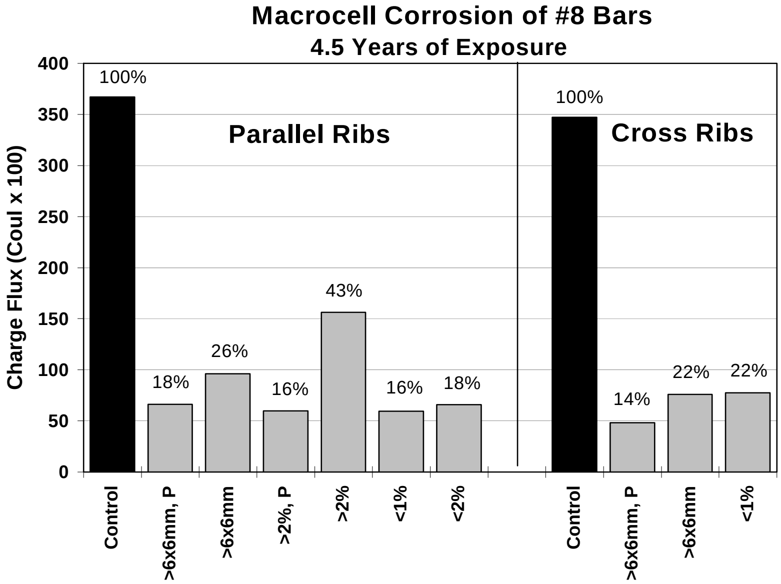


Fig. 8.58: Charge flux for all B specimens (#8 bars).

Clearly, the uncoated bars deteriorated at a faster rate than some of the coated bars. Patched bar specimens passed from 14 to 18% of the charge passed by their respective controls. Comparatively, the same patched bars passed from 11% to 14% of the charge passed by the uncoated bars after 2 years. Patched bars corroded at a slightly faster rate than damaged bars. Apparently, the effectiveness of patching diminished with time.

Virmani et al. have correlated charge flux with the amount of metal consumed experimentally.[48] Based on that correlation, the amount of metal loss, in grams, from any specimen was estimated by multiplying the charge flux by 1.04. The amount of metal consumed for each group after 4.5 years of exposure is summarized in Table 8.4. All the coated bars from series B lost more than 1 gram of metal after 4.5 years. In the worst case, 4.5 grams was lost, but is still much less than the 10 grams lost by the uncoated bar. In series A, the worst coated bar lost 0.7 grams of metal compared to 2.3 grams lost by the uncoated bar.

The metal consumption ratio is a useful indicator of the effectiveness of epoxy-coated reinforcement relative to uncoated steel. The ratio is calculated by dividing the amount of metal loss of the uncoated bar by the amount of metal loss of each bar group. This ratio shows the improvement in performance of each group of coated bars relative to the control groups. Obviously, the ratio is identical to the reciprocal of the charge percentage given in figures 8.57 and 8.58. Calculated performance ratios for all specimens are listed in Table 8.5.

Group No.	Damage Category and Condition	Series A	Series B
1	Control (Uncoated bars)	2.28	10.61
2	Spots > 6x6 mm, Patched	0.13	1.91
3	Spots > 6x6 mm, Exposed	0.05	2.78
4	Spots > 2%, Patched	0.01	1.73
5	Spots > 2%, Exposed	0.74	4.51
6	Cracks < 1%, Exposed	0.70	1.72
7	Spots < 2%, Exposed	0.05	1.91
8	Control (Uncoated bars)	5.57	10.03
9	Spots > 6x6 mm, Patched	0.08	1.40
10	Spots > 6x6 mm, Exposed	0.63	2.20
11	Pinholes < 1%, Exposed	0.08	2.24

Table 8.4: Metal consumed by corrosion after 4.5 years (Amounts in grams).

For series A, most performance ratios for coated bars were at least one order of magnitude better than uncoated bars, with improvements as high as 263 and as low as 3.1. All coated bars from group B had less than one order of magnitude improvement over the uncoated bars after 4.5 years, with performance ratios as high as 7.2 and as low as 2.4. There was not a dramatic decrease of performance ratios from those after 2 years of exposure. Performance ratio dropped in about half of the specimens in a period from 2 to 4.5 years, and increased in the others.

Group No.	Damage Category and Condition	Series A		Series B	
		2 Yr	4.5 Yr	2 Yr	4.5 Yr
1	Control (Uncoated bars)	1.0	1.0	1.0	1.0
2	Spots > 6x6 mm, Patched	104	17	8.2	5.6
3	Spots > 6x6 mm, Exposed	8.7	46	2.4	3.8
4	Spots > 2%, Patched	129	263	9.1	6.1
5	Spots > 2%, Exposed	4.7	3.1	1.7	2.4
6	Cracks < 1%, Exposed	16	3.3	18	6.2
7	Spots < 2%, Exposed	46	48	4.0	5.6
8	Control (Uncoated bars)	1.0	1.0	1.0	1.0
9	Spots > 6x6 mm, Patched	33	66	10	7.2
10	Spots > 6x6 mm, Exposed	20	8.9	3.1	4.6
11	Pinholes < 1%, Exposed	162	66	5.7	4.5

Table 8.5: Performance ratio of epoxy-coated bars to uncoated bars based on amounts of consumed steel after 4.5 years.

After 2 years of exposure it was concluded that the rate of increase of metal consumption of epoxy-coated bars was higher than that of uncoated bars.[10] Present findings after 4.5 years of exposure seem to support that statement. Two thirds of all coated specimens experienced a faster rate of metal consumption than that of the uncoated bars in the last 2.5 years of exposure. For uncoated bars, the increase in metal consumption in the last 2.5 years ranged from 212% to 335%. For coated bars, the increases were widely scattered, ranging from 127% to 33,363%.

Despite the huge increases of metal consumption in some cases, the improvement in performance of coated bars was still evident because of their very low initial corrosion. For instance, bar 3B1 (control) with an increase of 335%, experienced 10.6 grams of metal loss versus 1.7 grams of metal loss by bar 2B6 (damage < 1%), which had an increase of 33,363% in the last 2.5 years. If the four specimens with extremely high increases of metal consumption (above 1000%) are excluded, the average increase of metal loss was 294% for uncoated bars and 339% for coated bars, which were not significantly different. Coated bars included in the 339% average increase are generally the ones with highest amount of metal depleted.

8.5.3 Condition of Bar Surface

Surface Corrosion

Examination of the bar surface condition confirmed most of the trends determined by the measured corrosion currents. Uncoated bars corroded more than coated bars. Larger bars corroded more extensively and severely than smaller bars. Most of the surface of several of the small bars remained in good metallic condition (although not completely free of corrosion) despite a very high chloride content and presence of coating damage. Obviously, the epoxy coating was able to protect the bars in those cases. Patched bars did not always perform better than damaged bars and corrosion did occur in patched bars.

From examination of bars after specimen autopsy, a visual assessment regarding the relative performance of different bars was made. Tables 8.6 and 8.7 include a ranking of small and large bars according to their observed surface condition. Bars were rated from best to worst and were listed from top to bottom in that order. The rank number given by the column “visual examination” indicates the relative performance of that bar compared to the rest. For comparison, the rank number given by the column “charge flux” indicates the relative performance according to the measured charge flux.

Group No.	**Damage Category and Condition**	**Visual examination**	**Charge Flux**
3	Spots > 6x6 mm, Exposed	1	3
7	Spots < 2%, Exposed	2	2
4	Spots > 2%, Patched	3	1
2	Spots > 6x6 mm, Patched	4	6
11*	Pinholes < 1%, Exposed	5	4
9*	Spots > 6x6 mm, Patched	6	5
6	Cracks < 1%, Exposed	7	8
10*	Spots > 6x6 mm, Exposed	8	7
5	Spots > 2%, Exposed	9	9
8*	Control (Uncoated bars)	10	11
1	Control (Uncoated bars)	11	10

1: Best 11: Worst
* Cross Ribs

Table 8.6: Relative performance of bar specimens series A (#4). Assessment by visual examination and measured charge flux.

Group No.	**Damage Category and Condition**	**Visual examination**	**Charge Flux**
6	Cracks < 1%, Exposed	1	1
7	Spots < 2%, Exposed	2	3
3	Spots > 6x6 mm, Exposed	3	5
2	Spots > 6x6 mm, Patched	4	4
4	Spots > 2%, Patched	5	2
5	Spots > 2%, Exposed	6	6
1	Control (Uncoated bars)	7	7

1: Best 7: Worst

Table 8.7: Relative performance of bar specimens series B (#8). Assessment by visual examination and measured charge flux.

Although the correlation was not exact, there was good agreement in general between monitored currents and observed corrosion attack, with little difference in the rank order given to each specimen. There was a large discrepancy in the rank order of only one specimen, 3B.4 (damage >2%, patched), where observed corrosion was worse than predicted by monitored currents. Another important discrepancy was that in large bars with damaged spots greater than 6x6 mm, monitored currents predicted less corrosion on the patched than on the non-repaired specimen. Visual examination revealed that although corrosion was more severe at damaged areas than at patched areas, corrosion spread much more on the metal surface beyond the patched area.

Coating Adhesion to Steel

Bars were more susceptible to coating debonding at bent regions because of bar fabrication. In addition to weakening the adhesion, pinholes, tears, or cracks may develop in the coating during fabrication. The coating at the rib bases on the outer bend becomes very thin and prone to get damaged due to stretching. Cracks in the coating on specimens 2A.6 and 2B.6 were produced during fabrication. Damage in the coating, or even thinning of the coating if not damaged, may have allowed oxygen and salt solution to cross the film. Coating debonding facilitated this phenomenon by allowing the deleterious agents to traverse and accumulate below the coating. Fabricated bars then became more vulnerable and susceptible to corrosion at the bent zones.

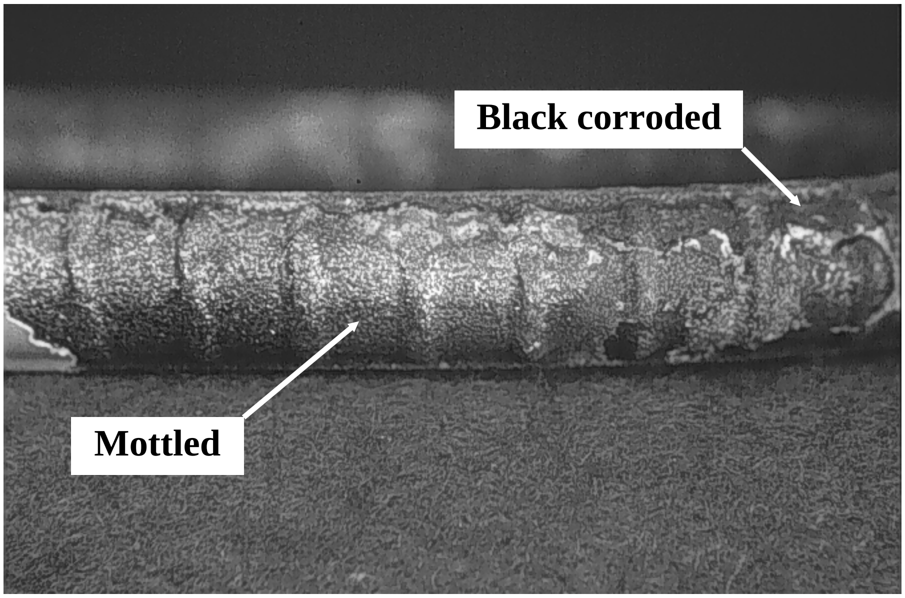
During the 4.5 years of cyclic exposure to salt solution, enough water permeated through the concrete and created a moist environment. This factor contributed to accelerate the loss of the already marginal adhesion at the bent zones. Loss of adhesion at the straight portions of many bars (all #8 bars and four #4 bars) confirmed this observation. Another contributing factor may have been the possible occurrence of cathodic disbondment around damaged areas. These two mechanisms will be discussed in the following section.

The straight portions of the bars had very strong initial coating adhesion compared to bent portions. After 4.5 years of exposure, all #8 bars and four #4 bars suffered adhesion loss at the straight portions. Contrary to specimens examined after one and two years, underfilm corrosion was substantial at many of the debonded straight portions, predominantly on large bars. Coatings with initially strong adhesion and absence of damage delayed but did not prevent corrosion after 4.5 years of exposure. Corrosion was more extensive and severe at the bent portions. Initial relative adhesion and damage between straight and bent portions was a crucial factor in the relative performance between straight and bent portions.

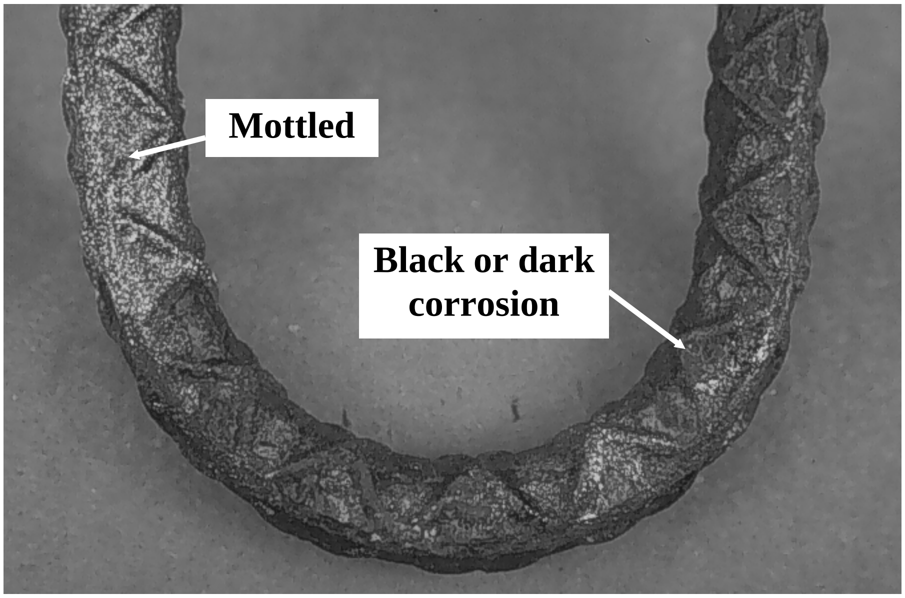
Undercutting

Corrosion under the epoxy coating after 4.5 years of exposure tended to be more extensive than the appearance on the coating surface first indicated. Most bars experienced widespread corrosion activity beneath the coating (undercutting). In contrast, undercutting for companion specimens after 1 and 2 years was less extensive. For some coated bar specimens, after the first year of testing, undercutting was usually confined to the vicinity of exposed steel areas, coating defects, and breaks documented before the testing. The majority of bars inspected after 2 years showed more widespread underfilm corrosion or localized corrosion around previously undetected pinholes.[10]

Undercutting occurred in the following forms: a) A change of appearance of the steel surface to a mottled, glittering golden-brown with no significant attack, such as pitting or loss of metal [Fig. 8.59(a)], and b) Uniform black or dark surface rusting with random reddish-brown (or other tones of brown) rust spots and some degree of attack at several portions, such as slight pitting, rust buildup, and loss of metal [Fig. 8.59(b)].



(a) Mottled, glittering golden-brown steel surface under the coating.



(b) Black or dark corroded surface.

Fig. 8.59: Forms of undercutting of epoxy-coated bars.

At portions of bars where coating adhesion was preserved (straight portions close to front face of specimens), the steel surface maintained its originally shiny, bright aspect. Bars with little corrosion activity (small bars) showed large portions with debonded coating and a mottled, glittering golden-brown surface underneath with very little, almost negligible corrosion attack. Bars with the greatest corrosion (large bars) showed large portions with debonded coating an a uniformly black or dark rusted surface. Clearly, portions of the bar with adhered coating and unchanged appearance of the steel surface underneath represented areas of no corrosion. Portions of the bar with debonded coating and uniformly black or dark rusted surface underneath represented areas of corrosion. An assessment of the role of those portions of the bar with debonded coating and unattacked, mottled surface underneath was more difficult.

As mentioned earlier, two possible mechanisms may have accounted for the loss of adhesion of the epoxy coating: Cathodic disbondment and adhesion loss by water action. These mechanisms are discussed in the following paragraphs.

Cathodic Disbondment

Any corrosion process requires the anodic and cathodic reactions. Active corrosion occurs at anodic areas while no corrosion takes place at cathodic areas. Anodic and cathodic areas usually coexist together on the same surface, with the cathode usually surrounding the anode. Cathodic disbondment has been reported to occur at areas with cathodic reaction.[133] It is possible then that portions of the bar with debonded coating and mottled surface underneath may represent areas with cathodic activity. The debonded coating may have been the result of cathodic disbondment. The change of appearance to a mottled surface may have been the result of the alkalinity produced by cathodic reactions at the metallic surface. The steel surface was preserved in relatively good condition, as would be expected in a cathodic area. At the black corroded areas, adhesion may have been lost because of oxide lifting.[24]

The phenomenon of cathodic disbondment at a defect in a coating is illustrated in Figure 8.60.[24, 78] Concrete porosity and voids, and coating defects allow access of deleterious substances to the substrate metal. The anodic reaction

$$Fe \rightarrow Fe^{2+} + 2e^{-} \qquad (8.1)$$

occurs at a coating defect that is coupled to the nearby cathode beneath the coating. Oxygen must migrate through the coating along with water in order to support the cathodic reaction

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad (8.2)$$

This is possible because epoxy coatings are not impermeable to oxygen, water, nor ions.[78] Cathodically generated alkalinity can react with the organic polymer to disbond the coating at the interface between coating and metal at a defect, as shown in Fig. 8.60. Such reaction is termed saponification. It has also been theorized that cathodic disbondment may proceed by an oxide dissolution mechanism rather than by alkaline degradation of the coating itself (based on the good stability of epoxy coatings in alkaline environments).[65] Cathodic disbondment may also occur at microscopic or smaller flaws in the coating to produce blisters, which do not require a physically obvious defect for initiation.[24]

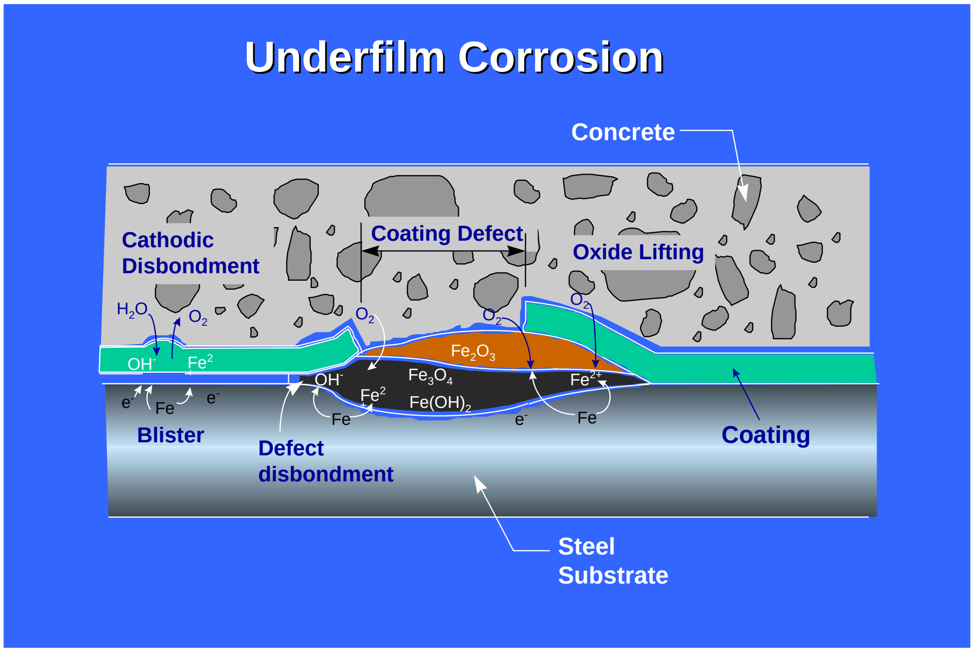


Fig. 8.60: Process of cathodic disbondment and oxide lifting in coatings.

Specimen design involved the use of a bottom layer with black bars, which was intended to act as a cathode. Since the top and bottom layers were linked, any anodic reaction at the top bar would be supported by cathodic reactions at the bottom bars. However, the occurrence of cathodic disbondment at anodic bars would mean that cathodic and anodic reactions also occurred on the same bar surface. It may be possible that at low levels of corrosion activity, cathodic reactions at the bottom bars could not be well established and the initial cathodic reactions would take place on the same top bar. As undercutting progressed at the top bar, the bottom bars would eventually take over to support the necessary cathodic reactions. Schieβl states that the corrosion initiation process is not affected by electrically coupling uncoated bars to coated bars, and that coupling to uncoated bars may only slightly accelerate cathodic disbondment in the initiation stage and increases the corrosion of the exposed areas. The bottom uncoated bars play a greater roll at an advanced stage of deterioration of the coating, accelerating the corrosion rate.[78]

Disbondment by Water

During the 4.5 years of cyclic exposure to salt solution, enough water permeated through the concrete and created a moist environment. It has been theorized and observed that coatings lose adhesion when subject to moist environments.[23, 65, 133] The coating is displaced from the substrate by a thin layer of water. The mechanism under which this phenomenon occurs is still unclear. Some of the theories were discussed in Chapter 4. The principle of wet adhesion loss was used for the hot water tests reported in Chapter 5. It should be emphasized that the condition of the steel surface of samples immersed in hot water was generally bright, preserving its original appearance. This appearance was different from the mottled surfaces in bars from macrocells, indicating that “something” happened at the steel surface. Of course, the exposure conditions of the two experiments were drastically different.

Underfilm Corrosion

Two possible mechanisms of underfilm corrosion may have taken place: Crevice corrosion and oxide lifting. The mechanism of crevice corrosion will be explained first.[24, 129] As already pointed out, corrosion initiated at either exposed areas or coating defects. Corrosion spread at the small crevices under the coating at the edges of exposed areas or discontinuities. Coating at adjacent areas started to lose adhesion by means of cathodic disbondment or water action (or perhaps a combination of both). Adjacent debonded coating formed very thin crevices and corrosion propagated under the coating in a mechanism similar to that of crevice corrosion. Dissolved oxygen was depleted by corrosion in the small volume of the crevice by the reduction reaction (8.2), impairing passivity and increasing the concentration of metal cations by the oxidation reaction (8.1), which attracted negatively charged chloride ions Cl^- from the bulk solution (hydroxide ions also migrated from adjacent areas, but they are less mobile than chloride and migrated more slowly). This resulted in an increased concentration of metal chloride within the coating crevice. The metal chloride hydrolyzes in water by

$$Fe^{2+} + 2H_2O + 2Cl^- \rightarrow Fe(OH)_2 + 2HCl \qquad (8.3)$$

where the aqueous solution of the metal chloride dissociated into an insoluble hydroxide and a free acid.

For reasons not yet understood, both chloride and hydrogen ions accelerate the dissolution rates [equation(8.1)] of most metals and alloys. Underfilm corrosion grew autocatalytically as more chloride was attracted to the coating crevice, promoting further hydrolysis and consequent acidity. As the corrosion within the crevice increased, the rate of oxygen reduction on adjacent surfaces also increases. This created a localized anode coupled to a cathode of larger area on the surrounding surfaces. Such surfaces are obviously cathodically protected but experienced further cathodic disbondment, which creates additional crevices under the coating and allows corrosion to progress under the film.

The presence of an acidic, clear brown solution at the interface between the substrate and the coating in the most corroded bars was evidenced by the observed solution spillage at the front face of specimens at the protruding bar ends and by the observed of drops of solution at the bar surfaces during post-mortem examination. This solution was also observed in specimens examined after two years of exposure, and by other investigators, and has been described as acid moisture accumulation or "local acidification."[65, 72, 73] Chemical analysis of small samples collected revealed the presence of hydrochloric acid HCl in the solution. HCl, which was produced by hydrolysis of the chloride solution [equation (8.3)] as explained above, is a strong acid that accounts for the low pH measured (between 3 and 4).[24] The fluid acid has been observed to contain 3 to 10 times as much chloride as the bulk solution.[129] Many of the observed corrosion products had the appearance of stains, seeming to indicate that the chloride solution may have partially dissolved and transported some of those products.

Oxide lifting occurs when anodic corrosion products accumulate under the coating, as illustrated in Fig. 8.60.[24] The lifting action of compacted oxides and resultant undercutting occurs during alternate wet and dry cycles. Flocculent oxide corrosion products in water are compacted by drying. Corrosion products form an inner layer of dissolved ferrous ions, Fe^{2+} and precipitated $Fe(OH)_2$, which partially oxidizes to form magnetite, Fe_3O_4, a black product. An outer hydrated layer of fully oxidized FeOOH completes the deposits of corrosion products. The cathodic reaction during anodic lifting again may be represented by equation (8.2) at the metal surface in the defect or possibly

$$8FeOOH + Fe^{2+} + 2e^{-} \rightarrow 3Fe_3O_4 + 4H_2O \qquad (8.3)$$

at the outer magnetite interface. Magnetite is sufficiently conductive to act as an electrode for cathodic reaction and Fe_3O_4 is reoxidized to FeOOH by dissolved oxygen. In general, oxide lifting involves electrochemical corrosion in the condensed aqueous phase during wet cycles. Colloidal corrosion products deposit during subsequent dry periods and cannot be easily redissolved or dispersed on rewetting. This results in a buildup of compact corrosion products in constricted crevices or at the interface between coating and metal, lifting or debonding the coating from the substrate.[24]

Epoxy coating looked more distressed and much thinner at more heavily corroded areas than at areas with little or no corrosion, and corrosion products adhered well to the backside of the coating. For this reason, coating was a little bit more difficult to peel with a knife at the more corroded areas. The blade usually cut through the rust layer instead of the metal/coating interface and the coating tore or broke in large and small pieces during the peeling operation. In contrast, coating integrity was maintained at uncorroded, debonded areas and could be lifted as a unit, without tearing, during peeling.

Corrosion Products

The main corrosion product found in coated bars was a uniform black or dark corrosion layer. Dark-greenish or greenish-black products were visible at several spots in the concrete surrounding the bars. Such products have been identified in the literature as magnetite Fe_3O_4.[134, 135] The black magnetite is converted to a green hydrated magnetite ($Fe_3O_4 \bullet H_2O$).[23] The black product is indicative of corrosion with restricted availability of oxygen at crevices that form under the coating. The role of magnetite in supporting cathodic reactions during undercutting and oxide lifting was already explained. Upon exposure to air, ferrous ions are oxidized to ferric ions Fe^{+3} and produced the more usual and stable reddish-brown corrosion product Fe_2O_3.[10, 23]

Another common product found during autopsy consisted of spots with a pasty, whitish matter deposited at several portions of bar surfaces. Usually, the whitish matter turned yellowish-brown, dull-brown, and orange-brown. The white pasty deposits have been identified in the literature as ferrous hydroxide $Fe(OH)_2$, which converts to magnetite.[23] These deposits were also seen in specimens examined after two years of exposure. In several cases, the whitish matter (usually combined with light-brown or yellowish-brown corrosion products) was deposited along a strip, giving the appearance of a solution trace. In other cases, whitish spots consisted of thinner films occupying large areas, having the appearance of a stain, perhaps remains of a solution. It would seem that such products traveled in a liquid solution through the bar-coating interface in an undercutting action.

Other corrosion products were deposited at random spots over the black corroded surface. Such products had varied colors; reddish-brown, light-brown, yellowish-brown, and orange-brown. These corrosion products have a higher state of oxidation than darker corrosion products. Oxidation of rust products require availability of oxygen, which was supposed to be limited beneath the coating. Two explanations are possible:

a) As undercutting progressed, the coating was debonded by deposition of rust products beneath the coating (oxide lifting). In addition to disbonding the coating, the buildup of rust may have eventually distressed the coating, resulting in pinholes, cracks, or thinning of the coating. Examination of bars after autopsy revealed that the coating at the most corroded areas was thinner than at less corroded portions. Some cracks in the coating were also observed at the most corroded areas. As more discontinuities developed in the coating, larger quantities of dissolved oxygen became available at the substrate, oxidizing portions of the black magnetite.

b) Coating on the bars was not immediately peeled after removal from the concrete, but about 24 hours later. Although the coating was not altered after bar retrieval from the concrete, the thinner coating was possibly more permeable to air and the bars may have been exposed to larger quantities of oxygen as compared to a more restricted oxygen environment inside the concrete. It is questionable how much oxygen could reach the substrate in a very short time.

A combination of cases (a) and (b) would seem more feasible. In any case, the presence of corrosion products with higher state of oxidation revealed a more advanced corrosion stage as compared to specimens examined after one and two years, where such products were not found.

Coating Blistering

Blisters are local regions where the coating has lost adhesion from the substrate and where water may accumulate and corrosion may begin. Most blisters may be formed by osmotic pressures from chloride solution. As water penetrates the coating to the interface, a concentrated solution is developed with sufficient osmotic force to drive water from the coating surface to the interface and a blister is formed.[133] A blister furnishes all the necessary elements for electrochemical corrosion: It provides a location for water accumulation, oxygen penetrates through the coating, and ionic materials leach from the interface or from the coating. The rate of corrosion appears to be controlled by the oxygen permeability of the coating.[133] The cathodic region is at the periphery of the blister and the anodic region is in the center of the blister where the oxygen concentration is low.[133]

Most blisters formed at the bottom side of bent zones of bars. As already mentioned, blisters were different sized and small blisters (up to 5 mm) were more abundant than large blisters (greater than 5 mm). As found in specimens examined after one and two years of exposure, a concrete void was always present adjacent to a blister in the coating (Fig. 8.61). Concrete voids provided an ideal environment for the formation of blisters, because chlorides, water and oxygen could be stored in those voids. Consequently, corrosion was particularly intense at bar locations facing concrete voids where corrosion products accumulated and increased in volume under the coating, eventually bulging or blistering the coating. The greater quantity of concrete voids at the lower half of the bar surfaces explains the prevalence of more blisters at those regions.

Unlike blisters observed after one and two years, most blistered areas had a very hard, solid consistency after 4.5 years of exposure. Several of the blisters observed after two years were soft and full of liquid and others were filled with black and brown brittle corrosion products.[10] Many blisters were associated with pitting. It may be possible that at very prolonged periods of exposure, the initially dissolved and brittle products solidified and hardened. As more corrosion products built up in the blister during wet periods, corrosion products were compacted during dry periods. As previously noted, examination of bar surfaces was conducted at least 24 hours after bars were retrieved from the concrete, and blisters may have dried during that period. However, 24 hours may not be long enough to turn a soft, brittle blister into a such a hard solid mound.

Fig. 8.61: Blisters always formed adjacent to concrete voids.

8.5.4 Concrete Environment

Influence of Concrete Consolidation

Quality and consolidation of the surrounding concrete were determinants in the corrosion performance of epoxy-coated bars. Upon examination of bar traces in concrete, surfaces above the epoxy-coated bars were smooth and glossy with a grayish-like appearance, the rib imprints were clearly defined, and the surface contained few voids. Concrete surfaces below the epoxy-coated bars had a chalky and porous appearance due to laitance, and more voids of different sizes were present.

The main factors causing differences in the texture of surrounding concrete above and below the bars have been thoroughly discussed by Kahhaleh.[10] Concrete above the bars is consolidated much better than concrete below the bars. During casting and consolidation, fresh concrete settles and air voids and bleed water rise to the top. Many of those air and water bubbles get trapped under the bars. When concrete cures and hardens, trapped water evaporates and air voids facing the bottom surface of the bars are permanently formed. In addition, settlement of concrete leaves a gap beneath the bars. The existence of a gap below the bars, along with less dense concrete and more voids, makes chlorides, water, and oxygen more easily accessible to the bottom surfaces of the bars than to the top surfaces, even though chlorides are penetrating from the top concrete surface. Concrete voids facing bar surfaces provide a physical space for the accumulation of chlorides and oxygen and the buildup and expansion of corrosion products, elements necessary for the formation of blisters.

Not coincidentally, more extensive rust staining and blistering were observed on the lower half of the bars than on the top. Concrete surfaces below the bars had more extensive rust staining and greater amounts of corrosion products than concrete surfaces above the bars (previous Fig. 8.43). The presence of laitance along the bottom bar trace in concrete was very probably the result of chemical reactions between the concrete and the acidic solution.

The influence of the concrete environment may help to explain why corrosion did not occur at the large exposed areas of bars 3A.3 (#4 bar, parallel ribs, damage > 6x6 mm) and 3A.7 (#4 bar, parallel ribs, damage <2%). As was already shown, the steel surface at such damaged spots preserved its original shiny and bright condition, without the slightest evidence of corrosion. The neighboring steel surface beneath the coating presented a mottled, glittery appearance with no evidence of corrosion attack or metal loss. Chloride content in the concrete at the level of the bars was 0.29% and 0.26% by weight of concrete for specimens 3A.3 and 3A.7, respectively. Although these values were below the average content of 0.34% by weight of concrete for all small bar specimens, they were still high enough to promote corrosion.

Concrete adjacent to damaged locations was examined and no evidence of concrete voids was found and the concrete was well consolidated. Apparently, dense concrete in close contact with the exposed areas effectively prevented the accumulation of chloride ions in great concentrations and severely restricted the access of water and oxygen, all necessary agents for corrosion initiation. In addition, the alkalinity of the cement paste maintained the protective oxide layer stable.

Observed corrosion in both bars occurred at zones away from exposed areas. In bar 3A.3, corrosion occurred at the outer side of the right bar leg close to the front face of the specimen. Coating was damaged at that location during fabrication (that spot was a point of restraint during bend fabrication). In specimen 3A.7, corrosion was observed at the lower portion of the inner bend. Coating was damaged at the transverse ribs during fabrication. In both cases, voids and porosity in the concrete were visible next to the corroded sites. Therefore, corrosion started at spots or sites that offered the most favorable conditions for corrosion initiation. In addition, the exposed areas at the outer bends may have been cathodically protected during the corrosion process. As previously discussed, mottled surfaces beneath debonded coating were very probably cathodic areas.

Influence of Initial Concrete Cracking

Cracks that follow the path of reinforcing bars have frequently been observed in concrete structures with epoxy-coated reinforcement.[15] Typically, such cracks are produced by shrinkage and plastic settlement of concrete and are developed during the early stages of curing. In addition, in a bond study of coated bars, flexural cracks were observed at every section containing a coated stirrup.[52] It was concluded that coated transverse reinforcement tends to act as a crack inducer. Also, crack widths were larger than those associated with uncoated bars. These types of cracks may be detrimental in aggressive environments because chlorides may access and reach the bars along their surface.

In the present study, plastic settlement cracks were observed on the top concrete surfaces of three specimens and, after about 2.5 years, the cracks propagated. Seven other specimens experienced cracking at different times of exposure, generally during the last 2.5 years of exposure. In total, eight specimens with larger bars and two specimens with smaller bars experienced cracking. Most cracks had a “U” shape following the line of the reinforcement and were located almost directly above the top bar. Crack widths were in the range of 0.08 mm to

0.20 mm. In comparison, none of the specimens examined after one and two years developed cracks during the course of the exposure, and in a few specimens, only the initial cracks due to plastic settlement with no further growth were observed.

Coated bars inside cracked specimens were among the most corroded. The only notable exception was specimen 1A.5, which suffered the worst corrosion among the specimens with small bars and yet did not experience concrete cracking. The good correlation between cracked concrete and corrosion damage seemed to indicate that cracks were caused by corrosion. Corrosion was more extensive in coated bars after 4.5 years than after 2 years. Most cracks were very narrow or hairline (about 0.08 mm wide) and no rust deposits or stains were observed inside the cracks. Corrosion-induced cracking in coated bar specimens was in an incipient stage at the end of 4.5 years of exposure. It would be expected that with longer periods of exposure, those cracks will allow a faster penetration of chlorides, water, and oxygen to the bar surface, further propagating the corrosion process.

8.5.5 Analysis of Study Variables

Uncoated vs. Coated Steel

Clearly, uncoated bars performed much worse than coated bars, as evidenced by monitored currents and potentials, and the observed condition of concrete and bars (Fig. 8.62). This is a very important fact that has to be kept in mind when evaluating epoxy-coated bars. Research by others[20, 22, 134] and results from this research clearly show that the epoxy-coating will not completely prevent corrosion of steel reinforcement. In fact, if chloride levels at the rebar level are high enough, corrosion of coated bars will be almost unavoidable. However, it is important to consider how extensive the corrosion damage would be if uncoated bars were used. None of the specimens with coated bars experienced extensive cracking, rust staining, delamination, and scaling of the concrete surface. The main purpose for using epoxy-coated bars is to improve performance of

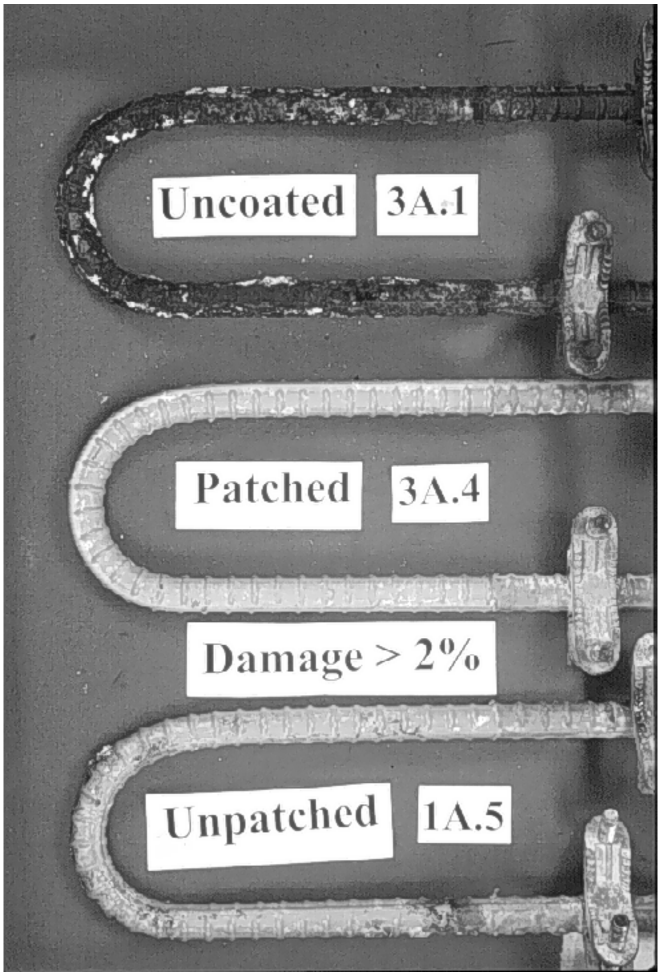


Fig. 8.62: Comparative performance of uncoated and coated bars after 4.5 years of exposure.

reinforced concrete infrastructure. Results from this study support the use of epoxy-coated bars over uncoated bars for concrete structures subjected to aggressive environments.

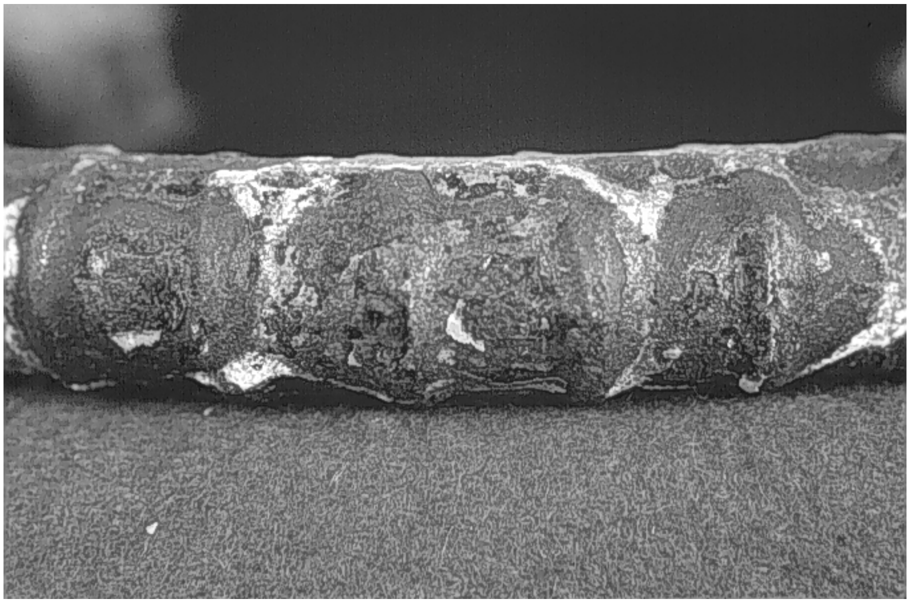
The coated specimen with largest metal loss as measured by charge flux experienced 43% of the charge flux of the respective uncoated bar after 4.5 years. This would mean that the worst performing coated bar was about 2.3 times better than the uncoated bar. The ratio for the worst performing coated bar after 2 years was 1.7. Comparison of performance ratios of all specimens after 2 and 4.5 years showed that almost half of the specimens performed better in a 4.5 year period than in 2 years. Although corrosion of coated bars increased from 2 to 4.5 years, uncoated bars experienced an even larger increase of corrosion activity and deterioration in the same period. From the experimental program alone, it is difficult to predict the probable service life of structures with epoxy-coated bars. Specimen design did not accurately reflect real field conditions. Some of the parameters were selected to accelerate corrosion. Concrete with high water/cement ratio and low concrete cover are not desirable characteristics. Finally, the performance reported herein corresponds to a coating formulation produced in the early 1990's and may not necessarily indicate how the most recent coatings would perform in similar conditions. Coatings produced in the late 1990's would be expected to have a better corrosion performance.

Effect of Coating Damage and Repair

Bars with damaged spots greater than 2% of the bar surface suffered the worst corrosion among coated specimens. With the remarkable exception of bar 3A.3, bars with damaged spots greater than 6x6 mm experienced similar levels of corrosion. In comparison, bars with patched damage experienced lower amounts of current, with the exception of bar 3A.4 (spots>6x6 mm, patched), that exhibited higher corrosion currents than the respective unpatched bar 3A.3. Despite displaying slightly lower currents, the steel surface of most bars with patched coating showed levels of corrosion similar to bars with exposed, damaged areas (Fig. 8.63). Corrosion products built up at exposed sites while only a very light rusting developed at patched areas. However, corrosion spread on the steel surface far beyond patched areas and was not dissimilar from the corrosion observed at bar surfaces beyond exposed areas. These observations were in good agreement with measured macrocell currents.

In general, corrosion in bars with exposed areas tended to be slightly more severe and corrosion in bars with repaired areas tended to be more widespread. Patching damaged areas on the outside of the bend only was not sufficient. Corrosion also propagated from mandrel indentations at the inside of the bend and at the outside of one straight leg (at point of support for bending operation). The only case where a bar with patched coating presented a substantially improved steel surface condition relative to a bar with exposed areas was provided by the small bars with parallel ribs and damaged spots greater than 2% of the bar surface.

(a) Patched bar 3B.2, outside bend.



(b) Bar 2B.3 with unpatched damage at outside bend.

Fig. 8.63: Comparative steel corrosion under the coating at outside bend of bars with damaged coating, with and without repair.

The presence of cracks in the coating may reduce performance of coated bars in the long term. The amount of metal consumption (charge flux) was very low for specimens examined after one and two years. Even for the specimens examined after 4.5 years, the amount of charge flux was very low during the first two years of exposure. However, a large increase in metal consumption occurred during the last 2.5 years of exposure. This suggests a slightly different corrosion mechanism than that observed for bars with larger exposed areas. A hypothesis for corrosion mechanism of bars with cracked coating will be formulated in a subsequent section.

Effect of Bar Size and Deformation Pattern

Both measured corrosion currents and examination of specimen conditions at the end of exposure clearly indicated that larger bars experienced more extensive and severe corrosion than smaller bars. Several factors may have contributed to the observed differences in behavior. Kahhaleh identified differences in the concrete environment surrounding the two different bar volumes as a significant factor.[10] Concrete consolidation around top bars is affected by the bar size. Formation of plastic settlement cracks and the concrete porosity and void structure are affected by variations in consolidation. Smaller and fewer voids were found around the #4 bars than around the #8 bars.

Another factor that has been identified in the literature to greatly affect corrosion performance is the ratio of concrete cover to bar diameter. Smaller ratios lead to worse performance. This ratio takes into account the importance of large concrete covers for adequate corrosion protection. The ratio to the bar diameter is intended to account for the scale factor. Specimens of both series A and B had the same concrete cover of 25 mm. The ratio of cover to bar diameter was therefore smaller for bars of larger size. In other words, for the same size of concrete cover, larger bars have greater chances of becoming more contaminated and more likely to be attacked by chlorides. Finally, discrepancies in the metallurgy between the two bar sizes may have contributed to the observed difference in behavior.

No clear trend was found in the performance of bars with different corrugation patterns. Among series A, bars with cross ribs tended to have larger average currents than bars with parallel ribs. Visual examination of autopsied specimens confirmed this trend. Among series B, though, bars with parallel ribs tended to show slightly higher average currents than bars with cross ribs. This trend could not be confirmed because the specimens with cross ribs were not autopsied for examination.

8.6 CORROSION MECHANISM

8.6.1 Macrocell Action on Uncoated Bars

A corrosion mechanism of uncoated bars after 2 years of exposure was earlier formulated by Kahhaleh[10] based on research findings by Clear and Virmani.[136] For specimens examined after 4.5 years, a similar mechanism is proposed but with some variants because there were some differences in the appearance of specimens with respect to those after 2 years of exposure. The observed differences in specimen condition after 2 and 4.5 years are as follows: a) Kahhaleh observed that uncoated specimens corroded more at their top sides than at the bottom after 2 years. However, after 4.5 years, more corrosion was observed at the bottom side than at the top. In both cases, more corrosion developed at the straight portions than on the bends. b) Cathodic bars in the specimens were free of corrosion after 2 years. In contrast, most cathodic bars experienced corrosion, with a few deep pits observed in some cathodic bars.

For the proposed corrosion mechanism, it can be reasonably assumed that the condition of uncoated bars after 2 years of exposure was the same shown by previous companion specimens examined after 2 years. As exposure continued, corrosion progressed until the uncoated bars showed the condition described after 4.5 years. Therefore, the mechanism for corrosion initiation and progression during the first half of the exposure is similar to that proposed earlier. Additional events occurred during the second half of the exposure and are incorporated in the proposed mechanism.

The proposed corrosion mechanism for uncoated bars is as follows: When a high enough level of chloride ions penetrated the concrete cover and reached the top uncoated bar, the pH of concrete at several locations lowered and the protective oxide film was broken. Corrosion micro-cells were thus initiated on the rebar surface. Such cells were primarily located at the straight portions of the bar, close to the front face of the specimen where bars project to the outside, possibly because of the larger availability of oxygen at those regions. Cathodic reactions were possibly supported at the bar surface adjacent to the concrete front face. The pH of the local anodes at the top bar was low (as evidenced by the presence of acidic solution) because of generation of hydrogen ions H^+ while the remaining surface maintained a relatively high pH because of the alkalinity provided by the concrete. This created an initial macrocell on the top bar that intensified metal dissolution at the anodes. Anodic areas were located mainly at straight portions and cathodic areas were located mainly at the bend.

The potentials of the micro-anodes decreased rapidly and reached very negative values, possibly more negative than -350 mV CSE. A large potential difference between the anodic sites and the cathodic steel at the bottom of the specimen set up a larger macrocell corrosion current between the two bar layers. Availability of both water and oxygen is necessary to support the cathodic reactions and to provide the electrolyte needed for developing a corrosion cell. Therefore, the large macrocell between top and bottom bar layers was possibly not triggered until after a few wet and dry cycles, when enough moisture penetrated inside the specimen and reached the bottom bars.

Corrosion progressed with periodic wet and dry cycles. Initially and during about the first 2 years, corrosion was more extensive at the top side of the bar because more chlorides reached and accumulated on the top sides earlier. Availability of oxygen made it possible for corrosion products to reach a higher state of oxidation, with the consequent volume increase that exerted a radial pressure against the concrete cover, causing early cracking. After cracking, greater amounts of chloride and oxygen reached the top bar, accelerating the corrosion process. As exposure continued, the greater porosity and void structure of the concrete under the top bar allowed a much greater accumulation of chlorides and corrosion progressed more extensively at the bottom surface, extending to the bent zone.

Between 2 and 4.5 years, chlorides continued to diffuse inside the concrete until they eventually reached the cathodic bars at the bottom of the specimen. When chloride concentration was large enough, corrosion started at the cathodic bars. Corrosion of “cathodic” bars occurred primarily on their side and bottom surfaces. When this happened, the originally simpler macrocell became a more complex corrosion process. The bars at the bottom were no longer purely cathodic and the measured current between top and bottom layers became inaccurate and should explain why the current readings in all control specimens became more erratic between 2.5 and 3.5 years of exposure.

To complicate matters, a macrocell effect among the bottom bars was observed: Usually, one of the bottom bars corroded much more than the others (in one specimen, one of the bottom bars did not show any corrosion). A complex system of corrosion cells remained, with anodic areas consisting of the straight portions and bent zone (lower side) of the top bar, plus the surface of a bottom bar with most corrosion. Cathodic areas were confined to the bent zone (top side) of the top bar, plus most of the surface (generally the upper half) of bottom bars with less or no corrosion.

Interestingly, a #4 bar with parallel ribs (3A.1) showed somewhat more severe and widespread corrosion than a #4 bar with cross ribs (3A.8). The opposite situation was expected because of the much higher average current density measured for #4 bar with cross ribs. When the bottom cathodic bars were examined, the corrosion in specimen 3A.8 was more extensive and severe than on the bar in specimen 3A.1. Undoubtedly, corrosion of bottom cathodic bars effected the macrocell currents measured.

A parallel but interrelated mechanism of deterioration was observed in control specimens. When corrosion-induced cracking propagated, chloride solution penetrated more easily and deeper towards the bottom parts of the specimen. Salt was deposited in capillary pores when water evaporated during the dry cycles. This created a concentration gradient because the remaining water close to crack surfaces had higher concentration of salt than water at the interior of the specimen. This gradient drove the salts in the water near crack surfaces towards the zones of lower concentration deeper inside. This transport process is called diffusion.[137] Upon re-wetting, additional chlorides penetrated capillary pores and diffused further in the next dry cycle.

Diffusion of chlorides in control specimens was greatly facilitated by the propagation and opening of cracks. The salt driven to the bottom parts of the specimen created another type of physical attack in the concrete. Salts in the form of crystals were left in the capillary pores when water evaporated during the dry cycles. Upon subsequent wetting, the crystals re-hydrated and grew, exerting an expanding force on the surrounding cement paste. The crystallization of salt in a zone having a free evaporation surface or to which the solution is raised by capillary forces results in destructive internal pressures that may crack and deteriorate the concrete.[128, 137, 138] It has been reported that moisture effects and salt crystallization are believed to be the two most damaging factors in the decay of historic stone monuments.[128]

The effect of disruptive forces by expansive hydrated crystals was visible in the lateral surfaces of the specimens in the form of concrete scaling. At scaled areas, the hardened cement paste and embedded fine aggregate particles were removed, leaving behind protruding coarse aggregate particles (Fig. 8.64). Large deposits of salt crystals were visible at scaled surfaces. The lateral surfaces with more extensively scaling were near the concrete cracks on the top surface, reinforcing the notion that cracks facilitated percolation of salts towards the inside. Both processes of salt weathering and corrosion-induced cracks interacted with each other to further propagate deterioration. Specimens with coated bars also experienced concrete scaling on their lateral surfaces, but the scaling was much less extensive and not severe. Undoubtedly, the lack of extensive concrete cracking greatly reduced the amount of salt weathering in specimens with coated bars.

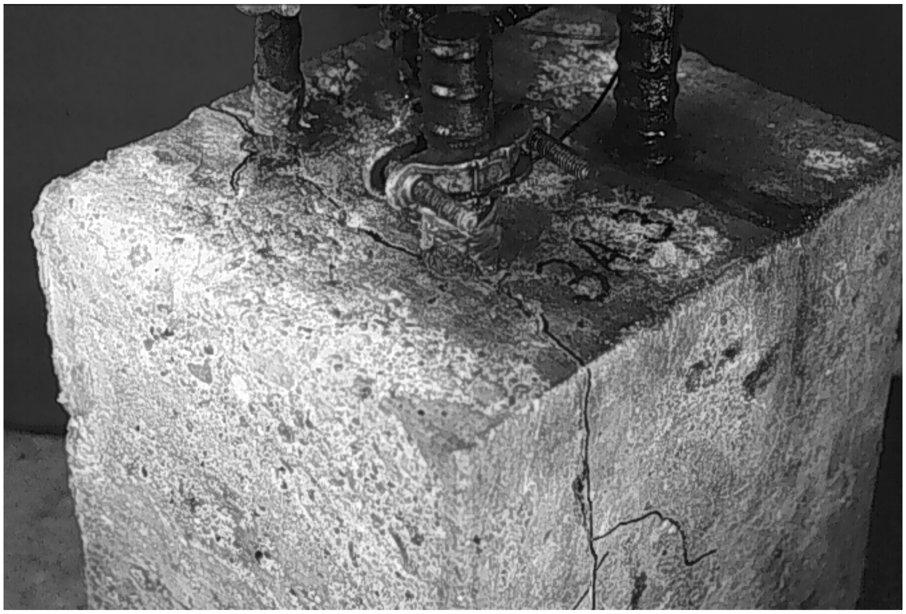


Fig. 8.64: Severe concrete scaling on specimen 3A.8 with uncoated bars.

8.6.2 Macrocell Action on Coated Bars

A corrosion mechanism of coated bars was construed by analyzing and comparing the corrosion progression of bars with varying degrees of corrosion. The earlier corrosion mechanism proposed by Kahhaleh[10] was taken into consideration but was adjusted to explain the particularities that occurred with the longer exposure. Corrosion started when enough chloride ions penetrated the concrete cover and reached the exposed areas (sites with damage or flaws in the coating) on the top coated bar to depassivate the steel. A porous concrete adjacent to or near exposed areas allowed for the accumulation of chlorides, oxygen, and water, all necessary agents for corrosion initiation. In contrast, exposed areas surrounded by very dense, well consolidated concrete (such as in bars 3A.3 and

3A.7) were free of corrosion. The limited areas available for corrosion initiation on the coated bars required higher levels of chloride accumulation to depassivate the steel as compared to uncoated bars.

The mechanism for corrosion initiation at local exposed areas or defects in the coating is illustrated in Fig. 8.65. Corrosion started at exposed areas, with anodes and cathodes developing locally, in a process similar to the Evans water drop experiment.[24] As corrosion progressed locally and the exposed area was covered by corrosion products, a self-polarization of the exposed area occurred. This induced a polarization in the opposite direction in the adjacent areas covered by the coating, and a cathodic reaction (with consequent cathodic disbondment) may take place at such areas.[78] Corrosion spread at the small crevices under the coating at the edges of exposed areas or discontinuities. Adjacent debonded coating (by cathodic disbondment, water action, or a combination of both) formed very thin crevices and corrosion propagated under the coating in a mechanism similar to that of crevice corrosion.

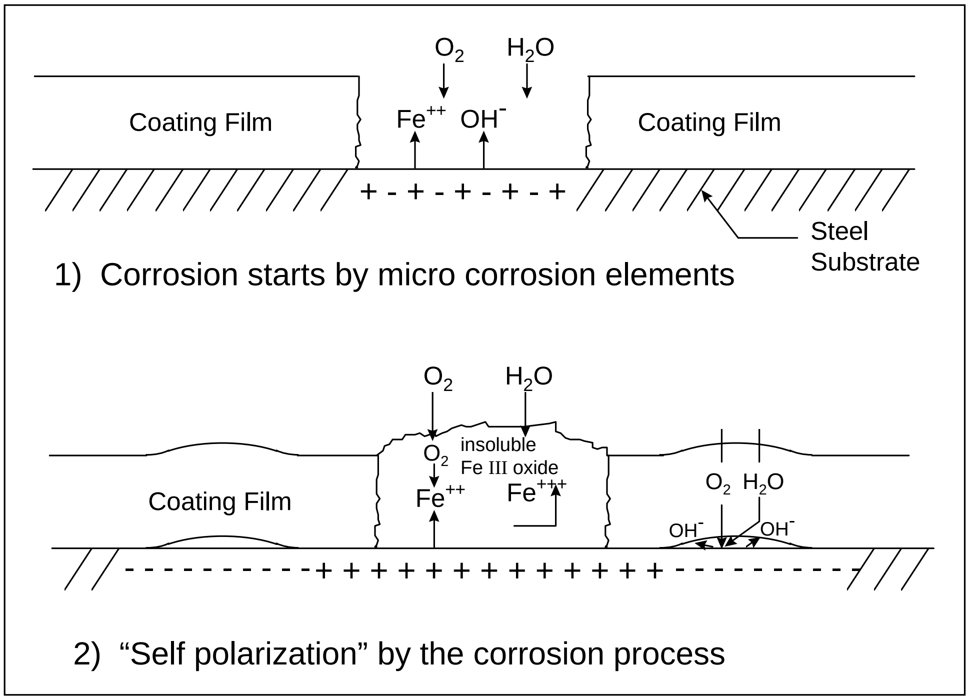


Fig. 8.65: Corrosion initiation mechanism in coated bars.[78]

Because of the presence of greater quantities of exposed or defective areas and weakened coating adhesion, corrosion generally started and was more extensive at the bent portion than at straight legs, as opposed to uncoated bars. The portions adjacent to the exposed sites (generally at the outer bends) were initially cathodic with respect to the primarily anodic exposed sites. The already marginally adhered coating at the bends was cathodically disbonded because of saponification of the coating produced by the alkalinity generated during the cathodic reaction. Cathodic disbondment extended beyond the bends into the straight portions of the bar. Coating adhesion may have also been lost by the moist environment and water action at the coating/substrate interface. Sometimes anode formation with cathodic disbondment started at a weaker spot in the straight portion, like in bar 3A.3, but the overall mechanism was the same. This hypothesis is based on experimental and field evidence that the substances causing coating disbondment migrate to the coating-substrate interface through coating defects rather than through the bulk of the coating (See Chapter 5, and references 18 and 20).

As already hinted before, the occurrence of cathodic disbondment at top bars indicated that cathodic and anodic reactions occurred on the same bar surface, forming a local corrosion cell. This seemed to indicate that the initiation process was characterized by self-polarization and occurred independently of any electrical coupling between coated and uncoated bars.[78] Cathodic reactions at the bottom bars would not be established until enough moisture reached the bottom bars (to provide the water necessary for oxygen reduction) and a large potential difference developed between the anodic sites at the top bar and the cathodic steel at the bottom of the specimen. Moisture also helped to reduce concrete resistivity, facilitating ionic flow between bar layers, thus causing the concrete to act as the electrolyte of the electrochemical macrocell.

Once a larger macrocell corrosion current between the two bar layers was set up, underfilm corrosion accelerated on the coated bar and oxide lifting took place. As already explained before, oxide lifting occurs when anodic corrosion products accumulate under the coating. The lifting action of compacted oxides and resultant undercutting occurred during alternate wet and dry cycles. In addition, disbonded coating facilitated migration of chloride solution to new locations under the coating. The pH at and near the anodic sites dropped to acidic levels due to hydrolysis of ferrous ion in chloride solution. The acid chloride solution promoted further anodic growth and dissolution. Undercutting progressed more extensively at the lower portion of the bars. The gap and void structure in the surrounding concrete allowed for a better travel, distribution, and accumulation of chloride solution and dissolved oxygen under the bars. Concrete voids provided the physical space for the expansion of corrosion products to form blisters. Corrosion in most bars spread from the outer and lower bends towards the inner bend and straight bar legs.

Typical corrosion products consisted of dissolved ferrous ion, Fe^{2+}, precipitated $Fe(OH)_2$, which partially oxidized to magnetite, Fe_3O_4, and perhaps an outer hydrated layer of fully oxidized FeOOH, which is common rust. Limited availability of oxygen beneath the coating caused most corrosion products to be in a low oxidation state. This accounted for the predominance of magnetite, which is the uniformly black corrosion product observed at the corroded surfaces, and for the smaller amounts of reddish-brown and other brownish corrosion products. Black corrosion products thinly spread and frequent accumulation of low pH, chloride rich liquid under the epoxy coating has also been found by other researchers.[20, 134] The slight volume increase and rust accumulation in some bars caused incipient concrete cracking (very fine, narrow cracks) in several specimens, or the opening and growth of plastic settlement cracks. Nevertheless, severity of concrete deterioration and width of cracks was much lower for coated bar specimens than for control specimens. Likewise, measured and observed corrosion activity on coated bars was below the level found on uncoated steel.

Corrosion mechanism in bars with cracked coating

As already noted, specimens with cracked coating showed very little activity during the first two years but much larger corrosion currents during the last 2.5 years of exposure. Examination of companion triplicates after 2 years showed either very minor (#8 bar) or no apparent corrosion (#4 bar). The last triplicates showed more extensive and uniform corrosion after 4.5 years of exposure. The presence of narrow cracks seemed to delay corrosion initiation and the corrosion rate remained low during the first two years compared to other types of damaged and exposed areas. These observations may suggest that a slightly different corrosion mechanism takes place for bars with cracked coating.

The following mechanism may have occurred: Coating cracks are very narrow and expose limited areas that required a longer time to develop a high enough chloride concentration for corrosion initiation. Corrosion started at about 1.5 years for bar 2A.6 and at about 2 years for bar 2B.6, with chloride concentrations at the level of the steel of about 0.15% and 0.19% by weight of concrete, respectively, as measured at companion concrete prisms. During this "incubation" time, chloride solution may have penetrated under the coating through the cracks and other damaged areas (such as mandrel indentations at the inner bends) as easily as through the larger exposed areas at other bars, as evidenced by the presence of trapped acidic solution in the bars after 4.5 years. Considering that the cracks indicated failure of the coating to pass the bend test, coating adhesion was presumably so weak that the process of solution penetration under the coating was greatly facilitated. Water penetration caused further loss of adhesion, which was as extensive as in other bars.

Corrosion activity was limited during the first 1.5 to 2 years of exposure because of the very small anodic surfaces. Corrosion progressed slowly under the coating crevices formed at the edges of the cracks, in a mechanism similar to that explained above. No macrocell action was yet established, and anodes and cathodes were formed on the same bar. At some point between 1.5 and 2 years, polarization at anodic areas on the top bar was sufficiently large to develop a larger macrocell action with the bottom bars. Corrosion accelerated rapidly thereafter aided by the macrocell action and the availability of chloride solution at the metal/coating interface.

Corrosion of cathodic bars

The bottom cathodic bars of a few specimens with top coated bars were mostly free of corrosion, as opposed to bottom cathodic bars from specimens with top uncoated bars. This finding was somewhat puzzling because it implied that the type of bar in the top layer affected the behavior of the bar at the bottom layer. Chloride contents at the level of the bottom bar were not directly measured. Chloride contents measured at the deepest levels (3.25 in) were similar for these specimens, so it is very likely that chloride contents at the level of the bottom bars were also similar for specimens with both coated and uncoated top bars. No explanation of this phenomenon was found in the literature but some hypotheses can be formulated:

1. When both top and bottom bars are uncoated and enough chlorides reach the bottom bars, the electrically continuous top and bottom layers may become a complex corrosion system. Macrocell currents may reverse and start to flow from bottom to top, making the bottom bars more anodic than the top bars. If enough chlorides reached the bottom bars in specimens with coated bars at the top layer, a possible reversal of macrocell current would be severely limited by the dielectric properties of the coating, presenting a path of high electrical resistivity for the top bars to become an effective cathode. This phenomenon could not be verified, though, because no reversal or change in sign was observed in the measured currents of control specimens.

2. The concrete in the specimens with uncoated bars experienced much greater deterioration than concrete in specimens with coated bars. The combined action of cracking and salt crystallization created a general state of distress that allowed greater percolation of chloride solution, which in turn worsened concrete deterioration. In contrast, concrete in specimens with coated bars was much less distressed and cracked. As a result, the concrete was dryer and maintained higher resistivity compared with concrete in specimens with uncoated bars.

Although the mechanism is uncertain, it seems that a twofold advantage was gained with the use of coated bars. Both top and bottom bars underwent less corrosion, even if only the top bar was coated. However, it would not be recommended to rely on top coated bars for corrosion protection of uncoated bottom bars in the field. Macrocell specimens did not accurately resemble real field conditions. The top and bottom bars in the specimens were electrically continuous, a condition that may not be present or certain in the field.

8.7 SUMMARY AND CONCLUSIONS

8.7.1 Summary

Macrocell corrosion experiments were used to study the performance of fabricated epoxy-coated bars damaged to various levels. Triplicate concrete prisms were built and each specimen had a fabricated coated bar in the top layer which was electrically connected to uncoated bars in the bottom layer. Chlorides intruded from the top surfaces in cyclic exposures up to a 4.5 year period. Time development of corrosion and corrosion currents were monitored and specimens were opened for examination of the bar condition after 1, 2, and 4.5 years. Results of autopsies performed after 1 and 2 years were reported elsewhere.[10] Results of autopsy from last replicate specimens after 4.5 years of exposure were reported in detail in this Dissertation.

8.7.2 Conclusions

The main conclusions of this study are summarized and grouped in the following categories:

Effectiveness of Epoxy Coated Reinforcement

Regardless of coating condition, coated bars performed much better than uncoated bars. Based on the measured charge flux, the worst coated bar performed about 2.3 times better than an uncoated bar (Fig. 8.58). None of the specimens with coated bars experienced extensive cracking, rust staining, delamination, and scaling of the concrete surface. Epoxy-coated bars can be effective in preventing deterioration of concrete infrastructure subjected to aggressive environments. Although corrosion of coated bars increased between 2 and 4.5 years of exposure, uncoated bars experienced an even larger increase of corrosion activity and deterioration in the same period. Corrosion currents in most specimens with coated bars were not increasing and seemed to have reached a steady-state after 4.5 years of accelerated exposure. The test results do not permit prediction of the probable service life of structures with epoxy-coated bars.

Several factors contributed to the improved performance of epoxy-coated bars. The coating delayed the initiation of corrosion and corrosion started at higher levels of chlorides compared with uncoated steel. The number of anodic areas was initially reduced by the presence of the coating. The dielectric properties of the coating offered a path of high electrical resistivity between the anode and the bottom cathode, thereby reducing the rate of corrosion. The coating limited the availability of dissolved oxygen and kept a large portion of corrosion products in a low state of oxidation, thus reducing the severity of corrosion. The lower distress in the concrete in specimens with uncoated bars slowed chloride penetration and diffusion, and preserved a denser and drier concrete with high electrical resistivity.

Effect of Coating Damage and Repair

Bars with greater and more frequent damage tended to perform worse. Patching coating damage slightly reduced but did not prevent corrosion in most specimens. Corrosion in bars with exposed areas tended to be slightly more severe and corrosion in bars with repaired areas tended to be more widespread. Patching damaged areas on the outside of the bend only was not sufficient, because corrosion also propagated from mandrel indentations at the inside of the bend and at the outside of one straight leg. Bars with coating cracks and exposed areas less than 1% experienced increasingly higher corrosion currents at the end of 4.5 years while other damaged bars seemed to have reached steady-state behavior.

The above conclusions are valid for the type of patching material tested. However, as was demonstrated in Chapter 5, different patching materials perform differently. The patching material used for the macrocell study had a very thin consistency and in fact, its production has been discontinued since the study started. The conclusions may have been different if other repair materials had been used.

Effects of Bar Size and Deformation Pattern

Larger bars experienced higher corrosion than smaller bars. Possible factors included differences in the concrete environment caused by the bar size, influence of concrete cover to bar diameter ratio, and discrepancies in the metallurgy between the two bar sizes. No clear trend was found in the performance of bars with different corrugation patterns.

Effects of Concrete Environment

Quality and consolidation of the surrounding concrete was a factor in the corrosion processes of epoxy-coated bars. More corrosion was observed at the bottom side of coated bars than at the top sides because the adjacent concrete was more porous with more and larger voids, was not well adhered, and was less dense than concrete above the bars. Consequently, chlorides, water, and oxygen were more easily accessible to the bottom surfaces of the bars, even though chlorides were penetrating from the top concrete surface. In two bars, exposed areas in contact with dense concrete did not corrode at all.

Cracks produced by shrinkage and plastic settlement have the adverse effect of allowing chloride penetration directly to the bar surface. Incipient corrosion-induced cracks in coated bar specimens generally propagated from shrinkage and plastic settlement cracks. Coated bars inside cracked specimens were among the most corroded.

Corrosion Mechanism

Corrosion started when enough chlorides penetrated the concrete cover and reached the exposed areas on the top coated bar to depassivate the steel. Corrosion spread at the small crevices under the coating at the edges of exposed areas or discontinuities. Adjacent debonded coating (by cathodic disbondment, water action, or a combination of both) formed very thin crevices and corrosion propagated under the coating in a mechanism similar to that of crevice corrosion. The corrosion initiation process was characterized by self-polarization and occurred independently of any electrical coupling between coated and uncoated bars. A macrocell effect was established at more advanced stages of corrosion, when a large potential difference developed between top and bottom bar layers, and enough moisture penetrated the specimen to sustain cathodic reactions at the bottom layer and to reduce concrete resistivity. When the macrocell current between the two bar layers was sufficiently large, corrosion products built up at exposed areas, underfilm corrosion accelerated on the coated bar, and oxide lifting took place. Undercutting progressed more extensively at the lower portion of the bars. Corrosion in most bars spread from the outer and lower bends towards the inner bend and straight bar legs.

Regardless of the level of corrosion, the epoxy coating extensively debonded from the steel substrate. Black corrosion products (magnetite) uniformly spread over the bar surface along with other corrosion products in lower amounts, and accumulation of low pH, chloride rich liquid were typically found under the epoxy coating. Limited availability of oxygen beneath the coating caused most corrosion products to be in a low oxidation state. The slight volume increase and rust accumulation in some bars caused incipient concrete cracking (very fine, narrow cracks) in several specimens.

Chapter 9. Beam Corrosion Study

9.1 GENERAL

Epoxy coated reinforcement has been used in concrete structures exposed to marine environments. Marine environments are particularly aggressive. Structures in such environments are exposed to water rich in salts, with sodium chloride as the main component. Sea water attacks concrete structures in several ways. Chlorides that penetrate the concrete may cause corrosion of the steel reinforcement, and subsequent spalling, delamination, and cracking. In warm climates, the high temperatures accelerate the corrosion process, and in cold climates, the combined action of freezing and corrosion are detrimental to the durability of the structures.

Corrosion of reinforcement is not the only mechanism of deterioration. As explained in Chapter 8, salts that penetrate capillary voids inside the concrete crystallize when water evaporates during prolonged dry cycles. Crystallized salts expand and exert large pressures that may lead to concrete scaling and cracking. This phenomenon occurs particularly at surfaces exposed to evaporation while other sides are wetted. Other forms of sea water attack occur in the form of chemical action of sea water constituents on cement hydration products, alkali-aggregate reaction, frost action in cold weather, and physical erosion due to wave action and floating objects.[128]

Marine and offshore structures are more vulnerable to corrosion at the tidal zone. Structural components (piles, foundations) submerged at deeper layers inside the ocean are much less susceptible to corrosion attack. The reason for this phenomenon is that oxygen is very scarce at greater depths inside the water. The tidal zone, however, is a very critical area of the structure in terms of durability. Such a zone, which may be a few meters in length, is wet during high tides and dry during low tides.

Exposure to wet and dry cycles in a saline media constitutes a very harsh condition, especially if the dry periods are relatively long and the wet periods are relatively short. During wet cycles, saline water penetrates the concrete through capillary voids. At subsequent dry cycles, water evaporates and leaves chlorides inside the capillary voids in solution with the remaining water. Since chlorides in solution are more concentrated closer to the surface where more water evaporates, a concentration gradient develops between concrete at the surface and concrete deeper inside the member. This gradient drives the chlorides from the surface into the concrete during the dry cycles. This process is called diffusion. The longer the dry cycles compared to the wet cycles, the greater the gradient (because more water evaporates), and the greater the diffusion.[137]

Once enough chlorides are driven by exposure to wet and dry cycles in the tidal zone, corrosion of reinforcement initiates and may be aggravated by a macrocell effect if there is electrical continuity of reinforcement between the tidal zone and the higher portions of the structure. The tidal zone has the highest concentration of chlorides and moisture and becomes primarily anodic, while higher portions of the structure have less chlorides and moisture but plenty of oxygen and become cathodic. Macrocell action of concrete column specimens in a simulated marine environment has been monitored in corrosion studies.[65]

Portions of the structure higher above the sea level are less severely attacked than the tidal zone. Although oxygen is abundant in those areas, the availability of chlorides in solution is limited. Nevertheless, portions above the sea level are more prone to corrosion than portions deeper below the sea level because chlorides are usually available through sea mist or spray.

Another corrosion deterioration process is that of bridge substructures and parking structures in northern environments. Deicing salts that are applied on the top surface of bridge decks may run off and leak trough joints or cracks and cause corrosion of substructure members (beams, caps, and piers). A similar process may occur in parking structures, where water or snow containing deicing salts is carried in on the undersides of vehicles. In addition, the edges of an open parking structure may be subject to ambient weather conditions. Runoff from the roof and floors may leak trough joints or cracks to contaminate and corrode structural members (slabs, beams, columns, walls, ramps, etc.). Macro corrosion cells of bridge substructure or parking structure members may be produced by differences in chloride concentrations and/or moisture content at several portions of the member.

Performance of a structure in a corrosive environment may be affected by the presence of cracks and loading condition. Concrete structures are expected to crack during their service life. Cracks may aggravate corrosion because chlorides, water, and oxygen may penetrate inside the concrete through cracks. As discussed in Chapter 8, structures with epoxy-coated reinforcement are particularly prone to crack at locations of coated transverse reinforcement, and cracks are usually wider than those occurring on structures with uncoated bars.[52] Some researchers found that corrosion increased with the increase in crack width.[139] However, there has been a continuing debate about the effects of cracks on corrosion of reinforcement. Some researchers assert that corrosion is localized at cracks and that the presence of narrow cracks (less than 0.3 mm wide) have little effect on the long-term corrosion performance of the structure.[36] In another research, uncoated bars in cracked concrete started to corrode soon after application of deicers, and crack width did not significantly change the rate of corrosion damage.[140] Others worry that designing for crack control leads to members with reduced concrete cover, making them more vulnerable to chloride diffusion. Whether corrosion leads to cracking, or cracking precedes corrosion has also been controversial.[35]

Regarding the loading condition, it was reported that subjecting test members to cyclic loading during exposure to salt solution resulted in minor chipping and flaking of the coating on bar deformations.[54] Stressed areas of the steel tend to become more anodic in the presence of chlorides at the damaged sites in the coating.[10] The effects of structural loading on inducing damage to the coating need to be investigated.

9.2 OBJECTIVES AND TEST CONCEPT

An experimental program was set up with the following objectives:

- Study the corrosion behavior of epoxy-coated bars with different degrees of damage in a exposure resembling a marine environment or runoff of deicing chemicals.
- Analyze the effect of flexural cracks and loading on the performance of epoxy coated bars.
- Determine if periodic application of cyclic loads effects corrosion performance.

To achieve these objectives, beams with separate arrangements of straight, bent, and spliced coated bars were tested. The beams were designed to simulate cracked, loaded concrete members exposed to very corrosive environments. A schematic view showing the test concept is shown in Fig. 9.1. During periodic cycles of loading and unloading, cracks are opened and closed, creating a mechanical action that pumps chloride solution (during wet periods) and oxygen (during dry periods) towards the reinforcement (Fig. 9.1).

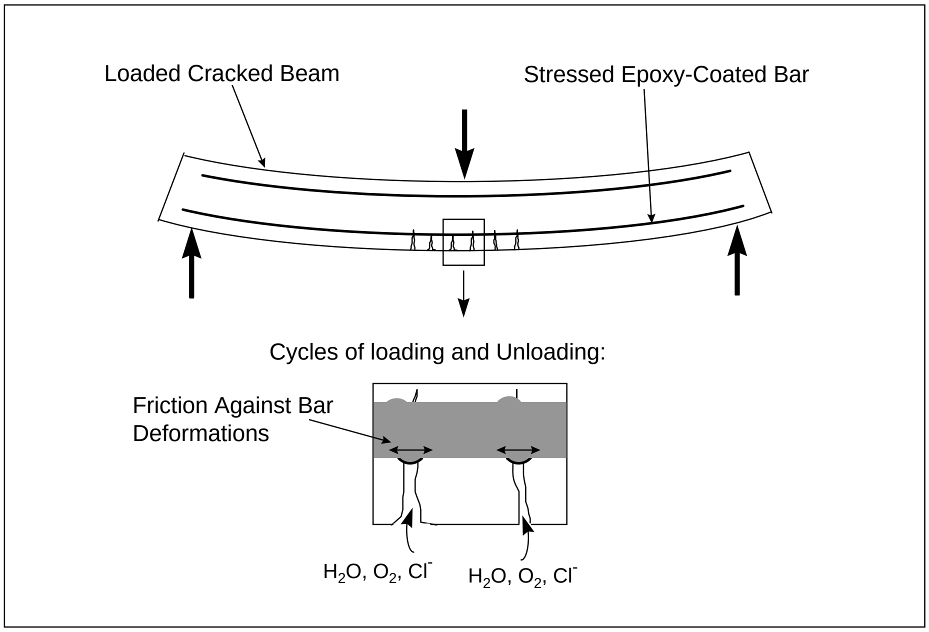


Figure 9.1: Concept of Beam Exposure Test.

Electrically isolated bars with various levels of coating damage were used in the specimens. The intention was to study field conditions where epoxy-coated bars are properly placed and assembled to avoid incidental electrical continuity. Isolated epoxy-coated bars may be susceptible to corrosion by local heterogeneities in the surrounding concrete and in the epoxy and steel surface condition that exist along the rebar.

The performance of coated fabricated bars, such as stirrups or ties, was also studied in the beam exposure experiment. Coated fabricated bars may be vulnerable to corrosion attack for several reasons. A coated stirrup generally performs as a crack inducer in a flexural member. Therefore, coated stirrups lie within the crack plane. The stirrup is also the closest part of the reinforcement to the concrete surface exposed to chlorides. Because the stirrup is fabricated after coating, adhesion may be marginal when chlorides arrive at the stirrup. The coating may be damaged during fabrication and patching may not be effective, as was already shown in Chapter 6. A stirrup may be the most vulnerable epoxy-coated component.

The performance of spliced coated bars at high moment regions was also investigated. At these regions, the cut end of one of the spliced bars is close to the cracks that develop under high moments. As shown in Chapter 6, repaired cut ends are very vulnerable to corrosion, which may spread beneath the coating along the bar. In the beam specimen, a stirrup was located close to the cut end of a spliced bar to induce the formation of a crack near the end of the bar.

Finally, the performance of bars where no attempt was made to isolate them from the rest of the coated reinforcement was investigated. From Chapter 8, it was shown that any incidental continuity between different layers of reinforcement may lead to macrocell corrosion. The two layers of longitudinal bars were not intentionally connected, so any incidental electrical continuity would represent a more realistic field condition.

9.3 TEST SETUP AND PROCEDURE

Thirty-four beam specimens were included in the test program. Beams were divided into three groups: Longitudinal bars, stirrups, and spliced bars with stirrups. Description of test variables, steel preparation, material characteristics, specimen design and preparation, test setup, monitoring, and post-mortem examination procedure are described in detail in reference 10. Some of the main features of the test setup and procedure are repeated here for clarity. The test variables were as follows:

Coating Damage

- Longitudinal bars in their “as received” condition, with no visible damage.
- Longitudinal bars with 3% damage of the bar surface area, with or without patching. The introduced coating damage was confined to the middle 3 feet length of the bar.
- Stirrups in as received condition with or without patching the ends.
- Stirrups with 3% damage of the bar surface with damage patched. The introduced coating damage was limited to the outer bends of the stirrup.
- Spliced bars with patched ends.

Loading Condition

- Uncracked Unloaded: No cracks or imposed loads during exposure.
- Cracked Unloaded: The beams were loaded to produce cracks with maximum width of 0.33 mm (0.013 in). The load was removed during exposure.
- Cracked Loaded: The beams were loaded to produce cracks of 0.33 mm (0.013 in) width. The load was maintained during exposure.

The crack width selected was based on ACI 318-89 crack limits for exterior exposure.

The beams were designed with a top layer of two #3 uncoated bars and a bottom layer of two #6 coated bars. The stirrups were #3 coated bars with 135° hooks. The epoxy coating material used for the bars in the beams was produced in the early 1990’s but was newer than that used in the bars for the macrocell study. As in the macrocell study, test results reported herein may not necessarily reflect the potential performance of epoxy coatings developed in the late 1990’s. The dimensions of the beam cross-section were 8 x 12 inches (0.2 x 0.3 m) as shown in Fig. 9.2. The concrete cover to reinforcement was 2 inches (50 mm) on all sides. The length of the beam was about 9.5 feet (2.9 m). As was the case for macrocells, a water-cement ratio of 0.57 was used to make the concrete more permeable to the corrosive solution.

The details of the three groups of beams are illustrated in Figures 9.3, 9.4, and 9.5. In group I (Fig. 9.3), the bottom coated bars were tested and monitored. To accomplish that, the bars were completely isolated from contact with any other metal. A coated stirrup was placed at midspan of the beam as a crack inducer. The

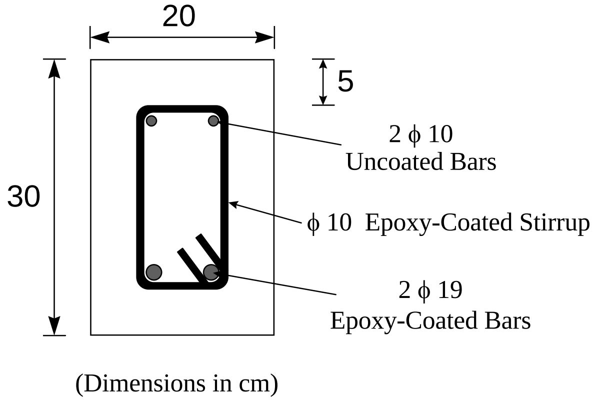
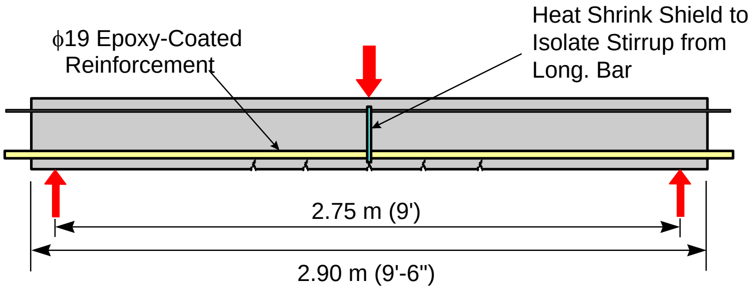


Figure 9.2: Dimensions of beam cross section.

LONGITUDINAL BARS	UNCRACKED UNLOADED	CRACKED UNLOADED	CRACKED LOADED^a
AS RECEIVED^b	B1, B2	B3, B4	B5, B6
3 % DAMAGE NOT PATCHED	B7, B8	B9, B10	B11, B12
3 % DAMAGE PATCHED		B13, B14	

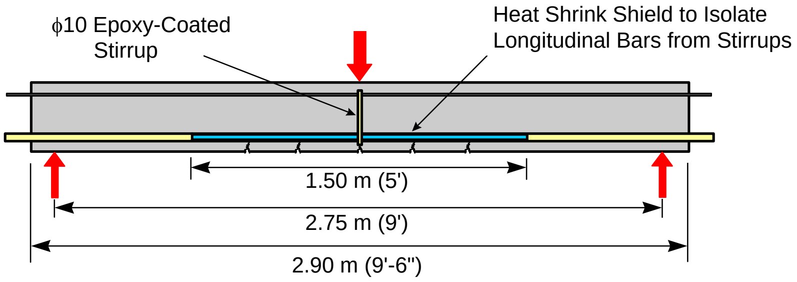


Underlined specimens exposed for 4.3 years

a Imposed loads causing bending about strong axis and to open cracks to 0.33 mm.
b No visible damage

Figure 9.3: Details of group I beam specimen.

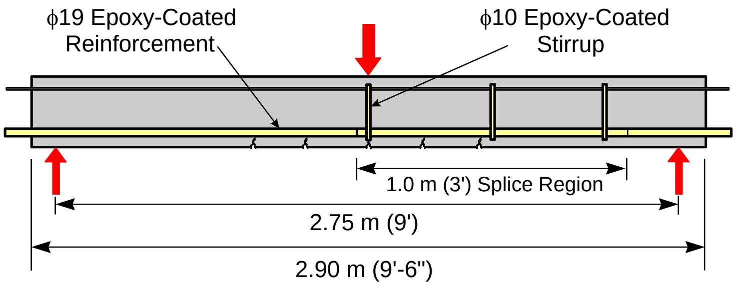
STIRRUPS	UNCRACKED UNLOADED	CRACKED UNLOADED	CRACKED LOADED^a
AS RECEIVED (NOT PATCHED)^c	B15, B16	B17, B18	B19, B20
AS RECEIVED (PATCHED)	B21, B22	B23, B24	B25, B26
3 % DAMAGE (PATCHED)		B27, B28	



Underlined specimens exposed for 4.3 years

Figure 9.4: Details of group II beam specimen.

LONGITUDINAL BARS AND STIRRUPS	CRACKED UNLOADED	CRACKED LOADED[a]
BOTH , 3 % DAMAGE (PATCHED)	B29, B30	
CUT ENDS FOR SPLICE , 3 % DAMAGE FOR STIRRUP, PATCHED	B31, B32	B33, B34



Underlined specimens exposed for 4.3 years

a Imposed loads causing bending about strong axis and to open cracks to 0.33 mm.

c No patch on bends

Figure 9.5: Details of group III beam specimen.

stirrup was encased in a heat shrink tube to avoid any electrical contact between the stirrup and longitudinal bars. In group II (Fig. 9.4), the coated stirrups were tested and monitored. The bottom longitudinal bars were encased in heat shrink tubes to isolate them from the single stirrup at midspan of the beam. No similar precaution was introduced for the top reinforcement at the location of the stirrup. In group III (Fig. 9.5), both longitudinal bars and stirrups were tested and monitored, including two beams with spliced bars. No attempt was made to isolate the straight bars from the stirrups. The coated longitudinal bars and stirrup were tied with plastic-covered wire. In beams with spliced bars, the bar ends of the shorter spliced bar are at the midspan of the beam. Three stirrups were provided within the spliced zone with one stirrup about 2 inches (50 mm) from the end of the splice in the middle of the beam.

There were two replicate specimens for each test condition. The two replicates were stressed back to back with the beams laying on one of their lateral sides, as shown in Fig. 9.6. A view of the test setup and the loading process are shown in Fig. 9.7 and 9.8. The beams were loaded so that the two longitudinal coated bars were on the tension side and the two uncoated bars were on the compression side of the beams.

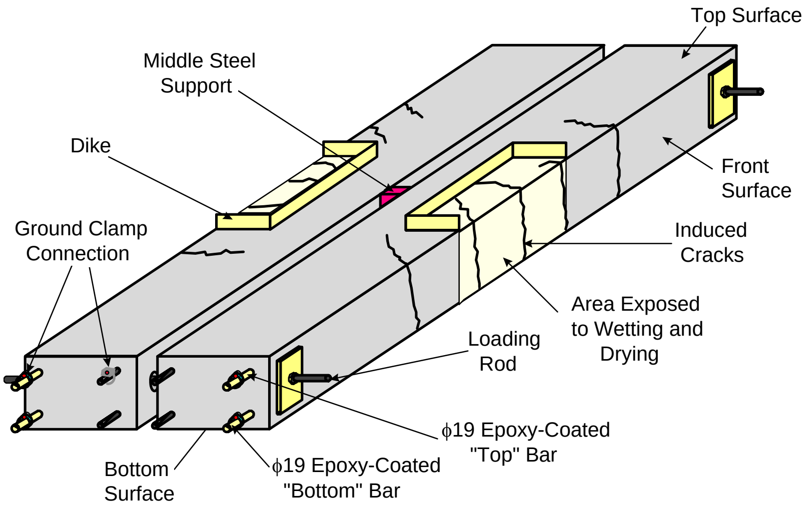


Figure 9.6: Model of beam exposure test specimens.

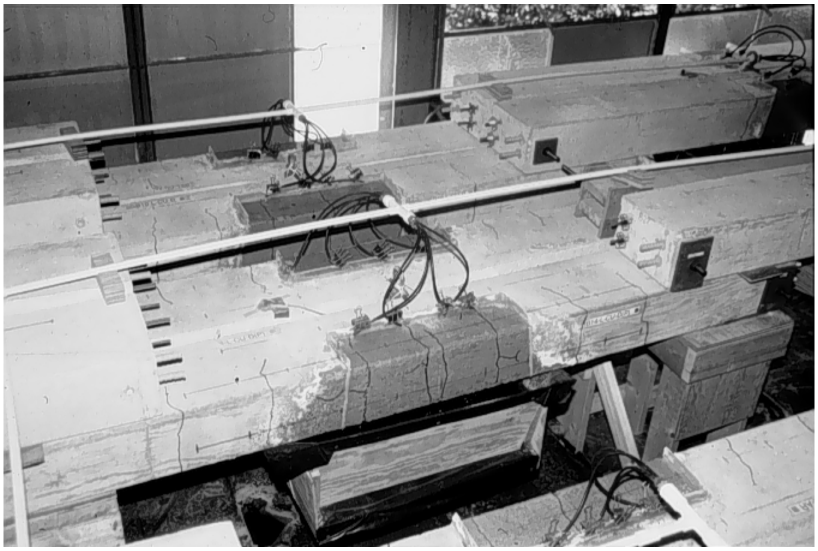


Figure 9.7: Overview of test setup.

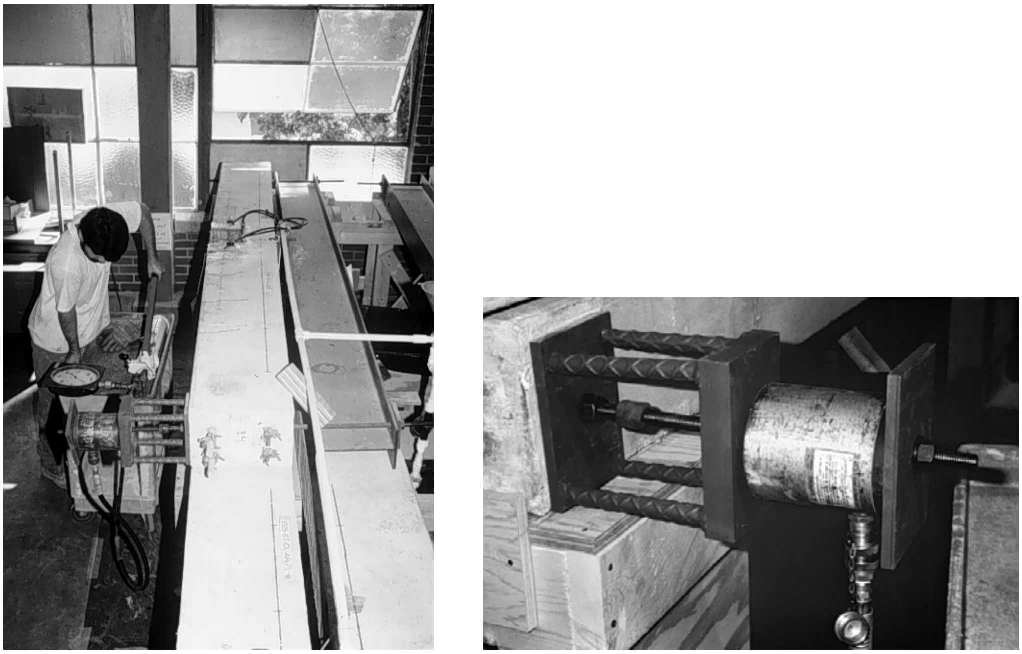


Figure 9.8: Loading process of beams.

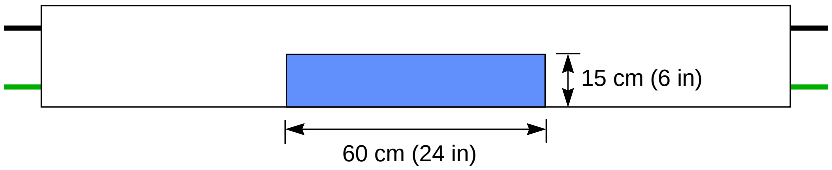
The exposure testing consisted on irrigating a portion of the beam surfaces with 3.5% NaCl solution (Fig. 9.7). The beams laid on one of their lateral sides throughout the exposure. Unless otherwise noted, the convention for identifying location of bars and beam surfaces was based on the position of the beams during the exposure (Fig. 9.6). Top or upper refers to the beam lateral surface facing upwards, where solution was directly irrigated onto. Bottom or lower refers to the opposite lateral surface facing downwards, where solution dripped down. Front surfaces were those on the tension side of the beam, where solution flowed down from the top surface. Back surfaces were the opposite surfaces on the compression side of the beams. Similarly, top or upper bars are those closer to the top surface, and bottom or lower bars are those closer to the bottom surface.

The label system to identify each beam had the following notation: B(beam number)-(type of monitored bar)-(crack and loading condition)-(coating condition). Each test variable was labeled as follows:

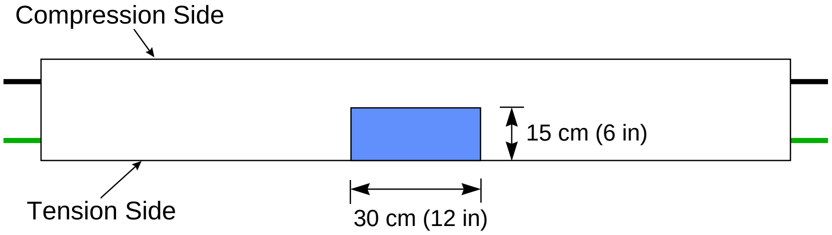
- *Beam number:* From 1 through 34
- *Type of monitored bar:* L (longitudinal bar), ST (stirrup), and SP (splice bar). [Note.- In beams with splice bars, stirrups were monitored too]
- *Crack and loading condition:* UU (uncracked, unloaded), CU (cracked, unloaded), and CL (cracked, loaded).
- *Coating condition:* AR (as-received), AR(P) [as-received and patched], D (3% damaged), and D(P) [3% damaged and patched].

For instance, the label B1-L-UU-AR represents beam number 1 where the longitudinal coated bars were monitored, the beam was uncracked and unloaded, and the coating was in its as-received condition. The label B27-ST-CU-D(P) represents beam number 27 where the coated stirrup was monitored, the beam was cracked and unloaded, and the coating had 3% damage but was patched.

Exposure cycles consisted of 3 days of continuous irrigation followed by 11 days of air drying, to complete a 14-day wet-dry cycle. The exposed area on the top surface was defined by a 6x24 in. (15x60 cm) rectangular area in beams where longitudinal bars were monitored, and by a 6x12 in. (15x30 cm) rectangular area in beams where stirrups or splices were monitored (Fig. 9.9). Exposed areas were at the middle of the beam, on the half portion close to the tension side of the beams, directly above the coated bars. Acrylic dikes 1.5 in. (38 mm) high were mounted with silicone around the exposed area to confine the irrigating solution. Salt solution flowed from the top surface down the adjacent vertical surface (tension side) and around to the bottom surface. Silicone was applied to form small dams along the borders of the irrigated area on the vertical front surface and on the bottom surface 6 in. (15 cm) from the edge.



(a) Group I Beams



(b) Groups II and III Beams

Figure 9.9: Dimensions of wetted region of beams.

The cracked beams were subjected to cycles of loading and unloading every seven days during days 2 and 9 of the 14-day cycle: In this manner, cyclic loads were applied one time during wetting and one time during drying. Five load cycles were imposed up to a level producing the selected maximum crack width. Figure 9.8 shows the process of loading the beams.

Corrosion activity in the beams was monitored by measuring the corrosion potentials periodically against a saturated calomel reference electrode (SCE). Fig. 9.10 shows the procedure for taking the potential measurements. Measurements were made by connecting the reinforcing bar to the positive terminal of a pH meter and the reference electrode to the negative terminal. The values were recorded to the nearest multiple of 5 mV. A damp sponge was secured around the tip of the electrode to improve conductivity. Measurement procedures were in accordance with ASTM C876.[141] At first, measurements were made at the end of each wetting period. After the fourth cycle, measurements were taken at the completion of every two wetting periods. Good conductivity was achieved when the concrete was still damp during the measurements. To improve concrete conductivity in the dry portions of the beam, a wetting solution (water and detergent) was used to pre-wet all points of measurement before taking the readings.

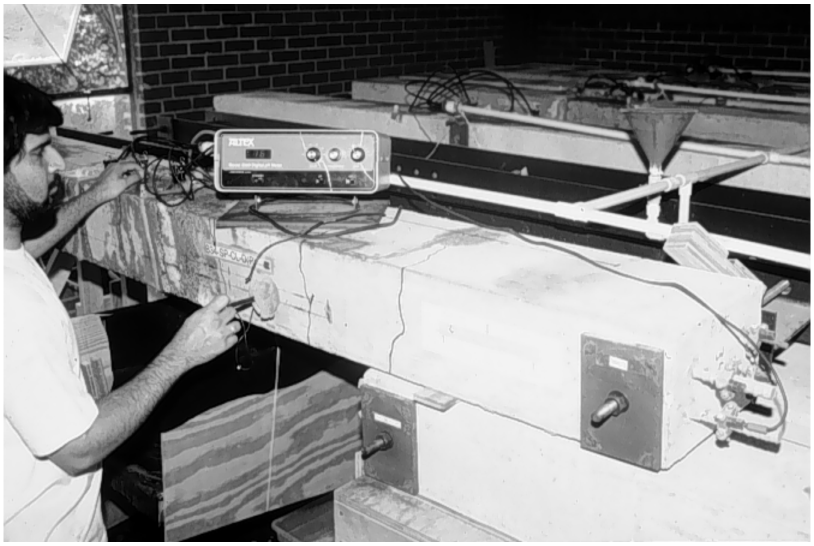


Figure 9.10: Corrosion potentials measurement.

Reference grid lines with measurement points were drawn on the beam surfaces to show the bar location. Points of measurement on the concrete surface along the longitudinal bars were spaced at every 15 cm (6 in.), over a 1.50 m (5 ft.) region along the middle of the beam where corrosion potentials were monitored. The spacing along the stirrup sides ranged from 5 to 10 cm (2 to 4 in.). Points along the stirrup were located at the middle of the vertical surface, at the four corners of the stirrup, and at the middle of the top and bottom surfaces. Location of points for measurement of corrosion potentials is schematically illustrated in Fig. 9.11.

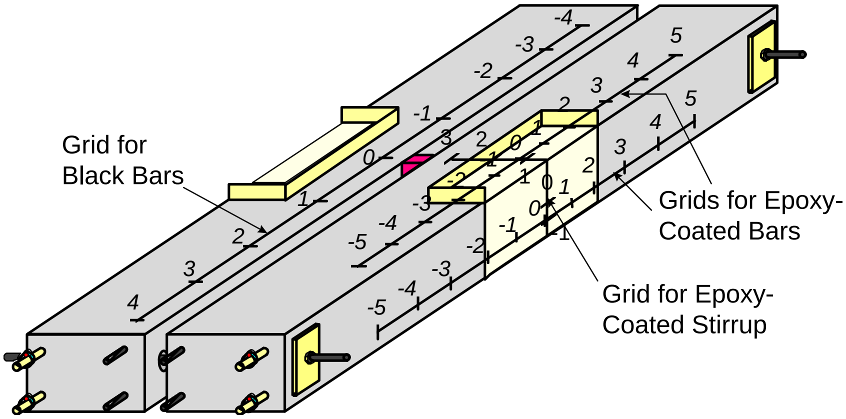


Figure 9.11: Grid points for corrosion potential measurement.

Crack maps and crack widths were documented and updated during the exposure period. Only selected cracks were monitored and measured every few cycles to detect changes in crack width. The crack width was measured using a crack comparator. Crack widths were initially measured at two points on the vertical surface: One point near the top and the other near the bottom surface. However, such points had to be changed as concrete deteriorated and made crack widths very difficult to measure.

Beam specimens were inspected visually at the beginning of the test and periodically thereafter. The objective of the examination was to observe any development of rust stains and corrosion-induced cracking.

9.4 OVERVIEW OF FINDINGS AFTER 1 YEAR

One-half of the duplicate specimens were opened at the end of 27 cycles of chloride exposure (one year). Exposure testing of the remaining specimens, originally scheduled to last 52 cycles (2 years), was lengthened to 112 cycles of exposure (4.3 years). Test results from the autopsy at the end of 1 year are presented and thoroughly discussed in reference 10. In order to have a background for the discussion of results for the last autopsied specimens, a comprehensive summary of the findings after 1 year is presented. The findings from specimen autopsy are summarized as follows:[10]

- Corrosion of epoxy-coated bars started much earlier in cracked members than in uncracked members.
- The impact of crack width on corrosion initiation and later progression was not significant.
- With more damage, bars corroded faster.
- Coated bars tended to resist corrosion at much higher chloride concentration levels than those associated with the onset of corrosion of uncoated steel.
- Corrosion was negligible when potentials remained below -400 mV SCE without significant potential gradients along the bar.
- Pitting corrosion was always associated with potentials in the range of -400 to -600 mV SCE and steep potential gradients above 200 mV.
- No correlation was found between underfilm corrosion and potential readings.

- As received longitudinal bars and stirrups in uncracked beams performed well, whereas those with damaged coating in cracked beams performed the worst. Longitudinal bars with damaged coating in cracked beams experienced significant localized pitting.
- Stirrups with coating damage, even if repaired, were susceptible to macrocell corrosion and loss of coating adhesion. Tying the stirrups to uncoated bars led to severe macrocell action.
- No rust staining of the concrete surface was observed despite the presence of cracks.
- Coated bars showed more propensity for corrosion initiation and progression when surrounded by less dense concrete, such as the concrete under the longitudinal bars and around several portions of the stirrups. The epoxy coating tended to breakdown and develop blisters at concrete voids in contact with the bar surface.

In the proposed corrosion mechanism, corrosion started in uncracked beams at coating defects and exposed areas in contact with sufficient amounts of chlorides. In cracked beams, corrosion started at crack locations and spread to adjacent areas undercutting the epoxy coating. Macrocell action was produced by differences in chloride distribution and moisture gradients coupled with damaged coating. Incidental electrical contact with uncoated bars also caused macrocell formation. Oxygen availability through the cracks aggravated corrosion severity. In general, corrosion progressed in a similar manner to that described for the macrocell specimens.

9.5 TEST RESULTS AFTER 4.3 YEARS

Exposure testing of the remaining duplicate specimens was terminated after 112 14-day cycles of chloride exposure (4.3 years). As for the previous companion specimens, observations were taken periodically, about every 2 to 4 months (every 6 months in the last 1.5 years). Special emphasis was placed in detecting signs of corrosion-induced cracking, surface corrosion, and progression of flexural cracking. As mentioned before, corrosion was monitored by measuring corrosion potentials at the end of every two wet cycles.

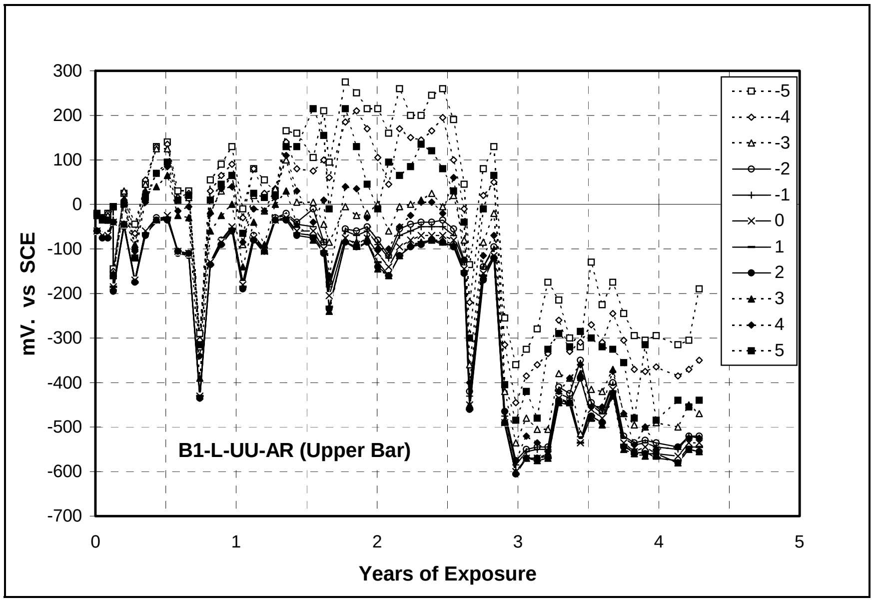
9.5.1 Corrosion Potentials

Corrosion potential measurements provide a means of monitoring corrosion activity of epoxy-coated bars. Potential readings may indicate if the steel is in a passive, active, or unstable active-passive condition. Potential readings may also be useful in indicating time to corrosion, which is marked by a significant drop in the potential value. After corrosion has started, the state of corrosion activity may be monitored by observing changes in the potential readings.

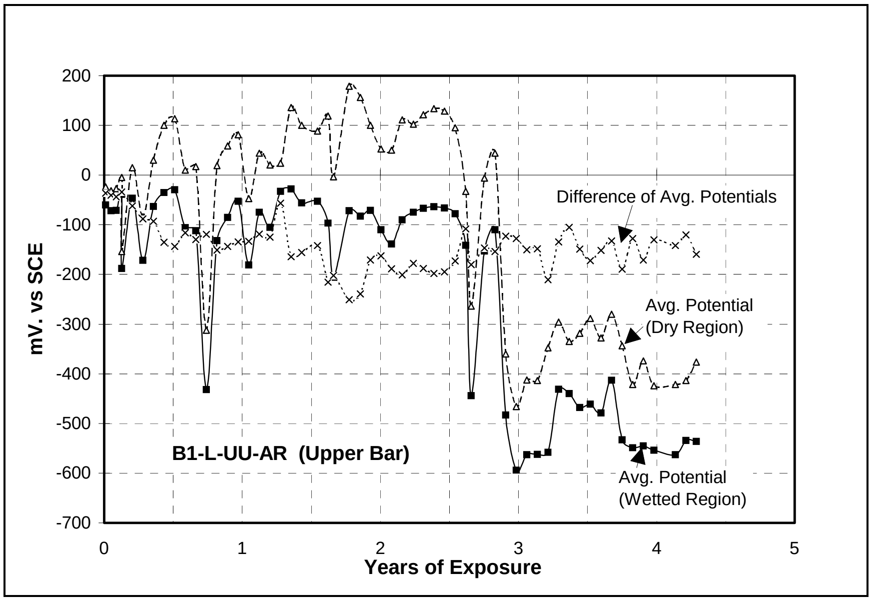
Measurement of corrosion potentials constituted the only technique used to monitor the corrosion activity of the beam specimens. The main drawback is that corrosion potentials only show the thermodynamics, but not the kinetics, of the corrosion process. This means that the potentials are useful in indicating the probability of active corrosion occurring on the steel. However, they do not indicate the rate of corrosion, that is, how fast corrosion occurs.[24] Therefore, a complete assessment of the amount of corrosion and overall condition of the bars cannot be made by analyzing the potential readings only. This circumstance greatly limited the possibility of an improved assessment of the specimens during the course of the exposure. Moreover, the limitations of the corrosion potential data should be taken into account when interpreting test results.

For previous duplicate specimens autopsied after one year, corrosion potentials of coated bars only were measured, and uncoated bars were not monitored. For the remaining specimens, corrosion potentials of the black bars in the compression side of the beams were also measured, with initial readings taken after about 1.3 years of exposure. Figure 9.11 shows the location of measurement points along the black bar location. Measurement points were spaced at every 30 cm (12 in.), with one point at midspan and successive points to the right and left. The zone of measurements typically extended up to 2.4 m (8 ft.), but in some cases it extended up to 1.2 m (4 ft.) only because of limited access to the surfaces. The decision to monitor the activity of uncoated bars was based on a desire to achieve a greater understanding of interactions between coated and uncoated bars that may lead to macrocell corrosion. Uncoated bars may also be subjected themselves to corrosion and their potential readings may shed some light on the behavior of concrete members with mixed epoxy-coated and uncoated reinforcement.

Figures 9.12 through 9.18 show some typical graphs of corrosion potentials measured on beam surfaces over time of exposure. Only beams with 4.3

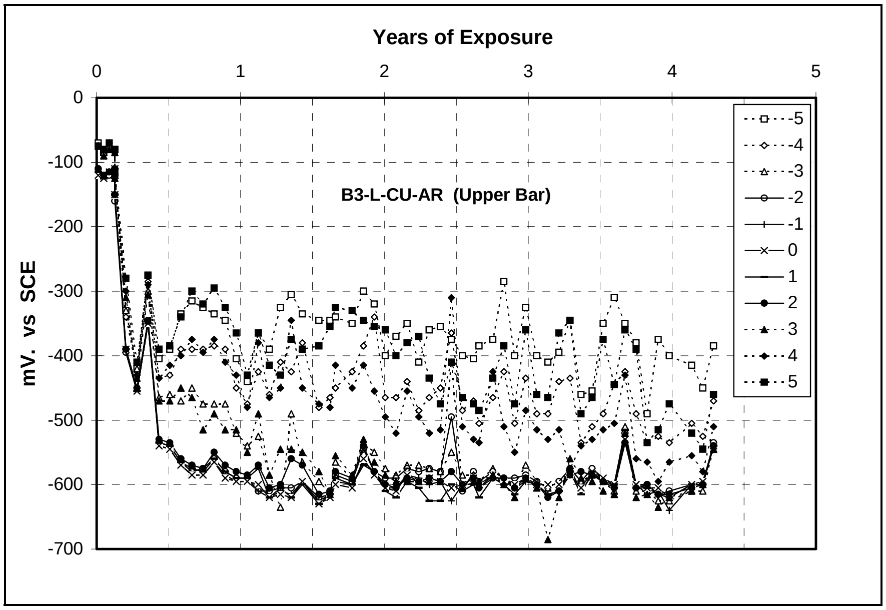


(a) Corrosion potentials along test bar (Wet and dry regions)

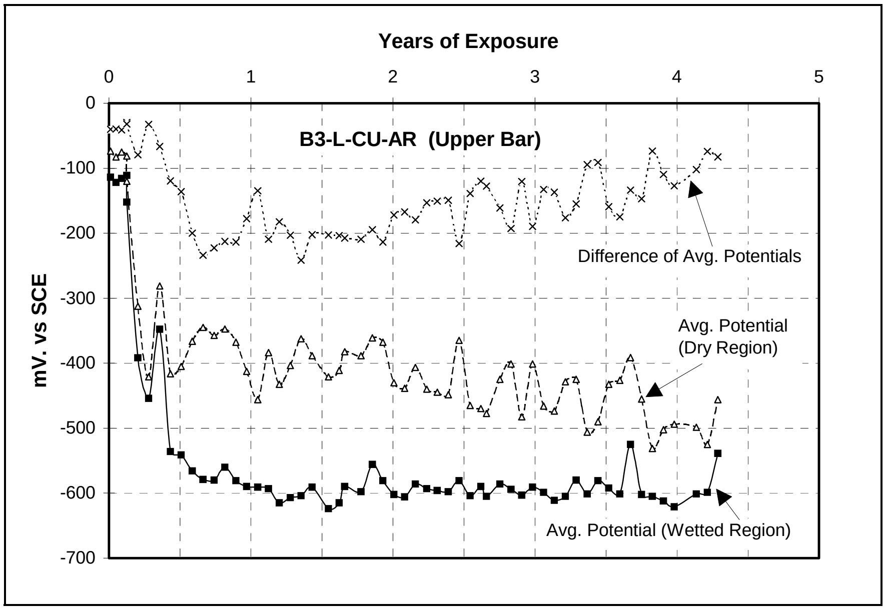


(b) Average potentials in dry and wet regions.

Figure 9.12: Corrosion potentials for beam B1 upper bar.

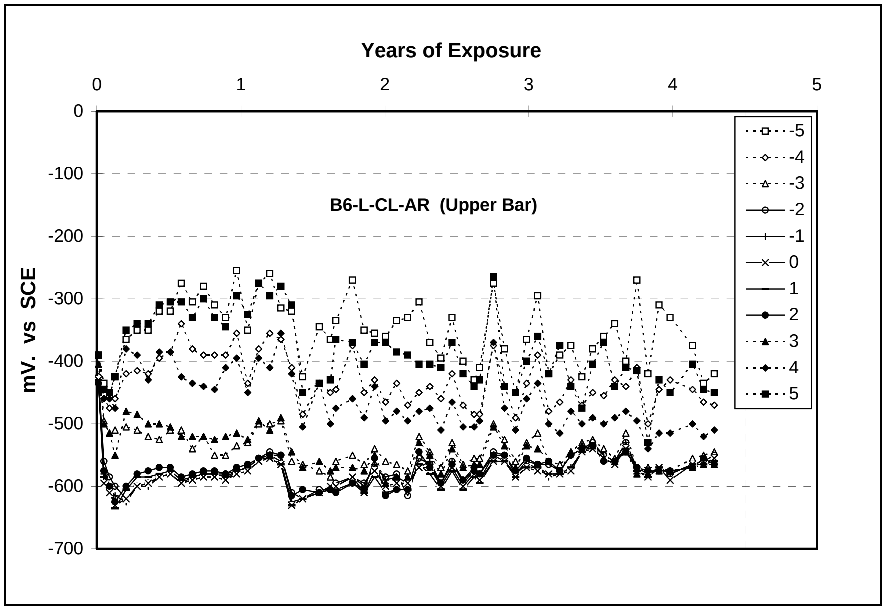


(a) Corrosion potentials along test bar (Wet and dry regions)

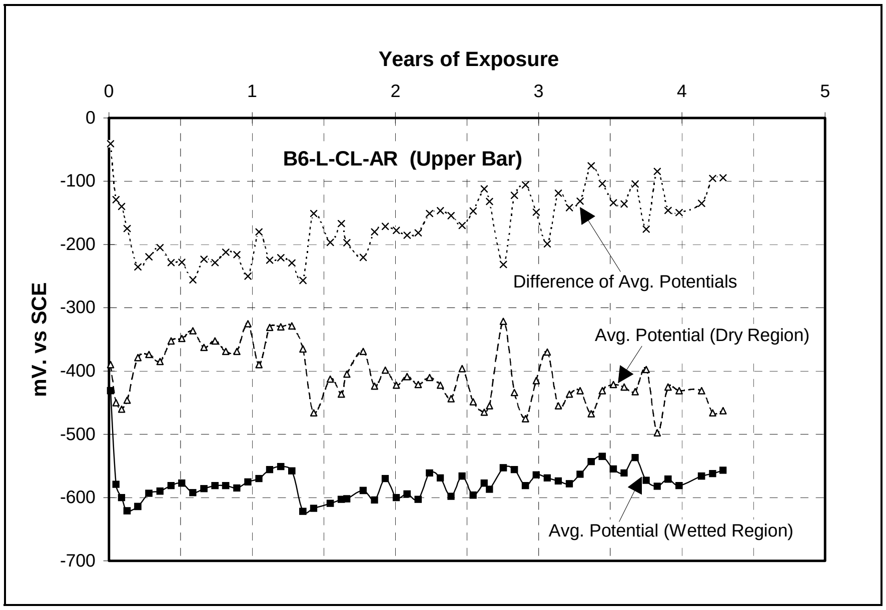


(b) Average potentials in dry and wet regions.

Figure 9.13: Corrosion potentials for beam B3 upper bar.

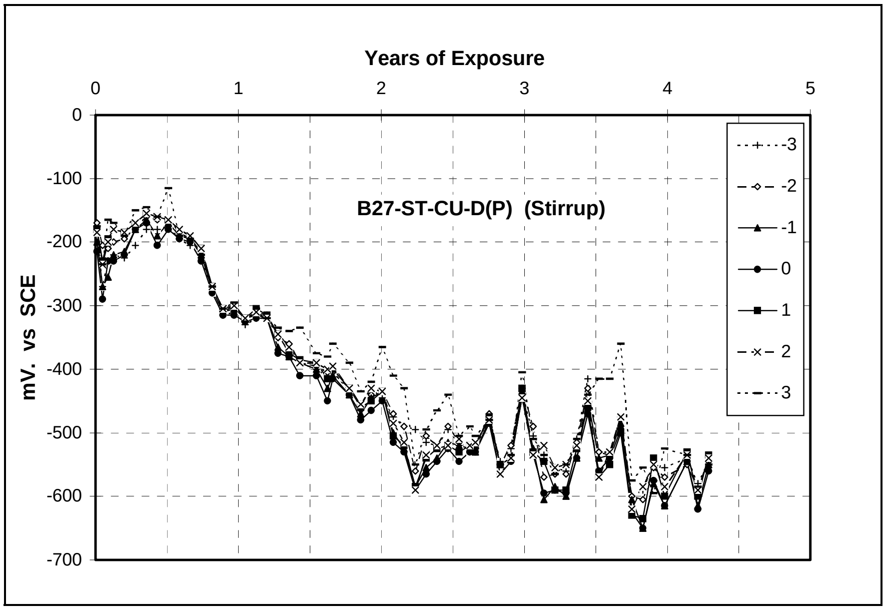


(a) Corrosion potentials along test bar (Wet and dry regions)

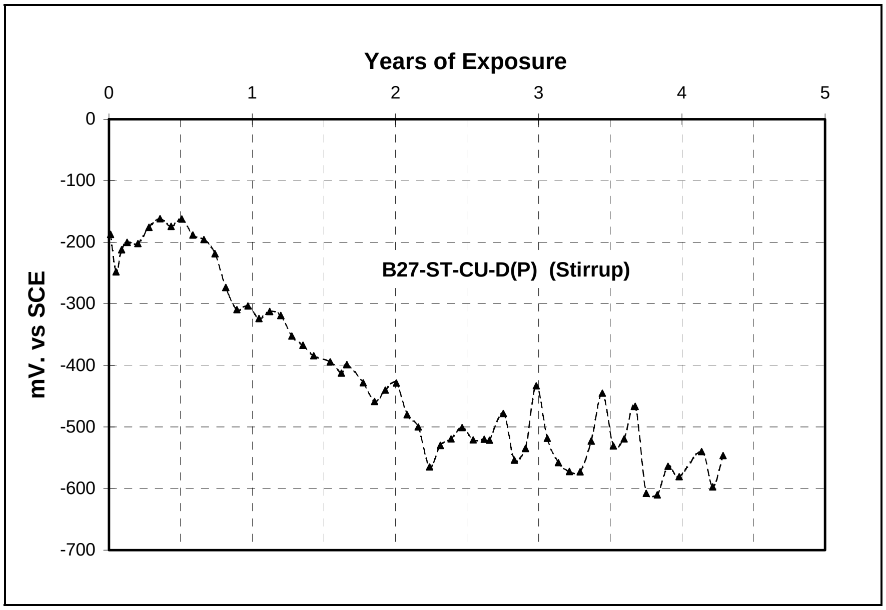


(b) Average potentials in dry and wet regions.

Figure 9.14: Corrosion potentials for beam B6 upper bar

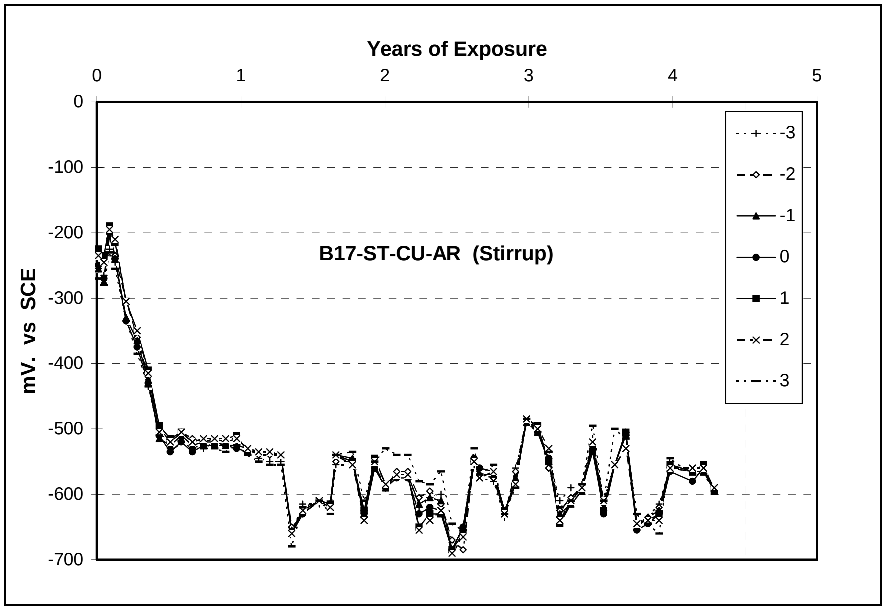


(a) Corrosion potentials along test bar (Wet and dry regions).

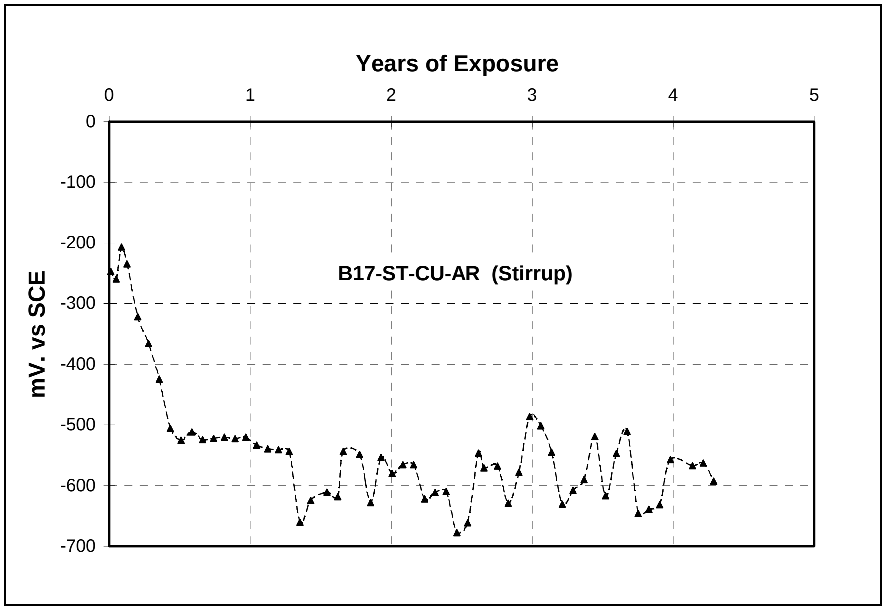


(b) Average corrosion potentials

Figure 9.15: Corrosion potentials for beam B27 stirrup.

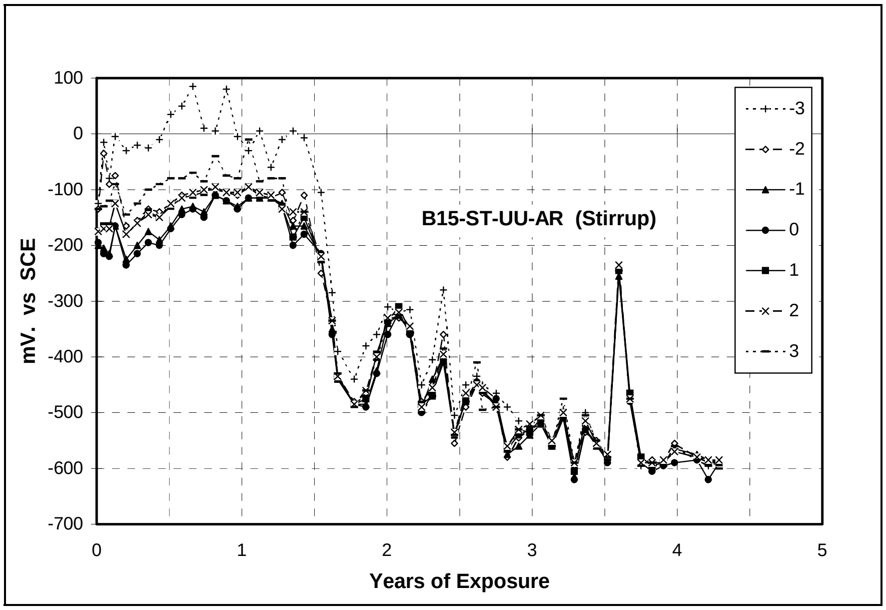


(a) Corrosion potentials along test bar (Wet and dry regions).

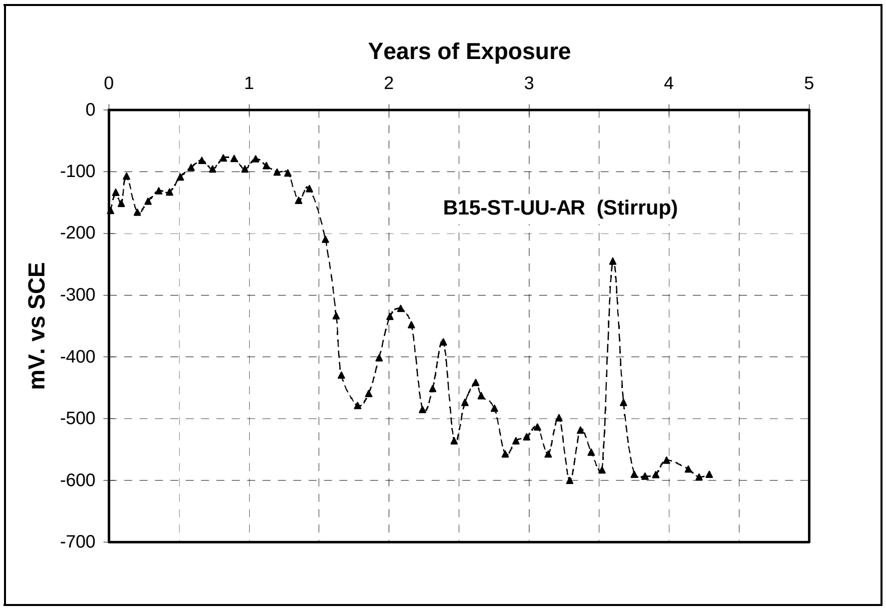


(b) Average corrosion potentials

Figure 9.16: Corrosion potentials for beam B17 stirrup.

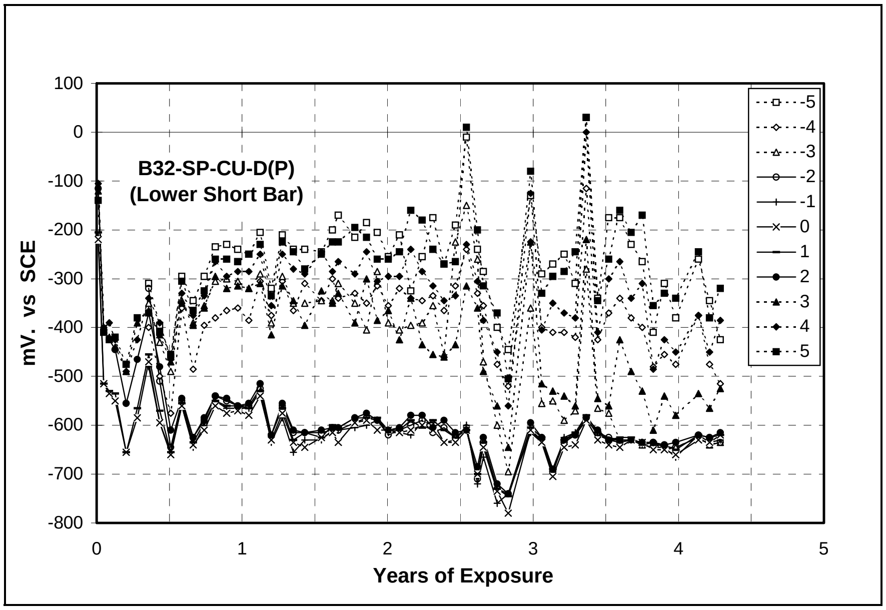


(a) Corrosion potentials along test bar (Wet and dry regions).

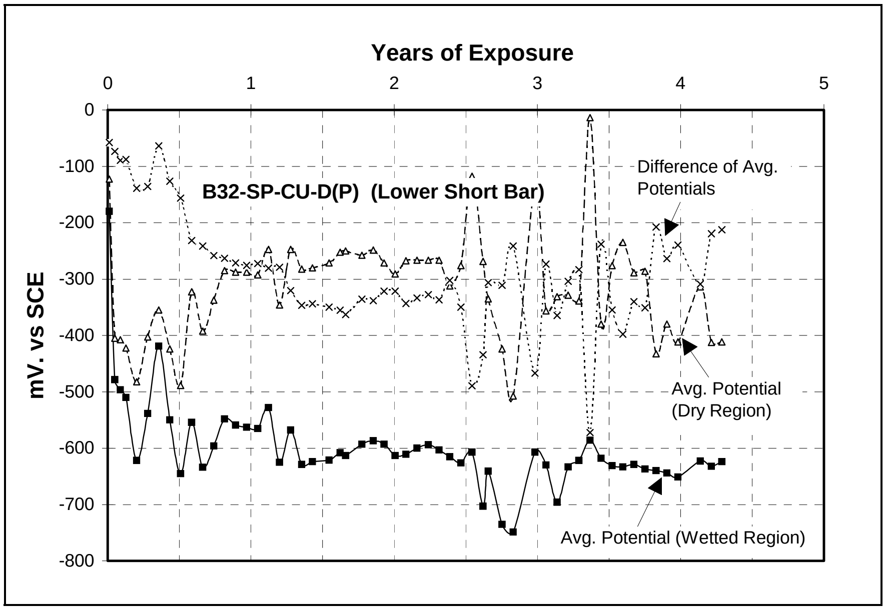


(b) Average corrosion potentials

Figure 9.17: Corrosion potentials for beam B15 stirrup.



(a) Corrosion potentials along test bar (Wet and dry regions).



(b) Average potentials in dry and wet regions.

Figure 9.18: Corrosion potentials for beam B32 lower short bar.

years of exposure are included. For coated bars, points -3 to +3 are within the wet zone, and the remaining points are in the dry zone. For uncoated bars, points -1 to +1 are close to the wet zone and points -2 to -4 and +2 to +4 are farther away form the wet zone. Graphs showing the average potential in the wet and dry zones and the difference between the average wet and dry potentials for coated bars are also shown in Figures 9.12 through 9.18. Graphs with average potential of the inner (-1 to +1) and outer (-2 to -4 and +2 to +4) points and their difference for uncoated bars are also included. Graphs showing average potentials over the monitored wet or dry lengths are much simpler and easier to understand than the graphs with potentials for each of the points because they are less congested. In addition, the difference of corrosion potentials between dry and wet zones (or inner and outer zones) may pinpoint steep gradients in potential that are indicative of severe corrosion. For stirrups, corrosion potentials at all seven points were averaged because most points were within the wet zone and the values were very similar.

Analysis of corrosion potential graphs shows that some bars exhibited highly negative potentials in the wet region at the beginning or shortly after the test was started. Other bars showed a delayed drop to highly negative potentials. Corrosion potentials for the great majority of coated bars, regardless of loading or coating condition, seemed to have reached a steady-state behavior after 4.3 years of exposure, with potential values in the range of -500 to -600 mV. These characteristics are outlined in the values listed in tables 9.1 through 9.3. The maximum average potential measured in the wet regions are listed in those tables. The initial potentials refer to those values measured after the first wetting period. Time to reach a maximum value in the wet region potential to a more or less consistent high negative value or to a fluctuating potential are also listed in the tables. The development of a highly negative potential (about -300 mV SCE) was considered to be a signal of the onset of corrosion.

Beam No.	Initial Average Potential after 4 Days of Exposure (mV)	Maximum Average Potential in Wet Zone (mV)	Final Average Potential in Wet Zone (mV)	Exposure Time to Maximum Drop of Average Potential	Time-to-Corrosion Initiation (Days)
B1-U	-60	-595	-535	1061	970
B1-L	-65	-620*	-465	606	606
B3-U	-115	-625	-540	74	74
B3-L	-105	-725*	-615	102	102
B6-U	-430	-620	-555	18	4
B6-L	-105	-635	-535	410	46
B8-U	-115	-585	-515	326	326
B8-L	-95	-635	-535	270	270
B10-U	-170	-610	-600	18	18
B10-L	-395	-620	-600	18	4
B12-U	-250	-570	-555	18	18
B12-L	-440	-605	-605	18	4
B14-U	-205	-1135*	-475	18	18

B14-L	-125	-800*	-600	18	18

*Suspect value U: Upper bar L: Lower bar

Table 9.1: Main corrosion potential values for beam bar specimens of Group I, longitudinal bars.

Beam No.	Initial Average Potential after 4 Days of Exposure (mV)	Maximum Average Potential in Wet Zone (mV)	Final Average Potential in Wet Zone (mV)	Exposure Time to Maximum Drop of Average Potential	Time-to-Corrosion Initiation (Days)
Longitudinal Bars Including Splice Bars					
B30-U	-135	-910*	-605	18	18
B30-L	-80	-1085*	-595	18	18
B32-U	-340	-1400*	-620	32	4
B32-L	-180	-750	-625	18	18
B34-U	-280	-835	-575	18	18
B34-L	-500	-660	-585	46	4
Stirrups					
B30	-145	-665	-530	46	18
B32	-120	-820*	-600	102	102
B34	-220	-630	-485	46	32

*Suspect value
U: Upper bar L: Lower bar

Table 9.2: Main corrosion potential values for beam bar specimens of Group III, longitudinal/splice bars and stirrups.

Beam No.	Initial Average Potential after 4 Days of Exposure (mV)	Maximum Average Potential in Wet Zone (mV)	Final Average Potential in Wet Zone (mV)	Exposure Time to Maximum Drop of Average Potential	Time-to-Corrosion Initiation (Days)
B15	-165	-600	-590	592	592
B17	-245	-680	-595	74 to 158	74
B19	-190	-655	-570	46	46
B22	-190	-570	-535	494, 817	522
B23	-215	-515	-510	130	130
B25	-205	-520	-335	46, 522	46
B27	-185	-610	-550	298 to 817	326

Table 9.3: Main corrosion potential values for beam bar specimens of Group II, stirrups.

A summary of black bar potentials for all beams is shown in tables 9.4 through 9.6. In most cases, the time to maximum potential drop and time to corrosion are unknown because the black bars were not monitored during the first year of exposure.

Beam No.	First Measured Average Potential after 1.3 Years of Exposure (mV)	Maximum Average Potential in Middle Zone (mV)	Final Average Potential in Middle Zone (mV)	Exposure Time to Maximum Drop of Average Potential (Days)	Time-to-Corrosion Initiation (Days)
B1-U	-220	-555	-525	522	522
B1-L	-275	-560	-545	466 to 760	648
B3-U	-400	-570	-570	-	-
B3-L	-430	-560	-560	-	-
B6-U	-465	-520	-465	-	-
B6-L	-505	-530	-505	-	-
B8-U	-55	-360	-360	1117	1117
B8-L	-105	-320	-300	1145	1201
B10-U	-350	-560	-560	-	-
B10-L	-380	-545	-540	-	-
B12-U	-440	-505	-495	-	-
B12-L	-505	-560	-550	-	-
B14-U	-295	-575	-555	Uncertain	-
B14-L	-415	-595	-565	-	-

U: Upper bar L: Lower bar

Table 9.4: Main corrosion potential values for black bar specimens of Group I.

Beam No.	First Measured Average Potential after 1.3 Years of Exposure (mV)	Maximum Average Potential in Middle Zone (mV)	Final Average Potential in Middle Zone (mV)	Exposure Time to Maximum Drop of Average Potential (Days)	Time-to-Corrosion Initiation (Days)
B15-U	+5	-430	-415	704	704
B15-L	-45	-535	-535	956 to 1089	1089
B17-U	-445	-555*	-450	-	-
B17-L	-480*	-480*	-340	-	-
B19-U	-420	-585	-505	-	-
B19-L	-480	-495	-370	-	-
B22-U	-25	-540	-515	592, 1005	1005
B22-L	-35	-540	-540	Undefined	900
B23-U	-395	-465	-250	-	-
B23-L	-410*	-480*	-465	-	-
B25-U	-435	-565*	-410	-	-
B25-L	-515*	-525	-495	-	-
B27-U	-405	-525	-330	-	-
B27-L	-390	-570	-495	-	-

*Suspect Value
U: Upper bar L: Lower bar

Table 9.5: Main corrosion potential values for black bar specimens of Group II.

Beam No.	First Measured Average Potential after 1.3 Years of Exposure (mV)	Maximum Average Potential in Middle Zone (mV)	Final Average Potential in Middle Zone (mV)	Exposure Time to Maximum Drop of Average Potential (Days)	Time-to-Corrosion Initiation (Days)
B30-U	-285	-570	-565	Undefined	-
B30-L	-430	-575	-555	-	-
B32-U	-250	-735*	-520	-	-
B32-L	-400	-745*	-530	-	-
B34-U	-450	-555	-555	-	-
B34-L	-505	-545	-535	-	-

*Suspect value
U: Upper bar L: Lower bar

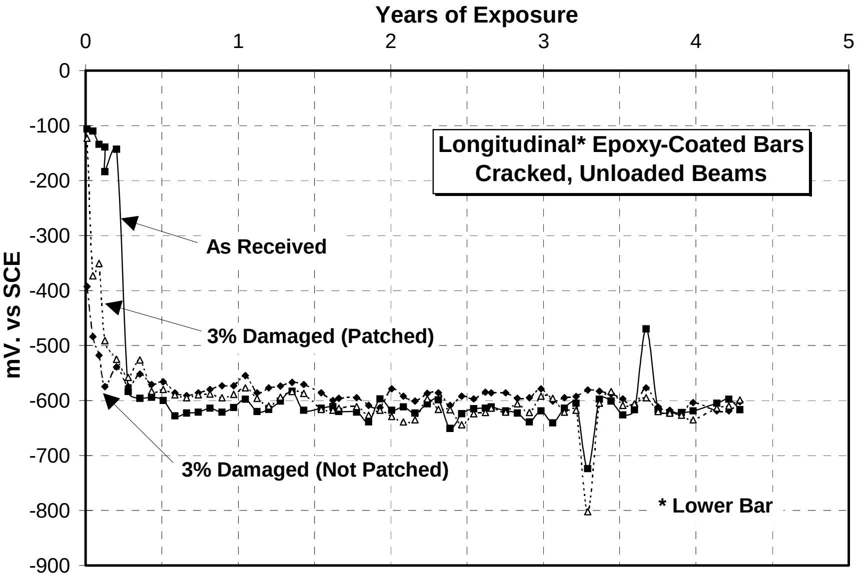
Table 9.6: Main corrosion potential values for black bar specimens of Group III.

In the following sections, comparative behavior of corrosion potentials between coated bars with different coating and loading conditions are presented for the three groups of beam specimens. The comparisons are based on the average corrosion potentials measured within the wet zone of the beams. Main trends of potentials displayed by uncoated bars are also included based on the average values at middle regions of the beams.

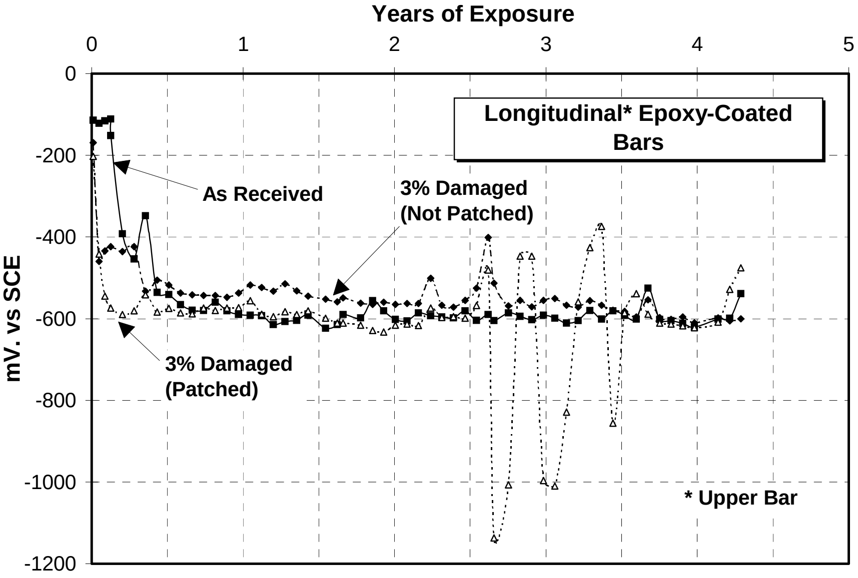
Group I Specimens (longitudinal bars)

Damage conditions

- There was little difference in behavior of cracked beams with different damaged conditions. The corrosion potentials were different during the first three to six months of exposure, but thereafter, the potentials for different coating conditions evened out and became similar (Fig. 9.19).
- The only exception to the preceding observation was represented by the lower bars of cracked and loaded beams. The coated bar in as-received condition had lower negative potentials than the bar with 3% damaged coating for the first 9 months. After about one year, there was a drop in the potentials of the as received bar, and both bar potentials were similar thereafter (Fig. 9.20).
- For uncracked beams, the as-received bars showed similar potentials as the 3% damaged bars in the first 8 months. After a sudden potential drop, as-received bars underwent lower negative potentials than bars with 3% damage in a period extending from 8 months to about 3 years. After that, corrosion potentials of the as received bar decreased to the same region as that for bars with 3% damage (Fig. 9.21). Overall, differences in coating condition were evident for uncracked beams from 1 to 3 years of exposure; thereafter, corrosion potentials became similar.

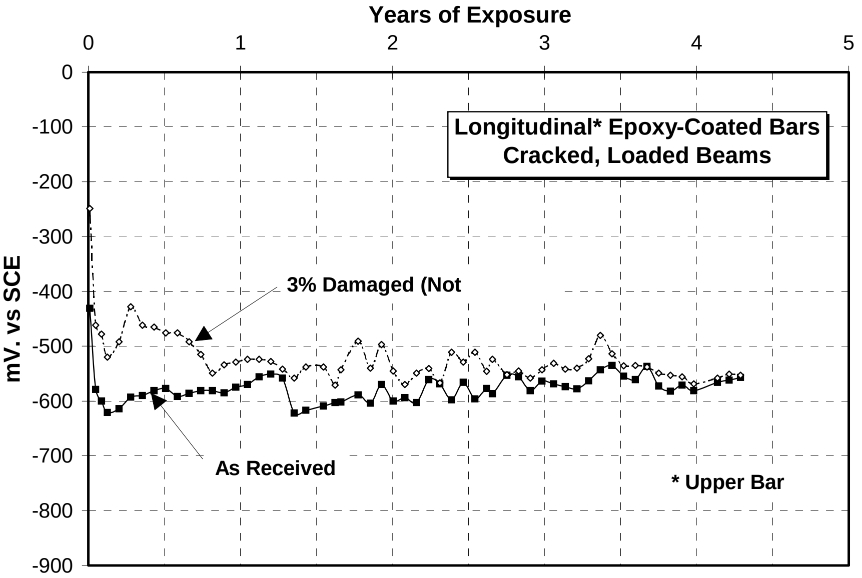


(a) Lower bar

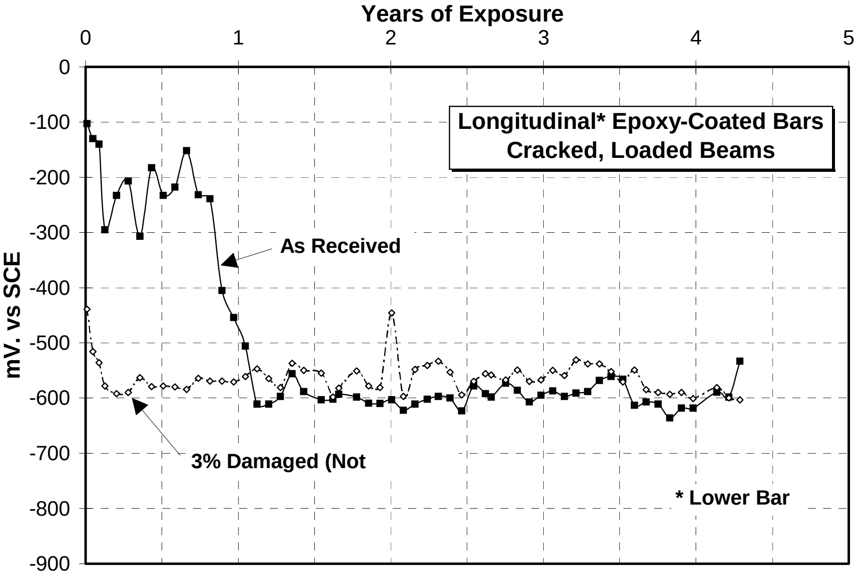


(b) Upper bar

Figure 9.19: Comparison of average corrosion potentials (wetted region) of longitudinal bars in cracked, unloaded beams with different levels of damage.

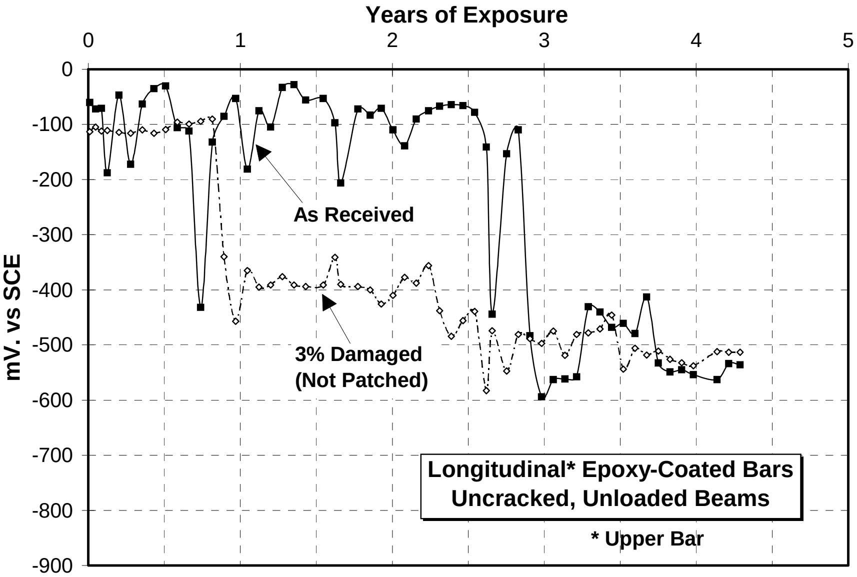


(a) Upper bar

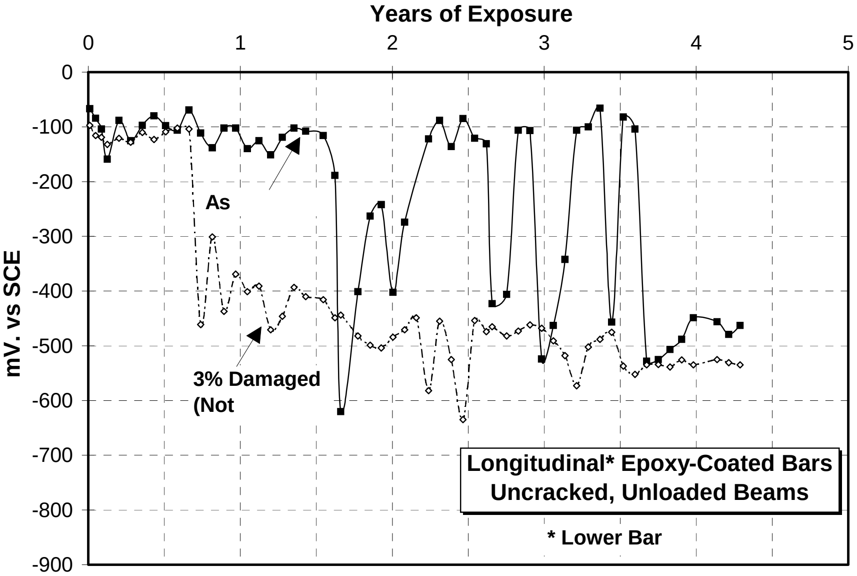


(b) Lower bar

Figure 9.20: Comparison of average corrosion potentials (wetted region) of longitudinal bars in cracked, loaded beams with different levels of damage.



(a) Upper Bar



(b) Lower Bar

Figure 9.21: Comparison of average corrosion potentials (wetted region) of longitudinal bars in uncracked, unloaded beams with different levels of damage.

- Overall, coated bars with different damage conditions experienced very similar corrosion potentials over the long term. The clearest distinction was that bars in an as-received condition had lower negative potentials than bars with 3% damage, both patched and unpatched [Fig. 9.19, 9.20(b)].
- There was no clear difference in the corrosion potentials between unpatched and patched damaged bars (cracked beams). In one case (cracked unloaded beams), potentials for the upper bar with patched 3% damage (beam B14) decreased faster to the -600 mV SCE region and stayed slightly more negative than potentials for the upper bar with 3% damage without repair (beam B10). See Fig. 9.19(b).

Loading Conditions

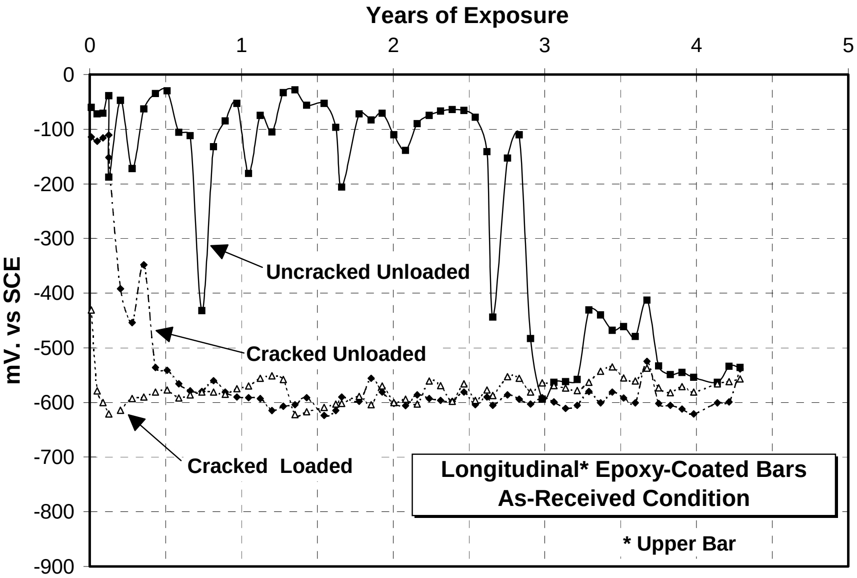
- Uncracked beams had lower negative potentials than cracked beams for about 3 to 3.5 years for as-received bars, and for about 8 months to 1 year for 3% damaged bars. Thereafter, corrosion potentials of uncracked beams suddenly dropped to the same level as bars in cracked beams (Figures 9.22 and 9.23).
    - The graph in Fig. 9.22(a) shows a comparison of potentials of upper bars in the as-received condition. Potentials for the bar in the uncracked, unloaded beam remained in the -100 mV SCE region up to 3 years, then dropped to the -500 to -600 mV SCE region. Bar potentials in the cracked unloaded beam decreased

    to the same -500 to -600 mV SCE region within 6 months. Finally, bar potentials in the cracked loaded beam started off at -440 mV SCE, then to the -600 mV SCE region in a short time.

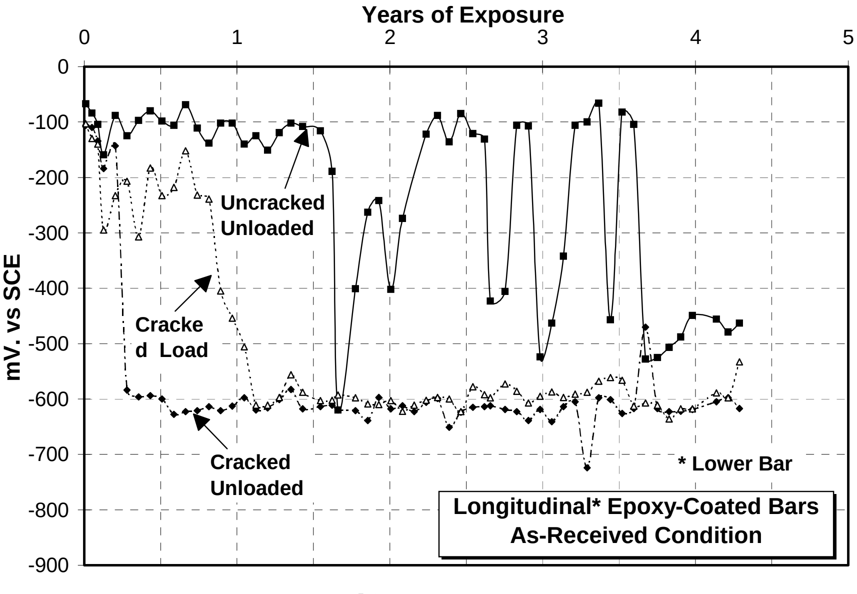
  - The graph in Fig. 9.23(a) shows a comparison of potentials for upper bars with 3% damage to the coating. Potentials for in the uncracked, unloaded beam dropped from -100 mV to -400 mV SCE at 1 year of exposure, and then to -500 mV SCE at 2.5 years. Potentials in the cracked unloaded beam dropped to -500 mV SCE within 6 months of exposure, and thereafter, potentials gradually decreased up to -600 mV SCE. Potentials in the cracked loaded beam decreased to -500 mV SCE in less than 3 months and thereafter fluctuated in the -500 to -570 mV SCE range.

- Loaded and unloaded beams showed only minor differences regardless of coating condition (Fig. 9.22, 9.23). In general, bar potentials for cracked, unloaded beams decreased to -500 to -600 mV SCE within 6 or less months, and potentials for cracked loaded beams dropped to the same level within 3 months.

The lower bar with coating in the as-received condition and in an uncracked, unloaded beam experienced an erratic behavior after 1.5 years of exposure with continuous jumps up and down between the -400 to -500 mV SCE range and the -100 mV SCE region [Fig. 9.22(b)]. This may be the result of poor electrical connections to the bar or some other instrumentation problem.

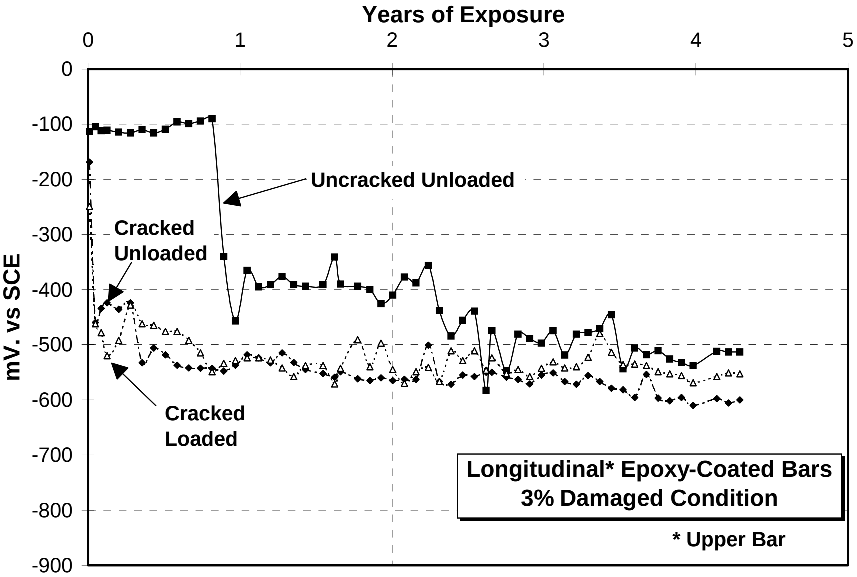


(a) Upper Bar

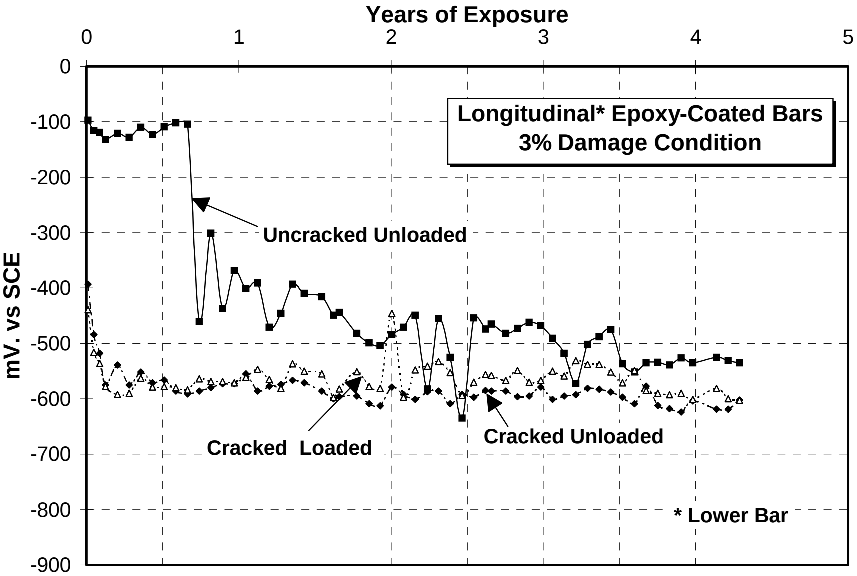


(b) Lower Bar

Figure 9.22: Comparison of average corrosion potentials (wetted region) of longitudinal bars with as received condition with different loading conditions.



(a) Upper Bar



(b) Lower Bar

Figure 9.23: Comparison of average corrosion potentials (wetted region) of longitudinal bars with 3% damage to coating and different loading conditions.

Black bars

- For most beams, average black bar potentials in the inner zone (closer to wet zone) were more negative (typically in the -500 mV SCE region) than those at the outer regions (farther away from wet zone), which were typically in the -200 mV to -300 mV SCE range, as seen in Fig. 9.24.
- Corrosion potentials in most cracked beams, loaded or unloaded, tended to become more negative with time and approached the potentials of the nearest longitudinal coated bar after 4.3 years of exposure (Figure 9.25). Potentials in cracked, loaded beam B12 were highly negative from the beginning.
- The upper black bar potentials in beam B1 (uncracked, unloaded) dropped from -200 mV to -500 mV SCE after about 6 months of exposure and the readings remained more negative than upper coated bar potentials (coating in as-received condition) up to 3 years (-520 mV vs. -70 mV SCE, approximately). However, at that time, upper coated bar potentials decreased rapidly and were similar to the upper black bar potentials for the remainder of the exposure period (Fig. 9.26).

- For beam B8 (uncracked, unloaded with 3% damage to coating), black bar potentials were less negative than coated bar potentials throughout the exposure period (Fig. 9.27).

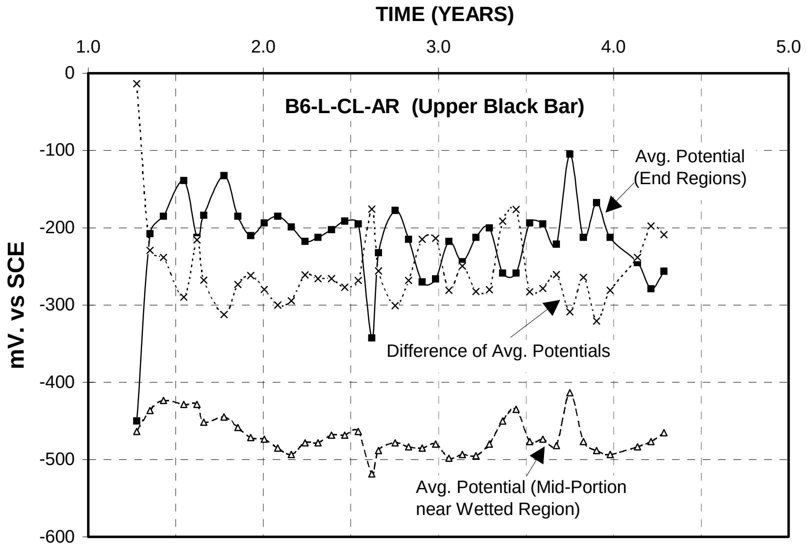


Figure 9.24: Corrosion potentials at different regions along upper, uncoated bar in beam B6.

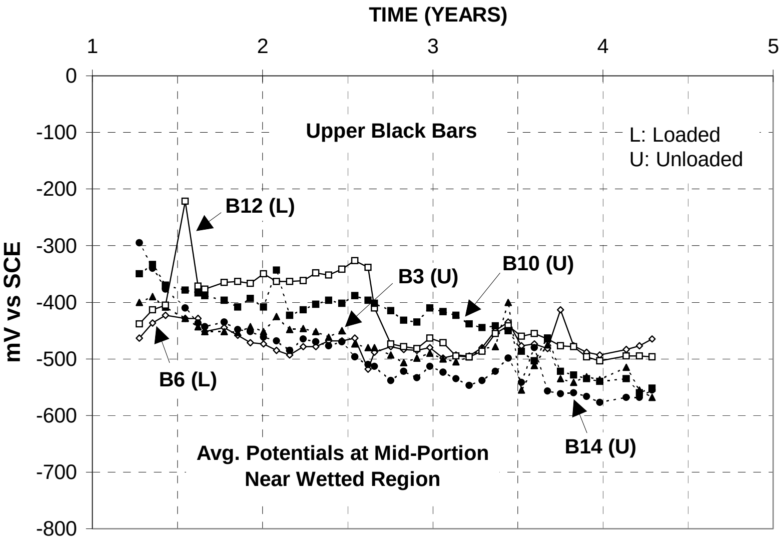


Figure 9.25: Corrosion potentials for upper, uncoated bars in cracked beams with different loading conditions.

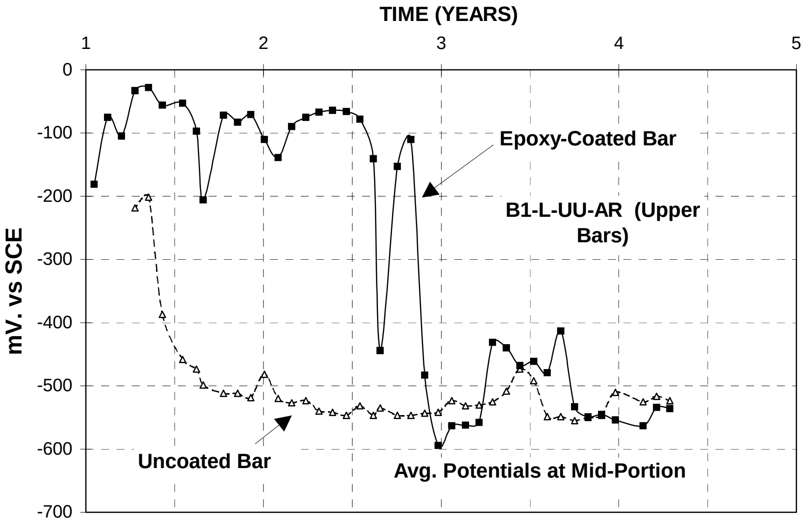


Figure 9.26: Corrosion potentials for upper, coated and uncoated bars, in uncracked beam B1.

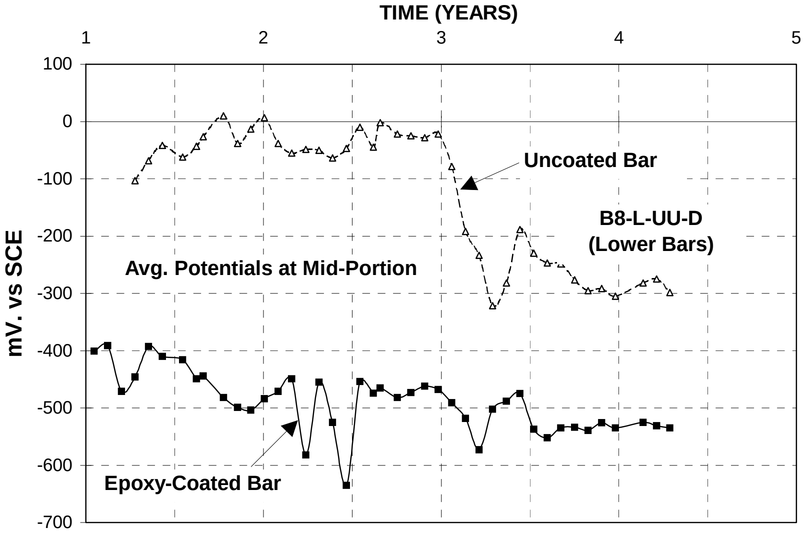


Figure 9.27: Corrosion potentials for lower, coated and uncoated bars, in uncracked beam B8.

Group II Specimens (Stirrups)

Damage Conditions

- In uncracked beams, stirrups with coating in the as-received condition, patched or unpatched, exhibited very similar behavior. Corrosion potentials were in the -200 mV SCE region up to 1.5 years of exposure and, subsequently, the potentials continuously declined up to the -550 to -600 mV SCE zone (Fig. 9.28).
- In cracked unloaded beams, a stirrup in the as-received condition without patching exhibited more rapid decline in potential readings than an as-received, patched stirrup and a stirrup with 3% patched damage.

However, after about 2 years of exposure, the potentials for the 3% damaged patched stirrup were nearly the same as the potential readings for by the as-received stirrup without repair (Fig. 9.29). The as received and patched stirrup experienced relatively large fluctuations in potential after 2.5 years but seemed to have approached the potentials of the as received stirrup at the end of exposure (Fig. 9.29).

- In cracked loaded beams, as-received and patched stirrup exhibited less negative potentials than those of an as-received stirrup without repair throughout the exposure period. As can be seen in Fig. 9.30, both stirrups experienced large fluctuations in readings in the last 2.3 years of exposure.

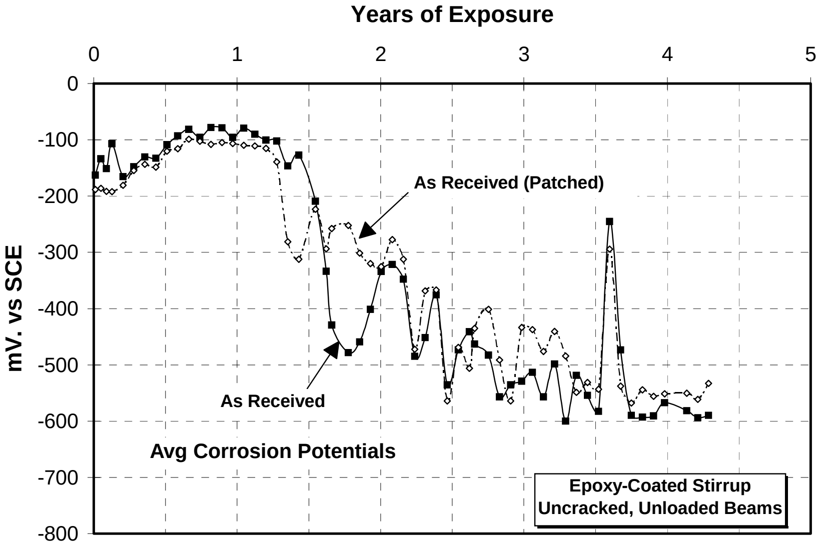


Fig. 9.28: Comparison of potentials of stirrups in uncracked beams with different coating conditions.

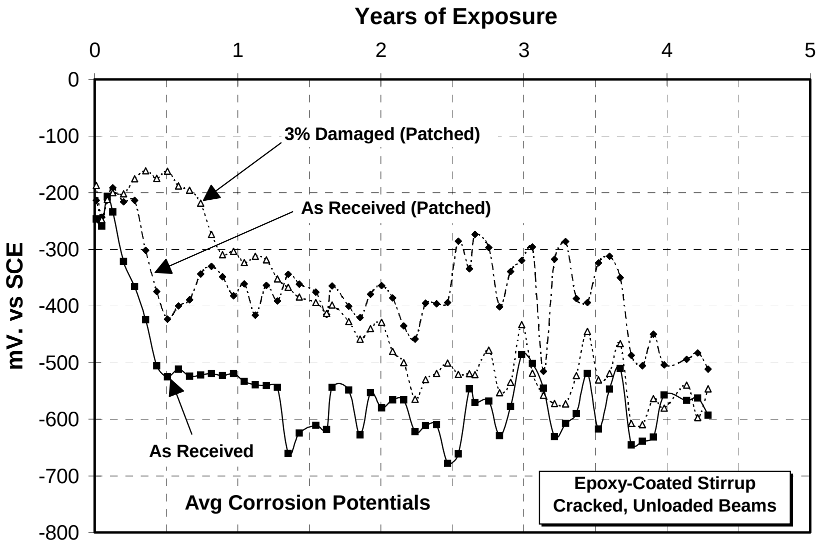


Fig. 9.29: Comparison of potentials of stirrups in cracked, unloaded beams with different coating conditions.

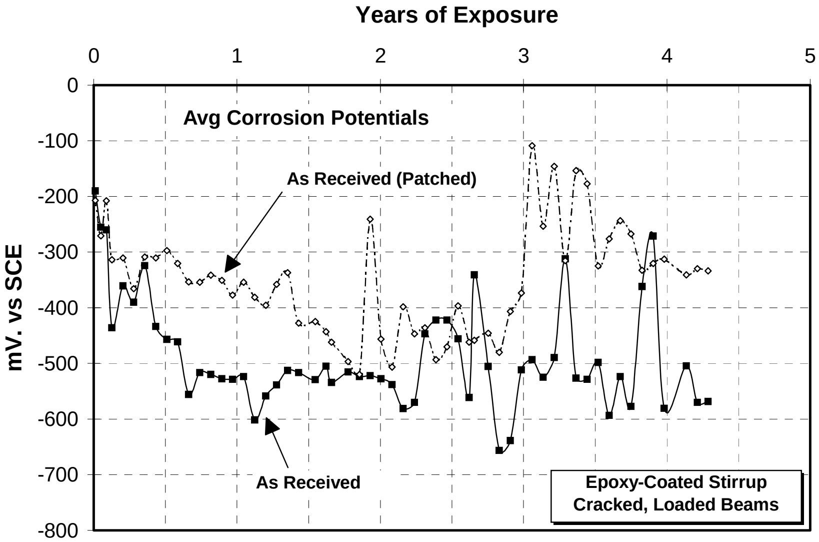


Fig. 9.30: Comparison of potentials of stirrups in cracked, loaded beams with different coating conditions.

Loading Conditions

- Uncracked beams stayed in the low negative potential region for about 1 to 1.5 years of exposure. Thereafter, corrosion potentials declined continuously to values around -600 mV SCE. The behavior between cracked and uncracked beams was similar after about 2.5 years of exposure (Fig. 9.31). In one case (beams with as received and patched coated bars), potentials for uncracked beams became more negative than those of cracked beams after 2.5 years of exposure (Fig. 9.32).
- There was not distinctive performance between cracked loaded and cracked unloaded beams regardless of coating condition (Fig. 9.31).

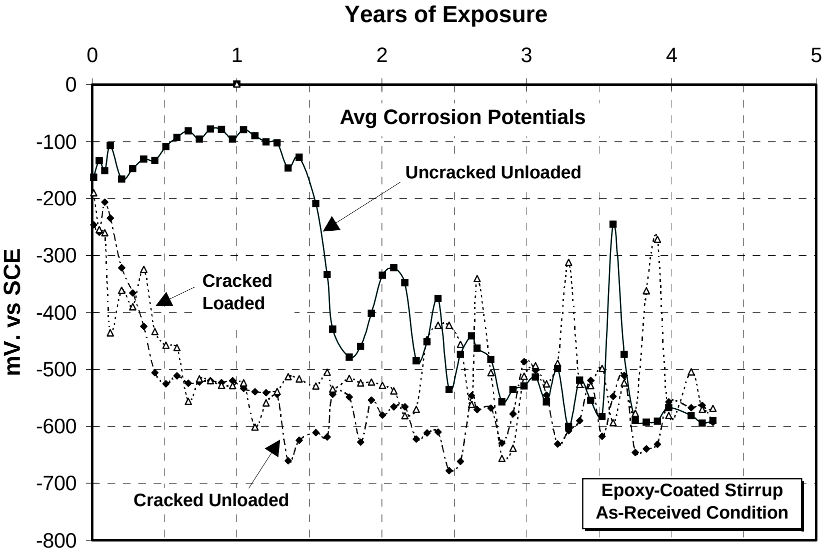


Fig. 9.31: Comparison of potentials of stirrups in as-received condition and different loading conditions.

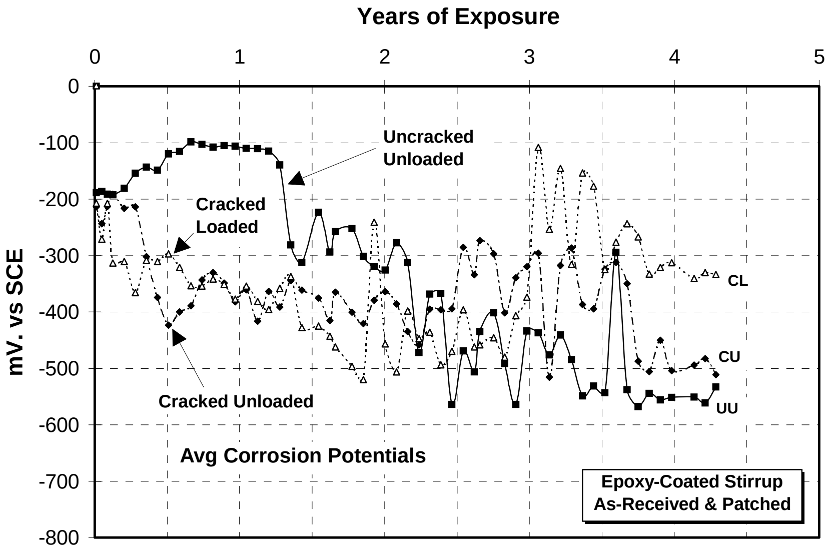


Fig. 9.32: Comparison of potentials of stirrups with as-received and patched bars and different loading conditions.

Black Bars in Beams with Monitored Stirrups

- For most beams, average black bar potentials in the inner zone (closer to wet zone and to stirrup) were more negative (typically in the -400 mV SCE region) than those at the outer regions (farther away from wet zone), which were typically in the -100 mV SCE range, as seen in Fig. 9.33.
- Average black bar potentials at the inner zone in uncracked unloaded beams were in the very low negative range (close to zero or positive) when monitoring of the black bars began at about 1.3 years of exposure. Subsequently, corrosion potentials tended to gradually decline and approached the highly negative values of the stirrups (Fig. 9.34).

- Average black bar potentials at the inner zone near the stirrup in cracked beams (loaded or unloaded) were already at high negative values when first measured at about 1.3 years of exposure, and tended to stay in the -300 to -500 mV range, with relatively large fluctuations (Figures 9.35 and 9.36).

Group III Specimens (Longitudinal bars, Spliced Bars, and Stirrups with no Electrical Isolation)

Coated bars

- There was no difference in behavior in longitudinal bar readings for beams with stirrups electrically isolated or without isolation (Fig. 9.37).
- Continuous coated bars exhibited behavior similar to that of spliced coated bars (Fig. 9.38).

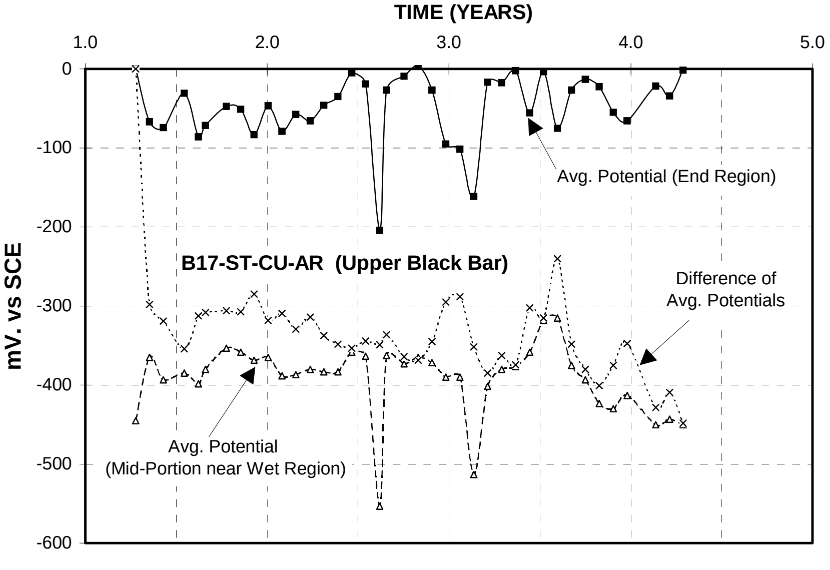


Figure 9.33: Corrosion potentials for upper, uncoated bar in beam B17.

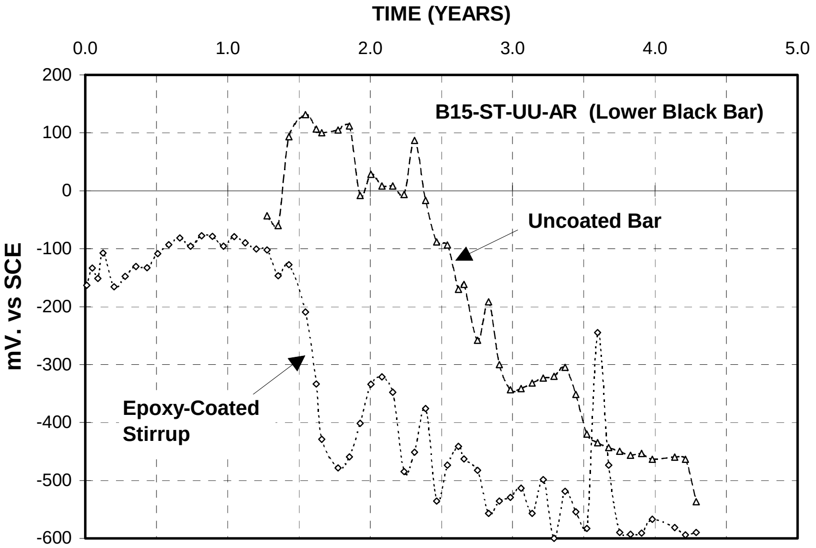


Figure 9.34: Corrosion potentials for lower, uncoated bar and epoxy-coated stirrup, in uncracked beam B15.

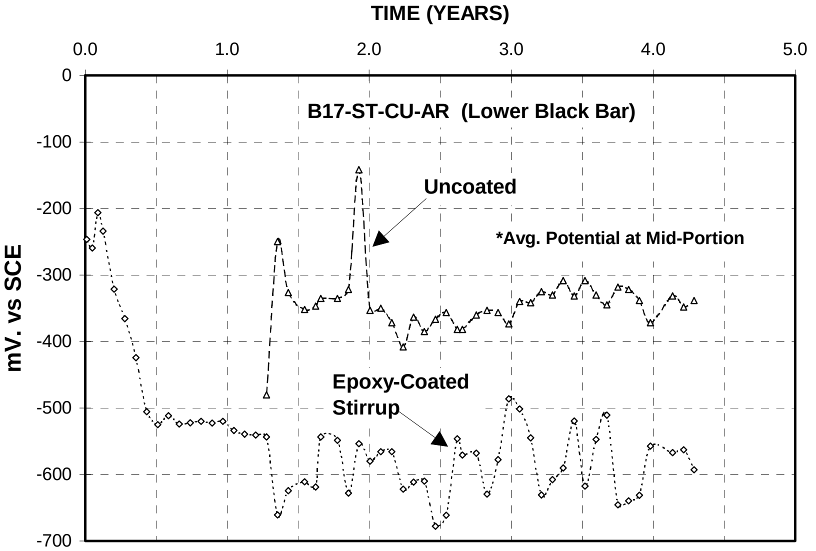


Figure 9.35: Corrosion potentials for lower, uncoated bar and epoxy-coated stirrup, in cracked beam B17.

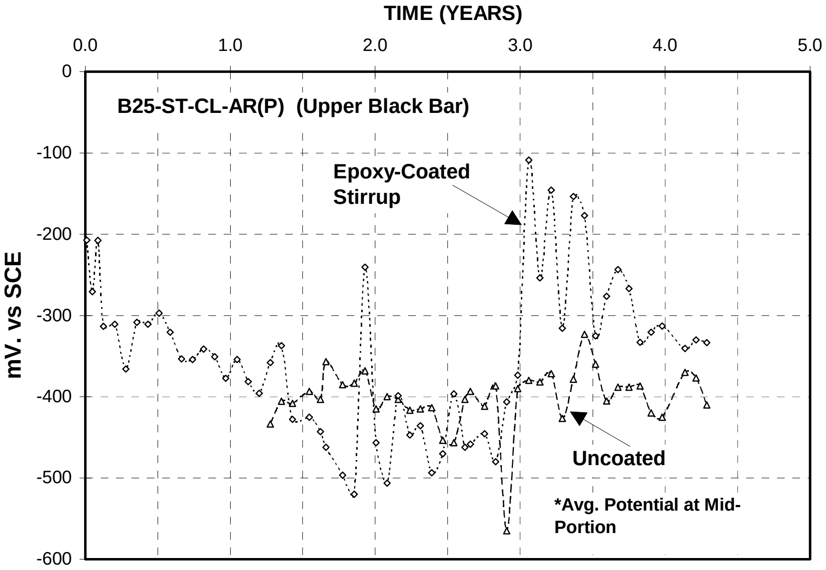


Figure 9.36: Corrosion potentials for upper, uncoated bar and epoxy-coated stirrup, in cracked beam B25.

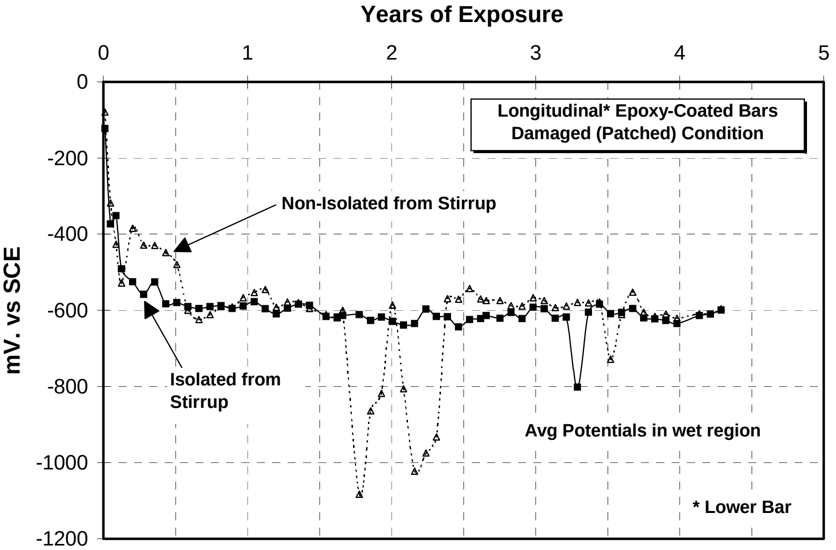


Figure 9.37: Corrosion potentials for lower, coated bars, with and without electrical isolation from stirrup.

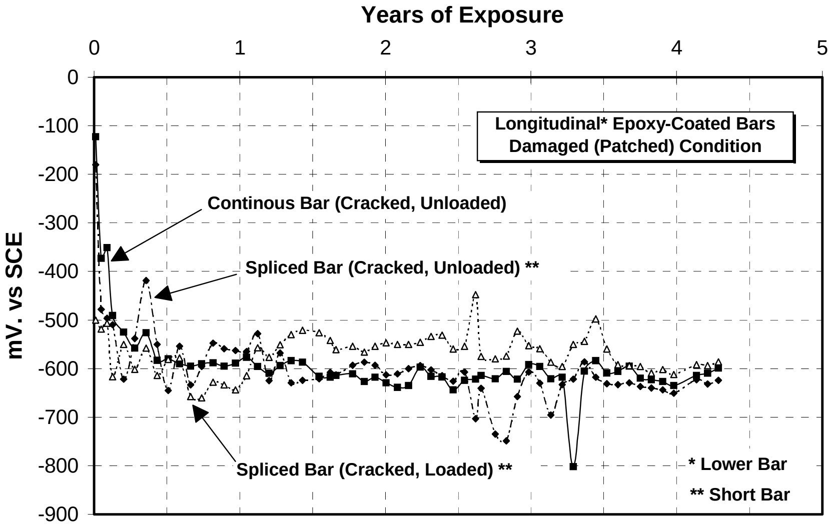


Figure 9.38: Comparison of potentials of continuous and spliced coated bars.

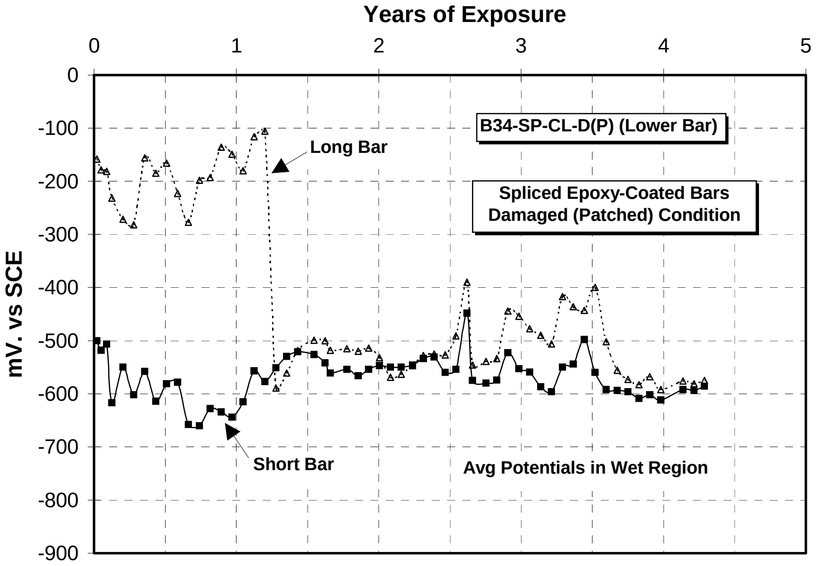


Figure 9.39: Comparison of potentials of long and short coated splice bars.

- In a spliced lower bar (beam B34), corrosion potentials of the longer bar stayed less negative than those of the short bar for about one year. Thereafter, the potential sharply dropped to the same level as that of the shorter bar which remained highly negative throughout exposure. See Fig. 9.39.

Black bars

- Except in beam B30, average black bar potentials in the inner zone (closer to wet zone) were more negative (typically in the -500 mV SCE region) than those at the outer regions (farther away from wet zone), which were typically in the -100 mV to -300 mV SCE range.
- After experiencing a rather gradual decline of corrosion potentials from 1 to 4.3 years of exposure, average black bar potentials in the inner regions (in the -500 mV SCE range) were only slightly less negative than average coated bar potentials in the wet zone (about -600 mV SCE).
- Corrosion potentials of the upper black bar of beam B30 decreased continuously up to about -550 mV SCE at the end of exposure for both inner and outer regions of the bar.
- Final potentials between upper and lower bars were similar.

In summary, corrosion potentials for nearly all coated bars reached values of -500 to -600 mV SCE after 4.3 years of exposure.

9.5.2 Specimen Surface Condition

In the discussion that follows, the convention for identifying beam surfaces was based on the position of the beams during the exposure (beams were laying on their sides in the exposure setup, as shown in Fig. 9.6). Specimens exposed to chlorides for one year did not show signs of rust staining on the concrete surface. Surface staining appeared during the second year of exposure and, after 4.3 years, a number of beams evidenced corrosion stains. All beams remaining after one year experienced some degree of concrete scaling, from light to severe. Small, fine cracks at random orientations appeared within the wet zone of several beams.

Rust staining and corrosion-induced cracking occurred mainly on beams from group II where coated stirrups were monitored. Extensive rust staining also occurred on beam 32 (cracked unloaded with 3% damaged and patched splice bar and stirrup) of group III. Very little rust staining was observed on beams from group I where longitudinal coated bars were monitored. The first corrosion-induced cracking was observed on beam 15 (uncracked unloaded with as received stirrup) and possibly occurred between 1.0 and 1.5 years.

Both uncracked and intentionally cracked (loaded) beams exhibited cracking under exposure with random orientation and no distinctive pattern within the wet zone, at the front and bottom beam surfaces (Fig. 9.40). Such cracks appeared between 2.5 and 3.6 years, and had a maximum width of 0.20 mm, but most widths were between 0.08 and 0.10 mm. No signs of rust were found at or around such cracks.

Concrete surfaces deteriorated and scaled within the wet zone and neighboring regions outside the wet zone of all beams (Fig. 9.41). Salt crystals accumulated and were visible on scaled surfaces. Salt crystals hardened to the point that they could not be removed with a putty knife. Extent of concrete scaling outside the wet zone was more extensive and severe at the bottom surfaces in the exposure position. Degree of scaling ranged from light to severe. Concrete surfaces away from wet areas remained in good to excellent condition in all beams.

Corrosion staining and cracking due to corrosion is described briefly in the following sections.

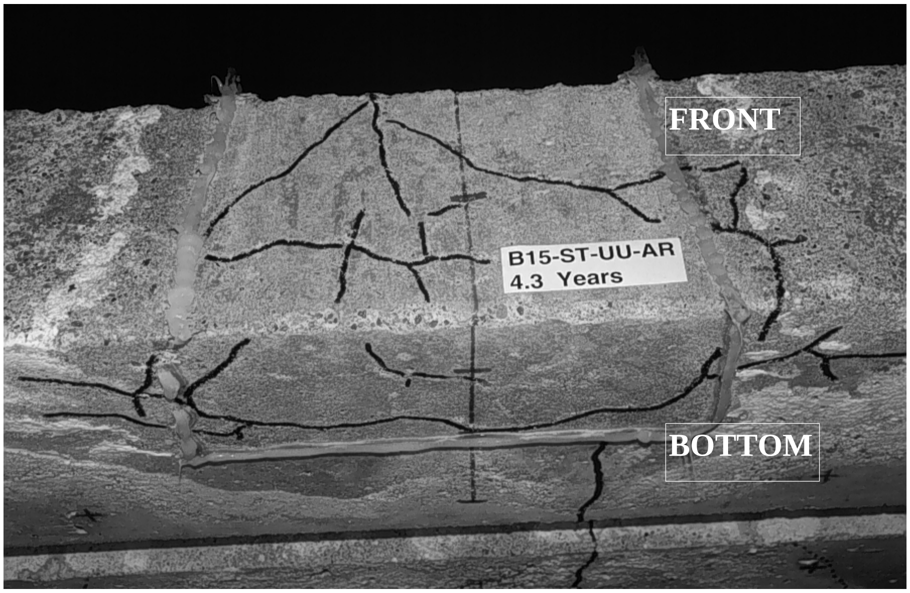


Figure 9.40: Surface cracking on previously uncracked beam B15 (front and bottom surfaces as in exposure).

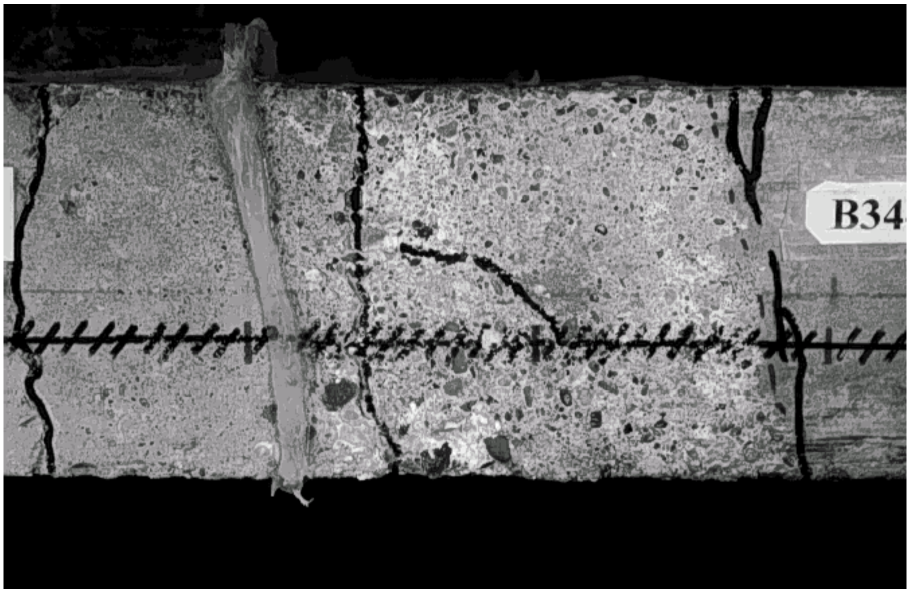


Figure 9.41: Concrete scaling and deterioration outside wetted region (front surface as in exposure).

Group I Specimens

Beam No.1 (Uncracked unloaded with as received bar)

A series of fine cracks at random orientations was detected at the front and bottom beam surfaces within the wet zone at about 2.8 years of exposure.

A crack perpendicular to the beam axis was first observed at the bottom surface of the beam at about 1.8 years. The crack extended across the face of the beam at midspan section, as shown in Fig. 9.42. The crack width was between 0.10 and 0.15 mm. The crack length increased on the front beam surface at about 2.4 years. No evidence of rust was found around the crack. The crack was characteristic of a flexural crack but the beam was intended to be uncracked and no permanent load was applied. It may be that during handling, a load was accidentally applied.

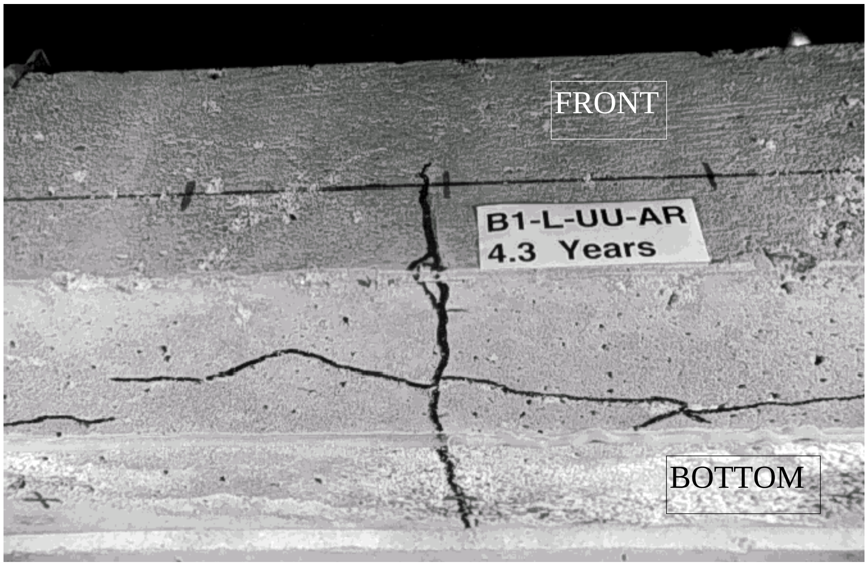


Figure 9.42: Cracking on initially uncracked, unloaded beam B1 (front and bottom surfaces as in exposure).

Beam No. 8 (Uncracked unloaded with 3% damaged bar)

A few small brown stains were first observed at about 1.9 years of exposure on the top surface of the beam within the wet zone.

A series of short cracks developed on the bottom surface within the wet zone (Fig. 9.43). Such cracks were detected at about 3.6 years of exposure and their orientation was parallel to the longitudinal beam axis. The cracks were narrow (0.10 to 0.15 mm wide).

Beam No. 12 (Cracked loaded with 3% damaged bar)

A spot with rust deposits formed on the front surface just outside the wet zone, close to the location of the lower coated bar (Fig. 9.44). The rust spot was first observed at about 2.4 years of exposure. The rust spot grew from about 12 mm^2 up to 50 mm^2 at the end of 4.3 years. A small reddish-brown spot close to the upper black bar was observed at midspan on the top surface at about 2.4 years. The spot gradually faded and was not visible at the end of exposure.

Group II Specimens

Beam No. 15 (Uncracked, unloaded beam, stirrup with as-received coating)

An apparent corrosion-induced crack was detected on the top surface of the beam, within the wet zone, to the left of midspan (Fig. 9.45). The crack was detected at 1.5 years of exposure and ran parallel to the beam longitudinal axis and close (2 cm) to the beam edge. The crack had a width of 0.15 mm. Brownish staining was observed around the crack. At 1.9 years, a build-up of rust was observed along the crack. A crack perpendicular to the first one extended towards

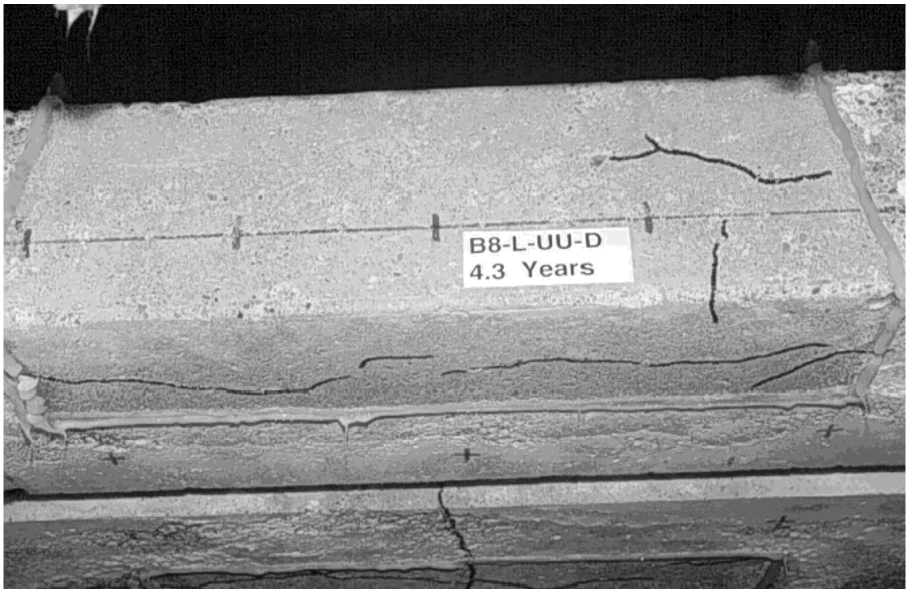


Figure 9.43: Cracking on non-precracked beam B8.

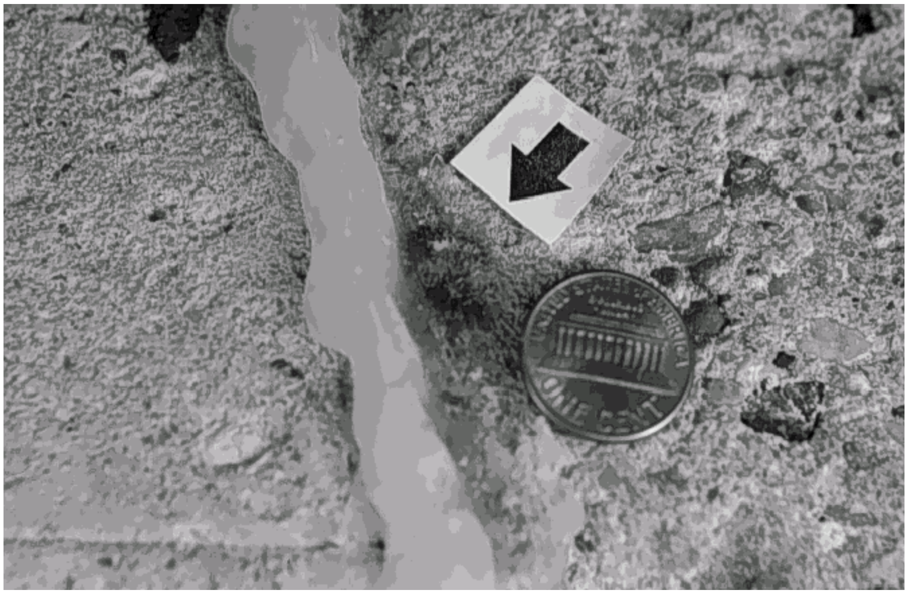
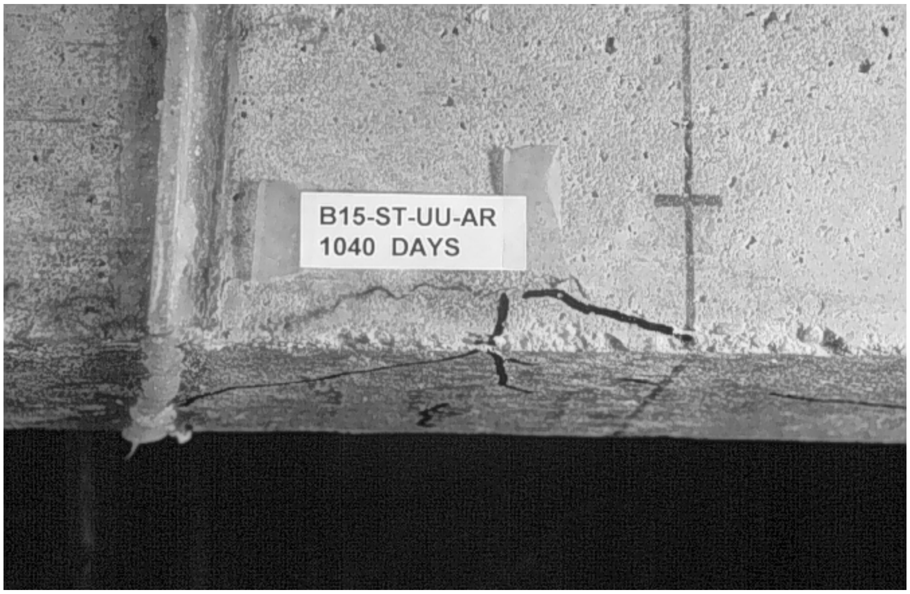
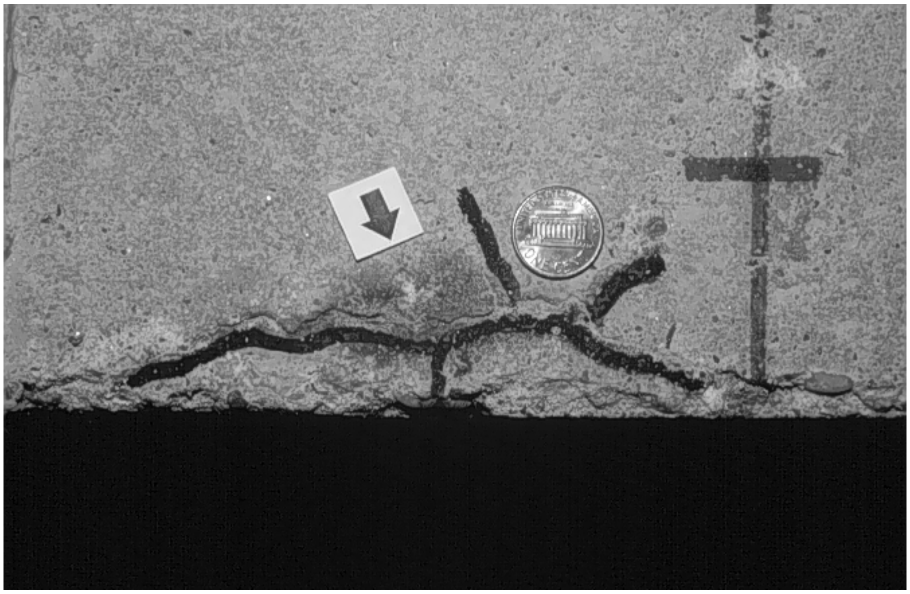


Figure 9.44: Rust spot just outside wetted region on beam B12.



(a) Aspect after 2.8 years.



(b) Close up. Aspect after 4.3 years.

Figure 9.45: Crack with rust exudation on top surface of beam B15.

and around the edge of the beam (crack width was 0.15 mm). At 2.1 years, additional rust built up and the initial crack widened to 0.4 mm. At 2.2 years, the crack extended and rust staining increased. More rust products and staining accumulated on the top surface after 2.5 years (Fig. 9.45). Overall, the size of the rust spot increased from about 7 cm^2 at 1.5 years to 11 cm^2 at 2.8 years. Rust staining around cracking on the top surface stabilized at the end of 3 years and was less prominent at the end of 4.3 years.

A series of long and short cracks (0.1 mm or less in width) with random orientation was detected on the front surface within the wet zone after 2.8 years of exposure (Fig. 9.46). Thereafter, additional short and long cracks with random orientation formed at the front and bottom surfaces, inside the wet zone. Crack widths ranged from 0.08 to 0.20 mm.

Beam No. 22 (Uncracked, unloaded beam, stirrup with as-received, patched coating)

A rust spot formed at the front surface, within the wet zone, close to the top surface and the left boundary of the wet zone, after about 2.2 years of exposure. The size of rust spot was about 28 mm^2. However, the rust spot started to fade away at about 2.7 years. Another dark-brown spot formed after 2.4 years on the front surface, within the wet zone, close to the lower bar location, adjacent to right boundary of wet zone. The spot started to fade at 2.8 years of exposure.

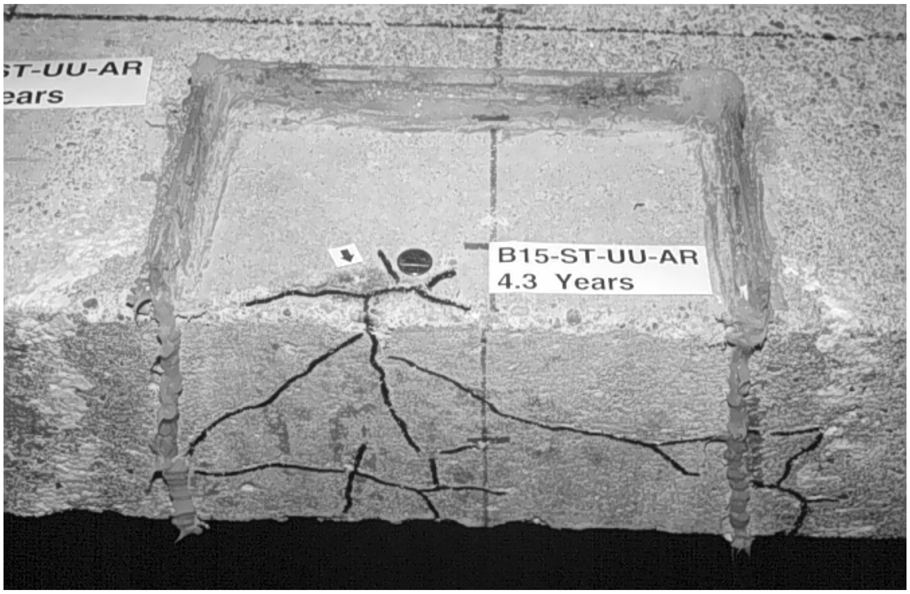


Figure 9.46: Random cracking on front surface of beam B15.

Figure 9.47: Random cracking on non-precracked beam B22.

After 2.7 years of exposure, a crack developed on the front surface, inside the wet zone, extending from top to bottom, perpendicular to the beam axis and adjacent to the left boundary (Fig. 9.47). Maximum crack width measured was 0.15 mm. The crack continued to grow and an extension on the front surface was observed at 3.6 years. The crack extended from the vertical crack further into the wet zone, parallel to the beam axis at the mid-height of the front surface. Additional crack extensions were observed. Maximum crack widths were 0.10 mm.

Beam No. 17 (Cracked, unloaded beam, stirrup with as received coating)

At 1.8 years, a rust spot of approximately circular shape formed on the top surface of the beam, outside the wet zone, located exactly at the end of the flexural crack induced by the stirrup at midspan and close to the upper black bar location (Fig. 9.48). After that, the size of the rust stain gradually increased with time. When first detected, the rust stain measure 144 mm^2 at 1.8 years and enlarged to 2,250 mm^2 after 2.8 years. After 2.8 years until the end of exposure at 4.3 years, the rust spot did not significantly increase in size.

A small dark-brown spot was observed on the top surface, outside the wet zone (just to the left of wet zone, near the front surface), at about 2.7 years of exposure. Another small dark stain was detected on the bottom surface, outside the wet zone (8.5 cm to the left of midspan), at about 2.2 years.

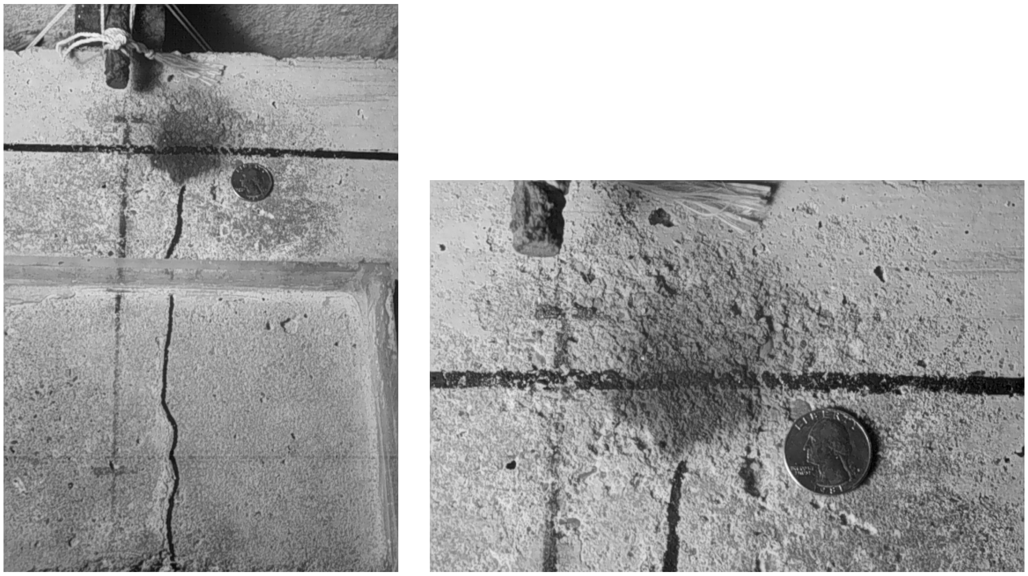


Figure 9.48: Rust spot on top surface of beam B17 at black bar location at midspan.

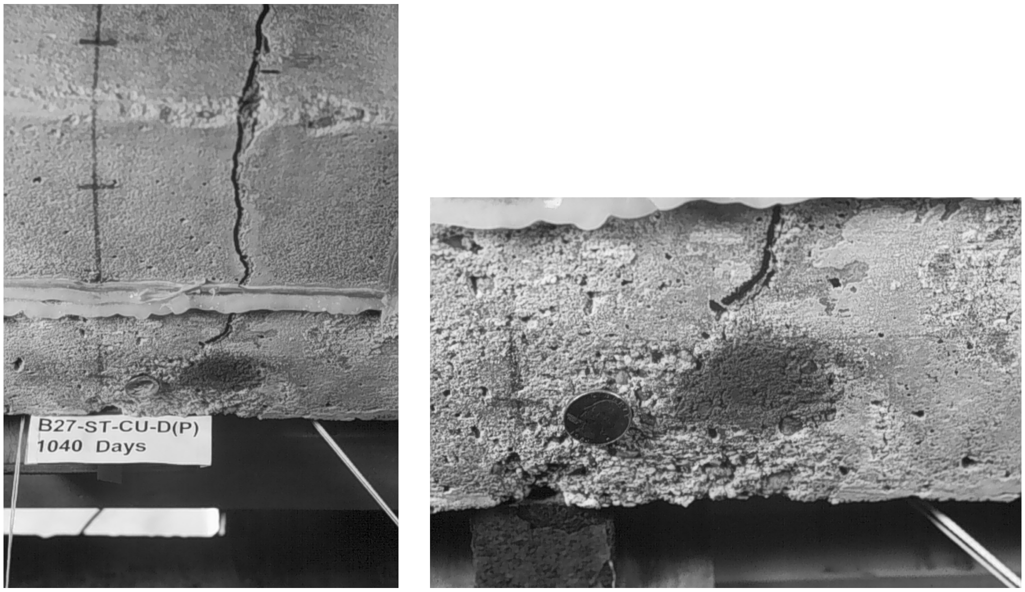


Figure 9.49: Large rust spot on bottom surface of beam B27 at black bar location at midspan.

Beam No. 23 (Cracked, unloaded beam, stirrup with as-received, patched coating)

A medium size rust spot and staining formed at the bottom surface, outside the wet zone, at the end of the flexural crack induced by the stirrup. The spot was first seen at about 1.8 years of exposure and measured 48 mm^2. It gradually increased to 400 mm^2 at the end of 3.6 years, with no significant increases thereafter.

Beam No. 27 (Cracked, unloaded beam, stirrup with 3% damage to coating and patched)

A rust spot of circular shape formed on the bottom surface of the beam, outside the wet zone, at the end of the flexural crack induced by the stirrup, close to the black bar location (Fig. 9.49). The rust stain was first spotted at about 1.8 years of exposure and measured 700 mm^2. Its size gradually increased with time up to 2,400 mm^2 at 2.5 years, with no significant increases in size thereafter.

A small rust spot appeared at the front surface outside the wet zone, within the zone of scaled concrete surface (to the left of wet zone, about 20 cm to the left of midspan, close to the lower bar location). The spot was first detected at 2.1 years and its size was 36 mm^2 at 2.8 years.

Beam No. 19 (Cracked, loaded beam, stirrup with as received coating)

Rust accumulated at a flexural crack at the stirrup location on the bottom surface, outside the wet zone and close to the location of the lower black bar. Rust was first observed at 2.7 years of exposure. When inspected at 3.6 years, the amount of rust became less prominent. A reddish-brown spot located just outside the wet zone and close to the bottom surface was first observed on the front surface at 2.7 years. It measured 28 mm^2 and was less visible at about 3.6 years.

Group III Specimens

Beam No. 30 (Cracked, unloaded beam with longitudinal bar and stirrup, 3% damage to coating, patched)

Small rust deposits were observed inside a concrete void at the bottom surface of the beam, inside and close to the boundary of the wet zone, at about 15 cm to the right of midspan. The spot was first seen at about 2.2 years and measured about 1.2 mm^2. It spread to 3.0 mm^2 at 2.5 years and was less visible at the end of 3.6 years.

Beam No. 32 (Cracked, unloaded beam; patched end on splice bars; stirrup with 3% damage to coating, patched)

Horizontal cracking (parallel to the longitudinal beam axis) developed on the front surface of the beam, originating from the vertical flexural cracks at mid-height of the vertical front surface. Horizontal cracks extended from one vertical crack to the next, as can be seen in Fig. 9.50. Such cracks were first detected at about 2.0 years of exposure and propagated within the next eight months. Crack width progressed from 0.10 mm at 2 years to 0.20 to 0.25 mm after 3.6 years.

Rust exuded from horizontal crack and adjacent vertical crack at the front surface of the beam within the wet zone, just to the right of midspan. The exudation of rust along with downward flow of solution during the wet cycle left a rust stain below the horizontal crack (Fig. 9.51). Rust along the crack extended 2 cm along the horizontal crack and 2.7 cm along the vertical crack. Rust staining increased up to a size of 400 mm^2 at about 3.6 years of exposure. The rust stain seemed to dissipate with subsequent wet cycles.

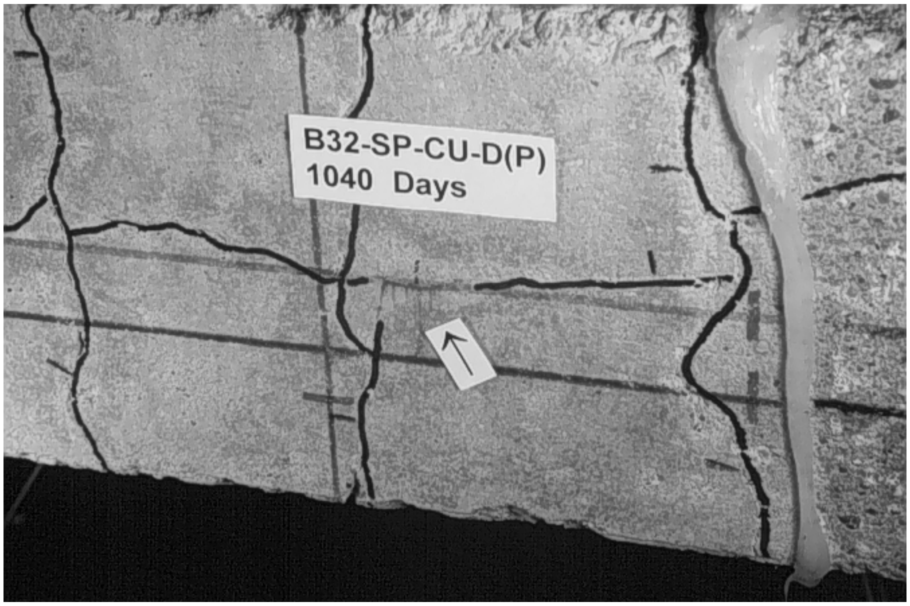


Figure 9.50: Horizontal cracking on front surface of beam B32.

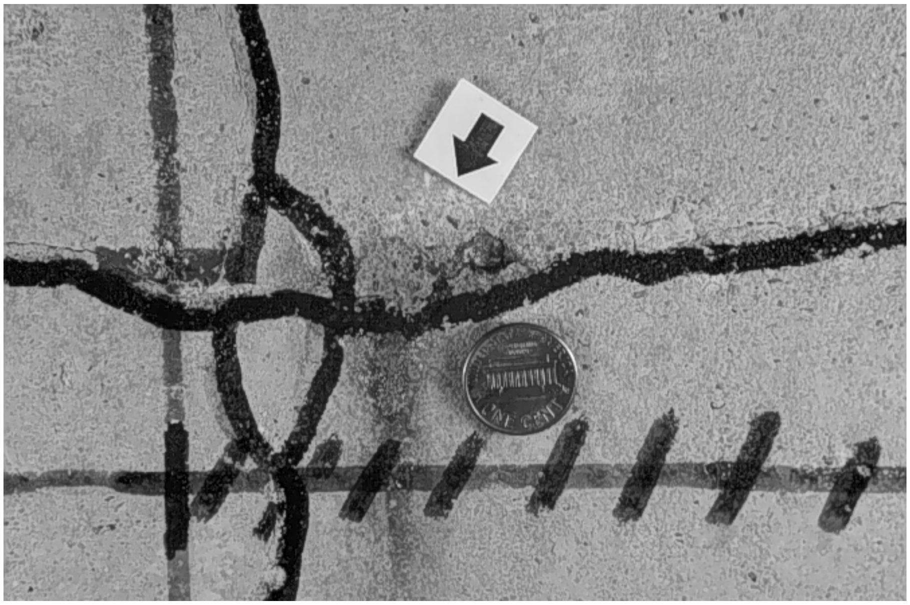


Figure 9.51: Rust exuding through cracks on front surface of beam B32

Beam No. 34 (Cracked loaded beam; patched end on splice bars; stirrup with 3% damage to coating, patched)

Rust accumulated inside a flexural crack at the bottom surface of the beam, inside the wet zone, just to the right of midspan section. The rust was observed at about 2.2 years and extended 2 cm along the crack and to the boundary of the wet zone.

In summary, 2 out of 7 beams of group I experienced minor rust stains only. Four out of 7 group II beams exhibited major rust staining. One of three beams in group III experienced major rust staining, and all beams in group III exhibited staining. Considering all beams, 11 out of 17 experienced rust staining.

9.5.3 Crack Widths

Widths of flexural cracks were measured periodically to monitor any changes produced by corrosion, concrete deterioration, and cyclic loading. Beams were initially loaded to produce a maximum crack width of 0.33 mm (0.013 in.). The magnitude of the cyclic loading was adjusted during the exposure to maintain the maximum crack width. In several cases, maximum crack width was in excess of 0.33 mm even with a very small cyclic load after several years of exposure.

As time of exposure increased, measurement of crack widths became more difficult. Concrete scaling and deterioration in the wet zones resulting from salt crystallization and erosion under the flowing solution roughened the concrete surface around the cracks. In many cases, cracks appeared wider than they really were. Frequently, concrete at crack surfaces was so eroded and disintegrated that the points where the widths were measured had to be constantly changed. For these reasons, crack width measurement in deteriorated concrete surfaces was not very reliable because some judgment was needed to determine crack widths.

Beam No.	**Maximum Crack Width (mm)**	**Comments**
Group I (Longitudinal Bars)		
B3 (AR)	0.15	Cracks did not open. Several horizontal cracks appeared on the front surface.
B10 (D)	0.20	Cracks did not open. Several horizontal cracks appeared on the front surface.
B14 [D(P)]	0.20	Cracks did not open. Several horizontal cracks appeared on the front surface. A new vertical crack formed.
Group II (Stirrups)		
B17 (AR)	0.30	Cracks did not open.
B23 [AR(P)]	0.25	Cracks did not open.
B27 [D(P)]	0.35	Cracks did not open.
Group III (Longitudinal Bars or Splices, Stirrups)		
B30 [L/ST-D(P)]	0.15	Cracks did not open. Horizontal cracks appeared between vertical cracks on front surface.
B32 [SP-D(P)]	0.30	Cracks opened a little bit. Horizontal cracks appeared between vertical cracks on front surface. Cracks on bottom surface lengthened.

Table 9.7: Maximum crack width of cracked unloaded beams after 4.3 years.

A summary of the maximum crack width at the end of exposure along with some brief comments are included in Table 9.7. Most cracks did not open, but several horizontal cracks (parallel to the longitudinal beam axis) extended between vertical cracks on the front surfaces.

9.5.4 Forensic Examination

General

Most of the specimens remaining after one year of exposure were autopsied after completion of 4.3 years of continuous exposure. The method used to open the specimens was similar to that used to open specimens after one year. The main difference was that the use of a jackhammer was minimized. To remove longitudinal bars, deep slots were saw-cut along the two surfaces next to the bar location at a depth slightly less than cover on the bar. Concrete cover was removed by chiseling with a hammer. In this way, the integrity of removed concrete segments was better preserved and damage to the epoxy coating was minimized.

The procedure to remove the stirrups was more involved and complicated. Unlike specimens opened at one year, the beams were not sliced in half. Instead, slots perpendicular to the beam axis were saw-cut around the beam at two cross sections, about 4 in. to the left and right of midspan. Concrete cover around the stirrup was then removed by chiseling. Concrete inside the stirrup was chipped with the jackhammer. Additional concrete around the longitudinal bars (epoxy coated and black) was chipped to remove the entire coated stirrup/longitudinal bars assembly.

All uncoated bars were removed from the beams for examination. The procedure was similar to that for longitudinal coated bars but became more difficult because of bond between the bars and concrete.

Six beams were not autopsied because they were scheduled for additional exposure testing. The beams that were not opened were the following:

- Group I: B3-L-CU-AR, B6-L-CL-AR, B12-L-CL-D
- Group II: B19-ST-CL-AR
- Group III: B30-L/ST-CU-D(P), B34-SP-CL-D(P)

Concrete Delamination

Before opening the specimens, signs of concrete delamination were detected by tapping the surface with a hammer. Despite the presence of large rust spots on several beams and additional horizontal cracking at other beams, none of the specimens developed concrete delamination.

Chloride Content

As was done previously, the chloride content per unit weight of concrete was measured at different depths. Concrete powder samples from different depths were obtained by drilling through the specimens at several selected points along the beam surface. Two samples for each representative depth were obtained.

Table 9.8 contains chloride contents by percent of concrete weight at several beam locations and depths from the top surface (corresponding to upper and lower bar locations). As expected, chloride concentration was greater at the wet zone and dissipated as the distance from the wet zone increased. However, chloride concentration was similar or slightly greater at the dry zone of the beam abutting the wet zone (compression side of the beam at midspan portion) than at the wet zone. Chlorides effectively penetrated the concrete through a relatively large portion of the beam beyond the wet zone.

Beam No.	*Wet Zone*		*At Crack in Wet Zone*		*At Crack in Dry Zone*		*Dry Zone near Wet Area*		*Dry Zone far from Wet Area*	
	*50-75 * mm*	*127-152 * mm*	*50-75 mm*	*127-152 mm*	*50-75 mm*	*127-152 mm*	*50-75 mm*	*127-152 mm*	*50-75 mm*	*127-152 mm*
B1	0.55	0.54					0.83	0.74	0	0
B3	0.46	0.67					0.67	0.99		
B8	0.42	0.53							0	0
B10	0.51	0.59	0.73	0.47			0.48	0.69	0	0
B14	0.72	0.62	0.64	0.63			0.77	0.69	0	0.28
Avg.	0.53	0.59	0.69	0.55			0.69	0.78	0	0.06
B15	0.56	0.60					0.39	0.02		
B17			0.60	0.69	0.97	0.70	0	0.02		
B22	0.57	0.61					1.05	0.96		
B23	0.63	0.69	0.56	0.61			0.66	0.82		
B25	0.60	0.52			0.66	0.62	0	0.31		
B27	0.50	0.59	0.55	0.45	0.59	0.62	0.10	0.58		
Avg	0.57	0.60	0.56	0.33	0.63	0.62	0.44	0.54	-	-
B30	0.74	1.06	0.94	1.06						
B32	0.65	0.70	0.70	0.82	0.89	0.81	0.66	0.67	0.29	0.58
B34	1.07	0.88	1.23	1.34						
Avg	0.82	0.88	0.95	1.08	0.89	0.81	0.66	0.67	0.29	0.58

*Depth from surface (upper and lower bar locations)

Table 9.8: Chloride concentrations (Percentage by weight of concrete) in autopsied beams after 4.3 years of exposure at several beam locations and depths from the top surface.

This finding was important because it indicated the presence of a high chloride content at the location of uncoated bars. The use of black bars in the compression zone was based on the premise that the bars would be outside the wet regions of the beams. However, after 4.3 years of exposure, chlorides penetrated and diffused through the concrete to the black bars. Uncoated bars subjected to high chloride contents are vulnerable to corrosion. The autopsies showed that uncoated bars underwent severe and extensive corrosion.

Flexural cracks adjacent to wet zones did not stop passage of chlorides to outer regions as they did in specimens examined after one year.[10] Instead, chloride amounts gradually decreased as a function of distance from the wet zone. Generally, chloride contents were low in regions farther than 60 cm (24 in) from the midspan section.

Table 9.9 shows that average chloride contents were higher after 4.3 years than after one year of exposure. As with specimens examined at the end of one year, chloride contents tended to be higher at crack locations. However, as can be seen in Table 9.9, the difference in chloride concentrations between crack and non-crack locations within the wet zone after 4.3 years decreased or disappeared, especially in groups I and II. Clearly, chloride diffused and penetrated within the concrete so extensively that chloride distribution was more uniform after more than four years of exposure.

As a reference, the average chloride concentrations in macrocell specimens at the level of the steel was in the order of 0.34% by weight of concrete, while average chloride concentrations in the wet zone of the beams (non-crack locations) at the level of upper or lower bars ranged from 0.53% to 0.88% by weight of concrete. As mentioned before, reported chloride thresholds to trigger corrosion of uncoated steel are in the range of 0.02-0.05% by weight of concrete.[10] These numbers give a clear idea of the severity of the exposure conditions for both coated and, especially, for uncoated bars.

Group No.	**Depth * (mm)**	**Wet Zone**		**At Crack in Wet Zone**	
		1 Year	**4.3 Years**	**1 Year**	**4.3 Years**
I	50 - 75	0.114	0.53	0.39	0.69
	127 - 152	0.154	0.59	0.43	0.55
II	50 - 75	0.302	0.57	0.595	0.56
	127 - 152	0.356	0.60	0.505	0.53
III	50 - 75	0.59	0.82	0.795	0.95
	127 - 152	0.55	0.88	0.75	1.08

*Upper and lower bar location

Table 9.9: Average chloride concentration (Percentage by weight of concrete) in the wet zone at two depths from the top surface, after 1 and 4.3 years of exposure.

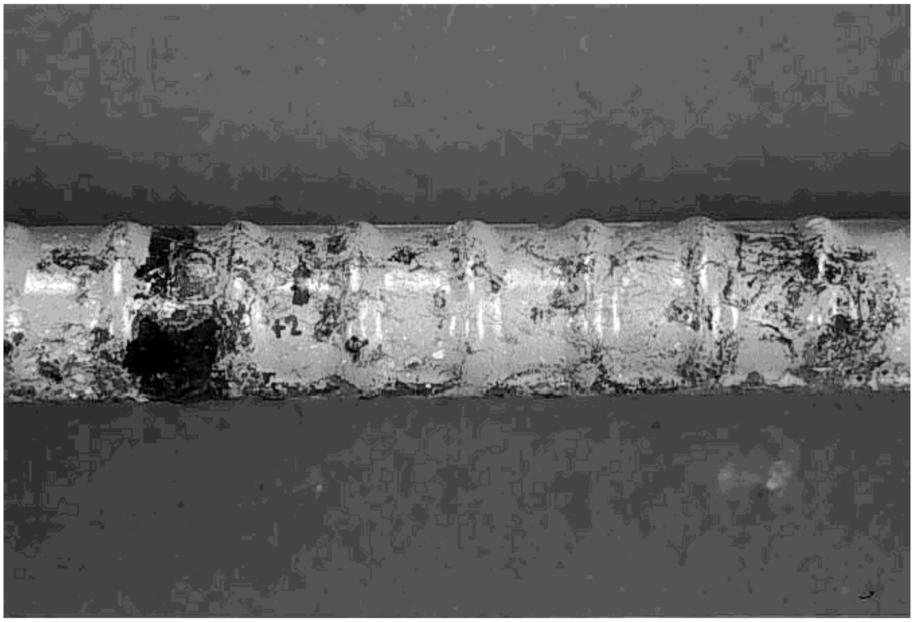
Appearance at Removal from Concrete

The following observations pertain to the appearance of the epoxy-coated bars before peeling the coating to uncover the metallic surface underneath. Results from such examination are shown later. Here, the condition of the coating surface and of the damaged areas is described. As was found later, the condition of the coating surface frequently differed from the condition of the metallic surface beneath the coating.

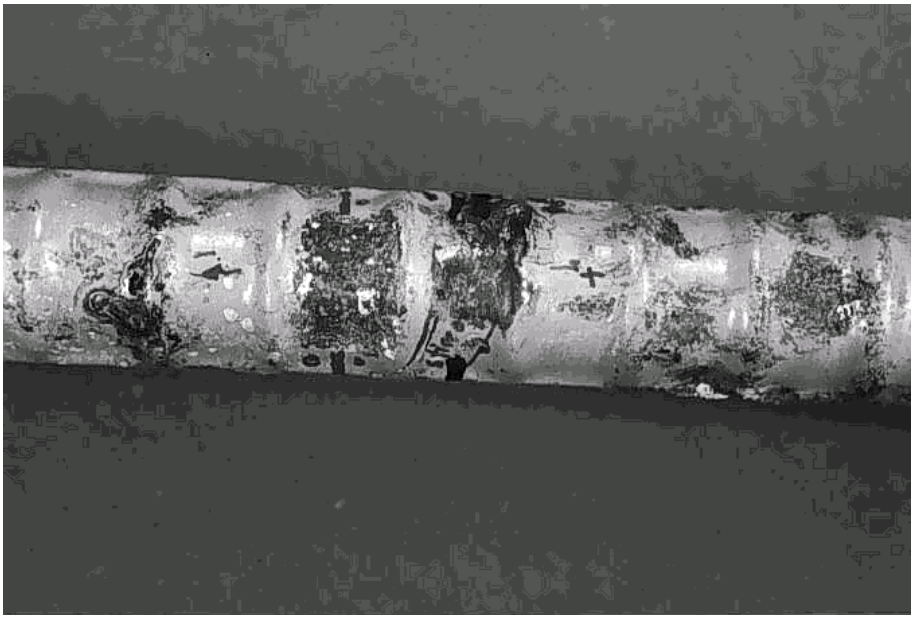
As in coated bars from macrocell specimens, the manifestation of corrosion consisted of rust staining, coating blistering, and corrosion attack of exposed areas (Fig. 9.52). The color of rust stains ranged from dark to light brown, and their appearance varied from dense to tenuous. Blisters size varied, with smaller ones being more prevalent. Corrosion did not always occur at the damaged, exposed areas. Minor corrosion was observed on patched areas. There was almost always a void in the concrete surrounding a blister. However, corrosion did not always occur at coating areas adjacent to concrete voids. Contrary to the observations from coated bars in macrocells, the appearance of brownish, liquid, acidic solution was not as pronounced in bars from beam specimens. The time between autopsy and end of exposure was longer for beams and could explain the difference observed.

Bar in As Received Condition

The as-received bars in beam B1 (uncracked, unloaded) were in excellent condition at the end of testing (Fig. 9.53). Both upper and lower bars were in pristine condition, with no evidence of damage, such as cracking or thinning of coating. There were only a very few small brown rust stains at isolated locations on both bars.



(a) Rust stains at lower bar of beam B10, portion within the wetted zone. Damaged spot at crack location.



(b) Bar of beam B10, portion at midspan (wetted zone).

Figure 9.52: Corrosion of longitudinal coated bars.

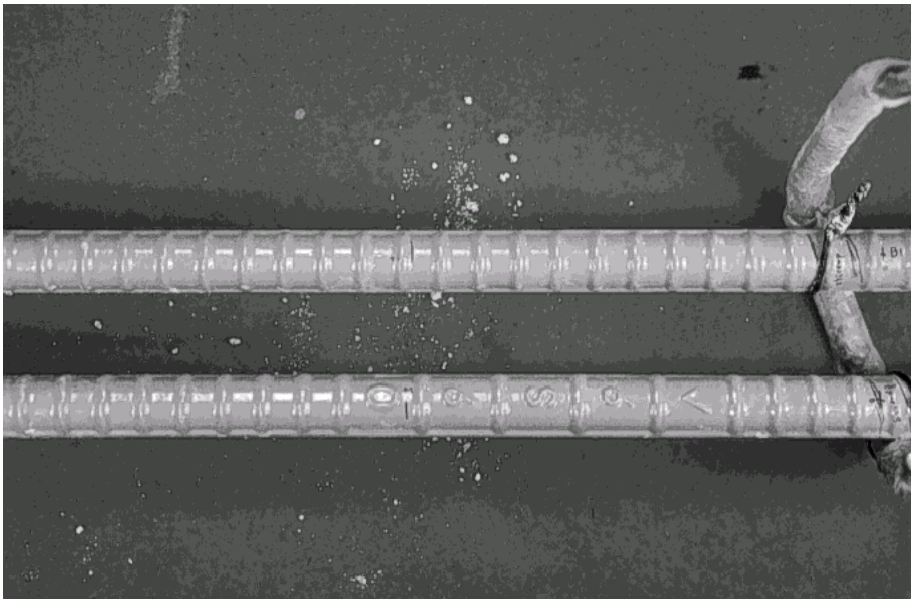


Figure 9.53: Longitudinal coated bars of beam B1 after 4.3 years of exposure.

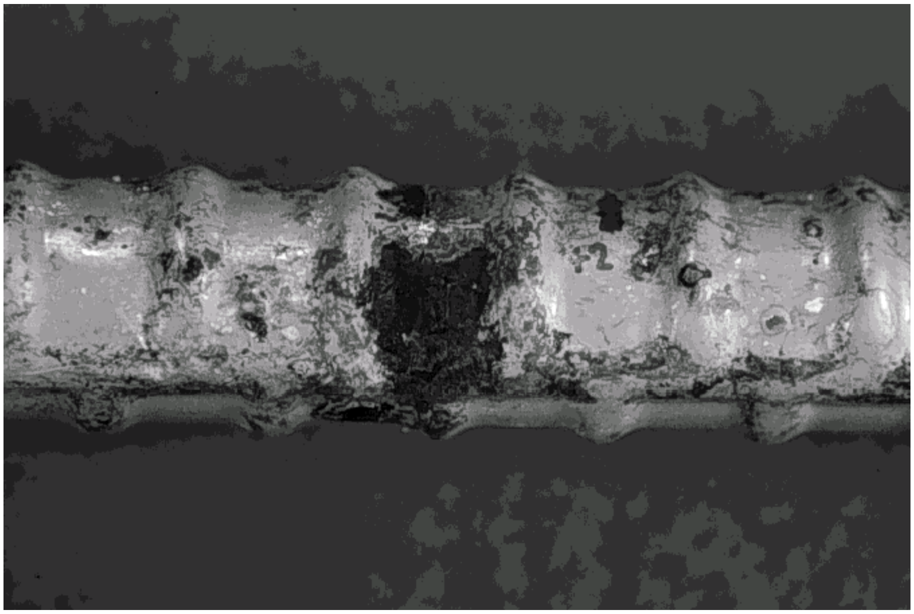
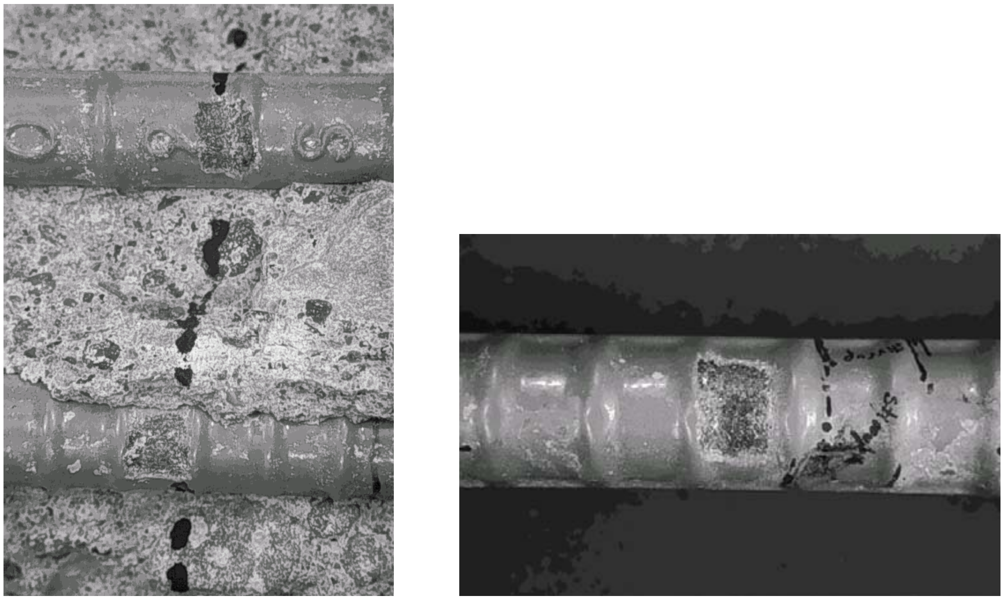


Figure 9.54: Build up of rust products at damaged spot on bar from beam B10.

Bars with 3% Damage

All bars with 3% damage underwent some degree of corrosion and rust staining on the coating surface, regardless of loading condition and presence of cracks. Damaged areas had a uniformly dark brown rust, in some cases with buildup rust products (Fig. 9.54). No deep pits were noticed. Interestingly, not all damaged areas corroded, and there were several exposed areas with a clean metallic surface, even in proximity with cracks! (Fig. 9.55). There was no specific pattern regarding location of corroded areas. Frequently, concrete adjacent to uncorroded exposed sites had only a few small voids.



(a) Outside the wet zone of of beam B10, about 43 cm to the left of midspan.

(b) Damaged spot located near stirrup and crack inside wetted region (Beam B10).

Figure 9.55: Uncorroded damaged areas near crack locations.

Away from damaged, exposed areas, the epoxy coating surface was stained in different ways. Typical stains were light-brown, brownish, dark-brown, and black. Shape and size of stains ranged from a series of very small stains grouped together to more isolated large stains (Fig. 9.52). A series of small blisters were usually observed at areas with more rust staining. Blister surfaces were typically dark or brown. At some locations, a series of short, fine cracks formed on the coating. Overall, the epoxy surface condition was relatively good considering the severity of the exposure for 4.3 years.

Bars with 3% patched damage (beam B14, cracked, unloaded) showed less extensive corrosion than bars with unrepaired damage. Several patched areas showed brown rust staining, from tiny freckles to larger stains. Several other patched spots had no rust spotting (Fig. 9.56).

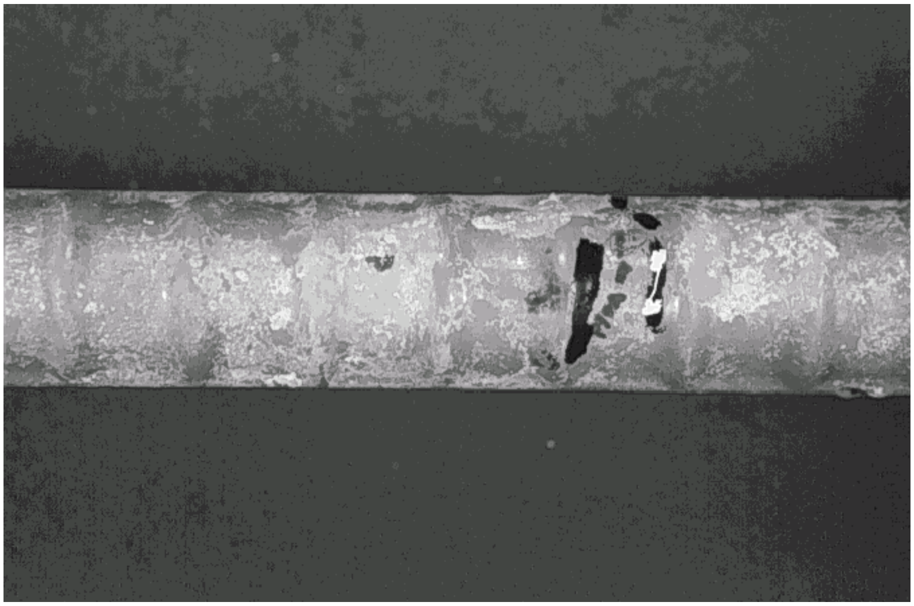


Figure 9.56: Aspect of uncorroded patched area on upper bar in beam B14, near crack location within the wetted zone.

In general, lower bars tended to have more corrosion than upper bars. Corrosion spread more at the bottom side (as in casting position) of the bars than on their top side.

Stirrups in As Received Condition

Rust staining was much more extensive on the side of the stirrup facing the concrete cover. The patch at the hook ends was accidentally chipped off during autopsy; exposed areas at patched ends showed dark rusting. Several dark lines evidencing coating distress and incipient cracking were visible at the most corroded portions, especially alongside longitudinal ribs. Overall, few blisters developed.

The stirrup from an uncracked, unloaded beam (B15) underwent extensive staining on two legs and on two bends. One leg was practically stain free. At the time of autopsy, there were four greenish or dark-greenish rust spots on one leg; after one or two days, their appearance changed to reddish-brown or orange-brown. The stirrup from a cracked, unloaded beam (B17) had rust staining that was more dense on the portion of the stirrup within the wetted zone (Fig. 9.57).

Stirrups in As Received Condition and Patched

More rust staining was observed on the outside than on the inside of the stirrups. Few blisters developed on the coating surface. Lines of coating distress or incipient cracking were observed at some of the more corroded portions. The patch at hook ends usually broke off during autopsy, but exposed areas were not always corroded (Fig. 9.58).

Figure 9.57: Rust staining of stirrup from beam B17 (portion within the wet zone).

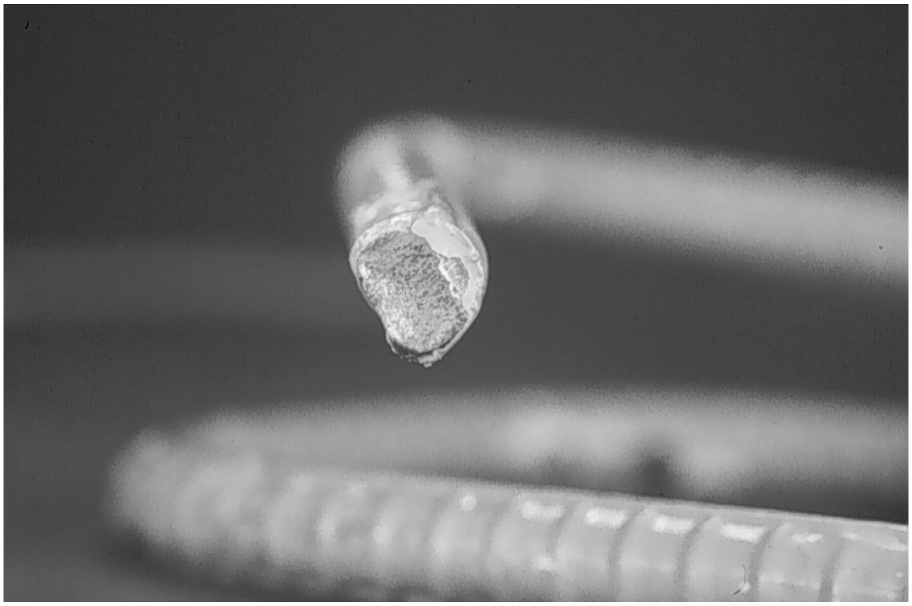


Fig. 9.58: Patch at bar end of a stirrup hook that broke during autopsy (beam B23). Metallic surface beneath the patch was uncorroded.

The stirrup from uncracked, unloaded beam B22 experienced extensive rust staining Many patched areas experienced extensive to moderate rust staining. The coating cracked alongside longitudinal rib at two stirrup legs. The stirrup from cracked, unloaded beam B23 developed extensive staining at one bend. The stirrup at cracked, loaded beam B25 showed more extensive rust staining on three legs and the coating cracked at several portions.

Stirrups with 3% Repaired Damage

Stirrups developed more extensive rust staining on the side of the stirrup facing the concrete cover. Corrosion was not concentrated at patched areas with respect to other bar portions. Several blisters were observed on coating surfaces. Cracks developed in the epoxy several weeks after autopsy. Extensive coating cracking developed several weeks after autopsy at longitudinal ribs.

The stirrup from cracked, unloaded beam B27 experienced extensive rust staining at three legs and one bend. Several blisters and coating breaks were observed on one leg. The stirrup in cracked, unloaded beam B32 (with splice bars) developed widespread rust staining at two legs and two bends (Fig. 9.59). The coating exhibited good condition at two legs. Patched areas at one bend and on one cut end did not develop corrosion and showed a clean steel surface. Remaining patched areas experienced tearing of the patch with visible dark corrosion of the exposed steel areas.

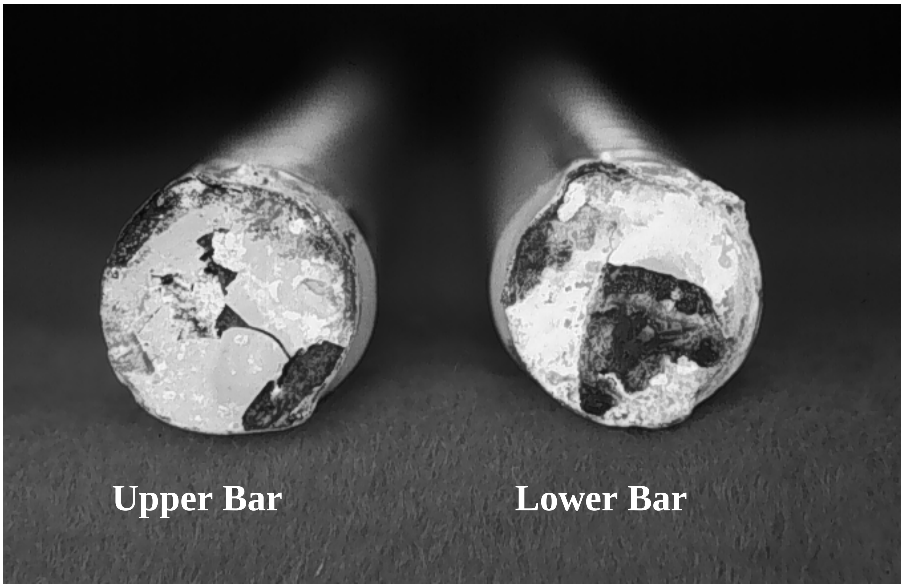
Fig. 9.59: Rust staining on a stirrup leg near the front beam surface (beam B32).

Bars in Splice Zone

Short Bars

The patch at the cut end of the bar cracked and left some portions of steel uncovered. The steel surface of unprotected areas was black or dark rust (Fig. 9.60). Several dispersed rust stains, ranging from dark to light, formed on the epoxy surface, mainly towards the top and front side of the bar (closer to the exterior beam surfaces). Rust staining extended about 23 cm from the bar cut end.

At the lower bar, the patch at the bar cut end broke and left a large exposed steel area. The exposed steel surface color was black rust (Fig. 9.60). Concrete paste residues stuck to remaining patched areas. Several dark, brown rust stains developed on the coating surface on the bottom side of the cast position of the bar, that is, towards the exterior front surface of the beam. No staining was observed on the opposite side of the bar. Rust staining extended up to 17 cm from the bar cut end.



(a) Patch at bar ends of splice bars broke during autopsy, showing a dark corroded surface underneath.

(b) Lower splice bar, appearance of bar end at time of autopsy.

Fig. 9.60: Patched ends of splice bars from beam B32 after 4.3 years of exposure.

Long Bars

At the upper bar, a few rust stains developed on the coating surface, mainly at their top side as in the casting position, that is, the side facing the inner core of the beam and adjacent to the overlapping short bar. Rust staining occurred to the right of midspan, within the spliced zone.

At the lower bar, several rust stains formed mainly at the side facing the exterior front beam surface. Rust stains extended from 8 cm to the left of midspan to 6 cm to the right of midspan. At the opposite side of the bar (facing towards the inner beam core), stains formed to the right of midspan.

Uncoated bars in Compression Zone

General

Black bars moderately to extensively corroded and several moderate to severe pits were observed. Corrosion typically consisted of uniform black or dark rust with widespread shallow pitting (Fig. 9.61). Several moderate to severe pits were observed in more corroded bars, as shown in Fig. 9.62. Loss of cross-sectional area was evident at locations. Dark-green rust was frequently observed at severe pits at the time of autopsy. After being exposed to oxygen, dark-green areas changed to reddish-brown or dark color. Numerous, scattered reddish-brown rust spots appeared above the black corroded surface of the bars after being exposed to air for several hours and days. Similar to uncoated bars in macrocells, drops of brown, acidic solution, formed on the bar surfaces a day after removal from the concrete. Corrosion was generally confined to the wet zone in bars from group I but extended beyond the smaller wet zone in bars from groups II and III. Fragments of concrete of different size remained stuck to several portions of bar surfaces, evidence of good adherence between concrete and uncoated steel.

Beams Group I

Black bars in three beams [two cracked, unloaded beams (B14 and B10) and one uncracked, unloaded beam (B1)] were moderately to extensively corroded. Several moderate to severe pits were observed in six bars with more corrosion (B1, B10, and B14). Black bars in the remaining uncracked, unloaded beam (B8) did not show much corrosion.

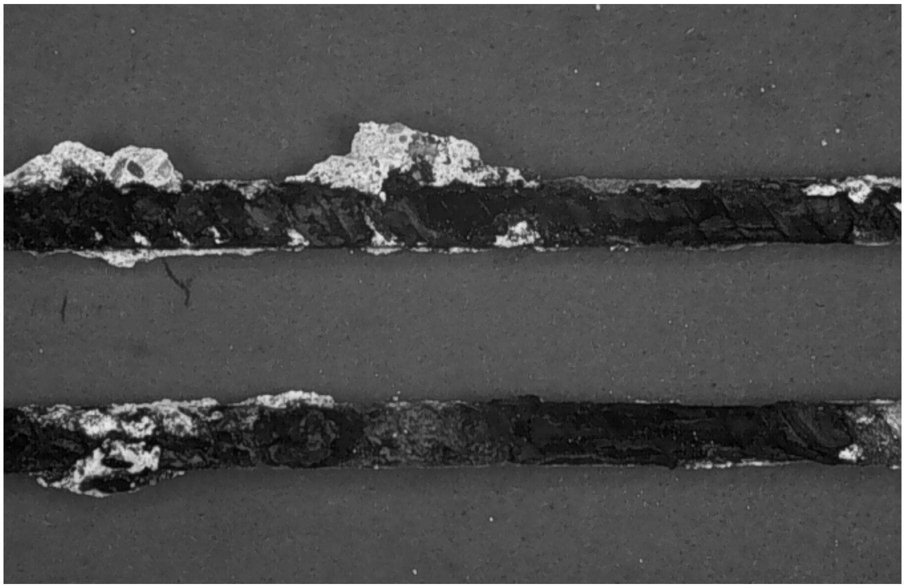
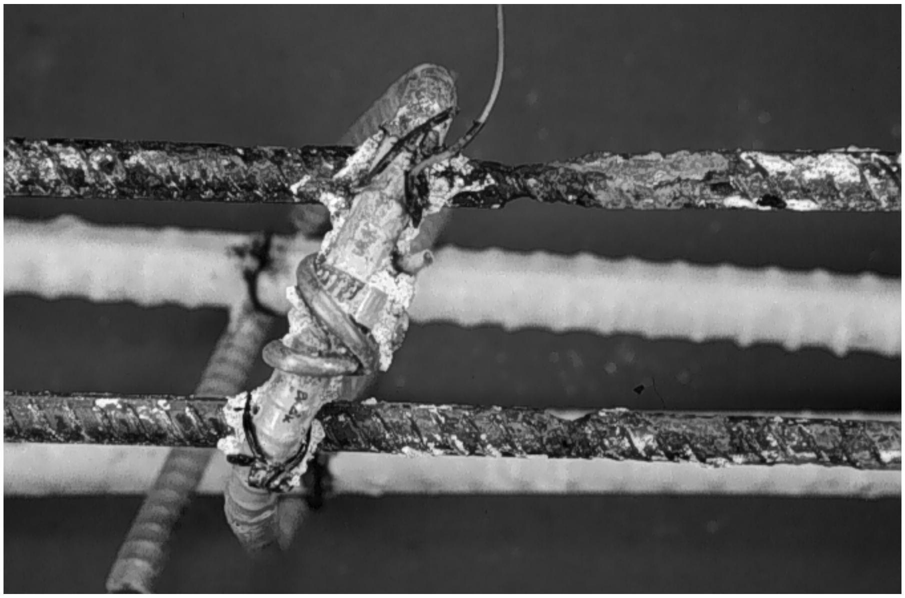


Fig. 9.61: Dark corrosion with widespread pitting on uncoated bars from beam B14.

(a) Severe pitting on lower black bar near coated stirrup (beam B23).



(b) Severe pitting on black bars near coated stirrup (beam B23)

Fig. 9.62: Severe pitting and loss of cross-section on uncoated bars near crack locations.

The extent of corrosion for each bar in terms of percentage of surface area and number and size of pits is summarized in Table 9.10. The amount of corroded surface is given as percentage of bar surface along a 0.9 m. length of bar at midspan. Since the wetted zone was 0.6 m. long, percentages of corroded surface greater than 67% indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Beam No.	**Bar**	**Corroded Surface (%)**	**No. of pits**	**Max. pit depth (mm)**	**Max. loss of cross-section (%)**
B1-L-UU-AR:	Upper	67	4	1.9	20
	Lower	31	2	1.4	17
B8-L-UU-D	Upper	28	0	0	0
	Lower	13	0	0	0
B10-L-CU-D	Upper	58	7	1.4	14
	Lower	50	5	2.4	23
B14-L-CU-D(P)	Upper	61	5	2.5	25
	Lower	81	4	1.3	30

Table 9.10: Approximate amount of corroded surface (percentage of bar surface along 0.9 m in midspan), pitting, and maximum loss of cross-section (percentage of bar cross-sectional area) of black bars of beams group I.

Severe pitting was observed in some bars, with maximum localized loss of metal up to 30% (Fig. 9.63). Maximum pit depths of 2.5 mm and 2.4 mm were observed. Bars tended to corrode more on the low side with respect to casting position. Unquestionably, black bars suffered more severe corrosion than longitudinal coated bars.

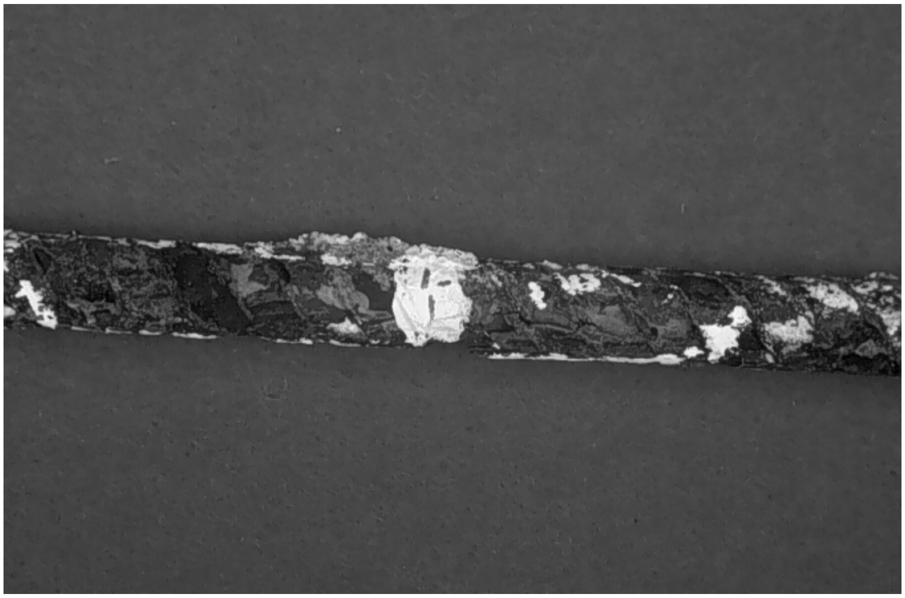


Fig. 9.63: Corrosion on lower black bar of beam B10.

<u>Beams Group II</u>

The extent of corrosion for each bar in terms of percentage of surface area along a 0.9 m. length of bar at midspan, and number and size of pits is summarized in Table 9.11. Since the wetted zone was 0.3 m. long, percentages of corroded surface greater than 33% indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Black bars in cracked beams, loaded or unloaded, experienced severe pitting corrosion. There was generally one very large, deep pit at the location of a crack. Extensive, dark greenish rust staining was observed around the largest, deeply pitted areas during the autopsy (Fig. 9.64). Maximum pit depths ranged from 2 mm to 5.2 mm. Maximum loss of cross-sectional area was 78% of the lower bar of beam B27. Severely pitted bars are shown in Fig. 9.65. One bar in beam 25 was so weakened at the severely pitted cross section, that the bar accidentally fractured while being examined (Fig. 9.66). Overall, corrosion extended from 20 cm to 51 cm along the bars, with most bars experiencing corrosion beyond the limits of the exposed, wetted areas (30 cm long).

Beam No.	**Bar**	**Corroded Surface (%)**	**No. of pits**	**Max. pit depth (mm)**	**Max. loss of cross-section (%)**
B15-ST-UU-AR	Upper	39	5	1	11
	Lower	42	3	1	11
B17-ST-CU-AR	Upper	50	9	2	40
	Lower	56	16	1.7	21
B22-ST-UU-AR(P)	Upper	56	7	1.5	19
	Lower	72	2	1	14
B23-ST-CU-AR(P)	Upper	22	5	2.7	30
	Lower	36	5	3.6	**55**
B25-ST-CL-AR(P)	Upper	47	3	5	**63**
	Lower	28	7	2.8	38
B27-ST-CU-D(P)	Upper	25	7	5.2	**65**
	Lower	50	4	3.3*	**78**

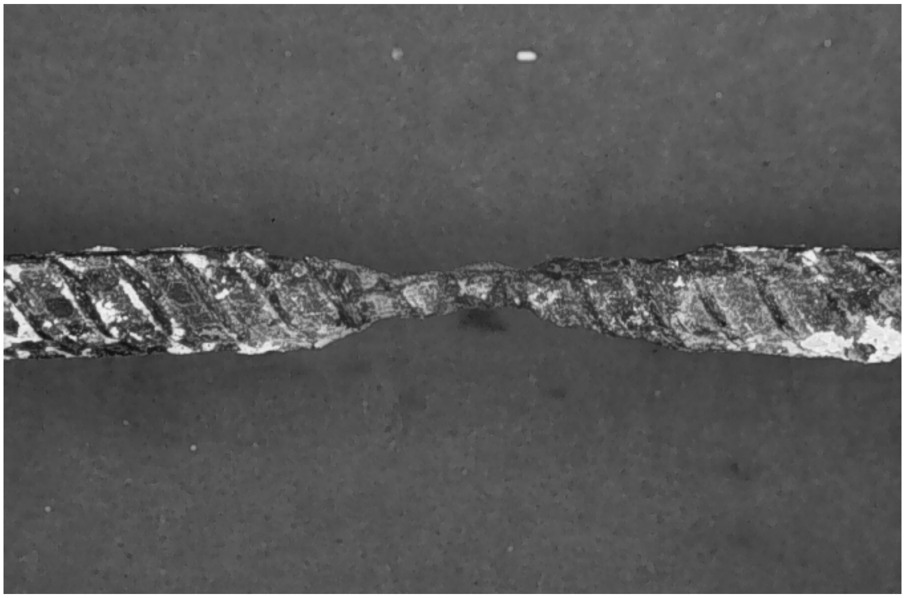
*Pitting all around the bar circumference

Table 9.11: Approximate amount of corroded surface (percentage of bar surface along 0.9 m in midspan), pitting, and maximum loss of cross-section (percentage of bar cross-sectional area) of black bars of beams group II.

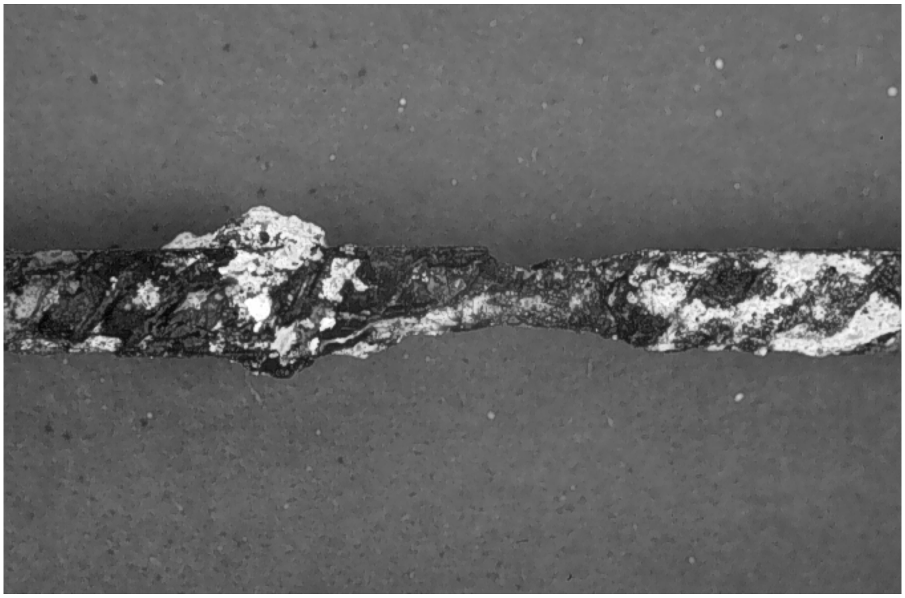
(a) Beam B1

(b) Beam B1

Fig. 9.64: Dark-greenish rust staining around black bars at pitted areas.



(a) Lower black bar of beam B27.



(b) Lower black bar of beam B23

Fig. 9.65: Very severe pitting and loss of cross-section on uncoated bars at crack locations (beam group II).

Fig. 9.66: Upper black bar in beam B25 fractured during autopsy at severely pitted location.

Beams Group III

The only beam autopsied in this group was beam B32, which was cracked and unloaded. Black bars in this beam experienced the appearance of one large, deep pit at a crack location, where the bars showed a discernible loss of cross-sectional area. Maximum pit depth was 2.6 mm for the upper bar and 2.0 mm for the lower bar. Both bars experienced a loss of cross-sectional area of 32%. Several other deep pits and shallower pits of smaller area were also observed. Corrosion extended 56 cm along the bars, well beyond the 30-cm stretch of the exposed, wetted zone.

Table 9.12 summarizes the extent of corrosion in terms of percentage of surface area and number and size of pits observed. Percentages of corroded surface greater than 33% indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Beam No.	**Bar**	**Corroded Surface (%)**	**No. of pits**	**Max. pit depth (mm)**	**Max. loss of cross-section (%)**
B32-SP-CU-D(P)	Upper	61	12	2.6	32
	Lower	61	9	2	32

Table 9.12: Approximate amount of corroded surface (percentage of bar surface along 0.9 m midspan), pitting, and maximum loss of cross-section (percentage of bar cross-sectional area) of black bars of beams group III.

Coating Removal

The steel surface was examined by peeling the epoxy coating. Similar to the procedure for macrocell specimens, a cut was made with a utility knife along one longitudinal rib (generally the rib located on the more corroded bottom side). The coating was then lifted by inserting the blade tip of an X-acto knife under the coating at the precut sections and prying the coating away from the bar. This gave an opportunity for assessing the adhesion of the coating to the steel substrate.

The coating was usually easy to peel on the portion of the bars within the exposure (wet) zone of the beams and gave an indication of nearly complete loss of coating adhesion (Fig. 9.67). Coating debonding progressed from the wet areas at midspan towards the outer, dryer zones and was more extensive in cracked beams than in uncracked beams. Coating adhesion was preserved outside the wet zones of the beams, usually about 0.50 m beyond midspan in beams with larger exposed areas (Group I). At splices (cracked, unloaded beam B32), coating debonded from the cut ends up to a distance of about 20 to 24 cm. In the uncracked beams, bars with 3% damage to coating showed much more adhesion loss than bars in an as-received condition. It was observed that adhesion was always lost around damaged, exposed areas, and the regions with good adhesion were located away from the damaged spots. The as-received bars in uncracked beam B1 had good adhesion within the wet zone, with only limited, isolated areas losing adhesion. The coating could be removed only in small chips (Fig. 9.68).

Coating debonded extensively at stirrups, as can be seen in Fig. 9.69. Coating was very easy to remove at the least corroded portions of the stirrups. It could be lifted up integrally, without breaking or falling apart in small pieces. Coating was less easily removed at the most corroded portions of the stirrups, where it came off in smaller pieces due to its very thin and deteriorated condition. Adherence of rust products to the coating also contributed to the higher degree of difficulty. Because of these factors, coating removal at stirrups was generally time-consuming.

In areas of the bars where adhesion was preserved, the steel surface beneath the coating remained in its original condition (bright, shiny surface) without corrosion. The steel surface beneath the coating at debonded areas changed in appearance and degree of corrosion, as will be discussed in the following section.

Fig. 9.67: Coating debonding of splice bar within the wetted region (beam B32).

Fig. 9.68: Coating adhered well throughout most portions of bars from beam B1.

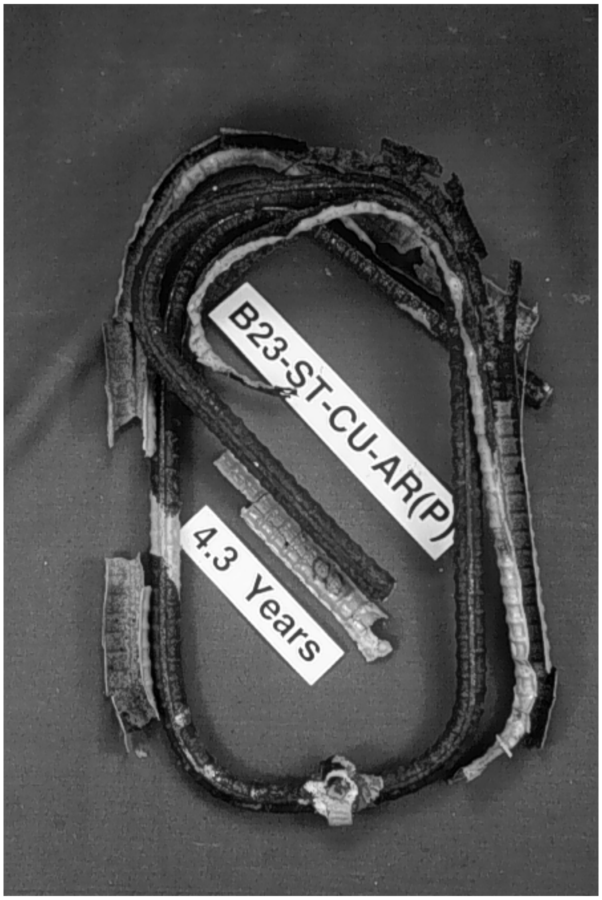


Fig. 9.69: Coating extensively debonded on stirrups.

Underfilm Corrosion

The following observations pertain to the appearance of the metallic surface underneath the epoxy-coating bars within the exposed regions of the beams. This examination was conducted after the coating was peeled to uncover the steel substrate. This task was facilitated by the extensive loss of adhesion experienced by the epoxy-coating within the wet regions.

Some observations noted for macrocells also held true for beam specimens: The greater the amount of rust staining on the epoxy coating, the greater the degree of corrosion on the steel surface beneath the coating. However, the amount of staining on the coating surface was not always indicative of the severity of corrosion of the metal substrate. Corrosion of the steel surface was generally more severe and extensive than the amount of corrosion that was apparent on the coating surface.

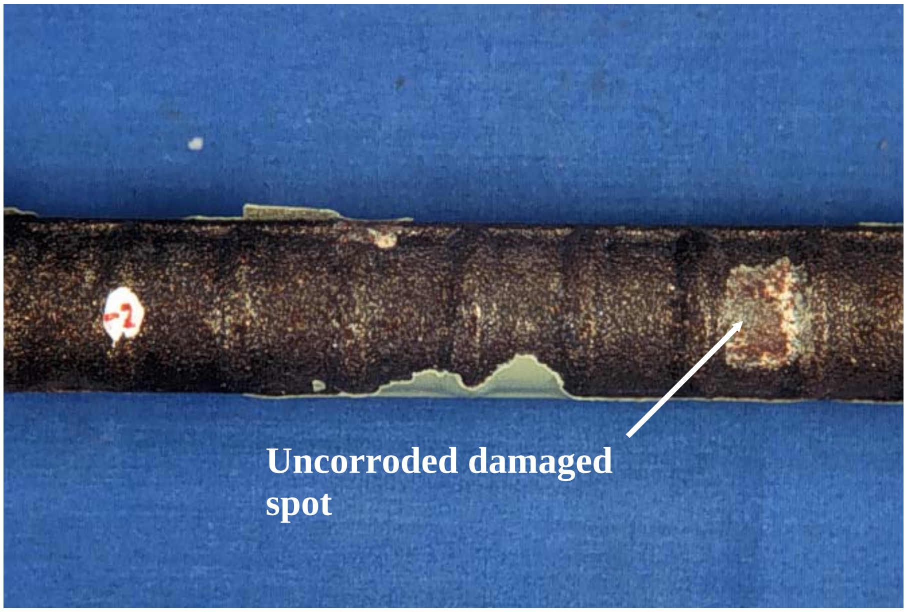


Fig. 9.70: Mottled surface at lower bar of beam B8 within the wetted region.

As in the case of macrocell specimens, two types of surface appearance were found beneath areas with debonded coating: 1) Surfaces with a mottled, glittery golden-brown or bronze appearance, with no corrosion products, as shown in Fig. 9.70; and 2) Dark or black corroded surfaces with accumulation of rust products (Fig. 9.71). Mottled surfaces were thought to be areas where cathodic disbondment took place, as was discussed in Chapter 8. There was not a specific pattern for location and distribution of mottled surfaces: At some bars mottled surfaces predominated in the middle 30-cm portion of the beams, while at other bars, most mottled surfaces were closer to outer portions of wet areas. Mottled surfaces were found more frequently on longitudinal bars than at stirrups.

Fig. 9.71: Dark corroded surface on longitudinal upper bar of beam B8 within the wetted region (zone at midspan).

Similar to macrocell specimens, a uniformly black or dark rusted surface developed at corroded portions of the bar. Depending on the severity of corrosion, shallow pitting and metal depletion, rust volume increase, and blistering developed to varying degrees (Fig. 9.71). No severe, localized, deep pits were found in longitudinal bars. Moderate pits were observed in some stirrups. The largest pits were less than 0.5 mm deep in longitudinal bars and 1.0 mm in stirrups. Figure 9.72 shows the worst pit observed in a stirrup. No drastic reduction of cross-sectional area was found in any longitudinal coated bar. Moderate reductions in cross-sectional area were observed in worst corroded stirrups. Variable amounts of dark rust powder came off during removal of the coating. Blisters had different size and smaller blisters were more abundant than larger blisters. Blistered areas had a very hard, solid consistency.

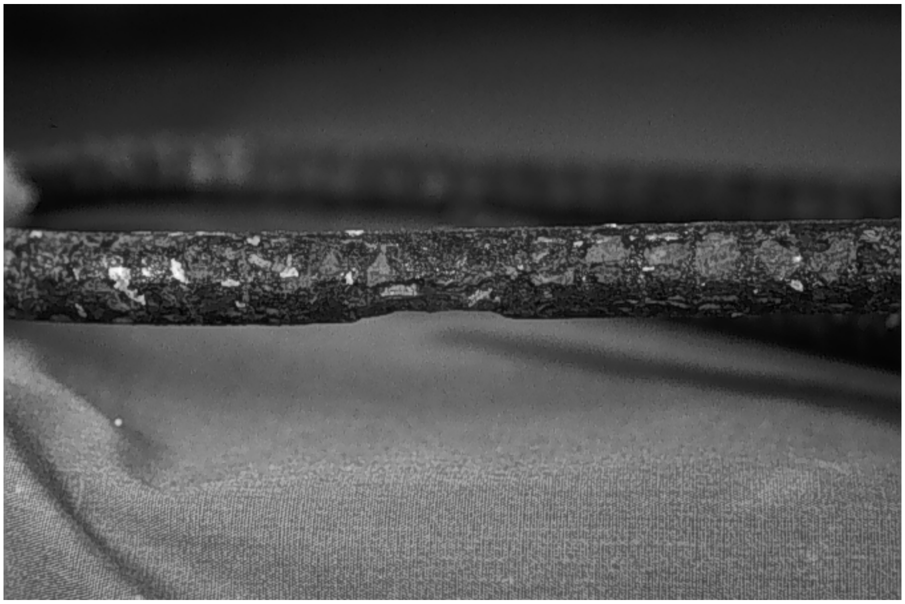



Fig. 9.72: Pitting on stirrup leg near the bottom beam surface (beam B17).

Areas with mostly reddish-brown rust deposits or pockets of varying size, shape, appearance, and amount were usually present above the dark corroded surface (Fig. 9.73). The size of such rust spots ranged from very large to small flecks. Appearance of rust spots was dependent on rust concentration, varying from a light film of rust to thicker layers of rust deposits. In a few instances, spots with whitish, pasty substance were observed. In one case (top bar in beam B14), a whitish stain was detected (bottom side of bar, 21 cm to the right of midspan) immediately after removing the coating. One hour later its color changed to brownish.

Fig. 9.73: Reddish-brown rust products on lower bar of beam B8 (Zone just outside of wetted region).

Whitish corrosion products were found less frequently on bar surfaces in beam specimens than on bars in macrocell specimens. A possible factor could have been that the epoxy coating on most beam bars was removed several weeks after autopsy. Exposure to air may have converted most of such products to the predominantly reddish-brown products observed. This may have also explained why brownish, acidic solution were more often found on bars in macrocells than in beams. The longer exposure to the atmosphere may have dried the solution. It should be pointed out, though, that when macrocell bars were exposed to air for several weeks after removing the coating, driblets or beads of brittle rust with wet consistency formed on their surface. No similar phenomenon occurred in beam bars.

Generally, the trends observed during examination of steel surfaces were similar to those found on examination of coating surfaces.

Bar in As Received Condition

As received bars in beam B1 (uncracked unloaded) were in excellent condition at the end of the experiment (Fig. 9.53). Coating adhesion was preserved throughout most of the bar surface on both upper and lower bars and the steel surface underneath was bright and shinny, as in its original condition. There were a few small areas where coating adhesion was lost and a mottled, glittery surface was observed beneath the debonded coating. Dark or black corrosion products were practically absent on the surface beneath areas with debonded coating. A few spots with a very thin film of reddish rust were observed at mill marks on both bars. A medium-sized (50 mm^2) dark and brown rusted area was observed near a mill mark on the bottom bar. The steel surface around all rust spots was mottled.

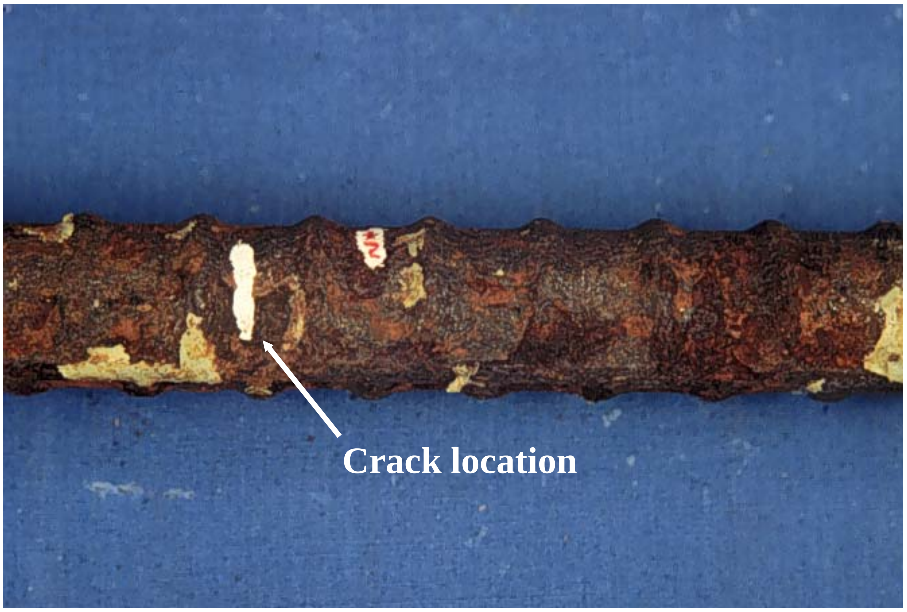
Bars with 3% Damage

Bars with 3% damaged showed extensive areas with both mottled and dark corroded surfaces. Mottled surfaces were slightly more predominant than dark corroded surfaces in bars from uncracked unloaded beam B8. There were very few zones with appreciable solidified rust. Pitting was very shallow, no deeper than 0.1 or 0.2 mm and there were few blistered areas. Reddish rust products accumulated near longitudinal ribs. The remaining bar surface was mottled, with very few spots with well adhered coating. Figures 9.70, 9.71, and 9.73 show mottled and corroded segments of both bars in beam B8.

Mottled surfaces were much more widespread than dark corroded surfaces in cracked unloaded beam B10. Pitting was shallow but slightly more severe than on bars from beam B8, with maximum depth of 0.5 mm at some portions. Also, brittle, thin flakes of rust came off during removal of the coating. Reddish rust tended to accumulate near longitudinal ribs. The remaining bar surface was mottled. The corroded portion of the lower bar in beam B10 is illustrated in Fig. 9.74.

The bars with 3% damage and patched (beam B14, cracked, unloaded) showed less extensive and widespread corrosion than bars with unrepaired damage Pitting was generally slight, with most pits not deeper than 0.2 or 0.3 mm. There were a few deeper pits with a depth of 0.5 mm at or near patches. Three patched areas on each bar were marked by dark corrosion and one patched area on the upper bar had a reddish rust accumulation beneath the patch. The remaining patched areas showed no visible corrosion. Reddish rust accumulated at several portions of dark corroded surfaces. The remaining bar surface was mottled.

As was previously observed during examination of the epoxy surface, lower bars tended to have more corrosion than upper bars. Corrosion spread more at the bottom side (as in casting position, side facing outwards to the exposed surface) of the bars than on their top side (side facing inwards).



(a) Zone around crack location near the edge of wetted region.

(b) Another view of zone around crack location near the edge of wetted region.

Fig. 9.74: Corroded portion on lower bar of beam B10.

Stirrups in As Received Condition

On a stirrup from uncracked, unloaded beam B15, the majority of the steel surface was covered with uniform dark corrosion and very shallow pitting (0.1 mm deep or less). Accumulation of reddish-brown rust was observed at most corroded portions, especially alongside longitudinal ribs and within pitted cavities. Metal beneath a patch at bar ends was corroded and dark in color. The worst pit covered 1.5 cm^2 area, and was 0.5 mm deep.

The stirrup from cracked unloaded beam B17 experienced more widespread and severe corrosion than the stirrup from beam B15. Practically all legs had uniformly dark corrosion with widespread shallow pitting (0.1 mm deep or less) and several deeper pits at the most critically corroded portions (Fig. 9.75). Reddish-brown rust accumulated at most corroded portions, especially alongside longitudinal ribs and within pitted cavities. The steel surface beneath patches at bar ends was uniformly dark. Pits 0.3 mm deep were observed on one stirrup leg (near the front beam surface). Another leg (near the bottom beam surface) had two relatively large pits (one pit had a an area of 1.4 cm^2 and was 1 mm deep, the other pit had an area of 3.14 cm^2 and was 0.3 to 0.4 mm deep). Figure 9.75 shows one such pitted area. The rusted metal was cracked and came off in flat pieces. One hook had 35% of surface area covered with shallow pitting (0.3 to 0.4 mm deep). A large (1 cm^2) pitted area with 0.6 to 0.7 mm depth was observed on that hook.

Fig. 9.75: Pitting on stirrup leg near the bottom beam surface (beam B17).

Stirrups in As Received Condition and Patched

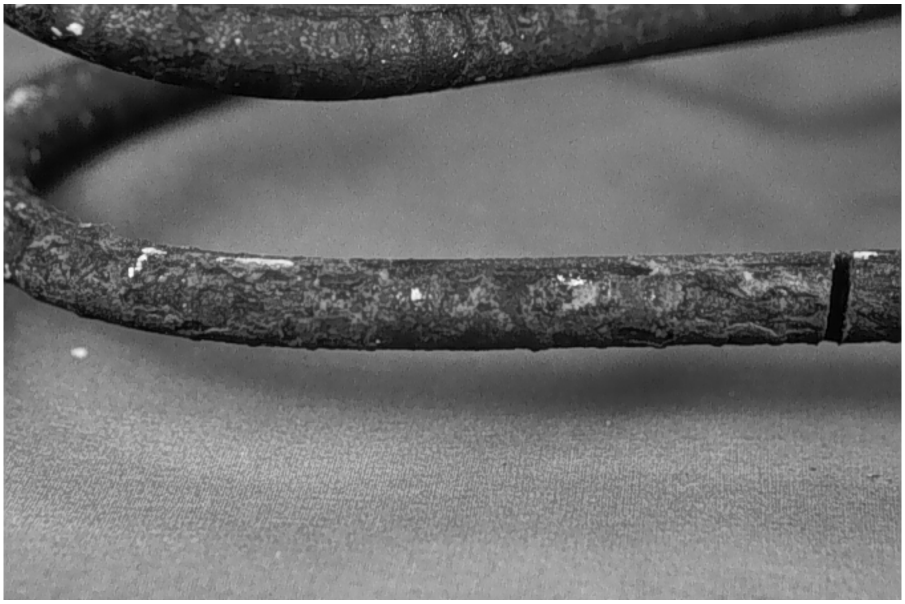
Most surfaces at stirrups from beams B22 (uncracked, unloaded) and B25 (cracked, loaded) experienced uniformly dark corrosion with shallow pitting (0.1 to 0.2 mm deep). Several blisters were observed on the corroded surfaces. Reddish-brown rust built up at most corroded portions, especially alongside longitudinal ribs and within pitted cavities. Metal beneath patches at bar ends was corroded and dark in color.

A stirrup from beam B23 (cracked, unloaded) had the least extensive corrosion of the patched stirrups. Mottled surfaces were observed at one side (surface facing the interior of the beam) of two legs, and at both sides of two legs. Metal beneath a patch on the hook end was clean and bright (Fig. 9.58). The remaining legs had a uniformly dark corroded surface, with shallow pitting (generally 0.1 mm deep, maximum depth of 0.3 mm at most corroded portions), and accumulation of reddish-brown rust on the most corroded legs.

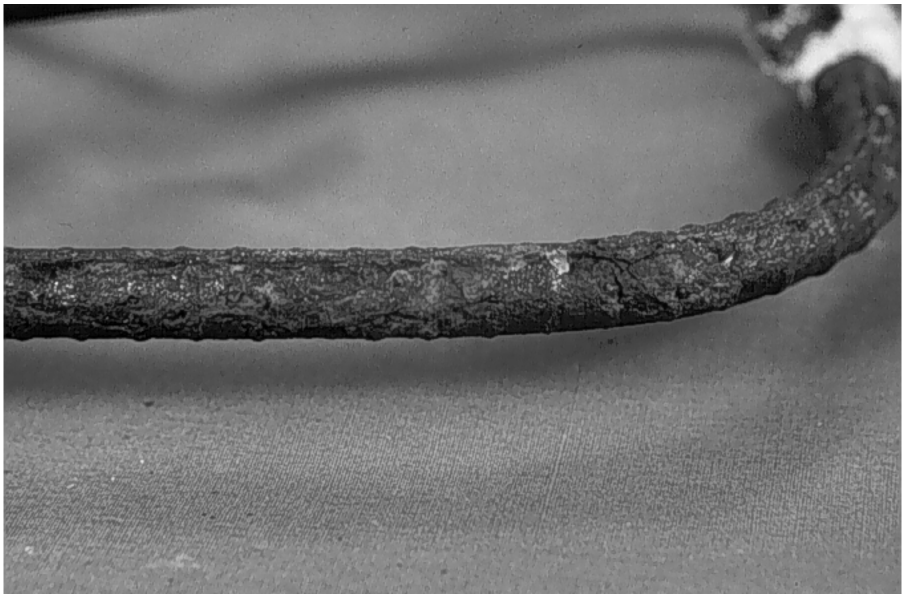
Stirrups with 3% Repaired Damage

The stirrup in beam B27 (cracked, unloaded) experienced widespread dark corrosion on most of its surface, with very shallow pitting (in the order of 0.1 mm) and reddish-brown rust inside pitted areas. Several small blisters formed on some legs. About 50% surface area at outside of bottom leg showed relatively deep pitting, with maximum depth of about 1.0 mm (Fig. 9.76). The front hook had widespread shallow pitting, with a large pit (area of 24 mm^2, 0.6 mm deep) at a bend corner underneath patched areas.

The stirrup in beam B32 (cracked, unloaded) had less widespread dark corrosion than the stirrup from beam B27. However, pitting was somewhat more severe at corroded portions of the stirrup from beam B32. As with all stirrups, reddish-brown rust accumulated inside pitted areas. Pits ranging from 1 mm^2 to 185 mm^2 of area, and from 0.3 mm to 0.6 mm of depth were noted (Fig. 9.77). Pits with maximum depth of 0.4 mm developed beneath the patched areas at two corners. The steel surface beneath patched areas at one corner was uncorroded and had a bright appearance.



(a) Portion within the wetted region.



(b) Portion outside the wetted region.

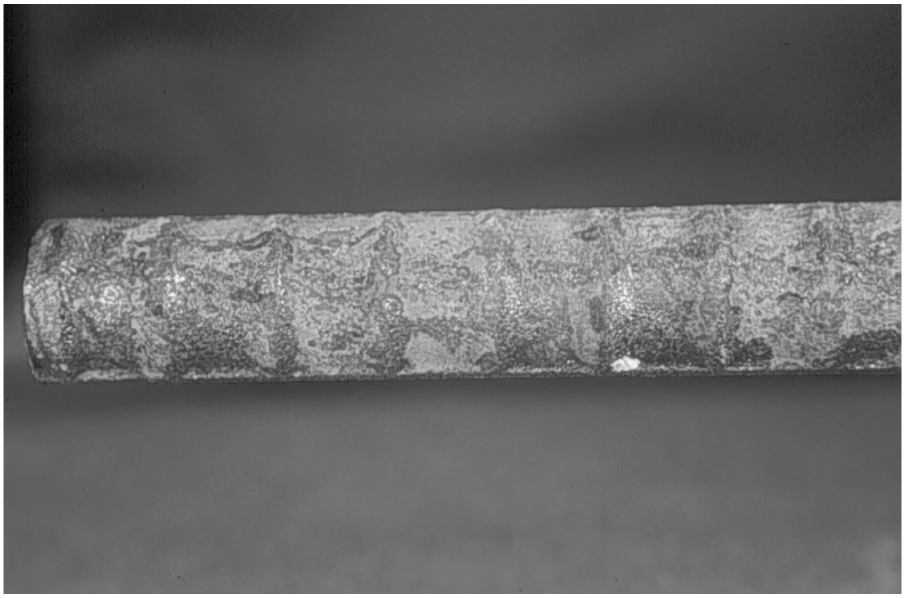
Fig. 9.76: Pitting along stirrup leg near the bottom beam surface (beam B27).

Fig. 9.77: Corrosion on stirrup leg (top in photo) and mottled surface on stirrup hook (bottom in photo). Portion near the front beam surface (beam B32).

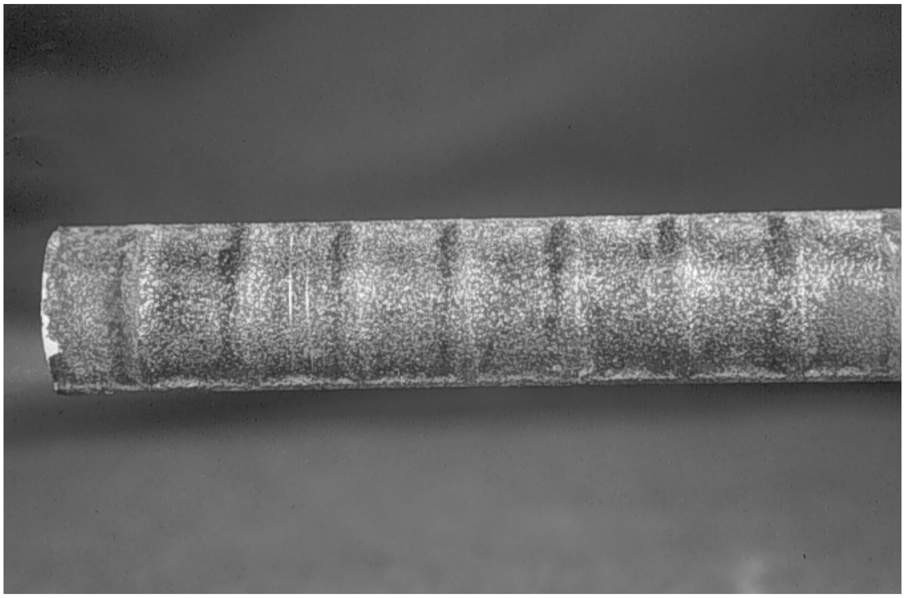
Bars in Splice Zone

<u>Short Bars</u>

A dark corroded surface with shallow pitting extended from the patched ends of the bars on one side of the bars. Reddish-brown and orange-brown rust products accumulated at more densely pitted areas (Fig. 9.78). It seemed that such products may have been deposited by the acidic solution produced by hydrolysis and progressed from the patched ends. Pitting was usually less than 0.5 mm deep. Bar ends showed a uniformly dark or black corroded metal surface with shallow pitting (Fig. 9.79). The steel exhibited a mostly mottled surface on the side opposite to the corroded surface (Fig. 9.78). Undercutting extended 20 cm to 24 cm from patched bar ends.



(a) Accumulation of reddish-brown rust products on side near the concrete surface.



(b) Mottled surface on opposite side facing the beam core.

Fig. 9.78: Appearance of steel surface of lower splice bar after 4.3 years of exposure (beam B32).

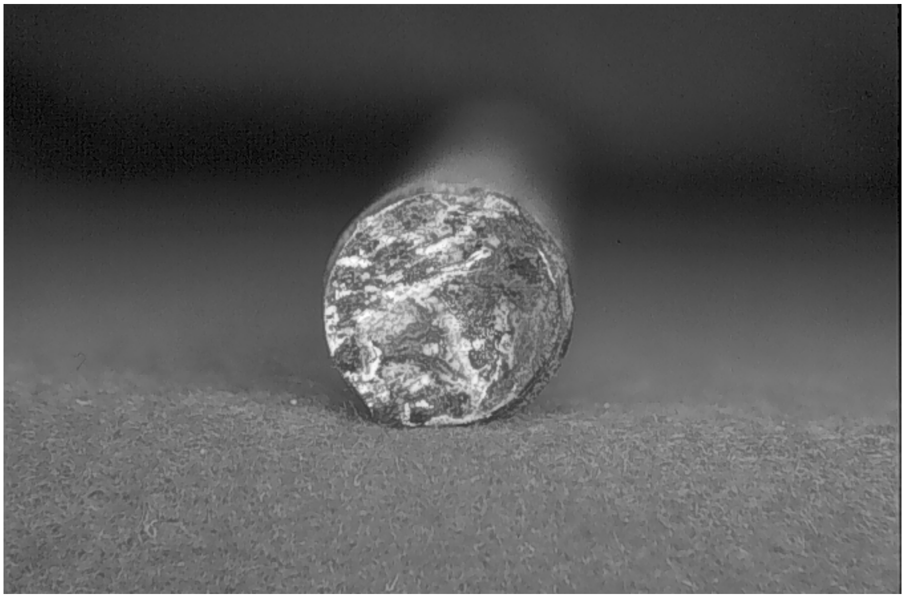


Fig. 9.79: Dark corrosion on steel surface beneath the patch at lower splice bar end of beam B32.

Long Bars

The steel displayed a mostly mottled surface on both sides of the bars, except at a few locations, where a slightly dark area with an accumulation of reddish-brown rust was observed. Slight pitting (0.2 mm or 0.3 mm deep) occurred at some portions. Undercutting extended 14 cm to 19 cm from the midportion of the beam. Overall, the bar surfaces were in very good condition after 4.3 years of exposure.

Bar Trace in Concrete

Coated Bars

Rust staining was generally confined to the concrete-bar interface and did not spread inside the concrete beyond the bar location. Rust around the stirrup in beam B32 stained the surrounding concrete extensively and exuded to the exterior surface through cracks, as discussed earlier. In all specimens, rust staining was more extensive in concrete near the surfaces (concrete cover) than on concrete at the interior of the beams. The size of rust stains ranged from large to very small and were dark greenish, dark or black, reddish-brown (bright to dark intensity), brownish, dark-brown, light-brown, yellowish-brown, and orange-brown. The appearance of dark-greenish stains changed within minutes or hours after the concrete was removed and exposed to the atmosphere. Dark greenish stains changed to one of the following colors: Reddish-brown, brown, reddish-brown combined with dark or black, and light-brown.

Rust stains in the concrete were located at and near concrete voids, next to coating imperfections and discontinuities (intentionally damaged spots, patched areas, as-received damage, cracks in the coating, pinholes, and mandrel-induced nicks), and alongside the path of the longitudinal lug below the bar. There was almost always a blister in the coating next to a rust-stained void in the concrete. However, there were many concrete voids, large and small, which were free of any rust products or staining.

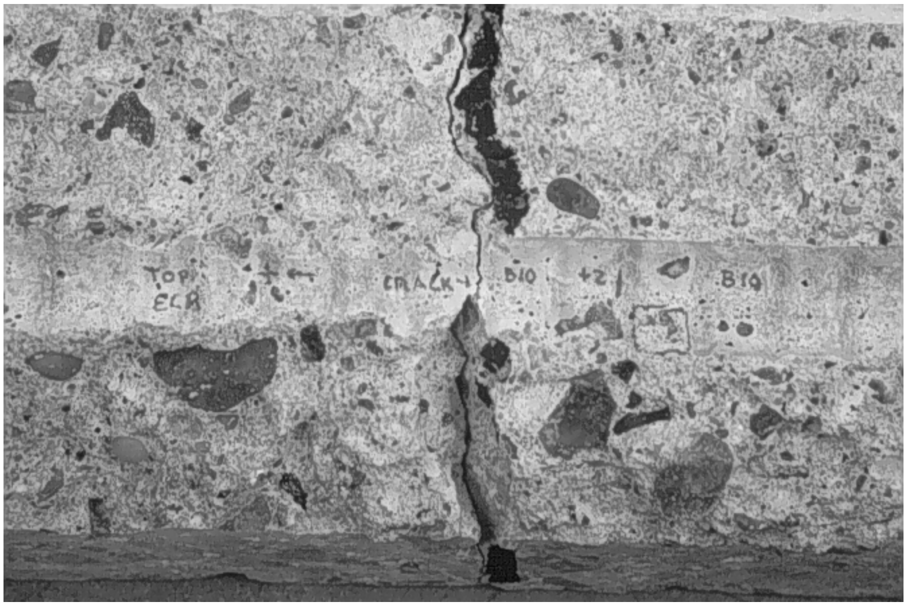
The bar trace in concrete above (in the casting position) epoxy-coated bars (towards the inner core of the beams) consisted of a smooth, shiny, glossy surface with a grayish-like appearance, the rib imprints were clearly defined, and there were few voids [Fig. 9.80(a)]. The bar trace in concrete below (in the casting position) epoxy-coated bars (towards the exterior beam surface) had a whitish-like appearance that looked more dusty and porous like laitance and had more voids of different sizes [Fig. 9.80(b)]. Chemical adhesion to concrete was lost, as evidenced by the ease in removing the bar from the concrete and lack of concrete adhering to the bar. Only a film of white dust from the concrete paste adhered to the bottom of the bars.

Uncoated bars in compression

Concrete surrounding heavily corroded uncoated bars was extensively rust stained (Fig. 9.81). Rust stains were very large, mostly black or dark and reddish-brown colored. Other observed stains were dark-green, bright orange, brownish, and yellowish-brown. Typically, dark-greenish stains would turn orange-brown, reddish-brown, or dark a few hours after exposure to the atmosphere. In general, rust stains penetrated the concrete far beyond the bar location at most areas where the bar was pitted. Stains penetrated cracks and expanded towards the exterior surface. Rust staining was mostly reddish-brown and orange-brown at areas closer to the exterior surface while it tended to be dark or black at the rebar level. Reddish-brown and dark rust was also observed inside large concrete voids above and below the bar.

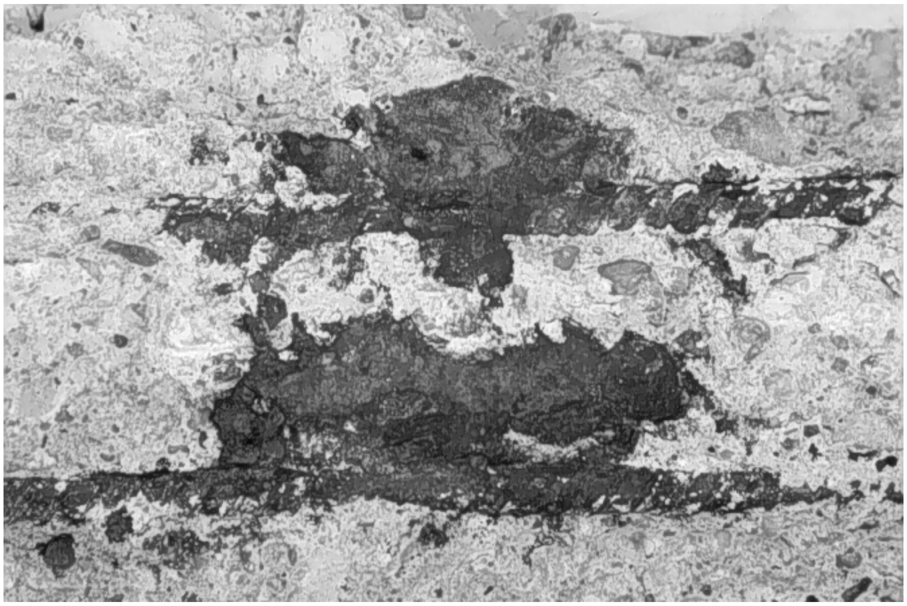
In non-stained areas, the bar trace in concrete above (in the casting position) the bar was porous with a grayish-like appearance, the rib imprints were not clearly defined, and there were few voids. The bar trace in concrete below (in the casting position) the bar had also a grayish-like appearance, but looked more porous because of laitance and had more voids of different sizes. Concrete adhered well to black bars as evidenced by the concrete that stuck to the bar surface after removal.

(a) Above epoxy-coated bars as in casting position.



(b) Under epoxy-coated bar as in casting position.

Fig. 9.80: Bar trace in concrete above and below epoxy-coated bars (as in casting position).



(a) Black bars in beam B14

(b) Black bars in beam B25

Fig. 9.81: Extensive dark or dark-greenish rust staining was observed on concrete around uncoated bars at severely pitted locations.

9.6 DISCUSSION OF RESULTS AFTER 4.3 YEARS

9.6.1 General

Results from corrosion monitoring, visual examinations, chloride analysis, and post-mortem examination are analyzed and discussed. Special emphasis is placed on comparing the results after 4.3 years of exposure with the results after 1 year of exposure. There may be factors that affect long-term corrosion behavior and that may change some of the previous findings and conclusions.

9.6.2 Time to Corrosion

Time to reach a highly negative corrosion potential was considered to be an indicator of time to corrosion. It must be kept in mind that corrosion potentials may not accurately reflect corrosion activity, especially rate of corrosion. Times of corrosion in the following discussion, therefore, should be considered rough approximations.

Longitudinal Bars

Corrosion initiation was governed by both coating condition and cracking condition. Times to corrosion in Table 9.1 were short for bars in cracked loaded beams which started to corrode sometimes after the very first wet cycle. Bars with as-received coating in a cracked, unloaded beam showed times to corrosion of about 2.5 and 3.5 months. Bars in uncracked unloaded beams had times to corrosion from 9 months to 1.6 years. The absence of cracks significantly delayed the onset of corrosion but did not stop corrosion, especially if the coating was damaged.

From Table 9.1, bars with 3% damage to coating in cracked beams, loaded or unloaded, started to corrode very early, oftentimes after the first wet cycle (4 to 18 days). Meanwhile, for three out of four bars with as-received coating in cracked beams, loaded or unloaded, corrosion was somewhat delayed (from 1.5 to 3.4 months). The damaged and patched bar did not show any delay in the initiation of corrosion.

Splice bars with patched ends in cracked beams began to corrode as early as 4 to 18 days. Longitudinal bars (3% coating damage and patched) not isolated from the stirrup in a cracked, unloaded beam had a short time to corrosion (18 days).

Stirrups

The most significant factors for time to corrosion of coated stirrups were the presence of cracks and the loading condition. From Table 9.2, stirrups in uncracked beams started to corrode at about 1.5 years of exposure. Stirrups in cracked, unloaded beams showed times to corrosion from 2.5 months to 4.3 months. Stirrups in cracked loaded beams had times to corrosion of about 1.5 months. No significant difference was observed for stirrups with as-received condition. However, corrosion at a stirrup with 3% coating damage and patched in a cracked, unloaded beam was significantly delayed, initiating at about 11 months.

A stirrup (3% coating damage and patched) not isolated from the longitudinal bars in a cracked, unloaded beam started to corroded at about 18 days. In contrast, the same type of stirrup not isolated from spliced bars in a cracked, unloaded beam started to corrode at about 3.5 months. A similar stirrup not isolated from spliced bars in a cracked loaded beam showed a time to corrosion of about a month.

9.6.3 Corrosion Activity

Corrosion Potentials

The layout of the longitudinal bars with respect to the exposure area influenced the pattern of potentials. Measured potentials at middle regions of the beams, subjected to wetting and drying, were highly negative, while potentials at regions outside the exposure zone were less negative. Highly negative potentials indicate that corrosion is very likely to be occurring, while low negative potentials indicate that corrosion is unlikely. As expected, measured potentials indicated that corrosion of coated (and uncoated bars also) bars was very likely occurring at the exposed areas of the beams. Chloride solution penetrated through concrete and cracks and anodically polarized exposed metal on the bar surface. Regions adjacent to wetted surfaces had intermediate to low negative potentials and bar surfaces were uncorroded. As mentioned before, corrosion potentials give no indication of the corrosion rate.

At the beginning of the exposure, corrosion potentials were not stable. Depending on the crack, loading, and bar condition, corrosion potentials reached stable values at different times. Reaching a stable potential corresponds to electrochemical equilibrium. Low negative potentials reflect a state of passivity of the steel. Reported potential ranges for steel passivity include the following: +100 to -100 mV SCE,[142] +100 to -200 mV SCE.[132, 143] Potentials indicating a general state of corrosion have been reported as: -450 to -600 mV SCE,[132] -350 to -475 mV SCE.[65]

In uncracked beams, potentials were in the -100 mV SCE range for about 8 months to 3 years. After that, potentials decreased suddenly to the -400 to -600 mV SCE range and remained stable thereafter. The bars in uncracked beams had passive behavior for an initial period (8 months to 3 years) before becoming anodic. The absence of cracks delayed corrosion initiation because chlorides had to diffuse through the concrete and build up in sufficient amounts at exposed metal on the bar surface. Once high enough chloride contents were reached, the steel depassivated and corrosion started. Examination of bar surface conditions from uncracked beams after one year and 4.3 years of exposure confirmed this hypothesis.

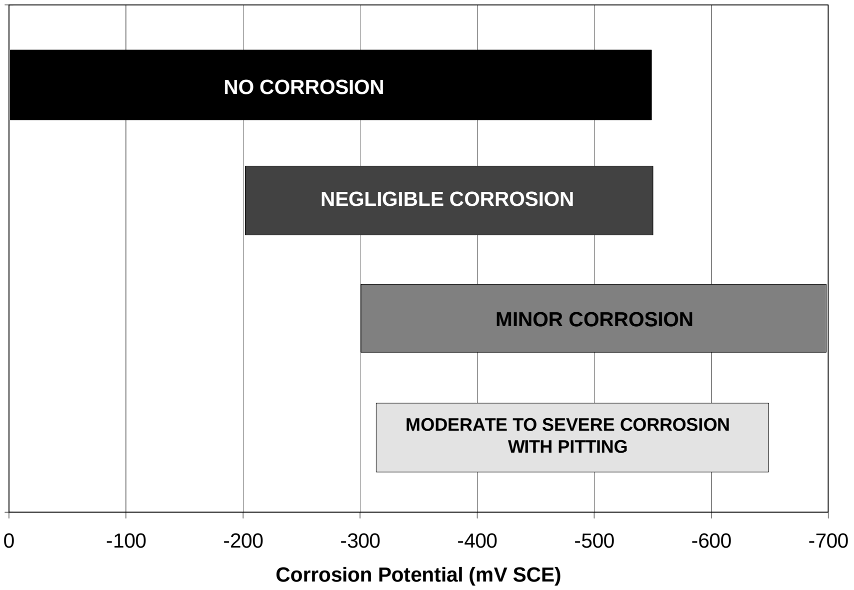
Initial potentials for cracked beams ranged from -80 mV to -430 mV SCE. The cause for these different initial potentials can be attributed to early contact of steel with chlorides penetrating through the cracks. Corrosion potentials for cracked unloaded beams decreased to -500 to -600 mV SCE within 6 months or less, and potentials for cracked, loaded beams dropped to the same level within 3 months. The presence of cracks made large amounts of chloride readily available to depassivate the steel in a short time. Beams with patched bar ends in splice zones exhibited large, early drops indicating quick failure of the patching material.

The mechanism by which corrosion potentials shift to more negative values is related to chloride reaction with ferrous ions produced by corrosion.[29] Potential shifts to more negative values indicate that corrosion cells are operating and not that more rust is accumulating. Consequently, similar potential could have been measured whether corrosion was confined to a minute holiday or distributed over a larger area. Highly negative potentials do not necessarily indicate significant corrosion.

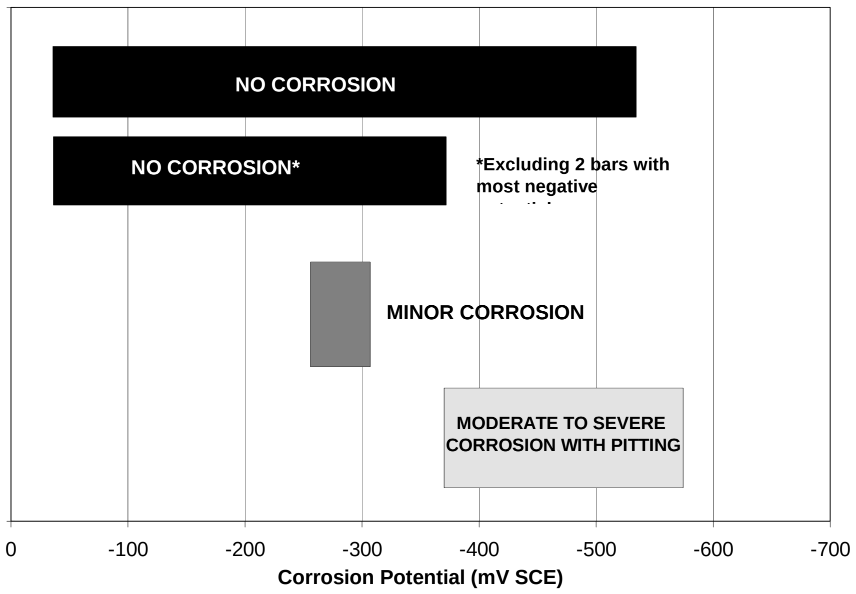
Potential drops were sometimes followed by fluctuations in the potential, which could be related to unsteady conditions associated with the transition of steel from a passive to an active state (depassivation). After the potentials stabilized, readings varied within a narrow range of highly negative values (-500 to -600 mV SCE), indicating that active conditions continued for the remainder of the test.

Corrosion progressed and pitting continued on some bars at a stable corrosion potential between -315 to -650 mV SCE. The localized low pH of the solution produced by hydrolysis within an active pit encouraged propagation of corrosion at the available potential level. Wheat and Eliezer,[132] and Arup[143] associated pitting corrosion with a potential range from -200 to -500 mV SCE.

Figure 9.82 illustrates the relation between corrosion activity and steel potential for epoxy-coated and black bars from tests in this study. Data from beams autopsied after one and 4.3 years were used for the correlation. Although there was a tendency for readings to become more negative as corrosion activity of epoxy-coated bars increased, there was a wide overlap of corrosion performance in the potential range of -300 to -550 mV SCE. Corrosion potentials less negative than -300 mV SCE indicated negligible or no corrosion. Likewise, corrosion potentials more negative than -550 mV SCE indicated moderate to severe corrosion with some cases showing only minor corrosion.



(a) Epoxy-Coated Bars



(b) Black bars

Figure 9.82: Relation between corrosion activity and steel potential from tests in this study (beams autopsied after one and 4.3 years of exposure).

For black bars, the overlap of bars with varying corrosion performance was in the potential range of -255 to -535 mV SCE. However, if the two bars showing the most negative potentials in uncorroded zones are excluded, the overlap drastically reduces [see Fig. 9.82(b)]. In this case, corrosion potentials less negative than -300 mV SCE correlated with either minor or no corrosion. Corrosion potentials in the range of -370 to -575 mV SCE were associated with moderate to severe corrosion.

As a reference, the ASTM C876 criterion for interpreting corrosion potentials of uncoated steel in concrete is as follows: Potentials more negative than -273 mV SCE (-350 mV CSE) indicate a high probability of corrosion. Potentials more positive than -123 mV SCE (-200 mV CSE) indicate a high probability of no corrosion. Potentials in the range of -123 mV to -273 mV SCE indicate uncertainty of corrosion.

Corrosion Potential Differences

As was reported by Kahhaleh, corrosion potentials alone are not always reliable for locating corroded areas as indicated in ASTM C876.[10] It has been found that the difference in potential between different portions of the bar is a better indicator to identify and locate corroding sites.[144] Clear and Virmani suggested that differences in potentials between anodic and cathodic portions was the more important indicator of corrosion activity.[136] ACI 222-89 likewise states that the larger the potential difference, the higher the corrosion rate.[7] It is the potential difference between the anode and the cathode, not the magnitude of the anode potential, that is the best indicator of corrosion rate.[10] Corrosion occurs at sites with higher negative potentials (anodic sites), while uncorroded sites exhibit potentials in the low negative region.

Several researchers have suggested different magnitudes of potential gradients to detect corrosion. Lehmann found that differences of 200 mV or more between sites within a distance of 15 to 30 cm could indicate corrosion activity.[27] High potential gradients were associated with pitting corrosion of uncoated bars.[143] Potentials in the high negative region (-450 to -600 mV SCE) without steep gradients were more indicative of general corrosion. When corrosion was absent or at a very low level of activity, potential differences rarely exceeded 100 mV.[7]

For the beam specimens autopsied after one year of exposure, Kahhaleh found that no corrosion was associated with potential gradients less than 150 mV SCE.[10] General corrosion (negligible, minor, or moderate) was associated with potential gradients exceeding 150 mV SCE. Pitting corrosion was associated with potential gradients greater than 200 mV SCE. These potential differences were based on average potentials at wet (anode) and dry (cathode) regions. The calculated gradients are based on measurement sites about 60 cm apart.

Maximum potential gradients for epoxy-coated bars between wet and dry regions after 4.3 years of exposure are tabulated in Tables 9.13 and 9.15. Similar potential gradients for uncoated bars between inner (mid 61 cm portion) and outer portions of the beams are tabulated in Tables 9.16 through 9.18 For uncoated bars, potential gradients are based on measurement sites between 61 cm and 76 cm apart.

Beam No.	Maximum Diff. of Avg. Mid and End Potential (mV)	Mean Diff. of Avg. Mid and End Potential (mV)	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust along 0.9 m of Midspan (%)	Severity of Steel Corrosion
B1-U	250	140	-555	0.3	Negligible
B1-L	330	185	-450	0.7	Negligible
B3-U	240	150	-620	*	*
B3-L	400	275	-620	*	*
B6-U	255	170	-580	*	*
B6-L	365	275	-620	*	*
B8-U	150	85	-540	30	Minor to Moderate
B8-L	330	155	-535	33	Minor to Moderate
B10-U	255	160	-610	14	Minor
B10-L	330	220	-600	29	Minor to Moderate
B12-U	265	155	-570	*	*
B12-L	335	170	-600	*	*
B14-U	200	115	-620	10	Minor to Moderate
B14-L	275	155	-635	15	Minor to Moderate

U: Upper bar L: Lower bar * Not Examined

Table 9.13: Relation of corrosion to potential measurements on beams of Group I, longitudinal bars.

Beam No.	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust of stirrup surface (%)	Severity of Steel Corrosion (Pitting in % of bar surface)
B15	-565	67	26% pitted
B17	-555	93	27% pitted
B19	-580	*	*
B22	-550	89	14% pitted
B23	-505	48	4% pitted
B25	-315	86	20% pitted
B27	-580	83	15% pitted

* Not Examined

Table 9.14: Relation of corrosion to potential measurements on beams of Group II, stirrups.

Beam No.	Maximum Diff. of Avg. Mid and End Potential (mV)	Mean Diff. of Avg. Mid and End Potential (mV)	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust along 0.9 m of Midspan	Severity of Steel Corrosion
Longitudinal Bars Including Splice Bars					
B30-U	155	70	-625	*	*
B30-L	225	115	-620	*	*
B32-U	360	215	-645	19	Moderate
B32-L	400	285	-650	21	Moderate
B34-U	355	230	-610	*	*
B34-L	375	295	-610	*	*
Stirrups					
B30	-	-	-470	*	*
B32	-	-	-580	55	26%
B34	-	-	-600	*	*

U: Upper bar L: Lower bar * Not Examined ** Percentage of bar surface

Table 9.15: Relation of corrosion to potential measurements on beams of Group III, longitudinal/splice bars and stirrups.

Beam No.	Maximum Diff. of Avg. Mid and End Potential (mV)	Mean Diff. of Avg. Mid and End Potential (mV)	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust along 0.9 m of Midspan (%)	Severity of Steel Corrosion (Loss of Cross-Section at Worst Location)
B1-U	415	315	-510	67	Severe (20% loss)
B1-L	410	295	-510	31	Severe (17% loss)
B3-U	250	130	-535	*	*
B3-L	445	245	-555	*	*
B6-U	320	255	-495	*	*
B6-L	420	320	-525	*	*
B8-U	230	145	-255	28	Minor
B8-L	530	220	-305	13	Minor
B10-U	215	150	-440	58	Severe (14% loss)
B10-L	520	345	-510	50	Severe (23% loss)
B12-U	380	215	-505	*	*
B12-L	345	230	-560	*	*
B14-U	205	100	-575	61	Severe (25% loss)
B14-L	350	235	-565	81	Severe (30% loss)

U: Upper bar L: Lower bar * Not Examined

Table 9.16: Relation of corrosion to potential measurements on beams of Group I, black bars.

Beam No.	Maximum Diff. of Avg. Mid and End Potential (mV)	Mean Diff. of Avg. Mid and End Potential (mV)	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust along 0.9 m of Midspan (%)	Severity of Steel Corrosion (Loss of Cross-Section at Worst Location)
B15-U	325	180	-355	39	Severe (11% loss)
B15-L	435	270	-465	42	Severe (11% loss)
B17-U	400	335	-415	50	Very severe (40% loss)
B17-L	335	180	-370	56	Severe (21% loss)
B19-U	425	310	-540	*	*
B19-L	405	255	-390	*	*
B22-U	455	290	-435	56	Severe (19% loss)
B22-L	510	295	-540	72	Severe (14% loss)
B23-U	300	195	-245	22	Severe (30% loss)
B23-L	380	280	-410	36	Very Severe (55% loss)
B25-U	350	215	-425	47	Very Severe (63% loss)
B25-L	455	345	-500	28	Severe (38% loss)
B27-U	340	280	-450	25	Very Severe (65% loss)
B27-L	485	360	-505	50	Very Severe (78% loss)

U: Upper bar L: Lower bar * Not examined

Table 9.17: Relation of corrosion to potential measurements on beams of Group II, black bars.

Beam No.	Maximum Diff. of Avg. Mid and End Potential (mV)	Mean Diff. of Avg. Mid and End Potential (mV)	Final Average Potential in Wet Zone (mV)	Percentage of Area showing Rust along 0.9 m of Midspan (%)	Severity of Steel Corrosion
B30-U	175	60	-570	*	*
B30-L	310	190	-565	*	*
B32-U	480	360	-545	61	Severe (32% loss)
B32-L	655	420	-560	61	Severe (32% loss)
B34-U	345	290	-550	*	*
B34-L	490	405	-545	*	*

U: Upper bar L: Lower bar * Not Examined

Table 9.18: Relation of corrosion to potential measurements on beams of Group III, black bars.

From tables 9.13 and 9.15, the degree of corrosion activity of epoxy-coated bars can not be clearly correlated with ranges of maximum or average potential differences. Longitudinal bars with negligible corrosion activity had a range of maximum potential differences between 250 to 330 mV SCE. Bars with minor to moderate corrosion had a range of maximum potential differences of 150 to 400 mV SCE.

A similar situation occurs with uncoated bars. The only two bars with minor corrosion had maximum potential gradients of 230 and 530 mV SCE. The rest of the uncoated bars (20) experienced severe corrosion with deep pits and areas with appreciable loss of cross-section. The range of maximum potential gradient for bars with severe corrosion was 205 to 655 mV SCE.

Table 9.19 shows the distribution of uncoated bars with severe pitting corrosion classified according to different ranges of observed maximum potential gradient. Clearly, most bars with severe pitting corrosion had maximum potential differences within the range from 300 to 500 mV SCE.

Range of Max. Potential Gradient (mV SCE)	**No. of Bar Samples**
200 to 300	2
300 to 400	7
400 to 500	8
500 to 655	3

Table 9.19: Distribution of uncoated bars with severe pitting corrosion.

Overall, maximum potential gradients above 200 mV could not be associated with a particular level of corrosion activity after 4.3 years of exposure. Corrosion in such bars varied from negligible to moderate. For uncoated bars, maximum potential gradients above 300 mV seemed to produce severe pitting corrosion.

Effects of Concrete Cracking

The adverse effect of concrete cracks on corrosion of reinforcement was evident from the beam exposure specimens examined after one and 4.3 years. Coated bars tended to exhibit slightly worst corrosion at or near crack locations (Fig. 9.83), as was more evident after one year of exposure. The effect of cracks was much worse on uncoated bars, which experienced severe pits and loss of metal at or near crack locations after 4.3 years of exposure.

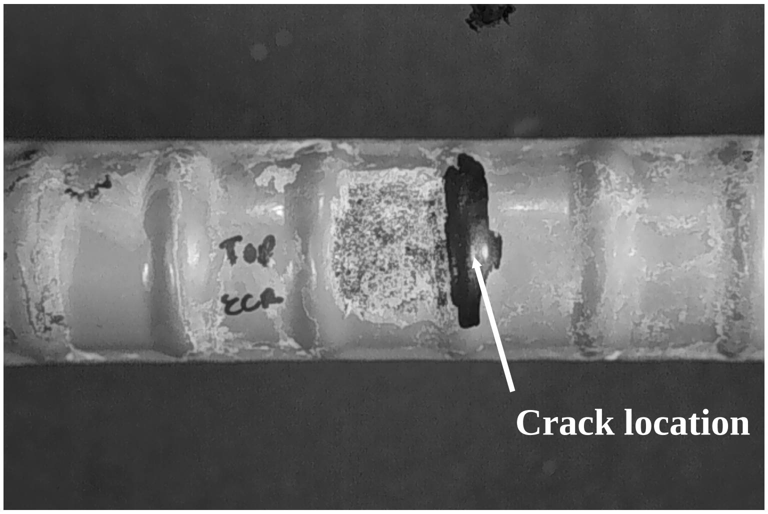
Fig. 9.83: Rust staining on coated bar trace in concrete around crack location at edge of wetted region (beam B10).

Chlorides accumulated at crack sites as a result of penetration by salt solution during wet periods. Free oxygen and other atmospheric pollutants (such as carbon dioxide) also accessed the bars through the cracks during dry periods. Periodic cyclic loading during wet and dry periods pumped water, chlorides, and oxygen towards the crack tip. The higher chloride concentration and low pH at crack locations produced loss of passivity at exposed steel areas and encouraged pitting corrosion. Such effects were much worse for uncoated bars because of a much larger steel surface available for cathodic reactions.

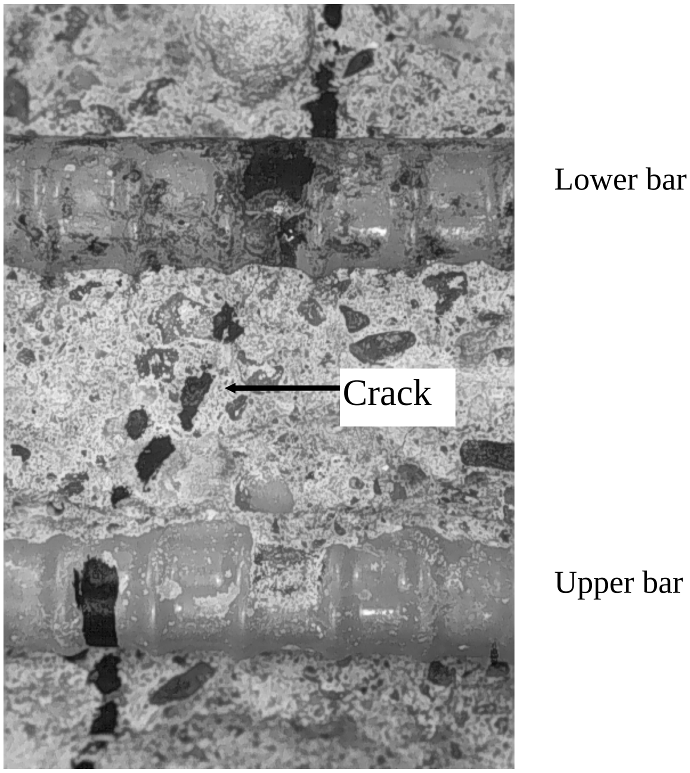
Several longitudinal coated bars did not experience corrosion on some damaged sites (patched or unpatched), even when located near crack locations within the wetted zone (Fig. 9.84). The steel surface beneath the coating around such locations was mottled. It seemed that some damage sites near crack locations remained passive while other damaged sites tended to become anodically polarized. Cathodic polarization may have protected damaged sites near cracks from active corrosion. Strangely enough, surrounding concrete at such spots was often porous and with many voids (Fig. 9.85).

The crack width may have had some influence on the phenomenon described above. For instance, in beam B14, corrosion occurred primarily around the widest crack (average width of 0.175 mm). However, the situation in beam B10 was less clear. At one crack near the left edge of the wet region, the damaged spot on top bar did not corrode but corrosion occurred on the bottom bar. The opposite was true for the crack at midspan. Both cracks seemed to be wider near the bottom surface of the beam.

In uncoated bars, severe pits were usually observed at or near crack locations. Interestingly, uncoated bars in beams from group I (longitudinal bars) underwent less severe pitting than uncoated bars in beams from groups II and III (stirrups and splice bars). Pits in uncoated bars from groups II and III were very deep and produced significant loss of cross-sectional area (Fig. 9.86 and 9.87).

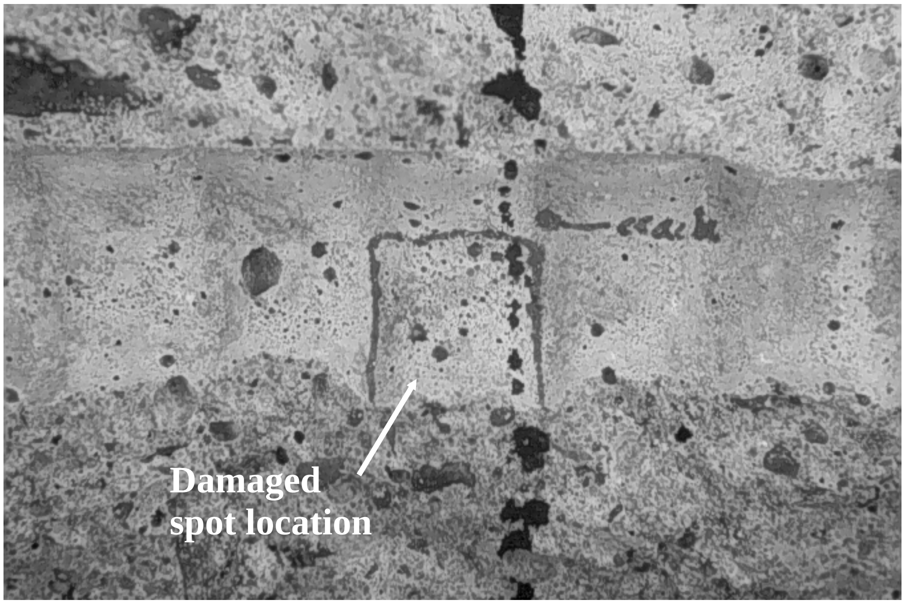


(a) Uncorroded damaged spot near a crack within the wetted region (Upper bar).

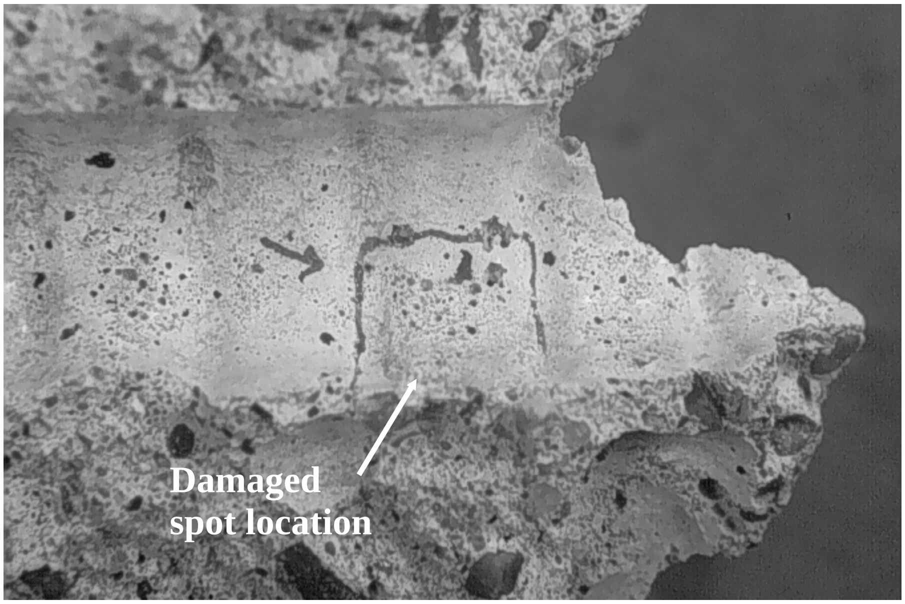


(b) Uncorroded damaged spot near a crack on upper bar. Damaged spot at crack location experienced extensive corrosion on lower bar.

Fig. 9.84: Uncorroded damaged spots on longitudinal bars of beam B10.



(a) Concrete surrounding uncorroded damaged spot outside the wetted region.



(b) Concrete surrounding uncorroded damaged spot within the wetted region.

Fig. 9.85: Concrete surrounding uncorroded damaged spots (Upper bar of beam B10).

(a) View immediately after autopsy.

(b) Another view after autopsy.

Fig. 9.86: Severe pitting corrosion of uncoated bars at crack location (beam B27).

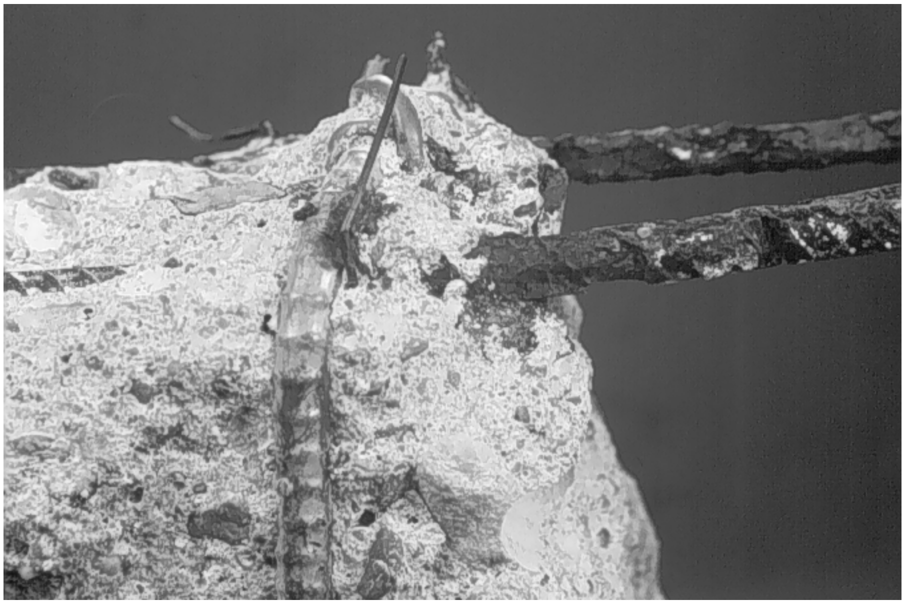


Fig. 9.87: Pitting corrosion of uncoated bars at crack location (beam B25).

Several factors may have contributed to this phenomenon. First, a larger area on the beam surface (twice as large) was exposed to chloride solution in beams from group I. Second, several cracks (from two to four) were enclosed within the wetted, exposed surface of beams group I, while one crack only (sometimes two) was enclosed within the exposed areas of beams groups II and III. In addition, cracks in group II beams were wider (0.15 to 0.35 mm) than those in group I beams (0.08 to 0.20 mm). Therefore, uncoated bars from beams group I were exposed to chlorides and moisture over a longer portion compared to uncoated bars from groups II and III. A smaller surface area of bar tended to be polarized and to become anodic in black bars from beam in groups II and III. Portions of the bar adjacent to anodic areas became cathodic. In consequence, uncoated bars from beam groups II and III tended to have a smaller anode and larger cathode, that is, a more unfavorable (smaller) anode/cathode ratio compared with bars from beam group I. The resulting driving force for corrosion was larger for uncoated bars from beam groups II and III.

A secondary phenomenon also may have accounted for the more severe corrosion of black bars from beams groups II and III. As was described at the beginning of this chapter, group I included beams where the stirrups were shielded inside plastic tubes. Any incidental continuity with uncoated bars was thus prevented. In group II beams, the stirrup was monitored and was not shielded. Unlike longitudinal coated bars, uncoated bars were not shielded at their middle portion, so any incidental continuity with the stirrup was not prevented. In addition, epoxy coating was damaged at the ribs on the inside of stirrup corners near uncoated bars. A similar situation occurred in beam group III, where no bar was shielded.

Although it is not certain that electrical continuity between stirrups and uncoated bars was established, it may have contributed to the macrocell corrosion of uncoated bars. Examination of the inside corners of stirrups near uncoated bars showed rust staining on the coating surface that originated from the uncoated bars. Such rust products could have bridged the metallic surfaces of the uncoated bars and stirrups through nicks in the coating. Examination of the metallic surface beneath the coating at the inside corners of the stirrups revealed a mottled surface with almost no corrosion. Any point of contact with corroding uncoated bars tended to become cathodic with respect to the anodic uncoated bars. The surface at the outside corners of a stirrup showed dark corrosion with shallow pitting in some cases, indicating that a local corrosion cell between the inside and outside stirrup surfaces was triggered as well.

Effects of Chloride Concentration

Initially and after one year of exposure, chloride concentrations were substantially different between cracked and uncracked locations. Uneven chloride distribution along the coated and uncoated bars was perhaps the most significant factor in the development of corrosion cells. Similar differences in chloride concentrations were observed between the top and bottom part of the stirrup, and between the front part (within the exposure area) and back part (in the compression zone). Such differences decreased significantly after 4.3 years of exposure, and chloride distribution inside the beam became more evenly distributed. Since corrosion cells were well established at later stages, the more even distribution of chlorides along the bars contributed to the propagation of corrosion over a larger surface.

At cracked and uncracked locations, more chloride was concentrated at the lower bar level than at the higher bar level. A similar situation occurred at uncracked locations after one year, but the opposite situation was observed at cracked locations. Chlorides accumulated at the lower bar level by capillary action as the chloride solution ran along the bottom concrete surface, and by gravity as the chloride solution entered from the top and front surfaces. These findings were consistent with observed corrosion on rebars, where lower longitudinal bars tended to corrode more than upper bars. Likewise, front and bottom legs of stirrups corroded more than top and back legs.

9.6.4 Condition of Rebar Surface

Surface Corrosion

Longitudinal Bars

The extent of corrosion for each bar in terms of percentage of surface area along a 0.9 m. length of bar at midspan and number of damaged spots is summarized in Table 9.20. Since the wetted zone was 0.6 m. long, percentages of corroded surface greater than 67% would indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Beam No.	**Bar**	**Corroded Coating Surface**	**Corroded Damaged Spots**
B1-L-UU-AR:	Upper	3%	N/A
	Lower	2%	N/A
B8-L-UU-D	Upper	19%	40%
	Lower	25%	43%
B10-L-CU-D	Upper	15%	32%
	Lower	25%	57%
B14-L-CU-D(P)	Upper	13%	20%
	Lower	13%	22%

Table 9.20: Approximate amount of rust stained epoxy surface (percentage of bar surface along 0.9 m midspan portion) and corroded damaged spots (percentage of spots).

Comparison of examined longitudinal bars from four beams reveals that the damaged condition of the epoxy coating was the most influential factor in the corrosion performance of the longitudinal bars. Little effect was produced by loading condition and presence of cracks. Patching coating damage seemed to improve performance by lessening the amount of corrosion. The percentage of corroded spots decreased with patching. Still, bars in good, as-received condition performed better than bars with patched damage.

Stirrups

The extent of corrosion on the coating surface of stirrups in terms of percentage of surface area is summarized in Table 9.21.

Beam No.	**Corroded Coating Surface**
B15-ST-UU-AR:	40%
B17-ST-CU-AR:	65%
B22-ST-UU-AR(P)	37%
B23-ST-CU-AR(P)	30%
B25-ST-CL-AR(P)	30%
B27-ST-CU-D(P)	38%
B32-SP-CU-D(P)	33%

Table 9.21: Approximate amount of rust stained epoxy surface (percentage of bar surface) of stirrups.

As-received stirrups underwent the most extensive rust staining. The stirrup in the uncracked beam underwent more extensive staining than stirrups in cracked beams. Damaged and patched stirrups experienced slightly more surface staining than as received and patched stirrups.

Splice Bars [Beam B32-SP-CU-D(P)]

The extent of corrosion on the coating surface of spliced bars in terms of percentage of surface area along 0.9 m in midspan is condensed in Table 9.22. Percentages of corroded surface greater than 33% would indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Bar	**Corroded Coating Surface**
Upper Short	4%
Upper Long	2%
Lower Short	8%
Lower Long	3%

Table 9.22: Approximate amount of rust stained epoxy surface (percentage of bar surface along 0.9 m in midspan) of spliced bars in beam B32.

Overall, the amount of rust staining on the coating surface of spliced bars was minimal. Lower bars underwent more staining than upper bars. Likewise, shorter bars experienced more rust staining than longer bars. Shorter bars had a patched cut end at the midspan of the beam.

Coating Adhesion to Steel

Most coated bars were susceptible to coating debonding over the length within the exposed, wetted areas of the beams (a stretch of about 61 cm). Coating debonding in longitudinal bars was much more extensive after 4.3 years than after 1 year of exposure. At previously autopsied bars, coating either remained well adhered to the steel or adhesion was lost only in the immediate vicinity of damaged spots, generally from 9 mm up to 13 cm around rust spots.

Two factors may have contributed to this phenomenon: a) The presence of moisture may have caused adhesion loss due to water penetration, in a mechanism explained in Chapter 8, and/or b) cathodic disbondment at portions contiguous to corroded areas. The occurrence of cathodic disbondment may explain the absence of corrosion at several damaged sites, which may have been cathodically protected.

As was noted in preceding paragraphs, as received bars from uncracked beam B1 maintained good coating adhesion after 4.3 years of exposure. It seemed that with absence of damaged areas, the solution no longer had an easy passage through and beneath the coating as was the case for bars with damaged areas. The presence of isolated portions of adhesion loss indicated that solution had to work its way through the coating at weak or defective areas. Likewise, the absence of large exposed sites for corrosion initiation prevented cathodic reactions and subsequent cathodic disbondment.

At spliced short bars (cracked, unloaded beam B32), coating debonded from the patched cut ends up to a distance of about 20 to 24 cm. Undoubtedly, patched cut ends presented a weak spot where corrosion started and solution penetrated and propagated under the coating. Coating adhesion was preserved at a distance of about 25 cm beyond the patched cut end of the splice bars. Spliced long bars experienced adhesion loss at their central portion at midspan, over a length of 14 cm to 19 cm.

Coating debonded extensively on stirrups. Several factors may have contributed to the extensive adhesion loss of stirrups. The stirrups were at the same plane of the cracks they induced and when the solution penetrated, the whole surface of the stirrup was exposed to saline water. In addition, the stirrups presented zones of weakened adhesion caused by fabrication or bending. Pinholes, tears, or cracks also developed in the coating during fabrication. Damage in the coating, or even thinning of the coating, may have allowed oxygen and salt solution to cross the film. Stirrups were more vulnerable at the bent zones where debonding started and propagated to the adjacent straight legs. Another contributing factor may have been cathodic disbondment at zones adjacent to damaged areas because of the cell process occurring between the anodic and cathodic sites on the steel.[24]

Undercutting

As in macrocell specimens, corrosion under the epoxy coating after 4.3 years of exposure tended to be more extensive than indicated by the appearance of the coating when the concrete was removed. Several longitudinal bars experienced widespread corrosion activity beneath the coating (undercutting). In contrast, undercutting for companion specimens after one year was less extensive, especially on longitudinal bars. For some coated bar specimens, after the first year of testing, undercutting was usually confined to the vicinity of exposed steel areas, coating defects, and breaks near crack locations, usually extending a few millimeters up to 75 mm. The majority of longitudinal bars inspected after 4.3 years showed more widespread underfilm corrosion.

A similar situation occurred with stirrups. After one year of exposure, corrosion at stirrups was more widespread than at longitudinal bars. Typical areas with corrosion included areas at or around damaged spots, stirrup leg closer to the bottom beam surface, contact points with black bars, hook ends, and bent areas. After 4.3 years, underfilm corrosion spread throughout stirrup legs.

Similar to macrocell specimens, undercutting occurred in the following forms: a) A change of appearance of the steel surface to a mottled, glittering golden-brown aspect with no significant pitting or loss of metal (Fig. 9.70), and b) Uniform black or dark surface rusting with random reddish-brown (or other tones of brown) rust spots and some activity , such as slight pitting, rust buildup, and loss of metal at several locations (Fig. 9.71 through 9.74).

At portions of bars where coating adhesion remained (generally outside the exposed or wetted areas), the steel surface maintained its originally shiny, bright aspect. On bars with little corrosion activity (some longitudinal bars), large portions with debonded coating and a mottled, glittering golden-brown surface underneath with very little, almost negligible corrosion attack were noted. Bars with the greatest corrosion (stirrups and damaged longitudinal bars) had large areas with debonded coating and with a uniformly black or dark rusted surface.

As explained in Chapter 8, mottled surfaces with a glittery golden-brown or bronze appearance were thought to be cathodically disbonded, that is, areas where cathodic reactions took place. The particular appearance of such areas may have been produced by the alkalinity generated in such reactions. At the dark corroded areas, the mechanisms of crevice corrosion and oxide lifting may have taken place. Such mechanisms were also described in Chapter 8.

As was already noted, lower bars tended to have more corrosion than upper bars. Corrosion spread more at bottom of the beam (as in casting position, side facing outwards to the exposed surface) of the bars than on the top side (side facing inwards). Nevertheless, corrosion at the top side of the bars was neither negligible nor significantly lower than that at the bottom side. This contrasted with bars examined after one year of exposure, where corrosion occurred mostly at the bottom side of the bars and little or no corrosion occurred at the top side of the bars.

The amount of underfilm corrosion for all epoxy coated bars from the three groups of beams is tabulated in the following sections.

Longitudinal Bars

The extent of coating debonding, mottled surfaces, and dark corroded surfaces for each bar in terms of percentage of surface area along a 0.9 m. length of bar at midspan is summarized in Table 9.23. Since the wetted zone was 0.6 m. long, percentages of corroded surface greater than 67% indicate that corrosion spread beyond the limits of the exposed, wetted zone of the beams.

Data from Table 9.23 confirmed most of the trends mentioned before. The damaged condition of the epoxy coating was a more influential factor than the loading condition and presence of cracks on the corrosion performance of the longitudinal bars. Patching coating damage seemed to improve performance because less corrosion was observed. Nevertheless, bars in good as-received condition performed better than bars with patched damage.

Beam No.	**Bar**	**Debonded Coating**	**Mottled Surface**	**Corroded Steel Surface**	**Max. Pit Depth (mm)**
B1-L-UU-AR:	Upper	9%	8.7%	0.3%	0
	Lower	3.5%	2.8%	0.7%	0
B8-L-UU-D	Upper	77%	47%	30%	0.1-0.2
	Lower	74%	41%	33%	0.1
B10-L-CU-D	Upper	95%	82%	14%	0.2-0.3
	Lower	98%	69%	29%	0.5
B14-L-CU-D(P)	Upper	97%	87%	10%	0.5
	Lower	95%	81%	15%	0.5

Table 9.23: Approximate amount of debonded coating, mottled surface, and corroded metallic surface beneath the coating (percentage of bar surface along 0.9 m in midspan); and severity of pitting.

Interestingly, bars with 3% damage in uncracked unloaded beam B8 experienced slightly more corrosion than bars with similar damage in cracked unloaded beam B10. This was contrary to what was found after one year of exposure, where corrosion in uncracked, unloaded beams was limited primarily to the exposed areas and did not spread beneath the coating. The presence of cracks made chlorides readily available to the bar surface in the early stages of exposure. In uncracked beams, chlorides penetrated by diffusion through the concrete, and levels sufficient to cause corrosion were eventually reached as evidenced by the significantly greater amounts of chloride after 4.3 years compared to those after 1 year. Chloride content at the location of the upper bar in the wet zone was 0.09% by weight of concrete after one year of exposure (beam B7), and about 0.52% by weight of concrete after 4.3 years of exposure (beam B8).

Stirrups

The extent of coating debonding, mottled surfaces, and dark corroded surfaces for each stirrup in terms of percentage of surface area are condensed in Table 9.24.

Beam No.	**Debonded Coating**	**Mottled Surface**	**Corroded Steel Surface**	**Pitted Surface ***	**Max. Pit Depth (mm)**
B15-ST-UU-AR:	98%	31%	67%	26%	0.5
B17-ST-CU-AR:	100%	7%	93%	27%	1
B22-ST-UU-AR(P)	100%	11%	89%	14%	0.5
B23-ST-CU-AR(P)	97%	49%	48%	4%	0.3
B25-ST-CL-AR(P)	100%	14%	86%	20%	0.3
B27-ST-CU-D(P)	100%	17%	83%	15%	1

B32-SP-CU-D(P)	100%	45%	55%	26%	0.6

*Pit depth ≥ 0.3 mm.

Table 9.24: Approximate amount of debonded coating, mottled surface, and corroded metallic surface beneath the coating (percentage of stirrup surface); and severity of pitting for stirrups.

From Table 9.24, it is readily evident that coating adhesion was lost in all stirrups. Underfilm corrosion spread throughout most stirrup legs and ranged from 48% to 93% of the stirrup surface. The remaining surfaces were mottled. A metallic surface with a bright, shinny appearance was practically non-existent after 4.3 years of exposure.

If the percentage of pitted surface is considered as the most important indicator to evaluate corrosion performance, stirrups can be classified from best to worst as indicated in Table 9.25.

Beam No.	**Pitted Surface***	**Rank**
B23-ST-CU-AR(P)	4%	1
B22-ST-UU-AR(P)	14%	2
B27-ST-CU-D(P)	15%	3
B25-ST-CL-AR(P)	20%	4
B15-ST-UU-AR:	26%	5
B32-SP-CU-D(P)	26%	6
B17-ST-CU-AR:	27%	7

*Pit depth ≥ 0.3 mm. 1: Best 7: Worst

Table 9.25: Stirrup performance ranking based on amount of pitted surface.

From Table 9.25, patched stirrups performed better than as-received stirrups. After 4.3 years of exposure, the concrete crack condition was not the most significant factor influencing the corrosion performance of coated stirrups, although loading seemed to have some effect.

The trends described above contrasted with those observed after one year of exposure. Stirrups in cracked beams experienced more widespread coating debonding and underfilm corrosion than stirrups in uncracked beams after one year. Clearly, a longer period of chloride exposure allowed for the diffusion and build up of chlorides to initiate corrosion at coated stirrups in uncracked beams. The absence of cracks, therefore, delayed but did not prevent the accumulation of significant amounts of chlorides at bar locations. Chloride contents at bar locations in cracked and uncracked beams were very similar after 4.3 years of exposure, as discussed in Section 9.5.4 (see Table 9.8).

Splice Bars [Beam B32-SP-CU-D(P)]

The extent of coating debonding, mottled surfaces, and dark corroded surfaces for each splice bar in terms of percentage of surface area along 0.9 m in midspan (0.45 m for short bars) are summarized in Table 9.26. Since the wetted zone was 0.3 m long, percentages greater than 33% indicated that the coating on bars debonded beyond the wetted zone of the beams.

Underfilm corrosion in short bars was more extensive than was initially apparent on the coating surface. Evidently, the patched cut end located at a crack location at midspan of the beam constituted a weak link, where chloride solution penetrated and migrated underneath the coating.

Bar	Debonded Coating	Mottled Surface	Corroded Steel Surface	Max. Pit Depth (mm)
Upper Short	53%	33%	19%	0.4
Upper Long	13%	11%	2%	0
Lower Short	45%	24%	21%	0.5
Lower Long	19%	16%	3%	0.3

Table 9.26: Approximate amount of debonded coating, mottled surface, and corroded metallic surface beneath the coating [percentage of bar surface along 0.9 m in midspan (0.45 m for short bars)]; and severity of pitting. Splice bars of beam B32.

Corrosion Products

The main corrosion product found in coated bars was a uniform black or dark corrosion layer. Dark-greenish or greenish-black products were visible at several spots in the concrete surrounding the bars. Dark-greenish spots were more often observed on black bars at the most severely pitted locations. As mentioned in the macrocell study, the black product (magnetite) is indicative of corrosion with restricted availability of oxygen at crevices that form under the coating.

Typically, reddish-brown corrosion products were deposited at random spots over the black corroded surface. These corrosion products had a higher state of oxidation than darker corrosion products. Presence of cracks made oxygen available for further oxidation of corrosion products. In addition, the coating on the bars was not peeled immediately after removal from the concrete, but about a few weeks later. The thinner coating at corroded locations was possibly more permeable to air and the bars may have been exposed to larger quantities of oxygen as compared to a more restricted oxygen environment inside the concrete.

Immediately after autopsy, corrosion in uncoated bars was black or dark, with dark-greenish products at deep pits. Upon exposure to the atmosphere, extensive reddish-rust products developed over the bar surface.

Coating Blistering

Most blisters formed on the bottom side of bars (as in casting position) facing the concrete cover. Blisters had different sizes and smaller blisters were more abundant than larger blisters. As found in beam specimens examined after one year of exposure, a concrete void was always present adjacent to a blister in the coating. The greater quantity of concrete voids at the lower half of the bar surfaces accounted for the greater quantity of blisters at those regions. As in macrocells, most blistered areas had a very hard, solid consistency after 4.3 years of exposure.

9.6.5 Concrete Environment

Influence of Concrete Consolidation

As in macrocells, quality and consolidation of the surrounding concrete affected the corrosion of epoxy-coated bars. The concrete surface above epoxy-coated bars was smooth, shiny, and glossy, with few voids. Concrete surface below epoxy-coated bars had small gaps and voids and porous-like structure resembling laitance. In addition, the surface below the coated bars as in the cast position was closer to the exterior, irrigated surfaces.

The porous, less dense concrete beneath the bar can retain more chlorides, while chloride accumulation above the bars is limited because the concrete is denser. Consequently, slightly more corrosion and blistering were observed on the lower half of the longitudinal bars than on the top half. Concrete surfaces below the bars had more extensive rust staining than concrete surfaces above the bars. Nevertheless, corrosion was observed on the upper half of the bars and was more extensive after 4.3 years than after one year.

The high complexity of the concrete environment may help to explain why corrosion did not occur at some large exposed areas of some longitudinal bars, even in the presence of nearby cracks! In addition to some possible cathodic protection, perhaps the concrete voids facing such areas were not interconnected with the concrete void structure. Although chlorides may have penetrated nearby cracks, there may be localized, isolated voids with little or no chloride. Also, the alkalinity of the cement paste could have maintained the protective oxide layer stable.

9.6.6 Analysis of Study Variables

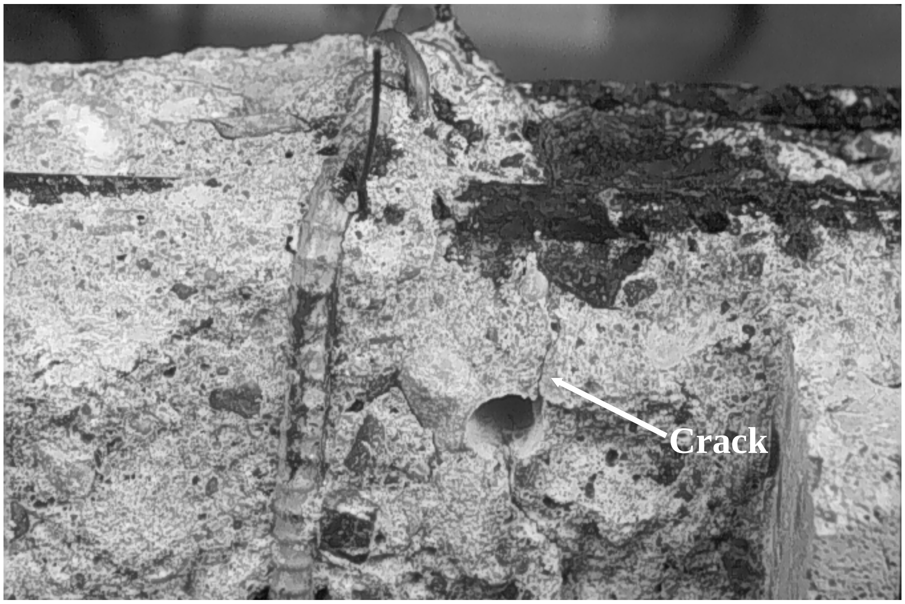
Uncoated vs. Coated Steel

A comparison of the performances of coated and uncoated bars was not one of the initial objectives of the beam corrosion study. Uncoated bars were used to reinforce the beams in the compression zone, with the premise that the bars would be outside of the exposed, wetted area. In many structures, epoxy-coated bars were used on parts of the structure exposed to chlorides and uncoated bars at other portions. However, the relatively long exposure to chlorides in this study resulted in corrosion of the uncoated bars. It was deemed important to document the condition of uncoated bars and compare their performance with that of coated bars. It is important to keep in mind that uncoated and longitudinal coated bars had different diameters (#3 for uncoated bars, #6 for coated bars). Coated stirrups had the same diameter as uncoated bars.

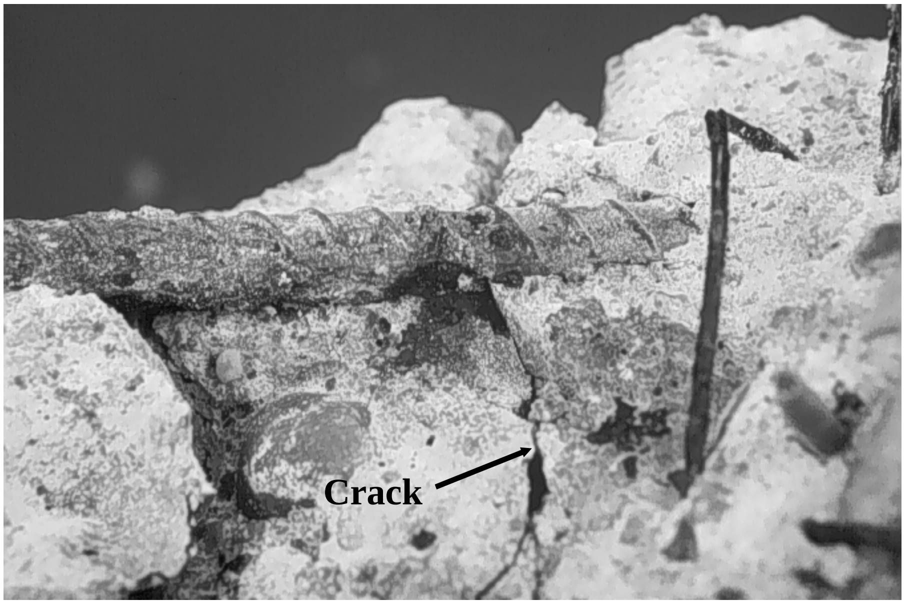
Uncoated bars experienced moderate to extensive corrosion with the formation of several moderate to severe pits. Substantial loss of cross-sectional area was evident at crack locations within the wet zone of beams groups II and III (Fig. 9.88). The strength of such bars was weakened by both reduction of cross-section and metallurgical degradation of sound steel. Large rust stains developed on the exterior concrete surface at the locations of severely pitted bars. Corrosion was generally confined within the wet zone in bars from group I but extended beyond the smaller wet zone in bars from groups II and III.

Both coated longitudinal bars and stirrups had less severe corrosion than uncoated bars. No deep pits or significant reduction of cross-section was observed on the steel surface of epoxy-coated bars. Corrosion generally consisted of a uniformly dark surface with shallow pitting.

Beam specimens resembled field concrete members more realistically than macrocell specimens did. The beams were relatively large, many of them were loaded and cracked, salt solution flowed over the surface instead of being ponded, concrete cover was larger, and a mix of coated and uncoated bars more closely resembling field reinforcement was used (some artificial elements remained, such as a highly concentrated salt solution applied in a particularly aggressive cyclic regime, and concrete with high water/cement ratio). Within this context, it was



(a) Pitting corrosion of uncoated bars at crack location (beam B25).



(b) Pitting corrosion of black bar at crack location (beam B23).

Fig. 9.88: Uncoated bars exhibited severe corrosion at crack locations.

encouraging to see the improvement obtained in durability by using epoxy-coated reinforcement. Unfortunately, the lack of real control specimens reinforced with a complete cage of uncoated bars made it not possible to perform a more meaningful comparison. As in the macrocell study, differences between test and field conditions should be kept in mind when analyzing and interpreting test results.

Finally, the performance reported herein corresponds to a coating formulation produced in the early 1990’s (newer than that for epoxy-coated bars in the macrocell study) and may not necessarily reflect the performance of coatings produced in the late 1990’s. Coatings developed more recently may perform differently than earlier formulations under similar exposure conditions.

Effect of Coating Damage

The damage condition of the epoxy coating was the most influential factor in the corrosion performance of longitudinal bars, despite the fact that some exposed steel areas did not corrode. Bars with 3% damage in both cracked and uncracked beams showed widespread coating debonding and extensive areas with both mottled and dark corroded surfaces. As received bars in uncracked beam B1 were in excellent condition at the end of the experiment. Only a few spots had a very thin film of reddish rust at mill marks. Coating adhesion was preserved throughout most of the bar surface and the steel surface underneath was bright and shinny, as in its original condition.

Analysis of corrosion potentials in uncracked beams showed that bars with 3% damage corroded much earlier than bars in as-received condition, but at about 3 to 3.5 years, some incipient corrosion activity was noted on bars with coating in as-received condition (Fig. 9.21). Differences in corrosion initiation between 3% damaged and as received bars in cracked beams were evident in the first three to six months only (Fig. 9.19). The implication of these trends was that bars with larger damaged areas experienced corrosion earlier and for a longer time than bars with as received condition.

Repair of Coating Damage

Longitudinal bars with 3% coating damage and patched (cracked unloaded beam B14) showed less extensive and widespread corrosion than bars with unrepaired damage. A few patched areas on each bar presented dark corrosion. Most patched areas showed no signs of corrosion (Fig. 9.56). Patching coating damage seemed to improve performance by lessening the amount of corrosion. Nevertheless, bars with a good as received condition still performed better than bars with patched damage. Despite the slight improvement in corrosion performance of patched bars, there was not clear difference in the corrosion potentials between unpatched and patched damaged bars (cracked beams). Although corrosion potentials indicated that both unpatched and patched, damaged bars underwent corrosion, they by no means could pinpoint differences in rate and severity of corrosion.

Stirrups with as received condition underwent more extensive and severer corrosion than as received and patched stirrups. Among patched stirrups, damaged stirrups experienced slightly worse corrosion than as received stirrups. Despite earlier potential drops experienced by as received stirrups, potentials of patched stirrups (both with 3% damaged coating and with as received condition) eventually reached similar potentials than those with unrepaired, as received condition as exposure time increased. Again, the final potential range was not useful in assessing the relative performance of coated stirrups.

Patched cut ends at splice bars experienced uniform dark corrosion beneath the patch, and corrosion progressed under the coating up to a distance of about 20 to 24 cm from the patched ends. Corrosion spread over the bottom side of the bars as in casting position, while the top sides of the bars exhibited a mostly mottled surface. Evidently, bar patched ends located at a crack location constituted a weak link, where chloride solution penetrated and migrated underneath the coating.

Effect of Loading and Cracking

Epoxy-Coated Bars

Compared to coating condition, little effect in performance of longitudinal bars was produced by loading condition and presence of cracks. No significant differences in corrosion severity and extent were observed among bars from cracked or uncracked beams, provided the coating was damaged. Corrosion potentials evidenced early corrosion initiation of bars in cracked beams. Bars in uncracked beams started to corrode after about one year when the coating had 3%

damage (Fig. 9.23), and after about 3 to 3.5 years when the coating was in its as received condition (Fig. 9.22). Loaded and unloaded beams with cracks showed very similar potential trends regardless of coating condition (Fig. 9.23).

Similar to longitudinal bars, performance of stirrups was not significantly effected by presence of cracks or the loading condition. For similar coating and loading condition, performance of stirrups in cracked beams was sometimes better than that of stirrups in uncracked beams (Fig. 9.32). For beams with similar coating and cracking condition, the stirrup inside an unloaded beam performed worse than that inside a loaded beam. Potential readings indicated that stirrups in cracked beams corroded earlier than stirrups in uncracked beams. Corrosion potentials between cracked and uncracked beams became similar after about 2.5 years of exposure.

Several longitudinal coated bars did not experience corrosion on some damaged sites (patched or unpatched) near crack locations within the wetted zone. Cathodic polarization and a complex concrete environment protected such spots from corrosion.

Uncoated Bars

The effect of cracks was much worse on uncoated bars than on coated bars. Uncoated bars experienced severe pits and loss of metal at or near crack locations after 4.3 years of exposure. Corrosion may have been worsened at any incidental contact between exposed areas at inside of stirrup corners and uncoated bars, producing electrical continuity between bars and aggravating the macrocell effect.

Longitudinal vs. Transverse Reinforcement

Among coated bars, stirrups underwent more extensive corrosion than longitudinal bars. The coating debonded practically around the entire surface of stirrups. Steel surface beneath the coating was uniformly dark corroded and presented relatively shallow pits on most of the stirrup legs. A deeper pitting (0.3 mm ≤ pit depth ≥ 1.0 mm) was observed over surfaces extending from 4% to 27% of the stirrup surface area.

Longitudinal bars developed less extensive and severe corrosion than stirrups. Except bars from beam B1 where adhesion was preserved, bars experienced coating debonding throughout and a little beyond the wetted zone. Extent of corrosion ranged from 0.3% to 33% of surface along the 0.9 m portion in midspan. Pitting was less extensive and shallower than that in stirrups.

Factors conducive to higher corrosion of stirrups included the presence of a crack in the same plane of the stirrup, their closer proximity to the exterior surface, weakening of adhesion and damage of coating caused by fabrication, and possible incidental continuity with the uncoated bars in the compression zone.

9.7 CORROSION MECHANISM

Kahhaleh proposed several corrosion mechanisms for epoxy coated bars (longitudinal bars and stirrups) inside beam specimens based on findings after one year of exposure.[10] Examination of bars after 4.3 years of exposure seemed to confirm the mechanisms proposed earlier. Corrosion mechanisms for coated and uncoated bars are described in the following sections, emphasizing subtle differences with mechanisms identified after one year and those identified after 4.3-years.

9.7.1 Corrosion of Coated Longitudinal Bars

Influencing Factors

Longitudinal bars extended through wetted middle portions and dry outer portions of the beams. In some bars, portions of the coating were intentionally damaged within the middle 0.9 m of the beams. In cracked beams, most cracks were located within the exposed, wetted regions of the beams. This situation created a non-uniform condition along the beams surface.

The middle portion of the beams was characterized by a high moisture and chloride content, while the outer portions were drier and had a lower chloride content. Even within the wet zone, conditions were not uniform: Chloride, moisture, and oxygen were more concentrated at crack locations, especially during the first year of exposure.

In uncracked beams, non-uniform conditions were produced by the heterogeneity of concrete. A denser concrete was observed on the side of the bars facing the inner core of the beams (top side as in casting position) while a less dense, more porous concrete was found on the side of the bars facing concrete cover (bottom side as in casting position). Chlorides and oxygen were more prone to accumulate at the sides of the bars facing the concrete surface.

Finally, the epoxy coating and bars themselves had non-uniform properties, characterized by the random location of damaged areas and holidays, uneven coating thickness, non-uniform steel metallurgy, among other characteristics.

All of the above factors produced non-uniform conditions along the bar surface that led to the formation of corrosion cells. Areas with exposed metal and higher chloride, moisture, and oxygen concentration were predominantly anodic. Such portions were frequently, but not exclusively, located at or near cracks. The cracks facilitated moisture and chloride migration. Areas with relatively high moisture and oxygen content but lower chloride concentration tended to become cathodic. Such portions were frequently, but not exclusively, located away from exposed areas and cracks and on the side of the bars towards the inner core of the beams. In fact, several exposed steel areas behaved cathodically even in the presence of nearby cracks. Large cathodic areas were also observed on the lower side of the bar facing the concrete cover. The position of anodic areas followed no particular pattern.

In summary, anodic and cathodic areas developed within the wet zone and roughly 15 cm beyond the wet zone on each side. Portions of the bar beyond 25 cm from the boundary of wet zones were corrosion-free with no loss of coating adhesion.

Corrosion Process

Corrosion mechanism of coated bars in beam specimens was similar to that observed in macrocell specimens, described in Chapter 8. At uncracked beams, corrosion started when enough chloride ions penetrated the concrete cover and reached the exposed areas (sites with damage or flaws in the coating) on the coated bar to depassivate the steel. At cracked beams, corrosion started much earlier because cracks facilitated moisture and chloride penetration. A porous concrete adjacent to or near exposed areas allowed for the accumulation of chlorides, oxygen, and water, all necessary agents for corrosion initiation. In contrast, exposed areas surrounded by non interconnected concrete voids, were free of corrosion.

Bar corrosion potentials shifted immediately to more negative values when chlorides contacted exposed steel surfaces, from below -100 mV SCE to more negative than -300 mV SCE. The magnitude of potential shift varied and caused temporary instability of the potential in some cases. The drop in potential in cracked beams was practically instantaneous upon contamination with chlorides. The earlier acceleration of corrosion at cracked locations reduced the fluctuation in the potentials of cracked beams.

When corrosion started at exposed areas, local, small anodes and cathodes developed. Exposed areas were self-polarized as corrosion progressed locally. A polarization in the opposite direction was induced in the adjacent areas covered by the coating. A cathodic reaction (with consequent cathodic disbondment) took place at such areas. Other exposed areas surrounded by dense concrete or non-interconnected concrete voids were cathodically polarized (Fig. 9.89). Corrosion spread at the small crevices under the coating at the edges of exposed areas or discontinuities. Adjacent debonded coating (by cathodic disbondment, water action, or a combination of both) formed very thin crevices and corrosion propagated under the coating in a mechanism similar to that of crevice corrosion.

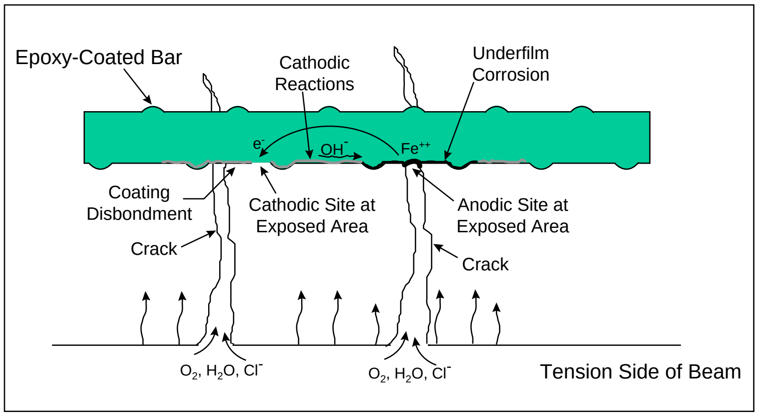


Figure 9.89: Mechanism of corrosion of coated longitudinal bar.

With time, underfilm corrosion progressed on the coated bar and oxide lifting took place. As explained in Chapter 8, oxide lifting occurs when anodic corrosion products accumulate under the coating during alternate wet and dry cycles. Undercutting initially progressed more extensively on the portion of the bars nearest the concrete surface. Undercutting was facilitated by easier distribution and accumulation of chlorides through the gap between bar and concrete and through the void structure in the concrete. Concrete voids provided the physical space for the expansion of corrosion products to form blisters.

The almost complete lack of debonded coating and corrosion of as-received bars reinforced the hypothesis that corrosion spread from damaged, exposed areas. The coating in as received bars was in a very good initial condition, with very few and small damaged areas. Although chloride levels were very high after 4.3 years of exposure, the coating provided a very effective barrier to the passage of chloride solution. The few, isolated areas where adhesion was lost were probably spots where the coating was most defective and chloride solution migrated through the coating.

Assuming that the original coating adhesion was roughly the same for all bars, it was clear that chlorides and moisture penetrated the coating rapidly and easily through damaged areas of the coating. Exposed areas were always surrounded by debonded coating, while the isolated portions where coating adhesion was preserved were located farthest away from the exposed areas. This observation provided further evidence that solution penetrated mainly through exposed areas of the bar, and was in agreement with findings by others.[18, 65, 76]

Macrocell effects on coated longitudinal bars were greatly limited by the coating itself and the effective isolation of the bars with other portions of the reinforcement. The epoxy coating shielded the steel surface from becoming continuously exposed to large amounts of moisture, chlorides, and oxygen. Although moisture and chlorides eventually penetrated the coating and reached the steel surface, underfilm corrosion progressed slowly because of the limited availability of oxygen under the coating. Underfilm corrosion was under cathodic control due to limited oxygen diffusion.

After 4.3 years of exposure, bars from cracked and uncracked beams with similar coating damage did not show much difference in the amount of corrosion, despite earlier corrosion initiation and progression on bars inside cracked beams. The epoxy coating significantly slowed the corrosion activity of bars in cracked beams by limiting oxygen diffusion. This protecting capability was greatly aided by the lack of macrocell action. In addition, chloride contents in uncracked beams eventually reached levels similar to those in cracked beams after 4.3 years. Apparently, the time of exposure was long enough for chlorides to accumulate inside uncracked beams and to corrode the bars. Deterioration levels similar to bars in cracked beams were reached.

Limited availability of oxygen beneath the coating caused most corrosion products to be in a low oxidation state. This accounted for the predominance of magnetite, which is the uniformly black corrosion product observed at the corroded surfaces. Variable amounts of reddish-brown and other brownish corrosion products were observed above the dark corroded surface.

No signs of corrosion-induced cracking were observed on exterior concrete surfaces. A few small brown stains were first observed on the top surface of beam B8 within the wet zone at about 1.9 years of exposure.

9.7.2 Corrosion of Coated Stirrups

Influencing Factors

Several factors adversely influenced the corrosion performance of coated stirrups: Stirrups were located entirely within the wetted regions, including patched ends. As crack inducers, they were located within the same plane of cracks (except in uncracked beams). Large amounts of chlorides, oxygen, and moisture surrounded the stirrups in cracked beams. Load cycling further increased the amounts of corrosive substances at the stirrup level. Stirrups were closer to the concrete surface than longitudinal bars. During fabrication, adhesion of the coating was weakened and the coating was damaged on the outside and inside of the bend.

Corrosion Process

Because of its similarities with that of longitudinal bars, the process leading to corrosion initiation and progression of coated stirrups will not be discussed in detail. Corrosion of stirrups was aggravated by the factors mentioned above. There were more similarities between the corrosion of stirrups and macrocell bars than between longitudinal bars and macrocell bars.

Corrosion generally progressed from patched areas on the outside of the bends and from patched ends towards the rest of straight legs. Weakened adhesion during fabrication greatly facilitated coating disbondment and underfilm corrosion. Again, the drop in potential in cracked beams was almost immediate at first contamination with chlorides. Corrosion was generally more extensive at the bottom and front legs, which implies that chlorides penetrated from the bottom surfaces by capillary action, in addition to the chlorides that diffused from the top.

Concrete environment around the bars was an important factor. There were several cases where the front leg of the stirrup was corroded while the nearby front hook end was mottled and its patched end exhibited a clean steel surface (Fig. 9.90). The corroding front leg was in the plane of the crack, while the overlapping front hook end was a few centimeters away from the crack plane.

Possible incidental continuity with uncoated bars through damage at contact points may have effected corrosion performance. Ribs at the inside of the bend of stirrup were damaged (in the form of smashed coating) during fabrication.

Tie wires used for cage assembly often cut partially trough the coating. Sometimes, the coated tie wire was stripped when twisted, causing the metal to be uncovered. Semi-conducting corrosion products may have bridged the gap between uncoated bars and exposed areas in stirrups.

Fig. 9.90: Stirrup leg near the beam front surface (top in photo) is corroded while stirrup hook is mottled (bottom in photo) (Beam B32).

During the first year of exposure, a strong macrocell action developed between the stirrup in a chloride contaminated region and uncoated bars extending along uncontaminated concrete. Cracks facilitated the ingress of chlorides and oxygen to the contact points and promoted initiation of corrosion. Most uncoated bars were initially cathodic and most stirrups were anodic (Fig. 9.91). This situation gradually changed as chloride contamination spread over a larger portion of the beams and corrosion of uncoated bars progressed. Uncoated bars became very anodic over a large surface near the wetted regions as more chloride accumulated on the bar surface, especially at crack locations. Meanwhile, in all stirrups, the portion of steel surface closest to the uncoated bars (inside of the back leg and adjacent bends) remained mottled, with no visible pitting. Parts of the stirrup became cathodic with respect to the anodic black bars and other anodic legs of the stirrup. The reduced availability of cathodic surfaces provided by black bars may have slowed the corrosion rate of stirrups.

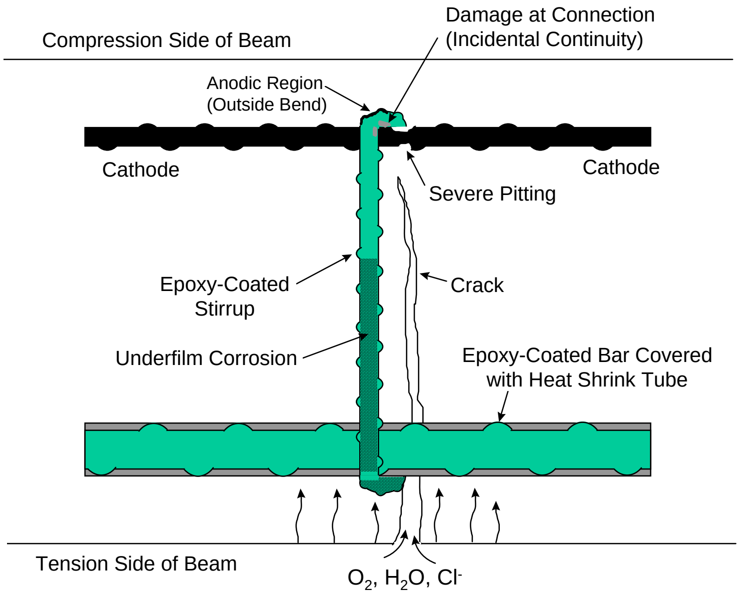


Figure 9.91: Mechanism of corrosion of coated stirrup.

After 4.3 years of exposure, stirrups from cracked and uncracked beams with similar coating damage did not show much difference in the amount of corrosion, despite earlier corrosion initiation and progression on stirrups inside cracked beams. After an initially fast rate of corrosion, the epoxy coating significantly slowed further corrosion activity of stirrups in cracked beams by limiting oxygen diffusion. This protecting capability was subsequently aided by the gradually diminishing macrocell action provided by the uncoated bars. Chloride contents in uncracked beams eventually reached levels similar to those in cracked beams after 4.3 years. Apparently, the time of exposure was long enough for chlorides to accumulate inside uncracked beams and to corrode the stirrups to levels similar to those for stirrups in cracked beams.

9.7.3 Corrosion of Uncoated Longitudinal Bars

Uncoated bars exhibited severe macrocell corrosion. The lack of a protective coating allowed the steel surface to be continuously exposed through wetted and dry regions, and through regions with variable moisture content and chloride contamination (Fig. 9.92). Bars became anodic within wetted regions, at crack locations or other locations where chlorides accumulated in high concentrations. Anodic regions were characterized by moderate or severe pits with dark-greenish corrosion products. Cathodic portions generally developed at wet-dry transition regions, where chloride content was slightly lower than that at wetted regions near midspan, but some moisture was available. Sometimes, cathodic regions were within the wetted zone, to the left or right of midspan, while the rest of the bar within the wetted region was anodic. Unrestricted availability of oxygen maintained corrosion under anodic control.

Uncoated bars in beams groups II and III underwent very severe pitting, with significant reduction of cross-sectional area and metallurgical degradation of sound steel. The macrocell effect was more intense than in beam group I, possibly because of a smaller wetted region typically enclosing one wide crack. Group I beams had a larger wetted region enclosing more narrow cracks. Consequently, a smaller anode/cathode ratio developed in bars from groups II and III, resulting in severe pitting at the crack location.

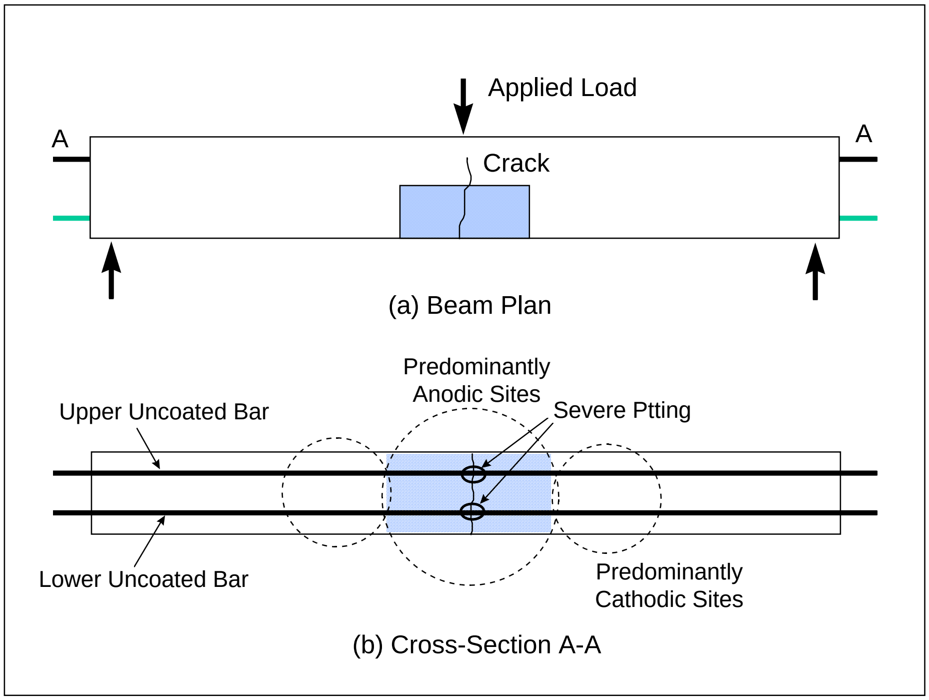


Figure 9.92: Macrocell corrosion of uncoated bars.

Uncoated bars in uncracked, unloaded beams experienced the least severe corrosion. The lack of cracks delayed the onset of corrosion and prevented the accumulation of chlorides in excessively high concentrations at crack locations. Corrosion tended to be more uniform and pitting was less severe.

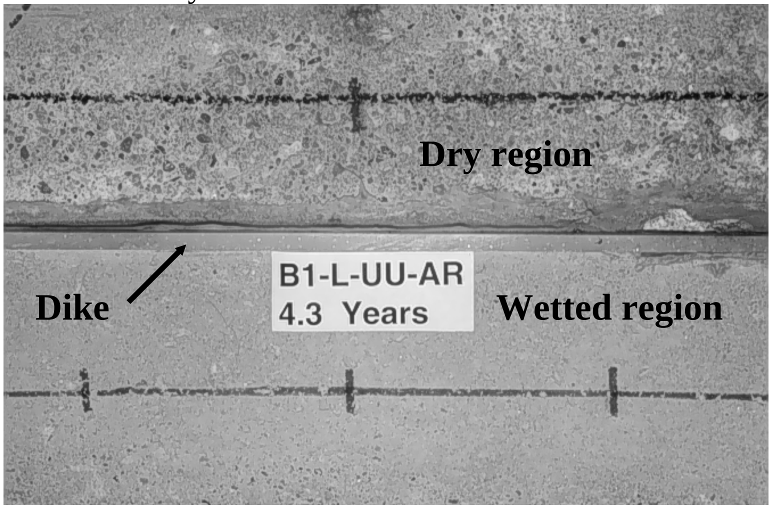
Large rust stains developed on the exterior concrete surface at the locations of severely pitted bars. No corrosion-induced cracking or spalling was detected after 4.3 years of exposure.

9.7.4 Concrete Deterioration

A mechanism of concrete deterioration, similar to that of macrocell specimens with uncoated bars, took place in all beams. As was mentioned early in this chapter, the concrete surface deteriorated and scaled within the wet zone and in regions outside the wet zone (Fig. 9.93). Concrete scaling outside the wet zone was more extensive and severe at the bottom surfaces, and the degree of scaling ranged from light to severe. Scaling was usually worse outside the wetted regions. Scaling extended up to 76 cm to each side of midspan in beams group I and up to 51 cm to each side of midspan in beams groups II and III.

In addition to concrete scaling, loaded and unloaded beams experienced cracking with random orientation, mainly longitudinal, at and around the wet zone (Fig. 9.94). Such cracks appeared between 2.5 and 3.6 years, and had a maximum width of 0.20 mm, with most between 0.08 and 0.10 mm. No signs of rust were found inside or around such cracks.

Concrete scaling and non-structural cracks were caused by forces from expansive hydrated salt crystals that were driven through concrete pores after periodic cycles of wetting and drying. When water evaporated during dry cycles, salts in the form of crystals were left in the capillary pores. Upon subsequent wetting, the crystals re-hydrated and grew, exerting an expanding force on the surrounding cement paste. The crystallization of salt in a zone having a free evaporation surface or to which the solution is raised by capillary forces, such as the regions adjacent to the wetted zone in the beams, results in destructive internal pressures that may crack and deteriorate the concrete.[128, 137, 138] Such surfaces are



(a) Beam B1, top surface (plan view).

(b) Bottom surface of beam B1, close up of crack at midspan.

Fig. 9.93: Concrete scaling inside and outside wetted regions. Scaling was more severe outside but near wetted regions.

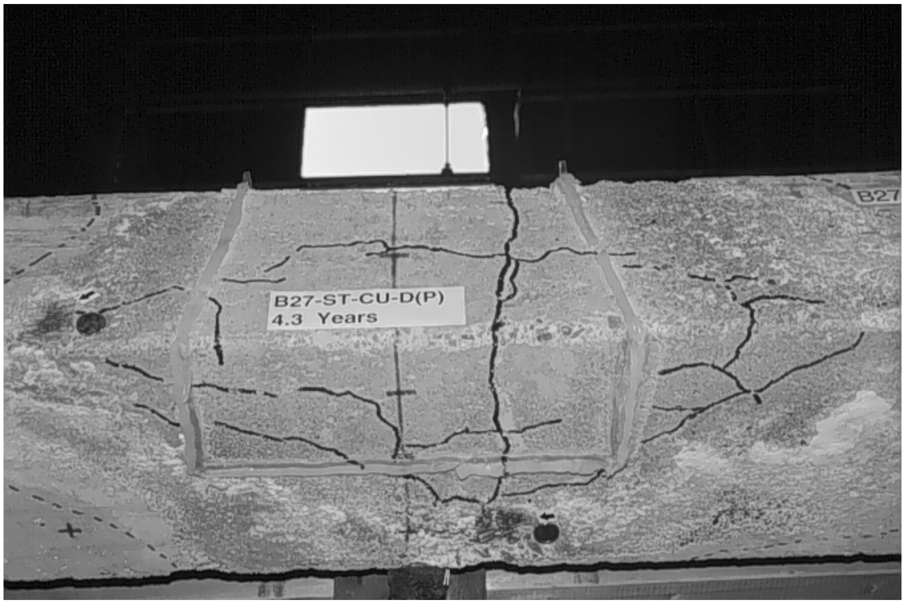


Fig. 9.94: Random cracking at and around wetted region of beam B27.

vulnerable because free evaporation results in an increase of salt concentration. At scaled areas, the hardened cement paste and embedded fine aggregate particles were removed, leaving behind protruding coarse aggregate particles (Fig. 9.93). Large deposits of salt crystals were visible at scaled surfaces.

Contrary to macrocell specimens, pre-existence of flexural cracks did not effect the amount of concrete scaling. Concrete deterioration was as severe in uncracked beams as was in cracked beams. It is possible that the type of solution exposure influenced the mechanism of concrete deterioration. A solution flowing from top surfaces down to side and bottom surfaces allowed chlorides to penetrate in three ways: a) Penetration from top by gravity, b) penetration from bottom by capillary action, and c) through cracks (when applicable). It seemed that a substantial amount of chloride solution penetrated the concrete when flowing over several concrete surfaces, as opposed to the top surface being ponded. Differences in cycling procedures may have been an additional factor. Beams had short wet periods and long dry periods, while macrocells had wet and dry periods of equal duration. Chlorides diffuse more effectively when wet periods are relatively short and dry periods are relatively long.[128]

9.8 SUMMARY AND CONCLUSIONS

9.8.1 Summary

A beam corrosion experiment was conducted to study the performance of longitudinal and fabricated (stirrups) epoxy-coated bars damaged to various levels. Duplicate specimens containing coated bars on the tension side of the beams, uncoated bars on the compression side, and a coated stirrup at midspan were prepared. The coating condition was varied to study effects of damage and patching on corrosion performance. A few specimens included splice bars with patched ends within the wetted region of the beams. Some beams were uncracked while others were cracked and either unloaded so that the cracks closed or kept under load to maintain the cracks width. The middle portion of beams was irrigated with a chloride solution in alternating wet and dry periods for 4.3 years. Loads were cycled on the cracked beams during the wet and dry periods. Development of corrosion and corrosion potentials were monitored and specimens were opened for examination of the bar condition after 1 and 4.3 years. Results of autopsies performed on half of the specimens after 1 year were reported elsewhere.[10] Results of autopsies from the remaining specimens after 4.3 years of exposure were reported in this Dissertation.

9.8.2 Conclusions

The main conclusions of this study are summarized and grouped in the following categories:

Effectiveness of Epoxy Coated Reinforcement

Both coated longitudinal bars and stirrups exhibited less severe corrosion than uncoated bars. No deep pits, significant reduction of cross-section, nor substantial metallurgical degradation were observed in the steel surface of epoxy-coated bars. Corrosion generally consisted of a uniformly dark surface with shallow pitting beneath the coating. Uncoated bars experienced moderate to extensive corrosion with the formation of moderate to severe pits. Substantial loss of cross-sectional area was evident at crack locations. Large rust stains developed on the exterior concrete surface at the locations of severely pitted bars. The benefits of using epoxy coating became more evident in cracked beams.

Effect of Coating Damage and Repair

The damage condition of epoxy coating was the most influential factor affecting the corrosion performance of coated bars and stirrups. Although a number of exposed areas did not corrode, bars with 3% damage to coating corroded more extensively than bars in a good as-received condition, that is, no visible coating damage. As received longitudinal bars were practically corrosion-free. Stirrups with as received coating, which was not in good condition, did not perform as well and corroded more extensively than stirrups on which the as-received coating damage was patched. Among patched stirrups, stirrups with added intentional damage experienced slightly worse corrosion than as-received stirrups. Longitudinal bars with patched 3% damage to coating showed less extensive and widespread corrosion than bars with unrepaired damage. Dark corrosion was noted on only a few patched areas on each bar. Patched cut ends at splice bars experienced uniform dark corrosion beneath the patch, and corrosion progressed under the coating up to a distance of about 20 to 24 cm from the patched ends.

Damaged (patched or unpatched) areas and patched bar ends represent a weak link in the coating, where chloride solution penetrated and migrated underneath the coating, and caused progressive coating debonding and corrosion. Nevertheless, several damaged, exposed sites in longitudinal bars experienced no corrosion, even when located near cracks within the wetted zone. Cathodic polarization and a complex concrete environment may have protected such spots from corrosion.

Corrosion Potentials

Measurement of corrosion potentials was a valuable tool to monitor corrosion activity and to asses time to corrosion. It was necessary to monitor the potentials periodically and over an extended period to avoid misinterpretation of results. Measuring potentials over a short period could be misleading. Potential shifts to more negative values only indicated that corrosion cells were established. With time, the potentials dropped and fluctuated. Potentials in all beams remained practically steady towards the end of exposure, within the range of -500 to -600 mV SCE, indicating that in most beams active corrosion conditions existed for the remainder of the test.

Measured potentials did not correlate with rate and severity of corrosion. A wide overlap of corrosion performance was observed in the potential range of -300 to -550 mV SCE. Generally, corrosion potentials less negative than -300 mV SCE indicated negligible or no corrosion. Potentials more negative than -550 mV SCE indicated moderate to severe corrosion in most cases but minor corrosion in others. For uncoated bars, corrosion potentials less negative than -300 mV SCE correlated with minor or no corrosion, while potentials in the range of -370 to -575 mV SCE were associated with moderate to severe corrosion.

Potential differences between wet and dry regions did not accurately reflect corrosion severity. Potential gradients greater than 200 mV did not seem to be associated with any well-defined level of corrosion activity in epoxy-coated bars after 4.3 years of exposure. Corrosion in such bars varied from negligible to moderate. For uncoated bars, maximum potential gradients above 300 mV were conducive to severe pitting corrosion. Kahhaleh reported that [shallow] pitting corrosion in coated bars was associated with potential gradients greater than 200 mV SCE after one year.[10]

Effects of Cracking and Loading

Compared to coating condition, loading condition and presence of cracks had little effect in performance of coated bars after 4.3 years of exposure. No significant differences in corrosion severity and extent were observed among bars from cracked or uncracked beams, provided the coating was damaged. The main influence of cracking was in time to corrosion initiation. Stirrups and longitudinal bars in cracked beams (loaded or unloaded) started to corrode within 1.5 to 6 months. Times to corrosion in uncracked beams were as follows: a) one year in bars with 3% damage to coating, b) 1.5 to 2 years in stirrups, and c) 3 to 3.5 years in bars with as-received coating.

In contrast to what was observed after 4.3 years, longitudinal bars and stirrups in cracked beams experienced more widespread coating debonding and underfilm corrosion than those bars in uncracked beams after one year of exposure. The absence of cracks, therefore, delayed but did not prevent the accumulation of significant amounts of chlorides at bar locations. Chloride contents at bar locations in cracked and uncracked beams were similar after 4.3 years of exposure.

Loaded and unloaded beams showed similar behavior regardless of coating condition. The loading condition seemed to have some effect on the performance of stirrups. For similar coating and cracking condition, the stirrup inside the loaded beam did not perform as well as one inside an unloaded beam.

The effect of cracks was much worse on uncoated bars than on coated bars. Uncoated bars experienced severe pits and loss of metal at or near crack locations after 4.3 years of exposure, reducing their strength and load-carrying capacity, especially in bars from beam groups II and III. The smaller exposed, wetted surfaces enclosing fewer but wider cracks in beam groups II and III may have produced a smaller anode/cathode ratio that was conducive to severe pitting corrosion. Corrosion may have been worsened by any incidental electrical continuity at contact points with stirrups that could have led to larger macrocell effects.

Mixing Uncoated and Coated Steel

The practice of mixing coated and uncoated bars in the same concrete member may lead to undesirable performance. Any incidental continuity between coated and uncoated bars could establish large macrocells that would be conducive to extensive corrosion. An additional risk is the possibility of corrosion of uncoated bars, which as was seen in this study, can be very severe.

Effects of Concrete Environment

Quality and consolidation of the surrounding concrete was an important factor affecting the corrosion of epoxy-coated bars. Longitudinal bars tended to corrode slightly more along the side facing the concrete surface, where more voids on the concrete were likely. Rusting of coated stirrups was frequently observed where concrete was more porous. Corrosion products and blisters were usually observed at concrete voids. Although concrete quality and consolidation were important, the complexity of the concrete environment also influenced the occurrence of corrosion along the bars. Corrosion was not observed at areas with exposed metal that were probably surrounded by isolated concrete pores, even when cracks were nearby.

Corrosion Mechanism

Corrosion in uncracked beams started when enough chlorides penetrated the concrete cover and reached the exposed areas on the coated bar to depassivate the steel. Corrosion started much earlier in cracked beams because cracks facilitated moisture and chloride penetration. Corrosion spread at the small crevices under the coating at the edges of exposed areas or discontinuities.

Adjacent coating debonded by cathodic disbondment, water action, or a combination of both, forming very thin crevices. Corrosion propagated under the coating in a mechanism similar to that of crevice corrosion. The corrosion initiation process was characterized by self-polarization. Other exposed areas, when surrounded by dense concrete or non-interconnected concrete voids, were cathodically polarized. In longitudinal bars, the epoxy coating shielded the bars from and prevented macrocell effects, while in coated stirrups, macrocell action could have been established by incidental continuity at contact points with uncoated bars.

Uncoated bars suffered severe macrocell corrosion. The lack of a protective coating resulted in the steel surface being continuously exposed all along wet and dry regions, and through regions with variable moisture content and chloride contamination. Large rust stains developed on the exterior concrete surface at the locations of severely pitted bars.

Chapter 10. Analysis of Factors Affecting the Performance of Epoxy Coated Reinforcement

10.1 GENERAL

When first used, fusion-bonded epoxy coatings, which had been developed and used for the pipeline industry, were directly applied to reinforcing bars without specific reformulation that would take into account their new environment. Obviously, there was practically no knowledge about the performance of epoxy coatings in a chloride-contaminated concrete environment. This created a learning curve that resulted in failure of the first products in several cases, such as in the Florida Key bridge substructures. The lessons learned from this and other failures, and from the continuous research that has been conducted, have improved the knowledge and is creating a new awareness of the relevant factors effecting performance of coated bars inside chloride-laden concrete.

The objective of this chapter is to present a synthesis of major findings and conclusions from the experiments conducted at various stages during the course of this research. The discussion will focus on the main factors that effected corrosion performance. A comprehensive analysis of the major implications and impact of this research is presented, always keeping in perspective relevant research findings by others, especially those involving some of the most controversial issues.

10.2 DAMAGE TO EPOXY COATING

Immersion tests,[10] and macrocell and beam studies all concluded that damage to epoxy coating was the most significant factor effecting corrosion performance. When epoxy coating was in good condition, without any visible damage, bars in beam specimens remained in very good condition. The steel surface maintained its original shiny appearance after 4.3 years of saline exposure (except at a few locations where minor corrosion was noted). All tests showed that the greater the size and frequency of damage, the more severe and more extensive the amount of corrosion.

Research by others has also shown the detrimental effect of coating damage in corrosion performance.[18, 71, 86, 134] The early failure of Florida Keys' bridge substructures has been partly attributed to presence of damage (within the permissible limits by applicable specifications).[20] Electrochemical impedance spectroscopy (EIS) and polarization resistance tests on bent and straight coated bar samples after 200 days of immersion in 3.5% NaCl solution performed by Chen showed similar findings.[145] Chen concluded that "the most crucial factor affecting epoxy-coated bar performance was the coating integrity." Bar samples with most corrosion were characterized by having a coating of poor quality with numerous damaged areas and pinholes, despite the fact that all damage and defects were patched. Thinner coatings performed poorly, mostly because they were more likely to have weak spots and were more susceptible to physical damage than thicker coatings. Even considering the poorest performance of coated specimens, the corrosion performance of coated bars was always better than that of uncoated specimens.[145]

Research conducted at Sumitomo Metal Industries in Japan with uncoated, galvanized, and epoxy-coated bars embedded in concrete prisms produced very similar results to the present research.[146] The prisms were pre-cracked and loaded to a steel tensile stress of 200 MPa (29 ksi) for two (lab exposure) and three (marine exposure) years. Bars with undamaged epoxy coating in cracked specimens exposed to natural marine environment and to accelerated exposure remained essentially uncorroded, regardless of film thickness and depth of concrete cover. The coating maintained its original appearance, adhesive strength, and scoring and peeling hardness. On the contrary, bars with damaged coating experienced various degrees of corrosion at damaged areas in the vicinity of cracks. Extent and severity of corrosion was dependent on film thickness and depth of concrete cover. Corrosion was more extensive with thinner coatings and shallower concrete covers.[146] In a field survey of four bridge decks in California, the presence of high chloride concentrations (0.7 to 4.6 kg/m^3) at the bar location did not initiate corrosion if there were no defects in the coating, indicating that undamaged epoxy coating provided satisfactory corrosion protection.[18]

Early versions of ASTM D3963 specifications and CRSI guidelines allowed up to 2% coating damage and maximum size of damaged areas of 6x6 mm.[64, 147] This and other damage limits allowed by US agencies were based on early research results by the FHWA, where no corrosion deterioration was observed in deliberately damaged bars.[51] Clearly, these limits were not adequate.

Findings herein and those of other researchers have caused a continuing revision of acceptable limits on unrepaired damage and patched surface. Other specifications (TxDOT, NACE) have set more stringent requirements and lowered the amount of permissible damage. More recently, an ASTM task group approved amending ASTM specification D-3963 to tighten the allowable damage provision. The new specification requires all visible damage to be repaired.[148] Likewise, TxDOT specifications require all visible damage to be patched, with a maximum patched area at the plant of 6 mm (1/4 in) total length in any linear 0.3 m (1 ft) bar length.[123] In the United Kingdom, the limiting damage specified by BS 7295 is 1% of surface area.[60]

10.3 REPAIR OF EPOXY COATING

Immersion tests,[10] macrocell and beam studies, and patching experiments all showed that patched areas are vulnerable to corrosion. Sound fusion-bonded epoxy coating provides much better protection than most patching materials. Patching damaged coating slightly reduced but did not completely prevent corrosion in beam and macrocell specimens. Patched bar ends were particularly vulnerable to corrosion. EIS and polarization resistance tests by Chen led to the same conclusion.[145] Corrosion of patched ends has been observed by others.[134]

CRSI guidelines limit the amount of damaged coating, including repaired and unrepaired areas, to 2% of the bar surface area per 0.3 m (1 ft) of bar.[64] ASTM D3963 specifications limit the maximum surface area of patched damage to 5%.[147] Again, these limits are clearly not adequate. Findings in this research project show that bars with 2% patched damage may undergo significant levels of underfilm corrosion. TxDOT specifications set slightly more restrictive limits, with a maximum patched area at the applicator of 6 mm (1/4 in) total length in any linear 0.3 m (1 ft). However, the precise amount of patched area is not clearly defined, because a variety of sizes could be fit within a 0.3 m length of bar, especially in bars with larger diameter.

In addition to a lack of requirements for maximum patched damage, current specifications do not provide adequate guidelines for proper coating repair procedures. The coating repair study shed some light regarding performance of different patching materials and procedures. Manufacturers claim that thorough surface preparation is essential for adequate performance of patching materials. Research performed in this study indicated that the most important factor was the type and properties of the patching material. Surface preparation had little effect. Therefore, no sophisticated surface preparation procedures need to be recommended for field application. Routine cleaning with a wire brush and a clean rag to wipe lose materials and dirt should suffice.

Patching materials of sufficient viscosity to produce a thick coating provided the best protection. However, materials with a thick consistency have a short curing time and can be very difficult to apply. A good compromise is material with moderate viscosity that produces a relatively large thickness and can be readily applied. The use of a thick patching material is more important for coating cut bar ends than for repairing damage coating along a bar. Sharp corners and rough cuts at bar ends were very susceptible to corrosion when thinner materials were used.

Until just recently, ASTM D3963-97 incorporated prequalification tests for patching materials, an area lacking in past ECR standards.[149] This standard now includes 400-hour salt spray and 28-day, elevated temperature, high-pH solution immersion as prescreening tests for potential patching materials. The tests are performed on repaired areas of coated flat panels. CRSI has developed a separate edge coverage test intended to assess the suitability of patching materials to adequately cover sharp edges at bar cut ends. The test is in the process of evaluation among laboratories to determine its reproducibility.[110] These provisions are evidently steps in the right direction to ensure that adequate patching materials are used.

10.4 BAR FABRICATION

Fabricated or bent coated bars tended to perform worse than straight bars. Fabricated stirrups in beam specimens performed worse than longitudinal bars. Likewise, large bent bars in macrocell specimens and immersion tests corroded extensively. Bending coated bars weakens adhesion of the coating to the steel substrate, and may also induce coating damage such as cracks, tears, and pinholes. Chen reported that fabricated bars were more susceptible to corrosion because of the higher incidence of damage introduced during bending.[145] In corrosion tests on concrete slabs by Treadaway and Davies, some coating deterioration in the form of underfilm corrosion was observed at ribs on the outside bends of bars. Corrosion was limited to the curved portion of the bar.[134] If the coating at bent areas is damaged, adhesion loss and underfilm corrosion commences at damaged areas and the progression of debonding and corrosion is facilitated by the weak steel-coating interface. The problem is exacerbated by the fact that fabricated bars, such as stirrups or transverse reinforcement, are usually closer to the exterior concrete surfaces. Moreover, in flexural members, coated transverse reinforcement will act as crack inducers, which means that cracks in the plane of the transverse reinforcement will be created. The combinations of all these factors make coated transverse reinforcement particularly vulnerable to corrosion.

Some standards, such as AASHTO M284 suggest that coating cracks without debonding from substrate need not be repaired.[150] Research results from macrocell specimens showed that corrosion progressed and accelerated in the longer term in bars with coating cracks. A revision of the standards in this aspect is suggested. As some of the latest standards (TxDOT, ASTM A775-97) specify, all visible damage should be patched. This should include any cracks in the coating, even if the coating does not seem to be debonded. Although coating may not disbond after bending, coating adhesion is usually weakened.

Rigid epoxy coatings that are applied to the bar after fabrication have been recently developed. Since the coating is applied after bars are fabricated, adhesion at bent areas is preserved. Such coatings are also theoretically more resistant to abrasion and scratching than are more flexible coatings. The use of such coatings deserve consideration for fabricated bars. However, corrosion testing in concrete specimens should be performed to assess the effectiveness of these new products. In this project, several samples coated with a rigid epoxy showed poorer adhesion than samples with flexible coatings before and after hot water immersion.

10.5 COATING ADHESION

The effect of coating adhesion for adequate corrosion protection is not well understood. Coating powder manufacturers and a number of researchers claim that good adhesion is crucial for satisfactory corrosion protection.[23, 65, 125] It is presumed that a poorly adhered coating will allow unrestricted transport of water, chlorides, and oxygen beneath the coating, causing widespread underfilm corrosion. It has not been clarified whether it is the amount of damage in the coating or the adhesion of the coating to the steel substrate that governs the rate of underfilm corrosion and coating disbondment.

With the exception of one study at the University of Western Ontario, there has not been a careful and systematic study of the effect of coating adhesion in corrosion protection, especially using coated bars embedded in concrete specimens. In bar specimens immersed in salt water (discussed in Chapter 5), it was found that specimens with poor adhesion before immersion showed a smaller corroded area than specimens with better initial adhesion. If the conventionally accepted notion that poor adhesion leads to poor performance is true, then it would be expected that bars with better adhesion before immersion would corrode less.

All macrocell specimens showed loss of adhesion at bend portions and adjacent straight legs after 2 and 4.5 years of chloride exposure, regardless of the level of corrosion activity. Likewise, coated stirrups in beam specimens showed widespread adhesion loss after one and 4.3 years. Kahhaleh suggested that adhesion loss could be beneficial because corrosion would spread along the bar and would not concentrate at certain spots and cause severe localized damage.[10] Longer term exposure showed that this hypothesis may not necessarily be true. Although bar corrosion was less concentrated and severe in coated bars than on uncoated bars, several pits of moderate depth were observed in coated stirrups.

The observed corrosion of epoxy coated bars in the present research reveals that adhesion of the epoxy coating is inevitably lost after a prolonged period of exposure to water and chlorides. Corrosion experiments and field inspections by others have also provided evidence of various degrees of coating disbondment after chloride exposure in concrete.[18, 20, 21, 86, 134, 151] On most beams, adhesion loss was slightly more extensive on fabricated bars than on straight bars. Underfilm corrosion was noticeably more extensive on fabricated bars than on straight bars. A first analysis would indicate that weakening of adhesion caused by bar fabrication seemed to be proportional to the observed adhesion loss and underfilm corrosion after chloride exposure. After fabrication, adhesion was weakened at bends in stirrups but was presumably preserved at the straight portions. After chloride exposure, adhesion loss and undercutting progressed from weakened (bend) portions to initially well adhered (straight) portions. Another factor could have been a difference in scale. Adhesion loss and undercutting are likely to progress more rapidly along a small stirrup surface than along a large longitudinal bar surface. Other factors effecting stirrup performance were discussed in Chapter 9.

The most remarkable difference in corrosion performance was not due to bar fabrication but due to differences in coating integrity. Straight bars from beam B1 were in excellent condition with no visible damage before chloride exposure. The bar condition was preserved without signs of corrosion nor extensive adhesion loss after 4.3 years. Longitudinal bars in the remaining autopsied specimens had intentional damage, patched or unpatched, and experience adhesion loss within the wetted region with varying degrees of underfilm corrosion. Since bars for all beams came from the same lot, it is reasonable to assume that all bars had similar coating adhesion before chloride exposure. Clearly, coating integrity was fundamental in the preservation of adhesion and its protective capabilities. In addition, it was found that adhesion loss always occurred around areas of damaged coating and was least affected at locations farthest from damaged coating. Similar observations have been made by Sagüés.[20] Visible holidays and coating defects were present on areas that experienced coating disbondment in coated bar segments extracted from four bridge decks in California.[18] This evidence suggests that the agents causing coating disbondment migrated to the coating-substrate interface through coating defects rather than through the bulk of the coating.

Experiments conducted at the University of Western Ontario showed that the mechanism of adhesion loss appeared to be water permeating the epoxy coating, which displaced the coating from the steel substrate.[51] Nevertheless, electrochemical tests indicated that the effect of adhesion loss in corrosion behavior was directly related to the presence of defects in the coating. If defects were absent, adhesion loss did not change the short term corrosion behavior. However, if defects were present, corrosion rate was directly related to the adhesion of the coating, i.e. poor coating adhesion resulted in high corrosion rates. The main factors improving coating adhesion identified in the study were an increase in the surface roughness and a decrease in the presence of contaminants.[51]

EIS and polarization resistance tests on bent and straight coated bar samples performed by Chen showed relevant findings regarding adhesion loss and corrosion.[145] Adhesion strength before immersion was similar for both straight and bent samples. After immersion, bent samples experienced more extensive adhesion loss than straight samples did. Extent of adhesion loss was strongly dependent on the coating type and source. There was not a clear correlation between adhesion strength after immersion and extent of corrosion. Several bent samples experienced adhesion loss but no signs of corrosion after immersion in chloride solution. The coating surface in those samples had no visible damage, pinholes, or discontinuities. Even very thin coating at rib bases provided protection as long as the coating had no defects. Chen stated that "adhesion loss can be the result, and not necessarily the cause, of epoxy-coated bar degradation."[145]

In an attempt to clarify the role of holes in the coating versus coating adhesion, a numerical model was developed at UMIST University.[125] The "Cottis Model" revealed that in the presence of holes in the coating in a low permeable concrete, the bar corrosion rate was governed primarily by the coating adhesion, and not by the relative size of the defects in the coating (Fig. 10.1). However, it was not explained whether such a model was validated in actual coated bar specimens, particularly in a real concrete environment.

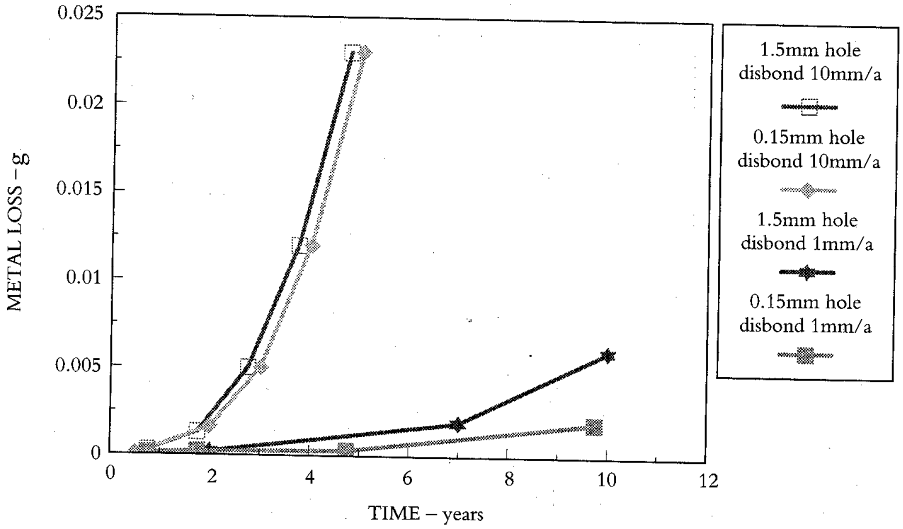


Fig. 10.1: Cumulative corrosion with time for epoxy-coated steel in low permeability concrete according to "Cottis Model" [UMIST].[125]

Although coating adhesion was not measured before exposure, some hypothesis regarding the role of adhesion can be drawn from the exposure studies conducted in this study. The effect of adhesion on corrosion performance may be similar to that of flexural concrete cracks. Weakening of adhesion by bar fabrication will accelerate loss of adhesion and underfilm corrosion (similar to the presence of flexural cracks). Adhesion loss and underfilm corrosion will be significantly slowed if there is good adhesion before exposure (similar to the absence of flexural cracks). Nevertheless, in the long term, adhesion loss and underfilm corrosion will progress in bars with initial good adhesion (provided that the coating is damaged) to levels closer to that of bars with initial weak adhesion. The longer the exposure, the more similar the amount of corrosion will be between bars with initially poor or good adhesion.

More research is needed to clarify the role of coating adhesion in the corrosion protection of reinforcing bars inside chloride-contaminated concrete. It is suggested that for future corrosion studies, epoxy-coated bar samples be obtained from the same bars used for durability experiments, and be tested for assessing their adhesion strength. Adhesion knife tests developed in Chapter 5, and cathodic disbondment tests, could be used for that purpose. At the end of exposure studies, adhesion loss and bar surface condition could be compared with the adhesion strength before exposure.

10.6 COATING QUALITY

The quality of both epoxy material and coating application effect corrosion performance. Experimental research by Chen suggested that quality of coating application may be more important than the type of epoxy material for satisfactory corrosion performance.[145] Sample source (coating applicator) and subsequent handling practices had the most effect on corrosion performance. In a durability study by CRSI on macrocell slabs, bar source was the only variable that correlated with a sudden worsening of corrosion of coated bars when exposure was changed from cyclic salt solution ponding to continuous tap water ponding.[46, 74] In an immersion study by the Building Research Institute (IBAC) in Germany, bars from source B meeting German guidelines exhibited less pitting corrosion and coating debonding than bars from source A meeting ASTM guidelines. It was suggested that the more stringent German guidelines resulted in improved performance compared with those meeting ASTM requirements.[111] The coating adhesion study discussed in Chapter 5 also showed that sample source was the most influential factor regarding adhesion strength. Since coating adhesion is an implicit indicator of quality of coating application, it then follows that the quality of coating application is greatly dependent on the sample source (coating applicator).

In addition to poor adhesive strength, the presence of large number of holidays (i.e. coating discontinuities) is indicative of a coating with bad quality. In a peer review study by WJE of slab specimens with coated bars, it was found that the number of holidays correlated with the development of macrocell corrosion current.[76] Chen obtained similar findings.[145] An excessive number of holidays is detrimental to the corrosion performance of epoxy-coated bars.

It is expected that an improvement in the quality of both the epoxy material and coating application will result in a finished product with better (fewer flaws) coating integrity. In addition to restricting the maximum allowable damage, efforts should be directed to improving the coating properties that reduce damage, such as abrasion and impact resistance, hardness, and flexibility, that may occur during all stages of fabrication, shipping, and construction. The production and application of better coatings with improved properties, and the observance of more stringent specifications will undoubtedly lead to an improved corrosion performance.

Improvements in the coating quality by a British coater involved the optimization of several factors:[125]

- Careful pre-selection of the reinforcement to ensure the supply of a material with consistent quality
- Optimization of the coating process with respect to surface preparation, material preheating, consistency of coating application, and post-curing of the applied coating
- Formulation of the resin system for epoxy coating to provide adequate flexibility while keeping a strong bond to the steel and retaining optimum barrier properties.

Further product development included chemical pre-treatments to modify the surface of the steel substrate before coating application. The adaptation of pre-treatments in the coating application process was claimed to have negligible effect on the overall production cost.[125] Chemical pre-treatments have been used at coating plants in the United Kingdom and Canada.[51, 119, 125]

For optimum corrosion protection, it would be ideal to produce epoxy coated bars of such quality that the integrity of the epoxy is preserved at all stages of production, transportation, storage, and construction. The less the amount of damage to be patched, the better. And if coating repair is needed, patching material should provide adequate thickness and be easy to apply. In addition to achieving good quality control at the coating plant, quality control measures have to be adopted at later stages after the bars leave the plant, to minimize the amount of coating damage, and to properly patch damaged coating when needed. Good quality control is more difficult to achieve in the field than in a coating plant. Nevertheless, most quality control measures for epoxy coated bars involve simple common sense rules that should not be difficult or costly to implement and follow. Observance of such rules requires proper training and field practice.

It should be emphasized that new epoxy coating formulations have resulted in products with improved properties, such as toughness, flexibility, and adhesion. Today's epoxy coating materials are much better than the first formulations used. Today's coating application methods have improved and quality control tests are more stringent than earlier methods. The voluntary certification program for epoxy coating applicator plants launched by CRSI in 1991 established stringent quality control procedures that exceed the basic requirements of most standard specifications.[152] Today's construction practices involving epoxy-coated bars are more conscientious than past neglectful practices. Today's epoxy coated bar specifications are more comprehensive, stringent, and accurate than first improvised and loose specifications based on overly optimistic interpretations of early research. All these factors combined should result in greater durability of concrete structures reinforced with epoxy coated bars. Test results from the durability studies reported in chapters 8 and 9 should be analyzed within this context. As already pointed out, coated bars in the macrocell and beam studies used coating formulations developed in the early 1990's. Coatings developed more recently may perform differently (presumably better) than earlier formulations under similar exposure conditions.

10.7 CONCRETE CRACKING

10.7.1 Flexural Cracks

The effect of flexural cracks on corrosion of reinforcement has been debated and was discussed in chapters 2 and 9. Some interesting findings arose from the beam exposure study regarding the role of flexural cracks in corrosion. The greatest effect of flexural cracks was in the corrosion initiation of coated bars. Coated bars in cracked members started to corroded much earlier than those in uncracked members. After one year of exposure, coated bars in cracked beams underwent more severe and extensive corrosion than bars in uncracked beams. Corrosion was mainly observed in the vicinity of cracks, in close agreement with findings by other researchers.[18, 54, 86, 139, 146] However, after an extended time of exposure (over four years), chloride penetration and corrosion was similar for bars in cracked and uncracked beams. There was no clear correlation of degree of corrosion with crack width. Flexural cracks were more detrimental to uncoated bars, where very severe pitting occurred at crack locations. It seemed that the most severe pitting in uncoated bars occurred at locations with wider cracks.

The above findings support in part both claims regarding concrete cracking and rebar corrosion. On the one hand, the lack of cracks definitively improved short term performance by significantly delaying corrosion initiation, supporting the claims by crack control supporters. On the other hand, chlorides will inevitably diffuse through uncracked concrete and bars will corrode in the long term. No significant differences in corrosion of coated bars were observed whether flexural cracks originally existed or not, thus supporting the claims by concrete cover advocates. Presence of cracks in concrete specimens did not increase corrosion of coated bars after 2 years of exposure in synthetic sea water in an experimental research by Salparanta.[71] Apparently, the cracks healed when calcium hydroxide from adjacent concrete leached into them.

It should be kept in mind that the concrete used in the beam study was highly permeable and of poor quality, which could explain the similarities in bar corrosion between cracked and uncracked beams after more than four years of exposure. The overwhelming evidence found in field structures, though, conclusively indicates that coated bars corrode more at crack locations.[18, 54, 86, 139, 146] Undoubtedly, a concrete of medium to good quality significantly slows chloride penetration, while cracks provide a direct path to the reinforcement, regardless of concrete quality. The accelerated nature of the beam study does not accurately reflect field conditions. For this reason, the adverse effect of concrete cracks on the corrosion of coated bars should not be based solely on the findings from the beam study.

For the case of uncoated bars, crack control advocates have a valid point. Although it was true that corrosion was mostly localized at crack locations, as claimed by concrete cover supporters, pitting corrosion was so severe that the structural integrity of uncoated bars was adversely effected. Crack width seemed to have some detrimental effect on the severity of pitting.

The bottom line is that if coated bars are used, there seem to be no significant differences in long-term performance between members with and without flexural cracks. For uncoated bars, flexural cracks can have a detrimental effect in the short and long term.

10.7.2 Plastic Settlement Cracks

Cracks that follow the path of reinforcing bars have frequently been observed in concrete structures with epoxy-coated reinforcement.[15] Theoretically, cracks parallel to coated steel bars are more damaging than cracks transverse to the bars, because large amounts of corroding agents could reach the bar surface.[31] These type of cracks are usually caused by shrinkage and plastic settlement of concrete and are developed during the early stages of curing.

The present study did not conclusively prove a more adverse effect of plastic settlement cracks. There were only three macrocell specimens with plastic settlement cracks, and corrosion-induced cracks propagated from the initially observed cracks. However, based on the total number of corroded specimens, it is obvious that corrosion also occurred in many other specimens that did not have initial plastic settlement cracks. Cracks produced by plastic settlement were very narrow and did not result in greater chloride content than that measured in specimens without initial cracks.

10.8 CONCRETE ENVIRONMENT

The concrete environment played a significant role in the corrosion of epoxy coated reinforcement. In addition to the role of cracks (already discussed in the preceding section), there were other concrete characteristics that effected coated bar corrosion: Thickness of concrete cover, concrete permeability, concrete consolidation, void and pore structure, and moisture content. Concrete permeability was not a test variable because all specimens were cast from the same concrete. However, the high water-cement ratio used for the mix made the concrete very permeable. Undoubtedly, performance would have been different if a less permeable concrete mix had been used.

The effect of concrete consolidation, and void and pore structure was a very important finding. The relative position of the surrounding concrete with respect to the bar in the casting position was important. Due to concrete settlement and the entrapment of air escaping to the surface, concrete below the bars was less dense and had more voids than concrete above the bars, and a small gap between the bar and concrete was formed below the bar. The presence of this gap and concrete voids provided the space necessary for accumulation of chlorides, moisture, and oxygen, leading to more corrosion at those locations.

It should be emphasized that the concrete environment oftentimes played a very complex role in the corrosion of coated bars. Several bars in beam specimens did not corrode at damaged sites, despite being located near cracks, and despite the presence of voids in the surrounding concrete. It is possible that concrete voids and pores facing uncorroded sites were locally isolated and not interconnected with the overall pore structure of the concrete. Since concrete is a non-homogeneous material, it is expected that moisture and chloride penetration inside the concrete will be non-uniform and have wide local variations.

The complexity of the concrete environment was made evident in polarization resistance measurements in macrocell concrete blocks performed by Chen.[145] Several specimens with uncoated bars had larger corrosion resistance values than some specimens with damaged epoxy-coated bars. Although samples from the same coated bars experienced extensive adhesion loss and poor corrosion performance after 200 days of immersion in 3.5% NaCl solution, uncoated bar samples experienced much more severe corrosion after solution immersion. Apparently, the concrete electrolyte medium protected some uncoated bar specimens.

Thickness of concrete cover is one of the most important factors in corrosion of reinforcement. Laboratory specimens and field inspections have consistently shown that a thinner cover leads to more rapid penetration of chlorides and earlier and more widespread corrosion.[68, 84, 134, 151] Cover thickness was not a test variable in the macrocell and beam studies. Nevertheless, the shallow cover of permeable concrete allowed for the relatively early corrosion initiation of macrocell specimens, especially those with uncoated bars.

It is evident that not only is the coating quality important for good performance, but quality of concrete is of equal importance. Concrete of low permeability should be specified and good concreting practices, such as proper placement and consolidation, and adequate curing, should be followed. Concrete cover to reinforcement should be ample. The use of epoxy-coated bars could be questioned when high quality concrete is being used (or vice versa). The severity of the environment should dictate such decisions. If the exposure conditions are particularly severe, high quality concrete and epoxy-coated bars would complement each other and would provide a lines of defense against the damaging effects of chlorides. It should be kept in mind that a low permeable concrete would also be expected to crack, and as was seen in the beam study, concrete cracking leads to early corrosion of reinforcement. If bars were uncoated, the risk of severe pitting corrosion at crack locations would be high. An effective and rigorous crack control method, such as prestressing, would be needed for satisfactory corrosion protection.

10.9 CORROSION MECHANISM OF EPOXY COATED BARS

The precise corrosion mechanism of coated bars inside chloride-contaminated concrete is still not well understood. The mechanism proposed in Chapters 8 and 9 was based on a re-construction of possible sequences of events that best conformed to the observed deterioration pattern of the bars at the end of exposure. Previously proposed mechanisms by others,[10, 65, 78] and the corrosion process of coatings described in the literature,[24] were taken into account. The corrosion pattern and products observed in both macrocell and beam studies were similar to those found in other studies.

Perhaps the most important implication of the corrosion mechanism is the role of coating defects and damage on corrosion initiation of coated bars. Another aspect is the observed adhesion loss that may be produced by cathodic reactions and moisture action. As a result, the importance of reducing or eliminating coating imperfections and damage, and of improving coating adhesion strength has been emphasized. Undoubtedly, if coating integrity and adhesion are deficient, the epoxy coating will not satisfactorily protect reinforcing bars from corrosion.

Much of the controversy about the effectiveness of epoxy coated reinforcement has derived either from an unclear understanding of the corrosion mechanism (and main controlling factors) or from precipitated conclusions based on preliminary research findings. An example of the latter case are the conclusions drawn from a field study by Weyers et al.[23] In a field assessment in three bridge decks and three marine pile structures in Virginia, the authors concluded that since the epoxy coating will be debonded from the steel when chlorides arrive, the epoxy coating will provide no additional service life. The authors based their conclusion on the observation that "when the coating has debonded, the rate of underfilm corrosion is faster than [that of] bare steel in concrete." Such observation was based on research results performed by others.[65] Care should be exercised when applying research findings in a study to a particular case in the field. Although the authors concern is valid, they did not provide field data from bridge structures of similar age reinforced with uncoated bars only. The claim that bars with debonded coating before chloride contamination will corrode faster than uncoated bars in concrete was assumed, but not supported, in the Virginia study. In the short immersion test discussed in Chapter 5, samples with poor adhesion before chloride arrival did not corrode any faster than those with better initial adhesion.

A similar situation occurred in a limited field study by the Georgia Department of Transportation.[21] Examination of bars from cores taken at tidal and splash zones from a bridge substructure in a coastal environment showed coating debonding in several cases, and underfilm corrosion in another case. Based on this very limited data, along with the documented evidence of good performance of Georgia highway structures with uncoated bars but good quality concrete and adequate cover, Griggs suggested the discontinuation of epoxy-coated bars in Georgia bridge structures.[21] Although the good performance of bridge structures with uncoated steel in Georgia cannot be disputed, it is not reasonable to conclude that epoxy coating will not perform properly based on an isolated case. Although underfilm corrosion of epoxy-coated bars is a common phenomenon documented in several studies, including this study, underfilm corrosion tends to be more uniform, less severe, and progresses more slowly than pitting corrosion in uncoated steel. It would have been interesting to see how uncoated bars would have performed in the coastal substructure in Georgia.

Opponents to the use of epoxy coating have stated that even perfectly coated and flawlessly handled reinforcing steel will begin to fail once salt penetrates the concrete and reaches the rebar. This is due to the inability of existent epoxy coatings to achieve long-term adherence to the rebar, according to detractors of epoxy coating.[148] The experimental evidence of this study does not support such assertions. Epoxy coatings generally start to disbond at discontinuities or imperfections. It would take a much longer time for a coating without defects and adequate thickness to disbond, since water would have to penetrate through the bulk of the coating. Moreover, evidenced provided by scanning electron microscopic examination of some epoxy chips from bars in chloride-contaminated concrete indicated that chlorides did not penetrate through the epoxy coating, but reached the steel surface through breaks in the coating.[76] In addition, the rate of corrosion when chlorides reach the steel substrate would be low, because of the very limited oxygen availability provided by the “flawless” coating. Any potential macrocell action would be significantly hampered by the electrical isolation and resistivity provided by the “perfect” coating. Research by the University of Western Ontario demonstrated that reduced adhesion does not compromise corrosion performance providing that the coating remains intact.[51]

10.10 FIELD PERFORMANCE OF EPOXY-COATED REINFORCEMENT

Florida DOT’s decision to discontinue the use of epoxy-coated reinforcement[50] and the controversy stirred by Clear’s statements questioning the real effectiveness of epoxy-coated reinforcement[8] was a shock to the epoxy coating industry. Consequently, recommendations made by the Federal Highway Administration (FHWA) led state DOT’s around the USA and Canada to re-evaluate the existing infrastructure with epoxy-coated reinforcement.[151] Field and laboratory studies from 92 bridge decks, two bridge barrier walls, and one noise barrier wall were summarized in Report No. FHWA-RD-96-092. The age of the bridges was from 3 to 20 years. The main conclusions are summarized in the following paragraphs.[96, 151]

The majority of inspected bridge decks had an overall good condition. Very few decks had delaminations and/or spalls, and most were not associated with epoxy-coated reinforcement. Concrete cracking was prevalent but did not appear to be corrosion-related. The chloride content at the rebar level for most bridges was equal or greater than the corrosion threshold for uncoated steel. No signs of corrosion were found on 81% of extracted bar samples despite chloride concentrations above 3.8 kg/m^3. More corrosion was found on bars at crack locations and than at uncracked locations. Coated bars did not corrode at uncracked locations even with high chloride contents of up to 7.6 kg/m^3. Corrosion was also more prominent at areas with shallow concrete cover. Moisture and a high chloride concentration were the principal agents for corrosion of coated bars. Coating disbondment was observed at both corroded and non-corroded areas, and was the result of prolonged exposure to moisture. Coating adhesion decreased with time of exposure. The number of coating defects and the amount of disbondment influenced corrosion performance. Corrosion and coating disbondment typically occurred at locations of visible holidays or bare areas. The overall conclusion was that "epoxy-coated reinforcement has reduced, if not completely eliminated, the deterioration of deck concrete resulting from corrosion of reinforcing steel."[96, 151]

In general, the main conclusions from the macrocell and beam studies reported herein are very similar to findings observed in field bridge decks. Regarding the role of concrete cracks, conclusions from field observations agreed closely with the findings after one year of exposure of beam specimens. Less agreement exists after 4.3 years of exposure of beam specimens (corrosion was similar for bars in both cracked and uncracked beams). Differences in concrete permeability and the accelerated nature of the experiment could account for the change. Concrete for beam specimens had a high water-cement ratio and the cyclic exposure was very severe and continuous. Chloride content at bar location in uncracked beams was as high as 11.8 to 13.8 kg/m^3, versus 7.6 kg/m^3 measured in uncracked field concrete, and 9.5 to 16 kg/m^3 for cracked field concrete. It is possible that with longer times of exposure, uncracked portions in field structures would start to show signs of corrosion as additional chlorides diffused. The drawbacks of laboratory specimens designed for accelerated exposure which lead to their inability to reflect field service life are highlighted by such comparisons.

Two particular cases are worth mentioning. In California field decks, corrosion did not occur when there were no defects in the coating, even with high chloride concentrations of up to 4.6 kg/m^3.[151] This finding closely agreed with what was observed for coated bars in beam specimens, emphasizing that the measured chloride content in the respective beam was significantly higher (12.2 kg/m^3). In contrast, no significant corrosion was observed in Virginia decks despite the presence of numerous holidays and bare areas in the coating.[151] This phenomenon was similar to the lack of corrosion at several damaged areas frequently observed in beam bar specimens.

Another field survey of 18 bridge decks in 14 states was reported by CRSI.[153] All of the inspected decks first used epoxy-coated bars in the 1970's, and each was the first known installation of coated bars in its state. All bridges were located in the areas of freeze/thaw where deicing chemicals were used. The survey was completed in 1993 and repeated in 1995-1996. State inspection records of bridges included a rating from 0 to 9.9 developed by the FHWA, with the top grade reserved for new condition. Ratings of 8, 7, 6, and 5 represent deck conditions from very good to satisfactory, in descending order. All decks were rated from satisfactory to very good, as illustrated in Table 10.1.[153]

Another study of 19 parking ramps built with epoxy-coated reinforcing steel from 1980 to 1985 was conducted by CRSI.[102] The ramps were located in Wisconsin, Minnesota, Michigan, Nebraska, and South Dakota. Although first used during the 1970's, epoxy-coated steel was not used in parking ramps until 1980. Therefore, the ramps surveyed were the first built with ECR. Twelve ramps were visually inspected. Ramp owners and engineers were interviewed, and supporting documentation reviewed for all 19 ramps. Limited corrosion with epoxy disbonding was noted in only one ramp and was attributed to inadequate concrete cover and construction errors. The study concluded that all ramps were performing adequately, with little or no damage since construction. In contrast, three parking garages with uncoated bars in Minnesota experienced extensive steel corrosion and delaminations, requiring extensive patching or replacement.[102]

State	***Mat***	***Year Opened***	***Initial Grade - Year***	***Latest Grade - Year***	***Deck Maintenance***
Iowa	Top	1975	8 - 1975	7 - 06/95	0
Illinois	Top	1977		7 - 12/95	0
Indiana	Top & Bottom	1976	7 - 1976	6 - 01/96	0
Michigan	Top & Bottom	1976	8 - 1980	7 - 10/95	0
	Top & Bottom	1976	8 - 1980	7 - 08/94	0
	Top & Bottom	1976	8 - 1980	7 - 08/94	0
Kansas	Top	1977	8 - 1977	7 - 1995	0
Minnesota	Top	1973	8 - 1973	8 - 08/95	0
Nebraska	Top	1976	N/A*	8 - 1996	0
	Top	1975	9 - 1975	7 - 1996	0
Wisconsin	Top	1976	9 - 1976	8 - 08/95	0

	Top	1976	9 - 1976	8 - 08/95	0
Maryland	Top & Bottom	1974	9 - 1974	7 - 07/96	0
Kentucky	Top	1975	7 - 1981*	7 - 06/95	0
Pennsylvania	Top	1973	6 - 1989*	5 - 07/95	0
Missouri	Top	1974	9 - 1973	7 - 12/95	N/A
Ohio	Top	1974	8 - 1985*	7 - 03/96	0
West Virginia	Top	1973	9 - 1973	6 - 02/96	0

*Initial grade unknown n/a= not applicable Data compiled 11/26/96

Table 10.1: Bridge deck condition based on FHWA ratings. Ratings of 9 indicate new condition. Ratings of 8, 7, 6, and 5 indicate very good to satisfactory condition in descending order.[153]

It should be pointed out, though, that many of these parking structures had other protective measures, such as concrete with low water/cement ratios, corrosion inhibitors, microsilica concrete, and concrete sealers. In addition, chloride levels in most cases were below the threshold value for corrosion initiation, and most slab systems were postensioned to reduce concrete cracking. Therefore, it is difficult to assess the specific contribution of epoxy-coated steel in the overall performance of the structures. The three garages with uncoated reinforcement were older (built in 1979, 1974, and 1963) and no mention was made of any other protective measures.

10.11 CORROSION MONITORING

Measurement of corrosion current for macrocell specimens was very useful and correlated well with observed corrosion. Corrosion potentials were useful in monitoring the performance of coated bars in beam specimens in three aspects: 1) assessing the likelihood of bar corrosion, 2) pinpointing zones of high probability of bar corrosion, and 3) detecting shifts in behavior from passive to active conditions. The main limitation in interpreting corrosion potentials was that, as expected, they gave no indication of the rate, severity, and extent of corrosion. Potentials shifts to more negative values indicate that corrosion cells were operating and not necessarily that more rust is accumulating.

Measured potential regions that correlated with moderate to severe corrosion for coated bars (-550 mV SCE or more negative) were more negative than the respective potential range that ASTM C 876 suggests as indicating high probability of corrosion for uncoated bars (-273 mV SCE or more negative). For uncoated bars in beams, the difference was not as large (corrosion observed at -370 mV SCE or more negative). Treadaway and Davies also found more negative potentials in coated than uncoated bars. The highly negative potentials of epoxy-coated bars suggests that corrosion was cathodically controlled.[134] The presence of the coating significantly reduced diffusion of dissolved oxygen to the steel surface, and the reduction process became diffusion or concentration controlled.

In a field study on bridge decks in Minnesota, there were many areas without corrosion and with potentials more negative than -350 mV CSE (-273 mV SCE). In general, areas with potentials more negative than -400 to -500 mV CSE (-323 to -423 mV SCE) often underwent severe corrosion of coated steel.[86] Hededahl and Manning reported high negative potentials (in the range of -45 to -463 mV SCE) on coated bars without visual evidence of corrosion activity.[154] In the beam study reported herein, coated bars with negligible corrosion had potentials in the range of -450 to -555 mV SCE. In general, corrosion potential ranges that are associated with coated bar corrosion varies among different studies. One reason for such differences is the difficulty in relating bar corrosion assessments made by different researchers. Frequently, assessments of bar corrosion are rather subjective, making comparisons difficult. A bar that looks "severely corroded" for one researcher may look "slightly corroded" for another researcher.

Unlike the findings after one year of exposure, maximum potential gradients after 4.3 years did not prove to be very useful nor reliable indicators of corrosion severity of coated or uncoated bars. Overall, maximum potential gradients above 200 mV did not seem to be associated with any particular level of corrosion activity in epoxy-coated bars after 4.3 years of exposure. Corrosion in such bars varied from negligible to moderate. For uncoated bars, maximum potential gradients above 300 mV seemed to be conducive to severe pitting corrosion. Interestingly, Sharp et al. reported of a survey where the assessment of potential differences and the rate of potential change gave a reliable diagnosis of corrosion rather than any absolute value of potential.[155] However, after monitoring potentials on beam specimens for up to five years, the pattern of surface potentials was found quite unrelated to the corrosion state, as opposed to their earlier work. In all cases, corrosion potential values had little correlation with corrosion condition.[155]

The ASTM C 876 test method was developed for measuring half-cell or corrosion potentials of uncoated reinforcement in concrete. Therefore, care and judgment are needed when measuring and interpreting corrosion potentials in structures with coated reinforcement. The development of a unified criterion for adequate interpretation of potentials for coated reinforcement is needed. For adequate assessment of corrosion, it is recommended that other corrosion monitoring techniques be used along with corrosion potentials. Three-electrode linear polarization resistance and electrical resistivity measurements have been used in field structures.[86, 151, 154, 155] Electrochemical impedance spectroscopy (EIS) has been used in the laboratory but seems to be too complex and sophisticated for field applications.[145]

Corrosion potential, linear polarization, and EIS measurements were conducted in a field study on bridge decks in Minnesota.[86] Overall, polarization resistance and impedance testing were found ineffective for locating areas of bar corrosion or poor coating, and were deemed unsuitable for routine field surveys. In general, areas with low resistance exhibited coating damage but there was significant scatter of data. Corrosion potential, polarization resistance, and EIS tests taken in the field produced significantly different results than tests taken at cores in the laboratory, although the relative performance between specimens was maintained. Presumably, field measurements are affected by factors such as concrete resistance, uncoated bottom reinforcement, areas of bar damage away from core locations, and area effects. In addition, there was poor correlation between resistance as measured by AC impedance and corrosion potential data. The study recommended that future refinements to linear polarization and EIS were needed before widespread implementation of these techniques on decks containing epoxy-coated steel.[86]

10.12 TEST CONDITIONS AND SERVICE LIFE

The durability studies reported in chapters 8 and 9 on macrocell and beam specimens were intended to be accelerated. The type of exposure regime was very aggressive and consisted of uninterrupted wet and dry cycles of ponding or irrigation of a highly concentrated chloride solution. It is difficult to determine how the selected test exposures relate to more realistic environments in the field, but it is expected that the test exposures be much more severe.

In addition to an aggressive test environment, the following characteristics were selected in the design of the specimens to promote early corrosion: Concrete with high permeability, shallow concrete cover, and little curing of concrete. For macrocell specimens, a large cathodic (bottom) steel area was coupled to a small anodic (top) steel area to produce a large corrosion driving force, and the distance between anode and cathode was reduced to facilitate the ionic flow. For beam specimens, weekly loading and unloading was intended to increase the flow of chlorides and oxygen towards the bar location.

The aggressive nature of the test exposure and the characteristics of the specimens created a somewhat artificial condition that made it difficult to correlate the length of the exposure during the test with an equivalent time of service in the field. The macrocells were subjected to a total of sixty 28-day cycles of wetting and drying during the 4.5 years of exposure, and the beams were subjected to 112 14-day cycles during 4.3 years. The years of exposure reported herein are not the same as years during service conditions, and it would be expected that the adverse effects produced under the test conditions during one year of cyclic exposure would be equivalent to the effects produced after a greater number of years under field exposure conditions. The precise relationship between the effects produced by test and field conditions will only be determined by monitoring the performance of companion laboratory and field specimens.

Chapter 11. Summary, Conclusions, and Recommendations

11.1 SUMMARY

The principal objective of this research was to investigate the integrity and corrosion performance of epoxy-coated reinforcement in aggressive environments. The research was organized in five parts: I) Literature survey, II) influence of coating operations, III) influence of concreting operations, IV) durability studies in concrete, and V) Synthesis. This study was part of a 7-year research project: Research program and results from the first 3 years are reported elsewhere,[10] and those from the last four years are reported in this Dissertation.

Part I: Literature Survey

A literature review on background information was conducted. Topics covered included background on corrosion of reinforcement in concrete, overview of epoxy coating materials and application processes, a brief review of the factors that influence performance of coated bars, a brief historical development of epoxy-coated bars, an extensive review of durability studies, and an overview of present status and future trends.

Part II: Influence of Coating Operations

The importance of coating quality and adhesion was discussed. Quality control measures, industry efforts to improve quality (CRSI Certification Program), and industry standards and specifications were reviewed and discussed. The nature and factors affecting coating adhesion, mechanisms of adhesion loss, available tests to evaluate coating adhesion, and prior research on coating adhesion evaluation were analyzed.

An experimental evaluation of hot water immersion and knife adhesion testing was conducted to determine the feasibility of these tests for coating adhesion evaluation. The objective was to develop a reliable adhesion test that could be performed quickly, repetitively, and economically at the coating plant and which test results could be objectively interpreted. ECR samples from different coating applicators, with varying bar diameters, and both straight and bent samples were tested. Other test variables included the temperature of the hot water bath, time of immersion, elapsed time between hot water immersion and adhesion test, different adhesion test operators, and different adhesion test procedures. Test results were discussed and analyzed. Different adhesion rating systems were devised and evaluated.

A pioneering experimental study of repair of coating damage was performed. No research in this area had been previously reported. In this research, the corrosion performance of several patching materials was investigated. The effect of different bar surface conditions and application procedures was examined. The effectiveness of patching bar cut ends was of particular interest. To evaluate the effectiveness of patching materials and procedures to repair epoxy coated rebar, three major series of experiments were conducted: a) cyclic immersion in NaCl solution, b) electrochemical impedance and polarization resistance, and c) hot water immersion-adhesion tests. In cyclic immersion and electrochemical tests, the corrosion performance of repair materials was studied. In the hot water test, the adhesion quality of patching materials was examined.

Part III: Influence of Concreting Operations

An experimental study was conducted to evaluate the degree of mechanical damage caused by concrete placement procedures. The effect of concrete consolidation on the epoxy coating using internal metal head vibrators was studied in preliminary phase. Additional damage tests were conducted in a second phase study using soft (rubber) head vibrators in addition to steel head vibrators. In addition, the degree and quality of consolidation obtained with a rubber head vibrator as compared to a metallic head vibrator were assessed.

For the damage tests, three types of test specimens were constructed, representing a column or bridge pier, a footing, and a deck slab. All reinforcement was epoxy coated and bars in each specimen had different diameters. Two identical forms and reinforcement cages were constructed for each type of specimen: One for use with the metal head vibrator, and the other for the rubber head vibrator.

Quality of consolidation was assessed in fresh and hardened concrete specimens. The energy imparted to fresh concrete by each type of vibrator head was measured with small, high sensitivity, high frequency accelerometers partly embedded in the concrete. Vibration tests were conducted in two unreinforced, freshly placed concrete blocks, each one with one type of vibrator head. Frequency, horizontal and vertical acceleration were measured while the concrete was being vibrated.

A total of eight block specimens of different size and with varying amounts of coated and uncoated reinforcement were constructed for evaluation of consolidation in hardened concrete. The degree and quality of consolidation with the rubber and metallic head vibrators was determined through both a visual examination, and measurement of density and permeable void content of extracted cores from vibrated specimens.

Part IV: Durability Studies in Concrete

Macrocell specimens were built by embedding triplicate fabricated coated bars in concrete prisms and linking them to uncoated bars. Salt water was ponded in a cyclic wet and dry regime to contaminate the concrete with chlorides. Test variables included the amount of coating damage, repaired vs. unrepaired damage, bar size, and bar deformation. Control specimens with uncoated bars were included. Corrosion currents flowing from coated bars to uncoated bars were monitored over a period of sixty 28-day cycles (4.5 years). The corrosion rates of coated and uncoated bars were measured and compared. Forensic examinations were conducted on each triplicate at 1, 2, and 4.5 years to relate corrosion measurements to physical bar condition. One-year and two-year autopsies were previously reported elsewhere.[10] The 4.5-year autopsy was discussed in this Dissertation.

Duplicate concrete beams were reinforced with unlinked coated and uncoated bars. Salt water was irrigated over the middle portions of beams in a cyclic wet and dry regime over a period of 112 14-day cycles (4.3 years). Various arrangements of longitudinal bars, stirrups, and splices were considered. Test variables included the condition of the coating (as received or 3% damage), and repaired vs. unrepaired bars. Some beams were uncracked while others were cracked and either unloaded or kept under load to maintain cracks at a specified maximum crack width. Cyclic loads were applied on cracked beams during wet and dry periods. Corrosion activity was monitored by corrosion potential measurements. Beam condition and changes in crack width were observed during exposure. Forensic examinations were conducted on each duplicate after 1 and 4.3 years to relate corrosion measurements to actual bar condition. The one-year autopsy was previously reported in reference 10. The 4.3-year autopsy was discussed in this Dissertation.

In both macrocell and beam studies, the selection of the exposure procedure, test parameters, and specimen characteristics was intended to produce a very aggressive environment and to accelerate corrosion of the specimens.

11.2 CONCLUSIONS

11.2.1 General Conclusions

Effectiveness of Epoxy Coating

Clearly, **coated bars performed much better than uncoated bars**, as evidenced by monitored currents and the observed condition of concrete and bars. Uncoated bars experienced moderate to extensive corrosion with the formation of several moderate to severe pits. Substantial loss of cross-sectional area was evident at crack locations within the wet zone of beams. In comparison, although epoxy coating did not completely prevent corrosion of steel reinforcement, none of the specimens with coated bars experienced extensive corrosion cracking, rust staining, delamination, and scaling of the concrete surface, as specimens with uncoated bars did. No deep pits or significant reduction of cross-section was observed on the steel surface of epoxy-coated bars. Corrosion generally consisted of a uniformly dark surface with shallow pitting.

From the experimental program alone, it was not possible to predict the probable service life of structures with epoxy-coated bars. Specimen design did not accurately reflect real field conditions and some of the parameters were selected to accelerate corrosion. The coating performance reported herein corresponded to a formulation manufactured in the early 1990's. Coatings presently used may perform differently under similar conditions.

Damage to Epoxy Coating

The main conclusion of this study is that **damage to epoxy coating was the most significant factor effecting corrosion performance**. When epoxy coating was in good condition, without any visible damage, bars in beam specimens remained in very good condition, and the steel surface maintained its original shiny appearance after 4.3 years of saline exposure. All tests showed that the greater the size and frequency of damage, the severer and more extensive the amount of corrosion. The requirements of former specifications allowing up to 2% coating damage and maximum size of damaged areas of 6x6 mm clearly were not adequate. Specifications for permissible damage should have been more stringent and established a lower percentage and size of permissible damage.

Fabrication and Installation

Another factor that influenced corrosion performance was fabrication of coated bars. Fabricated or bent coated bars tended to perform worse than straight coated bars. Performance was compromised because bending coated bars weakens adhesion of the coating to the steel substrate, and may induce coating damage such as cracks, tears, and pinholes. Corrosion progressed and accelerated in the longer term in bars with coating cracks at the outer bend. The provision of some standards suggesting that coating cracks without debonding from substrate need not be repaired is wrong and should be revised.

The practice of mixing coated and uncoated bars in the same concrete member may lead to undesirable performance. Any incidental continuity between coated and uncoated bars could establish large macrocells that would be conducive to extensive corrosion. Uncoated bars can be subjected to corrosion regardless of electrical continuity.

Repair of coating damage

Patched areas are vulnerable to corrosion, particularly bar ends. Patching damaged coating slightly reduced, but did not completely prevent, corrosion in beam and macrocell specimens. The most important factor in coating repair was the type and properties of the patching material, with surface preparation having little effect. Patching materials of viscous consistency, able to produce large thicknesses, provided the best protection. Sophisticated surface preparation procedures did not provide improved performance over routine cleaning with a wire brush and a rag.

Coating Adhesion

Adhesion of the epoxy coating is inevitably lost after a prolonged period of exposure to water and chlorides. Fabricated bars in beams and macrocells showed extensive loss of adhesion at bent portions, regardless of level of corrosion activity. Coating integrity was fundamental in the preservation of adhesion and its protective capabilities. Adhesion loss always occurred around areas of damaged coating and was improved at locations farthest from damaged coating. The effect of coating adhesion for adequate corrosion protection is not well understood. Specimens with poor adhesion before immersion in salt water showed a smaller corroded area at the end of immersion than specimens with better initial adhesion before immersion. The coating adhesion study evidenced that sample source was the most influential factor for adhesion strength, revealing that the quality of coating application by different coaters can vary greatly and affects adhesion of the coating.

Concrete cracking

The greatest effect of flexural cracks was in the corrosion initiation of coated bars. Coated bars in cracked members started to corroded much earlier than those in uncracked members. However, as the time of exposure increased, chloride penetration and corrosion was similar between bars in cracked and uncracked beams. The absence of flexural cracks in the concrete delayed, but did not prevent the onset of corrosion of coated bars. No clear effect was observed by crack width. The effect of flexural cracks was more detrimental in uncoated bars, where very severe pitting occurred at crack locations. Pitting corrosion was so severe that the structural integrity of uncoated bars was adversely effected. Apparently, the most severe pitting in uncoated bars occurred at locations with wider cracks.

Concrete Consolidation

As previously found by Kahhaleh,[10] corrosion was more widespread below the bars where the concrete was less dense, had more voids, and was less adhered to the bar compared to the concrete above the bars.

In consolidation tests in concrete, rubber head vibrators caused less damage to epoxy-coated reinforcement than did comparable metal heads. With sufficient periods of vibration and appropriate spacing of insertion points, a rubber head vibrator can satisfactorily consolidate concrete.

Corrosion Mechanism

The most important implication of the proposed corrosion mechanism is the role of coating defects and damage in the corrosion initiation of coated bars, and the observed adhesion loss possibly produced by cathodic reactions and moisture action. Reducing or eliminating coating imperfections and damage, and improving coating adhesion strength are essential to ensure adequate performance.

11.2.2 Conclusions from Various Parts of the Study

Coating Adhesion Study

- Hot water and knife adhesion tests can be used to evaluate coating adhesion of epoxy-coated reinforcement. The usefulness of such tests in discriminating and identifying good from bad quality coatings (quality control) was demonstrated in this study. The methods do not require special or sophisticated equipment and reduce the subjectivity inherent in prior tests.

- There was poor correlation between adhesion tests and bend tests. Bend tests were not reliable indicators of coating adhesion and were more a measure of coating flexibility.
- There was good agreement between results from the more controlled and objective hot water and adhesion tests and those from the more subjective TxDOT peel test.
- Test results from immersion in salt solution were inconclusive. No clear correlation was found between adhesion strength and size of corroded area. Additional long-term research is needed to determine the effect of adhesion strength on corrosion protection of epoxy-coated reinforcement. Presently, there is no clear understanding of the relationship between these two properties.

Coating Repair Study

- Performance of patching materials was greatly dependent on their consistency and texture. Materials of greater viscosity and shorter curing time produced patches of greater thickness. Thicker patches performed better than thinner patches.
- Patching materials that provided the best performance had poor workability and were difficult to use.

- Patched bar ends were very vulnerable because of difficulty in patching sharp bar end edges. Presence of burrs and slag also impaired patch effectiveness.
- Flame-cut and patched bar ends had the worst corrosion performance.
- Bar ends patched by the coating applicator showed very poor performance.
- There was no clear effect of the cleaning and application procedures and size of damaged area on the patch material performance.

Concrete Consolidation Study

- Epoxy coating can be substantially damaged during placement and consolidation of concrete by internal vibrators.
- The use of rubber-head internal vibrators significantly reduced the amount and size of damage in the coating.
- Vibration tests in fresh concrete showed that the metallic head vibrator imparts slightly better consolidation to the concrete than the rubber head vibrator. Greater horizontal acceleration, larger radius of influence, and 10% higher frequency were achieved with the metal head.
- More concrete voids next to the coated bar surface were observed at greater distances from the point of insertion of the vibrator.
- Both metallic and rubber head vibrators can provide good concrete consolidation if good practice is followed.

- Concrete voids were always observed, even when concrete was considered to be well consolidated. Typical radii of influence used on construction may not remove voids beneath bars.

Macrocell Corrosion Study

- Coated bars performed much better than uncoated bars. Based on the measured charge flux, the worst coated bar performed about 2.3 times better than an uncoated bar.
- Bars with greater and more frequent damage tended to perform worse. Exposed areas played an important role in the corrosion initiation and mechanism of coated bars.
- The combination of bar fabrication and coating damage was detrimental to corrosion performance. Corrosion in most bars spread from the outer and lower bends towards the inner bend and straight bar legs.
- Regardless of the level of corrosion, the epoxy coating extensively debonded from the steel substrate, especially at the bent portion.
- Patching coating damage slightly reduced but did not prevent corrosion in most specimens. Corrosion in bars with exposed areas tended to be slightly more severe and corrosion in bars with repaired areas tended to be more widespread. The patching material used in the macrocell study had a very thin consistency and is no longer produced.

- Patching damaged areas on the outside of the bend only was not sufficient. Corrosion also propagated from mandrel indentations at the inside of the bend and at the outside of one straight leg.
- Bars with coating cracks and exposed areas less than 1% experienced increasingly higher corrosion currents at the end of 4.5 years.
- Larger bars experienced higher corrosion than smaller bars. Possible factors included differences in the concrete environment caused by the bar size, influence of concrete cover to bar diameter ratio, and discrepancies in the metallurgy between the two bar sizes.
- No clear trend was found in the performance of bars with different deformation (bar lug) patterns.
- Quality and consolidation of the surrounding concrete influenced the corrosion of epoxy-coated bars. More corrosion was observed at surfaces surrounded by less dense, very porous concrete with more and larger voids (bottom side of coated bars).
- The practice of mixing coated and uncoated bars in the same concrete member may lead to undesirable performance. Any incidental continuity between coated and uncoated bars could establish large macrocells that would be conducive to extensive corrosion. Uncoated bars can corrode regardless of electrical continuity conditions.

Beam Corrosion Study

- Both coated longitudinal bars and stirrups underwent less severe corrosion than uncoated bars within the same specimen.*
- Uncoated bars experienced severe pitting with substantial loss of cross-sectional area at crack locations.
- Greater coating damage led to more corrosion. In straight bars, epoxy coating with no visible damage provided excellent protection, while bars with 3% damage to coating underwent moderate underfilm corrosion. As-received and patched stirrups performed better than stirrups in the as-received condition.
- Patching damaged coating slightly improved performance but did not completely prevent corrosion.
- Patching bar cut ends was ineffective. Underfilm corrosion spread from patched ends.
- The main influence of concrete cracking and the loading producing cracks was on the time to corrosion initiation. Coated bars in cracked specimens corroded much earlier than those in uncracked beams, but in the long term, corrosion among coated bars from cracked and uncracked beams was similar. The absence of cracks delayed but did not prevent the accumulation of significant amounts of chlorides at bar locations.

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* As stated in Chapter 9 (Section 9.6.6), there were no control beam specimens completely reinforced with black bars that allowed a direct comparison of the performance of coated vs. uncoated bars. The comparison presented herein should be cautiously interpreted.

- The effect of concrete cracking was particularly detrimental to uncoated bars. Severe pitting corrosion was observed in several uncoated bars at crack locations.[**]
- Coated bars tended to corrode slightly more when surrounded by less dense, more porous concrete.
- Measured corrosion potentials did not correlate with rate and severity of corrosion. Potential difference between wetted and dry regions did not accurately reflect corrosion severity.

11.3 RECOMMENDATIONS

Based on the above research findings, a set of recommendations for proper quality control, design, and construction practice is proposed in the following sections.

11.3.1 Quality Control

Epoxy coating should be of good quality to satisfactorily perform its function. Desired characteristics include adequate flexibility, adhesion, abrasion resistance, thickness, and integrity, among others. This research has shown that among these properties, coating integrity is likely to be the most important characteristic for satisfactory corrosion performance. Coating integrity refers to the condition where the coating does not have discontinuities, such as flaws, pinholes, cracks, damage, or other areas where the metal substrate is exposed. Coating adhesion has been considered a very important property for adequate

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[**] Uncoated bars were in the compression side of the beams, away from the wet portion. The effect of cracks on the performance of black bars located within the wetted region of the beams could have been worse.

corrosion resistance. However, corrosion performance could not be related to quality of adhesion in this study. There was extensive adhesion loss with varying degrees of underfilm corrosion in macrocell and beam specimens with epoxy-coated bars. Quality control efforts at the coating plant should emphasize the manufacture of a final product **free of defects** and with strong adhesion.

Coating Integrity

The coating should be free from holes, voids, cracks, contamination, and damaged areas discernible to the unaided eye. The general quality of the coating can be evaluated by holiday detection but always accompanied by careful visual inspection. The number of holidays per linear meter (or linear foot) should not exceed the maximum allowable of applicable standards [Six per linear meter (two per linear foot) in TxDOT specifications].

To preserve integrity, all visible coating damage should be patched. At the production line (before transportation), the amount of damage to be patched should not be larger than 0.5% of the bar surface. This research showed that larger amounts of damage, even if patched, are vulnerable to corrosion. In addition, bars are likely to undergo additional damage during later stages of transportation, handling, and placement. Recommended patching practices are described in subsequent sections.

Coated bars should not be bent tightly unless required by structural design. Hairline cracking occurs on the outer surfaces of tight bends of smaller diameter bars. Some standards allowed the presence of cracks in the coating as long as the coating was not debonded. This specification is incorrect, as the macrocell study showed that corrosion propagated over the long term on specimens with this type of damage.

Coating Adhesion

The relevance of coating adhesion and its relationship to corrosion performance could not be conclusively proved in the present study. Nevertheless, quality control measures to ensure adequate adhesion should be implemented. The rationale is that there are several factors during the coating process that effect adhesion of the final product. Such factors include surface cleaning and preparation, anchor pattern, quality of base steel, temperature during application, and curing time. Poor coating adhesion before the bars are placed in service is usually related to poor application of the coating at the plant.

Hot water and adhesion tests are useful and practical quality control tools for the evaluation of coating adhesion. Test procedures developed in this study are recommended for implementation. Until additional research is conducted to substantiate the role of adhesion, acceptance criteria will have to be judiciously established. Since the effect of adhesion strength on corrosion protection is not clearly understood, a very stringent acceptance criterion may not be justified. If time constrains preclude more accurate evaluation, tests involving a higher degree of subjectivity and easy to perform could be implemented. An example of one such test is the TxDOT Peel Test. This research indicated that such a subjective test yielded results similar to those of more objective tests.

The use of bend tests as the only method of evaluating epoxy coating adhesion should be discouraged, as has been proposed in some standards. A combination of bend tests with adhesion tests will enable a better evaluation of the coating quality, assuring good coating flexibility and adequate adhesion strength.

Improved coating formulations incorporating chemical pretreatment of the steel surface can improve the adhesion of the coating and their use is recommended.

11.3.2 Design and Construction Practice

Handling, Transportation, Storage, Assembly, and Installation

To minimize the amount of damage to the epoxy coating, proper procedures for handling, transportation, storage, assemblage, and installation of coated bars should be followed. Such procedures are described in Appendix A. In essence, those procedures are aimed at avoiding any form of operation or handling that may chip the coating. The use of padded materials to bundle and band bars and to protect areas in contact with equipment, lifting bars with spreader beams using multiple lifting points, use of wood cribbing, not dragging bars, not walking or moving heavy equipment on bars, protection from ultraviolet rays and the environment, and avoiding long periods of outside storage are some of the most common field recommendations.

Cutting, fabrication, and welding of coated bars should be minimized and well controlled. Project specifications should cover field cutting and require coating of bar cut ends with proper patching material. Flame cutting should be forbidden. This research proved the difficulty of repairing flame-cut ends and their poor corrosion performance. Shear and saw cutting are acceptable, but shear cutting may create a rougher end surface with more sharp edges, especially with bars of larger diameter that are difficult to cut. Field bending or straightening should be avoided if possible. If bending or straightening are performed, any damaged coating should be repaired.

Concrete Placement [Kahhaleh, Herman, Gustafson and Neff]

Whenever possible, consolidation of concrete by external vibration should be preferred. If internal vibration is performed, vibrators with a rubber-encased head should be used to reduce abrasion of the epoxy coating. The present research proved the viability of rubber head vibrators in significantly reducing coating damage. Pounding of the vibrator head between the rebar cage and formwork should be avoided, since this can introduce significant damage to the coating.

The procedure to consolidate concrete should not only be aimed at minimizing coating damage but at producing well consolidated concrete. Poorly consolidated concrete around damaged areas of the coating can lead to rebar corrosion as was noted in this study. ACI recommended procedure for consolidation of concrete provides valuable guidance. When using rubber head vibrators in particular, points of insertion of the vibrator head should be closely spaced and time of vibration should be long enough to permit all trapped air to escape.

Repair of Damaged Coating

All visible damage and bar cut ends should be patched. Coating damage should be repaired with patching materials that provide a uniformly thick coating layer, especially at sharp edges and slag ridges on bar cut ends, and surfaces facing downwards. Minimum patch thickness should be 14 mils. Patching materials of high viscosity and thick texture provide excellent protection but are difficult to use. The use of materials with medium viscosity (pot life of about 2 hours) provide good corrosion protection and are relatively easy to use. Discontinuities on the patch surface should be avoided. Slag and burrs should be removed from bar cut ends. Epoxy coated bars should not be flame-cut and patched. For surface preparation, loose particles (mud, dirt) and grease should be removed with a wire brush and/or a rag. Very thorough or sophisticated surface preparation is neither practical nor warranted, as was shown in the present research. The patch should be allowed to cure before further handling of bars or placing concrete over the bars.

If coating damage exceeds the limits allowed by project specifications, the bars may have to be replaced. Clearly, repair of damaged coating is tedious, time-consuming, and expensive. Avoiding coating damage in the first place is always more effective and less costly.[152]

Design Issues

The use of coated and uncoated bars in the same concrete member should not be specified. Macrocell corrosion may develop at any incidental continuity between layers of coated and uncoated bars. In addition, uncoated bars may be subjected to severe corrosion, especially at members with flexural cracks. If feasible, bars coated after fabrication should be specified. The maximum amount of total coating damage (patched and unpatched) should be clearly specified.

Based on the present research, maximum patched damage should not be greater than 1% of bar surface area.

If the expected environment is particularly severe, good quality concrete with low permeability should be specified. Proper consolidation and curing of concrete are equally essential. Specifying ample minimum concrete cover would significantly slow the ingress of chlorides to the rebar level. A maximum permissible crack width may be specified (although no correlation between crack width and corrosion of coated bars was found, specimens with severely pitted uncoated bars had wider cracks). Crack width limitations should not be so severe as to conflict with provisions for adequate concrete cover (for coated bars, ample concrete cover would be more beneficial than the presence of narrow cracks). ACI Committee 201 provides useful guidelines for producing durable concrete.[31]

For structures where long-term durability is essential, provisions for cathodic protection (should it become necessary) could be made. Cathodic protection may provide an ideal supplement to coated bars, because the impressed current concentrates more effectively at damaged, exposed areas and at coating imperfections. Current requirements are thus significantly reduced to more practical levels. This provision would be very practical for cases where there is electrical continuity through the entire reinforcement assembly, such as epoxy coated welded wire fabric.

11.3.3 Future Research

Recommendations for future experiments:

- Control specimens completely reinforced with uncoated bars should always be available in durability studies. The lack of such specimens hindered a more meaningful assessment of the performance of coated bars in the beam study reported in Chapter 9.
- Ideally, bars should not protrude outside the concrete. The preventive maintenance of protruding bar ends was cumbersome and tedious. However, chloride corrosion at wire connections could be a problem if bar ends do not protrude. A good alternative would be to coat protruding bars ends with a thick layer of industrial epoxy coating.
- Both corrosion potentials and corrosion currents (or corrosion rates) should be monitored in any durability study. This would allow for a better understanding of the corrosion behavior of the specimens and of the relationship between two corrosion parameters.
- Samples for chloride analysis should be obtained from the test specimens during various stages of the experiment (for instance, after a few cycles, halfway through the exposure, and at the end). This would enable a better estimation of the chloride content that triggers corrosion of epoxy-coated bars. If possible, additional companion specimens could be opened for examination at different time periods to assess the condition of the reinforcement that is associated with a certain chloride content.
- Chloride contents should be measured at a range of depths: Shallower to the bar location, at the level of the bar location, below the bar

location, and deeper inside the member. In macrocell specimens in particular, chloride measurements should be taken at the level of the bottom (cathodic) bars.

Additional research is suggested in the following areas:

- More research is needed to clarify the role of coating adhesion in the corrosion protection of reinforcing bars inside chloride-contaminated concrete. It is suggested that for future corrosion studies, epoxy-coated bar samples be obtained from the same bars used for durability experiments, and be tested for assessing their adhesion strength. Adhesion loss and bar surface condition after exposure could be compared with the adhesion strength before exposure.
- The effect of cracking on the corrosion performance of structures with high-performance concrete and uncoated bars needs to be investigated. Although high-performance concrete has low permeability, relatively wide cracks may form. As was evidenced in this research, uncoated bars can corrode severely at crack locations.
- Better patching materials that provide adequate film thickness and that are easy to prepare and apply need to be developed. For this purpose, the engineering properties that make a patching material perform well need to be defined. Pre-qualification tests for patching materials need to be investigated.
- Future research efforts should be aimed at defining the relationship between parameters from accelerated tests (adhesion strength,

- Improved coating formulations with superior adhesion strength and resistance to undercutting even in the presence of damaged areas should be researched and developed.

Appendix A. Guidelines for Design and Construction Practice of Epoxy-Coated Reinforcement

A.1 GENERAL

Good quality control and proper design and construction practices need to be implemented and followed to preserve the integrity of the epoxy coating. Guidelines for design and construction practice of epoxy-coated rebars are suggested in this appendix. Design guidelines from ASTM,[63, 149] TxDOT,[123] CRSI,[64] and other documents from the literature were revised. Suggested guidelines are based on a compilation from such documents complemented with results from this research.

A.2 RELEVANT CONCLUSIONS FROM PREVIOUS STUDIES[10]

The following conclusions were drawn from previous experiments performed as part of the present research and were reported by Kahhaleh.[10] These findings are relevant to the recommended guidelines for epoxy-coated bars of this Appendix. Other conclusions applicable to the proposed guidelines were listed in Chapter 11.

A.2.1 Holiday Detection

- Holiday detectors are not reliable for detecting voids or pinholes in the epoxy coating. Inconsistent results were produced by varying sponge moisture and operator.
- The slower the speed of detection, the higher the number of responses obtained.
- The number of responses obtained can only indicate possible defects in the coating, but not the location and size of existing defects.

A.2.2 Immersion Test of Bent Epoxy-Coated Bars

- Corrosion initiated at any damage to the epoxy coating, such as pinholes, cracks, and large exposed areas. Corrosion progressed under the coating from damaged areas and holidays.
- All patched areas showed corrosion activity after a few weeks of immersion.

- Corrosion on damaged spots introduced during bending on the inside of bends was as severe as on the outside.
- Properly equipped mandrels greatly reduced the amount of coating damage and subsequent corrosion of bent bars on the inside of bend.
- Smaller bars (#4) were more susceptible to hairline cracking when bent to a smaller radius than larger bars (#8).

A.3 GUIDELINES FOR EPOXY-COATED REINFORCEMENT

Based on the findings of this research and the literature, a set of recommendations for proper design and construction practice is proposed in the following sections.

A.3.1 Quality Control

Epoxy coating should be of good quality to satisfactorily perform its function. Desired characteristics include adequate flexibility, adhesion, abrasion resistance, thickness, and integrity, among others. This research has shown that among these properties, coating integrity is likely to be the most important characteristic for satisfactory corrosion performance. Coating integrity refers to the condition where the coating does not have discontinuities, such as flaws, pinholes, cracks, damage, or other areas where the metal substrate is exposed. While other coating properties may contribute to performance, quality control efforts at the coating plant should emphasize the manufacture of a final product free of defects.

Coating Integrity

The coating should be free from holes, voids, cracks, contamination, and damaged areas discernible to the unaided eye. Holiday detectors have been used to verify the coating integrity by detecting coating discontinuities. These devices were found to be not very reliable in a previous study, and detector responses were effected by test operator, sponge moisture, and speed of operation. Their use is cautiously recommended. The general quality of the coating can be evaluated by holiday detection but always accompanied by careful visual inspection. For more accurate results, the sponge should always be wet and it is suggested that the detector be passed at a low speed. Holiday detectors at the production line are useful for internal quality control of the coating operation, but independent holiday detection with a portable detector should be performed on random samples for acceptance purposes. The number of holidays per linear meter (or linear foot) should not exceed the maximum allowable of applicable standards [Six per linear meter (two per linear foot) in TxDOT specifications].

All visible coating damage should be patched. At the production line (before transportation), the amount of damage to be patched should not be larger than 0.5% of the bar surface. Bending of bars should be performed with properly equipped mandrels to avoid damage at the inside of bends and outside of straight leg. Protective sleeves on mandrels should be used for that purpose. Coated bars should not be bent tightly unless required by structural design. Any hairline crack in the outer bent surface should be repaired. Proper handling and storage practices should be followed at the coating plant and in the field to minimize the amount of damage on the bars.

Coating Adhesion

Adhesion of the epoxy coating can be evaluated with hot water immersion followed by knife adhesion testing. A recommended procedure for hot water-adhesion testing is outlined in Appendix B. Until additional research can substantiate it, acceptance criteria will have to be arbitrarily established. The TxDOT Peel Test is recommended for quick pre-screening and detection of poorly applied coatings, and does not require hot water immersion. If possible, the use of a knife calibrated to produce uniform forces is desirable to eliminate possible variances by the test operator.

A.3.2 Design and Construction Practice

Prejob Meeting [152]

For successful implementation of proper construction guidelines and procedures, the roles and responsibilities of all parties involved with the coated bars should be established and clarified before construction. Specifications, construction practices, and inspection procedures should be reviewed. Rebar delivery schedules and storage sites should be discussed. The owner's representative should clearly communicate the intent and mechanisms to enforce these provisions established.

Handling and Transportation [10, 152]

Proper practice for handling and transportation should be aimed at avoiding any form of impact or violent abrasion with bars or other hard surfaces that may chip the coating. At the coating plant, bars should be bundled and banded with padded materials to protect the bars during handling and transportation. Equipment for handling coated bars should have protected contact areas. For this purpose, nylon strings, padded straps, or padded wire rope slings can be used.[53, 64, 152]

During transportation, bars should not be skidded from the truck bed. Instead, power-hoisting equipment should be used to move the bars. If a hoist is not available, smaller bar units or individual coated bars should be carefully unloaded by hand. Bundled bars should be lifted with a strong back, a platform bridge, or a spreader beam with multiple lifting points to prevent sagging of bundles during lifting. Spreader cables with at least two point lifting can be used in the absence of a spreader beam.[10, 53, 64] Wood cribbing helps to minimize damage.[53] The use of chains or cable chokers should be forbidden. Bundles should be smaller than those typically used for uncoated bars. A sufficient number of wood blocks can be placed on the truck to prevent sagging of the bundled bars during shipping. Nylon straps need to be tightened across the trailer load at several intervals to reduce vibration during transportation.

During unloading, bars should be inspected for coating damage. If damaged bars are found, the carrier and fabricator should be notified. Bars with extensive coating damage that can not be repaired at the job site should be rejected. Bars with slight damage should be repaired.

Storage [10, 152]

Outside storage of epoxy-coated bars should not be prolonged because of possible detrimental effects when exposed to an adverse environment. It has been reported that exposure to ultra-violet rays, heating/cooling cycles, and salt water spray can degrade the protective qualities of the coating.[50, 65, 87] CRSI guidelines recommend outdoor exposure be limited to 30 days.[156] To avoid long-term storage, delivery of coated bars should be coordinated with schedule of bar placement.

Bars should be stored in adequate conditions to prevent physical damage by impact from other objects and to protect them from adverse environmental agents. Suitable protective materials, such as opaque polyethylene sheeting, should be used to cover the bars and allow adequate ventilation. For stacked bundles, the protective covering should be draped over the sides of the bundle and around the perimeter of the stack. It is important to allow air circulation around the bars to prevent condensation under the cover.

Bars should be stored away from traffic and equipment, and close to final position of installation. Coated bars should be grouped in small manageable bundles and arranged so any group of bars can be accessed without having to dislodge or move others. Coated bars should never be stocked in large entangled piles directly on the ground. Instead, bars should be stocked in ordered bundles on wooden blocks or other protecting cribbing above the ground. Spacing of supporting blocks should be close enough to prevent sags in the bundles. Non-metallic tags should be used to identify the bars.

Assemblage and Installation [10, 152]

Coated bars should be handled with special care during the assembly of the reinforcing cage and positioning in concrete forms to avoid or minimize the amount of coating damage. Coated bars should never be dragged to their final locations. Walking on or moving of heavy equipment over coated bars should be minimized. Heavy objects or tools should never be dropped on the bars. Plastic-covered tie wires should be used to assemble reinforcing cages to minimize cutting of the wire into the bar coating and avoiding electrical continuity. To avoid electrical contact between bar layers or the potential corrosion at contact points, bar chairs and supports can be protected by epoxy or plastic coating, but the use of plastic bar chairs is highly preferable. Chairs supporting the top coated bars should rest on the formwork instead of the bottom reinforcing bars. If splicing or coupling systems are used, the installed splice should be epoxy coated, including steel splice sleeves, bolts, and nuts.

Cutting, fabrication, and welding of coated bars should be minimized and well controlled. Field cutting must be authorized by the engineer. Project specifications should cover field cutting and require coating of bar cut ends with proper patching material. Flame cutting should be forbidden. Shear and saw cutting are acceptable, but shear cutting may create a rougher end surface with more sharp edges, especially with bars of larger diameter that are difficult to cut. Field bending or straightening should be avoided if possible. If bending or straightening are performed, any damaged coating should be repaired. Welding or mechanical coupling of coated bars should not be permitted except when specified by design. TxDOT specifications include procedures for surface preparation and coating before and after welding.[123]

Coated bars in reinforcing cages should be carefully inspected before placing concrete to detect and repair any visible damage. All damaged areas and bar cut ends should be patched with a suitable repair epoxy.

Repair of Damaged Coating

All visible damage and bar cut ends should be patched. Coating damage should be repaired with patching materials that provide a uniformly thick coating layer, especially at sharp edges and slag ridges on bar cut ends, and surfaces facing downwards. Minimum patch thickness should be 10 mils. Patching materials of high viscosity and thick texture provide excellent protection but are difficult to use. The use of materials with medium viscosity (pot life of about 2 hours) provide good corrosion protection and are relatively easy to use. Discontinuities on the patch surface should be avoided. Slag and burrs should be removed from bar cut ends. Epoxy coated rebar should not be flame-cut and patched. For surface preparation, loose particles (mud, dirt) and grease should be removed with a wire brush and/or a rag. The patch should be allowed to cure before further handling of bars or placing concrete over the bars. If coating damage exceeds the limits allowed by project specifications, the bars may have to be replaced.

Concrete Placement [10, 127,152]

Concrete placement operations should be performed carefully to minimize coating damage. Equipment used for placement of concrete should be maneuvered properly to minimize physical impact on bars. Runways for concrete buggies and pump hoses should be set up. Runways should be supported and moved carefully to minimize coating damage and to avoid displacing the bars. Concrete should not be dropped from a high position. Whenever possible, consolidation of concrete by external vibration should be preferred. If internal vibration is performed, vibrators with a soft (rubber-encased) head should be used to reduce abrasion of the epoxy coating. Pounding of the vibrator head between the rebar cage and formwork should be avoided, since this can introduce significant damage to the coating.

Project specifications should included a proper procedure for consolidation of concrete with epoxy-coated bars. When using rubber head vibrators in particular, points of insertion of the vibrator head should be closely spaced and time of vibration should be long enough to permit the escape of all trapped air.

Design Issues

The use of coated and uncoated bars in the same concrete member should not be specified. If feasible, bars coated after fabrication should be specified. The maximum patched damage should not be greater than 1% of bar surface area.

For severe environments, good quality concrete should be specified. A low water-cement ratio, adequate cement content, control of aggregate size and grading, and possible use of mineral admixtures are some provisions to obtain a concrete of low permeability. Concrete should be properly consolidated and cured. Minimum concrete cover should be ample. A maximum permissible crack width may be specified. For structures where long-term durability is essential, provisions for cathodic protection (should it become necessary) could be made.

Appendix B. Proposed Knife Adhesion Test

B.1 SCOPE

B.1.1 The objective of this test method is to evaluate the quality of the adhesion between fusion-bonded epoxy coating and the steel surface of reinforcing bars.

B.1.2 The test method provides an indication of the relative quality of coating adhesion after production but may not predict adhesion loss accurately during service.

B.1.3 Although a pass/fail criterion is not provided, consistent poor ratings may be cause for rejection. However, failure to pass the adhesion test does not necessarily mean that the performance of epoxy-coated bars will not be satisfactory during service.

B.2 SUMMARY OF TEST METHOD

B.2.1 Adhesion testing may be performed after immersion in hot water according to Section B.8 to provide a very harsh test condition and to attempt to simulate the bar condition after long service. The use of hot water immersion is optional and left to the discretion of the testing agency. Adhesion strength is determined by trying to remove a precut area of coating with a test knife.

B.3 APPARATUS

B.3.1 Vise or similar clamping system with protective pads.

B.3.2 A testing knife calibrated to produce a constant force at all test locations, as described in Chapter 5.

B.3.3 X-acto blade #23

B.3.4 Utility knife with sharp blades.

B.4 SAMPLING AND FREQUENCY OF TESTING

B.4.1 Bars should conform to applicable specifications regarding coating thickness and number of holidays.

B.4.2 If hot water immersion is performed, replicate samples from at least three different locations along the bar should be obtained for each production bar tested.

B.4.3 If hot water immersion is not performed, adhesion tests can be performed directly on long production bars on at least three different segments along the bar.

B.4.4 At least two bars of each size from each production lot should be tested.

B.5 ADHESION TEST METHOD

B.5.1 Secure the sample in a vise. The vise clamps should have protective padding to avoid damaging the coating. With a sharp utility knife, cut an X through the epoxy coating. For bars smaller than #6, it may be necessary to make a V-cut to have an adequate testing area. The cut should penetrate through the entire thickness of the coating so that the metal is visible. The interior angle of the cut should be 45° approximately, but it can be modified later to obtain more accurate results. Two adhesion tests are performed at the X-cut, one on each flap. Four "X" or eight "V" cuts are made on each sample between deformations (two or four on each bar side, respectively). No cuts should be made within the portions extending 2.5 cm from the bar ends. If testing is performed on long production bars, eight "X" or sixteen "V" cuts are made on each bar segment between deformations (four or eight on each bar side, respectively).

B.5.2 Position the tip of the test knife in the vertex of the flap formed by the "X" or "V" cut, making sure the blade is in direct contact with the steel surface. The knife should be held at an angle of approximately 30° tangent to the curvature of the bar.

B.5.3 Apply a 2 kg force to the test knife while rotating it about its longitudinal axis to create an uplifting effect to the coating. The blade should advance along the bisecting line of the angle formed by the "X" or "V" cut. The test is completed when the epoxy coating inside the test area breaks and is no longer removed in one triangular piece. Remove all lose and unbonded material. Repeat the procedure in all flaps. Use a new blade for each specimen (or bar segment of long production bar) or when the blade becomes dull or damaged.

B.5.4 Measure the width in millimeters of the last section of the epoxy coating flap that was removed before the coating failed. The width is inversely proportional to the adhesive strength of the coating and is termed "rating."

B.5.5 If the width is too small and difficult to measure, reduce the interior angle of the "X" or "V" cut and repeat the test. If the entire flap can be removed completely, increase the interior angle of the flap and repeat the test. Readings of 5 mm or larger are considered to represent poor adhesion and are all taken as 5 mm.

B.6 REPORT

B.6.1 Report the following information:

B.6.1.1 Adhesion rating (width in millimeters of flap at section where the coating failed).

B.6.1.2 Bar source, indicating type of epoxy powder, name of coating applicator, bar size, name of steel mill, and bar lot number.

B.7 INTERPRETATION CRITERIA

B.7.1 Ratings of 1 mm or less are indicative of good adhesion.

B.7.2 Ratings of 4 mm or greater are indicative of poor adhesion.

B.8 HOT WATER IMMERSION (OPTIONAL)

B.8.1 Apparatus

B.8.1.1 Water bath with temperature control, circulator, and thermometer. The bath should be capable of heating water to the desired temperature with an accuracy of ± 2°C, and should have a circulator for stirring the water to obtain a uniform temperature.

B.8.1.2 Tap water

B.8.2 Preparation of specimens

B.8.2.1 Specimens 12.5 cm in length and free from bare areas are cut from production bars with a chop saw.

B.8.2.2 The specimen ends are sealed with an epoxy resin or similar material that provides a watertight seal. The seal should be fully cured before immersing the sample.

B.8.3 Test Method

B.8.3.1 Heat the water bath to a temperature of 75°C ± 2°C.

B.8.3.2 Submerge the specimens inside the bath. It is recommended that bars be suspended so that their entire surface is exposed to the circulating hot water. Samples should be spaced at least 2 cm from each other and from the bath walls.

B.8.3.3 After 24 hours ± 1 hr of immersion in hot water, remove the specimens and let them dry at laboratory temperature (about 23°C ± 3°C) for at least 6 hours before adhesion testing.

B.9 KEYWORDS

B.9.1 Adhesion, knife adhesion test; hot water immersion; fusion-bonded epoxy coating; steel reinforcing bars.

Appendix C. Details for Repair of Coating Damage - Cyclic Immersion Test

C.1 STUDY VARIABLES

C.1.1 Patching Materials Properties

Three types of patching materials were used for the cyclic immersion study. A fourth epoxy material, not specifically formulated for repair of epoxy coating damage, was also used in several specimens. This material was originally used to seal water-tight the ends of bar samples with damaged areas on the bar surface (types I and II as described in Chapter 6). The characteristics of each epoxy material are described in the subsequent paragraphs.

Patching Material A (Scotchkote 413/215 PC) [157]

Patching material or compound *A* is a two-part, thermosetting, epoxy liquid coating, formulated to cure at ambient temperatures. It is designed as a touch-up or repair material for items coated with a particular type of fusion bonded epoxy coating (produced by the same manufacturer). In other words, patching compound *A* should be used to repair compatible epoxy coating.

Preparation of patching materials involves mixing the two parts in a ratio of 1:1 by volume. The two parts are combined and mixed thoroughly until a uniform color is obtained. The patch compound may be applied immediately after mixing. This is an improvement over an earlier formulation from the same manufacturer. The older formulation required that, after mixing, the mixture stand for 60 minutes before using. Because of its liquid consistency, the patching material may be applied easily by spray, brush, or roller. Some of the most important characteristics are as follows:[157]

- **Color:** Light green (color matched to the compatible fusion bonded epoxy coating
- **Unit Weight:** 1 pint unit (0.47 L) = 1.3 lbs. (589 g)
- **Coverage:** 14.9 ft^2/lb @ 8 mils dry film
- **Mix Ratio:** 1:1 by volume
- **Sag (mils):** 0 @ 12
- **VOC:** 327 g/l
- **Viscosity:** 95-98 K.U.

• **Shelf Life:**	18 months (unmixed, unopened container)
• **Pot Life:**	See graph in Fig. C.1
• **Drying Time:**	See graph in Fig. C.1
•**Closed Cup Flash point:**	Part A 98°F (36°C)
	Part B 185°F (85°C)

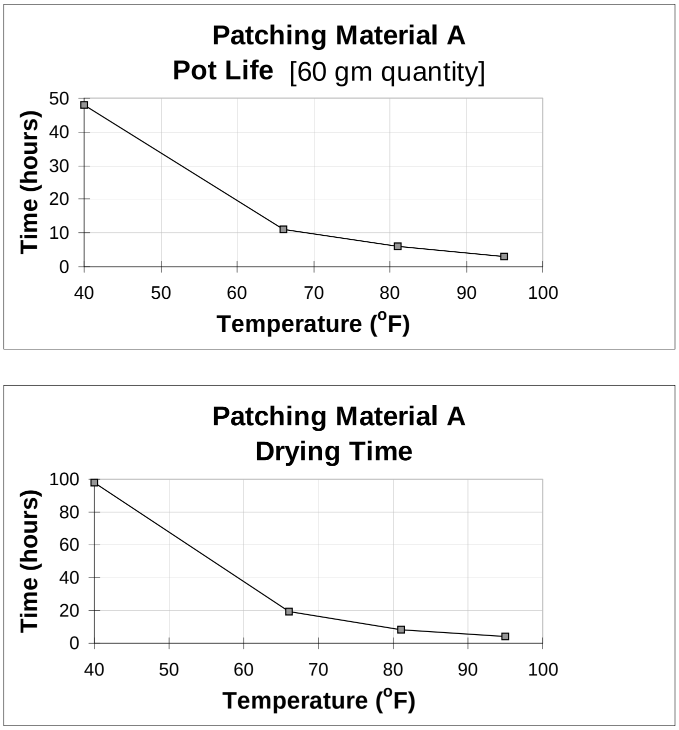


Figure C.1: Graphs showing pot life and drying time of patching material *A*.[157]

The manufacturer claims that for best results, patch compound *A* should be used at a temperature of 50°F (10°C) or higher during application and cure. Minimum application temperature is 40°F (4°C). Average temperature during patching application and cure for the actual specimens was about 19°C, well above the minimum recommended. Approximate drying at touch time of 5 hours and hard drying time of 8 hr were observed during actual sample preparation.

Patching Material B (Nap-Gard 7-2727)

Like material *A*, patching material or compound *B* is a two-part, thermosetting, liquid epoxy coating, formulated to cure at ambient temperatures. It is designed to repair damaged, fusion bonded epoxy coating produced by the same manufacturer. Similar to epoxy material *A*, patching compound *B* should be used to repair a compatible epoxy coating.

Mixing and application procedures are identical to those for material *A*. The two parts are combined in a ratio of 1:1 by volume and mixed thoroughly until a uniform color is obtained. The patch compound may be applied immediately after mixing. Because of its liquid consistency, the patching material may be applied easily by brush or roller.

Although still liquid, patching material *B* has a thicker and more viscous consistency than material *A*. In addition, material *B* cures faster than material *A*. Patching material *B* has an approximate drying at touch time of 3 hours and hard drying time of 5 hours, both shorter than those for material *A*.

Quantitative material properties were not available from the manufacturer.

Patching Material C (Lilly Industries)

Similar to materials *A* and *B*, patching material *C* is a two-part, thermosetting, epoxy coating, formulated to cure at ambient temperatures. The main difference is that material *C* is an epoxy resin coating instead of an epoxy liquid coating. Material *C* has a considerably thicker, more viscous consistency than patching materials *A* and *B*. This difference in material consistency is more remarkable with respect to material *A*, the thinnest of the three materials. The cured patch surface of epoxy material *C* is very hard, as opposed to the softer surfaces of cured materials *A* and *B*. There were cases where consistency of cured material *C* was rubbery and flexible. This probably occurred because of an inadvertent variation in the mixing proportions of the two parts.

The mixing procedure is similar to that for patching materials *A* and *B*. Parts “1” and “2” are combined and mixed thoroughly until a uniform color is obtained. The color of mixed resin is bright green. The patch compound may be applied immediately after mixing. Because of its thick consistency, the resin has very little workability and is difficult to prepare, mix, and apply. Unlike patching materials *A* and *B*, epoxy repair material *C* cannot be applied by spray, brush, or roller. A short, stiff rod, such as wooden stick, tongue depressor, spatula, etc., is needed to thoroughly and vigorously mix the resin and to apply it on the desired surface.

Epoxy repair material *C* cures considerably faster than epoxy materials *A* and *B*. Its pot life and drying time are very short. During specimen preparation, the observed average drying at touch time was about 10 minutes and hard drying time was 15 to 20 minutes. This property adds to the problem of poor workability of the epoxy material. Not only is the resin difficult to mix and apply, but it has to be applied very quickly in a very short time before it starts drying and hardening. The epoxy repair material rapidly becomes firmer and more difficult to use.

Quantitative material properties were not available from the manufacturer.

Epoxy Material D (Industrial Coating)

Material *D* is a two-part, thermosetting, industrial epoxy coating formulated to cure at ambient temperatures. However, epoxy material *D* was not specifically formulated to repair damaged, fusion bonded epoxy coating. In this project, epoxy material *D* was primarily used to seal water-tight both ends of patched rebar specimens to be immersed in salt solution. Although material *D* was not initially part of the investigation, it was decided to test its effectiveness as a tentative repair material for damaged epoxy coating. Fewer specimens were repaired with industrial coating *D* than with patching materials *A*, *B*, and *C*.

Industrial coating *D* has very similar properties to patching compound *C*. Its drying at touch time of about 10 minutes and hard drying time of 15 to 20 minutes are practically the same as those for patching material *C*. Like material *C*, epoxy resin *D* has a very thick and viscous consistency, and is difficult to mix and use. Therefore, mixing and application procedure is the same as for patching material *C*. Once cured, the coating surface is hard, comparable to that of material *C*. The color of mixed resin is gray.

C.1.2 Types of Patching Procedures

Fourteen coating repair procedures, ranging from unprepared surfaces to specially clean surfaces, were investigated. A detailed description of each procedure is included in the following paragraphs:

a) *Patching Immediately Applied after Laboratory-Type Surface Cleaning (Control)*

In order to compare different repair procedures, a control procedure was arbitrarily defined. Such a procedure should produce a surface so “surgically” clean that it could only be achieved in the laboratory. The cleaning process consisted of the following steps:

<u>Bar Cut Ends</u>

1) Sharp edges at perimeter of the bar cut section were cleaned from burrs and slag, rounded, and smoothed using a wheel grinder and wheel brush. In addition, the sharply ridged slag surface in flame-cut bar was smoothed and rounded as much as possible.

2) The metallic surface was cleaned to a near-white, polished finish with the aid of a wheel brush. All dirt, rust, grease, and other contaminants were thoroughly removed.
3) After the bar had cooled off, remaining grease and dirt on the surface was removed by firmly rubbing with acetone-wet cotton balls to produce a shinning, bright metallic surface.
4) Shortly after the acetone was removed with a cotton cloth, patching material was applied with a small paint brush. Repair material *C* was spread with a small wooden stick because of its thick and viscous consistency.

Damaged Areas on Bar Surface

Trying to obtain a perfectly clean surface on typical damaged areas on epoxy coated bars is nearly impossible because of their small size. Therefore, a control procedure was defined using the following steps:

1) On an undamaged epoxy coated bar sample, portions of the coating were removed using a wheel brush. Samples were prepared for the following two cases: a) coating was removed at the bar surface between ribs, and b) coating was removed at bar corrugations or ribs.
2) The uncovered metallic surface was cleaned to a near white, polished finish with a wheel brush. An effort was made to get rid of as many coating remains as possible.
3) After the bar cooled, remaining grease and dirt on the surface was removed by firmly rubbing with acetone-wet cotton balls to produce a shinning, bright metallic surface.
4) Shortly after acetone was dried with a cotton cloth, patching material was applied with a small paint brush. Repair material *C* was spread with a small wooden stick because of its thick and viscous consistency.

b) Patching Immediately Applied after Damage and Surface Cleaning (Wire Brush)

Samples in this group were prepared as follows:

Intentionally damaged areas:

1) Intentional damage of rectangular shape was caused as previously described
2) The uncovered metallic surface was cleaned with a wire brush immediately after coating damage
3) Patching material was applied with a small paint brush immediately after wire brushing.

Bar cut ends:

1) Bar samples were cut with a torch or a chop saw
2) The uncovered metallic surface was cleaned with a wire brush immediately after bar cutting
3) Patching material was applied with a small paint brush immediately after wire brushing.

In both cases, the idea was to reproduce the case where patching is applied on the most optimally cleaned surface that could feasibly be attained in the field.

c) Patching Applied on Smoothed and Cleaned (Wheel Grinder/Brush) Bar End (No Outdoor Exposure)

Bar cut ends of this group were prepared in almost the same manner as samples from the control group *a*. The only difference was that samples were not cleaned with acetone after wheel brushing.

This group was originally intended to be the control for bar cut ends, but it was realized soon that further cleaning with acetone provided a more thoroughly cleaned surface. Since samples were already prepared, this group was also included in the study.

d) Patching Applied on Wheel Brush-Cleaned Bar End (No Outdoor Exposure)

Bar cut ends of this group were prepared as follows:

1) Bar samples were cut with a torch or a chop saw
2) Metallic surface was cleaned with a wheel brush to a near-white finish immediately after bar cutting
3) Bar cut ends were touched up with patching material using a small paint brush. Patching application was performed soon after surface cooled off.

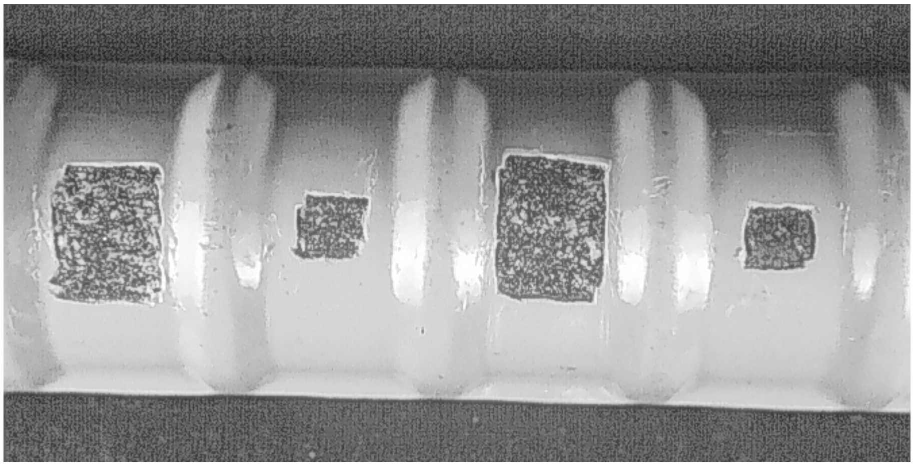
Samples from this group were similar to those from group *c* but without rounding and smoothing sharp edges (at the perimeter of the cut section) or sharp slag ridges.

e) Patching Applied on Surface Cleaned (Wire Brush) after Outdoor Exposure

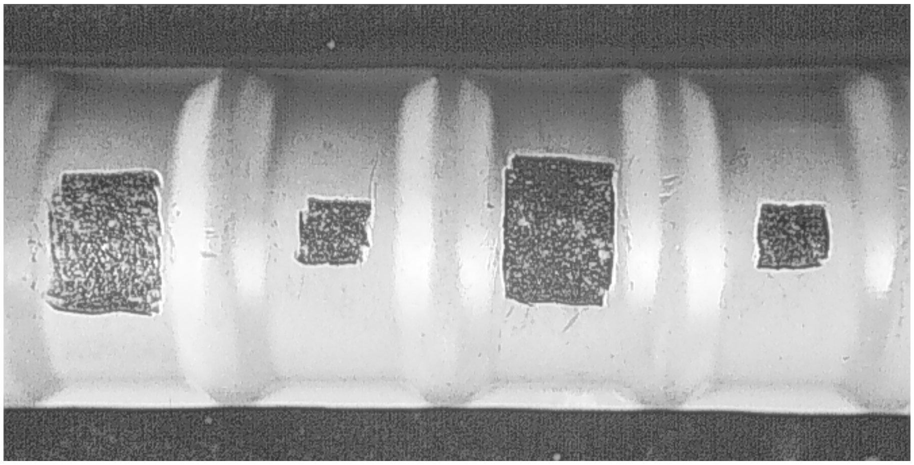
Sample preparation procedure consisted of:

1) Creation of intentional coating damage (or production of bar cut ends by cutting with a torch or chop saw)
2) Outdoor exposure (rain, sun, wind, dust, etc.) of ECR samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Surface cleaning with a wire brush
4) Patching application with a small paint brush immediately after surface cleaning. Patching material *c* was spread with a small wooden stick because of its thick and viscous consistency.

This type of surface preparation and patching application can be realistically applied in the field with proper site supervision. Special care would be needed to ensure that patching application not be delayed after surface preparation. An illustration of a sample before and after surface preparation is shown in Fig. C.2.



(a): Appearance of damaged areas after 2 weeks of exterior exposure.



(b): Appearance of damaged areas after wire brushing.

Figure C.2: Appearance of damaged areas before and after surface cleaning with a wire brush.

f) Patching Applied after Short Outdoor Exposure of Previously Cleaned Surface (Wire Brush)

Samples were prepared as follows:

1) Coating surface was intentionally damaged (or bar cut ends were produced by cutting with a torch or chop saw)
2) Epoxy coated bar samples were subjected to outdoor exposure for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Damaged exposed surfaces were cleaned with a wire brush
4) ECR samples were subjected to additional outdoor exposure for 24 to 48 hours, until some rusting developed on the exposed metallic surfaces.
5) Surfaces were patched without additional cleaning.

In this case, the situation in which patching application is delayed by one or two days after wire brushing was investigated. This practice would not be uncommon in the field (should wire brushing be performed at all).

g) *Patching Applied on Smoothed and Cleaned (Wheel Grinder/Brush) Bar End after Outdoor Exposure*

Repair procedure consisted of the following steps:

1) Cutting of epoxy coated bar with torch or chop saw
2) Outdoor exposure of bar samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Smoothing and round shaping of sharp edges at perimeter of cut section, and trimming off slag using a wheel grinder.
4) Wheel brushing of surface until a near-white finish is obtained
5) Touching up of surface immediately after prepared surface cools off

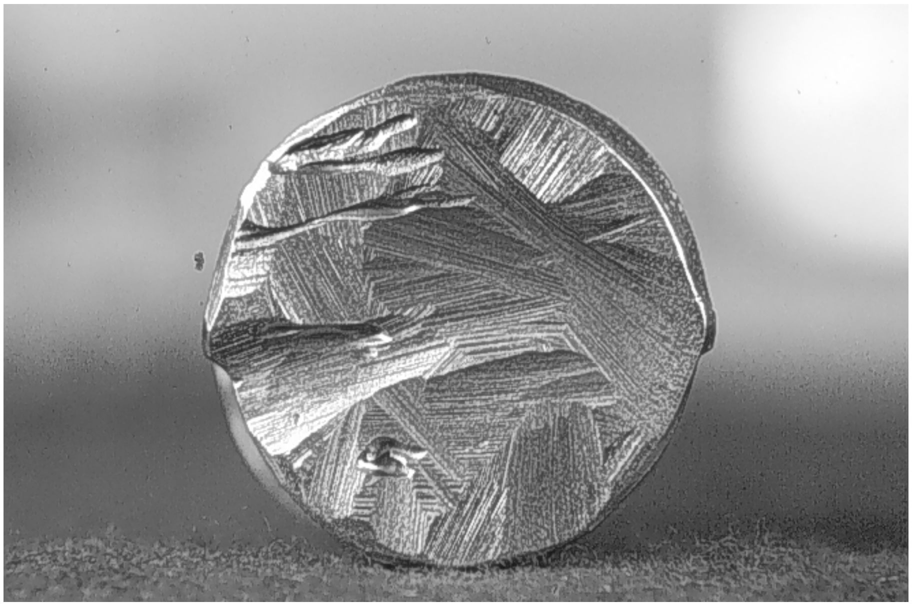
The effectiveness of this repair procedure on a typical bar surface cut in the field was investigated. An illustration of a sample before and after surface preparation is shown in Fig. C.3.

h) *Patching Applied after Short Outdoor Exposure of Previously Smoothed and Cleaned Bar End (Wheel Grinder/Brush)*

This repair procedure consisted of the following steps:

1) Cutting of epoxy coated bar with torch or chop saw
2) Outdoor exposure of bar samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface

(a): Torch-cut bar end after 2 weeks of exterior exposure



(b): Torch-cut bar end after surface preparation with a wheel grinder and a wheel brush.

Figure C.3: Appearance of flame-cut bar end before and after surface preparation with a wheel grinder and a wheel brush.

3) Smoothing and round shaping of sharp edges at perimeter of cut section, and trimming off slag using a wheel grinder.
4) Wheel brushing of surface until a near-white finish is obtained
5) Additional outdoor exposure for 24 to 48 hours until some rusting develops
6) Touching up of bar ends with a small paint brush without additional surface cleaning

The effect of delaying touching up of bar cut ends one or two days after being subjected to an outstanding surface preparation was investigated.

i) Brush-Applied Patching on Untreated Surface after Outdoor Exposure

Coating repair procedure consisted of:

1) Creation of intentional coating damage (or production of bar cut ends by cutting bar with a torch or chop saw)
2) Outdoor exposure (rain, sun, wind, dust, etc.) of ECR samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Patching application with a small paint brush without any surface cleaning

Patching application without cleaning rusted or dirty metallic surfaces is the most common coating repair procedure employed in the field.

j) Spatula-Applied Patching on Untreated Surface after Outdoor Exposure

The steps of this coating repair procedure were as follows:

1) Creation of intentional coating damage (or production of bar cut ends by cutting with a torch or chop saw)
2) Outdoor exposure (rain, sun, wind, dust, etc.) of ECR samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Patching application by spreading epoxy material with a wooden stick on unclean surface

This coating repair procedure is similar to procedure *i*. The only difference is that, because of its very thick and viscous consistency, the epoxy material has to be spread with a wooden stick. A bar specimen repaired with this procedure can be seen in Fig. C.4.

Figure C.4: Repaired bar end. Epoxy material was spread with a small wooden stick.

k) Hand-Applied Patching on Untreated Surface after Outdoor Exposure

Coating was repaired or touched up according to the following sequence:

1) Creation of intentional coating damage (or production of bar cut ends by cutting with a torch or chop saw)
2) Outdoor exposure (rain, sun, wind, dust, etc.) of ECR samples for about 1 to 2 weeks, until rusting developed on the exposed metallic surface
3) Patching application by spreading epoxy material with a glove covered finger on unclean surface

Messy repair procedures such as this have been observed at construction sites.

l) Brush-Applied Patching on Untreated Surface Immediately after Saw or Torch Cutting

Bar cut ends were touched up according to the following procedure:

1) Bar was cut with a torch or chop saw
2) Patching material was applied with a small brush on untreated surface immediately after torch or saw cutting.

Torch or saw cutting heats the bar surface in the vicinity of the cut section. It is an improper repair procedure to apply the patching material without letting the surface cool. The effectiveness of applying a repair epoxy material on a hot steel surface was investigated.

m) Hand-Applied Patching on Untreated Surface Immediately after Saw or Torch Cutting

Bar cut ends were touched up according to the following procedure:

1) Bar was cut with a torch or chop saw
2) Patching material was applied by spreading epoxy material with a glove covered finger on the unclean surface immediately after torch or saw cutting.

This repair procedure is similar to procedure *l* but was performed in a more messy way by applying the patching material with a glove covered finger. Improper repair procedures like this have been observed at construction sites. Figure C.5 illustrates such a repaired surface.

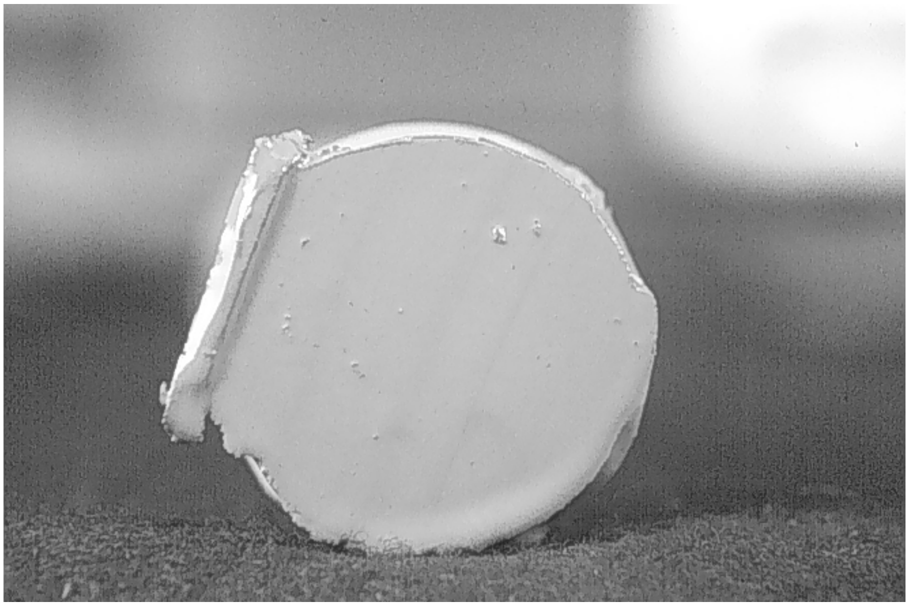


Figure C.5: Repaired bar end. Epoxy material was spread with a glove-covered finger on a hot steel surface.

n) Touch-up of As-Received Patch

Shipped epoxy coated bars had cut ends that were originally touched up at the coating plan. Several samples containing such “as-received” patching were prepared for study. However, coating or patching damage was present at many of those samples. Repair and touch up of the “as-received” patched ends was done and the specimens were subjected to salt solution exposure.

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