Implementation of Composite Wrapping Systems on Reinforced Concrete Structures Exposed to a Corrosive Laboratory Environment

by

Laura Alexandra Fuentes, B.S.

Thesis

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

Master of Science in Engineering

The University of Texas at Austin

May 1999

Implementation of Composite Wrapping Systems

on Reinforced Concrete Structures Exposed to a

Corrosive Laboratory Environment

APPROVED BY

SUPERVISING COMMITTEE:

David W. Fowler

James O. Jirsa

Harovel G. Wheat

To Will.

Acknowledgments

I thank my advisors Dr. David W. Fowler and Dr. James O. Jirsa for their kindness and guidance throughout my research. Their experience and technical intuition have on more than one occasion broadened my perspective and enabled me to effectively solve the problem at hand. I will not forget their faith in my ability and integrity. They have both made my experience as a graduate student a truly rewarding one.

Dr. Harovel Wheat's knowledge on all aspects of corrosion and her friendly disposition concerning my inquiries are deeply appreciated.

I extend my sincere gratitude and best wishes to Paul Guggenheim, from Delta Technologies. This project would not have been possible without his generosity and support. Working with him was a wonderful learning experience.

I would like to thank everyone at the Texas Department of Transportation and especially Jon Kilgore, Randy Cox, and Alan Kowalik for their help and support.

The staff and students at the Ferguson Structural Engineering Laboratory and at the Construction Materials Research Group were essential for the timely completion of my work. My sincere appreciation is extended to Mike Rung, Wayne Fontenot, and Gordon Sheppard for their help.

I thank Rose Rung, Martha Schleicher and Mike Gonzales for their kindness and efforts concerning this project.

My friend and research partner Stewart Verhulst has been an invaluable help over the past two years. His not-so-funny jokes made a hot Texas summer seem like a breeze. I hope that our friendship will continue to grow well into the future.

Lastly, I send my love to my family. I thank Jorge, Krystyna, Patricia, Patrick, Javier, Dandy and Nemo. The distance that separates us is overcome by the strength of our bond. Os quiero.

May 7, 1999

Implementation of Composite Wrapping Systems

on Reinforced Concrete Structures Exposed to a

Corrosive Laboratory Environment

by

Laura Alexandra Fuentes, M.S.E.

The University of Texas at Austin, 1999

SUPERVISOR: David W. Fowler

The corrosion of reinforced concrete structures in marine environments is a severe problem causing gradual deterioration of today's infrastructure. The use of composite laminates as protective barriers on the concrete surface has increased over the past years. In this study, material properties and installation procedures for two FRP systems are described. A test program for evaluating their perfromance in long-term corrosion protection is discussed. Specimens wrapped with these composites will be exposed to aggressive wetting cycles in a laboratory environment. Variables being studied include: specimen shape, effect of cast-in chlorides, flexural cracks, repair materials, corrosion inhibitor, length of wrap, resin selection and concrete surface condition.

Table of Contents

List of Tables

List of Figures

Chapter One
Introduction

1.1 Introduction

Corrosion of reinforcing steel in concrete leads to the premature failure of many structures exposed to harsh environments. Rust products form on the bar, expanding its volume and creating stress in the surrounding concrete. This leads to cracking and spalling, both of which can severely reduce the service life and strength of a member. Corrosion of reinforcing steel in concrete structures is one of the most expensive problems facing civil engineers in the United States. The structural integrity of many bridges, overpasses, parking garages, and other concrete structures has been impaired by corrosion, and repairs are urgently required to ensure public safety [Jones, 1996].

As structures approach the end of their design life, new and improved methods for repair and rehabilitation of corroded members must be developed. To prevent and arrest corrosion activity at an early stage, accurate detection techniques are necessary. Traditional ways of protection and monitoring offer many advantages and disadvantages. Because of the increasing number of corrosion-related problems in the field of structural design, research is continuously being conducted to evaluate and implement efficient repair strategies.

At the University of Texas at Austin, in a research effort sponsored by the Texas Department of Transportation, a series of long-term exposure tests evaluating the performance of fiber-reinforced plastic (FRP) wrappings for reinforced concrete durability were undertaken. The study implemented a procedure for the encapsulation and epoxy-injection of specimens containing corroded epoxy-coated bars and plain bars. Further investigations in the use of composites for corrosion protection were encouraged [Unal, 1998].

In response to these conclusions, TxDOT research project 1774, entitled *Effect of Wrapping Chloride Contaminated structural Concrete with Multiple Layers of Glass Fiber/Composites and Resin* was initiated. In this project, variables such as the effect of cast-in chlorides, cracks, repairs, wet surfaces, wrap length, and presence of corrosion inhibitor will be studied. Reduced-scale specimens were designed to simulate actual field conditions. Delta Technologies provided proprietary composite materials for use in the study. A second FRP system was designed by personnel at the IMPACT laboratory of the Texas Materials Institute [Joyce et al., 1998] using fibers and resins. In this report, the use of both systems in a corrosive environment will be discussed.

Delta FRP wrappings are being used in a current rehabilitation project by TxDOT in Lubbock, Texas. Corrosion data recorded prior to the repair implementation will be compared to post wrap results to verify the system's effectiveness.

1.2 Corrosion of Steel in Reinforced Concrete

The mechanism of corrosion in concrete must be well understood in order to implement methods of detection, monitoring and repair. Corrosion is the result of chemical reactions between a metal or metal alloy and its environment [Jones, 1996]. It may cause the gradual deterioration of structures and may reduce their expected service life. The structural capacity of a concrete member may be significantly reduced by bar corrosion. Cracking of the surrounding concrete may accelerate the initiation of corrosion. In steel with more than 1.5 percent corrosion, the ultimate load capacity begins to reduce, and at 4.5 percent corrosion, the ultimate load is reduced by 12 percent – probably a result of reduced bar diameter [Emmons, 1994]. There are two forms in which corrosion attacks the reinforcing steel in concrete structures: chloride induced corrosion and carbonation.

Concrete is a highly alkaline material (pH = 12-13). In this range of alkalinity, steel is protected from corrosion by a passivating film. Calcium hydroxide leaches out of uncured portland cement with addition of water, creating an alkaline solution that forms an initially resistant passive film on steel surfaces. However, this film can be destroyed if the pH is lowered by carbonation or if aggressive elements such as chlorides penetrate into the concrete. When the cover is too thin or porous, corrosive damage to concrete results primarily from access of water solutions containing dissolved oxygen. No damage occurs in very dry concrete due to the absence of water, nor in water-saturated concrete because oxygen cannot reach the steel [Jones 1996].

Chlorides are intorduced into the concrete through contact with environments such as sea water or de-icing salts, or they can be found in the concrete even before the structure is in service (cast-in chlorides). In both cases, when the concentration of chloride ions around the steel is sufficient (approximately 1.0 to 1.5 lb/yd^3 [Sherman, 1993]), and if oxygen and water are present, a localized breakdown of the passivating film occurs, thus creating a galvanic cell. These local areas become anodes, and the surrounding passive regions are the cathodes. As the steel increases its oxidation state, rust products expand and set up tensile forces in the concrete, eventually leading to cracking and spalling.

Carbonation in concrete is a reaction between acidic gases in the atmosphere (CO_2) and the products of cement hydration. This reaction reduces the pH of concrete to about 10, thus eliminating concrete protection of the steel and destroying the film around the rebar. If water and oxygen are present, corrosion is initiated. In industrial environments, where the concentration of carbon dioxide is high, carbonation of concrete structures is a serious risk [Emmons, 1994]. However, in sound, dense concrete with sufficient cover, carbonation is not expected to reach the embedded steel during the structure's service life. With adequate quality controls throughout the construction period, most modern highway structures are not severely affected by this problem, and more attention is usually focused on reducing the damage caused by chloride penetration.

Corrosion of steel reinforcement involves metal dissolution at the anode and oxygen reduction or hydrogen evolution along the cathode depending upon the corrosive environment (Equations 1 through 5) [Jones, 1996]. These are a series of electrochemical processes accompanied by a flow of electricity. A sort of natural battery develops at the reinforcing steel structure, generating a low-level internal electrical current [Concorr, 1996]. Corrosion leads to the formation of an unstable ferrous oxide ($Fe(OH)_2$), which in the presence of oxygen, produces a corrosion product known as rust, that occupies a higher volume than the steel rebar. This creates strong internal forces, which lead to cracking of the surrounding concrete. Carbon dioxide and chlorides are available at the crack locations, and are thus able to penetrate deeper into the member, speeding up the corrosion process. Loss of reinforcing steel area in concrete through corrosion may result in long term strength reduction [Unal, 1998].

Anodic Reaction

$Fe + 2e^- \rightarrow Fe^{2+}$ Metal Dissolution (Equation 1)

Cathodic Reactions

$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$ Oxygen Reduction (Equation 2)

$2H^+ + 2e^- \rightarrow H_2$ Hydrogen Evolution (Equation 3)

$2Fe + 2H_2O + O_2 \rightarrow 2Fe(OH)_2$ Ferrous Oxide Formation (Equation 4)

$2Fe(OH)_2 \rightarrow 2Fe(OH)_3$ Rust Formation (Equation 5)

A repair and rehabilitation strategy that will interrupt one of these electrochemical transfers must be selected to prevent serious damage and loss of service life.

1.3 Overview of Protection and Detection Strategies

Many factors influence the durability of a reinforced concrete structure. It is possible to greatly reduce the risk of corrosion by proper material selection and by implementing the suitable design and maintenance principles. Due to the limited duration of this project, many of the items discussed below were manipulated in the laboratory to accelerate corrosion of the reinforced concrete specimens.

High quality concrete is more resistant to chloride penetration and carbonation [Vaca, 1993]. Low permeability is crucial in defining durable concrete. This property is affected by the following variables: water-cement ratio, concrete cover, curing process, compaction, and characteristics of the mix constituents. Design and construction practices are very influential in defining corrosion resistance. Concrete must be designed, compacted and cured to minimize defects that will allow for rapid ion penetration. Precise engineering drawings must include drainage provisions and angles of inclination to avoid water accumulation on the concrete surface. Supervision during the construction phase must ensure that concrete cover, steel spacing and placement, vibration techniques, and finishing are all done according to the specifications. It is important to protect the steel from rain and chemicals that might cause it to corrode before placement. A harsh environment will cause corrosion even in the highest quality steel-reinforced concrete. Alternating wet/dry cycles are very detrimental to concrete structures. Marine exposure is one of the most severe environments in nature accelerating the corrosion process. De-icing salts and other chemicals facilitate the penetration of chlorides and increase the likelihood of corrosion. High temperatures, contaminated soils, industrial and polluted air are other factors that increase the rate of corrosion. Increasing the resistance of the concrete cover to the penetration of chlorides is the primary measure used in increasing the service life of marine structures.

The basic repair principle is to create a protective barrier around either the concrete or the steel, thus decreasing permeability, and preventing the penetration of unwanted elements into the structure. Some of the techniques relying on this idea are epoxy coatings, dense concrete, inhibitors, overlays, and sealers. FRP wrappings also work to eliminate water and oxygen from entering the concrete, thus creating an airtight barrier system around the structure. Electrochemical methods such as cathodic protection are also used to reduce corrosion damage.

The corrosion of steel is an electrochemical process that produces an electric current, measurable as an electric field on the surface of the concrete. Most detection techniques currently used rely on the electrochemical nature of corrosion for their data collection. A wide variety of instruments produced by different manufacturers exist for this purpose. They may vary in size, cost, application methods, underlying theories, and information given. The most used method is the half-cell potential procedure. In addition, visual inspections should complement any monitoring program, but they may not detect corrosion early enough to prevent serious damage. The acoustic emission (AE) method detects acoustic waves generated by flaw growth, thus providing early and accurate data on corrosion activity. The following two chapters of this report will provide detailed information on the most widely used corrosion detection techniques and protection strategies.

1.4 Objective

Because of the long-term aspect of Project 1774, this report represents an initial account of both laboratory and field studies. The report will provide procedures and specifications on the material selection and construction practices. The specimen variables chosen for analysis are defined, and a detailed monitoring program for future data collection is furnished. In addition to presenting laboratory work, a complete review of existing corrosion detection and repair methods is presented. In the following chapter, composite use in construction, and more specifically, for rehabilitation of damaged reinforced concrete is described. The information will be helpful in identifying other civil engineering and government groups conducting research on FRP or having completed successful infrastructure projects.

The objectives of this part of project 1774 are to:

- Determine the long-term effectiveness of a commercially manufactured FRP system in reducing corrosion damage in chloride contaminated structural elements subjected to long-term exposure.
- Study the performance of a generic composite system in a similar corrosive environment.
- Evaluate the performance of several traditional repair techniques and materials, including patches done with latex-modified concrete and epoxy grout, and corrosion inhibitors, on specimens with and without fiber wrapping that will be exposed to a corrosive environment.

A parallel study, also part of project 1774 and conducted by Verhulst [Verhulst, 1999], involves the monitoring of corrosion-damaged bridge elements repaired using fiber wrapping. The damaged bridges are located in Lubbock, Texas.

Chapter Two

Protection of Reinforced Concrete Against Corrosion

Civil engineers have been fighting a battle against corrosion for many years. Many of the currently used protection techniques significantly slow down the rate of metal oxidation by interrupting one or more of the electrochemical reactions necessary for damage to occur. Rehabilitation of damaged structures extends service life by enhancing corrosion resistance. However, the traditional methods do not fully arrest corrosion. Researchers are constantly seeking out improved protection strategies involving new materials resistant to environmental damage. The use of FRP for this purpose has increased dramatically in recent years. In this section, several accepted methods for increasing concrete durability, with a special focus on composite laminates are discussed.

2.1 Surface Repair of Damaged Concrete

A successful surface repair must replace damaged concrete, provide adequate strength and protect the reinforcement from aggressive elements [Emmons, 1994]. The conventional strategy for repair of chloride-contaminated structures is outlined below.

- Select the appropriate concrete repair material to provide a high-quality patch and ensure a strong bond to the substrate, as well as dimensional compatibility. The chosen repair material should have mechanical properties similar to those of the original concrete. Bond strength is a key factor in determining the success of a repair, as a strong bond will reduce shrinkage cracks that could impair concrete durability [Nawy, 1997]. A low-shrinkage material reduces the extent of time-dependant effects such as creep and shrinkage, which weaken dimensional compatibility.

- Remove damaged concrete up to one inch below reinforcement, or until reaching sound substrate. The repair area should be free of sharp angles to avoid high stress concentrations [Nawy, 1997]. Clean concrete surface to eliminate small debris. High pressure water jets can remove all loose particles and also clean the bar surface.

- The surface of the exposed concrete must be thoroughly wet, but with no standing water. A compatible bonding agent may be used.

- Clean steel and any other metal components by using sandblasting or mechanical abrasion to remove rust products.

- Depending on the extent of damage suffered by the bars, one of the following solutions is selected:
    - provide a supplemental bar over affected length
    - replace bar.

- Provide protection for the steel by encapsulation or cathodic protection. Coatings such as epoxy and zinc-based compounds are commonly accepted. Epoxy coatings may reduce the bond strength at the concrete/steel interface but bond is generally not a critical problem.

- Concrete or patch placement methods must be chosen according to surface orientation, surface area, accessibility, steel concentration, and full depth or partial depth repairs. In any circumstance, care must be given to complete removal of all voids through consolidation, so that the surface cavity is completely filled, and the reinforcement is surrounded by sound concrete that is not segregated [Emmons, 1994].

- Apply a sealer or protective coating on the surface of the member for additional corrosion resistance. An impermeable barrier may lead to failure because of vapor in the concrete becoming trapped at the barrier/concrete interface. Vents or "breathable" membranes must be used.

- Crack repair on concrete that will not be removed is also recommended to prevent further penetration of chlorides. This can be done by epoxy injection, high molecular weight methacrylate injection, or grouting.

Selecting a proper repair or overlay material may be the single most important step in providing a durable rehabilitation remedy. Cause of distress, operating and exposure conditions, placement techniques, and user performance requirements will all influence the decision making process. Table 2.1 presents the most common repair materials.

Table 2.1. Summary of Repair Materials [Emmons, 1994], [Fowler, 1998]

Repair Material	Properties
Portland Cement Mortar	Moderate drying shrinkage,
Portland Cement Concrete	Low drying shrinkage, perfect dimensional compatibility
Microsilica Modified Concrete	Low drying shrinkage, high compressive strength
Latex Modified Concrete	Low drying shrinkage, excellent freeze-thaw resistance, high cost, good bond strength
Polymer Modified Mortar	Moderate drying shrinkage, excellent freeze-thaw resistance, high crack resistance and tensile strength
Magnesium Phosphate Concrete	Moderate drying shrinkage, excellent freeze-thaw resistance, rapid-hardening cement, good bond, extremely resistant to many acids
Epoxy Mortar	Low drying shrinkage, excellent freeze-thaw resistance, very low permeability, good bond, high resistance to chemical attack
Methylmethacrylate Concrete	Moderate drying shrinkage, excellent freeze-thaw resistance, very low permeability, can be highly flammable and toxic
Shotcrete	Moderate drying shrinkage, good for vertical surfaces (spray-on process), limited forming needed, wasted material due to rebound

2.2 Commonly Used Protection Methods

A properly applied repair material provides good protection of the steel against corrosion. The permeability of the concrete is reduced, its pH is higher, and the structure is more durable. In most cases, however, it is advisable to use additional means of protection. The three basic types are concrete surface, steel and electrochemical protection methods.

2.2.1 Concrete Surface Protection

A barrier applied onto the concrete surface isolates the structure from the environment, and protects it from aggressive service conditions. Many techniques protect the surface of the concrete, thus enhancing the structure's durability. Typical barriers include overlays, coatings, impregnation, and membranes.[Emmons, 1994].

a) Overlays

Overlays are commonly used to protect a structure from an aggressive environment. The presence of an additional layer of repair material increases the overall permeability, thus reducing the rate of carbonation and chloride penetration. Any of the repair materials can be used for overlay construction, but the most frequently encountered are portland cement concrete, latex modified concrete, low slump dense concrete, and microsilica concrete. The latex emulsion in latex modified concrete lowers the concrete's permeability by filling the internal capillaries and voids in the paste [Sherman, 1993]. Good consolidation and vibrating are very important during construction to ensure a strong bond and minimal segregation.

b) Coatings

This method involves applying a film-producing material to the surface of the concrete to increase its durability. Many organic and inorganic coatings are available. The rate of application and number of coats applied may vary depending on the selected product and exposure conditions. Coatings contain the following elements: binder, filler, pigments, additives, dispersing agents, and solvents/dilutants [Vaca, 1993].

c) Impregnation

Impregnation consists of treating the surface of the concrete with a material that penetrates into the pore structure, thus modifying its water absorption and vapor transmission abilities. Three types of impregnation methods exist: hydrophobic, partly filling, and sealing. These methods differ in the extent of capillary filling. All three techniques produce an effective barrier against water and chlorides. It is very important to have a clean surface before applying the material. The capillaries and voids must be free of dirt and ready to be saturated.

d) Elastomeric Membranes

Elastomeric membranes are similar to coatings because they also are intended to provide a protective film on the concrete surface and eliminate water penetration. However, membranes are also flexible and can move without rupturing. This allows for elongation of material depending on the service conditions. The most commonly used types of membranes are preformed sheets or liquid-applied materials.

e) Inhibitors

By definition an inhibitor is a substance which retards the rate of a chemical reaction [Shaw, 1997]. A corrosion inhibitor reduces the oxidation rate of reinforcing steel. Corrosion inhibitors are liquid components that can be added at the time of mixing or sprayed or rolled onto the concrete surface. They are intended to penetrate and travel through the concrete matrix to reach the steel, to form a protective layer around the rebar. These chemicals prevent the intrusion of chlorides by chemically stabilizing the passive layer around the steel. Most inhibitors are calcium nitrite-based compounds, and have been successfully used in many water treatment and petroleum refining applications.

2.2.2 Steel Protection

a) Epoxy Coatings

Encapsulation of the steel with an epoxy coating is intended to insulate the reinforcement from the electric currents in the concrete. This is still the most widely used method against corrosion of reinforcing steel. Fusion-bonded epoxy coated steel is available, or the coating can be sprayed onto the surface of the bar at the site [Fowler, 1998]. It is extremely important to protect the rebar during transportation, handling and placement. Any chipped areas will create local anodes and accelerate corrosion. Repair of the damaged coating should be done according to procedures in ACI Committee 222 [ACI, 1991]. Another concern regarding this technique is the potential decrease in bond strength due to the epoxy coating's smooth surface.

b) Alkaline Slurry Coating

Alkaline slurry coatings, like new concrete, have a high pH which should protect steel by enhancing the alkaline environment around the bar [Emmons, 1994]. Some of these systems rely on non-passivating epoxies as a binder for the passivating fillers.

c) Sacrificial Anodes

Sacrificial coatings consist of applying a metallic film on the surface of the bar. The material used for the film will corrode preferentially when coupled to the steel. The most commonly used sacrificial anode is zinc. It can be applied at the factory on new bars or on the site with brushes after the steel has been thoroughly cleaned. A zinc plate attached to the concrete surface and connected to the steel will also corrode before the steel, increasing the structure's durability. Impressed voltage systems attached to the concrete surface will reverse the current flow to protect the steel. Anodes are electrically connected to the bars and must be continuously monitored for adequate performance.

2.2.3 Electrochemical Protection

The two electrochemical methods available for increasing reinforced concrete durability are cathodic protection and electrochemical chloride removal.

a) Cathodic Protection

This system consists of applying cathodic polarization to the corroding steel bars. It can be used both as a rehabilitative or a preventive measure. There are two ways of reducing the rate of dissolution by using cathodic protection: use of a sacrificial anode or application of impressed current [Vaca, 1993].

A sacrificial anode method couples two dissimilar metals. The anodic dissolution of the noble metal decreases. Sacrificial anodes are usually made of zinc, aluminum or magnesium. This system requires no electrical power source or monitoring. However, the anode is eventually consumed and must be periodically replaced [Vaca, 1993].

Application of impressed current is the most common form of electrochemical protection. The electrical resistance of concrete to the passage of protective current can be overcome by the application of an external current. Several systems exist for this type of application, the most efficient being those that lead to continuous anodes: conductive polymer wire mesh system, titanium mesh anode system, conductive coating anode system, and metallic sprayed zinc anode. The electrical continuity of the reinforcement must be verified prior to installation. Contact between the anode and the steel must be avoided because it will lead to short circuits [Vaca, 1993].

b) Electrochemical Chloride Removal

This technique is similar to cathodic protection but it uses a temporary anode and higher current density to "desalinate" the concrete. An electrolyte layer captures and removes chloride ions causing corrosion. Factors influencing chloride removal are the type of contamination (it is easier to remove penetrated than cast-in chlorides), amount of chlorides, water to cement ratio, temperature, and amounts of reinforcement. The main advantage of this method over cathodic protection is that it is temporary, resulting in lower installation and maintenance costs [Vaca, 1993].

2.3 Composite Wraps for Durability

Much of today's research to improve the durability of reinforced concrete structures focuses on the use of FRP in large-scale infrastructure projects. Composites exhibit excellent corrosion resistance and strength-to-weight ratio comparable to steel. Reduced maintenance and repair expenses justify their higher initial cost. This section will define key terms related to composites, present an overview of their use in civil engineering, and focus on FRP wraps as a protective barrier against corrosion.

2.3.1 Overview of Composites [Bassett, 1998]

a) Definition

A composite is formed of two or more distinct substances combined to produce a new material with structural properties not present in any individual component. Fiber reinforced plastics are also known as composites, and they are used in the infrastructure because they can add strength where needed and reduce weight. The main advantages of FRP are:

- High strength-to-weight ratio
- Corrosion resistance
- Radio wave and magnetic transparency
- Electrical insulation
- Fast assembly and construction

A composite is made up of fibers and a matrix. The fibers usually have a very high tensile strength (500 ksi for a single E-glass filament), but no buckling strength. The polymer resin matrix binds the fibers together and distributes the load evenly across the surface of the material. It also offers protection to the fiber from moisture, ultraviolet light and chemicals.

b) Fiber Reinforcement Design

Every composite has three defining characteristics regarding fiber reinforcement: fiber type, form, and orientation.

In order of increasing cost, the three main fiber types are glass, carbon, and aramid. The selection of the fiber depends on the required properties and project budget.

- Glass fibers are silica-based glass compounds containing metal oxides.

  E-glass fibers are electrical insulators and are the most widely used.

  S-type fibers exhibit higher strength than E-glass and corrosion properties. E-CR fibers have the highest corrosion resistance.
- Carbon fibers are more brittle and show galvanic corrosion next to metals. They are sold as "tow", a bundle of untwisted carbon filaments.
- Aramid fibers have a high tensile strength and are very flexible [Bassett, 1998].

Fibers are supplied in bundles for protection. The most common fiber forms for infrastructure are rovings, tow, and fabrics. All three types keep the fibers aligned prior to resin impregnation. A roving is a collection of untwisted continuous glass or aramid filaments. A tow is a bundle of untwisted carbon filament bundles.

The fiber orientation is also called fiber architecture. Fibers can be parallel or perpendicular to the longitudinal axis, depending on the manufacturer and the use. In general, and regardless of the selected orientation, the end result is a transversely isotropic material.

c) Resin Selection

The most common type of resins used for infrastructure are thermosetting resins, which reach a final rigid form during the curing process, because they offer on-site fabrication and modest cost. A thermoplastic resin is usually processed at higher temperatures and can be reshaped when reheated. The following is a list of commonly used thermosetting resins [Bassett, 1998].

- Unsaturated polyester resins are the most used because of their low cost, ease of fabrication, and good performance history.

- Vinyl esters resist water penetration, shrinkage, and chemical attacks. They surpass polyesters in aggressive environments where corrosion is likely to occur.

- Epoxy resins show excellent adhesion to concrete, little shrinkage, high corrosion resistance, and good adaptability to different manufacturing processes.

- Polyurethane resins have very good chemical resistance, low chloride diffusion, high toughness, and are resistant to UV rays.

- Phenolics are mostly used to fabricate materials that must pass smoke emission, toxicity, and combustion requirements.

d) Manufacturing Process

Many different manufacturing processes exist to blend fibers and resins into a composite material. These two components can be combined at a factory or at the job site in many cases. The most important element in the manufacturing process is the complete saturation of the fibers with the resin. All air bubbles must be removed from the composite prior to load application.

The basic automated techniques are pultrusion (good for structural columns, beams, rebar, tendons, and cables), filament winding (cylindrical shapes such as pressure vessels), and molding. Non automated techniques, such as the hand lay-up method, are used frequently for composite repair applications. The usual procedure involves cleaning the concrete surface and rolling on a first layer of resin. The woven fabric is then placed and compacted to ensure adhesion and saturation. An additional layer of resin is applied over the fabric. A slightly modified version of the hand lay-up technique is used for FRP wrapping of beams and columns exposed to environmental damage.

2.3.2 Structural Engineering Applications

Fiber-reinforced polymer composites (FRPC) have been successfully used in structural applications as reinforcement embedded in the concrete or as strengthening plates attached to the exterior surface of weakened members [Bassett, 1998]. Composites have replaced traditional construction materials in many other large-scale infrastructure projects [Bassett, 1998]. These materials have a high specific strength and are very resistant to corrosion. Their high cost, however, is a disadvantage over more traditional systems. Their superior efficiency in more structural applications has yet to be determined to standardize their use. The following series of examples illustrates a wide range of FRP applications in civil engineering [Basset, 1998].

- Composite cables that serve as stays, prestressing tendons, and external structural reinforcement.
- Beams and girders created from optimized cross section design and fiber placements.
- FRP trusses that have high stiffness and low deflection in long span structures.
- Column and post pilings that withstand large vertical loads without bending or buckling.
- Composite gratings and handrails that reduce maintenance costs in an exterior structure.
- FRP laminates and wraps that strengthen deficient designs, increase load bearing capacity and prevent structural deterioration in existing concrete structures.

The remainder of this chapter focuses on the use of FRP wraps for durability considerations.

2.3.2 FRP Wraps for Corrosion Protection

"Over 1500 reinforced structures throughout the world have been reinforced with FRP laminates" [Basset, 1998]. Although many of these are seismic applications, the use of composite wraps for corrosion repair and prevention is rapidly increasing. In table 2-2 a list of composite wrap manufacturers is presented.

FRP laminates have been used for encapsulation in seismic regions where wrapping a member increases its load capacity and ductility, thus reducing the damage suffered from earthquakes. In non-seismic regions, these systems have strengthened utility poles and rehabilitated piers and bent caps [TxDot / CTR, 1998]. Composites are useful in strengthening reinforced concrete because they increase the structure's capacity without adding weight. In earthquake retrofitting, the goal is to make the column more ductile. A composite jacket prevents the concrete from spalling and allowing the steel to buckle.

The California Department of Transportation (Caltrans) has permitted the wrapping of bridge columns with FRP in addition to the better known technique of steel jacketing of existing columns constructed for resisting earthquake loads. Caltrans strengthened columns in San Diego using XXsys Technologies' Robowrapper equipment, an automated wrapping machine [Bassett, 1998]. The Kansas DOT has encased two bridge columns for aesthetic repairs of moderate spalling due to road salt corrosion. The Wisconsin DOT has wrapped about twelve bridges to rehabilitate spalled surfaces subjected to corrosive environments [Wilson, 1996].

The Texas DOT has wrapped several bridges in Lubbock with composite laminates to protect them from corrosion. The bridges had shown damage in the form of severe cracking and spalling due to water penetration. After a thorough repair, many bridge bents were wrapped by Delta Technologies (see Figures 2.1 and 2.2).

Figure 2.1 Endcap Delamination

Figure 2.2 Wrapped beam end

The University of Toronto, in a joint research project with the Ministry of Transportation of Ontario, studied the effect of FRP wraps on specimens exposed to corrosion tests. Their report, entitled “Repair of Delaminated Circular Pier Columns by ACM” confirmed the effectiveness of advanced composites in corrosion protection. Researchers repaired their specimens with different grouts, and then wrapped them with two layers of FRP. The strengths of the encapsulated columns in all cases were equal to or greater than those of the original uncorroded columns. This project used the Tyfo Fibrwrap System manufactured by Fyfe Co. This material is composed of a woven fabric made up of glass and aramid fibers. It is resistant to salt, soil, and other corrosive elements [Sheikh et al.]. This team of researchers also concluded that the system was easy and quick to install. The reduced traffic interruption during a field application would help offset the higher initial cost of FRP wraps.

In spite of a growing number of successful projects involving composite wraps, certain civil engineering groups question their long-term performance in harsh environments. In their article " Repair and Protection of Concrete Exposed to Seawater", Sohanghpurwala and Scanell declared non-structural composite jackets to be non-effective for marine structures. Columns submerged in seawater are usually wrapped around the splash zone, where continuous wet and dry cycles accelerate corrosion. Capillary action allows water to rise up and become trapped in the jacket. Chloride levels rise, and because the concrete is never fully dry, the rate of corrosion actually increases dramatically. The authors claim that wrapping the structure worsens the situation, because the degradation is out of sight and the level of damage is masked. The Florida DOT conducted a study on the Bryant Patton Bridges that confirmed these claims [Sohanghpurwala, 199. In 1990, several bridge columns were wrapped with fiberglass jackets. Three years later, these jackets were removed, exposing severe corrosion damage in all columns. The detrimental effects of FRP encapsulation are crucial in determining the effectiveness of such systems.

The problem of rehabilitating corrosion damaged structures, or protecting new members from such damage has not been fully investigated. Additional experimental case studies are needed to demonstrate the long-term behavior and properties of FRP wrappings. The Ferguson Structural Engineering Laboratory (FSEL) at the University of Texas at Austin is currently participating in a joint research project with TxDOT to answer these questions.

Table 2.2. FRP Wrap Manufacturers [Bassett, 1998]

Company	Product	Project
Delta Structural Technology, Inc. Amarillo, Texas	Applies Tyfo's Fibrwrap system. Glass fiber impregnated at site with saturating machine. Hand lay-up.	UT/TxDOT corrosion protection study (project 1774) TxDOT bridge rehabilitation project in Lubbock, TX.
XXSys Technologies San Diego, California	• Robowrapper Equipment, automated filament winding machine. Applies 350 lbs of composite in 7 hours. Resin cured with an oven. • Hand lay-up also possible	Seismic and Corrosion repair with CALTRANS
Fyfe Co. L.L.C. (Hexcel Fyfe until 1997) Pleasanton, California	Fibrwrap system. 2-in-wide carbon fabric strips impregnated at site with a saturating machine (bath and rollers). Hand lay-up.	Slab strenghtening with South Carolina DOT.
C.C. Myers, Inc. Ranch Cardova, California	SnapTite composite jacketing system. Precured epoxy shells adhere to column.	Seismic retrofit and rehabilitation of damaged columns
Hardcore Dupont Composites LLC New Castle, Delaware	Precured jackets made from glass reinforced/epoxy vinyl ester composites	UT/ TxDOT corrosion protection study
Tonen Corporation Tokyo, Japan	Forca Tow Sheet material, dry sheet with unidirectional carbon fibers. Proprietary epoxy pressed in with squeegees.	Crack propagation prevention study with DelDOT and the University of Delaware.
Mitsubishi Chemical Canada Ltd. Vancouver, Canada	Unidirectional carbon fiber tape with low epoxy resin content, and backed by fiberglass scrim cloth for easy handling. Hand lay-up.	Girder shear strength Reinforcement with Alberta Transportation and Utilities Department.

2.3.3 Previous Research at the University of Texas [Unal, 1998]

Prior to project 1774, a research study for evaluating the effectiveness of FRP encapsulations was carried out by Unal [Unal, 1998]. A summary of that study and its findings is discussed here.

a) Description of Setup

Unal's test program consisted of 6 beams designed to simulate loaded, cracked specimens exposed to extremely corrosive environments for accelerated testing. The beam dimensions were 6 in. x 12 in. x 9 ft. The reinforcement consisted of two No.3 black bars placed at the top and two No.6 epoxy-coated bars at the bottom. There was also an epoxy-coated stirrup placed at midspan.

Corrosion activity had been monitored in the beams and chloride levels had been determined in all specimens for about 5 years prior to encapsulation. Encapsulation of four of the samples strictly adhered to the procedure outlined by the manufacturers (Hardcore Composites). The remaining two beams were left unwrapped and served as control samples. The beams were placed in a saltwater tank and submitted to thirteen cycles of exposure, one cycle consisting of one wet week followed by three dry weeks. Cloth was placed over the beams to ensure uniform flow of the 3.5 % saline solution. A retaining pool was designed and built to catch the solution for recycling during the exposed period and for holding the solution during the dry period. The beams were placed on wood stands in the pool. Corrosion activity was monitored using half-cell potential readings and acoustic emission testing.

At the end of the exposure cycles, the beams were removed from the pool and the following evaluations were performed:

- extraction of cores to determine depth of resin impregnation,
- chloride content measurements,
- opening of the beams to observe level of steel deterioration.

b) *Application Procedure* [Hardcore DuPont Composites, 1996]

One FRPC product, Hardshell^{TM}, was manufactured by Hardcore DuPont Composites for seismic retrofit, concrete corrosion and freeze-thaw damage, structural repair, and structural formwork.

Hardshell's FRPC systems consist of a woven fiberglass jacket, which is subsequently infused with epoxy vinyl ester resin. The space between the polymer sheet and the concrete surface is filled with vinyl ester, epoxy, or blended resins. A vacuum bag then seals the wrapping, and the resin is drawn into the cavity to seal all structural cracks and provide a tight bond between the concrete surface and the composite layer. Prior to injecting the resin, evaluation is intended to remove moisture in the concrete. Ideally, the filled cracks prevent moisture and air ingress. Since oxygen and water are necessary for corrosion, the removal of any one of these components should reduce the damage.

The installation of this system is divided into the following eight steps, which took about four days to complete with a four man work force.

- Plate and angle fabrication
- Concrete Surface Preparation
- Plate and angle installation
- Seam Preparation

- Airtight waterproofing membrane
- Infusion preparation
- Infusion
- Post infusion clean-up

Table 2.3 Hardshell Material Properties [Hardcore, Inc.1996]

• **PREFABRICATED COMPOSITE PLATES** "White Steel" Uniform properties in all directions ■ 50 ksi tensile strength ■ 3.6 msi modulus ■ 3 % elongation
• **WATERPROOF BARRIER MEMBRANE** ■ 435 psi tensile strength ■ 100 % elongation
• **EPOXY VINYL ESTER RESIN** ■ 11 ksi tensile strength ■ 12 % elongation ■ 400 centipoise resin

- Plate and Angle Fabrication

The plates and angles were made up of E-glass fiber reinforced composites and were prefabricated in a controlled facility using the SCRIMP (Seeman Composite Resin Infusion Molding Process) vacuum infusion process. This reduced the amount of work to be done in the field, as all laminates would also be pre-cut to fit the exact member's dimensions. Plates and angles were sandblasted for better adhesion and felt stripping was attached to one side, creating an offset which serves as a bond line or channel for the adhesive to cover the entire member surface.

- Concrete Surface Preparation

Pressure washing or grit blasting to prepare the surface of the concrete. The new material will bond properly to the concrete if the laitance produced by fine particles is removed. No primer is required. A distribution media can be applied to ensure adequate and comprehensive flow of epoxy.

- Plate and Angle Installation

The plates and angles were tacked to the concrete so that the waterproofing membrane could be applied and the adhesive infused. The plates were then erected in groups of opposing pairs. The temporary glue was applied and held in place with wood jigs until dry. Angles were easier to install because of their shape. Only glue and concrete nail tacks were required. After installing the plates and angles, injection ports were attached to the concrete for vacuum drawing and epoxy injection purposes.

- Seam Preparation

The airtight waterproofing membrane must cover and span all seams to be functional. This becomes problematic when covering lap and butt joints, or interfaces between columns and bearing caps. An autobody filler was used in these cases. Hand mixed batches of the membrane are also applied to all seams to ensure that full coverage is achieved when the membrane is sprayed.

- Airtight Waterproofing Membrane

In order to vacuum infuse, an airtight seal must be provided over the plate and angle system. Plastic bags can be used to accomplish this in the laboratory. For real structures, the “Eliminator S” product by Sterling Lloyd can be used. It is an acrylic- based polymer spray-on liquid plastic that hardens in 45 minutes. It also protects the system against UV lighting and moisture.

- Infusion Preparation

The encased concrete structure is fitted with feeder inlets and vacuum ports, which are placed strategically to ensure a quick and complete infusion. Vacuum is drawn and leak tests are performed on the system to test the integrity of the airtight seal, patching materials can be used to fix the leaks. The patches are removed following the infusion. Perfect vacuum is rarely achieved immediately after the vacuum is drawn. The structure must remain under vacuum for 24 hours to remove excessive moisture. Only then is it ready for infusion.

- Infusion

The system is designed to draw the adhesive in from the bottom ports, through the structure, and out through the top vacuum ports. The felt strips direct the flow so that the entire structure is infused. As the adhesive rises through the structure, it penetrates the entire concrete structure via the voids and cracks, creating one solid structure. Any air leaks are sealed with tape. Once the adhesive has hardened, the infusion process is complete. Vacuum must remain on the system for 24 hours until the adhesive reaches its optimal mechanical properties.

- Post-Infusion Cleanup

After the 24 hour curing period, all the hoses are removed. Temporary patches are replaced by permanent ones. An acoustic test is performed to verify that the adhesive has covered the entire structure. If hollow areas are larger than 5% of the total surface area, a second infusion is performed.

When successfully applied, Hardshell creates an efficient corrosion resistant system. The multiple composite layers should protect the structure from the environment, deicing salts and freeze-thaw cycles. It aims to solve the problems caused by rebar corrosion. The prefabricated fiberglass plates and angles are permanently glued to the concrete using a vacuum infusion process, thus eliminating the two main components of corrosion: oxygen and water. In addition, the adhesive should fill all voids and cracks, making polymer concrete. In reality, however, the system behaves far from ideally. Tests performed indicate that corrosion is not fully arrested after wrapping a structural member.

c) Results

From the half-cell potential data, it was found that the readings for the encapsulated beams remained at a constant level similar to that prior to wrapping, while the readings for the control specimens had a tendency to become more negative. This seems to indicate that corrosion activity was still present in the encapsulated beams due to trapped air and moisture. Since there is no direct correlation between the half-cell reading and the extent of corrosion damage, it cannot be concluded that the unwrapped beams performed worse than the encapsulated ones because they were both above the threshold for 90 %

probability of activity taking place. It was necessary to open up the beams to determine the condition of the reinforcement.

In addition, Unal found that chloride contents were above the level for corrosion in all beams. The cores taken at crack locations showed no impregnation of the resin during the infusion process. Cores were observed under ultraviolet light because naked eye observations proved to be insufficient. Upon opening of the beams, a green viscous fluid indicative of corrosion activity was found surrounding the bars of all specimens. The interior of the concrete surface of encapsulated samples appeared to be wet, demonstrating that moisture had been trapped inside the beam during wrapping. In general, it was also noted that epoxy-covered bars performed better than the black bars, which suffered severe loss of cross-sectional area. The black bars in the encapsulated beams were more damaged than those in the bare specimens. Pitting corrosion was visible at the ends of these bars, whereas it had not been observed before encapsulation nor on the unwrapped beams. Unal concludes his research with the following remarks:

- The evacuation procedure did not remove moisture from the beams and there was no penetration of the resin other than at large cracks. The beams were thus encapsulated with moisture trapped inside, which worsens the condition compared to an unwrapped beam.
- The encapsulation process makes it difficult to visually detect any signs of corrosion on the concrete surface.
- Epoxy-coated bars showed signs of superior performance when compared to the black bars. However, it is not possible to assess the performance of the encapsulation process or membrane that have not suffered severe corrosion prior to encapsulation.

Unal encourages further investigative efforts in composite use for encapsulation of elements exposed to aggressive environments.

Chapter Three

Detection of Corrosion in Reinforced Concrete

To prevent and arrest corrosion activity in its early stage, accurate detection techniques are necessary. Many technologies are available for the acquisition of reliable information on the location, extent, and rate of concrete deterioration. Each technology has its advantages and limitations, as well as strict guidelines for correct application. By studying these properties, a well-designed monitoring program can be implemented, thus reducing the risks associated with corrosion in structures. The chosen test method should be nondestructive, to allow for multiple visits with limited damage; reproducible, thus yielding consistent results; simple, so that it can be performed with ease at the site by non expert personnel; and accurate, providing engineers with meaningful results.

This chapter presents several detection and monitoring methods, and focuses on how to apply these techniques in wrapped structures. A combination of these techniques can be used at specific times. Visual inspection will be most effective before the FRP wrap is applied. Electrochemical methods and acoustic emission are useful in monitoring encapsulated structures. Chloride content determination and permeability tests can evaluate the performance of the protective system during a post-exposure “autopsy”.

3.1 Visual Inspection

Visual flaw detection techniques should not be neglected because of their "low-tech" nature. A thorough optical site evaluation can locate clear signs of deterioration due to corrosion. Location and extent of cracking, as well as information on the general condition of the concrete in a structure, can be determined by direct and indirect observations [Concorr, 1996]. Fine cracks can indicate the onset of corrosion and may help in assessing the severity of a specific problem. Spalls, delaminations, and rust stains indicate a high level of corrosive activity and require more elaborate repair. Water stains on the concrete may indicate areas exposed to leaks, below joints or drainage pipes. Information can also be obtained from drawings, construction and maintenance records. While conducting an inspection, the engineer should have all the structural, material, and construction practice information pertaining to the site. Areas with low cover or where low permeability concrete was used should be considered at higher risk because such characteristics facilitate the penetration of chlorides. If records containing such information are not available, the use of pachometers for cover determination and surface air flow devices for permeability is suggested. If the inspector locates a potential weak zone on the surface of the concrete, further optical aids should be used for a more precise evaluation.

When conducting the field investigation, locations and widths of cracks should be noted on a sketch of the structure. A crack comparator will measure crack widths up to an accuracy of 0.001 in. This instrument is a small hand-held microscope with a built in scale on the viewing lens [Concorr, 1996]. Crack measuring clear cards are also available. They can be easily stored in a wallet and allow for quick estimates. Observations such as exposed reinforcement, rust stains, delaminations, and spalled areas should be noted on a sketch. Crack movement can be monitored with mechanical movement indicators, which give a direct reading of crack displacement and rotation through signal amplification.

Internal conditions at specific crack locations can be observed with the use of flexible shaft fiberscopes or rigid borescopes. These industrial telescopes enable surfaces inaccessible to the eye to be seen [Halmshaw, 1991]. A fiber optic probe consisting of flexible optical fibers, lens, and an illuminating system is inserted into a crack. This method gives clear high-resolution images of remote objects. A flexible hose enables multidirectional viewing. However, the equipment is expensive, and large cracks are necessary for adequate access. Whatever the results of this telescopic viewing, any area with cracks large enough to insert a probe in them should be properly repaired to avoid serious corrosion damage.

Although useful as general condition surveys, visual investigations can be faulty for obvious reasons. They lack accuracy, are highly subjective, and have no early detection capacity. By the time a rust stain is visible on an exterior concrete surface, the steel reinforcement may already be heavily corroded and microcracks may have developed in the member. Once physical damage is visible in the form of cracking or spalling, little can be done other than completely replacing the deteriorated bar and surrounding concrete. Structures subject to harsh environmental conditions should be continuously monitored by more powerful nondestructive techniques capable of early corrosion detection. In addition, FRP wraps conceal the surface of the concrete, and all deterioration is hidden. For these applications, it is important to establish monitoring programs that can detect corrosion through the composite. A few such methods are discussed below.

3.2 Acoustic Emission

Many of the current techniques currently used in the field for corrosion damage assessment lack accuracy and cannot provide information before significant corrosion has taken place. The acoustic emission (AE) method detects the weak stress generated by flaw growth. As corrosion products form on the steel, the reinforcement swells. This applies stress to the surrounding concrete, which in turn creates micro-cracks. During the expansion, stress waves are generated when the pressure is high enough to break the interface layer. The growth of these microcracks is proportional to the rust product on a corroding rebar. Therefore, the AE wave frequency and duration should be indicators of the extent of corrosion activity. Detectability depends on three factors: the amplitude of the wave at the source, attenuation as it travels to the sensor, and the sensitivity of the instrumentation [Moran/Labine, 1984]. The operator must take into account these factors when determining sensor placement and spacing, to ensure that the entire structure is being monitored appropriately. Background noise must be eliminated from the data collected by setting a threshold below which no hits are recorded.

The corrosion of reinforcing steel in concrete has been previously studied by applying AE techniques. In January 1998, Li, Zdunek, Landis, and Shah from Northwestern University established a direct relationship between the corrosion rate and AE rate for rebar in HCl solution. They placed several rebar samples (rebar alone, rebar coupled with copper, rebar with anodic current polarization) in solutions of varying HCl concentration. The investigators found that the AE events were highest for the specimens exposed to higher concentrations of HCl, and that the plain bar had the lowest number of AE events when compared to the polarized bar (most hits) and the bar coupled with copper. It appears from this study that the AE rate is proportional to the corrosion rate of the steel. The sensitivity of this technique to detect corrosion activity on the rebar is very high, since the sensors pick up stress waves generated at these stress levels.

The same team of researchers also tested AE techniques on steel bars embedded in concrete. Due to the expansion of corroding steel, the reinforcement is too large to fit freely in the space it previously occupied within the concrete matrix. Pressures have to be applied to both the surrounding concrete and the bar. Once again, these pressures develop stress waves that will be gathered by the AE data acquisition system. The reinforced concrete samples tested in this investigation were subjected to a saline solution in alternating wet and dry cycles. Transducers were attached at different locations along the steel to better determine the exact location of corrosion. The event amplitude for each sensor was plotted to verify the results obtained. Different arrival times for the first hit for different sensors helped locate the position of the activity. This location was verified when performing an autopsy on the beams. The signal obtained was of high frequency, as expected for rapid crack growth. This study also showed that there was a large increase of AE events about 20 days after initiating the recordings, due to the concrete cracking after a significant amount of rust has accumulated on the steel bar. By comparison, half-cell readings and measurement of galvanic current did not show an increase until 12 days later. This demonstrates that AE will detect corrosion in the early stages of its development and allow for sooner implementation of remedial and rehabilitative techniques.

In Japan, an AE study led by Yuyama, Okamoto, Ohtsu, and Kishi evaluated a series of beams deteriorated due to corrosion of reinforcement. They compared emissions for three types of specimens: specimen with no corrosion damage, deteriorated specimens with crack widths of 1 mm and 4 mm. They found that the severity of the corrosion level increases with the crack width in any given specimen.

In addition, testing done at the University of Texas at Austin also supports the use of acoustic emission as a promising technique for corrosion detection and monitoring. Unal studied a procedure involving encapsulation and epoxy injection as a way of extending the life of corroding reinforced concrete structures. Corrosion activity had been monitored for 4 years prior to the full encapsulation of the beams, and for one year thereafter. As a supplemental test, AE sensors were attached to the exposed bars and corrosion was monitored for a few days using this method. Unal reports that the data are similar to that obtained in previous research, and he encourages further investigations in this field.

The results of previous research suggest that acoustic emission techniques might be an innovative way of detecting and continuously monitoring corrosion of steel in reinforced concrete structures. This technique seems particularly promising for encapsulated structures because the weak stress waves will travel through the composite to be picked up by AE sensors. However, most evaluations of this technique for structural applications are qualitative and simply make comparisons between different specimens allowing for a primitive correlation between AE hits and corrosion activity. Also, AE studies for corrosion in reinforced concrete structures have used reduced scale specimens, which have an inherent degree of error due to continuous wave reflection. If this method is to be implemented as a substitute for other currently used standards, it must be studied in more detail. Signature analysis and source location are the key factors for future research. Real structures should be monitored for relevant data. Acoustic emission technologies have been used extensively in industrial plants for pressure vessel and tank car applications. Current studies must be focused on monitoring of reinforced concrete structures.

3.3 Electrochemical Methods

Since the corrosion of steel is an electrochemical process, a wide variety of instruments produced by different manufacturers have been developed for measuring an electric field on the surface of the concrete. They may vary in size, cost, application methods, underlying theories, and information given. The following is an introduction to methods of potential and rate measurement.

3.3.1 Half-Cell Potential

The open circuit of steel in concrete potential can be measured with respect to an electrode known as a reference electrode. By making measurements over the entire surface of reinforced concrete, a distinction can be made between corroding and non-corroding areas.

Half-cell potential readings can be used to determine the probability of corrosion at a given location at the time of the reading. When steel corrodes in concrete, a potential difference exists between the anodic and the cathodic areas on the reinforcing steel. This difference can be detected by placing a copper-copper sulfate reference electrode on the surface of the concrete and by measuring the potential difference between the bar and a wet sponge on the member's surface. The reference cell connects the surface of the concrete and the steel to a voltmeter, which reads the potential at that location. Such readings are usually taken at several spots on a concrete surface in a grid-like pattern to establish which areas are potential weak zones. The readings are interpreted in the following manner, according to the test method of ASTM C 876:

- Readings more positive than -0.20 V: 90% probability of no corrosion
- Readings between –0.20 and –0.35 V. corrosion activity is uncertain
- Readings more negative than –0.35 V: 90% probability of corrosion taking place.

Positive readings are invalid because they usually mean that insufficient moisture is present in the concrete. Amount of carbonation and salt concentration can also lead to inconclusive readings and erroneous judgements. These readings are not usually used to detect corrosion in post-tensioned strands, nor can they detect corrosion when reinforcing steel is discontinuous from the voltmeter. They provide no indication on the rate of corrosion, as the method only provides potential for corrosion at a specific time and location. Potential readings should be taken periodically to obtain a history of any specific structure, as well as its tendency to corrode with time. Contour maps with equipotential lines can be drawn to identify areas of high probability of corrosion. Half-cell readings cannot be taken through

FRP laminates. To make a connection between the steel and the concrete, lead wires must be attached to the reinforcement and small holes must be cut through the wrap to expose the concrete surface. These alterations can impair the performance of the composite system. Care must be taken between readings to seal up any openings and prevent moisture and chloride intrusion.

Several commercial instruments capable of multiple recordings and storage are currently available. SDS Company has designed and built self-contained units consisting of an electrode, a sponge, and a voltmeter. Results can be stored in the machine's memory. This makes it possible to take a large area assessment directly on the display of the indicator, which plots the data on the screen in color bands designating the potential. SDS has also created a system on wheels for quick evaluation of large horizontal surfaces such as bridge decks and parking garage floors. This product includes electrodes with moistening wheels for continuous wetting up to a length of 200 m. It automatically measures surface potential at preselected intervals, as the wheels adjust to the object profile.

3.3.2 Corrosion Rate Measurement

Techniques for the measurement of corrosion rates in reinforcing steel are a recent development. These methods allow for estimates of the remaining service life of a structure given its rate of deterioration. The higher the rate, the sooner spalling and delaminations will appear [Concorr, 1996].

Early experiments demonstrated that the degree of polarization at a given applied current was greater for lower corrosion rates. Today, the polarization resistance technique is widely used for tests of reinforced concrete structures. The method is based on the Stearn-Geary analysis, which states that the corrosion rate of a probe is inversely proportional to its polarization resistance [Moran/Labine, 1984]. Instruments used in the field apply a small voltage perturbation to the reinforcement and measure the steel's response, and thus its polarization resistance. The resulting current is then recorded as a measure of the corrosion rate.

The following products are all used to measure corrosion rate of steel reinforcement:

- The 3LP Device, manufactured by KCC, Inc.
- The Gecor Device, manufactured by GECOISA, Spain, and
- The PR – Monitor, manufactured by Concorr.

Both the Gecor and the 3LP devices are based on the linear polarization technique, but the 3LP applies a potential sweep to the steel and then measures the current at several polarization levels. The PR – monitor also relies on the linear polarization technique, but it is capable of calculating the corrosion resistance by applying an AC signal from a high frequency generator [Concorr, 1996]. All three instruments allow for tests on both vertical and horizontal surfaces. The main difficulty in field applications is accurately determining the steel area directly under the concrete surface being tested. This is important because the corrosion rate is given in units of current per area of steel. False area information will give misleading results. However, exact information can be difficult to obtain for heavily reinforced structures. Operators select areas immediately above the reinforcement and adjacent to the cores to ensure electrical connections. The engineering drawings should be consulted and a pachometer should be used whenever possible. Corrosion data measurements are also influenced by environmental factors such as ambient temperature and concrete moisture. To accurately predict corrosion activity, a collection of readings should be taken at any given location to account for such changes.

a) 3LP Device

Manufactured by Kenneth C. Clear, Inc., this instrument utilizes a three-electrode linear polarization technique to measure corrosion rate. The steel bar being tested is called the *working electrode*, the *reference electrode* is usually a copper-copper sulfate half cell and it senses potential changes induced on the steel by a current, introduced into the system by a *counter electrode*. A cathodic current is applied manually until the reinforcing steel is polarized by 12 mV from the static potential. Current values corresponding to overpotentials of 0, 4, 8, and 12 mV are recorded and input to a computer program which calculates corrosion rate (I_{corr} in mA / sq. ft) using the Stern Geary equation. The results are then interpreted as follows [K.C.Clear Inc.]:

- $I < 0.20$ mA/sq.ft — no corrosion damage expected
- $0.20 < I < 1.0$ mA/sq.ft — corrosion damage possible in 10 to 15 years
- $1.0 < I < 10$ mA/sq.ft — corrosion damage expected in 2 to 10 years
- $I > 10$ mA/sq.ft — corrosion damage expected in 2 years or less

This instrument is very sensitive to any knob adjustments. Because the potential sweep has to be repeated every time the desired overpotentials are reached, it is often necessary to start the procedure over.

b) Gecor Device

This instrument is also based on the linear polarization technique. It measures the corrosion rate of steel under a guard ring. The instrument's screen prompts the user to input the steel area, and it performs all other calculations. It automatically calculates the corrosion rate, with no additional input required from the operator. The data are stored after identification of the measurement location. The results are interpreted as follows (from the Gecor Users manual):

- I < 0.1 μA/sq.cm: passive condition
- 0.1 < I < 0.5 μA/sq.cm: low corrosion
- 0.5 , I , 1.0 μA/sq.cm : moderate corrosion
- I > 1.0 μA/sq.cm : high corrosion rate

c) PR-Monitor

The PR-Monitor uses the guard ring concept to measure the rate of corrosion through a potential control stepping sequence. It is controlled by a laptop computer which records data automatically at each test location. A menu-driven screen prompts the operator to select step size, number of steps, time between steps, and the potential with respect to static potential for beginning the stepping sequence [Cortest]. The electrode assembly for this instrument consists of a counter electrode (CE) and a "guard ring" electrode which surrounds both the CE and the reference electrode. The guard ring provides better confinement for the CE current to the area directly below the CE, and thus allows for a more accurate calculation of corrosion rate for the PR. The calculations are performed at the end of each measurement and are displayed as corrosion rate in mils per year (mpy) or mm/yr. Permanent data records are kept in the laptop memory for future use. The PR-Monitor manufacturer does not provide any data interpretation guidelines, but the results can be converted into units of μA/sq.cm (mpy/0.468) and the Gecor device recommendations can be applied [Concorr, 1996].

3.4 Chloride Content

The amount of chlorides in concrete greatly influences the extent and rate of corrosion. Determining the percentage of chlorides present at different depths in the structure is crucial in predicting the level of deterioration and remaining service life. The extent of chloride ion penetration in the concrete is also a good measure of the effectiveness of a given protective system. Because FRP wraps are supposed to arrest corrosion by preventing the ingress of harmful elements, the amount of chlorides in a wrapped structure should be very low.

Pulverized concrete samples are necessary to determine the chloride ion content of suspect areas. An electric rotary hammer drills ¾-inch holes into the concrete at three depths: ½ to 1, 1 to 1-1/2, 1-1/2 to 2 inches. The concrete dust is collected at each depth. Stainless steel scoops remove residual dust from the bottom of the holes. To avoid contaminating dust from different layers, an air pump can be used to clean the hole between samplings, and the drill bit and scoop are rinsed with distilled water after each use. The acid soluble amount of chlorides of hardened concrete is determined by mixing the powder samples with an acetic acid fluid extraction as outlined in the ASTM C1152 specification. The results are presented as percent chloride by sample weight. A value of 0.2 % is usually a reliable indication of damaged concrete, vulnerable to corrosion.

3.4 Permeability Testing

Permeability tests are another method used to determine the effectiveness of a structure in resisting chloride ion and moisture penetration. Unfortunately, these tests are destructive because they require extracting cores from the structure. They should be performed at the completion of the laboratory project to evaluate the performance of the composite wraps.

A coring machine with the appropriate size bit is used to obtain four-inch diameter cores. These samples are examined at the laboratory where they are cut into 2 inch slices and exposed to an electrical current according to ASTM C-1202-91. An external potential forces chloride ions to pass through the concrete from one end of the slice to the other. The test measures the permeability in terms of coulombs. The results are then grouped in terms of relative permeability according to the following guidelines [Sherman, 1993]:

- 2000 – 4000 coulombs: moderate permeability
- <1000 coulombs: low permeability
- >4000 coulombs: high permeability

Chapter Four
Project Definition

To explore the performance of composite systems as corrosion protection for reinforced concrete, the TxDOT developed project 1774, "Effect of wrapping Chloride Contaminated Structural Concrete with Multiple Layers of glass Fiber/Composites and Resin". A number of manufacturers of proprietary systems approached TxDOT engineers regarding the use of fiber wrapping to improve durability or to repair corroded reinforced concrete structures. In the absence of reliable technical data, TxDOT was reluctant to approve the use of these systems.

4.1 Scope

Based on the conclusions of previous studies on FRP wraps, additional variables are being investigated in project 1774. The relevance of factors such as element shape, surface condition, and protection strategy will be evaluated. Representative field conditions will be simulated. To accelerate the oxidation of the reinforcement, many of the "worst case" field-encountered scenarios are implemented in the laboratory tests.

4.1.1 Specimen variables

Sixty reinforced concrete specimens are being monitored for this project. Table 4.2 summarizes the variables and a description of each specimen is included.

a) Size and Shape

In order to represent both columns and beams, 18 rectangular and 42 circular shapes were selected for this study. More emphasis was placed on studying circular shapes because piers submerged in seawater are often selected for FRP wrapping applications. The specimen dimensions are presented in Table 4.1.

Table 4.1 Specimen Dimensions

Shape	Length	Cross Section
Rectangular	3’	10” x 10”
Cylindrical	3’	10” diameter

b) Steel Reinforcement

All specimens were constructed with steel cages formed of longitudinal and transverse reinforcement. Metallic tie wire was used to attach the rebar to the spiral.

The tie wire also maintains electrical continuity necessary for monitoring purposes. Plastic chairs fastened to the cages ensured that the 1-in. cover requirement was met for all specimens. A small cover was chosen to accelerate corrosion. The reinforcing bars were cut in 39-in. lengths, so that 3-in. of reinforcement protruded on one end of both the beams and the cylinders. The portruding bars facilitate monitoring, as most methods for corrosion detection require a direct connection to the steel.

c) Cast-in Chlorides

Because of the detrimental effect of chloride ion penetration, two different concrete mixes were used in the project. Some specimens were cast with concrete containing chlorides, others with uncontaminated concrete. The chlorides were added to quicken the onset of corrosion, and to compare the effectiveness of FRP wrappings on structures with varying amounts of chlorides. The chlorides were added to the mixing water at the ready-mix plant before delivery at the laboratory. Regular salt was included to achieve a 3.5 % saline solution by weight. This yields a contamination level similar to those measured in field tests in marine structures. A threshold value of 0.2% chlorides by weight of cement may initiate the corrosion of reinforcement in a marine structure.

d) Flexural Cracks

Numerous cracks at the surface of a reinforced concrete member facilitate the intrusion of corrosive elements into the structure, thus accelerating damage. The penetration of chlorides is more rapid in areas with cracks [Taheri, 1997]. In real structures, internal restraints to deformations create areas of high stress, where microcracking may develop, thus increasing the permeability of the concrete. Crack width and propagation are important parameters in the chloride transport mechanism.

Isolated fine cracks have little effect on the permeability of the concrete. A connective system of fine cracks increases the rate of chloride penetration significantly.

Most heavily damaged columns and beams in the field exhibit cracking. This condition was reproduced in the laboratory by loading some specimens until flexural cracks of a given width appeared on the surfaces. Usually a width of 0.020 mils was considered to be sufficient. The specimens are unloaded during exposure and monitoring. Cracked specimens are expected to corrode earlier than uncracked ones.

e) Pre-Existing Concrete Condition

Two pre-existing concrete conditions were evaluated: undamaged; and damaged and repaired. The undamaged specimens will be monitored with the concrete as cast. The specimens selected for repair will help to determine the effectiveness of two different patching materials: latex modified concrete (LMC) and epoxy grout (EG). Prior to repairing the specimens, a portion of the concrete was removed using a chipping hammer. Two placing techniques, drypacking, form and cast-in-place were used. Standard procedures and TxDOT specifications regarding material selection and repair procedure were followed.

In addition to the standard repair method and the FRP wrapping, a corrosion inhibitor, Sika's Ferrogard, was applied on a few specimens to study the effect of a third protection technique. This material was donated by Sika and was applied according to the manufacturer's guidelines.

To verify the adhesive properties of a composite wrap in marine environments, a few cylindrical specimens with wet surfaces were wrapped. They were placed in buckets containing 3.5 % salt water for 24 hours prior to the encapsulation. All rectangular specimens were wrapped with dry surfaces.

f) FRP Wrapping Systems

The performance of two different composite systems in a corrosive environment was investigated. The first system was manufactured by Delta Technologies, and was donated to project 1774. The second system was designed and fabricated at UT, and was be designated as the “Generic” system. If the latter proves to be a viable corrosion prevention and repair method, general specifications for FRP laminates can be developed by TxDOT. The generic system incorporates vinyl ester (VE) and epoxy (E) resins, and uses fabric from Owens Corning. Delta’s system uses one resin type (TYFO S) and one fabric type (SHE-51). The curing agents for the epoxy based resin varied depending on the surface condition of the concrete (EPON 3090 for wet, EPON 3234 for dry)

The wrapping lengths were varied to simulate several conditions. All wrapped beams were encapsulated to about 30-in., thus leaving a small portion of the specimen uncovered at the end where the reinforcement was exposed. The other beam end was completely wrapped. The wrapped columns are either fully or partially enclosed, with the bottom ends always unwrapped. To simulate field conditions, where it is impossible to wrap a column to the foundation or below the waterline due to access difficulties. Partially wrapped columns were either wrapped to the waterline or six inches below the average waterline, to study the effect of capillary action on composite wraps.

Tables 4.2 and 4.3 describe each specimen in detail. The first denotes shape (R for rectangular, C for cylindrical), and the following letters differentiate chloride contaminated mixes from uncontaminated ones (C for chlorides, NC for no chlorides). The Gen or Del status denotes specimens wrapped with a hybrid system formed of Delta’s fabric and the Generic system’s resin. VE stands for Vinyl ester, E for epoxy, LMC for latex-modified concrete, and EG for epoxy grout. Blank entries in the last four columns imply dry, uncracked, unrepaired, and specimens without inhibitor, respectively. All rectangular specimens were wrapped with dry surfaces.

Unwrapped specimens are control elements, and will be indicators of what happens to unmodified structures. The unwrapped specimens permit evaluation of single protective systems (repair materials, inhibitor alone), of the effect of cracks on the durability of a structure, and of the influence of large amounts of cast-in chlorides in the concrete.

Table 4.2 Rectangular Specimens

Specimen	Wrap		Components	Concrete Condition	Concrete Repair	Inhibitor
	Type	Length, in				
RC 1	Generic	27	E 862/3234		LMC	Ferrogard
RC 2	Generic	31	VE	Cracked		
RC 3	Delta	24		Cracked		
RC 4	No wrap			Cracked		
RC 5	Delta	27			LMC	
RC 6	Gen/Del	33	E 862/3090		LMC	
RC 7	Generic	30	E 862/3234	Cracked		
RC 8	No wrap				LMC	
RC 9	Gen/Del	24	E 862/3090	Cracked		Ferrogard
RNC 1	Delta	24				
RNC 2	No wrap					
RNC 3	Generic	27	E 862/3234			Ferrogard
RNC 4	Generic	36	VE		LMC	
RNC 5	Delta	30		Cracked		
RNC 6	Gen/Del	30	E 862/3090	Cracked	LMC	
RNC 7	No wrap			Cracked		
RNC 8	Generic	24	E 862/3234	Cracked		

Table 4.3 Cylindrical specimens

Specimen	Wrap		Components	Surface	Concrete Condition	Concrete Repair	Inhibitor
	Type	Length, in	Resin/curing agent				
CC 1	Delta	24	Tyfo S				Ferrogard
CC 2	Gen/Del	30	Tyfo S	Wet		LMC	
CC 3	Delta	24	Tyfo S			EG	
CC 4	Delta	24	Tyfo S			LMC	
CC 5	Generic	36	862/3234		Cracked	Patch	
CC 6	Generic	36	VE/411		Cracked	Patch	Ferrogard
CC 7	Delta	24	Tyfo S		Cracked		
CC 8	Delta	36	Tyfo S			LMC	
CC 9	Delta	24	Tyfo S				
CC 10	No wrap						Ferrogard
CC 11	No wrap						
CC 12	Generic	30	862/3234	Wet	Cracked		
CC 13	Generic	24	862/3234		Cracked		
CC 14	Generic	24	862/3234			LMC	Ferrogard
CC 15	Generic	24	862/3090		Cracked		Ferrogard
CC 16	No wrap					EG	
CC 17	No wrap					LMC	
CC 18	No wrap				Cracked		
CC 19	Generic	24	VE			LMC	
CC 20	Generic	24	VE/411				Ferrogard
CC 21	No wrap				Cracked		Ferrogard
CNC 1	Generic	27	862/3234	Wet	Cracked	Patch	
CNC 2	Generic	36	862/3234		Cracked		
CNC 3	Generic	24	862/3234				Ferrogard
CNC 4	Delta	24	Tyfo S				
CNC 5	Delta	36	Tyfo S		Cracked		
CNC 6	Generic	24	VE	Wet	Cracked	Patch	
CNC 7	No Wrap						Ferrogard
CNC 8	No Wrap				Cracked		Ferrogard
CNC 9	Generic	24	VE			LMC, p	
CNC 10	Delta	24	Tyfo S		Cracked		
CNC 11	No Wrap					LMC, p	
CNC 12	No Wrap					EG, p	
CNC 13	Generic	24	862/3234		Cracked		Ferrogard
CNC 14	Generic	36	862/3234		Cracked		Ferrogard
CNC 15	No Wrap				Cracked		
CNC 16	Delta	24	Tyfo S			LMC	
CNC 17	Delta	24	Tyfo S			EG	
CNC 18	Generic	24	862/3234			LMC	Ferrogard
CNC 19	Generic	24	862/3234				
CNC 20	No Wrap						

4.1.2 Exposure Cycle

All specimens will be maintained in a pool and are subjected to exposure cycles composed of one wet week followed by two dry weeks. This exposure regime is typical of marine splash zones. It accelerates corrosion by ensuring the continuous transport of chloride ions to the steel surface. The columns are standing in the pool, and the beams are laid on their side, at an inclined angle. During the wet cycle, the columns will be immersed in 1-ft. of water, and the beams will be irrigated by a wetting system formed of PVC pipes placed over the specimens. Openings in the pipes will allow water to trickle onto the beams, and the inclination of the specimens will lead to water accumulation at the beam-ends. Rectangular specimens are kept out of the stagnant water by cinder blocks. The salt water used during the wetting cycle is a 3.5% NaCl solution.

Before each wet period, water is pumped into the pool from an adjacent storage tank. During the wet cycle, the same pump lets the saline solution circulate within the pool and the PVC pipes, maintaining a constant depth of 1-ft.. At the end of the wet week, the water is pumped out of the pool and back into the tank, and the specimens air dry for two weeks.

Chapter Five
Specimen Construction

The construction of test specimens and material selection were determined in consultation with TxDOT engineers and using applicable bridge design specifications [TxDOT, 1993].

5.1 Specimen Cages and Forms

The first step in the fabrication process was to construct the steel cages for the reinforced concrete specimens. All reinforcement was grade 60 steel. The longitudinal reinforcement consisted of 4 - #6 black (uncoated) bars for both the columns and the beams. The transverse reinforcement differs between the circular and the rectangular specimens.

5.1.1 Rectangular Specimens

The cages for the beams consisted of 4 - #6 bars in the longitudinal direction (two bars on top, two in the bottom), and 3 - #2 bars in the transverse direction. The spacing between stirrups was 10 inches. The transverse reinforcement was bent on a mandrel to create a U shape, and attached to the longitudinal bars by using tie wire. Bending was done in accordance with ACI 318-89 requirements for minimum bend diameters for stirrups and ties. Plastic chairs were attached to the cages to ensure a 1-in. cover on all sides. Figure 5.1 shows a detail of the cross section.

Individual forms for the beams were built out of plywood, in compliance with item 420.9 of the TxDOT specifications [TxDOT, 1993]. They were oiled 24 hours before placing the concrete to allow for easy removal after the specimens had cured.

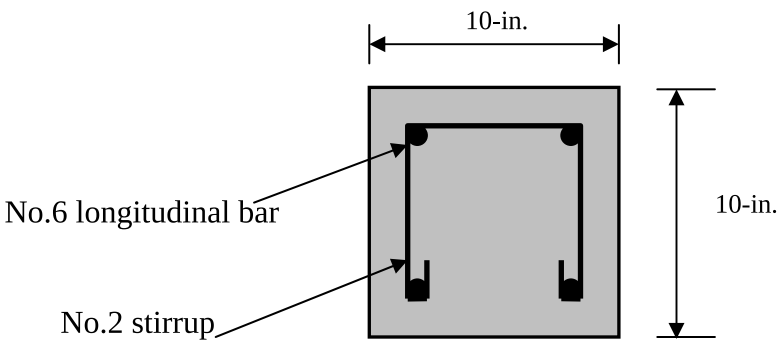

Figure 5.1 Cross Section of Beams

5.1.2 Cylindrical Specimens

The cages for the columns consist of four no.6 longitudinal bars and 8 - #2 spiral loops, spaced 10-in. apart, as transverse reinforcement. As for the beams, plastic chairs and metallic tie wire were used. Individual circular loops were cut out of a continuous spiral for the transverse reinforcement. This eliminated the lateral tension caused by a large coil, and facilitated overall placement. Figure 5.2 shows a detail of the column cross section.

The column cages were placed in prefabricated, 10-in. inner diameter cardboard forms. The tubes were attached to plywood and were sealed with silicone.

Several rows of cylindrical molds were built, ensuring stability and adequate placement

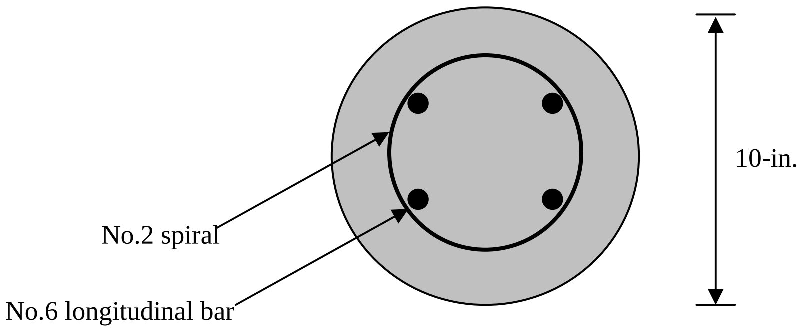

Figure 5.2 Cross Section of Columns

5.2 Concrete Design

To accelerate corrosion under laboratory conditions, high permeability concrete was desired. This property had to be achieved while still maintaining sufficient strength. A trial batching was done to determine the mix properties.

5.2.1 Trial Batch

a) Composition

The trial batch for verifying concrete permeability and strength was based on a standard mix from the ready-mix supplier. The mix was developed for laboratory use and provided strengths closer to design values than typically provided at construction sites where the design is often quite conservative (higher than design values). For the purposes of this study, the water-to- cement ratio (w/c) was lowered from 0.75 to 0.65 to increase the strength. Two trial batches were mixed: one with cast-in chlorides and one without. For the chloride contaminated mix, regular iodized food grade salt was added to the mixing water to achieve a 3.5% NaCl solution. An air-entraining agent was added to the mix to increase the permeability further. The final air entrainment values were 2.5% for the first mix (without chlorides) and 3% for the second mix (with chlorides). The final w/c was about 0.7 for both mixes, as water was added to increase workability. Table 5.1 lists the mix proprotions for 1 yd^3.

Table 5.1 Trial Mix Design

Cement	385 lbs
Water	268 lbs
Coarse Aggregate (3/4")	1926 lbs
Sand	1629 lbs

b) Mix Properties

After curing for 28 days in a moist chamber, both compression strength and permeability tests were performed. Both tests were performed according to ASTM standards C39 and C1202-97, respectively. For the permeability test, cores were extracted from both rectangular and cylindrical specimens. The results are presented in Tables 5.2 and 5.3. The mix was considered to be satisfactory for the project.

Table 5.2 Compression Strength

	Avg. Strength, psi
With cast-in chlorides	3,104
Without chlorides	2,951

Table 5.3 Permeability

		Average charge passed, Coulombs	**Permeability Rating**
Rectangular	**No chlorides**	4,263	High
	Chlorides	4,500	High
Cylindrical	**No chlorides**	3,615	Moderate/High
	Chlorides	4,195	High

5.2.2 Final Batch

a) Desired Properties

Based on the results from the trial mix, the modified version of the standard mix was approved for use.

Given the specimen dimensions and numbers, 2 yd^3 of chloride-free mix and 2.5 yd^3 of chloride contaminated mix were needed. An excess of 1 yd^3 was added to both orders to account for losses during placement and test cylinder requirements.

Based on the concrete design, and to achieve a 3.5 % saline solution, approximately 34 lbs of salt were necessary. This amount was added to the mixing water at the plant.

b) Concrete Placement

During concrete placement, the outside temperature was 82 degrees and the relative humidity was 43 %. Table 5.4 presents slump measurements. Water was added to both mixes at various intervals to increase slump and workability. Cylinders were cast for permeability and strength tests.

Table 5.4 Slump measurements

	Initial Slump, in	**Water added, gal**
Chloride Mix	1	8
Chloride-Free Mix	1	6

Initially, the concrete was placed directly from the truck to the forms by a chute. The flow could not be controlled and the rectangular timber forms were damaged. The forms required additional clamping and bracing to prevent collapse. Also, the chute was too large to allow for easy placement of concrete into the 10” cylinder forms. The chute was replaced by wheelborrows and buckets for the remaining specimens.

Concrete was placed into the forms in successive layers to minimize segregation. Each layer was consolidated with immersion-type vibrators immediately after deposit. Points of vibration were established to ensure complete consolidation and placement of the concrete around the steel cages and into all corners of the forms. For the rectangular specimens, the vibrator was inserted at sloping angles and allowed to penetrate a few inches into each preceding layer. Vibration was more complicated for the columns due to their smaller opening, increased height, and bulky reinforcement. These factors made it difficult to consolidate the lower layers of concrete.

As soon as the concrete was placed and vibrated, the top surface was leveled, struck off and screeded. A small quantity of concrete was carried in front of the screed to completely fill all low spots across the face.

The specimens were covered with plastic sheets and damp burlap mats for wet mat curing. This method keeps the concrete continuously wet throughout the curing period. The specimens were cured for 28 days.

Figure 5.3 Placing Concrete in Cylindrical Forms

Figure 5.4 Vibrating Concrete in Columns

Figure 5.5 Wet-Mat Curing of Beams

c) Results

In table 5.5, the results from compressive strength and permeability tests for both mixes are presented.

Table 5.5 Test Results

	Strength, psi	Permeability Rating
Chloride Mix	4,964	High
Non-Chloride Mix	3,170	High

After removing the forms, it was observed that the rectangular specimens were well consolidated and had a smooth finish. A few of the timber forms had bulged during the initial placements, and the corresponding beams had slightly curved sides. The difficulties experienced during placement for the columns were visible in the form of severe honeycombing for about one third of the cylindrical specimens. This problem was resolved by patching and repairing damaged areas, and rejecting a small number of columns.

5.3 Pre-Wrap Preparation

5.3.1 Cracking

The specimens selected for flexural cracking were loaded until cracks of sufficient width appeared on their surface. The maximum crack width allowable in service is 13 to 20 mils. Similar crack widths were obtained experimentally. Figure 5.3 presents the loading configuration.

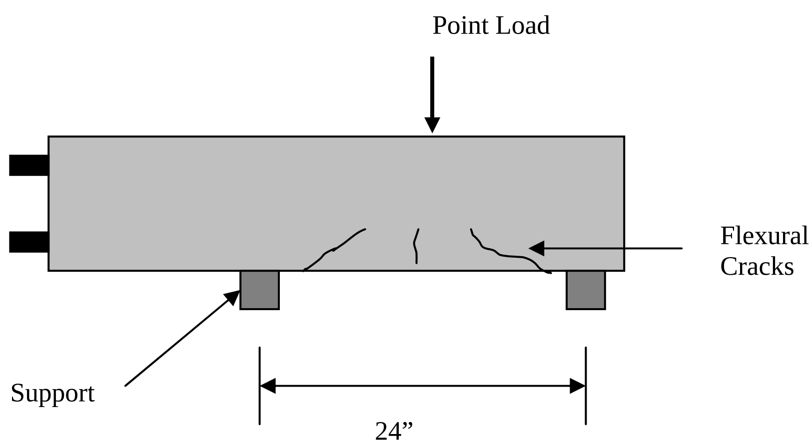

Figure 5.6 Loading Configuration

The rectangular specimens were loaded on one side only. Columns were loaded on two sides to achieve a uniform crack distribution. It was important to obtain cracks in the bottom part of the column, that is exposed to saltwater. While the specimen was loaded, crack widths were measured with a crack comparator. Photographs were taken for future reference. Table 5.6 lists the crack widths for each loaded specimen.

Figure 5.7 Cracked specimen

Table 5.6 Crack Data

Specimen	Maximum Load, kips	Maximum Crack Width, mils
RNC 4	51	13
RNC 5	69	13
RNC 6	65	13
RNC 7	65	13
RNC 8	58	13
RC 2	75	20
RC 3	70	40
RC 4	63	16
RC 6	72	13
RC 7	65	16
RC 9	69	16
CNC 1	43	16
CNC 2	43	20
CNC 5	49	250
CNC 6	52	20
CNC 8	51	20
CNC 10	44	20
CNC 13	44	25
CNC 14	49	25
CNC 15	47	16
CC 1	50	13
CC 5	37	13
CC 6	39	20
CC 7	43	20
CC 8	31	13
CC 13	35	20
CC 15	53	13
CC 18	52	16
CC 21	58	13

5.3.2 Repair

a) Material Selection

Two materials manufactured by Sika Corporation were chosen for the repair work: an epoxy grout (Sikadur 42, Grout Pak) and a latex-modified concrete (SikaTop 122 Plus) [Sika,1996]. Both choices comply with TxDOT specifications for repair mortars [TxDOT, 1993]. Appendix A contains material properties and application guidelines for both products. Good dimensional compatibility between the repair materials and existing concrete was expected.

b) Surface preparation

Repairs for the beams were done on the top surface at a depth of 1-in. The columns were repaired from the bottom to a height of 16-in., at a depth of 1-in., over one half of the specimen.

Unsound concrete was removed with a chipping hammer, with care taken to not damage the reinforcement. Concrete around the steel was removed with a chisel and hammer, and all loose particles were cleaned off with a pressure air hose. All exposed reinforcement was cleaned with a wire brush to remove dirt and any traces of corrosion that may have developed.

Twenty-four hours prior to placing the repair material, the concrete was saturated with clean water. Immediately before placement, all remaining puddles of excess water were removed.

Figure 5.8 Chipped Specimen

c) Application Method

Timber forms were placed around the rectangular specimens for placing the repair materials. Metal flashing sheets were attached around the columns with hose clamps. Small openings were left at the top of the repair area to pour in the materials. All forms were sealed with silicone.

The separate components for both materials were mixed mechanically with a low speed drill according to Sika specifications. Small fractions of the components were held back or added to the mix as appropriate and necessary to achieve a good flow. Materials were poured into the forms (with cups and scoops), consolidated and leveled. The latex-modified concrete had to be scrubbed into the repair for the beams, while the epoxy grout poured freely in, filling all voids and edges. Both products were made to fill the cylindrical forms. Vibrators were tapped along the side of the metal flashing for the columns, and carefully inserted into the repair at an inclined angle for the beams.

Small repair areas were patched by drypacking. Portions of the repair materials were made thicker for this purpose.

Repairs were covered with plastic and wet burlap, and left to cure for 4 days.

Figure 5.9 Mixing the Repair Materials

Figure 5.10 Vibrating the Columns

Figure 5.11 Drypacking

5.3.3 Corrosion Inhibitor

Sika corrosion inhibitor was applied on a few specimens to test the effectiveness of this protection method on both FRP wrapped structures and unwrapped ones. Sika Ferrogard is a modified Amino Alcohol Corrosion Inhibitor [Shaw, 1997]. It is applied in liquid form and reportedly penetrates through the concrete to form a thick film (100-1000 angstrom) on the steel to displace chlorides. The inhibitor moves through the structure by capillary suction and absorption. According to the manufacturer, it is effective at high chloride levels (up to 1 to 2 % by weight of cement), and in carbonated concrete. The Ferrogard product is a multifunctional inhibitor because it reduces iron dissolution at the anode and oxygen access at the cathode.

Sika Corporation recommends the use of Ferrogard as part of a larger corrosion protection strategy. The inhibitor can be applied as a post treatment following localized repair techniques. The concrete surface onto which the inhibitor will be applied must be clean, dry, and free of dirt and residues. In the laboratory, this was done by a pressure air hose. Two layers of inhibitor were applied with paint rollers, with a one-hour time interval between layer applications.

Chapter Six
FRP Wrapping

The specimens designated for wrapping were divided into two main categories according to the composite used for wrapping. The composition, material properties and application methods for both systems are described in this chapter. A photographic essay illustrates all steps of the encapsulation procedure.

6.1 Delta System

Delta Corporation wraps structures with composite systems to strengthen them against seismic loads, increase their ultimate capacity, and protect them from degradation caused by corrosion. Delta relies on Hexcel Fyfe Co. to provide the FRP system elements: woven fibers that will be saturated with epoxy resin. Hexcel Fyfe's Fibrwrap product is used in all of Delta's projects, and is designed to add strength, ductility, and confinement to structures. Claims of improved durability and corrosion resistance are secondary. This laboratory investigation will attempt to determine their suitability for durability problems.

6.1.2 System Components and Material Properties

The composite system is made up of the fiber TYFO SEH 51 and the epoxy matrix TYFO S. Appendix B contains Delta Specifications on wrap applications and material properties.

SEH 51 is a woven fabric of E-glass rovings, whose primary fabric is glass. Most of the glass rovings are in the 0° or warp direction. E-glass is used as a general-purpose fiber where strength and high electrical resistivity are required [Hartman, 1996]. Both E-glass and Kevlar are included in the 90° or weft direction. The warp to weft ratio is 17:5 by weight. The fabric's total weight is 27.2 oz / yd^2 [Delta, 1998].

TYFO S is a two-part ambient temperature curing epoxy resin matrix. It is formed of an epoxy system, TYFO A, and a curing agent, TYFO B. These two components must be mixed in a ratio of 100:42 (TYFO A: TYFO B). The working range of this compund is 40-100°F [Delta, 1998].

Hexcel Fyfe reports the environmental durability of this composite system based on tests performed on sample panels [Falabella, 1993]. Six different exposure conditions were used, including weatherometer aging, thermal aging at 140° F, ozone exposure at 1 ppm and 100° F, alkaline soil burial at 90-100°, salt-water at room temperature, and fresh water at room temperature. All tests were run for 1000 hours, and panels were flipped when necessary to ensure a uniform exposure. Panel weight was measured before and after each test, and any changes in general appearance were noted. The chemical resistance of fibers is measured as a percent weight loss. The lower this value, the more resistant a given fiber is to corrosive attack. The results of this durability study will be an indicator of the system's ability to protect reinforced concrete structures against corrosion.

The tests show no adverse effects on strength due to thermal aging or weatherometer exposure cycles. Weight measurements show small changes after exposure, with the values ranging from –0.13% to +0.74% after the ozone and alkaline soil tests, respectively. Panel weight changes after the salt and fresh water exposure are summarized in table 6.1. The positive weight change, although small, indicates moisture absorption by the composite system. This can be detrimental to reinforced concrete structures that rely on FRP wraps to prevent the ingress of water.

Table 6.1 Panel Weight Changes [Falabella, 1993]

Exposure Condition	**Weight Change**
Salt Water	+0.23%
Fresh Water	+0.21%

6.1.2 Wrapping Procedure

a) Preparation

To ensure adequate adhesion and a secure encapsulation of the concrete, all specimens were prepared according to Delta’s specifications. Surfaces were clean and free of all rough edges that could cut the fibers or create voids underneath the wrap. This was done by grinding the surface of the concrete. The corners of the beams were rounded to a ¾-in. radius by the same method. The specimens were dry, with no free moisture at the time of application.

Columns were placed standing on a plastic sheet to be wrapped in this position. The rectangular specimens were placed vertically on timber supports, with the extruding reinforcement towards the floor. This stabilized the beams while allowing for proper encapsulation of the ends.

A saturation table was constructed with elevated sides to prevent resin from spilling over. The table was covered with a protective plastic sheet.

All the necessary equipment (mixing buckets, paint rollers, paint trays, squeegees knives, scissors, a mechanical mixer, protective clothing) was gathered prior to the scheduled wrapping date.

b) Application

Fabric dimensions were measured and cut to allow for three continuous layers and an additional 6-inch lap length around each specimen, and fabric squares were cut for the beam ends. The fabric roll was progressively unraveled on a plastic sheet, and cut with scissors to the correct dimensions (Figure 6.1). The individual sheets were then placed on the saturating table.

The epoxy matrix components were mixed according to the design ratio. The exact amount for each element was measured in separate buckets. TYFO B was then poured into TYFO A and both ingredients were mixed with a shear mechanical mixer for 4 minutes. The epoxy was then distributed among a few paint trays, and applied onto the fabric with paint rollers (Figure 6.2). When applying the resin onto the fabric, it is important to fully saturate the fibers, which should become translucent. White spots indicate dry areas. While the fabric was being saturated, a film of epoxy was rolled onto the clean concrete surface of the specimen to be wrapped. The final composite system is designed to contain 0.8 lbs of resin per pound of fiber [Guggenheim, 1998].

Once the fabric was fully saturated, it was manually applied on the concrete specimens. A minimum of two people was necessary to wrap each specimen. The composite must be applied in such a way as to produce a uniform, constant tensile force distributed across the surface. This was easier to achieve for the cylinders because of their geometry. Air bubbles were pushed out manually from under the wrap before beginning a new layer, and continuously for two hours after completing each wrap. For the rectangular specimens, the beam ends were wrapped first with three square pieces of fabric, and then the sides were done with a continuous sheet (Figures 6.3 and 6.4).

c) Post-Wrap Treatment

Following the wrap application, and once the composite had achieved a tacky surface, each specimen was thoroughly inspected. Entrapped air was rolled out whenever possible. Voids and bubbles in the wrap were marked on the composite. These irregularities can be identified acoustically by tapping the composite surface and waiting for hollow sounds. The defects were repaired by injecting a thick epoxy mix into the wrap (Figure 6.5). A hole was drilled on each side of the air pocket, and a syringe injected the resin. Generally, the columns needed fewer injections than the beams. Delta recommends applying thickened resin onto the concrete surface to fill all holes before applying the wrap, or on overhead surfaces for better adhesion.

To control the resin flow into the air pockets, Cab-O-Sil TS 720 was added to the epoxy mix. This thixotropic additive is a thickener-filler manufactured by Cabot Corporation and commonly used in Delta applications. Thixotropic materials greatly reduce the corrosion resistance to some chemicals [Dow, 1996]. Their use is not recommended for corrosion protection liners. For structural applications, Cab-O-Sil should also be used with caution to maximize the strength of the composite.

To prevent loose fabric from absorbing moisture, all edges of the FRP wrap were ground off. The thickened resin was applied on all seams and edges to completely seal off these areas (Figure 6.6).

Within 72 hours of the wrap application, but not before the surface had achieved a tacky feel, each composite was painted with two coats of white Hi Bild Aliphatic Polyurethane from Sherwin Williams (Figure 6.7).

All leftover materials and equipment were properly disposed of and cleaned after their use.

6.2 Generic System

6.2.1 Materials Selection

The generic wrap will evaluate two thermosetting resins: epoxy and vinyl ester, to determine their effectiveness as corrosion protection for concrete structures and compare with the effectiveness of Fyfe's proprietary system. The resin for the generic wrap was selected as a likely candidate for infrastructural applications due to its 1) desirable mechanical properties, 2) low cost, and 3) ready availability from large commercial manufacturers who supply resins for similar infrastructural applications. The unidirectional, woven E-glass fabric reinforcement for the generic wrap was selected to be 1) hoop-wound, due to ease of application by hand lay-up, 2) high areal weight, which minimizes lay-up time, and 3) composed of E-glass, which is readily available at low cost with reasonable mechanical properties; these characteristics are typical of fabrics used for commercial wrap applications [Joyce et. al, 1999] . The fabric used for both epoxy and vinyl ester systems is the same. The generic system was selected by personnel at the IMPACT Laboratory of the Texas Materials Institute [Joyce et. al, 1998]. Appendix C contains material properties and specifications for all materials sued in the Generic wrap. Table 6.3 lists typical room-temperature properties of both epoxy and vinyl ester resins.

a) Epoxy Resin [Shell, 1995]

The Shell Chemical Company supplied all materials for the epoxy resin and provided recommendations regarding resin and curing agent selection. The epoxy resin system is formed of EPON™ Resin 862 and a curing agent. Two different curing agents were used, depending on the concrete surface condition prior to wrapping: EPI-CURE™ 3090 for wet specimens, EPI-CURE™ 3234 for dry ones.

EPON™ Resin 862 was selected among Shell's family of Liquid EPON resins because of its good chemical resistance, and demonstrated performance in marine structures. This product has been frequently used in engineering studies and was recommended by Dr. Karbhari at the University of California in San Diego. It is a liquid epoxy resin often used for chemical resistant linings, FRP pipes, tanks, and grouts. Its low viscosity facilitates handling in cold weather environments.

EPI-CURE™ 3090 is an aliphatic amidoamine adduct curing agent. It has moderate viscosity and must be combined in a 1-to-1 ratio by weight with the resin. It provides good adhesion to wet surfaces, including underwater applications onto concrete [Shell, 1998].

EPI-CURE™ 3234 is a polyamine curing agent. Its viscosity is higher than that of product 3090. This curing agent was used on all specimens to be encapsulated with dry surfaces. Table 6.2 lists the principal properties of both curing agent types [Shell, 1998].

Table 6.2 Curing Agents for Epoxy Resins [Joyce et. al, 1998]

	Aliphatic Amine EPI-CURE™ 3234	**Amidoamine EPI-CURE™ 3090**
Advantages	- Room temperature cure - Low viscosity - Low formulation cost	- Reduced volatility - Convenient mix ratios - Good toughness
Limitations	- Strong skin irritant - High vapor pressure	- Poor elevated temperature performance
Applications	- Adhesives - Grout Castings - Electrical encapsulations	- Construction adhesives - Concrete bonding - Trowelling compounds

b) Vinyl Ester Resin

The Dow Chemical Company supplied the vinyl ester resin. This company was selected because it is the manufacturer of the most widely used vinyl ester resins. DERAKANE™ resins are commonly used with catalysts, promoters, accelerators, and retarders. These components optimize mixing and curing processes. Dow does not produce the activators, but offers instead a list of manufacturers whose products are compatible with DERAKANE™, and a detailed guide to the vinyl ester fabrication process. Dow also provides recommendations of the mixing ratios for all these components.

Their DERAKANE™ 411-C50 resin product was used because of its enhanced corrosion resistance to chemical attack from both acids and alkalies, at room and elevated temperatures. It is also the cheapest resin within the DERAKENE™ family. This resin can be exposed to salt brine at a maximum temperature of 210° F and is often used in chemical processing industry applications. It has a much lower viscosity than the epoxy resin from Shell.

A catalyst (also called initiator) is added to the resin to initiate the chemical reaction that causes the resin to cure. In this case, methyl ethyl ketone peroxide (MEKP) from the Norac Company was chosen because of its consistent and reliable results, low toxicity, and moderate cost. High-energy molecules (free radicals) released by MEKP decomposition are necessary to start the curing process. This catalyst is sold as a 9% active oxygen solution of MEKP and a plasticizer. It provides approximately 25 minutes of gel time at 77°F. Care must be exercised when handling MEKP to prevent contamination with water that would impair the curing process. This catalyst requires using a cobalt naphthenate promoter (CoNap) to speed up and enhance the cure by causing the MEKP to decompose [Dow, 1996; Elf-Atochem, 1996].

CoNap is the most effective promoter with MEKP. It is a dark, purple liquid sold as a solution of 6% active cobalt in a solvent. A very small amount of CoNap is necessary to decompose a large amount of MEKP. These two components should never be mixed together directly, as a violent reaction will occur. Instead, the promoter must be thoroughly mixed into the resin before adding the catalyst [Dow, 1996].

An inhibitor is used to retard the gel time of the resin. At the beginning of the cure reaction, the MEKP free radicals react with the inhibitor instead of the resin which remains liquid for a longer period of time. This delay time is when fabrication should take place, before the resin gels and no longer flows like a liquid. When all the inhibitor is used up, the catalyst reacts exothermically with the resin, quickly increasing its viscosity. The inhibitor 2,4-Pentanedione (2,4-P) was selected for the generic wrap. It can be incorporated into the system of MEKP and CoNap at levels of 0.05 to 0.30% by weight. This will retard gelling of the resin without damaging the properties of the final product [Dow, 1996].

Following Delta's example, Cab-O-Sil was used as a thickener for post repair treatment for epoxy and vinyl ester wraps.

Table 6.3 Room-temperature properties of liquid resins [Joyce et.al, 1998]

	EPOXY Epon Resin 862	**EPOXY Epon Resin 862**	**VINYL ESTER Derakene 411-C-50**
Mix Ratio Parts			
Resin/curing agent	100/100 **Epi-Cure 3090**	100/15.4 **Epi-Cure 3234**	
Resin/catalyst			100/1.25 **MEKP**
Resin/ promoter			100/0.25 **CoNap**
Resin/ inhibitor			100/0.075 **2,4-P**
Viscosity (cps), 77F	4,300 *	775	100
Liquid density (g/cc)	1.23*	1.23	1.025
Tensile strength (psi)	12,000*	12,000	11,500
Tensile Modulus (ksi)	470*	470	490
Elongation (%)	6.6*	6.6	5.5
Flexural strength (psi)	18,540*	18,540	17,000
Compressive Strength (psi)	15,300*	15,300	16,500
Compressive Deformation (%)	8.0*	8.0	7
Heat Distortion Temp. (°F)	107*	107	215

* Value recommended by Shell Chemical company [Shell, 1998]

c) Fabric

The fabric used for the generic wrap was a Knytex Reinforcement Fabric supplied by Owens Corning. The specific product chosen for this study is A260-50, a warp unidirectional woven roving made of long continuous glass fiber strands. A thermoplastic yarn is woven into the weft direction and heat set to prevent the warp fibers from slipping. This fabric style was selected because it is the heaviest material available for customer purchase at Owens Corning. Table 6.4 presents the fabric properties.

Table 6.4 Fabric Properties [Owens Corning Fabrics, 1998]

Fabric style	**Weight, Oz./yds.**	**Roll length, yd**	**Roll Width, in.**	**Roll Wt., lbs.**	**Thickness (Dry), in.**	**Ratio 0-90°**
A260	25.7	85	50	189	0.036	98:2

6.2.2 <u>Wrap Design</u>

Based on Delta's laminate composition, a ratio of 0.8 lbs. of resin per lb. of fiber was used as a basis for the Generic wrap design. This implies a 35% fiber volume fraction and a 65% resin volume fraction. All quantity calculations for the different system components are based on these figures, and on the recommended mix ratios provided by the manufacturers.

The first step in determining the volumetric quantities is to calculate the wrap thickness. For the generic design, two layers of fabric were implemented. The wrap thickness is then calculated as follows [Shell, 1998]:

$$\text{Thickness} = \frac{(\text{Number of layers}) \times (\text{Weight})}{(\text{Fiber Volume}) \times (\text{Fiber Density})}$$

The total volume of the wrap is then calculated by using the following equation:

$$\text{Total Wrap Volume} = (\text{Thickness}) \times (\text{Lateral Surface})$$

Where Lateral Surface values are area calculations and depend on the specimen being wrapped (rectangular, cylindrical at waterline, cylindrical below waterline, cylindrical full).

From the total volume, the individual values for fiber and resin volume can be obtained based on the 35-65% composition.

$$\text{Fiber Volume} = 0.35 \times (\text{Total Wrap Volume})$$

$$\text{Resin Volume} = 0.65 \times (\text{Total Wrap Volume})$$

Knowing the resin volume and density, its weight is given by the following equation:

$$\text{Resin Weight} = (\text{Resin Volume}) \times (\text{Resin Density})$$

The amounts of all other additives are calculated by using their respective mixing ratios by weight with regard to resin quantity.

- For the Epoxy System:

  Weight of EPI-CURE 3090 = 1.0 x (Epoxy Resin Weight)

  Weight of EPI-CURE 3234 = 0.154 x (Epoxy Resin Weight)

- For the Vinyl Ester System:

  Weight of MEKP = 0.0125 x (Vinyl Ester Resin Weight)

  Weight of CoNap = 0.0025 x (Vinyl Ester Resin Weight)

  Weight of 2,4-P = 0.0006 x (Vinyl Ester Resin Weight)

Finally, the additive volumes are given by the following equation:

Additive Volume = (Additive Weight) / (Additive Density)

The exact quantities of resin, curing agent, catalyst, promoter, and inhibitor were determined for each specimen by following the previously outlined sequence of calculations [Joyce et. al, 1999]. The values were then doubled to account for material loss during application.

6.2.3 Application

The application process for the Generic wrap was very similar to that of Delta's. All specimens were clean and free of rough edges prior to the encapsulation. Two separate sheets of fabric had been cut for each specimen. The resin was spread onto the fabric on the saturating table, and the wraps were then applied to the specimens.

The components for the epoxy resin were measured individually and mixed in a container with a mechanical mixer. The first attempt at mixing EPON RESIN 862 with EPI-CURE 3234 resulted in a highly exothermic reaction that caused the paint rollers and mixing containers to melt. Switching to larger mixing containers solved this problem by increasing the heat sink capacity.

After preparing a first batch of epoxy resin and curing agent 3090 for the wet specimens, it was obvious that this curing agent increased the viscosity of the resin to unworkable levels. Spreading the resin with paint rollers could not properly saturate the fabric. Putty knives also proved to be ineffective. Finally it was decided that EPI-CURE 3234 would be used as a curing agent on both wet and dry specimens.

The vinyl ester resin was mixed without difficulty. However, this resin caused the fabric to tear apart when lifted. The wrap had to be applied with care onto the concrete surface. The final result was often a damaged if not destroyed composite. This problem was first attributed to the vinyl ester's low viscosity (100 cps) which would cause it to run off the fabric. Further investigation indicates that the glue in the fabric might have reacted adversely with the resin. The hot-melt adhesive thermoplastic glue apparently dissolved when placed in contact with the vinyl ester.

The post-wrap treatment for the generic system was identical to that of Delta's: identification of voids, injection with Cab-O-Sil thickened resins, seam sealing, and paint application.

6.3 Photographic Essay

All activities shown in this series of photographs apply to both Delta and Generic systems, as the wrapping procedures were the same, regardless of the products.

Figure 6.1 Cutting the fabric

Figure 6.2 Saturating the Fabric with Resin

Figure 6.3 Wrapping A Beam End

Figure 6.4 Wrapping Beams

Figure 6.5 Injecting Voids

Figure 6.6 Sealing Joints of Column Wrap

Figure 6.7 Painting Wrapped Column

6.4 Laboratory Testing

Sample panels were fabricated and tested by personnel at the IMPACT Laboratory of the Texas Materials Institute. The fabrication procedure for a standard 12-in. x 12-in. panel is outlined below, per Delta procedure [Delta, 1998].

- Lay a Mylar polyester release sheet on a clean floor section. This sheet should be wrinkle-free and extend beyond the edges of the panel fabric.
- Spread a resin base onto the release sheet by using a paint roller.
- Apply two layers of fabric with resin in between each sheet and over the last one.
- Leave the panel to cure for at least 48 hours.

Different combinations of fabric and resin were used to determine the properties of several hybrid composite systems in addition to the Delta and Generic wrap designs. Panels were made using TYFO resins with A260 (generic) fabric, TYFO resin and TYFO fabric, vinyl ester resin and A260 fabric, epoxy resin and A260 fabric. These sample laminates were subjected to various tests to determine their strength, failure mode, exact composition and void content. Strength results have been normalized with respect to fiber content to allow for comparisons between different panels. Average values are listed in Table 6.5.

For testing purposes, all specimens were ¾-in. wide, and about 0.055 to 0.095-in. thick. The loading tests were performed on an Instron Testing Machine in displacement control at 1 mm/min. Most specimens were strain gauged on front and back sides using CEA-125-UT gauges to monitor longitudinal strains [Joyce et. al, 1999].

Tests were performed on both preconditioned (pc in Table 6.5) and non-preconditioned panels (npc). Preconditioning was done according to Delta specifications, by holding the panels at 140°F for 48 hours [Delta, 1998].

Table 6.5 Average Test Results [Joyce et.al, 1999]

Panel Type		Strength, Ksi		Failure Mode	Composition by Volume	Void Content, %
		pc	npc			
Generic Epoxy	3234	89	91	Lots of longitudinal splitting before failure at fiber matrix interface.	45 % fiber 55 % resin	- 1.47
	3090					
Generic Vinyl Ester		130	98	Lots of longitudinal splitting before failure at fiber matrix interface.	47 % fiber 53 % resin	-1.86
Delta		79	73	Simultaneous failures at two locations of Kevlar transverse reinforcement.	35 % fibers 65 % resin	-0.19
Delta Resin/ Generic Fabric		88	92	Similar to Generic epoxy failure. Progressive longitudinal splitting leads to failure.	38 % fabric 62 % resin	1.44

Several conclusions can be drawn from these experiments.

- The void content is negligible for all systems. This should be an advantage in the corrosion protection capabilities of the wraps. Small negative values for void content are due to experimental errors introduced by background noise during testing. These values should be rounded off to zero.

- Only the Delta system exhibited final proportions as intended in the original design (35% fibers, 65% resin). Deviations from this composition in the generic system can be attributed to limited experience in predicting material losses and true amounts needed for complete saturation.

- Delta panels failed in a brittle fashion, with no warning. The generic panels behaved in a more ductile manner, with considerable longitudinal splitting before failure.

- Preconditioning significantly increased the strength of the vinyl ester panels, other systems remained close to non-preconditioned strength levels.

Chapter Seven

Corrosion Development and Monitoring

The effectiveness of the FRP wraps as corrosion protection devices will be determined by exposing the specimens to saltwater and periodically measuring the corrosion potential on the concrete surface.

7.1 Salt Water Environment

To accurately simulate a corrosive environment, all specimens were placed in a pool where they undergo cyclic wetting and drying by a saltwater solution.

7.1.1 Pool

A retaining pool was built on a 14-in.-thick elevated concrete slab. The walls of the pool were fabricated by anchoring 8-ft. x 4-ft. plywood sheets into the slab. Adjacent walls were connected to one another to ensure stability. All joints were sealed off with silicone.

The pool was lined with plastic sheets and insulation boards to prevent leaks. Insulation boards were placed against the concrete floor to provide a form of cushioning. Two layers of 6-mil thick polyethylene plastic covered the boards. A final layer of 20-mil thick black high-density polyethylene was laid over the thinner sheets. All plastic layers entirely covered the floor and interior walls.

The columns are standing vertically in the pool on small pieces of wood to prevent them from standing in puddles of excess water during the dry cycles. The beams were laid on their side on blocks covered with plastic. The rectangular specimens were placed at an angle to allow the water to flow across the top surface. Laminated identification tags were attached to the exposed steel on all specimens to facilitate data recording and cataloging.

7.1.2 Irrigation System

A drainage hole in the base of the pool allowed for a connection between the pool and a pump. A 10-ft. diameter galvanized steel storage tank was placed next to the pool, and filled with a saline solution.

On the first day of each wet cycle, the pump draws water from the storage tank into the pool, to create a 1-ft. deep water level. The pump then circulates the water within the retaining pool through a system of PVC pipes placed over the beams. Holes were drilled into the pipes for water distribution. The beams are covered with cloth to ensure a wet condition throughout the cycle.

Upon completion of the wet cycle, the pump is disconnected from the PVC irrigation system and begins to draw water out of the pool and back into the storage tank. A filter attached to the drainage hole prevents dirt and other loose particles from entering the pump and damaging it.

7.1.3 Pump Selection

The pump selection was based primarily on capacity and corrosion resistance. The chosen pump is a 1/8-HP naval bronze straight centrifugal pump, purchased from

Grainger. It is especially designed for saltwater circulation and marine settings, and can pump 1140 gallons per hour at 4-ft. of head.

7.1.4 Salt Water Solution

The storage tank was filled with approximately 1000 gallons of tap water. This is the volume necessary to fill the retaining pool to a depth of 1-ft. A 3.5% saline solution was created by mixing 300 lbs. of salt into the water. The solution is stirred before each cycle to achieve a homogeneous mix.

Figure 7.1 Storage Tank Filled with Salt Water

Figure 7.2 Irrigation Pipes Over Beams

Figure 7.3 Row of Columns

7.2 Corrosion Monitoring

7.2.1 Detection Method

The half-cell potential method described in ASTM C 876 will be used throughout the duration of project 1774 to monitor corrosion activity in the specimens. This method provides indications of the probability of corrosion activity at a given location and time.

To provide access to the concrete surface, small openings had to be made in the FRP wraps. A circular saw was used to cut 1.5-in. diameter holes into the composite. For the columns, this was done directly over a longitudinal bar, 16-in. from the bottom of the column to keep the openings from being submerged in the saltwater solution during the wet cycle. On the beams, the circular openings were drilled at the bottom left corner of the ends, directly over the reinforcement as well. To prevent water penetration during exposure, all holes were covered with removable plastic buttons sealed onto the specimens with silicone.

The connection to the steel was made with lead wire attached to ground clamps. The clamps were then attached onto the exposed end of the bar over which the opening was made for each specimen. The exposed ends of the bars had all been previously ground to remove any rust that could interfere with the readings. All exposed steel and metal clamps were covered with grease to prevent corrosion.

A copper-copper sulfate reference electrode and voltmeter are available for project use. An electrical junction device is necessary to provide a liquid bridge between the surface of the concrete and the half-cell. This is accomplished by pre-wetting a sponge with a liquid household detergent solution, and attaching the sponge onto the end of the reference electrode. A lead wire must be coupled to the reference electrode to allow for connections with the voltmeter. The procedure for data collection is outlined below.

- Electrically connect the reinforcing steel to the positive terminal of the voltmeter by inserting the clip at the end of the lead wire hanging from the ground clamp into the voltmeter terminal.

- Insert the lead wire connected to the half-cell into the negative (ground) terminal of the voltmeter.

- Place the reference electrode covered with the wet sponge on the concrete surface and do not move.

- Observe the voltmeter. Record the potential value when it no longer fluctuates with time.

The first set of readings was taken on the unwrapped specimens before beginning exposure. Unwrapped specimens will be monitored after each full cycle (one wet week, two dry weeks) is completed. Contact between the reference electrode and the concrete is made at the same locations as for the wrapped specimens: 16” above waterline and over clamped bar for columns, at bottom left corner of beam-ends. The wrapped specimens will not be monitored with the same frequency because removal of the plastic covers over the concrete can impair the wrap’s effectiveness by exposing the specimens to water and chlorides. For these specimens, data will be recorded at the completion of every four full cycles (once every three-month period).

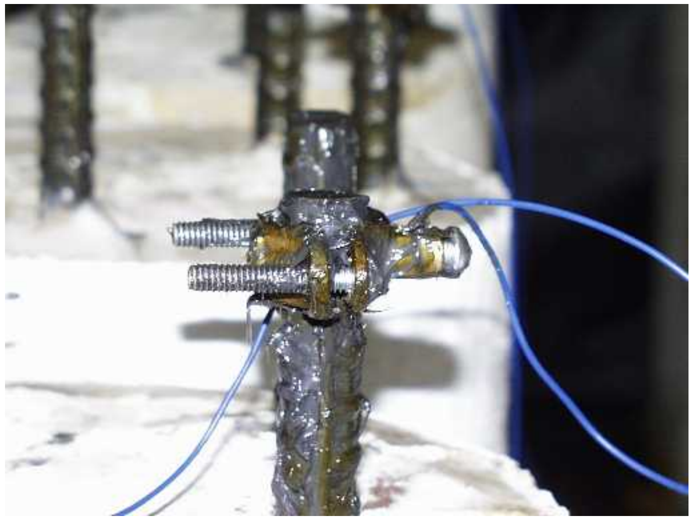

Figure 7.4 Detail of Greased Ground Clamp

Figure 7.5 Access Hole on Wrapped Column

7.2.2 Results-Up-To-Date

The effectiveness of the FRP wraps as corrosion protection strategies can only be properly determined after a long-term exposure to a marine-simulating environment. The results obtained in the first few months of exposure cannot be conclusive. Based on the first set of readings, it seems that little corrosion activity is taking place, if any at all. All values are more positive than –200 mV, which is interpreted as a 90 % probability of no corrosion activity. Half-cell potential readings taken prior to initiating exposure are presented in Appendix D.

Chapter Eight

Summary and Conclusions

Corrosion of steel bars in concrete is a problem of great concern throughout the world. Gradual deterioration of embedded reinforcement may reduce the load capacity of a structure and adversely affect its service life and durability. Numerous corrosion protection technologies exist, but none of them have proven to be sufficiently reliable or completely successful in solving the corrosion problem.

8.1 Summary

The use of fiber-reinforced plastics in civil engineering applications has increased in the past years. The properties of these materials make them ideal candidates for use in certain aggressive environments. Composites have been incorporated in construction because of their low weight, high strength, and corrosion resistance. FRP laminates wrapped around columns in seismic zones increase ductility and prevent collapse by providing confinement to the structural element. Several composite manufacturers have also sold their products as corrosion protection methods, based on the idea that they act as a barrier against chlorides, water, and oxygen. While a few such applications have been successful, certain experiments demonstrated the deleterious effects of FRP wraps that lock moisture and salts into the structure and prevent observation of corrosion activity. Similar problems must be avoided in strengthening applications, where the wrap might be impairing the structure's durability without showing any signs of internal corrosion.

This project will evaluate the following variables related to corrosion protection.

- Performance of a commercially available FRP wrap system, manufactured by Hexcel Fyfe and applied by Delta Corporation.
- Performance of a laboratory generic system.
- Influence of wrap length: full, at waterline, and below waterline encapsulation.
- Adhesion of the FRP wraps on wet concrete surfaces.
- Performance of a liquid corrosion inhibitor: Sika Ferrogard.
- Effect of localized concrete surface repairs using two different materials: latex-modified concrete and epoxy grout.
- Effect of numerous flexural cracks on the concrete surface.
- Effect of cast-in chlorides.

Corrosion in reinforcing steel is a slow and gradual process. To accelerate the laboratory testing, aggressive wetting cycles have been established in addition to measures taken during construction that will facilitate oxidation (highly permeable concrete, cast-in chlorides, and low cover). For meaningful results, a minimum monitoring duration of three or more years may be needed. Half-cell potential readings will be taken during the exposure period. Photographs of activities during construction, repair, wrapping, and monitoring stages were taken for reference purposes. Individual photographs of cracked and repaired specimens will be particularly useful in determining possible causes of elevated corrosion potential.

Keeping up with composite industry progress will also be helpful during this time to establish the performance of wraps in the field. Further studies involving polyurethane wraps might be of interest because of this material's "breathing" capabilities.

Encapsulated bridges in Lubbock, Texas will be continuously monitored with permanent embedded electrodes. Guidelines concerning this activity can be obtained from a companion report [Verhulst, 1999].

8.2 Conclusions

Definitive conclusions cannot be made yet concerning the performance of the composite protective laminates due to their limited exposure to the laboratory wetting cycle. Important findings related to construction, wrap application, and corrosion detection are summarized below.

8.2.1 Repair Materials and Methods

Repairs performed on selected specimens using epoxy grout and latex modified concrete are aesthetically pleasing and appear to be structurally sound. These two repair materials were easy to work with and place. The metal flashing used as formwork around the cylinders proved to be a good method of material confinement during application and wet-mat curing.

8.2.2 Composite Wraps

The Delta FRP system was applied without difficulty thanks to the expertise and guidance of company personnel. The Delta system shows no visible defects or flaws, and presented no problems during fabric saturation and specimen wrapping.

The generic system was still in its early development and experimental stage at the time of its application. Much was learned during specimen encapsulation concerning material behavior, and both the system design and implementation technique were greatly improved over the length of this project. Overall, the epoxy system behaved well after correcting minor obstacles. The curing agent chosen for wet surfaces proved to be too viscous and, therefore, inadequate for this type of application, and was replaced with a curing agent appropriate for both dry and wet surfaces. The vinyl ester system resulted in a mostly disintegrated wrap and heavily damaged fabric. This is probably due to a destructive chemical reaction between the wrap and the resin.

The Cab-O-Sil used as a resin thickener for sealing wrap joints might prove to be a weak spot in the corrosion protection of both systems [Joyce et. al, 1999].

8.2.3 Test Method Results

The half-cell potential method of corrosion detection seems to be the most appropriate in this study because of its ease of measurement and recorded consistency in similar projects. The wires permanently attached to specimen reinforcement allow for quick access to both columns and beams.

The results obtained so far indicate a 90% probability of no corrosion activity in all specimens. These values are expected to change significantly as the exposure time increases. A highly permeable concrete mix, numerous flexural cracks, low cover, and cast-in chlorides should increase the rate of oxidation.

Appendix A

This appendix contains specifications from Sika Corporation on the materials used for repair: epoxy grout (Sikadur 42 Grout-Pak) and latex-modified-concrete (SikaTop 122 Plus).

Appendix B

This appendix contains Delta specifications on wrap application and material properties.

Appendix C

This appendix contains material specifications for all components of the Generic wrap systems: epoxy resin (EPON 862), curing agent for dry surfaces (EPI-CURE 3234), curing agent for wet surfaces (EPI-CURE 3090), and vinyl ester resin (DERAKENE 411).

Appendix D

Table D.1 Rectangular Specimens

Specimen	Potential, mV
Date	2 / 25 / 99
RC 1	
RC 2	
RC 3	
RC 4	+ 24
RC 5	
RC 6	
RC 7	
RC 8	- 30
RC 9	
RNC 1	
RNC 2	+167
RNC 3	
RNC 4	
RNC 5	
RNC 6	
RNC 7	+ 32
RNC 8	

Table D.2 Cylindrical Specimens

Specimen	Potential, mV
Date	2 / 25 / 99
CC 1	
CC 2	
CC 3	
CC 4	
CC 5	
CC 6	
CC 7	
CC 8	
CC 9	
CC 10	+270
CC 11	+ 40
CC 12	
CC 13	
CC 14	
CC 15	
CC 16	- 30
CC 17	- 70
CC 18	+ 18
CC 19	
CC 20	
CC 21	- 111
CNC 1	
CNC 2	
CNC 3	
CNC 4	
CNC 5	
CNC 6	
CNC 7	+ 270
CNC 8	+ 66
CNC 9	
CNC 10	
CNC 11	+ 150
CNC 12	+ 40
CNC 13	
CNC 14	
CNC 15	+ 180
CNC 16	
CNC 17	
CNC 18	
CNC 19	
CNC 20	+ 64
CNC 21	+ 255

WORKS CITED

1. Bassett, Susan. *Composites for Infrastructure, A Guide for Civil engineers.* Ray publishing, Wheat Ridge, Colorado, 1998.

2. Concorr Inc., *Assessment of Physical Condition of Concrete Bridge Components*. FHWA-SHRP Showcase, Participants Workbook, July 1996.

3. Delta Structural Technology. Composite Information. Amarillo, Texas.

4. Dow Plastics. *Fabricating Tips – DERAKENE Epoxy Vinyl Ester Resins.* Bulletin Number 125–00082-196. January 1996.

5. Emmons, Peter H., *Concrete Repair and Maintenance Illustrated,* R.S. Means Company, Inc, 1994.

6. Falabella, R., Neuner, J., Isley, F.P. *Environmental Durability and resin Stoichiometry Studies of TYFO S High Strength Column Wrapping System.* Hexcel Corporation, Pleasanton, California. September 1993.

7. Fowler, D.W., *Repair and Rehabilitation of Damaged Reinforced Concrete Structures.* Class Notes. University of Texas at Austin. Spring 1998.

8. Fowler, T., *Nondestructive Testing Methods with an Emphasis on Acoustic Emission.* Class Notes. University of Texas at Austin. Fall 1998.

9. Gallagher, R.B., Robinson, C.H. *Understanding Methyl Ethyl Ketone Peroxides.* Official Publication of the Composites Fabricators Association. April 1995.

10. Halmshaw, R. *Non-Destructive Testing.* Edward Arnold, London, U.K., 1987.

11. Hardcore DuPont Composites, *Column and Pier Cap Retrofit*, Process Description and Individual Component Specification, April 2, 1996.

12. Hartman, D.R., Greenwood, M.E., Miller, D.M. *High Strength Glass Fibers.* Owens Corning Technical Paper.

13. Integrated Mechanics of Processing And Composite Manufacturing Technologies (IMPACT) Laboratory, Department of Mechanical Engineering and the Texas Materials Institute, The University of Texas at Austin; Dr. Tess J. Moon, Director.

14. James Instruments Inc., www.ndtjames.com, 1998.

15. Jones, Denny A., *Principles and Prevention of Corrosion*. Prentice Hall, Upper Saddle River, NJ. 1996.

16. Joyce, P., Miret, D., Moon, T.J., *Assessment of Candidate Material Systems for Infrastructure Applications: Fabrication and Testing,* Journal of Materials in Civil Engineering, in preparation for publication in 2000.

17. Moran/Labine, editors, *Corrosion Monitoring in Industrial Plants using Nondestructive Testing and Electrochemical Methods,* ASTM STP 908, 1986.

18. Nawy, Edward G. *Concrete Construction Engineering Handbook.* CRC Press, Boca Raton, New York, 1997.

19. Page , C.L., Bamforth, P.B., Figg, J.W. *Corrosion of Reinforcemnt in Concrete Construction.* Proceedings from the Fourth International Symposium on Corrosion of Reinforcement in Concrete Construction. Cambridge, U.K., 1996.

20. Project Agreement between the Texas Department of Transportation and the Center for Transportation Research at the University of Texas at Austin, Project 1774, September 1997.

21. SDS Compannny, *CANIN Corrosion Analyzing Instrument*, www3.tcsn.net/sdsco/011.htm, 1998.

22. Shaw, M. *Migrating Corrosion Inhibitors for Reinforced Concrete Protection.* Proceedings from the 7th International Conference and Exhibition on Structural Faults and Repair, U.K., 1997.

23. Shell Chemical Company. Product Information Guide. 1998.

24. Sheikh, S., Pantazopoulou, S., Bonacci, J., Thomas, M., Hearn, N. *Repair of Delaminated Circular Pier Columns by ACM.* Final report. Ontario Joint Transportation Research Report. MTO Reference Number 31902.

25. Sherman, Mathew Robert, "*Field Evaluation of Bridge Corrosion Protection Measures*", Master's Thesis, University of Texas at Austin, 1993.

26. Sika Corporation. Construction Products Catalog. 1996

27. Sohanghpurwala, A.A., Scanell, W.T. *Repair and protection of Concrete Exposed to Seawater*.

28. Taheri, A., Van Bruegel, K. *Chloride Penetration into Concrete Structures in Aggressive Marine Environment, Experimental Simulation.* Proceedings from the 7th International Conference and Exhibition on Structural Faults and Repair, U.K., 1997.

29. Texas Department of Transportation. *Standard Specifications for Construction of Highways, Streets, and Bridges.* 1993.

30. Unal, Muhammed Alp, *Evaluation of a Procedure for Encapsulation and Epoxy Injection of Corroding Reinforced Concrete Structures*, Master's Thesis, University of Texas at Austin, 1998.

31. Vaca, R., *Electrochemical Procedures to Rehabilitate Corroded Concrete Structures,* Master's Thesis, University of Texas at Austin, 1993.

32. Verhulst, Stewart, *Evaluation and Performance Monitoring of Corrosion Protection Provided by Fiber-Reinforced Composite Wrapping,* Master's Thesis, University of Texas at Austin, 1999.

33. Yuyama, Okamoto, Ohtsu, and Kishi, *Evaluation Criteria for Acoustic Emission Examination of Reinforced Concrete Structures*.

34. Zongjin et all., *Application of Acoustic Emission Technique to Detection of Reinforcing Steel Corrosion in Concrete,* ACI Materials Journal, January-February 1998, pp 68 – 76.