IMPROVING STANDARD BRIDGES THROUGH AESTHETIC GUIDELINES AND ATTRACTIVE, EFFICIENT, CONCRETE SUBSTRUCTURES

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to my parents

ACKNOWLEDGMENTS

This project was conducted at the Phil M. Ferguson Structural Engineering Laboratory with much of the background information gathered by the author from travel throughout Texas. The funding of this project was provided by the Texas Department of Transportation. The author was also supported through a National Science Foundation Fellowship and the Margaret N. Maxey Endowed Graduate Fellowship at The University of Texas at Austin.

The project was supervised by Dr. John E. Breen. His guidance, advice and thoughtfulness were invaluable to me throughout my graduate studies in Austin. His interest and dedication to both his students and his profession has been a source of inspiration. Prof. D. Andrew Vernooy, from the School of Architecture, was a co-supervisor for the project. Prof. Vernooy added considerably to the success of the project while continually challenging the research team to consider new ideas and ask new questions.

I am grateful to the other members of the research team for their excellent work towards the completion of this project. Scot Listavich and Steve Ratchye, both having combined architectural and engineering talents, provided valuable contributions to the Guidelines. None of us knew how big the Guidelines project would become but working with them made the task enjoyable. I would also like to extend my thanks to Carl Holliday and Marina Martinez for their contributions to the project. Robbie Barnes researched and developed an initial precast substructure system for the project. His input, suggestions and patience with incessant questions is much appreciated. It has been a pleasure to work with such an intelligent and kind person.

I would like to acknowledge the “tag team” project coordinators, Norman Friedman and Dean VanLanduyt of the TxDOT Design Division. Norman’s input and enthusiasm for our work contributed greatly to its success. Dean’s review of the preliminary work and his expertise has been very helpful.

The advice and expertise of many other practitioners has contributed significantly to the success of this project. I would like to thank Tom D’Arcy and Cliff Freyermuth for their recommendations and for invitations to present my work at meetings of the Precast Concrete Manufacturer’s Association of Texas and the American Segmental Bridge Institute, respectively. Comments and suggestions gathered at such meetings have helped shape this project. I would also like to thank Bill Dailey, John Dobbs, Skip Plotnicki, Gregor Wollmann, and David Hartman for their expertise and recommendations.

My travels throughout Texas involved meeting with numerous engineers across the State. In particular I would like to thank the engineers with whom I met in the Austin, Corpus Christi, Dallas, El Paso, Houston, Pharr, San Angelo and Wichita Falls districts.

I would like to extend my thanks to Theresa Augsburger of University Publications who designed and typeset the layout for the Guidelines. She did a superb job under many time constraints and it was a pleasure to work with her. Stewart Watson provided a number of photographs for the completion of the Guidelines. I have enjoyed his enthusiasm and lively discussions concerning bridge aesthetics.

Much of the experience of working at Ferguson Lab is getting to know the other students. I am thankful for having the opportunity to work around so many bright, fun and genuine people. I would like to thank Valerie Andres and Jeff Schmitz for their encouragement early on in the project. I am also grateful for the help of Jeff West and Keith Thompson as I was finishing. I will miss the distraction of laughter and discussions with Reagan Herman and Andrea Schokker.

I would also like to acknowledge and thank the staff at Ferguson Lab for all of their help. Sharon Cunningham, Laurie Golding, Kelly James, April Jenkins and Cindy McCright have been very supportive. I appreciate all of their effort and kindness. I would also like to thank the technicians and in particular, Wayne Fontenot for his interest in the project and his photo contributions.

Outside of the lab, I am indebted to Shannon Beeley for her invaluable friendship. Her gracious love and support have meant more to me than I could possibly say. I could have dedicated this work to her but I'm afraid bridges probably bore her.

I would also like to express a special thank you to Paul MacKinnon, my favorite conflict manager and friend. He has deftly handled any conflict instigating tendencies I've had and his love, support and kindness have helped sustain me in the final year of this project.

I am grateful to be blessed with such a wonderful, supportive and entertaining family. Phone calls, e-mail and vacations spent with any or many of my brothers and sisters, "outlaws," and nephew and nieces were always something to look forward to when I felt I was spinning my wheels. Finally, I would like to express my deepest thanks to my parents. Their love, support and encouragement is unending. They are wonderful parents, a pair of shining stars.

Sarah Billington
August 1997

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Publication No._________

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The University of Texas at Austin, 1997

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Designed for economy and function alone, standard highway bridges of short and moderate spans often detract from rather than enhance the environment in which they are built. Such an unimaginative display of structural engineering does little to express the rapid growth and exciting advancement of this profession.

Aesthetics & Efficiency Guidelines have been developed that are primarily intended for use by bridge and highway engineers designing standard short and moderate span bridges with an emphasis on bridges using precast concrete superstructures. Four example applications of the Guidelines to standard bridge projects in Texas show general approaches and varied economic benefits and/or costs.

Recognizing that the appearance and efficiency of standard short and moderate span bridges can be greatly improved with more thoughtful substructure design, an attractive and efficient substructure system has been developed for use with standard superstructure systems in Texas. The proposed system of match cast precast segmental elements post-tensioned together on site combines high strength prestressing steel with high performance concrete for improved durability and structural efficiency. Attractive cast-in-place substructures as an alternate to the current common Texas substructure practice utilizing circular columns and rectangular bent caps are also presented.

Applications of this research to two existing projects in Texas are summarized and the resulting impact reviewed. Implementation strategies for further application of the research are given.

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CHAPTER 1
INTRODUCTION

1.1 Background

Bridges are an essential part of any infrastructure. They span countless obstacles to connect the roads of our highway systems. Bridges can be found in a variety of settings from congested urban areas to under-populated rural locations to beloved park environments. Many bridges are in highly visible and dramatic settings. As a result, these structures have caught the imagination of the public, in particular of many writers and artists, in the past (Figures 1.1-1.2).

The vast majority of the world's bridges are of short and moderate spans. Yet it is not these most common bridges but rather the monumental long-span bridges that are the most noticeable and striking due to their size and often scenic settings. Many long-span monumental bridges are considered works of structural art[1]. The much more prevalent short and moderate span bridges simply remain functional and non-descript (Figure 1.3). It is these more moderate-sized bridges which dominate our highway landscape yet typically fail to catch even the imagination of the engineers who design them.

Designed for economy and function alone, standard highway bridges of short and moderate spans often detract from rather than enhance the environment in which they are built. Such an unimaginative display of structural engineering does little to express the rapid growth and exciting developments in this profession. Rapid advances in the state-of-the-art of engineering design, materials and construction provide engineers with countless new options for short and moderate span bridge design. High performance materials, advanced methods of fabrication and innovative construction techniques may now be combined in new ways to result in different forms and original solutions for bridge design. Engineers must now take on the challenge to design bridges that are not only functional and economical, but attractive additions to their landscape.

The call for more attractive bridges has been made throughout the world. Top structural engineers from many countries are eager to share their design ideas and their collective belief that it is the duty of all structural engineers to design efficient *and* attractive structures[2,3]. Much of the attention on bridge aesthetics has been paid to long-span bridges, while short and moderate span bridges have largely been overlooked. Designers are just beginning to address the appearance of shorter span bridges. While there is certainly a large amount of literature calling for

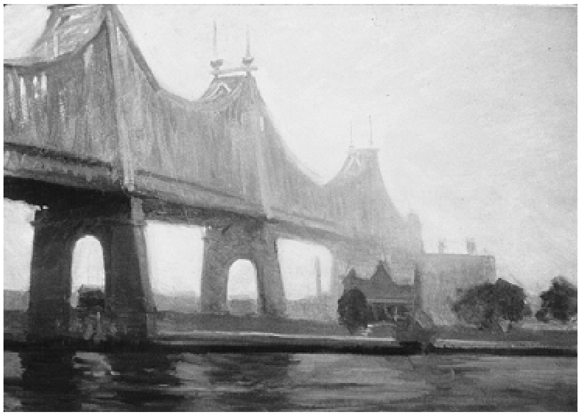


Figure 1.1 "Queensborough Bridge," Edward Hopper, 1913

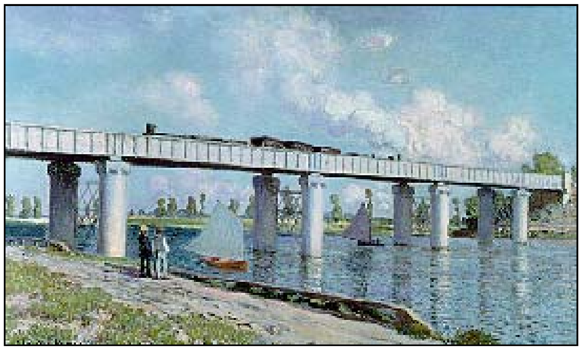


Figure 1.2 "The Railroad Bridge at Argenteuil," Claude Monet, 1873

better bridge aesthetics (Appendix A), it is now timely that more attractive bridges *be built*, not just "called for."

Figure 1.3 A typical standard overpass in Texas

Many State DOT's have made important steps resulting in the construction of more attractive bridges. State DOT's in particular are now more concerned with maintaining a positive image with the tax-paying public and are therefore taking steps toward the development of a more attractive infrastructure. Many States have developed Aesthetics Guidelines for the design of more attractive bridges.[4,5] The Texas DOT (TxDOT) has made great strides towards improving the appearance of their bridges through the development of U-beams and trapezoidal box beams particularly for urban areas (Figure 1.4). An increased use of attractive retaining wall patterns (Figure 1.5) and new railing types (Figure 1.6) has also added to the recent improvement of highway bridge aesthetics. TxDOT is now expanding the State's Roadway Beautification program to include the bridges of their highway system (Figure 1.7).

Many more significant improvements can be made to the standard bridges of Texas. An increased awareness by highway planners and bridge designers of the visual effect of their engineering decisions is necessary for the design and construction of more attractive structures. As every element of a bridge will affect its appearance, it is time for engineers to look at the appearance of every element. In particular, attractive substructure designs that provide an alternate to the current common practice of cast-in-place circular columns with prismatic bent caps and more attention given to the planning and layout stage of design will greatly improve the aesthetics of standard highway bridges. Attention to non-structural details such as drainage, joint types and materials, color and texture of concrete, and how these details may enhance or detract from a well thought-out project will also make considerable improvements to the appearance of these bridges (Figures 1.8-1.9).

More attention must be given to the environment in which a new bridge will be built. It is wrong to assume that the same standard bridge will be appropriate to cross I-10 through Houston, a stream in the Hill Country, the Rio Grande in El Paso and a highway overpass in East Texas. Economics currently dictate a few standard bridge types for such a variety of settings. As a result, designers are remaining "prisoners of the familiar," designing the same bridge for sites with a variety of constraints and characters. In particular, substructures are a major visual disturbance for these standard bridges. Additionally, current cast-in-place substructure construction leads to extensive traffic delays and rerouting headaches. Little effort has been made to investigate new substructure shapes, designs and construction methods.

Figure 1.4 The Texas U-beams were developed with aesthetics in mind.

Figure 1.5 A variety of attractive retaining wall patterns are available today.

Figure 1.6 The recently developed C411 rail series used in Texas.

Figure 1.7 Wildflowers bloom along many Texas highways each Spring.

Figure 1.8 Lack of attention to concrete finish results in an unattractive pier.

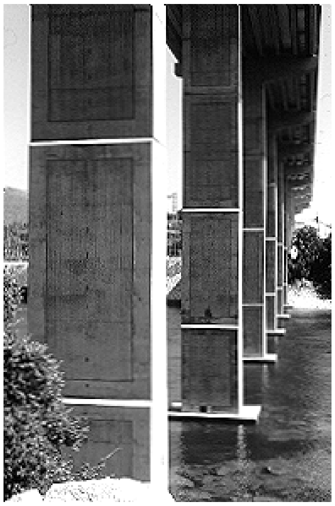


Figure 1.9 Simple use of formliners provide an attractive finish.

Short and moderate span bridge design in Texas has been dominated in the past 20 years by precast pretensioned concrete superstructure bridges (Figure 1.10). This began in the 1950's when precast prestressed concrete was first introduced in the United States. Soon after, with the introduction of high strength steel for prestressing, prestressed concrete became a very economical and durable alternative for bridge construction. The development of highly efficient plant production methods for precasting has kept this form of construction economical. State-owned bridges in particular (Figure 1.10b) are predominantly prestressed concrete because they are durable and economically most competitive. In 1996, these bridges typically cost \$310 per square meter (\$29 per square foot). Precast concrete superstructure systems were used for 75-80% of new highway construction let in Texas between September 1994 and August 1995. (During this time, all new construction in Texas averaged \$345/m^2 (\$32/ft^2). In 1994, only 5 other States had averages below \$430/m^2 (\$40/ft^2) while the national average was \$710/m^2 (\$66/ft^2).)

The high repetition of precast superstructure elements, low cost of labor and availability of concrete all contribute to this very economical bridge type. The superstructure girders are slim, efficient and often attractive. However, many problems have been identified with the substructures of these bridges. The predominantly cast-in-place substructures are typically the least durable element of these bridges, particularly in aggressive environments.[6] On-site labor and construction of the substructure often leads to excessive and undesirable traffic delays (Figure 1.11). The unattractive forest of columns created by the multi-column bent substructures is an unfortunate addition to any environment. For these many reasons, alternative substructure designs and construction methods are being investigated.

Precasting offers an alternative for substructure design that can move much of substructure fabrication off-site and into the precasting plant. The efficiency of mass production and the high quality control of fabrication in a precasting plant has made precast superstructure elements an extremely economical form of construction. These same techniques may certainly be applied to substructure elements. On-site labor and construction time will be shortened thus substantially reducing traffic delays and rerouting during construction. High performance concrete may be used more consistently with higher quality control in a precast plant. This should result in more durable substructures with a higher quality and more attractive finish. The higher strength of high performance concrete allows for hollow sections. Hollow sections result in material savings, keep hauling and erection weights low and decrease foundation costs. The use of post-tensioning with

precast substructures can further improve durability by eliminating cracking under service loads and providing stiffer vertical elements to keep lateral deflections low.

The repetitive use of cast-in-place formwork for a few standard column shapes has proven economical in the past. New problems now call for new solutions using state-of-the-art technology. In particular, problems such as durability, quality control, construction time, the impact construction has on the environment, and bridge aesthetics must be addressed. Precasting is one option for improved substructure design. Repetition of forms is essential to keep the bridges economical. Any proposed precast systems for standardization must be applicable to a wide range of problems. As precasting will not be advantageous for every bridge site, new cast-in-place shapes should be investigated - ones that use a higher quality of concrete, and have careful attention paid to their details to improve durability and prevent unwanted staining (Figure 1.12).

Recognizing that the creative imagination of engineers is often stifled rather than cultivated in many engineering offices and in typical engineering curricula, a research project was proposed to the Texas Department of Transportation (TxDOT) by the University of Texas at Austin Center for Transportation Research (CTR) to address the problem of the efficiency and aesthetics of Texas' short and moderate span bridges and their substructure systems. By addressing efficiency, or the minimization of wasted material and construction time, the function and construction of the bridge is tied more closely to the economy of the bridge. The precast superstructure systems so commonly used throughout Texas have been proven successful through their efficiency, elegance and economy. Through CTR Project 0-1410, attention is now being turned towards improved substructure design, to advance the proud Texas tradition of building functional, economical and attractive bridges for their highway system.

Figure 1.11 Extensive on-site equipment for cast-in-place multi-column bents.

Figure 1.12 An attractive cast-in-place substructure.

1.2 Objectives

1.2.1 Objectives of the Project

The objectives of CTR Project 0-1410 as proposed to TxDOT are[7]:

1. To develop conceptual plans and visual guidelines for improving the aesthetics and efficiency of widely used moderate-span bridge systems;

2. To introduce more attractive structural forms and textures in substructures though increased use of precasting or, where appropriate, in-situ casting utilizing improved form systems similar to those used in precasting;

3. To reduce construction time, cost of traffic delay and rerouting during construction, and field concreting problems by increased precasting of bridge substructures;

4. To develop conceptual plans for several demonstration projects and to refine those plans based on field experience and observations; and

5. To provide useful design guidelines and examples for improving the aesthetics and efficiency of substructures for Standard Bridge Systems.

The objectives of this project have been carried out in detail by four Graduate Research Assistants associated with this project. Preliminary design guidelines were developed by Scot Listavich (M.S.E., 1995) and are presented in his Thesis entitled *The Development of Aesthetic Guidelines for Short and Medium Span Texas Bridge Systems*[8]. The background was largely completed and an initial precast single column substructure system developed for Objectives 2 and 3 by Robert Barnes (M.S.E., 1996). This work is presented in Barnes' Thesis entitled *Development of a High Performance Substructure System for Prestressed Concrete Girder Highway Bridges*[9]. Work towards Objectives 4 and 5 was carried out by Steve Ratchye (M.Arch, M.S.E. 1997). Ratchye's Report[10] includes a series of case studies applying the principles developed in the design guidelines to four existing and varied sites in Texas. Ratchye's research work was further developed by the author and research team for inclusion in the final design guidelines.

Further development and restructuring of the guidelines for Objectives 1 and 5 have been completed by the author resulting in a manual which is Volume II of this dissertation entitled *TxDOT Aesthetics & Efficiency Guidelines*. This work is being used by Ratchye to complete Objective 4. Development of a precast substructure system for Objectives 2 and 3 begun by Barnes has been analyzed and continued by the author with extensive contributions from the research team, designers, precasters, form manufacturers and contractors. The original concept has been substantially modified and expanded to cover a wide range of substructure types generally found in Texas.

1.2.2 Objectives of the Dissertation

There are four major objectives of this dissertation. The first objective is to present the background and development of the final *TxDOT Aesthetics & Efficiency Guidelines* (TxDOT Guidelines). The second is to illustrate their appropriateness and applicability to problems TxDOT faces in standard highway bridge design. The third objective is to present suggested alternative substructure designs for use with standard superstructure systems common in Texas. With more attention paid to substructure design, the appearance and efficiency of standard precast bridges can be greatly improved. In particular, the development of a specific precast substructure system for consideration for standardization is presented. Through careful investigation of available technology for different substructure fabrication and erection techniques, a family of geometries, materials and techniques most appropriate for TxDOT are presented. Many design implications for the newer types of substructure systems are discussed as well. The fourth objective is to document the possible benefits of applying this research to practice. Benefits as well as drawbacks in terms of aesthetic consequences, safety, serviceability and economy considering both initial and life-cycle costs are demonstrated through case studies using the TxDOT Guidelines. Further benefits and possible drawbacks of precast substructure systems are addressed through discussions of past and future applications of such systems to short and moderate span bridge construction.

1.3 Scope

The scope of this dissertation is to document the completion of the objectives described above in Section 1.2.2. The dissertation consists of two volumes. Volume I contains the chapters of the basic background dissertation including five Appendices. Volume II is the sixth appendix presenting the *TxDOT Aesthetics and Efficiency Guidelines* (Guidelines) - one of the major resulting outputs of the project.

In Volume I, Chapter 2 is a literature review of several of the most important documents concerning broad design and construction issues for improved efficiency and aesthetics of short and moderate span bridges. Additional literature reviews pertaining more closely to the development and use of design guidelines and the development and use of precast substructure systems are presented in Chapters 3 and 4 respectively.

Chapter 3 outlines the development and refinement of the TxDOT Guidelines. This work includes a review of existing design guidelines for improving bridge aesthetics, an informal survey of the public's opinion of the bridges of Texas, a photographic survey of the short and moderate-span bridges of Texas and interviews with District and Area Engineers throughout the State. The focus and goals of the TxDOT Guidelines and an outline of that document are presented.

Chapter 4 presents a suggested alternative substructure system for the standard short and moderate span bridges of Texas. The main focus of this chapter is on the development of a precast substructure system for standardization in Texas. This includes a review of past projects, a brief survey of state-of-the-art technology for precasting substructures, a discussion of concerns expressed by designers and construction industry personnel in Texas and a proposal for a new substructure system including design, fabrication, and erection sequences. Additional discussion includes alternative designs for a geometrically similar cast-in-place substructure system and a system of both precast and cast-in-place elements.

Chapter 5 presents numerous options for cast-in-place substructure design for short and moderate span bridges. The goal of this chapter is to show the variety of standard substructure systems available and the ways in which their appearance and efficiency can be enhanced.

Chapter 6 covers applications of the entire research project including possible benefits as well as potential drawbacks to using the TxDOT Guidelines or implementing the alternate substructure systems proposed. Chapter 7 describes areas for further implementation of this research. Chapter 8 provides a summary and conclusions of this work.

There are five appendices in Volume I of this dissertation. Appendix A is a bibliography of numerous articles and books identified by the researchers that pertain to the aesthetics of bridges as well as precast substructure design. Appendix B is a brief summary of the informal survey of the public conducted in Texas and presented in Chapter 3. The weighting of the survey results and limitations of interpreting the results are discussed. Appendices C and D present detailed design calculations and drawings for a precast hammerhead and frame bent respectively, using the precast substructure system presented in Chapter 4. Appendix E presents a discussion of longitudinal braking force requirements in various different bridge design codes and specifications, a topic mentioned briefly in Chapter 4. The sixth appendix (Appendix F) contained in Volume II of this dissertation is the *TxDOT Aesthetics & Efficiency Guidelines*.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

An extensive literature review has been carried out through the course of the research project. Literature was collected on a variety of topics providing background and insight for both the *TxDOT Aesthetics & Efficiency Guidelines* (Guidelines) and the design, fabrication and erection of substructures for short and moderate span (10m-45m, (35'-150')) bridge systems. Literature most pertinent to the development of the Guidelines covered the topics of,

1. *General bridge aesthetics,*
2. *Existing guidelines for aesthetic bridge design,*
3. *Aesthetics for short and moderate-span bridges,*
4. *Aesthetic evaluation of bridges.*

Background information for the development of improved substructure systems included literature on,

5. *Past experience with precast substructure design,*
6. *Use of high performance concrete in standard bridges, and*
7. *Durability of concrete bridges, in particular precast post-tensioned structures.*

A bibliography containing much of the literature review separated into the above categories is presented in Appendix A. Section 3.3 contains a review of the existing bridge aesthetics guidelines that were instrumental in developing the Guidelines (Item 2 above). Section 4.2 presents a brief review of the important literature concerning the development of alternate substructure systems for use with precast concrete superstructure bridges (Items 5-7 above).

The remainder of this chapter will focus on seven of the most important articles and collections of articles, as determined by the author, from the literature review concerning bridge aesthetics.[11-20] Most aesthetics-related writing in the past has focused on monumental long-span bridges. While some of the key references outlined are directed principally towards long-span bridges, much of the literature is applicable in different ways to the problems that face State transportation engineers for short and moderate span bridge design. For example, the economy of construction is an important aspect of aesthetic considerations when designing with public funds. Therefore emphasis on economy tends to be a recurring theme in the key references. Lessons drawn from large projects may also provide useful guidance for smaller bridges.

Specific articles among these seven key references can provide an interested "beginner" a concise and thorough description of the value and necessity of aesthetic considerations for bridge design. The depth and applicability of the subject for all bridge forms can be quickly understood. A discussion of the applicability of this literature review to the research presented in this dissertation follows in Section 2.3.

2.2 Literature Review

2.2.1 *"The Aesthetics of Bridge Design", Christian Menn*[11]

Published in 1985 by the Bulletin of the International Association for Shell and Spatial Structures (IASS), "The Aesthetics of Bridge Design" is an excellent introduction to the application and role of aesthetics in good bridge design. Recognizing that a large amount of significant material covering philosophical aspects of bridge aesthetics as well as careful analyses of existing bridges already exists, Menn focuses his paper instead on guidance for designers on how to develop good design concepts for bridges that include attention to aesthetics.

The article focuses primarily on fundamentals of aesthetics in bridge design. The fundamentals fall into two categories; integration of a bridge into its surroundings and the design of a bridge as a structure in itself. Under the latter focus, Menn covers topics of:

Transparency - visibility through a bridge,

Slenderness - the ratio of the span length to girder depth,

Regularity and Simplicity - a call for symmetry, and regularity in span lengths and element sizes, and

Artistic Shaping - designing structural elements to conform to stress conditions.

Concerning artistic shaping, Menn discusses the place for artistic decoration or embellishments in bridge design. He strongly emphasizes that such embellishments should be carried out only by "real" artists and that the "normal" engineer should rather focus on shaping elements to comply with the static flow of forces.

Menn concludes the article with a discussion of the relationship between aesthetics and economy. He suggests that in most cases where the guidelines he has laid out are followed, the additional costs for typical moderate span bridges should amount to no more than 1-2% of the construction costs. Recognizing the dramatic artistic impression that longer spans can have on the viewer, Menn suggests allowance of up to 5-7% additional costs to increase span lengths of projects designed originally with more moderate spans.

2.2.2 <u>Bridge Aesthetics Around the World</u> - Transportation Research Board, National Research Council [2]

This extensive compilation of articles concerning bridge aesthetics was published in 1991 and represents opinions from authors in 16 countries around the world. In addition to the articles, this compilation contains an annotated bibliography with references to over 250 articles, books and papers on the subject of bridge aesthetics. Topics range from general guidelines for bridge aesthetics and evaluation techniques to specific issues of aesthetics for short and moderate span pedestrian and/or highway bridges to cultural influences on bridge design. A wide variety of bridge systems, span lengths and material types for bridges are addressed.

2.2.3 <u>Esthetics in Concrete Bridge Design</u> - American Concrete Institute (ACI), MP-1[3]

Published in 1990, this collection of papers is a record of the proceedings of four ACI convention sessions on aesthetics in concrete bridge design. Two of the sessions were held at the Fall 1987 ACI convention in Seattle, WA and two were held at the Spring 1988 ACI convention in Orlando, FL. The authors of the papers are predominantly bridge engineers as well as some "bridge architects" from around the world. The many authors discuss topics ranging from personal experience, aesthetic vision and recent designs to philosophical discussions of aesthetics, aesthetic principles and aesthetic rules. A number of papers specifically address State (US) highway bridges, the interrelation of economy and aesthetics or the aesthetics of pier design.

2.2.4 The California Tradition

The California Department of Transportation (Caltrans) has had a long standing tradition of addressing aesthetics in their bridge designs. The goals and approach taken by the department have been well documented. Arthur Elliot, former Bridge Engineer of Caltrans, is the author of *"Esthetic Development of California's Bridges"*[12] presented at the 1980 ASCE Convention in Portland, Oregon. Elliot argues that engineers must not ask "how to make a bridge beautiful" but rather, how does one make a beautiful bridge. Aesthetics along with safety and function are related to a three-legged stool - each leg is essential. Elliot then traces the history of striving for beauty in the design of bridges in California through descriptions of the different bridge types and forms which have been experimented with by Caltrans over the years.

A more recent Chief of the Office of Structure Design at Caltrans, James Roberts, writes as well on the California tradition of designing attractive bridges. In *"Aesthetic Design Philosophy Utilized for California State Bridges,"*[13] Roberts discusses the important collaboration between bridge structural engineers, maintenance engineers, construction engineers, bridge architects, and geological engineers in order to determine the most appropriate bridge form for a given site. Through extensive discussions of the cost impact of Caltrans' consideration of aesthetics as an integral part of design, Roberts shows that designing attractive structures does not add a significant cost to their bridges. The attractive and economical results are achieved through encouragement by all levels of management that designers should strive for beautiful bridges as well as use a variety of bridge forms repetitively. A similar and also important article by Roberts entitled *"Aesthetics and Economy in Complete Concrete Bridge Design"*[14] appears in the ACI MP-1 publication described above.

John Ritner, Chief Bridge Architect at Caltrans is the author of *"Bridges Produced by an Architectural Engineering Team"*[15] which describes the actual methods and principles used by the designers at Caltrans to produce attractive bridges. Ritner discusses the "team approach" taken by Caltrans and the importance of collaboration between bridge engineers and bridge architects at the earliest possible stages of design. As well, architectural treatments are presented as changes in form or surface texture that do not compromise the structural function and purpose of the bridge. This concise and thorough paper gives several very clear examples of how significant improvements to visual appearance can very easily be made considering all elements of a bridge; abutments, columns, superstructure, etc. Several award-winning structures are presented and discussed as well.

2.2.5 IABSE Congress, 1980

The Eleventh Congress of the International Association of Bridge and Structural Engineers (IABSE) held in Vienna in 1980 had one of eleven themes devoted to "Aesthetics in Structural Engineering". Of the fifteen papers presented,[16] five articles are specifically related to structural bridge design. These include,

> <u>Bridge Aesthetics: 1925-1933</u> (Billington), A review of active discussions during this time period on the role of engineers working with or without architects to achieve aesthetic design excellence,
>
> <u>The Engineer and Bridge Aesthetics</u> (Bagon, in French), An analysis of the causes of problems in bridge aesthetics, suggestions for what not to do and brief guidelines for the design of attractive bridges,
>
> <u>On the Manual for Aesthetic Design of Bridges</u> (Tahara, Nakamura), A presentation of a design manual to raise the aesthetic awareness of bridge designers in Japan and to improve even to a small extent the attractiveness of their bridges,

Bridge Aesthetics (Slater), A paper arguing that the character of a bridge is more often determined by spatial proportions, in particular void shapes, and layout. Suggestions are given for bridges as relating to their landscape, bridges with multiple approach spans, bridges on highways and arch rib bridge forms,

Research in Aesthetics of Standard Bridges (Grelu et. al., in French), A three-step methodology for designing attractive moderate span bridges as a whole rather than addressing aesthetics separately. A detailed example is given of the methodology applied to a moderate span highway bridge.

2.2.6 Concrete International, July 1995[17]

A special collection of six articles was gathered and printed together in the July 1995 Concrete International magazine of ACI. Of particular interest to designers of standard highway bridges is Antonio Garcia's article *"Treasures or Trash?"*[18] The everyday issues of short and moderate span design are very well-addressed in this article. Emphasis is placed on showing that aesthetics is not something added or appended to a bridge at the end of the design process, but rather an integral part of good bridge design. Issues of alignment, drainage and joint details, and rehabilitation are discussed. Consideration of the location of a bridge, consistency among the bridge elements and effects of standardization are addressed as well.

Another article particularly germane to the topic of this dissertation is *"Aesthetics in the Design of Precast Prestressed Bridges"* by Maestro et. al.[19] In this article, the authors discuss aesthetic ideas such as the logic of the structural form, harmony, elevation vs. cross section, and slenderness ratios. Specific precast prestressed bridge elements are addressed as well.

2.2.7 Structural Engineering International, April 1996[20]

A series of seven articles was devoted to the subject of "Aesthetics in Structural Engineering" in the April 1996 issue of Structural Engineering International (SEI). The articles are written by seven leading structural engineers from Europe and one from the United States (one paper is co-authored). Five of the articles focus specifically on bridge aesthetics. Some of the common themes are the collaboration of architects and engineers with both positive and negative effects and the examination of the design process as leading to attractive bridge design. While many of the articles focus on long span bridges, many of the ideas, principles and methods are applicable to short and moderate span bridges.

While this issue of SEI devotes a specific section solely to aesthetics in structural engineering, the magazine in general very often has articles pertaining to state-of-the-art bridge design. Study of recent and past bridge projects that emphasize aesthetics with state-of-the-art design such as are found in SEI, is important for the continuing education of all engineers.

2.3 Summary - Relevance and Use of the Literature Review

The seven articles and groups of articles described in Section 2.2 give a thorough overview of the many issues faced and solutions achieved by designers in the past, present and future when addressing aesthetics in their bridge designs. Despite the wealth of information on general bridge aesthetics that does exist, there are only a handful of significant papers that really address issues of aesthetics of short and moderate span bridges within the economic bounds often set by State Departments of Transportation (DOT's). Even the few articles that do address the issue of economy with aesthetic bridge design cannot be applied to all DOT's. Different structural systems, structural materials and construction methods are more economical in different regions of the country. As these aspects of bridge design have a considerable impact on the visual impression of a bridge, guidelines or successful project prototypes in one State very often cannot be economically extended to another State.

An extensive literature review of available material on bridge aesthetics is certainly educational however, and can provide a wealth of ideas. To be of any use, the ideas and experiences of past designers must be viewed within their context - their setting, their time, their local political, social, and economic conditions. It is most important to understand how designers achieved attractive structures within the constraints of their projects. It is this analysis of the design process and the many factors that affect the process that must be studied and modeled for future bridge designs. Such analysis and understanding can then supply a framework for designing attractive structures. A thorough understanding of design processes rather than specific aesthetic rules, *is* transferable across time, and across political, social and economic climates. Design processes may vary according to bridge type but the understanding of how a certain bridge type is formed will give designers insight into where they can better influence the appearance of *their* bridges; where changes can be made within their own design constraints, and what solutions are feasible that will result in elegant structures.

This literature review has provided an introduction to methods of design that have been successful in the past and a review of state-of-the-art bridge design. Such information provides a base as well as inspiration to apply the knowledge gained to develop more attractive solutions for the standard short and moderate span highway bridges that dominate our landscape.

CHAPTER 3
DEVELOPMENT OF AESTHETICS & EFFICIENCY GUIDELINES

3.1 Introduction

State Departments of Transportation have traditionally taken pride in their job of providing the public with safe, functional and economical highways and bridges. The Federal and State highway systems continue to be expanded and rebuilt in this tradition. The majority of the new bridges constructed are of short and moderate spans (10m-45m, 35-100'). Much construction and reconstruction is now occurring through heavily populated areas thus having considerable lasting aesthetic and environmental effect on local users and neighbors. Likewise, even with bridges in under-populated areas, there is often considerable public concern about any negative effects highways and bridges might have on the local environment. As a result, the job of State transportation engineers has become much more challenging. Highway planners and bridge engineers must now not only provide safe, functional and economical designs, but they must also address the visual and environmental impact of their designs. Focusing on bridge design, the *aesthetics* and the *efficiency of both material use and construction methods* are two key areas needing attention so that engineers can better address the impact of their designs on the users and the environment.

3.1.1 Aesthetics and Efficiency of Long Span Bridges

There are many successful examples of elegant and efficient monumental, long span bridges (spans greater than 45m). With large projects, efficient use of materials and efficient construction methods are tied very closely with the economy of the project. The minimization of wasted material very often leads to highly economical designs and, with added consideration, designs that are slender and attractive as well (Figure 3.1). Engineers can benefit greatly through careful study of successful long-span bridges of the past. An appreciation for, and better understanding of bridge aesthetics can be gained. Then, similar or refined ideas can be applied to other long span projects.

Figure 3.1 The Ganter Bridge, Switzerland

3.1.2 Aesthetics and Efficiency of Short and Moderate Span Bridges

With short and moderate span bridges, it is much less likely that the efficient use of materials and efficient construction methods traditional for economical structures will result in attractive designs. Due to the economics of standardization, minimizing wasted material (which often leads to attractive and elegant designs) has in many cases proven to be uneconomical for short and moderate span bridge design. For example, modern techniques like pretensioning call for uniform depth girders. Tailoring the depth to match the moment diagram and hence save material is not practical on the long pretension lines utilized. Thus the extremely rigorous standardization often necessary for the sake of economy tends to stifle the creativity of engineers designing short and moderate span bridges. This trend is not present in substructure design where less standardization is used and where most construction is cast-in-place. Yet designers tend to pay relatively little attention to aesthetics and economy for these bridge elements. The interaction between aesthetics, efficiency, economy and the effects of standardization on the design of short and moderate span bridges must now be addressed. New attractive solutions that will be economical, simple to construct and not wasteful of materials must be the goal of engineers designing standard bridges of moderate spans.

3.1.3 The Need for Aesthetics and Efficiency Guidelines

During formal education, engineers may be exposed to issues of efficiency in design but they are rarely expected to address the aesthetics of their designs. In the workplace as well, there is very little guidance for engineers wishing to address both aesthetics and efficiency more closely in design. In particular, the aesthetics and efficiency of short and moderate span bridges has been sorely neglected.

A number of State DOT's have recognized that addressing aesthetics adds an important new dimension to bridge design. Many DOT's have begun to address aesthetics more formally though the development of guidelines for aesthetic bridge design with encouraging results (see Section 3.2).

Currently, the Texas Department of Transportation (TxDOT) has only a brief half-page statement concerning aesthetics in their Bridge Design Guidelines.[21] The recent 1996 LRFD AASHTO Specification for Highway Bridges has a slightly more expanded section addressing aesthetics but it remains cursory and generalized.[22] Engineers at TxDOT however, have been making a strong effort recently to address the aesthetics of their highway projects and in particular, the bridges they design for the State. A few results of their efforts are depicted in Figures 1.4-1.6, and Figure 1.9. The public has recognized and been receptive to these efforts (see Sections 3.3.2-3.3.3) and TxDOT has now decided to go forward with developing their own set of guidelines for improving the aesthetics and efficiency of the bridges of Texas. Work towards the development of a set of guidelines titled the *TxDOT Aesthetics and Efficiency Guidelines* (referred to as the Guidelines) is presented in this chapter.

3.2 Literature Review

There are a number of existing manuals of aesthetics guidelines for bridge design. A few are written for State DOT engineers and focus on improving short and moderate span bridges. The guidelines of other DOT's are particularly useful in terms of providing a basis from which to develop the TxDOT Guidelines. Existing guidelines for State engineers address many issues specific to short and moderate span bridges. In particular, economics is an important concern, as the engineers are designing State-owned bridges that are paid for by tax-dollars.

There are other aesthetics guidelines in existence that are more general and are meant to apply to all types of bridges; long and short spans, masonry, timber, concrete or steel bridges, and arches, beams, or cable bridges. Still other sets of guidelines may address the aesthetics of just one specific type of bridge such as railroad bridges. Examination of both broad and specific (i.e. not necessarily State DOT) guidelines is useful and informative. Although not focused on bridge types most often constructed in Texas, such guidelines supply engineers with important principles inherent to good bridge design that can apply to all types of bridges.

Many of the ideas from existing sets of aesthetic guidelines have been helpful in developing the Guidelines. Brief descriptions of some of the existing guidelines examined are presented herein. A discussion of the most influential ideas gained from this literature review concludes this section.

3.2.1 Existing Guidelines

Bridges, Fritz Leonhardt[23]

German engineer Fritz Leonhardt developed a set of guidelines in his book *Bridges*. These guidelines are organized by categories of bridges; arch bridges, beam bridges, cable-stayed bridges, and suspension bridges. Throughout his guidelines, Leonhardt emphasizes nine principles of aesthetics. They are:

- **Clarity of function** - Efficient appearance, clear form and imparting a feeling of stability
- **Proportion** - Balance and harmonious relationships between elements
- **Order** - Symmetry, repetition and limited number of lines, directions and edges
- **Refinement of form** - Optical corrections, light and shadow and skew angle views
- **Integration into the environment**
- **Color** - Harmonious coloring
- **Texture** - Break in monotony of large expanses of concrete
- **Character** - Deliberate effect on user and positive user-friendly impressions
- **Complexity** - Limited variety to evoke interest while maintaining order

Leonhardt also emphasizes the importance of layout, planning and roadway alignment on overall bridge aesthetics.

Aesthetic Bridges, Maryland Department of Transportation[4]

The Maryland Department of Transportation has developed guidelines titled *Aesthetic Bridges*. specifically for State DOT engineers. Their guidelines are organized in the order of the design process. They address issues involving the geometry and layout of the bridge, superstructure design, substructure design, color & texture and signs, lighting & landscaping. Site-specific considerations are addressed in separate sections and cover such topics as bridges in urban vs. rural areas or bridges spanning water vs. a highway. The Maryland Guidelines emphasize the importance of six ideas referred to as the keys to success. These are:

- **Strength through form** - Shape elements to respond to their structural function
- **Clear display of structure** - Display role of each element and show how forces act
- **Unity -** All elements should contribute to a single whole
- **Economy** - The bridge should serve its function with a minimum amount of material
- **Proportion** - Each element size should relate clearly to the overall structure
- **Appropriateness** - The bridge should have a clear and consistent relationship to the area around it

The goal of the Maryland guidelines is to aid designers in making explicit decisions concerning aesthetics just as they would make decisions for structural members, safety or cost.

Aesthetic Guidelines for Bridge Design, The Minnesota Department of Transportation[5]

The Minnesota Department of Transportation has developed a set of guidelines very similar to those of the Maryland DOT. Minnesota's guidelines begin with a section on fundamentals of aesthetic design and a section on the aesthetic design process. The fundamentals of aesthetic design presented include:

- **Visual Design Elements** - Line, shape, form, color, texture
- **Aesthetic Qualities** - Proportion, rhythm, order, harmony, balance, contrast, scale, unity
- **Aesthetic Design Objectives -** Functional clarity, Scale and Proportion, Order and Balance, Simplicity and Continuity, Site/Environment Integration
- **Aesthetic Design Hierarchy**
    - -- Principle Aesthetic Design Factors - superstructure type and shape, geometry and relationship to site, pier location and shape, abutment location and shape, interaction between bridge and its surroundings
    - -- Secondary Aesthetic Design Factors - railing details, surface colors and textures, architectural embellishments, lighting

More detailed discussions including design examples are given for superstructure design, substructure design, bridge related components (railings, drainage, signs, etc.) and bridge categories (interchanges, grade separations, long-span bridges, etc.).

“Bridge Design Aesthetics,” California Department of Transportation

As discussed in Section 2.2, the California Department of Transportation (CALTRANS) has had a long-standing tradition of emphasizing the importance of aesthetics in their bridge designs. Section 7 of their Bridge Design Practice Manual is titled "Bridge Design Aesthetics."[24]

This Section begins by defining a beautiful bridge,

> *Beautiful Bridge* - A beautiful bridge makes a minimal impression on the environment, has good proportions both in its integral parts and in the space outlined by its parts. It is composed of one dominant structural system using a minimum number of bents with a minimum number of columns per bent. Size, shape, color and texture on superstructure, columns, and abutments are utilized to either call attention to or play down, the role of these structural parts.[24]

The design philosophy at CALTRANS of encouraging beautiful structural design is emphasized from the top management down. A section of the department titled Aesthetics and Models keeps this emphasis alive by coordinating with engineers from the very beginning of each project.

Another key element to designing beautiful bridges at CALTRANS that is emphasized in their Bridge Design Practice Manual is the choice of structural type resulting from a "type selection meeting." The type selection meeting involves input from professionals representing all disciplines involved with bridge design. Professionals include representatives from the divisions of Specifications, Design, Aesthetics and Models, Construction, Estimating, and Maintenance.

More detailed discussion is provided concerning railings, girders and decks, and column shapes, in particular column cross sections and the use of tapered and flared columns. There is also a section devoted to aesthetic considerations for seismic retrofits.

"<u>Development of Aesthetic Guidelines for Short and Medium Span Texas Bridge Systems</u>"

A preliminary set of aesthetic guidelines was developed for the Texas Department of Transportation by Scot Listavich under the same research project as this dissertation. Listavich's preliminary Aesthetic Guidelines cover 40 topics representing ideas to be applied to the short and medium span bridge systems of Texas.[8] These 40 topics are divided into three main groups; Form, Composition and Entity (Figure 3.2). These three groups represent an approach to aesthetics in bridge design that involves consideration of individual forms of a bridge and how they come together in the whole composition (Form), consideration of ideas that are applied to the whole composition rather than individual parts (Composition), and consideration of the bridge's role in its environment and how the bridge interacts with its setting (Entity). Each of these groups and their related topics is presented in six steps. These steps are:

1. Title
2. Introduction Statements including definition of the title.
3. Initial Figures illustrating the principle subject.
4. Additional or Diagrammed Figure further illustrating idea.
5. Discussion/Transition statement leading to following topics.
6. List of following Topics

These Guidelines are thorough and present an extensive amount of useful information for application to short and medium span Texas bridge systems.

Miscellaneous Guidelines

The Wisconsin DOT has a small chapter on aesthetics in their bridge manual.[25] Key ideas briefly discussed include unity through form, simplicity of design, focal points, feature of relief, and proportion of elements. The Wisconsin DOT is in the process of developing a more comprehensive set of guidelines similar to those of the Maryland and Minnesota DOTs.

The Illinois DOT developed a set of guidelines specifically for use on bridge projects for one highway,[26] Highway I-255. One emphasis was on streamlining the bridges - using single spans for highway over- and underpasses to avoid the need for piers where possible. Surface treatment was carefully planned to harmonize with the natural environment. Different treatments were used for bridges of different functions - one texture was used for bridges crossing the interstate and a different texture was used for interstate bridges crossing local roads. Careful planning from the outset of design resulted in a very attractive set of bridges with the attention to aesthetics costing less than 3% of the project cost.

The Swiss National Railway (SBB) has a set of guidelines for their railway structures.[27] Issues briefly discussed include the engineering work’s relationship to the environment, form, structural system, texture, color, environmental impact and protection and landscaping. After these issues are presented, numerous examples, both good and bad are pictured and discussed. The examples include railway bridges, underpasses (under railways), overpasses (crossing railways), tunnel portals, retaining walls and noise barriers.

AESTHETIC GUIDELINES

- **Form-**
  - *Refinement of Form-*
    - Form Related Idea:
      - Shape
      - Elevation
      - Section
      - Footprint
    - Form Related Strategy:
      - Accentuation (Highlighting Form)
      - Continuity
      - Optical Corrections
      - Light and Shadow
      - Structural Expression
  - *Proportion-*
    - Proportional Idea:
      - Proportioning System
      - Scale
    - Proportional Strategies:
      - Functional Layout: Elevation and Section
      - Relative Sizes of Components
      - Application to Composition as a Whole
- **Composition-**
  - *Order-*
    - Symmetry
    - Repetition
    - Hierarchy
    - Transformation
    - Rhythm
  - *Texture-*
    - Fine-Scale
    - Medium-Scale
    - Large-Scale
  - *Color-*
    - Thematic
    - Entropic
- **Entity-**
  - *Integration into the Environment-*
    - Texture
    - Color
    - Proportions
    - Transitions
    - Order
  - *Clarity of Function-*
    - Clear Form
    - Clear Circulation
    - Safety and Stability
    - User-Friendly
  - *Character-*
    - Complexity
    - Economy of Means
    - Social Implications
  - *Aging-*
    - Graffiti
    - Drainage Staining
    - Wear Staining
    - Paint Chipping and Peeling

Figure 3.2 Outline for TxDOT Aesthetics Guidelines by Listavich[8]

3.2.2 Summary

The numerous ideas and organizational methods displayed in many of the existing guidelines have been carefully studied and analyzed to provide a background for the Guidelines. Some of the previously used strategies are important and appropriate for guidelines for Texas while others are not.

In Leonhardt's book, *Bridges*, the nine principles of aesthetics presented are well explained. These principles are ideas that are often taught to students in architecture school but rarely are discussed among engineers. While the principles certainly have applications to engineering works, these applications are less clear to an engineer who has never considered aesthetics in bridge design. The principles are presented and many photographs of different bridges are shown but the connection between the two is weak. There are very many principles and very many ways to carry them out. However, no guidance is given as to how to put them together in one project. The extensive use of photographs of actual bridges and the effectiveness of comparative photographs is a very positive feature of the book and will be adopted for the Guidelines.

Maryland's Aesthetic Bridges is more specifically aimed at helping a State engineer develop an awareness of bridge aesthetics. The organization of these guidelines in the order of the design process is highly effective. This order is logical for DOT engineers and it is easy to follow. This organization inherently shows the importance of addressing aesthetics at all stages of the design process, not just at the end with add-on details. Another important feature of these guidelines is the ability to read the document at different "levels" (Figure 3.3). Main ideas are in bold type with further explanations underneath. As well, all photographs have captions to further illustrate the ideas presented. Such organization allows a reader to browse casually or study in depth and yet always receive useful information from the document.

The organization of Minnesota's guidelines (following the order of the design process) is similar to Maryland's and is a positive feature for any DOT guidelines. Minnesota's mention of the hierarchy of design is a key point that should be stressed more emphatically - the importance of the overall form and the structural components, not simply the details. This idea of looking at where aesthetics belongs within the whole bridge design process is one that should continue to be stressed in future guidelines.

While California generally uses very different structural systems for their highway bridges than does Texas (cast-in-place concrete continuous box girders vs. simply supported precast pretensioned concrete girders, respectively), their approach to aesthetics is excellent and can be applied to any type of structure. Their overriding design philosophy which emphasizes the importance of addressing aesthetics is stressed from their top management down. As a result, aesthetics is considered in the beginning of every bridge project. The existence of an entire section of the department (Aesthetics and Models) devoted to visual analysis of potential bridge types for a project is a clear indication of the pride CALTRANS takes in designing beautiful bridges. While these organizational features at CALTRANS cannot be directly transferred through guidelines alone, small steps can be taken to reach such a high level of aesthetic awareness. An emphasis on considering aesthetics from the beginning and the importance of visual aids including both physical and computer-generated models will be made in the Guidelines.

Listavich's Guidelines were very useful in laying the groundwork for the final version of the Guidelines. The ideas and principles presented specifically address Texas bridge systems. They pinpoint areas where more thoughtful consideration should be given in design. Most of these principles and ideas have been incorporated into the new version. The clear presentation of ideas with illustrations was recognized to be essential for a useful and "user-friendly" document to result.

In looking at other guidelines such as those from Wisconsin and the SBB, it is clear that the use of visual aids is one of the most effective ways to develop a reader's awareness of bridge aesthetics. Words and principles alone as presented in Wisconsin's brief guidelines are important but yet are not convincing without photographs (Figure 3.4). The SBB guidelines show clearly that a good photograph with a brief statement explaining the connection between a principle and the built form is far more valuable than pages of poorly illustrated written explanation (Figure 3.5).

3.3 Background for TxDOT Guidelines

To best serve the engineers of TxDOT it was necessary to gain an understanding and appreciation of the challenges that the engineers of TxDOT face. The types of bridges these engineers most often design were studied as well as the most common detailing problems that concern them - specifically details that effect aesthetics and efficiency. Interviews with highway planning engineers, bridge engineers, and landscape architects throughout the State were conducted to better understand the concerns of the local DOT offices and the challenges that their specific geographical and cultural climates create. An informal survey of the public (the tax-payers and

essential owners of the State bridges) was conducted to get a feel for the public perception of their highway system.

All of this information was gathered as background information for developing the Guidelines. As the Guidelines are to be primarily for the engineers of TxDOT, the background information gathered in Texas and presented in this section was essential so that the Guidelines would best serve their primary users.

3.3.1 Photo Surveys

An extensive photographic survey of roughly 2500 slides (~700 different bridges) was conducted to identify the characteristics of short and moderate span bridge types used in Texas. Examples of both attractive and unattractive short and moderate span bridges were photographed. A photographic survey was also made recording successes and failures of non-structural details (such as railings, drainage and textured surfaces) and how such details can enhance or detract from a project. The general routes taken for gathering the majority of the photographs are shown in Figure 3.6.

3.3.1.1 Short and Moderate Span Bridge Types

The short and moderate span bridges of Texas fall loosely into five major bridge categories. Each bridge type has a different setting and very often a different set of users. Identifying such differences is important when addressing the aesthetics and efficiency of these bridges. The different bridge categories are;

- Highway grade separations - urban and rural locations
- Urban elevated highways and interchanges
- Stream crossings
- Low water crossings along the Gulf Coast
- Bridges in park settings or “environmentally sensitive” locations

Highway Grade Separations

Grade separations include both overpasses and underpasses. Grade separations in rural locations will typically be viewed only by quickly moving traffic. In addressing aesthetics, the overall form, or the appearance of the bridge as a whole from a distance will have the most visual impact on the viewers (Figures 3.7-3.8). Attention to small scale details such as texture or relief will go virtually unnoticed. In addressing construction efficiency, construction time may or may not be of concern for grade separations in rural areas. For example, if the required separation is for a school bus route, construction may need to proceed rapidly. If the highway that is crossing or being crossed is not heavily used, construction time and methods may not be so critical as traffic delays will most likely not be a problem. Availability of materials is a concern for particularly remote sites.

Grade separations in urban locations will often be viewed both by quickly moving traffic and slower moving pedestrians, or people in neighboring buildings. Here, both the visual impression of the overall structure *and* smaller scale details that will be seen by the "slower" users and viewers are important (Figures 3.9-3.10). Particular care for long-term appearance is essential where distinct signs of aging (such as staining) will have negative psychological effects on neighbors and users. Construction efficiency may be essential to avoid unwanted traffic delays. Construction methods that speed up construction time in heavily congested areas will be desirable for both the contractors and the public.

Urban Elevated Highways and Interchanges

Urban elevated highways are usually heavily viewed from directly underneath by pedestrians and crossing traffic and obliquely underneath by frontage road traffic and pedestrians. Urban elevated highways often cut through existing neighborhoods or commercial districts thus having a profound effect on the highway's "neighbors" (Figures 3.11-3.12). Interchanges directly in an urban area have an impact on the surroundings similar to that of urban elevated highways. Interchanges outside of an urban area on the other hand give the strongest visual impression when viewed from a distance as a whole (Figures 3.13-3.14). Attention to small-scale details viewed only by slow moving traffic or pedestrians is generally not important for remote interchanges.

Construction efficiency is often essential for urban elevated highways and interchanges in populated areas. Traffic delays can be costly and construction methods should be explored that will speed up on-site construction. While it is desirable to use the most economical construction method for a project, engineers, planners and contractors also recognize the hidden costs (as opposed to up-front design and construction costs) associated with excessive traffic delays and traffic re-routing. In certain situations direct construction cost increases may be justified to avoid the cost of undesirable traffic problems. Some interchanges outside of cities will not produce extensive traffic problems and thus may not be heavily influenced by rapid construction procedures.

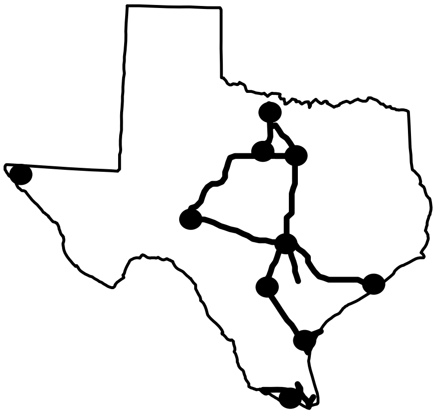


Figure 3.6 General sites and routes taken for the photo survey of Texas bridges and non-structural details of Texas bridges

Figure 3.7 A heavy, cluttered overall appearance

Figure 3.8 A light elegant overall appearance

Figure 3.9 Attractive overall form and details of abutment, rail and substructure

Figure 3.10 Attractive overall form and details of abutments and substructure

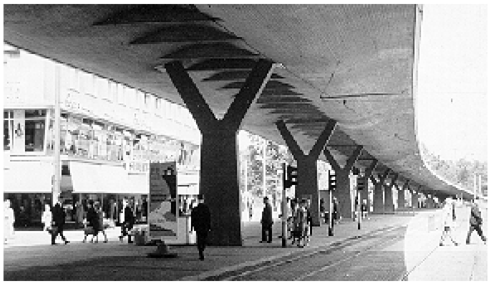


Figure 3.11 Heavy pedestrian use under an attractive urban elevated highway

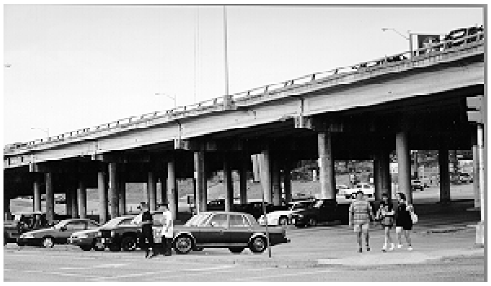


Figure 3.12 Heavy pedestrian use under an ugly urban elevated highway

Figure 3.13 Interchange with a clean, simple appearance

Figure 3.14 Interchange with a confusing, heavy appearance

Stream Crossings

In some districts around the State, stream crossings make up the majority of the bridges built by TxDOT. Stream crossings are very often hidden from view and many motorists would not know they are crossing a bridge if not for the presence of a rail along the side of the road. Many engineers feel that the aesthetics of such bridges is irrelevant. However in the case of stream crossings that are visible from roadside parks or curved approaches, attention to the aesthetics of the structure can provide an attractive addition to a natural setting rather than a thoughtless jumble scarring the landscape (Figures 3-15-3.16).

Efficient use of materials and efficient construction methods will depend on the remoteness of the stream crossing site. Structural elements, material use and construction techniques for these crossings are most often chosen based on availability and local contractor experience.

Causeways

Causeways are low water crossings along the coastal regions that often have a raised portion to allow passage for water traffic. These highly visible structures are often on curved alignments and can be viewed not only by boat traffic but also by motorists approaching and using the causeway. These long structures often have a very dramatic visual impact from great distances as well as an effect on the experience of local water traffic at a close range (Figures 3.17-3.18).

Efficient use of materials and efficient construction methods will be very closely tied with accessibility to the site. Cast-in-place concrete placement from barges could be replaced with the use of precast driven piles and precast pile caps.[28] The effect that materials and construction methods chosen will have on durability is vital. The salt water environment of causeways is one of the most aggressive environments that can lead to corrosion of reinforcement in concrete members.

Bridges in Park Settings and Environmentally Sensitive Areas

Numerous short and moderate span bridges are built in environmentally sensitive areas. Examples of environmentally sensitive areas include parks that are highly valued by their users as well as habitats for wildlife or endangered species. Bridges built in these environments are often unwanted by the public. Thus, it is essential that they be designed to blend in and enhance their setting. They should never be an eyesore and detract from a site’s natural beauty. Attention to designing an elegant overall form and careful detailing for final appearance and attractive aging are very important considerations for bridges in these sensitive areas (Figures 3.19-3.20).

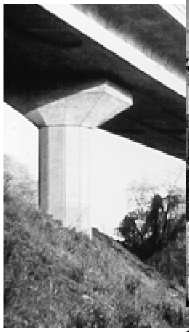


Figure 3.15 A "clean" addition to a natural setting

Figure 3.18 A low water crossing on the Gulf Coast near Corpus Christi, Texas

Figure 3.16 A cluttered forest of columns

Figure 3.17a The JFK Causeway in Corpus Christi, TX from a distance

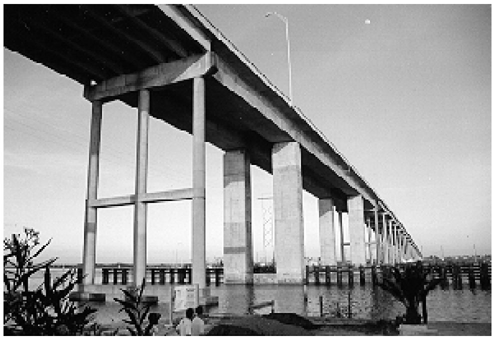


Figure 3.17b A "close-up" view of the JFK Causeway

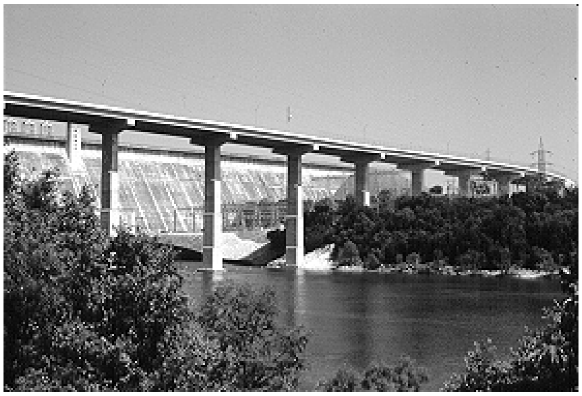


Figure 3.19 An attractive addition to an environmentally sensitive site

Figure 3.20 An eyesore in a popular park area in Austin, Texas

Efficient construction methods are advantageous to minimize the impact that construction might have on the site. Innovative use of “top-down” construction (in particular with precast construction) should be examined. Top-down construction refers to constructing the substructure and/or superstructure from above - typically from the abutment and then moving out along the previously constructed portion of the bridge. This method of construction eliminates the need for extensive formwork or scaffolding to be set up on the ground (in the environmentally sensitive area) and also moves construction equipment and its impact on the surroundings up off the ground. Some examples of successful use of this method of construction are the Linn Cove Viaduct in North Carolina,[29] the Vail Pass and Glenwood Canyon structures in Colorado[30,32] and the Loop 1 bridge over the Barton Creek Greenbelt in Austin, TX.[31]

3.3.1.2 Non-structural Details

A photographic survey of non-structural details on the short and moderate span bridges of Texas was conducted. Examples of attractive non-structural details as well as highly unfortunate non-structural details were recorded (Figures 3.21a&b).

A certain amount of non-structural detail is required for almost every bridge project. These details include edge barriers and railings, pedestrian access, drainage provisions, joint types, and sign and lighting supports and locations. Other details which must be addressed and allow for considerable freedom in choice are overhangs, surface texture and/or color.

Figure 3.21a Texture accents this elegantly tapered pier

Figure 3.21b Tacked on drainpipes and peeling paint create a feeling of decay

It is apparent in surveying a wide range of bridges in Texas that thoughtful attention to non-structural details is essential for the design of attractive bridges. For instance, slenderness is a very attractive attribute for bridges. When looking at non-structural details, the choice of edge barrier and rail and how this effects the apparent slenderness of the bridge will be important. As shown in Figure 3.22, apparent slenderness is defined as the clear span length divided by the apparent depth of the structure. The apparent depth includes the beam depth, the depth of the slab and the depth of the solid portion of the rail and/or edge barrier above the slab.

Another important non-structural detail effecting apparent slenderness is pedestrian access on a bridge. Attention to the level of accommodation provided for pedestrians can effect edge barrier and rail requirements (Figure 3.23a). This in turn will effect the apparent slenderness of the bridge (Figure 3.23b). The choice of overhang length will effect apparent slenderness through shadows cast on the depth of the superstructure. Larger overhangs will cast larger shadows which mask the depth of the span and give the bridge a more slender appearance (Figure 3.24).

With careful planning, the service life and durability of the structure may be improved through attention to non-structural details. Attention to drainage details and joint types can prevent or limit unwanted staining. Drain pipes may be tacked on as afterthought appendages (Figure 3.25a) or may be more attractively hidden within the structure (Figure 3.25b). Small raised edges, or berms, may be incorporated into designs to direct water to drain pipes and avoid unwanted dripping down the outside of the substructure. Attention to the types of joints used for the roadway will also effect the apparent aging of the structure. Open joints allow for the passage of water from the roadway above carrying with it dirt, debris, broken down jointing material, and in some areas of Texas, de-icing salts, all of which cause staining and may lead to corrosion problems in the substructure (Figure 3.26).

Staining is a maintenance problem that can be handled in many other creative ways through attention to details of surface texture. Certain textures such as exposed aggregate and some formliner patterns can essentially mask staining (Figure 3.27). Relief can be designed into columns to direct water flowing down the substructure to run in a groove. The groove would be dark due to shadows and will therefore not appear significantly different if the groove is exposed to dark staining. The choice of surface textures has also been seen to deter graffiti “artists” (Figure 3.28).

Attention to surface texture may also eliminate the need to paint the concrete bridges and in particular the substructures. Painting concrete essentially turns a maintenance free material into a maintenance intensive material as the paint typically peels and chips within a few years of a fresh

Figure 3.25a Drainpipes tacked onto the substructure

Figure 3.25b Outlet of an internal drainpipe

Figure 3.26 Substructure staining due to the open joint above

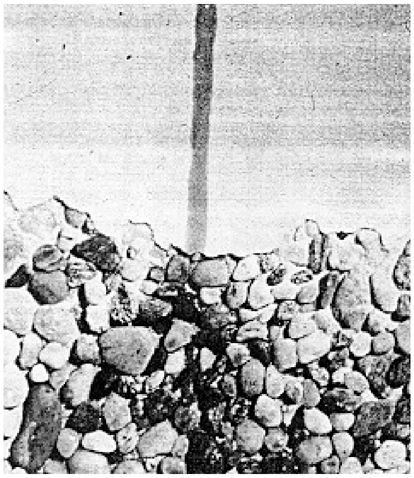


Figure 3.27 Exposed aggregate (below) masks staining well[87]

Figure 3.28 Graffiti "artists" typically prefer a plain canvas to a textured one

coat (Figure 3.21b). With more careful attention to surface treatments and drainage up front, painting can be avoided and the life-cycle costs of maintaining the bridge can be reduced (Figure 3.29).

Clearly, attention to non-structural details will be an important part of bridge design. Not only will good non-structural detailing enhance the aesthetic qualities of the bridge but they may lead to more durable structures that require less maintenance and will have a more lasting value for its users.

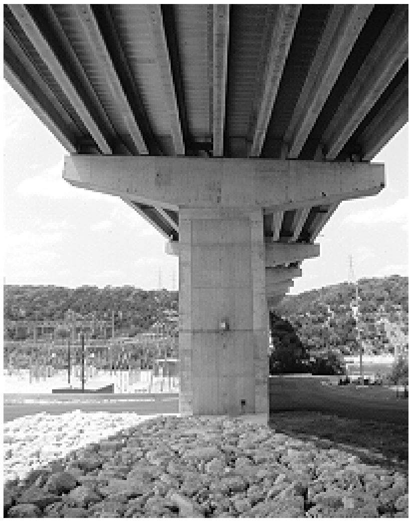


Figure 3.29 A formlined surface and internal drain reduce maintenance needs

3.3.2 Interviews with TxDOT Personnel

The author conducted a number of interviews with TxDOT engineers, planners and landscape architects throughout the State. These interviews were conducted in July and August of 1995 as well as in January, 1996. The titles and positions of the people at the time they were interviewed are listed below:

<u>Corpus Christi District</u>:	Tom Bell, Bridge Engineer
<u>San Angelo District</u>:	John Dewitt, Bridge Engineer
	Mark Tomlinson, Bridge Engineer
	Joseph Morales, Area Engineer, San Angelo
	Jerry Fields, BRINSAP Engineer
<u>Dallas District</u>:	Van McElroy, Bridge Engineer

Pharr District:	Steve Walker, Landscape Architect
	Jody Ellington, Area Engineer, Raymondville
El Paso District:	Mary May, District Engineer
	Ray Lopez, Bridge Engineer
	Charles Berry, Bridge Engineer
	Richard Mason, Landscape Architect
Houston District:	J.C.Liu, Bridge Engineer

To better understand the relationship between the various positions held by the interviewees, Figure 3.30 shows the organization of TxDOT. The Design Division in Austin generally acts as a consultant to the district and area offices, doing design work for the smaller offices when they have too much work for their office or they do not have the in-house capabilities for a certain project.

Some of the questions raised and the responses given included:

What is the perception of the engineers as to what their role is?

The most common theme in response to this question was that engineers feel their job is to get the public on the roads quickly, safely and economically. The biggest thrust is on economics - producing cost effective designs, working within the budget.

Many interviewees felt that TxDOT engineers took pride in their work and would like to consider aesthetics more. However there was a strong consensus among the less senior personnel that without the approval or consent of upper management, they would not be permitted to carry out new ideas for more attractive solutions. Among the more senior personnel there was a mix of reactions to the consideration of aesthetics. Some felt that aesthetics always meant increased costs and were therefore resistant to discussing the topic, while others were interested in finding economical and attractive solutions to better serve the public and their cities.

How much in-house bridge design is done in your office?

The larger district offices (Dallas, Houston, El Paso) do a considerable amount of in-house bridge design but much work is also sent to the Design Division in Austin. The smaller district offices concentrate mostly on roadway layout and alignments. In the past, bridge design often

dictated roadway alignments but the opposite is true today. The general trend now is for highway planners to design the highway and tell the bridge designers where the bridge will start and stop.

While much of the design work is carried out in the larger district offices and the Design Division in Austin, the district offices as well as the area offices do make suggestions and requests as to what type of superstructure and slab they would prefer for their projects.

How much communication is there between highway planners and bridge design engineers?

Communication between the highway planners and bridge designers generally equates to communication among the area offices, the district offices and the Design Division in Austin. The general consensus is that communication is very good between the parties. There is some concern however, about knowing which office should be responsible for which part of a design. This results from in-house capabilities being limited in smaller offices. While some work can be done in-house, often it must be sent either from the area office to the district office or from the district office to the Design Division. As a result, there is often not much continuity from one project to the next or even within a single project as so many different engineers in different offices may complete a separate part of the project.

How receptive are local contractors to new design ideas?

In most districts, the engineers have a good working relationship with local contractors. Many engineers are comfortable with and do call contractors for advice concerning design and construction issues. There is a general feeling that contractors are receptive to new ideas but that it is important to have the contractors attend meetings and discussions with TxDOT about new ideas right from the beginning.

How much do local engineers get out on the site? Who does?

Responses to this question varied considerably. In a few districts bridge engineers almost always visit the site before beginning the design. In others, bridge designers do not. Rarely do highway planners visit the sites. Often, the Advanced Planning personnel are the only engineers to visit the site (they are required to) and this may occur up to 5 years before design work begins. Photogrammetry, or aerial photographs for surveying are always taken but these black and white photographs do not give designers a feel for the site as seen by future users.

Many engineers in the districts felt it would be easy to visit the sites, take pictures and send copies to Austin if the Design Division would be doing the bridge design.

How does the politics of right-of-ways (ROW's) and businesses affect planning? When ROW's are settled are they essentially "set in stone"?

Most engineers agreed that once a public hearing had been held concerning the location of a new project, the layout could not be changed. If changes were proposed that would improve the efficiency of the structure or result in cost savings, there might be an opportunity to make the changes. Rarely would any alignment changes be made strictly for improved appearance. If changes are made after a public hearing, compensation may need to be paid to businesses who feel they will be adversely affected by new changes.

What sort of computer graphics are available and used?

All of the offices are equipped with computer facilities that have good computer graphics packages. However, very few of the offices use these packages. The engineers feel it takes too much time to learn the software, new versions are released too quickly and there is little then justification for spending the time to learn them. Some engineers dislike the use of three-dimensional computer modeling as it is not representative of what the public will actually see (signs, light posts and other visual “obstacles” are often omitted). As a result, the public having initially seen “clean” or “simplified” computer images, may be unhappy about the final built form.

How do you feel about painting concrete?

Generally, everyone was opposed to painting concrete due to the maintenance problems of needing to continually repaint. Some engineers did like the way painted structures looked but felt the maintenance problems out-weighed the appearance benefits. In El Paso however, painting has been considered essential due to the heavy graffiti problem in their city. Other surface treatment options for their bridges such as staining or exposed aggregate would need to be sand blasted continually to remove graffiti. The surface would be ruined within a few years because of the extensive and constant graffiti problems in El Paso.

Each district seemed to face different problems in terms of the obvious signs of aging on their bridges that they typically cover with paint. The Corpus Christi District has a considerable amount of mold collecting as dark gray patches on their bridges while in El Paso it is dry dirt that accumulates on their bridges. In most other districts, dirty run-off water from the deck heavily stains substructures and in urban areas there is the added problem of exhaust pollution accumulating on the bridges.

What are the rough figures for what types of structures are built?

The majority of bridge projects in the Corpus Christi and San Angelo Districts are for stream crossings (~80%) and overpasses (~20%). The Corpus Christi District uses precast T-beams most often with precast I-girders and box beams used as well. The projects in the El Paso District are about 80% overpasses and 20% stream crossings. Much of the work in El Paso is in widening and repair of existing structures. The Dallas and Pharr Districts have roughly equal numbers of stream crossings and grade separations with Dallas also having a considerable square footage of interchange work in their district (Interchange designs generally get sent to the Design Division). Most of the projects in Houston are new construction for interchanges. Trapezoidal concrete box girders are popular in Houston and steel plate girders and steel box girders are often used for the large curved spans on interchanges in the city.

What is the typical cost per sq. ft. of bridges in this district?

The cost of precast I-girder bridges in most Districts was comparable to the State average of \$310/m^2 (\$29/ $ft.^2$). The El Paso District was the exception with precast concrete bridges costing roughly \$590/m^2 (\$55/$ft.^2$) due to there being only one concrete supplier in the area.

3.3.2.1 Summary

Meeting with the many different engineers and landscape architects across the State provided important background for the development of the Guidelines. Understanding the duties and concerns of the local engineers was essential in developing guidelines that would be most useful to them. There was a strong interest for the Guidelines on the part of almost all of the engineers and landscape architects interviewed.

3.3.3 Informal Survey of the Public

An informal survey of the public in Texas was conducted. The goal of this survey was to determine the public's interest and feelings about a part of their infrastructure that is paid for by their tax dollars. What do they think of their highway bridges? Do they notice them? Do they care about

them? Should the State bother to address the aesthetics of these structures? A copy of the survey questions asked is found in Appendix B. A large amount of information was gathered from the responses to these questions. However, only the questions particularly important to the development of the Guidelines are presented here. These include questions that display the interest or disinterest of the public in having their State engineers address aesthetics when designing State highways.

Face to face interviews were conducted with approximately 400 people at various locations across Texas. The interviews generally lasted from three to five minutes. The locations of these interviews are shown in Figure 3.31. As seen in Figure 3.32a, the number of interviews conducted in Austin were much greater than any other location. The effect of the Austin pool did not significantly skew the data except in the response to a few questions. Where the responses in Austin did skew the data, the Austin pool was reduced to a percentage more equal to the percentages of the other nine survey locations. With Austin "weighted," each location represents between 4-11% of the responses (Figure 3.32b). (See Appendix B for further explanation). For the figures in this section, if the Austin pool was weighted, it is indicated beneath the question as "(Austin weighted)."

The responses to the survey represent a wide geographical and cultural mix of people surveyed. The occupations of those surveyed (Figure 3.33) also show that opinions were gathered from a realistic cross-section of workers, students and retirees throughout Texas.

The surveys from Austin were conducted by approximately 45 different students as an assignment for their Concrete Bridge Design class at the University of Texas at Austin. One result of such a wide variety of surveyors was that the amount of information recorded for each survey varied. To display clearly the amount of information gathered, two separate numbers appear at the bottom of each figure. The first number represents the percentage of people who responded to the question. As some questions asked for more than one answer, the second number represents the total number of responses given. Another important aspect of the large number of different surveyors is the assumptions made by the author in interpreting the responses. These assumptions and their limitations are discussed in Appendix B.

Some background questions were asked at first to determine how much the public feels affected by their built environment. As seen in Figure 3.34, the appearance of buildings is important to the vast majority (over 90%). While bridges are typically a less frequent site than buildings in most locations, the appearance of a bridge had at least some effect on over 85% of those surveyed.

When asked about favorite bridges (Figure 3.35) the majority of the public's favorites were out of State bridges with the Golden Gate bridge amounting to 35% of the out of State favorites. Close to one third of the favorite bridges were in Texas. Some responses mentioned only a certain type of bridge such as suspension bridges, arch bridges or covered bridges. These are represented on Figure 3.35 as "Specific Type." Of those who named one specific bridge, only 10-15% of these bridges were of short or moderate spans (an exact percent was not possible to determine as some of the names of the bridges were unfamiliar to the author).

The series of questions asked that were particular to Texas and to Texas Bridges are shown in Figures 3.36-3.38. The majority of the public surveyed is on the highways almost every day. A surprising 80% of the people surveyed notice at least some of the standard bridges in the State. Of those on the highways almost every day, a similar 82% said they notice at least some of the bridges.

While 30% of the responses shown in Figure 3.38a were positive towards Texas bridges, the majority of comments were negative. The bridge comments were particularly negative by respondents from urban areas of Texas. Respondents from the international border towns felt more favorably towards Texas bridges (Figure 3.38b).

While the public had certain opinions about the bridges in Texas, they also were aware of bridges in other states. By far, the public felt that California had the nicest looking bridges (Figure 3.39a). Geographically, the Northeast and the West Coast seemed to have the most attractive bridges in the minds of those surveyed (Figure 3.39b).

Many of these responses might be representative of the States having nicer monumental bridges so it should not necessarily reflect negatively on Texas's short and moderate span bridges. However, clearly bridges can make an impression and are identified with their State. The image of a State can be enhanced or diminished through it's infrastructure.

The public was also asked to describe the culture in Texas. The responses varied but, interestingly, showed a very positive, friendly and diverse culture. When compared to the appearance of their bridges, there is little consistency between what the State represents to the people and what a considerable part of their infrastructure represents to them (Figure 3.40).

Finally, the public was asked if they felt the State would be justified in spending their tax dollars on improving the appearance of the standard bridges of Texas. The response is quantified in Figure 3.41. While the majority of those interviewed did approve of tax dollars being spent on building more attractive bridges, almost 40% were against such spending. Looking only at the

responses of those who notice the bridges, there was no significant difference in the percentage of people for or against tax money going towards improved bridge aesthetics.

Many other comments and concerns of the public regarding highway bridges were recorded. Safety was a big concern as well as avoiding traffic delays during construction. When asked to make suggestions for improvements, a majority of the responses referred to surface treatments such as painting, using more color and "decorating" the bridges.

3.3.3.1 Summary

Surveying the public on their impressions and concerns about the short and moderate span highway bridges in Texas was a valuable exercise. At least some of the standard bridges in the State are noticed by 85% of the people surveyed. People do notice their local bridges and do identify with them. The appearance of these bridges therefore can reflect the quality of life of the area. Attention to bridge aesthetics is also an opportunity for the State to display its care for the public when spending their tax dollars on an important part of their infrastructure.

When questioned about their favorite bridges, over 85% of the people surveyed named bridges that were long-span and often monumental bridges such as the Golden Gate Bridge in San Francisco. Short and medium span bridges are not attracting their attention. This may or may not be a reflection on the aesthetic qualities of the bridges. Perhaps short and moderate span bridges will never be "favorites". However, these short and moderate span bridges are a recognizable and impressive part of their built environment. The predominance of negative comments concerning these bridges of Texas shows considerable dissatisfaction with their appearance. There is a call for more attractive standard highway bridges.

There is an interesting challenge involved with recognizing the public's suggestions for improvements and their feelings towards spending tax money to improve bridge aesthetics. Most of the comments for improvements dealt with surface treatments, in particular color and decorations. Although many surface treatments do not require excessive costs, in general added color or decoration will increase costs. While 60% of the public felt the State is justified in spending tax dollars to improving bridge aesthetics, the 40% who are opposed is a significantly strong voice. What is important for engineers to recognize is that improvements must be made and searched for that will remain economical. Surface treatments are attractive and can and should be used in highly visible locations to enhance a good project. However, good engineering design with attention to improved layouts, choice of structural systems, and overall form will have more of an impact with very little if any increase in cost.

The public seems generally unaware of state-of-the-art bridge design. Engineers however, are aware of and have a better understanding of the elegant possibilities in engineering design. The strong tradition within the field of structural engineering of designing elegant *and* economical structures must be carried on. Elegant structures in the past generally have minimized unnecessary detail. The popularity of California's bridges shows what an important and good visual impression can be made with elegant structures that are simple and not "decorated". Attention to the appearance resulting from each engineering decision in the past has and in the future should continue to result in attractive structures.

As State engineers are well aware, safety and economics are typically the overriding concerns for everyone. However, the positive interest in bridge aesthetics by the public should be seen as a call for more innovative and attractive designs that will still remain economical. Knowing that the public is in support of having more attractive bridges should act as an inspiration for State engineers to strive for engineering elegance in their work.

3.4 Themes for the TxDOT Aesthetics & Efficiency Guidelines

A number of different principles, ideas and "keys for success" have been identified in previous aesthetics guidelines for bridges (see Section 3.2). Emphasizing such ideas in a set of guidelines is important and such emphasis should be found throughout the entire document. For the Guidelines, effort has been made to synthesize into three simple themes, many of the key principles that are inherent to good bridge design (including many of those addressed in previous guidelines). By minimizing the number of themes, the ideas they encompass can be more effectively understood and implemented. Rather than having up to 10 separate topics to address and apply to one project, the TxDOT engineers will be asked in the Guidelines to consider how their designs will hold up to the ideals of three main themes.

The three themes are listed here and are discussed in depth in the following sections:

(1) **Aesthetics, Efficiency and Economics** - the interrelationship of these disciplines in engineering design.

(2) **Vision** - the importance of having an overall design concept for a project.

(3) **Coherence** - the integration of the engineered design and the design concept with each decision to form a coherent, attractive structure.

3.4.1 Aesthetics, Efficiency, and Economy

The first theme in the Guidelines is that there is a strong interrelationship between aesthetics, efficiency and economics in every good bridge design. **Aesthetics** in bridge design is defined in the Guidelines as the visual appearance or impression given by the structure. Considering the visual impact of a bridge to be important, all engineering design decisions should be sensitive to bridge aesthetics. **Economics** plays a key role in bridge design particularly for public works. Engineering design decisions must always be related to their economic impact on a project. The **efficiency** of a design is directly connected to and joins together both aesthetics and economy.

Efficiency may be thought of in terms of material efficiency or construction efficiency. Material efficiency refers to optimizing material use - or minimizing wasted material. Construction efficiency refers to minimizing the time and simplifying the process of fabrication and erection. For short and moderate span bridges in particular, optimizing the construction method will often override optimizing material use for efficient design. In relation to economics, efficiency in design may for instance lead to decreasing material amounts or increasing the rate of construction, thus directly effecting the cost of the project. In relation to aesthetics, material efficiency or, minimizing wasted material, may allow the pure structural form to shine forth, thus dictating the bridge’s appearance. Efficiency therefore affects and is affected by both economics and aesthetics. For a successful result, efficiency must balance the two. It is an assumption and “prejudice” of the author and research team that efficient structural forms are a key component to the design of attractive structures. This partiality is maintained throughout the Guidelines.

Ideally, an efficient design will be one that is both attractive and economical. Different projects however, will certainly have different constraints and perhaps different demands of the public. Certain projects may demand special attention to the visual impact while others may be more controlled by a tight budget. While the emphasis of certain designs may focus more on the appearance than on the economy or vice versa, neither discipline may be entirely neglected. Efficient design will strive for economy and attractiveness no matter what the constraints are and in a balance that satisfies both the owners and the users.

To display the interconnectedness of the disciplines of aesthetics, efficiency and economics, consider three examples where the project focus is function, construction and maintenance, respectively.

Function - A balance of aesthetics, efficiency and economics can be achieved by focusing on the function of the bridge and its elements. If the bridge is to span a valley, an efficient form might be an arch - the valley walls are natural abutments therefore eliminating the need for man-made abutments (Figure 3.42). If the bridge is to span a highway (grade separation) a slender beam system might be chosen to satisfy clearances and minimize the height of the built up approaches. Angled piers may be chosen to provide more horizontal clearance without increasing the central span, and to minimize foundation requirements by taking advantage of required retained earth or abutments (Figure 3.43). Focusing on the function, efficient forms are chosen to take advantage of natural conditions (valley) or project constraints (need for abutments or certain vertical clearances). Searching for an efficient form in these examples has a direct effect on economics - foundation costs could be minimized. Such decisions also have a direct effect on the aesthetics of the structure. The visual impression of the structure results directly from the choice of overall form. Clearly this choice of form at the outset has more aesthetic effect than any embellishments or additional color or texture that could be added at the completion of the project.

Construction - Aesthetics, efficiency and economics may be driven by construction methods. For the use of highly repetitive bridge elements, precasting is cost effective. In congested areas, this method of construction may be much faster than cast-in-place construction thus reducing traffic delays and on-site labor. This has been conclusively shown in the development of highly efficient, slender precast pretensioned I, U and box beams. The slender and efficient use of concrete for these superstructures has had a direct positive effect on bridge aesthetics. However, in the case of substructure design, most short and moderate span bridges use standardized but less attractive and inefficient cast-in-place systems. Often large amounts of highly repetitive form assembly, bar placement and field concreting are carried out at hazardous and inefficient elevations over long time periods which can substantially disrupt or constrict traffic (Figures 3.44-3.45). A more artistic and efficient substructure shape could be precast economically for repetitive use (Figure 3.46). Quality control and material characteristics would be improved with precasting and lead to more attractive finishes and more durable substructures. The attractive finishes and improved durability will decrease future maintenance costs as well by no longer requiring painting. On site construction time could be considerably reduced leading to lessened traffic disruption and traffic control costs.

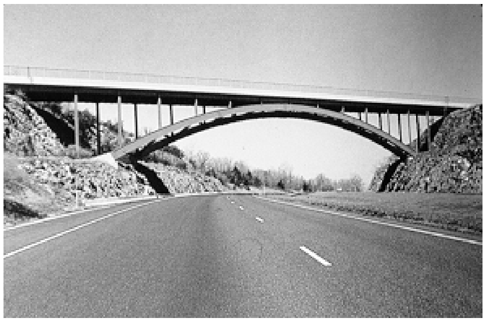


Figure 3.42 An arch bridge taking advantage of the natural abutments

Figure 3.43 Angled strut piers decrease the clear span and superstructure depth while increasing clearance for traffic passing through (photo, Reference 23)

Figure 3.44 Highly repetitive substructures requiring extremely tall and strong forms

Figure 3.45 Repetitive cast-in-place columns requiring considerable on-site labor and space

Figure 3.46 Precast concrete substructure systems can be efficiently fabricated and erected with attractive and durable results.

Maintenance - Aesthetics, efficiency and economics may be combined while concentrating on maintenance issues for a project. Many nagging and expensive maintenance issues result from problems with "surface" aesthetics, such as unwanted staining of concrete, or peeling of paint. Bridges in highly visible locations may be designed with a focus on avoiding such maintenance problems. For instance, with attention to issues of proper drainage considered at the outset as part of the plans, aesthetics will be improved with negligible cost (Figure 3.47). An efficient design will incorporate problem-solving details in an attractive and economical way. Drain pipes may be hidden inside hollow columns or drip lines may be incorporated into the structure to avoid or control unwanted staining. Attention to surface treatments such as exposed aggregate or use of texture and formliners can replace the need for painting thus ensuring an attractive appearance while decreasing maintenance and life span costs (Figure 3.48).

3.4.2 Vision - Developing a Design Concept

The second major theme in the Guidelines is that a designer must have a vision or, develop a design concept for each project. It is important for the designers to have an *initial vision* of how the bridge will function and appear in it's *final form*. The basis of a vision or design concept may vary widely. It may be a result of the geography or the local culture. It may result from the support conditions expressing structural function or local construction practices. Vision has always been a necessary element of successful engineering works.

Great engineers of the past conceived and carried out their vision of what an appropriate and attractive structure would be for a particular site. Swiss engineer Robert Maillart was driven by the desire to build very light elegant structures that were simple to construct. His structures were often designed as entries in design competitions where the low price solution was usually the winner. Efficiency, constructability and low cost were driving forces behind his vision for winning bridges (Figure 3.49). The elegance of Maillart's designs clearly show that beauty does not have to equate with costly.

The former Figg & Muller Engineers Inc., had a tradition of developing and carrying out visions for their designs. They were the designers of five segmental concrete bridges along I-70 through Glenwood Canyon in Colorado (Figure 3.50). The breathtaking beauty of the canyon was well appreciated as it was the site of the most frequently hiked trail in Colorado at the time the project began in 1981.[32] Figg & Muller's vision for this bridge was sensitive to the natural beauty of the site and focused on the design of structures that would harmonize with the environment. Post-

Figure 3.47 Use of internal drain pipes

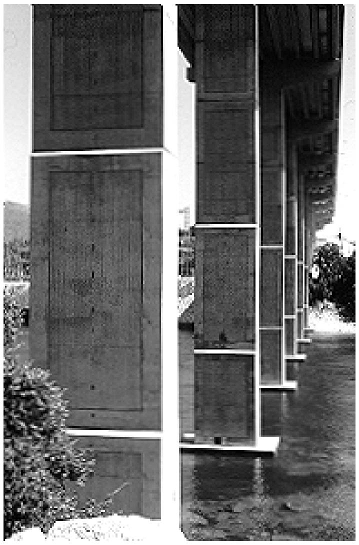
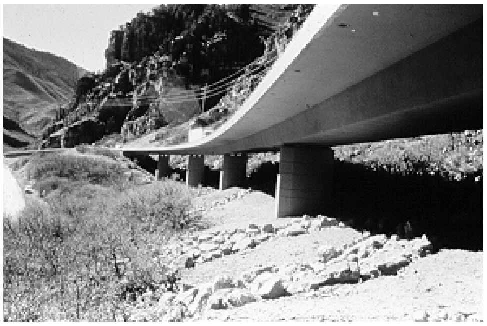


Figure 3.48 A formlined surface eliminates the need for painting.

A vision of expressing the thinness possible with reinforced concrete in an arch form.

Figure 3.49 Maillart's Salginatobel bridge in Switzerland



A vision of harmonizing with the striking beauty of the environment

Figure 3.50 One of five segmental bridges along I-70 through Glenwood Canyon tensioned segments were chosen as the structural system for both the piers and the superstructure and a major portion of the work was carried out from the already placed superstructure (Figure 3.51). This method of construction minimized site impact by reducing the large amount of temporary bracing built from the ground below, typical of cast-in-place construction. Segments were cast indoors using the short-line method allowing fabrication to occur indoors year round - an important feature in Colorado's typically harsh climate where the construction season is short.[32] All of these techniques were efficient and economical solutions that the engineers chose in order to comply with their vision of harmonizing with the environment. The success and attractiveness of the project is clear and was recognized in a project description; "...the roadway blends into the scenery so smoothly that it seems a natural part of the canyon. ....as is so often the case, this natural appearance was gained only through careful planning and painstaking attention to details."[32]

TxDOT as well has built bridges with a vision of minimizing environmental impact on the surroundings. The Loop 1 ("Mo-Pac") extension over Barton Creek in Austin is a standard precast I-girder bridge with attractive single column hammerhead bents. The precast beam superstructure was placed from above to minimize disturbance to the site below (Figures 3.52a&b).

There was a consistent vision behind the US183 elevated highway in Austin (Figure 3.53). Attention was paid to the environment as human scale was introduced through relief in the tall columns. At the same time the progressive and technological environment of Austin was expressed in the state-of-the-art technology of the precast segmental box girder. The interesting new column shape is an innovative solution to expressing both the construction and structural function of the bridge. The notch in the "Y"-shaped piers provided a support for the erection truss used to erect the superstructure. The need for temporary supports or attachments to the piers was minimized. The function of the piers to carry the bridge loads down to the foundations is expressed in the unique "Y" shape. The exposed steel carries tension and the concrete is primarily in compression.

In all of these examples, the vision and design concepts were developed through experience over time. Vision is not a sudden inspiration attained only by a chosen few artists. Rather, vision is the product of long and careful consideration throughout one's career. Some examples follow.

Maillart began many of his projects by imitating previous designs. Examining his work, one can see the development and evolution of his design concepts. The Inn River Bridge at Zuoz, Switzerland completed in 1901 was a 3-hinged box arch with solid side walls. When the bridge was in service, Maillart noticed cracks appearing in the walls. Upon investigation, he realized that the

Precast segmental superstructure placed
on erection trusses using a launching gantry
from the already built deck

Figure 3.51 Minimizing site disruptions

Figure 3.52a Steel girders positioned for straddle cranes

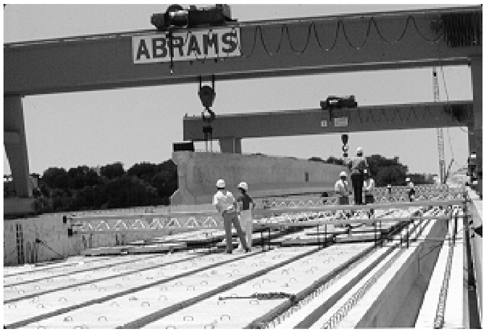


Figure 3.52b Placement of precast girders using straddle cranes

Figure 3.53 US 183 in Austin Texas during construction

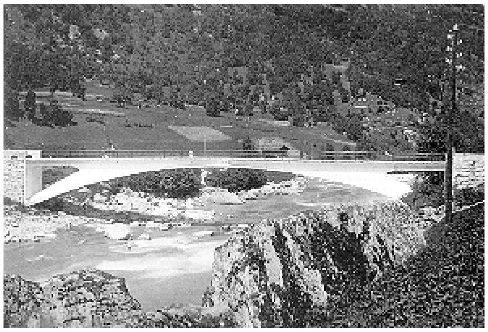
cracks were due to shrinkage and temperature problems and that in fact the solid wall of concrete was not needed structurally. In a later design of a three-hinged arch for the Rhine River Bridge at Tavanasa, Switzerland completed in 1905, Maillart removed the unnecessary material resulting in a new and elegant form that was more efficient than that of the Zuoz - the amount of unnecessary material was reduced. With each new design, new challenges were faced and new structures, ones that were further refined, were the result (Figures 3.54-3.55).[33]

In Texas, the continuous development of design concepts can be seen as well. In the past, many short span slab bridges with trestle bent substructures were built. These were simple to construct as well as economical. Over the years, TxDOT has developed the use of the highly efficient and economical precast, prestressed I-girder for bridge superstructures. TxDOT carried out their vision for efficient economical design in pursuing this new form. Aesthetics were improved as well. Longer and more slender spans were achieved, allowing for less substructure and therefore increasing the visibility through the bridge (Figures 3.56-3.57).

The development and construction of segmental box girder bridges is another example of refining design concepts in Texas. Segmental concrete bridge construction has been developed and advanced over time in Europe and more recently in the US. Economic savings through the ease of construction has been the guiding vision for the development of segmental bridge construction.[34] Both the economy and flexibility of construction techniques for building precast segmental box girder bridges led to the design of the first of these bridges in the US - the JFK Causeway in Corpus Christi, Texas (Figure 3.58). A later segmental box girder water crossing was the Long Key Bridge in Florida designed by Figg & Muller. Here the basic ideals from the JFK Causeway of economy and flexibility in construction were incorporated and refined to form a different and very attractive structure (Figure 3.59). Figg and Muller then brought their experience and ideas back to Texas where the choice of a segmental box girder bridge fit the vision for their design of the San Antonio “Y” project. The “Y” project bridges were to be built in congested urban areas where speed of construction was essential, high visibility required particular attention to aesthetics and the use of public funds demanded an economical solution (Figure 3.60). A number of years later, TxDOT saw the vision of the “Y” project fitting well with the US183 project in Austin and also chose to design and construct segmental concrete box girder bridges for their elevated highway. The vision for economy, attractiveness and speed of construction was carried further through the design of segmental piers to speed construction and improve the piers’ surface texture (Figure 3.61). Each project’s vision incorporated a basic ideal of segmental bridge design - economy of construction.

Cracks appeared in the side walls of this three-hinged box-arch when the bridge was put in service.

Figure 3.54 Robert Maillart's Inn River Bridge at Zuoz, Switzerland.



The side wall material not required structurally was removed from this three-hinged arch resulting in a new, elegant, and more efficient form.

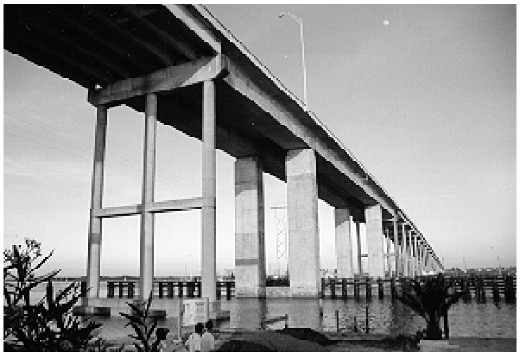
Figure 3.55 Maillart's Rhine River Bridge at Tavanasa, Switzerland.

A common bridge system used in Texas up to the 1960s

Figure 3.56 Short span slab bridges with trestle bent substructures

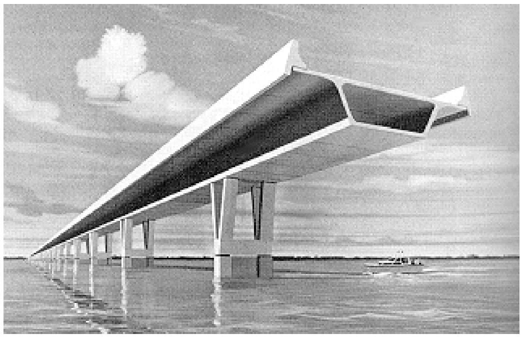
The development of standard precast prestressed I-girders has economically increased span lengths and reduced the number of required substructure units

Figure 3.57 Prestressed I-girder bridge



A vision of improving economy through a flexible construction technique

Figure 3.58 The JFK Causeway in Corpus Christi, Texas



Segmental bridge construction with a different and very attractive result.

Figure 3.59 The Long Key bridge

Segmental construction provided attractive and rapid construction for the highly visible and congested urban site

Figure 3.60 The San Antonio "Y"

Segmental construction allowed for rapid construction and improved surface finish

Figure 3.61 US 183 in Austin, TX

And each project can be seen as development or refinement from the previous one, all with efficient and quite different aesthetic results.

The study of past works to understand what the key visions were for various projects in different contexts helps guide the design process. It is also important for engineers to write or speak about their own projects to share ideas and experiences. Communication furthers collaboration between designers and builders. Familiarity with previous works of other engineers provides a foundation from which engineers may develop new forms or ideas for the bridges that they design.

Regardless of how vision and design concepts develop, the TxDOT Guidelines urge that the concept must be considered at *all* stages of the design process - from planning and layout to super- and substructure design to non-structural details such as choice of railings or surface texture. With design intentions formulated at the outset, guidelines will then be useful in aiding designers to carry out their vision for a bridge. Guidelines are simply a set of tools to be accessed and referred to when needed. Designers must hold true to their ideas and vision for a design in order to produce well-integrated and attractive structures.

3.4.3 Coherence

The third major theme of the Guidelines is that all projects must be coherent. Coherence for the Guidelines is defined in two ways, as an intellectual objective and as an objective for the final design form. As an intellectual objective, coherence for bridge design in accordance with the Guidelines refers to the integration of the engineered design and the design concept with each decision. As an objective for the design form, coherence is achieved when a structure is seen as one united composition rather than the sum of unrelated parts. The relation of each bridge element to another should have an apparent logic. A coherent form will have well-integrated parts. Standardized bridges in particular are made up of many individual elements. The successful integration of the elements together *and* in accordance with a design concept or vision for the bridge will lead to an attractive, coherent design.

Coherence may be striven for with every step and every decision made during design. Coherence also requires attention to how the many different parts of a design will come together. The principles of efficient and economic design applied in accordance with an aesthetic vision for a bridge must guide each step. All decisions made with the same set of goals in mind will lead to a well-integrated structure. Decisions which are as basic as the support layout or as detailed as drainage pipe locations all have an important effect on the coherence of a structure. (Detail decisions are particularly important for life span and maintenance considerations.) There are many examples of bridges which have attractive layouts and overall form (Figure 3.62) yet which have little attention to non-structural details (Figure 3.63). While the objective of relating the bridge elements to one another may be achieved, the objective of adhereing to the design concept at every step of the design process was not. The result is a non-coherent, unattractive structure when seen up close. Another common example of non-coherence occurs when bridges with poor layouts or dull forms are simply painted differently or covered with a textured facade (Figure 3.64). The objective of relating bridge elements to one another for coherent design is ignored. Instead, an attempt is made to mask the lack of attention to element relation. Such attempts to mask a dull form are rarely successful and the result typically remains an unattractive structure.

A classic example of a coherent structure is the Linn Cove Viaduct along the Blue Ridge Parkway in North Carolina. The attractive setting alongside Grandfather Mountain demanded a structure that would enhance and not detract from the site's natural beauty. The vision then developed by the designers was one of harmonization with the environment with the least amount of environmental impact on the surroundings. The idea of harmonization was first addressed with the geometric layout through the decision to have the bridge follow the curve of the mountain side (Figure 3.65). This was carried out in superstructure design through the use of a segmental box girder - a form of construction well-suited to curved layouts. Segmental construction was used for the elegant substructure design as well. Pier segments were precast using local materials in a highly efficient form. They were lowered into position from the already built deck and later post-tensioned together. This novel construction technique ensured minimal disruption of the surroundings and thus complied well with the vision of harmonization with the site. Further harmonization was achieved by coloring the concrete to match the natural rock surroundings.[35] This attractive, coherent project was the result of careful attention to the design concept. The concept had been developed at the outset and carried out through each decision - from the layout to the structural system to the non-structural details. The viaduct won a Presidential Design award in 1984.

The Chillon Viaduct in Switzerland was built in a similar environment of treasured natural beauty as the Linn Cove Viaduct. The Chillon Viaduct however, can be seen as carried one step further in terms of artistic shaping and a more coherent relationship between the superstructure and the substructure (Figure 3.66). The continuous segmental hollow box girders are haunched over the supports reflecting the larger moments at this location (the connection between the horizontal and vertical structural elements). The substructure is made up of two slender walls per pier. Both of these element forms (haunched girders and wall piers) have an improved material efficiency compared to the Linn Cove Viaduct and give the Chillon Viaduct a light, elegant appearance when viewed from the side - the most heavily viewed angle.

When coherence is referred to in the Guidelines, it is meant to remind the engineers both to combine their engineering decisions of efficiency and economy with their overall design concept and aesthetic intentions for their bridge and to carefully consider the relation of the the different bridge elements to each other.

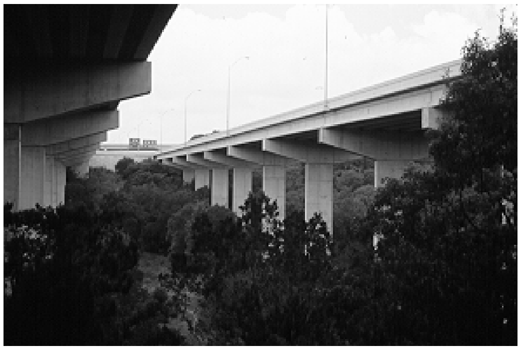


Figure 3.62 The even, repetitive single-column bents provide an attractive and well-balanced appearance.

Figure 3.63 Lack of attention to concrete finish detracts greatly from the overall bridge form. These piers are heavily viewed from a popular hike & bike trail

Figure 3.64 An attractive coat of paint does little to improve this awkward skewed layout

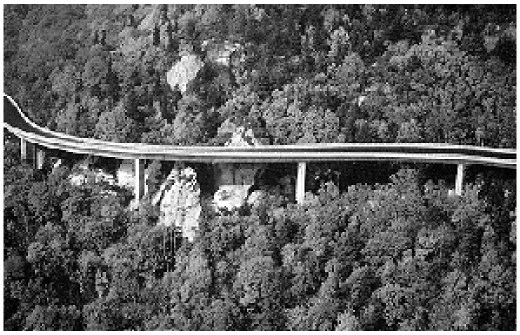


Figure 3.65 The Linn Cove Viaduct in North Carolina

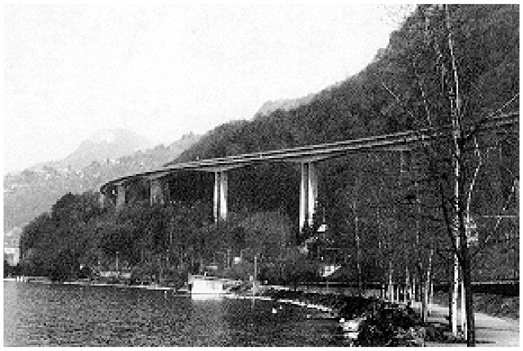


Figure 3.66 The Chillon Viaduct on Lake Geneva in Switzerland

3.4.4 Summary

These themes appear in all sections of these guidelines. Ideas and principles from previous guidelines have been implicitly incorporated into the Guidelines. Some of the previous ideas can be pecifically grouped under the headings of addressing aesthetics, efficiency and economics, developing a design concept, or striving for coherence (see Maryland and Minnesota Guidelines, Section 3.2.1). Other ideas such as those addressed by Leonhardt (Section 3.2.1) are techniques and tools that can be used to carry out the themes of the Guidelines.

The three themes of the Guidelines are presented with numerous examples and the ideals of the themes are continually referred to throughout the document. The intent is to have the engineers adhere to these ideals to improve the overall appearance of their bridges within their economic constraints.

3.5 Goals of TxDOT Aesthetics & Efficiency Guidelines

Texas is recognized nationally as being at the forefront of building highly efficient and economical precast prestressed concrete bridge superstructures. Therefore the Guidelines for bridge design are focused primarily on issues related to concrete bridge design. Presently, these standard prestressed girder and slab superstructure bridges dominate the Texas landscape. With more careful attention given to layout and substructure design, the overall attractiveness and efficiency of these bridges can be greatly improved.

Aesthetics is often a matter of individual preference. It is an issue that can be addressed by everyone. Many designers and engineers feel that factors such as safety, serviceability and function are too restrictive to allow for attention to aesthetics or that attention to aesthetics automatically means greatly increased costs. These guidelines are proposed to dispel these beliefs, to exhibit the numerous opportunities that engineers and planners have to make aesthetic decisions throughout the design process and to provide specific recommendations, principles and examples that can help designers and planners develop more attractive bridge structures. With an understanding of the limitless possibilities that may improve a bridge's appearance, more attractive structures can be built that remain safe, serviceable and economical.

3.5.1 Engineering and Aesthetics

These guidelines are meant to be used from the beginning of the design process, not as a type of “quick fix” once the design is complete. The reason for this is that artistic and visual impressions of bridges are made as a result of the *overall* structure (geometry, layout and structural function of elements) not ornamentation. Therefore the Guidelines emphasize the ways in which different engineering decisions will effect the aesthetics and efficiency of the project. Figures 3.67-3.70 are a few examples of such considerations taken from the Guidelines.

Figure 3.67 shows a number of different layout options possible for a four lane bridge. Each option effects not only the engineering design but also the appearance of the built structure. Figures 3.68a&b show the aesthetic results of using two 2-lane bridges in place of one 4-lane bridge, similar to the proposals of Options III and IV in Figure 3.67.

Figure 3.69 is another excerpt from the Guidelines that displays the benefits of making quick “back-of-the-envelope” calculations. In evaluating the cost of increasing the apparent slenderness of a three span overpass, a quick study was made to determine the economics of pushing abutment walls back and increasing span lengths. Various span length increases were examined for different bridge widths. In the case of pushing abutments back by 40 ft. each (Case II), an extra substructure unit would be required. Of course, this option is dependent on the use of the space underneath the bridge. In four of the six cases examined, either savings were achieved or minor costs were incurred in solutions which resulted in more slender and attractive structures. Only two of the six cases incurred appreciable costs. Most importantly, such quick studies in the Guidelines are used to show engineers how simple engineering decisions can lead to considerably different visual results. These studies and calculations displayed in the Guidelines are easy to perform - the cost data for instance, is readily available for each District. It is important to stress to the engineers the ease with which such studies can be made. As a result, the economic impact of layout changes that will effect the bridge’s appearance can be made quickly therefore allowing for many alternatives

to be examined. Examining many alternatives is essential in the early stages of a design when changes can still be made - before time-consuming analysis is conducted and designs are "locked in."

With the design options shown in Figure 3.70, the engineer may choose a continuous superstructure system with or without moment connections to the supporting piers. Where columns are not integral with the superstructure, continuity of the superstructure may be desired to minimize the number of deck joints required and therefore improve the riding surface. (Flexible supports could be used to further reduce the number of expansion joints required along the bridge.) A moment connection between the superstructure and substructure may be chosen and is often required in seismic regions. Clearly the visual impressions of these two structural systems are quite different.

Figure 3.68a A wide bridge can create a dark cluttered space

Figure 3.68b Splitting a wide bridge into two separate bridges allows more light to reach underneath

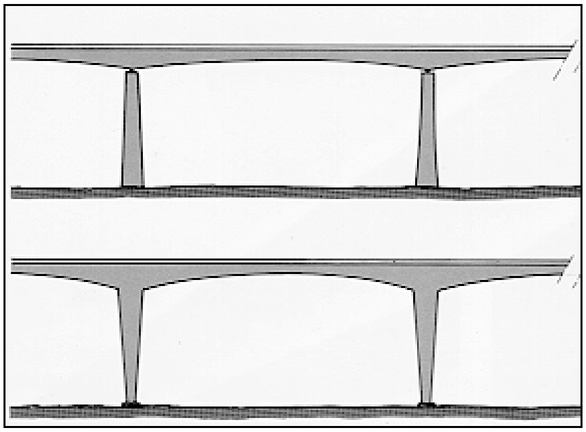


Figure 3.70 Different structural systems creating different visual impressions[23]

The examples in Figures 3.67-3.70 clearly show the ability of the designer to effect the bridge's appearance through straightforward engineering decisions such as structural system and layout choices.

For successful results, aesthetic considerations must be made at each step and should never be afterthoughts. While attention to non-structural details is important, it should not be the primary concern in bridge design. Details are best considered as a means to enhance the aesthetic decisions already made regarding the overall bridge structure.

3.5.2 Propose Questions Rather Than Rules

Engineers are most accustomed to Codes and Specifications that are basically books of rules. US Codes in particular are often prescriptive (rather than performance based) leaving little room for engineering ingenuity. This "rule-book" approach typical of codes would not be successful in Aesthetics & Efficiency Guidelines. Aesthetics in particular is subjective. There is never a unique "correct" solution for a bridge in a particular site. With aesthetics, the problem often arises that engineers feel they lack creativity. As aesthetics is so rarely discussed in most engineering curricula, the Guidelines have been developed as an educational document as well as a guide.

To spark creativity, the Guidelines propose questions for designers to ask rather than provide lists of "do's" and "don'ts" which tend to stifle creativity. Pointing out where the engineering decisions affect aesthetics is a way to join the familiar with the less familiar so as to result in more creative and more attractive bridge designs.

3.6 Outline of TxDOT Aesthetics & Efficiency Guidelines

3.6.1 Organization and Scope

An outline of the Guidelines is given in Figure 3.71. The entire Guidelines are presented in Volume II of this dissertation. The Guidelines are organized in the order of the design process. They contain suggestions of what to consider at each phase of design to lead to efficient and aesthetically pleasing structures. Typical decisions which can enhance aesthetics are illustrated and are related directly to other considerations such as function, safety, serviceability and economics. Possible aesthetic improvements are pointed out while still utilizing the most suitable and economical structural shapes and standard bridge components.

In each of the chapters covering the design process (Chapters 2-5), the many design options in terms of structural systems are presented. Potential aesthetic results or improvements are discussed. Each topic is presented along with illustrations of its relevance and effect on aesthetic results as well as implications for efficiency. Suggestions are given for the best implementation of proposed ideas. Case studies are made at each design step to outline aesthetic improvements and potential economic impacts of the suggestions offered.

At the conclusion of the guidelines, a chapter entitled “Particular Settings” addresses the most important considerations for given scenarios and site conditions. These scenarios include urban expressways, causeways, urban interchanges, overcrossings in both urban and rural settings, and bridges in environmentally sensitive areas. An additional small chapter is included that covers issues to consider when widening existing bridges.

Appendix A presents different aesthetic “techniques” that may be employed throughout the design such as proportioning systems or optical corrections. These are techniques typically taught in architecture schools but rarely introduced in engineering education. These are helpful tools that are simple to use and easy to learn. Appendix B presents information on surface treatments for concrete. Surface treatments discussed include exposed aggregate, formliners, color through staining or painting, and concrete pavers. These surface treatments are discussed in terms of aesthetic options, typical uses, maintenance concerns and relative costs. Appendix C presents an alternative substructure system that is made up of primarily precast (match cast) column and cap elements. This system is presented more fully in Chapter 4 of this dissertation.

3.6.2 Layout

Determining the most appropriate layout for the Guidelines was an important task. It was essential that this document be "user-friendly" - helpful to both bridge and highway engineers at various levels and above all, easy to read, follow and implement. Meetings of the research team with various publishers led to the hiring of University Publications of Austin, TX, to design the layout of the document.

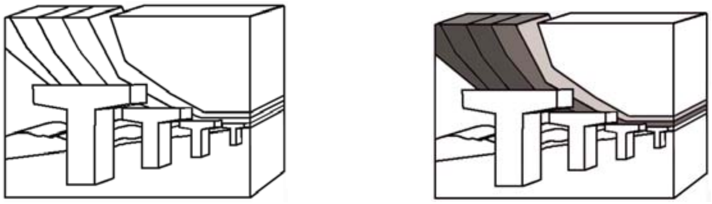
The "landscape" orientation of the page was chosen to allow more room for comparative photographs. The binding at the top of the page also allows for easier reading and reference on a desk full of other codes, calculation pads and plan sheets. The top half of the guidelines can be propped up against other books or a back wall.

The Guidelines were designed to be read at many levels, similar to the Maryland DOT Guidelines. Informative quotes are pulled out into side margins. These quotes can be read alone and give the reader a good understanding of the ideas presented in the Guidelines. Captions beside the figures as well allow for an understanding of the basic idea being illustrated. If a certain idea is particularly attractive to someone, they may then go in and read the text on that topic. The more curious reader will benefit from reading the entire text. There are also a number of pages referred to as "sidebars" that are not a part of the body of the text but are examples of applications of principles presented. Each of these "sidebars" occupies a full page and has a similar blue background. The case studies, also not part of the body of the text but still different from the sidebars have a similar background as the sidebars but are of a different color. A special logo was designed for the upper right-hand corner of each page to signify which chapter the reader is in. When in the Planning & Layout Chapter, only the ground of the logo is highlighted. In the Superstructure Chapter, only the superstructure of the logo is highlighted and so on (Figure 3.72).

The attractive appearance of the final product and the ability of the document to be read at different levels of interest is essential for this to be a useful document and not simply another manual that will collect dust.

3.7 Summary

Thorough investigation of existing guidelines, photo surveys of many short and moderate span Texas bridge types and interviews which indicated many concerns of the designers, owners and users of the standard highway bridges in Texas provided a strong background from which to develop



Basic logo, no highlighting

Logo for Superstructure Chapter

Figure 3.72 Example of logo used for the main chapters of the Guidelines

the TxDOT Aesthetics & Efficiency Guidelines (Guidelines). The Guidelines are a manual that bridge designers and highway planners can refer to throughout the design process. This manual is meant to illustrate to the engineers how their engineering decisions are impacting the aesthetics and efficiency of their designs. The Guidelines offer suggestions and propose questions for designers to ask during design, rather than provide a book of rules with do’s and don’ts.

Three major themes incorporating numerous ideas and principles for attractive structures have been emphasized throughout the Guidelines. The first theme asserts that designs must strive to balance aesthetics, efficiency and economics. The second theme stresses that each design must be carried out according to an initial vision or design concept for the bridge. Design concepts must be developed by all parties involved in a given bridge project. The third theme maintains that designers must strive for coherence in their projects by adhering to the design concept at each stage of the design process.

Developing aesthetic awareness can begin with such a set of Guidelines but must also be nurtured in all engineers through support from top managers in engineering offices. As well, there must be a willingness of all parties involved in a bridge design to come together and address constraints and pertinent issues at the outset of a project.

With more attention given to aesthetics and efficiency through use of the Guidelines, the Texas Department of Transportation can continue to design safe, serviceable structures that will enhance their settings and the Texas highway system. The Guidelines challenge State DOT engineers to be creative and to include aesthetics equally with the more commonly recognized engineering disciplines of economy and efficiency. More attractive and more efficient short and moderate span bridges, bridges that account for the vast majority of our highway bridges, must now be designed. Following the TxDOT Aesthetics & Efficiency Guidelines as an initial step toward more creative design, designers will be able to maintain pride in their work while the public maintains pride in their State.

CHAPTER 4
ALTERNATE SUBSTRUCTURE DESIGN - PROPOSED PRECAST CONCRETE SYSTEM

4.1 Introduction

The current common practice in Texas for bridge substructure design and construction is basically the same now as it was forty years ago. Cast-in-place circular columns with cast-in-place rectangular bent caps is the most widely used system. Occasionally rectangular single or multi-column bents with rectangular or inverted T bent caps are used. These are frequently found in urban settings. However, substructure design in general has stagnated. Creativity has been stifled through the desire to re-use the same shape for every project for economic savings. Poston et. al. summarized a survey of common pier designs built between 1960 and 1980.[36] The survey results represented information on over 155,000 built piers as reported by 38 organizations including 24 States and the Federal Highway administration. The vast majority of pier types designed by these organizations fall into two categories - category A for single columns (Figure 4.1a) and category A for multiple column bents (Figure 4.1b). The cross sections of the various columns are predominantly one of three shapes for single column piers and one of two shapes for multiple column piers (Figure 4.2). The trend towards monotony in pier design has been nation-wide, not just particular to Texas.

The substructure designs most commonly used in Texas are not only fairly ugly, but they have not proven to be particularly durable. Fifty-four-percent of the State owned bridges (“On-system bridges”) in Texas that are deficient have substructures in “poor condition” or worse. “Poor condition” is defined as advanced section loss, deterioration, spalling or scour.[37] With increased understanding of durability problems and developments in state-of-the-art technology to avoid such problems, new designs, materials, details and methods of construction must be applied to substructure design. Numerous improvements can be made in terms of appearance, material and construction efficiency and economics in the standard highway bridge substructures of Texas. New designs may include new shapes for both cast-in-place and precast substructure systems. Materials that may be applied to substructure design include high performance concrete and prestressing steel. Details of structural connections and of non-structural surface treatments can and should be investigated. New methods of construction such as precasting segmental piers, can offer economic savings for bridge designs in some locations.

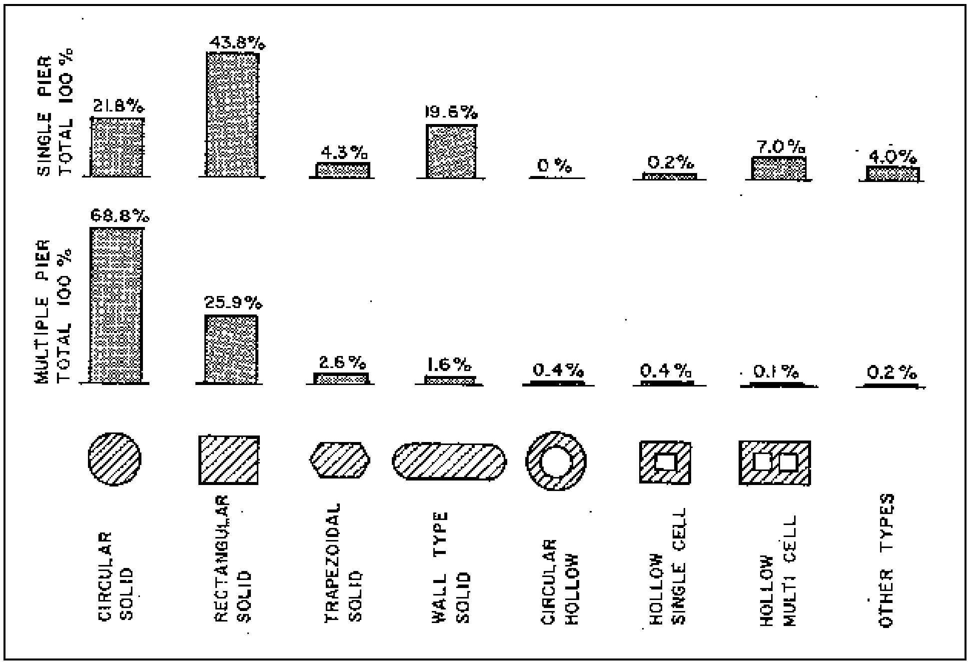


Figure 4.2 Survey results of pier cross sections built from 1960-1980[36]

The goal of Chapters 4 & 5 of this dissertation is to document the development of new substructure options for the Texas Department of Transportation (TxDOT). The substructure systems explored are compatible for use with the precast beam superstructure systems used throughout the State. This Chapter reports on a primarily precast substructure system that was developed for a wide range of project types and sizes. A limited preliminary system was developed by Barnes and is reported in Reference 9. Section 4.2.3 presents the preliminary design and Sections 4.2.4 and 4.2.5 discuss the evaluation of the preliminary system and redesign for a final proposed system. Alternative substructure options using all cast-in-place elements or both precast and cast-in-place elements are discussed in Section 4.3.

4.2 Development of a Precast Substructure System

4.2.1 State-of-the-art Technology

Precasting of bridge elements in the past has been primarily for superstructure elements. Precast girders of I, T, U and box cross sections make up the majority of the short and moderate span highway bridges in Texas. As discussed in Section 3.4.2, precast segmental box girder construction was first introduced in the United States in 1971 for the JFK Causeway in Corpus Christi, Texas. Twin segmental box girders were designed and constructed for the main spans of this causeway (Figure 4.3). Since the introduction of precast segmental construction to the United States, a large number of other segmental box girder superstructure bridges have been completed (see References 29-30,32,35,38-45). This method of construction for box girder superstructures has proven to be very economical, particularly for highly repetitive moderate span as well as long span projects. The state-of-the-art for segmental construction is evolving and there are numerous different construction methods for segmental superstructure bridges.[30,34] This bridge type can result in very elegant designs (Figure 4.4) and is a durable system.[46]

Application of precast segmental technology to substructure design has been more limited. In particular, segmental construction for shorter span bridge substructures (spans less than 45m (150')) has been explored very little. Where precast substructures have been used, they have been used for a variety of project types with a variety of different substructure elements being precast. A brief survey of past projects utilizing precast substructure elements, recent trends for segmentally precast short and moderate span bridge elements as well as future applications for precast substructure systems is presented in the following sections.

4.2.1.1 Past Projects with Precast Segmental Substructures

Precast segmental substructures have distinct advantages for certain design situations. Speed of construction, construction in difficult to access sites and minimization of construction's environmental impact are key reasons that precast segmental construction has been used in the past. Large projects allow for efficient production of repetitive elements in the controlled environment of a precasting yard or plant. Plant production is particularly advantageous in harsh environments where the construction season is short. Precast elements can be fabricated year round in a precast plant. Precasting pier elements minimizes the amount of on-site construction work thus reducing traffic re-routing and delays as well as the environmental impact of the construction process. References 29-30, 38-39, 40-42, 44 and 47-50 describe a number of projects where segmental construction of piers has been used advantageously. A brief summary of many of these projects is given in Reference 9.

Different elements within substructure systems have been precast for different projects. At Redfish Bay,[28] precast pile caps were placed over drilled precast piles to construct a long low water crossing (Figure 4.5). Precasting the pile caps saved the contractor six months of construction time by avoiding the need to place fresh concrete over water. Precasting also provided better quality control for concrete placement. At the Linn Cove Viaduct, hollow pier elements were precast and then lowered into place from the newly constructed superstructure above to minimize construction impact on the site below (Figures 4.6).[29] Precast piers were used at Vail Pass to minimize site impact (Figure 4.7).[30] Precast caisson elements have been used for a number of water crossings to speed construction (Figure 4.8).[51,52] The high quality control of concrete fabrication in a precast plant was used advantageously for hollow column segments that would support an ocean pier in South Africa.[53] The interlocking, stacked, hollow column segments were used as a dense corrosion-resistant form that was filled with tremie concrete. The largest bridge project carried out in the middle east as of December 1989 was the Bahrain Causeway which was constructed almost entirely out of precast elements.[54] Pile foundations, pile caps and pier shafts for six pile caps on either side of the three main spans of this causeway were all precast. Precast hammerhead caps have also been used in the past to top cast-in-place columns (Figure 4.9).

Past projects, although limited in number, have shown that precasting substructure elements is feasible and advantageous for a wide variety of project types. New applications for precast substructure elements continue to be explored.

4.2.1.2 Recent Trends for Segmental Construction of Short and Moderate Span Bridges

Segmental construction has traditionally been used in moderate and long span superstructure design. This method of construction is now being further explored for applications with short to moderate span super- and substructure design.

A joint committee of the Precast Concrete Institute (PCI) and the American Segmental Bridge Institute (ASBI) has developed standards for precast segmental box girder sections for use with spans between 30-45m (100-150ft.) for span-by-span erection and 30-60m (100-200ft.) for balanced cantilever construction. These standards can accommodate deck widths of 8.4-13.5m (27-44ft.). Standard design sheets with design examples have been assembled by committee members from different bridge design offices in the United States.[55] Designs similar to the standards being developed have been used successfully for moderate span bridges constructed by the span-by-span method such as at the Florida Keys,[38,39] in San Antonio, TX[43] and in Austin, TX.[44]

The bridge design firm J. Muller International has developed a segmental bridge system for spans between 15-35m (50-115 ft.) named the Segmental Concrete Channel Bridge System.[56] This system of channel segments is longitudinally post-tensioned together and may be transversely pre- or

Figure 4.3 The JFK Causeway in Corpus Christi, TX, 1971

Figure 4.4 The San Antonio "Y" project in Texas shows off the elegance possible with segmental concrete bridge design

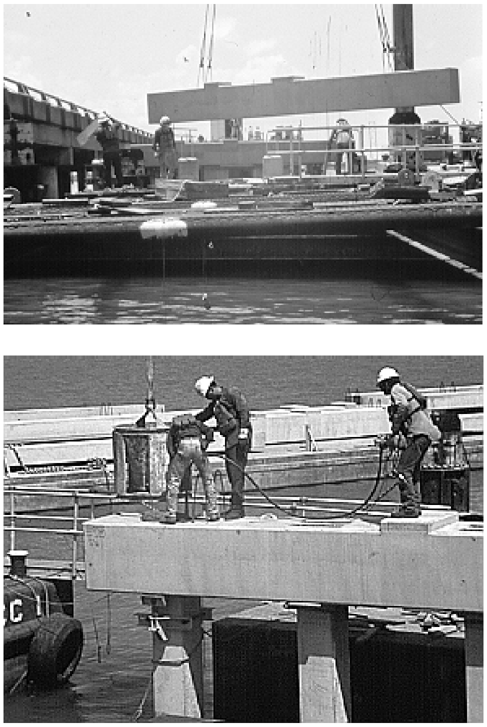


Figure 4.5 Precast pile caps for the Redfish Bay low water crossing

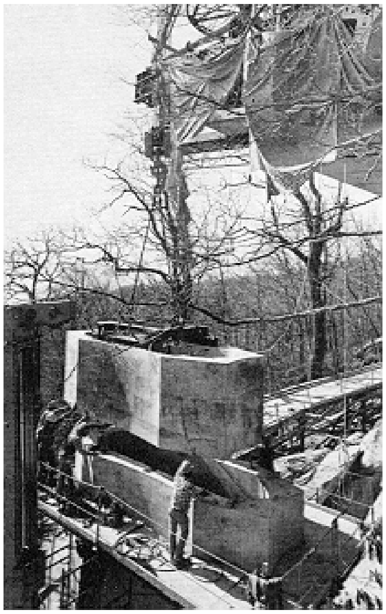
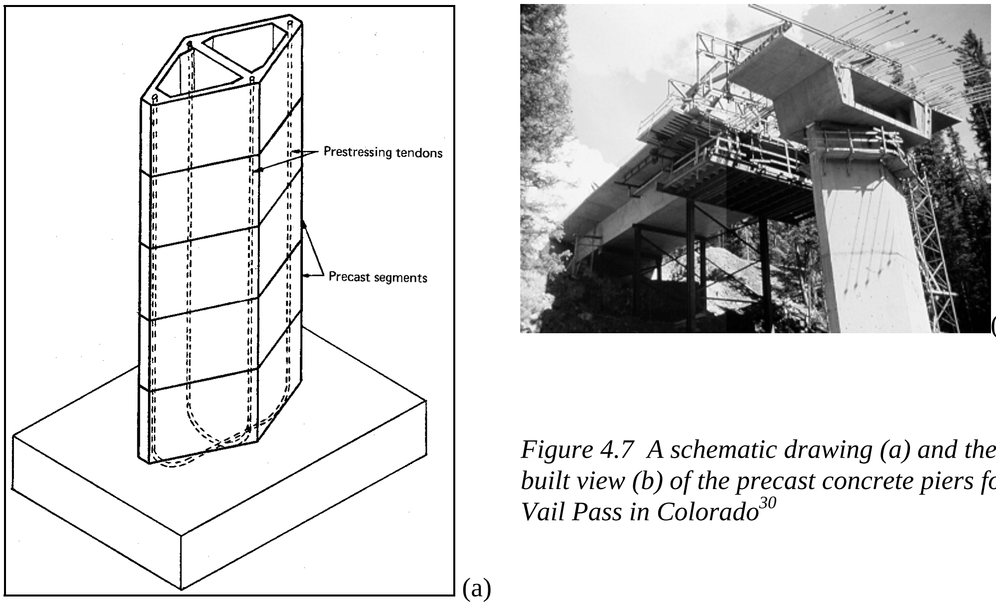


Figure 4.6 Precast hollow concrete pier segments lowered into position from the deck above at the Linn Cove Viaduct in North Carolina[29]



(a)

(b)

Figure 4.7 A schematic drawing (a) and the as-built view (b) of the precast concrete piers for Vail Pass in Colorado[30]

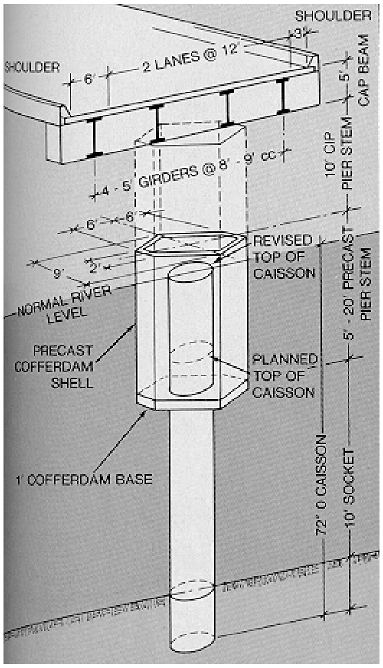


Figure 4.8 Precast cofferdams used to speed construction

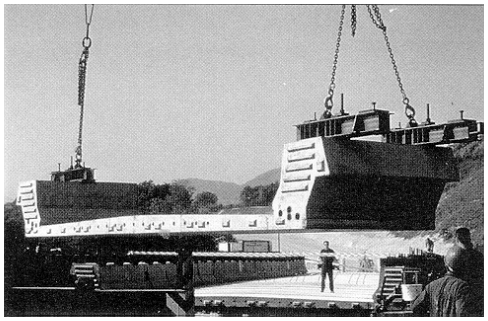
Figure 4.9 Placement of a precast pier cap on a cast in place column

post-tensioned (Figure 4.10). Key features of this system include increased clearance for standard highway overpasses, shorter construction time and lower life-cycle costs.

The recent trend of applying segmental construction technologies to short and moderate span bridges has also been explored for substructure design. TxDOT has designed precast segmental piers for three moderate span bridge projects in Texas: US Highway 183 in Austin (Figure 4.11), State Highway 249 over Louetta Blvd. in Houston (Figure 4.12), and most recently, an overpass over Interstate Highway 10 near El Paso, TX. The designs for the latter two were essentially the same.

Technical sessions at industry conferences often include presentations on the use of precast substructure elements for both new design and rehabilitation projects.[57,58] A number of practitioners attending presentations by the author on the substructure system presented in Section 4.2.5 have expressed interest in learning more about this system for possible use in their design firms. Some engineers attending commented that they frequently use precast substructures for their bridge designs for successful, rapid construction.

A recent project using precast substructure elements for a moderate span precast girder bridge is the Edison Bridge over the Caloosahatchee River in Fort Meyers, Florida designed by HDR Engineering, Inc.[58] The precast substructure units used non-prestressed reinforcement connected with grouted sleeve couplers. Separate northbound and southbound structures were designed with 43m (142') spans made up of 1830mm (72") deep Florida bulb T's supported by precast frame bents. The bents were made up of I-shaped columns that were cast in single pieces up to 12.5m (41') tall. The largest column segment weighed 395kN (89kips). The caps were up to 18.5m (61') long. In order to keep the weight low, they were inverted U-sections (Figure 4.13). The largest cap segment weighed 690kN (155kips). The caps had solid sections over the columns to provide horizontal shear transfer from the cap to the columns in accordance with the seismic criteria for the area. The column segments were connected to the cast-in-place footings and to the precast pier caps with mechanical couplers (grouted sleeve couplers). To ensure a "perfect" fit, similar patterns (basically metal sheets with measured openings) were used to align the dowels from the footing and to align the placement of the sleeves in the pier segment. The pattern in the field had sleeves to keep the dowels vertical during construction. Similar patterns were used for the dowels protruding from the top of the column segments and for the sleeve locations in the cap. The top of the caps were horizontal to facilitate placement over the dowels in the column segments. The two-percent cross slope necessary for the deck was then achieved through variable height bearing seats cast on top of



(a) Precast channel segments make up the superstructure. The primary load-carrying system is the parapet walls

(b) A completed channel bridge

Figure 4.10 The Segmental Concrete Channel Bridge System developed by J. Muller International for spans of 15-35m (50-115')

Figure 4.11 Precast segmental piers at US 183 in Austin, TX

Figure 4.12 Precast piers for a grade separation in Houston,TX

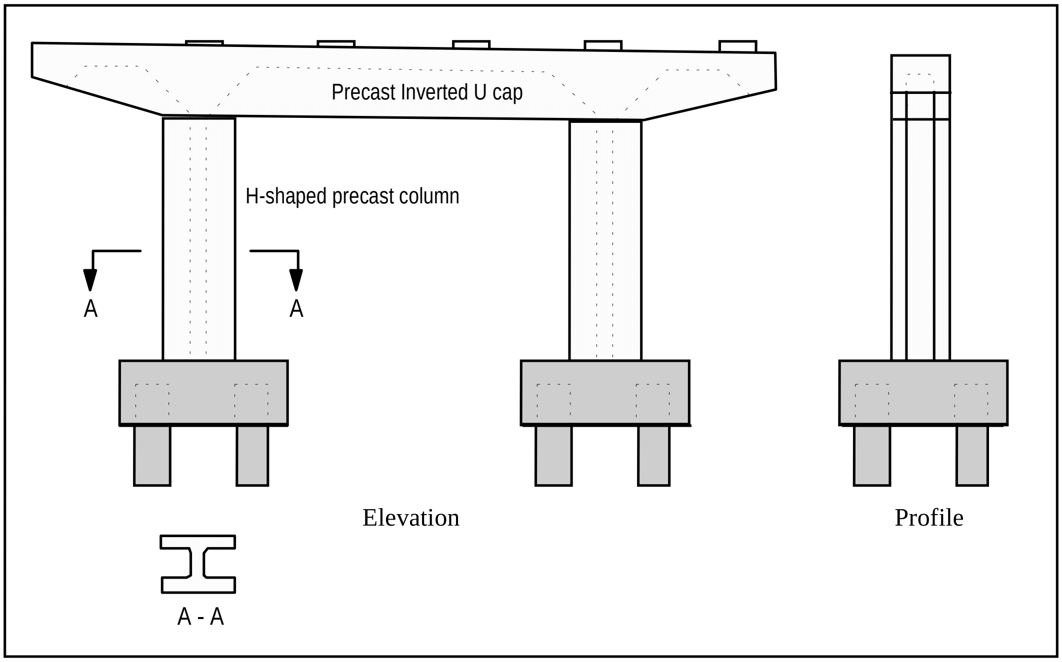


Figure 4.13 Schematic of the Edison bridge precast bents

the cap at the bridge site. In 1992 dollars, the columns cost \$543 per cubic meter (\$415/yd^3) and the caps averaged \$745 per cubic meter (\$570/yd^3).

A preliminary study for developing precast bridge substructures that could be standardized for moderate span bridges, in particular moderate span water crossings, was completed for the Florida DOT in May, 1996 by LoBuono, Armstrong & Associates, HDR Engineering, Inc. and Morales and Shumer Engineers, Inc.[59] The initial phase of the study involved a survey of the use of precast substructures in the United States. It was found that most State DOT's, Florida contractors and major precast concrete industries were primarily concerned with connection details for precast substructures. The second phase of the study involved identifying a number of precast substructure options for pile bent caps, and columns and caps for multi-column and hammerhead bents. A number of shapes and fabrication options were then rated by consultants and representatives from both contracting and precasting industries. A recommendation was made to limit precast element weights to 530kN (120kips) and to limit the number of necessary connections. Connections discussed included mechanical couplers such as grout sleeve couplers, post-tensioned connections, welded connections and reinforcing bar lap splices. Table 4.1 and Figure 4.14 show the section types recommended for further investigation as an outcome of the study.

Component	**Configuration**	**Configuration**
Multi-Column Pier Cap *(Figure 4.14a-c)*	Solid Rectangle (IA)	Inverted U (III)
Multi-Column Pier Column *(Figure 4.14d)*	Hollow Rectangle - Rounded Corners (IIIB)	I-Shaped (IVA)
Pile Bent Caps *(Figure 4.14e)*	Solid Rectangle (IV)	Inverted U (I)
Hammerhead Pier Cap *(Figure 4.14f)*	Solid Rectangle (IRB)	
Hammerhead Pier Column *(Figure 4.14g)*	Hollow Rectangle - Rounded Corners (IIB)	Double I-Shaped (III)

Table 4.1 Precast substructure components chosen for further study for the Florida DOT

4.2.1.3 Future Applications

The benefits of precasting substructure systems for short and moderate span bridges are promising. Recently designed precast substructure elements have been successful in decreasing on-site construction time. As a result, traffic delays and re-routing were minimized - reducing an indirect cost to the public. Reducing construction time has advantages in many parts of Texas (Figure 4.15). Particularly in congested urban areas, new highway or light rail construction may cause significant traffic problems. The faster that necessary bridge structures can be built with minimum traffic disruption, the less difficulties there will be for the public as well as the engineers and city officials.

The current trend of minimizing the construction industry's impact on the site of new construction is important to maintain good public relations and to protect the environment. Precasting substructures moves that portion of construction to a precasting plant and avoids the need for element fabrication, formwork assembly and concrete placement on site. The result is less

Figure 4.15 Traffic congestion could be relieved sooner with faster highway bridge construction

equipment and therefore less interference with the site during construction.

Precasting allows for higher quality control of the concrete. High performance concrete (HPC), a more durable material than normal strength concrete, requires higher quality control for proper fabrication. HPC can therefore be more efficiently and economically mixed and placed in a precasting plant than on site. Precasting also allows for more attractive finishes than cast-in-place concrete.

The positive feedback and interest from practitioners is a sign that precasting is a new option for substructure design. Recent success with precast substructures and the proven efficiency, economy and durability of precast segmental construction for superstructure design in the United States[46] point to a positive future for precast segmental substructure design.

For superstructure design, the trade-off between the construction simplicity of constant depth sections and the material efficiency of variable depth sections has shown the former to be more economical with shorter span structures. A similar trend can be seen with substructure designs. Highway structures of short and moderate spans with heights under 15m (16.5') are typically constructed with piers of constant cross-section.[36] The savings due to the simplicity of constructing constant column sections typically outweighs any material savings achieved by tapering the columns. As a result, standardization is particularly attractive for short and moderate span bridges of moderate height. Constant cross sections lend themselves more easily to economical standardization.

As precasting substructures is a fairly new area of design, there is limited field information on their behavior and performance. More importantly, there is limited contractor experience with this form of construction. One of the biggest hurdles to overcome with developing new precast substructure systems is dispelling many unfounded negative beliefs about such systems held by "prisoners of the familiar." Through attention to industry concerns and knowledge of successes and failures of the past, functional, economical and attractive new substructures can be designed and built. With careful implementation of this recent trend in substructure design, the advantages of precast segmental substructure systems will shine forth.

4.2.2 Criteria for a Texas Precast Substructure System

Looking specifically towards developing a precast substructure system for TxDOT, a number of needs and constraints must be met. The criteria for the precast substructure system are that the system must:

- be for use with precast beam superstructures,
- be economically competitive with current practice,

- be sized for fabrication and erection with existing plants and construction equipment,
- make use of precaster and contractor experience,
- improve durability,
- be designed in accordance with AASHTO Bridge Design Specifications[22,60-61] and the TxDOT Bridge Design Manual.[21]

A precast substructure system for Texas must be compatible with precast concrete I, T, U and box beam superstructure systems as these are the predominant superstructure systems used in Texas. The substructure system must be economically competitive with current substructure systems. Economics of the design should consider not only initial dollar costs but also indirect costs and benefits to the public due to construction time and impact. While it is recognized that the initial cost of a precast system will be higher, the system must be developed with forms and details that can easily be standardized. With wide re-use, standardization will bring costs down over time and make a precast system economically competitive with cast-in-place systems for many bridge projects.

An additional approach to keeping the initially higher costs of a precast system down, is to develop a system that makes use of existing precast plant facilities and equipment in Texas. The construction equipment (predominantly the cranes) required for substructure erection should be compatible with the equipment requirements for superstructure erection. Therefore element weights should be kept below 700-750kN (160-170kips) (This is roughly the weight of the largest prefabricated beams used in Texas). Limiting element weights for erection will also keep hauling costs down.

Durability is a major concern that must be addressed by the developed system. Introduction of high performance concrete and the use of post-tensioning in the substructure will be advantageous. Finally, the system must be designed in accordance with the most current AASHTO bridge design specifications and the TxDOT Bridge Design Manual. The AASHTO Specifications include the 1996 *AASHTO Standard Specification for Highway Bridges*, *Sixteenth Edition*[60] (Standard AASHTO), 1994 *AASHTO LRFD Bridge Design Specifications*[22] (LRFD AASHTO), and 1994 Interim *Guide Specifications for Design and Construction of Segmental Concrete Bridges*[61] (AASHTO Segmental Spec.). Each of the issues mentioned in this section are discussed in more detail in Section 4.2.5 where the final proposed system is presented.

4.2.3 Preliminary System - Proposal I

A preliminary precast substructure system, Proposal I, was developed as a part of this research project by Barnes and is summarized in this section. A more detailed report of this work can be found in Reference 9.

Proposal I is a substructure system made up of predominantly precast elements (Figure 4.16). Details were developed for single column (hammerhead) bents with inverted T caps for use with AASHTO Type C, Type IV, and “Texas U-beam” pretensioned girders. Four different column sizes with one basic cap shape were designed to be assembled for varying heights and widths of standard bridges. These same sections were envisioned to be able to be combined to form straddle and frame bents, again for varying heights and widths (Figure 4.17). This part of his study was largely conceptual and final details were not developed for the multi-column bents. Column segments would be precast using match-casting techniques. The segments would then be hauled to the site and post-tensioned together on top of their foundations.

4.2.3.1 Elements of the Precast Substructure System - Proposal I

The precast hammerhead column developed in Proposal I is depicted in Figure 4.18. The substructure is made up of three basic segment types; column segments, a “template” segment and inverted T cap segments. Inverted T caps were chosen over rectangular bent caps for reasons of improved visibility through the bridge as well as increased clearance underneath the substructure. There are two areas specified for geometry control with these substructures, a joint at the base under the first column segment, and a joint at the top of the column shaft under the top column piece (the “template”). These two joints are cast-in-place with a high quality epoxy concrete. The other joints are match cast and epoxy filled. These geometry control locations are further explained in this section and in Section 4.2.3.3. The design criteria for the substructure units made up of these precast elements are outlined in Reference 9 and are based upon provisions in the three separate AASHTO specifications mentioned in Section 4.2.2 - the Standard AASHTO,[62] the 1994 LRFD AASHTO,[22] and the 1994 Interim Segmental Specifications.[61] The Standard AASHTO used for Proposal I was the 1992 edition with revisions in 1993 and 1994.[62]

Four hollow column segment sizes were designed (Figure 4.19). Column segments were hollow to reduce the weight of the elements for hauling and erection. These hollow sections were developed for use with high performance concretes having strengths of up to 69 MPa (10,000psi).

Provisions for post-tensioning ducts as well as shear keys were developed. An area was included on the side walls for an optional recess or insertion of a formliner.

Four template segments were designed, one for each of the different column sizes. The template segment is basically a construction aid. The idea for the template was adopted from the recent Northumberland Strait Crossing (NSC) project in Canada connecting New Brunswick and Prince Edward Island.[40-42] The NSC girder units, fabricated on shore, were precast segmentally and post-tensioned together into haunched span units up to 197m (645') long. The central segment of each haunched span, or the pier segment, was match cast in the casting yard to the topmost pier segment - the template. A template is defined in the Webster's Dictionary as "a mold [in this case a precast element] used as a guide to form a piece being made".[63] During NSC erection the light template piece (weighing only 890kN (200kips) which is light when compared to a 66.7MN (15,000kip) girder segment) could be quickly aligned and cast into place atop the pier. The girder segments were then floated to the site, and placed upon and post-tensioned down to precast piers (Figure 4.20). These large, heavy girder segments were then placed on the template for a "perfect" fit in under one hour. The tips of the cantilevers for these segments after placement were within 20mm (0.8") of their designed positions - a clear testimony to the excellence of this construction method. The haunched girder segments cantilevering out from the piers were then connected with precast "drop-in" spans to complete each bridge span (Figure 4.21).

Although the precast substructure system developed in Proposal I is on a much smaller scale than the NSC project, the erection time can none-the-less be greatly reduced and the geometry control improved through having the precast cap match cast to a template (Figure 4.18). The lighter template piece can be properly aligned in the field to the proper deck cross slope and set with a cast-in-place joint more quickly than the heavier, awkward-shaped cap. For Proposal I the template is essentially a smaller column segment. This small size allowed the template to be not only a construction aid, but also an artistic opportunity. An interesting shape could easily be accommodated for this small segment. A flared chamfer was chosen to visually integrate the vertical shaft with the horizontal cap (Figure 4.22).

The inverted T caps would be match cast segmentally (Figures 4.18 and 4.25) similar to the way segmental girders are match cast. Post-tensioning duct and shear key locations are provided. The bottom of the ledge of the cap tapers in two dimensions. In elevation, there is a taper increasing the ledge depth from the tip of the cap to the face of the template and column (Figure 4.23a). In plan, the bottom surface of the ledge tapers from the full width of the ledge at the tip of the cap down

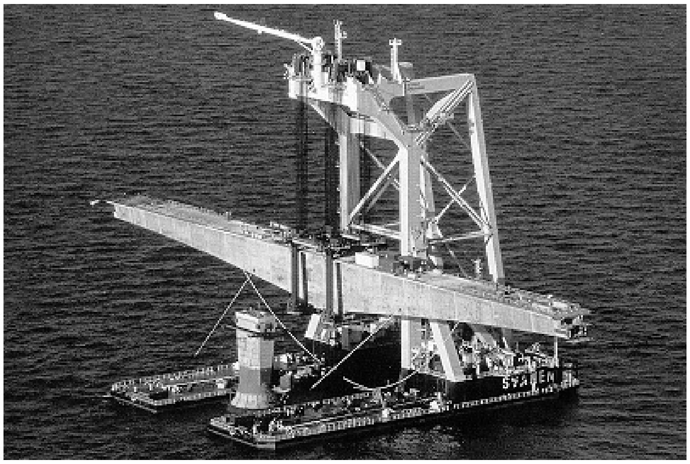
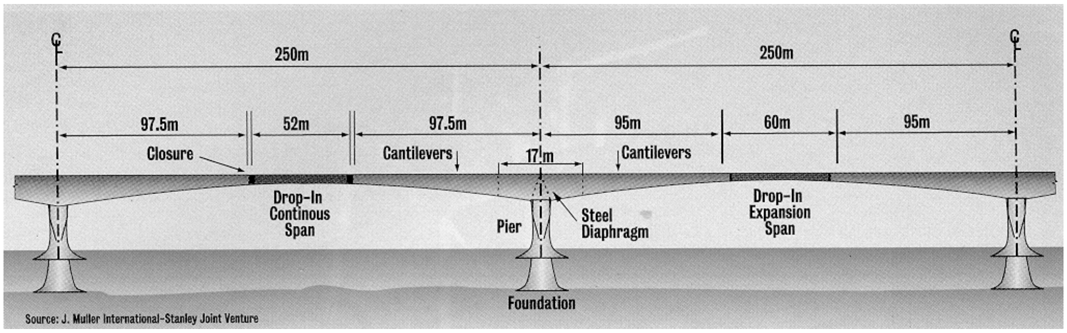


Figure 4.20 Placement of a 200m (655') precast segmental girder for the Northumberland Strait crossing.[40]



Source: J. Muller International-Stanley Joint Venture

Figure 4.21 Drop in panels connecting haunched girder segments at the Northumberland Strait Crossing.[40]

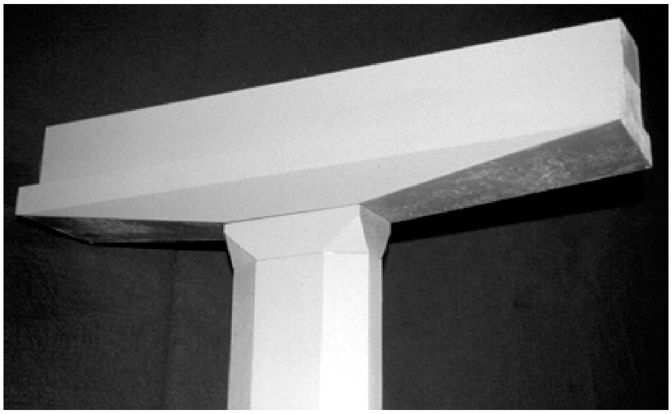
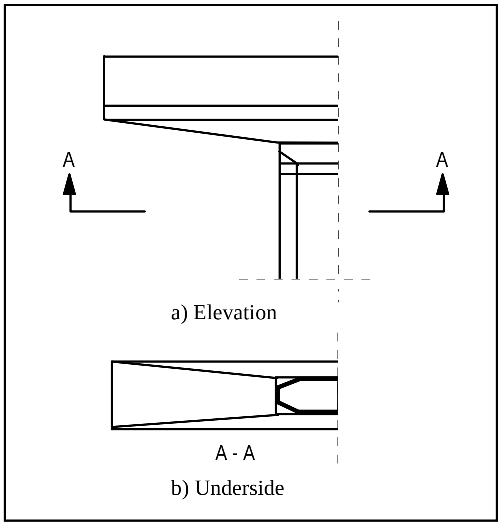


Figure 4.22 Column and cap visually integrated with flaring chamfers on the template segment of Proposal I

to the narrower width of the template at the template and column face (Figure 4.23b). The increased depth of the tapering cap at the column face provided additional moment and shear resistance at this critical section. The amount of taper provided was more than adequate structurally but was kept at this depth for an attractive visual transition, integrating the horizontal cap and the vertical column. Tapering the cap gave an interesting and striking appearance but made cap form details complex for varying cap lengths.



a) Elevation

b) Underside

Figure 4.23 Inverted T cap taper for Proposal I in elevation and plan

4.2.3.2 Fabrication Sequence - Proposal I

The fabrication sequence for the precast substructure elements of Proposal I is outlined in Figures 4.24-4.25. The column segments are match cast in their vertical position. Vertical casting has many advantages. Formed surfaces will make up all finally visible faces of the column. The concrete can be better consolidated around the ducts and the inner core form. Handling will be easier as the segments will be stored, hauled and erected in the same orientation as they were cast. Because of the advantages to vertical casting, the “short-line” method is used in which the casting equipment is never more than two segments high. Minimizing this height allows for easier assembly and lifting.

Template segments are cast separately (“loose-fit”). The template is then placed under an opening in the formwork of the cap and is aligned for the proper cross slope of the future bridge. The cap is then cast using the “long-line” method in which the entire cap is match cast in its final relative position and alignment with the template. Long-line casting allows for variations in cap lengths, in tapered soffit inserts, and in joint locations.

4.2.3.3 Erection Sequence and Connection Details - Proposal I

After the drilled shaft, spread footings or pile cap foundations at the bridge site are completed, precast substructure elements can be hauled to the site for erection. The erection sequence is shown in Figure 4.26. The first segment is placed and aligned on adjustable supports on top of the footing. There is also the option of casting a recess into the footing and placing the first segment extending downward into the recess. A common adjustable support system would be a steel frame that can be adjusted with screw threads or shims. Once aligned, the post-tensioning bars (PT bars) are threaded into anchors previously cast into the foundation. The bottom segment is then "locked" in position with a cast-in-place joint. The height of this cast-in-place joint can vary in accordance with the final height required for the pier. Pier segments are to be cast in 2400mm, 1200mm, and 600mm (96", 48", 24") tall segments. Therefore the maximum required height of the cast-in-place joint will always be less than 600mm (24").

Once the first segment is permanently in place, the next segment can be lifted into place above the first segment. PT bars are placed and coupled while the new segment is held above the previously placed segment. Epoxy is applied to each face of the joint and the top segment is lowered into position. Post-tensioning bars are then stressed to provide a minimum 0.28MPa (40psi) pressure across the joint for even setting of the epoxy. The 0.28Mpa (40psi) pressure is required by the 1994 Interim AASHTO Segmental Specifications.[61] Remaining column segments are placed similarly.

After the last ordinary column segment is placed, the template segment is placed on temporary adjustable supports and aligned to provide the necessary cross slope and elevation for the match cast cap. This joint is then formed and "locked" in place with a cast-in-place joint. Both cast-in-place joints are envisioned as constructed of a highly durable, strong jointing material of similar quality to the rest of the column shaft. Providing the second designated geometry control joint under the template serves two purposes. First, this geometry control joint allows for accurate cap placement. Second, any unforeseen out of straightness resulting from initial setting and subsequent placement of column segments can be corrected at this joint.

With the template in place, the primary cap piece can be rapidly positioned into its match cast alignment on the epoxy joint and post-tensioned down to the column. Whether post-tensioning bars or looped post-tensioning strand are used, all post-tensioning operations can be carried out from above. Secondary cap segments can next be lowered into place with simple "hooking" hardware attached to the top of the cap segments. For controlled placement, one method would be to attach a hook to the secondary cap segment that can be placed over a rod between lifting beams on top of the

primary segment. This method was used successfully for erecting the JFK Causeway in Corpus Christi (Figure 4.27). Once the secondary cap segments are in their match cast position, the cap is post-tensioned together and the superstructure can be placed. Depending on the erection sequence for the superstructure, the cap may need to be post-tensioned in stages to avoid exceeding stress limitations. This is of particular concern across segmental joints where no tension is permitted at any stage.

4.2.4 Evaluation of Proposal I - Industry Concerns Addressed

Upon completion of Proposal I for a precast substructure system, details were presented to a number of industry personnel for review and comments. Meetings were held with representatives from the precast industry including designers, precasters, formwork manufacturers, and material suppliers. A presentation introducing this system was also given to TxDOT engineers from across the State. Other presentations were given at national conferences including the 1996 American Concrete Institute (ACI) Fall Convention in New Orleans, Louisiana, the 1996 American Segmental Bridge Institute (ASBI) Convention in Orlando, Florida, and the 1997 Transportation Research Board (TRB) Conference in Washington, D.C.

The presentations at the national conferences were well-received. A few State DOT engineers were interested in the precast system but felt they would have difficulty finding local contractors to do the work. As mentioned in Section 4.2.1.2, many practitioners requested more information on the system for their own development in the future. A few practitioners commented that they have been precasting substructures for small local projects successfully for years.

The meetings with industry personnel and the presentation to TxDOT engineers were the most helpful in furthering the development of the precast substructure system. Important concerns and questions were raised that resulted in substantial subsequent improvements in the original proposal. Other concerns were recognized as commonly held beliefs that were more of “old wives tales." None-the-less, such reservations and perceptions needed to be addressed to dispel false notions. The key concerns addressed included the cap being segmental as opposed to one piece, the suitability of the system for fabrication in precasting plants more accustomed to precast girders, relative merits of match casting vs. loose fit fabrication, concerns over epoxy joints vs. mortar joints, and the worries over problems in grouting of vertical tendon ducts.

4.2.4.1 Segmental Cap

One of the key concerns frequently raised about Proposal I was the configuration of the cap. The cap being segmentally constructed and erected was viewed as a large obstacle to adopting the entire system. A wide range of engineers indicated that using only a single cap piece in hammerhead bents or a pair of cap pieces not segmentally joined but rather with match cast joints in multiple column bents would be more desirable. The segmental cap scheme was originally chosen due to the large and heavy size of the entire cap. As discussed in Section 4.2.2, precast element weights needed to be restricted to less than about 700-750kN (160-170kips) to keep hauling and erection costs down. The longest cap needed for the single pier system is 13.1m (43’) for a 14m (46’) or three-lane roadway. If cast as one unit, such a Proposal I cap would weigh close to 1100kN (250kips). In addition, some concerns were expressed about the form complexity with the tapering of the cap soffit.

To ease the erection process, a new scheme using only single prismatic cap pieces was developed and investigated. The new scheme is presented in Section 4.2.5.

4.2.4.2 Suitability for Fabrication in Precast Plants

The goal of this study is to develop a precast substructure system which could become a standard substructure design option. Standardization will make the system become increasingly economical through widespread use. It is important therefore to have a system that is attractive to all parties involved with fabrication and erection of standard bridge systems; both contractors and precasters.

Match cast segmental caps require post-tensioning. The segmental caps of Proposal I could be fabricated by either precasters or general contractors. While a post-tensioned system will be attractive for general contractors, a pretensioned system, not part of Proposal I, would be most attractive for many PCI member precasting plants. A high rate of fabrication and use of existing precast plant pretensioning bulkheads and equipment will ease the investment costs of implementing a new standard for substructure design. Pretensioning the cap element will also reduce the amount of non-prestressed reinforcement required in the cap to prevent cracking during transportation and handling.

Therefore, after evaluating Proposal I, it was felt that the post-tensioned system should be secondary and the primary option should be a pretensioning proposal for the precast caps. A new cap fabrication sequence needed to be explored that would give precasters a fabrication, forming and pretensioning option more suited to their existing plants. However, in the interest of the project's future use, a revised system should also have an alternate post-tensioned cap option for general contractors. Regardless of where the fabrication of such a system is performed, the system can still be standardized. Standard plan sheets as well as standard formwork should be developed.

4.2.4.3 Match casting vs. Loose fit; Epoxy vs. Mortar Joints

There were many questions and concerns about the type of joints chosen for the segments in Proposal I. The jointing material is directly related to the casting procedure. Dry joints or epoxy joints can be used with match cast segments while mortar or cast-in-place concrete is used with segments fabricated individually (“loose fit”).

Dry joints are permitted only in mild climates that do not experience freezing or exposure to salt water. This limitation prohibits use in most locations in Texas. Dry joints also lack the uniform bearing surface provided by the epoxy filled joints and are more prone to edge crushing. Therefore dry joints were not considered. The option of using a thin coat of epoxy to seal match cast joints has had excellent success in the past contributing to both erection ease and durability. The thin coat of epoxy lubricates the joint during segment placement and thus allows for easy, accurate joining of the segments that were aligned and match cast during fabrication, with little site measurement. The segments "auto-seat" into their match-cast positions. With loose fit fabrication, each segment must be carefully aligned and held on site before jointing. As each joint is a geometry control joint, a thicker joint of mortar is required.

The option of match casting with epoxy joints was chosen over loose fit fabrication with mortar joints for reasons of durability and construction speed. Although loose fit fabrication can occur at any rate the precaster chooses (depending on how many sets of forms the precaster or contractor invests in), the procedure of placing mortar and aligning segments on site is difficult and time-consuming to perform accurately. This is a major drawback for a system developed to speed up on-site construction. Difficulties arise also with ensuring the quality and even distribution of the mortar between the segments. This can lead to partially filled joints, stress concentrations, cracking and eventually corrosion of the reinforcing steel. Mortar joints have had durability problems in the past (Figure 4.28).[64] Measures to ensure mortar durability at every joint would be required. In fairness it must be pointed out that it is still necessary with the proposal herein to have two cast-in-place alignment joints in each of the otherwise match cast piers. Concrete or mortar placed in these locations must be durable and the tendons protected.

Match casting of column segments can be performed at an economical rate completing at least one segment per day per casting machine. With match casting, alignment is taken care of in the casting yard. The previously aligned and "perfect fit" casting of segments allows for rapid placement on the construction site. The excellent durability record of epoxy joints is promising. Therefore to maximize both construction speed and substructure durability, a system of match cast segments with epoxy joints was developed.

4.2.4.4 Grouting of Vertical Tendons

Some practitioners have questioned the reliability of grouting vertical tendon ducts. However, many guidelines have been developed for this procedure giving successful results.[65] Pressure grouting in particular has been successful in the past. Recent experience in Texas (US Highway 183 in Austin) and Florida (State Road 430 over Seabreeze Boulevard in Volusia County) has been very positive with regards to pressure grouting vertical tendon ducts. Concerns about this procedure appear to stem from lack of experience rather than poor performance in the past.

4.2.5 Final System - Proposal II

After consultation with a variety of members of the construction industry, the precast substructure system of Proposal I was modified and extended for use with single, straddle and frame bents. The industry concerns discussed in Section 4.2.4 were addressed and suggested improvements were incorporated into the new system, Proposal II. The process by which the new elements were developed is discussed in the following Sections. Complete calculations and plans for several examples of Proposal II are included in Appendices C and D.

4.2.5.1 Pier Segments - Proposal II

The four column sizes suggested in Proposal I were substantially revised and are shown in Figure 4.29. While four column sizes are included in Proposal II, one of these is a considerably smaller section suitable for many frame bents. The dimension transverse to the cap of all pier segments was selected as 1200mm (48") to correspond with the width of the cap stem. These matching dimensions facilitate the continuation and anchorage of post-tensioning steel from the column into the cap. Column post-tensioning is either post-tensioning bars or strands. Post-tensioning bars would be coupled to anchors cast into foundation caps. Post-tensioning strand would be threaded from the top of the cap into ducts passing through a 180 degree turn in the foundation cap resulting in both ends of the strand exiting the top of the cap (similar to Figure 4.7a and shown in Figure 4.45). Thus, all strand anchorages and post-tensioning operations are performed at the top of the cap. Column erection including foundation connections and post-tensioning options is further discussed in Section 4.2.5.5.

The column dimension parallel to the cap (transverse to the span of the bridge) for each column size is 1200mm, 1800mm, 2400mm or 3000mm (48”, 72”, 96”, or 120”). The column segments are designated as P12, P18, P24 and P30 to correspond with the longer plan dimension of the column segment. Pier segments can be cast in 600mm, 1200mm and 2400mm heights (24”, 48”, and 96”) and should be cast with a high performance concrete. Figure 4.30 shows typical column detailing for a 2.4m tall P18 pier segment.

The basic hollow pier shape of Proposal II is similar to that of Proposal I. One detail was changed regarding corner chamfering. The corner chamfers for Proposal II vary proportionally along the column long dimension with the increasing pier dimensions. In Proposal I, the corner chamfers had the same dimensions regardless of pier size. The visual effects of different column chamfering techniques are discussed in Section 5.2.5.

The pier segments of Proposal II have no recess built into the form. The wall thickness and concrete covers for the piers can easily accommodate inserts or formliners attached to the formwork. The designer is free to choose whatever type of insert or formliner, if any, would be most appropriate for a given project. The exact type of insert should be chosen after the cap longitudinal reinforcement is determined. This longitudinal cap reinforcement (discussed further in Section 4.2.5.2) dictates the location of column reinforcement. A formliner pattern will remove a certain portion of concrete cover for the column reinforcement. The amount of cover that may be removed by the insert must still leave proper cover for the column reinforcement (dictated by exposure conditions and specified in AASHTO Specifications).

The engineer may also choose whether or not the joints between pier segments will be accented with chamfers. Backing bars can be tack welded to standard steel forms to create chamfers. The bars can be simply ground off if chamfers are not desired for the next project. Chamfering joints helps hide staining caused by epoxy oozing out of the match cast joint during post-tensioning operations. However, chamfering the joints calls attention to the joint and gives the pier a masonry-like appearance, which may or may not be desirable. The choice of pier appearance will be the engineer’s. The author prefers unchamfered joints.

Shear keys are provided at the chamfered corners. The walls of the hollow pier segments provide room for post-tensioning bars (PT bars) of up to 36mm (1.375”) with a strength of 1030MPa (150ksi) or 1100MPa (160ksi) as well as multi-strand tendons up to the current 19K6 size made up of 19-25mm (0.6”) strands with a strength of 1860MPa (270ksi). The hollow core of the segments provides room for internal drainage ducts without reducing section efficiency. As shown in Table 4.2, pier segment weights for Proposal II are comparable to those of Proposal I and are easily within the capacity of cranes used for handling precast concrete girders.

	Pier Segment 2.4m (8’)	**Weight kN (kips)**
Proposal I	P20	85 (19)
	P24	101 (23)
	P28	116 (26)
	P36	148 (33)
Proposal II	P12	58 (13)
	P18	80 (18)
	P24	102 (23)
	P30	124 (28)

Table 4.2 Pier segment weight comparison

4.2.5.2 Bent Caps and Template Segments

The bent cap design of Proposal I changed considerably for Proposal II. Match cast segmental caps were seen by industry personnel as too cumbersome. Construction speed and efficiency would be greatly improved if the cap could be precast and handled as one segment. The cap dimensions for Proposal I resulted in extremely heavy cap elements. A cap length of 7m (23’) from Proposal I would weigh 700kN (160kips) - around the desired maximum weight for any precast element in the system (discussed in Section 4.2.2). The range of design dimensions for the proposed substructure system requires a single cap element to be up to 13.1m (43’) for a 3-lane bridge with a shoulder. The maximum 7m (23’) single cap element of Proposal I is wide enough only for a single lane bridge with a shoulder.

To have a system whereby the cap would be one single precast element up to 13.1m (43’), the weight of the caps from Proposal I needed to be reduced considerably. The taper of the cap in Proposal I had been designed for structural efficiency as well as visual integration of the horizontal cap with the vertical pier. (The taper increases where the moment and shear in the cap are highest and thus visually represents the flow of forces from the girders to the column and foundation.) By removing the taper, the cap weight could be reduced by 22%. Removing the taper also reduces the internal lever arm at the critical section at the column face. Rather than providing additional reinforcement to make up for the reduced internal lever arm, the design bending moment for the cap was substantially decreased by reducing the cap weight and by widening the template underneath the cap (Figure 4.31). The structural efficiency of the segmental pier was essentially transformed from a tapered cap to a tapered column. Rather than deepening the cap section at the cap-column interface to better resist the moment, the column section was widened to shift the point of critical moment in the cap outwards so that lower moment capacity would be required.

Removing the cap taper also removed the need for a complex form system for the cap - one that could handle tapers for different length caps. Such a form system signaled to many industry personnel a higher risk and higher uncertainty of successful fabrication. It was indicated that this could lead to substantially increased costs. Although a tapered cap is visually attractive and structurally efficient (efficient use of materials), the economy of this design alternative would be sacrificed. This dilemma was a good example of how engineers must strive to balance the three engineering disciplines of aesthetics, efficiency and economy (discussed in Section 3.4.1) within the project constraints. In this case, a primary concern for the design of a prototype precast substructure system was that it could be easily standardized. Economical standardization dictates the use of simple, re-usable and easily sealed forms. The tapered cap of Proposal I did not meet this criteria and thus an alternative system - one that resulted in a better balance of aesthetics, efficiency and economy - was necessary. The resulting uniform depth cap and tapered template for Proposal II provides an system that is attractive, efficient (in terms of material requirements, fabrication and constructability) and more economical particularly for standardization.

The small template sections of Proposal I were increased substantially in size and were made proportional with each pier size. The resulting template elements for Proposal II are short, flared pier segments. A flared template provides a stronger visual integration between the pier and cap than a subtle cap taper would provide. The decreased bending moment at the critical section in the cap requires less cap reinforcement. Figure 4.32 shows the four template sizes of Proposal II. Each template size corresponds to one of the four pier segments. They are similarly designated and referred to as T12, T18, T24 and T30. As shown in Table 4.3, their weights are within the 700-750kN (160-170kip) maximum range.

Template Segment Proposal II	**Weight kN (kips)**

T12	56 (13)
T18	175 (39)
T24	395 (89)
T30	748 (168)

Table 4.3 Template weights for Proposal II

To further decrease the weight of the cap, the structural function of the cap was examined. As shown in Figure 4.33, the flow of forces can be seen from simple strut and tie models. Examining the flow of forces for the solid cap of Proposal I (Figure 4.33c & d) shows areas where the concrete is not needed structurally - in the center of the stem and in the bottom outer corners of the ledge. Figure 4.34 shows the sequential process of removing the unwanted material and the effect the material removal has on the weight of a 13.1m (43’) cap - the longest single cap piece required for the system. Removing this unnecessary dead load from the inverted T cap further reduces the amount of reinforcement required in the cap.

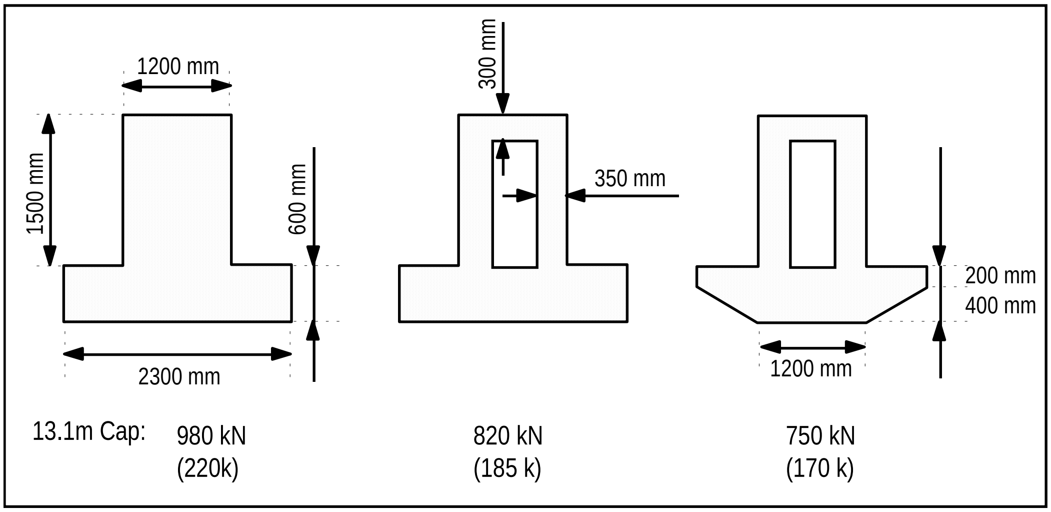


Figure 4.34 Modifying the cap cross section led to a reduced cap weight.

The precast cap elements may be longitudinally pretensioned, post-tensioned or a combination of both. The web walls of the inverted T stem were minimized to 350mm (14”) in the cantilevered portions and 375mm (15”) at the cap-column connection. This width provides adequate cover for anchorage zone and shear reinforcement with sufficient room for concrete placement and consolidation around the longitudinal cap reinforcement. Figure 4.35 shows details of a precast cap with two longitudinal reinforcing options - one fully pretensioned and one fully post-tensioned. Figure 4.36 shows larger scale portions of the cross sections at the cap/column connection to show the cover and spacing of the three prestressing options. For the fully pretensioned option, each wall can accommodate 4 columns of 12.7mm (0.5”) diameter pretensioning strands on 50mm (2”) centers, a 50mm (2”) duct for column PT bars with proper coupling sheaths, and interior cover (Figure 4.36a). The walls can also accommodate 100mm (4”) ducts for 19K6 multi-strand longitudinal tendons instead of pretensioning strand with the column PT bars located up to 50mm (2”) closer to the outside cover of the stem (Figure 4.36b). This will require up to a 10 degree bend in the stirrup at the base of the stem to accommodate the sheathing and coupler for the column vertical PT bars (see cross section B2 in Figure 4.35c). A combination of cap longitudinal pretensioning and post-tensioning may also be accommodated using the two outer columns of pretensioning and a maximum of a 100mm (4”) duct (required for a 19K6 multi-strand tendon) for post-tensioning (Figure 4.36c). For this scheme too, the column PT bars will be closer to the outside cover of the stem. The pre- and post-tensioning combination for cap longitudinal reinforcement will be typical for frame bents. Due to the low column overturning moments in frame bents, the amount of vertical post-tensioning required can typically be handled in the column "ends" (as indicated on the P24 segment of Figure 4.29). In this case, the PT bars will be located towards the center of the inverted T stem and the coupler sheathing will not interfere with and therefore not require any additional bending of stirrup cage reinforcement. The varying location of the vertical PT bars dependent on cap longitudinal reinforcement must be accounted for in column design (including cover requirements when form inserts are being chosen).

While the center of the cap stem would be primarily hollow, solid portions are required at the ends for cap anchorage zones when longitudinal post-tensioning is used (Figure 4.35a). Anchorage zones are also required over the column for the column reinforcement not anchored in the webs of the stem. Table 4.4 gives a comparison of cap weights for one, two and three-lane bridges using single element caps from Proposals I and II.

Bridge Width	**Cap Length* m (ft.)**	**Total Cap Weight, kN (kips)**	
		Proposal I	**Proposal II**
1 lane (7.6m)	5.8 (19)	540 (121)	335 (75)
2 lanes (10.4m)	9.5 (31)	885 (200)	545 (123)
3 lanes (14m)	13.1 (43)	1230 (277)	750 (170)

* no skew

Table 4.4 Single precast element bent cap weight comparison

4.2.5.3 Bent Configurations - Proposal II

The four pier sizes, four corresponding templates and the single depth but variable length cap section can be combined in numerous ways to make up a wide range of substructure units extending from single column bents to straddle bents and frame bents (Figure 4.37). These bents can support roadways up to 32m (105’) wide and up to 18m (59’) tall. A variety of skews may be accommodated as well. The inverted T cap can support AASHTO Type IV Girders and 1370mm (54”) deep Texas U-beams. A similar cap with a shorter stem could be fabricated for use with shallower standard precast concrete girders. Shallower girders could also be supported on the deeper caps with built-up bearing seats.

All bent caps may be fabricated in single elements up to 13.1m (43ft.) long. Therefore all single column bents are constructed with just one cap segment. Cap segments may be pretensioned or post-tensioned. Straddle and frame bents join two cap sections with a cast-in-place joint and longitudinal post-tensioning. These wider bents can accommodate caps up to 27m (88’) in length with just two cap segments (two 13.1m (43’) segments with an 800mm (31”) cast-in-place joint). Wider bents can be accommodated with two piers and two long segments and one match cast shorter cap segment fabricated and erected as described in Sections 4.2.3.2 and 4.2.3.3. Alternatively, three piers and three caps could be utilized.

The pier segment chosen for a project will vary depending on project constraints. Roadway width, span lengths, road curvature, pier height and bent skews will all effect the pier size requirement. Other factors affecting the choice of pier size will be concrete strength and type of column reinforcement chosen. For instance, an 18m (59’) single column pier supporting a 14m (46’) roadway could be handled with the P30 segments with a concrete strength of 56MPa (8ksi) or with the P24 segments with an 76MPa (11ksi) concrete. This is because the controlling factor for the pier design is the compression stress at service loads resulting from column post-tensioning necessary to prevent tension across the segmental joints under bi-axial bending.

With the frame bents, the pier segment size should initially be chosen based on structural requirements. In many cases, the smallest column section may suffice for column loads. However with longer bents, a larger column section and therefore larger template section will reduce critical bending moment and shear forces in the cap. The designer must balance issues of economics and constructability when choosing between using larger column sections or more cap reinforcement. For aesthetic reasons as well, the designer may choose to use larger column sections for a long frame bent. Slender columns under a wide superstructure may appear visually weak and unsafe.

Design calculations and details for a single column pier using P24 segments for a total clear height of 10m (33’) supporting a 14m (46’) roadway are shown in Appendix C. A combination of post-tensioned strand and bars are used for the column and the cap is designed to be pretensioned. Design calculations and details for a frame bent using P12 segments to support a 21.3m (70’) roadway are given in Appendix D. Here only post-tensioning bars are used for the column and the cap segments are both pretensioned and post-tensioned. A discussion of pier design and detailing can be found in Sections 4.2.5.6 to 4.2.5.8.

4.2.5.4 Fabrication Sequence - Proposal II

Column segment fabrication would be the same as described in Section 4.2.3.4 and shown in Figure 4.24. Provisions for fasteners in the sides of the sections for bolting the upper segment forms to the existing segment should be the same ones used for attaching temporary devices for handling the segments. This will minimize the number of holes or “disturbances” to the section.

The template segments will be cast individually. The top portion of the template is essentially a quadrilateral plate. This is an area that can be screeded to varying heights to provide necessary cross slope for the cap. The overall plate height varies depending on the template size. This variation according to template size allows each template to readily provide up to a 3% cross slope for the cap (Figure 4.38). The table in Figure 4.38 gives example plate heights for each template segment that can provide a 0-3% cross slope. Required cross slopes greater than 3% can be accommodated by using the 3% cross slope in the template and then by varying girder bearing seat elevations for the remainder. A minimum height of 50mm (2”) is provided on the ends.

The screeding to the desired cross slope can be facilitated in steel forms by providing a triangular chamfer strip, tack welded to the inside of the form. This screeding guide (“screed rail”) should be welded to both the inside of the outer form and the outside of the inner core form (Figure 4.39). The rail on the outside form will create a chamfer at the site of the future cap-template joint. This chamfer should hide epoxy drippings in this awkward location which would be difficult to clean during erection. The screed rail on the inner core form would provide a ledge to support elements for forming the cap. When the cap is later match cast to the template, form surfaces are needed to prevent fresh concrete from entering the hollow portion of the template segment. The tack welded screeding rails could easily be removed (ground off) with negligible form damage for the next template segment if a different cross slope is required. If wooden forms are used for either the inner or outer template form, wooden screed rails could be used. All inner core forms should be “drafted”

or angled outward slightly as they rise to facilitate easy removal. An angle as small as 10mm over 2.4m would suffice (0.5” over 8’).

Ducts for post-tensioning bars must be cast into the template segment. A pattern sheet could be fabricated to ensure proper location and alignment of ducts. A pattern sheet would simply be a metal plate with the duct locations from adjacent column sections drilled into it. The pattern sheet is placed at the bottom of the template segment while ducts are placed to ensure that the ducts will be properly aligned across this joint. Approximately four additional ducts of 40mm (1.5”) diameter must be cast into the template for placement of a flowable high strength grout to completely fill the joint between the top pier segment and the template segment. This joint detail is further discussed in Section 4.2.5.5 where the erection sequence of these piers is outlined.

Fabrication of the caps will be much more involved than fabrication of the column segments. There are a number of workable schemes for fabricating the caps with the necessary match cast joint between the bottom of the cap and the top of the template segment. Some fabrication options are better suited for pretensioning and others are better suited for post-tensioning.

For pretensioning, a fabrication system for the caps that can be easily adopted by existing pretensioning plants was developed. This system involves casting the cap in two stages. In the first stage, the ledge of the cap would be match cast to the previously cast template. This operation could be done with the template supported from the ground and the ledge form supported above (Stage 1 in Figure 4.40a and Figure 4.40b). Web reinforcement would extend above the ledge. The casting operations would require concrete placement not more than 3.6m in the air. This imposes no problem on existing precast plant equipment. Once the ledge is cast and the concrete cured, the ledge would be transported to an existing pretensioning bed (Stage 2 in Figure 4.40a). With a number of ledges in the bed, pretensioning strands would be placed and forms for the inverted T stems set up. Post-tensioning ducts for the column and if required, for the cap, would be aligned and the concrete placed. For most of the single cap segments, pretensioning will suffice (no post-tensioning will be required) for the cap’s longitudinal reinforcement. Only in cases with long caps that need to be stage tensioned will post-tensioning be required. In the case of frame caps, post-tensioning will be required to join the cap segments and provide positive moment reinforcement in the closure and span between the piers (Figure 4.37 and 4.46).

A two-staged casting of the cap for this pretensioning scheme eliminates the need for self-stressing forms (forms with ends that essentially act as bulkheads) that will be 2-4m (6.5’-13’) in the air. Staged casting allows the precaster to use existing pretensioning beds and bulkheads. Staged

casting also eases concrete placement as problems due to trapped air under the ledge that would occur with a single closed form can be avoided (Figure 4.41). In single stage casting, vibration of the ledge down through the walls of the stem would be extremely difficult with pretensioning strand running throughout. With the staged casting, concrete shear keys will need to be set into the ledge for shear transfer in the concrete for the final structure. Web hanger reinforcement for shear will also need to extend upward at this location. As shown in Figure 4.40a, the stirrups required for the cap would be cast into the ledge. This provides a good detail using unspliced stirrups and also a cage with which to lift the ledge into a pretensioning bed. Consideration of the different concrete strengths in the ledge and stem at release of the tendons will need to be accounted for to properly assess prestress losses due to elastic shortening (see pages C37-C40 of Appendix C for example calculations).

Another possible method of cap construction that eliminates the need for self-stressing forms 2-4m (6.5’-13’) in the air would be to insert the template segment in an opening below grade and match cast the cap to the template while the cap is supported at grade level (Figure 4.42). This would require the precaster to depress the template up to 2.5m (8’) below grade (for the largest template - T30). Casting could again be staged with the ledge being cast first and then placed in a pretensioning bed. Other fabrication options include match casting the cap in one stage above the template in a self-stressing form. Another option for the fabricator would be to cast a single cap in one stage resting at grade level in self-stressing forms or in a short pretensioning bed with the template inserted in an opening in the ground to facilitate the required match cast joint.

An advantage to fabrication in a precasting plant as opposed to field concreting is that the quality of high performance concrete can be better controlled. Use of high performance concrete with its high early strength allows for higher turnover of pretensioned elements. This helps make element fabrication economical. Pretensioning the elements will also reduce the amount of non-prestressed reinforcement typically required to prevent cracking during handling of the elements to be post-tensioned on-site.

Fabrication of precast caps that will be entirely post-tensioned can be performed in a precasting plant or in a temporary precasting yard. Again, the template segment can rest on the ground with the cap formed and concrete placed 2-4m (6.5’-13’) in the air or the template can be placed in a recess below grade and the cap cast above while supported at grade level. The entire cap could be formed for one cast in either situation since self-stressing forms or bulkheads for pretensioning would not be used. However, as previously discussed, two stage casting is

recommended for constructability. Post-tensioning ducts running throughout the walls of the stem will add to the difficulty of vibrating the ledge concrete if placed in a single cast.

4.2.5.5 Erection Sequence - Proposal II

The erection sequence for the column segments for Proposal II is similar to that of Proposal I. Normal foundation construction is carried out with provisions for column post-tensioning bars and/or strands provided in the foundation cap, or footing. For the column post-tensioning bars (PT bars), anchors and bar couplers must be cast into the footing. Post-tensioning strands (PT strands) require ducts curving 180 degrees. The curving ducts in the footing facilitate the threading of the PT strands from the top of the cap down through the footing and back to the top of the cap once the cap is placed. This allows all final column post-tensioning operations to be performed at the top of the cap with no disruption to the completed foundations.

The first column segment is placed on adjustable supports on the previously cast footing. The footing could be designed to have a recess in which to place the first segment. With a recess however, the overall footing (or pile cap) depth will be increased. This will be uneconomical in many locations in Texas where rock is located just below the surface. Increased excavation costs will often dictate using footings and pile caps that are as shallow as possible. For most situations, the first pier segment will therefore be placed on top of the footing.

The first segment is aligned on adjustable supports, such as the simple steel frame adjusted with screw threads or shims as described in Section 4.2.3.3. An example of this method used recently in Austin, Texas is shown in Figure 4.43a. Column post-tensioning ducts are spliced to the duct provisions (to the anchorages for PT bars or to the curved ducts for PT strand) in the footing, internal drainpipes are placed and joint reinforcement is tied. This first segment is then locked into position with a cast-in-place joint (Figure 4.43b). The first joint should be a concrete of similar quality to the pier segments. This joint may vary from 300mm to 600mm depending the required height of the pier. A number of first segments may be placed and aligned for a project before they are “locked” into position with this cast-in-place joint. Due to the relatively small amount of concrete needed to set each segment (less than 2.3m^3 (3yd^3) for the largest segment), placing concrete for more than one segment at a time will be more economical and less time consuming in terms of disruptions to the site due to field concreting.

With the first segment set, the next pier segment can be lowered into place. Before the segment is set down, PT bars are coupled and then epoxy is placed on the faces of adjoining segments (Figure 4.43c). The segment is then lowered into position. The match cast joints with aligning shear keys will allow for rapid placement. With proper alignment control carried out during the match casting process, no further alignment changes should be needed in the field. The newly placed segment must then be post-tensioned to the existing pier to provide a surface pressure of 0.28Mpa (40psi) (Figure 4.43d). (The 0.28Mpa, 40psi requirement is part of the 1994 Interim AASHTO Segmental Specifications. This requirement may be lowered to 0.07MPa (10psi) in future revisions.[66] This will mean that a 3m (10') segment of any cross section will itself provide the necessary 0.07MPa (10psi) pressure and temporary post-tensioning will not be required. For shorter segments, a second segment can be placed above to apply this pressure while the epoxy sets. Avoiding the post-tensioning operations for each segment placement in the future should decrease labor costs considerably and increase construction speed.)

With the final pier segment in position, the template segment can then be placed. The template is set on adjustable supports, PT ducts are spliced and the segment is aligned to provide the proper cross slope for the match cast cap. This joint can be very small (75-100mm (3"-4")) and will be filled with a durable high strength epoxy grout. Grouting the joint will typically be more economical than placing such a small amount of concrete at heights up to 18m (59'). A bracing system bolted to the template and the top pier segment from the inner core can be used to hold the segment in place once the proper alignment is achieved (Figure 4.44). The joint is then formed and a flowable high strength grout is placed through ducts in the template segment. After the joint has cured, the template segment can be post-tensioned to the pier and the temporary bracing can be removed.

The cap is placed next. Epoxy is applied to the bottom of the ledge and the top of the template segment. The cap is then easily set on top of the template to which it has been previously match cast. No special alignment procedures are necessary for this heavy element. It is simply set in place, self-aligned due to the match cast shear keys, and is vertically post-tensioned to the pier (Figure 4.45). The recess in the cap for the vertical post-tensioning anchor plates can then be filled with a highly durable, perhaps epoxy concrete. Any required longitudinal post-tensioning of the cap is performed next. In some cases, staged post-tensioning of the cap may be necessary. This post-tensioning would be alternated with placement of the superstructure girders.

The erection process for frame bents less than 27m (88') wide made up of two cap segments is shown in Figure 4.46. Pier erection is the same as that for single column bents. Each match cast cap segment is then vertically post-tensioned to a pier. Any additional segments required between

the cap segments for the frame bents wider than 27m (88') would be added in the manner described in Section 4.2.3.3 - the additional segments are longitudinally post-tensioned to the first cap segments that have been vertically post-tensioned to the piers. The remaining joint between the cap segments would then be formed, post-tensioning ducts spliced and non-prestressed reinforcement tied. Cast-in-place concrete is then placed in the joint. Once the joint concrete has cured, the entire cap can be post-tensioned, providing positive moment reinforcement at the mid-span of the bent. Again, staged post-tensioning may be required during placement of the superstructure.

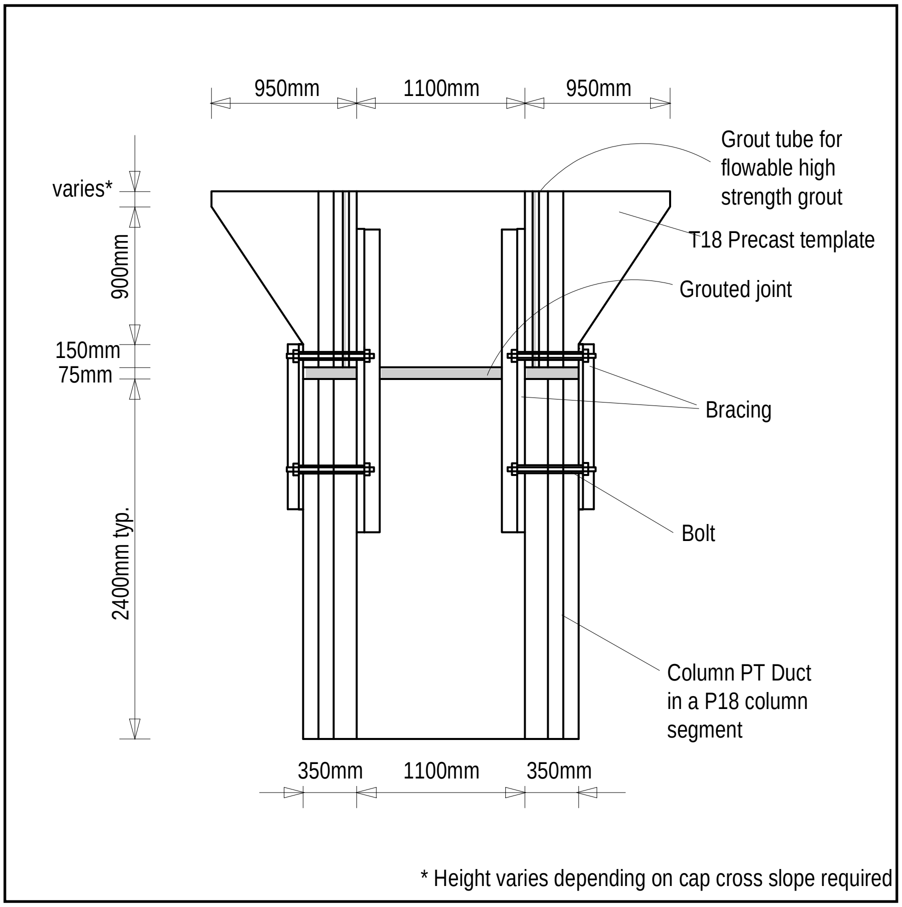


Figure 4.44 Cross section through a P18 pier showing grouting of the template to the top column segment

For the frame bent caps and the single column bent caps requiring post-tensioning, an additional cast in place cover could be added to the ends of the cap to cover the post-tensioned anchor plates. This addition can be attractively chamfered as shown in Figure 4.50. A chamfered end minimizes the visual disruption to the profile of the bridge that blunt bent cap ends often create. The chamfers will also integrate the cap more attractively to skewed layouts (similar to the octagonal columns proposed for the bents in Figure 5.39).

4.2.5.6 Precast Substructure Design Process - Proposal II

This section will outline the general procedure for designing a precast substructure bent. Two specific examples with detailed computations are given in Appendices C and D. Specific calculations and design equations mentioned in this section will be referenced to the designs in these Appendices.

The loading on a precast substructure bent should be in accordance with the prevailing Code or Specifications used by the engineer. In addition to satisfying serviceability and strength under service and ultimate loads respectively, any pertinent serviceability or strength requirements must be satisfied under construction loads. Construction stress limits may be critical in pier design due to the unbalanced moments imposed while girders are being placed.

Variations in the design forces will dictate the specific pier section and corresponding template size to be used. With experience, the designer will have a feel for what pier size is required for certain pier configurations, pier heights and roadway widths. The larger pier sections will generally be required for the single column and straddle bents where column moments can be considerable. Frame bents typically experience less bending and will often allow use of the smaller pier sections.

While the current practice at TxDOT is to design all multi-column bent caps as if pin-connected to the bent columns, multi-column (in this case two-column) precast bents should be analyzed as frames with moment connections between the cap and columns. In particular, secondary moments caused by the longitudinal post-tensioning of frame bent caps must be accounted for in design.

Slenderness effects must be considered in the pier analysis. A second order analysis that accounts for the effects of prestressing will be the most desirable solution. Approximate methods such as the moment magnifier method and the P-delta method as outlined in AASHTO Standard and

LRFD Specifications can be used as well. These methods were not specifically developed for use with prestressed columns and therefore some modifications should be made when using them. The design examples in Appendices C and D were based on column moments amplified using the moment magnifier method (pages C10 and D10). As the service limit state dictates no cracking of prestressed members under service loads, uncracked sections were assumed when magnifying service load moments. Therefore the only modification to the stiffness of the section at service load levels is for creep effects (β_d). When magnifying column moments under ultimate loads, a reduced stiffness which accounts for cracking, creep and shrinkage effects as specified in the AASHTO Standard or LRFD Specifications should be used. This will be conservative as it neglects the enhanced stiffening effect due to prestressing in the columns. The moment magnifier method is a conservative approximate method. It should be replaced by a refined second order analysis when slenderness effects dominate. In such a second order analysis the beneficial effects of prestressing can be considered. Slenderness effects will usually be more critical in the bridge longitudinal direction (weak axis of the column) than in the transverse direction (strong axis of the column) for the proposed precast substructure system if the superstructure is simply supported. With a continuous superstructure, slenderness effects for longitudinal bending should not be critical.

After the determination of critical load effects (axial, shear and moment) are completed, a final pier size should be selected. Amplified moments may have to be revised for the changed size and an iterative procedure utilized. Segmental pier design will generally be controlled by service load conditions. The column section and reinforcement is selected based on satisfying the zero tensile stress limit and the maximum service compression load stress specified in the AASHTO Codes. This also will be an iterative process; selecting a section size, determining the amount of reinforcement required and determining the required concrete compressive strength. The ultimate capacity of the columns must then be checked by constructing an interaction diagram. The interaction diagram for a prestressed column is constructed similarly to that of a non-prestressed reinforced column by determining the failure envelope of axial and flexural load combinations through a strain compatibility analysis. One important difference with prestressed columns is that both the steel and concrete have initial strains due to the prestressing that must be accounted for in analysis. It should not be assumed that the ultimate strength of the prestressing steel will be developed at ultimate load conditions. Example calculations for an interaction diagram for a prestressed column is shown on pages C12 and D12 as well as in Reference 67.

Main flexural reinforcement for the cap can be handled with pretensioned and/or post-tensioned steel combined with non-prestressed reinforcement for the ledges. Pretensioning will reduce the amount of non-prestressed reinforcement required in the cap for handling. In the case of straddle and frame bents, some post-tensioned reinforcement will be required to provide positive moment reinforcement between the supports and tie the cap segments together. Secondary moment effects due to post-tensioning in the frame and straddle bents (essentially rigid frames) must be considered. Examples of the design of cap flexural reinforcement are given in Appendices C and D beginning on pages C22 and D18.

Choosing an appropriate tendon layout for frame bents in particular will be an iterative process. Stress limitations must be met during construction as well as at service loads. A controlling factor may often be that no tensile stress is permitted across a joint that has no bonded non-prestressed reinforcement passing through it. This will normally be the case at the cast-in-place closure joint. There are a number of design options to handle stress limitations when they are critical at this joint, and when a cast-in-place closure at the center alone is not satisfactory. One option is to specify a field weld splice between non-prestressed bars that are cast extending from the end of the cap (Figure 4.47a). Precasting will provide suitable tolerance levels for the location of the non-prestressed reinforcement extending from the cap ends to allow for field welding. Another option for handing stresses across the cast-in-place joint is to move the joint away from the most critical load area (Figure 4.47b). However, moving the joint from the center will require cap elements of different lengths. The unbalanced load condition particularly of the longer cap element during construction may control the design of the column. As well, the two cantilevers making up the central span of the frame bent are intentionally match cast to provide appropriate cross slope for the deck. This advantage will diminish if the joining cantilevers have considerably different deflections due to unbalanced loads. The caps are not very flexible. For example in the bent shown in Appendix D, moving the location of the joint by one meter removed the need for staged post-tensioning during erection yet resulted in only a half inch deflection difference. A third option shown in Figure 4.47c is to use temporary post-tensioning bars across the top of the cap between the two cap recesses that accommodate the column post-tensioning anchorages. This option will be most useful when stress limitations are not satisfied during construction - when the loads caused by the post-tensioning at the center of the span are not balanced by the dead load of the girders. Temporary PT bars across the top of the cap may allow for full post-tensioning initially rather than requiring a more time consuming staged post-tensioning scheme. Depending on the tendon layout chosen, the provision of PT bars across the top of the cap could remain in place rather than be only temporary during erection. The size and number of these PT bars will dictate the necessary depth of the recess above the columns to accommodate post-tensioning operations for these bars (which will occur after the column post-tensioning is completed) and provide them with adequate cover if they are to remain in place permanently.

Once the main cap flexural reinforcement is designed, the caps must then be detailed to adequately transfer the girder loads from the ledge to the stem of the inverted T cap. The Strut and Tie method is an efficient method for designing the cap ledge and hanger reinforcement (page C28a). The traditional method used by TxDOT for inverted T ledge and hanger reinforcement is for solid inverted T's with an unchamfered ledge.[21] This method may be used for the proposed cap with a modification for determining punching shear resistance (pages C28b and D32). The distribution requirements of the reinforcement for the Strut and Tie method will be more efficient but the amount of required reinforcement for the two methods should be similar. The hanger reinforcement shear capacity check as per Reference 21 does not account for shear resistance provided by prestressing.

The shear capacity of the cap must be analyzed next. Shear-torsion behavior must be checked as well (pages C31 and D35). Shear forces should be resisted mostly by closed stirrups. Draped post-tensioning can also aid in resisting shear forces (V_p) and the flexural reinforcement layout may be altered to better resist shear where desired. Closed stirrups should be used in each of the webs of the stem. This detail will provide both shear resistance and a support for interior side face crack control reinforcement (Figure 4.35b & c). Shear reinforcement requirements must then be compared to hanger reinforcement requirements. Hanger reinforcement must be supplemented with additional stirrups where shear resistance requirements are not fully satisfied (pages C35 and D41).

The ledge, hanger, and shear reinforcement may all be designed by the Strut and Tie method as outlined in Section 5.6.3 of the LRFD AASHTO Specification. This design method should lead to more economical design and better understanding of the flow of forces than traditional AASHTO methods. However, codification of Strut and Tie modeling is often unclear and difficult at times to apply, particularly when a large number of ultimate load cases must be checked. With more design examples and text books covering this method and with further clarification as to its advantages and limitations, the Strut and Tie method may become the design method of choice for these rather deep inverted T caps. If traditional AASHTO methods are used, strut and tie models are recommended for an initial understanding of the flow of forces. Then, the traditional methods should be used carefully and will usually provide conservative detatiling for familiar applications.

4.2.5.7 Precast Substructure Design Details

A number of separate detailing considerations are presented below:

(a) Detailing of the hollow columns should be in accordance with recommendations developed by Taylor, Rowell and Breen at the University of Texas at Austin.[68] Recommended detailing includes:

1. Two layers of longitudinal reinforcement should be provided in each pier wall, one layer near each face of the wall.
2. Maximum lateral spacing of longitudinal reinforcement should be limited to 1.5 times the wall thickness or 450mm (18"), whichever is smaller.
3. Maximum longitudinal spacing of lateral reinforcement layers should be limited to 1.25 times the wall thickness or 300mm (12"), whichever is smaller.
4. Cross ties between layers of reinforcement are recommended at maximum longitudinal and lateral spacing of 600mm (24"). Cross-ties should be alternated in a "checkerboard" pattern and connect points where lateral and longitudinal bars intersect. This reinforcement prevents buckling of longitudinal bars. Additional cross ties are recommended at the top and bottom of each segment.
5. Lap splicing of transverse bars should be avoided, if possible. Otherwise, lap splices should be enclosed by the hooks of cross ties.
6. Corner regions of segments should be well confined in order to enhance performance under biaxial bending.
7. Post-tensioning ducts should be grouted in order to promote integral action between post-tensioning bars and the concrete section.
8. A minimum of 1% longitudinal non-prestressed reinforcement should be provided.

The last recommendation listed above is primarily aimed at reducing the effects of creep and shrinkage in these vertical compression members. A recent study at the University of Texas in Austin has shown this minimum requirement to be appropriate for non-prestressed columns. Concrete strengths of 28MPa (4000psi) and 56MPa (8000psi) were tested.[69] With the use of HPC (as proposed for the precast substructure system developed herein), concrete stiffness is enhanced. A limit less than 1% may be sufficient depending on verification from studies. In addition, the minimum required non-prestressed reinforcement in precast segmental substructures is not continuous across the segmental joints. While this reinforcement will be stressed under load, it is not required nor depended upon to carry load. Creep will have a more significant effect on column post-tensioning through loss of prestress. A minimum amount of non-prestressed reinforcement will be required for shrinkage and temperature effects. A minimum percent less than 1% will most probably suffice. Considerable material quantity savings could be realized with a reduced value such as 0.5%.

(b) The portion of the cap above the column post-tensioning must be recessed to allow for post-tensioning operations and provide adequate cover for the post-tensioned anchors once the recess is filled. A recess of 250mm (9.85") should typically suffice.

(c) All shear reinforcement should be provided for in the initial stage of the two-stage cap fabrication. Full stirrups of one continuous bar should be cast into the ledge. The ledge may then be lifted by the cage to be placed into a pretensioning bed for casting of the stem (see Section 4.2.5.4). Casting the full stirrups in the first stage avoids the need for hanger reinforcement being spliced and producing a poor detail.

(d) Anchorage zone detailing for the post-tensioned anchor zones is most easily handled using the Strut and Tie method as outlined in Section 5.10.9 of the LRFD AASHTO Code (see example calculations beginning on pages C41 and D45). Pretensioned anchor zones must be detailed as well as outlined in Section 5.10.10 in LRFD AASHTO (page C47). Post-tensioned anchor zones for longitudinal cap reinforcement at the ends of the cap segments will require a solid stem in these portions (Figures 4.35a and 4.48). This will increase the weight of the cap.

Post-tensioning anchorage zone design and detailing requires attention to both the local zone and the general zone as defined in Section 5.10.9 of the AASHTO LRFD Specifications. Reinforcement for both the local and general zones for the vertical post-tensioned bars anchoring into the webs of the cap stem can be provided with orthogonal grid bars (bursting reinforcement). Vertical multi-strand tendons will be anchored in the center of the stem, another area where the hollowed portion is filled in. Anchorage zone reinforcement for both vertical and horizontal multi-strand tendons will generally require spirals for the local zone. Post-tensioning suppliers have standard details for spirals accompanying these special anchorage devices and are responsible for the specification of local zone reinforcement. The details provided to design engineers are typically for use with 28-34MPa (4000-6000 psi) concrete. In the case of higher strength concrete, anchor spacing and the size of the spiral confining reinforcement required is sometimes reduced if tests have been performed at the higher concrete strength. This will be beneficial for the design of the proposed precast substructure system where space for large tendons is limited. For example, an engineer with the supplier VSL indicated to the author that an equation often used to estimate required anchor spacing dimensions is directly related to the concrete bearing strength at the end of the local anchor zone (Equation 4-1).[70]

$$X = \sqrt{\frac{1.15\mathrm{GUTS}}{f'_{ci}}} \tag{4-1}$$

where: X: Anchor spacing, center-to-center
GUTS: Guaranteed ultimate tensile strength of the anchored post-tensioning tendon
f'_{ci}: Concrete compressive strength at the time of stressing

Anchor spacing will decrease with an increase in concrete compressive strength. Spiral reinforcement sizes, in particular the outer diameter of the spiral, could possibly be reduced along with anchor spacing. If the smaller spacing and spiral sizes are desired, acceptance tests *must* be performed on these special anchorage devices with higher strength concretes in accordance with the procedures outlined in AASHTO Division II Article 10.3.1.4.4.

In general, local zone design will be governed by the device characteristics indicated by the post-tensioning hardware supplier. However, the designer may use Equation 4-1 as a quick check to determine if certain tendon sizes will be feasible with chosen concrete strengths. It will be desirable in certain situations such as when the large 19K6 multi-strand tendons are required for the vertical post-tensioning, to reduce the spiral size. Overly conservative spiral dimensions will make placement of longitudinal cap reinforcement that runs next to the spirals unnecessarily difficult (Figure 4.48).

(e) Non-structural details for this precast substructure system include maintenance concerns and improved substructure appearance. Internal drainpipes should be included in the design of all substructures (Figure 4.49). However for the drainpipes to be of use, they must be kept free of

debris and blockage. Design and maintenance considerations must be coordinated so that dependable drainage methods are specified.

(f) With careful quality control, the surface of precast elements can be attractive and relatively uniform, thus removing the need for painting. Other alternatives to painting which should always be considered are stained surfaces, rubbed finishes and sandblasted surfaces (see Appendix B in Volume II, *The TxDOT Aesthetics & Efficiency Guidelines*).

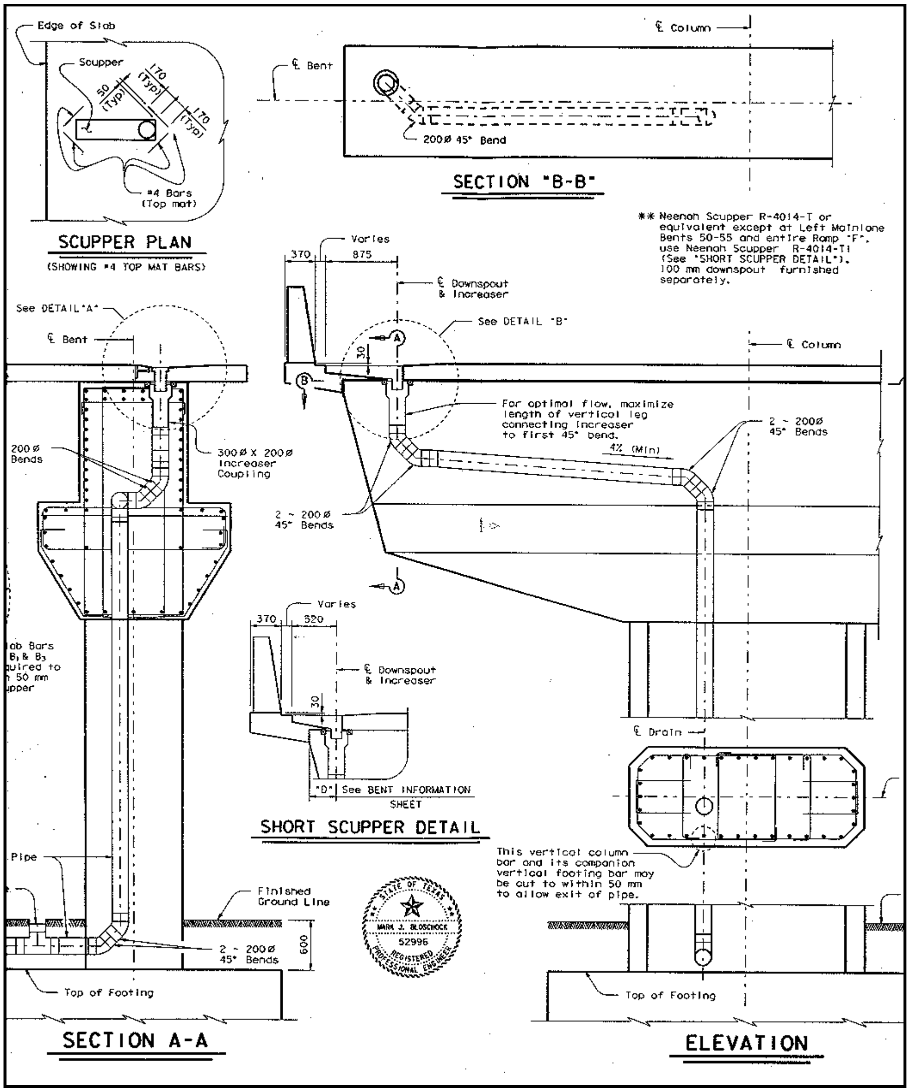


Figure 4.49 Details for an internal drain pipe in an inverted T cap bent

4.2.5.8 Observations on LRFD AASHTO Bridge Specifications

In the process of designing post-tensioned substructures using the proposed system, a few important observations on the new LRFD specification were made. First, the longitudinal braking force in the LRFD AASHTO is considerably increased over the Standard AASHTO specification. Table 4.5 shows the value of the braking force for different lane simply supported bridges comparing the LRFD and Standard AASHTO codes with the Ontario Highway Bridge Design Code[71] and the Swiss (SIA) Standard 160.[72] The equations for longitudinal braking for each code are given in Appendix E. The reason given in the LRFD version for the considerable increase is the improved braking technology of trucks as well as the fact that the new provision will now be more in line with other respected codes. The commentary to the Ontario code explains that the provision is based on theoretical energy principles. However it is noted that there have been no known failures to bridge columns due to longitudinal braking forces when designed for lower braking loads. The experience in Texas has shown longitudinal braking forces not to be a problem. Until specific evidence is presented to the contrary, it is recommended that the current (lower value) Standard AASHTO provision be used for longitudinal braking loads.

In TxDOT experience, column design in the past has never been controlled by longitudinal moment. Under the new LRFD provisions the longitudinal bending moments in certain designs (in particular frame bents) will be greater than transverse bending moments particularly for shorter columns where transverse wind loads are not as critical. The effect on design efficiency will most probably not be large. The bending moments in frame bents are generally quite low and as seen in the design example in Appendix D, service stress limits are easily satisfied. Steel requirements for the cast-in-place alternative (page D15) may need to be increased with increased longitudinal moments to satisfy biaxial bending requirements.)

	Standard AASHTO kN (kips)	**LRFD AASHTO kN (kips)**	**Ontario Bridge Code kN (kips)**	**1989 SIA Standard 160 kN (kips)**
No. of lanes considered	@ 1.8m (6') above deck surface	@ 1.8m (6') above deck surface	@ deck surface	@ deck surface
1 lane	23 (5)	96 (22)	160 (36)	180 (40)
2 lanes	46 (10)	160 (36)	240 (54)	180 (40)
3 lanes	62 (14)	204 (46)	240 (54)	180 (40)
4 lanes	68 (15)	208 (47)	240 (54)	180 (40)

Table 4.5 Longitudinal Braking Force Requirements for various Codes

The second observation made in regard to the AASHTO LRFD Specification is in its treatment of design with prestressing steel. There is some debate among code making bodies over the current prestressed concrete design philosophy in the United States. This philosophy, also found in the AASHTO LRFD Specification, is that stresses be limited under service loads to prevent cracking in members with prestressed reinforcement. This approach differs from the treatment of members with only non-prestressed reinforcement where cracking is permitted at service loads but must be controlled. Further discussion of these differing design philosophies can be found in References 73-77. Presently, the service limit state will almost always control the design of prestressed columns. This is particularly true for segmental columns where no tension is allowed across the segmental joints under service loads. The resulting amount of prestress prevents cracking under service loads and is often far in excess of what is necessary for the ultimate limit state. Regardless of one's position on the general philosophy of prestressed concrete design, there are direct positive benefits to having the service limit state control design. By not permitting cracking in the columns at service load levels, durability is obviously improved and fatigue will be no problem. In addition, not allowing cracking results in increased column stiffness and therefore less slenderness (P-delta) effects. Further studies are required to determine if these benefits are justified by the substantial increase in prestressing reinforcement above that required for the strength limit state.

4.3 Cast-in-place Substructure Alternatives

Alternatives to the previously discussed precast substructure system include designing a substructure using the same geometric form but entirely cast-in-place or designing substructures of similar geometric form that are made up of combinations of both cast-in-place elements and precast elements. In Texas, benefits and drawbacks can be found with both an entirely cast-in-place system (CIP system), a cast-in-place column with precast cap system (CIP column-PC cap system) as well as a precast column and cast-in-place cap system (PC column-CIP cap system).

4.3.1 Cast-in-place Non-prestressed Alternates

The precast substructure system for Proposal II can easily be constructed as an entirely cast-in-place system with non-prestressed reinforcement. To facilitate cast-in-place construction, solid sections should be used. Use of high performance concrete is recommended for improved substructure durability.

The inverted T caps would be designed in accordance with current common practice in Texas. Such inverted T caps can be found throughout Texas particularly in urban settings. Column design would also follow the same procedures as current common practice. The chamfered shape of Proposal II can easily accommodate required reinforcement to resist critical column forces as shown on pages C15 and D14 where non-prestressed column alternates were investigated for the Proposal II precast substructure design examples. The amount of steel necessary was between 1-2% of the gross area of the solid column.

4.3.2 Cast-in-place Columns, Precast Bent Caps

With a CIP column-PC cap system, construction of cast-in-place columns can proceed directly following the casting of the foundation cap or footing. As typically used in many bridges, drilled shaft foundations may be continued above ground as the columns for a bent system. Precast caps can then be placed above the columns. This system is more efficient for forming than both a complete cast-in-place system and a PC column-CIP cap system. The column forms can be supported from the ground. The often heavy and awkward formwork for a CIP cap is avoided. The cranes required for superstructure erection can be used to place the precast caps directly before girder placement. The labor force required for this form of construction is grouped efficiently as well. A “cast-in-place” crew can work continually from the foundation to the columns. They can be replaced by the “precast placement” crew for placement of the caps, girders and possibly deck panels.

A disadvantage of this system is that the cap pieces are the heaviest elements of the substructure for hauling and erection. The cap is also the more cumbersome element to precast compared to column segments. With cast-in-place columns, a geometry control joint would be required underneath the precast caps to set them at appropriate cross slopes. This would require balancing the heavy cap piece while alignment changes are performed. An alternative would be to use built up bearing seats on the caps to provide deck cross slope. Other disadvantages include disruptions to the site due to column forming, concrete placement and curing.

4.3.3 Precast Columns, Cast-in-place Bent Caps

With a PC column-CIP cap system, a cast-in-place footing is followed by precast columns post-tensioned together as presented in Sections 4.2.3.3 and 4.2.5.5. The bent caps must then be formed and cast-in-place. The cap must be post-tensioned to the column to provide a fixed connection between the cap and column for the single column piers. Post-tensioning of the cap to the column will also be necessary for two-column frame bents and straddle bents where moment transfer to the columns is desired. After the cap is cured and post-tensioned to the column, erection can proceed with the placement of the precast girders. This erection process alternates from cast-in-place footings to precast columns to cast-in-place bent caps to precast girders. This requires an alternating labor force and equipment usage.

There are many advantages to a PC column-CIP cap system. Precast column segments are light and easy to haul and erect. Match cast columns will allow for rapid column erection on site. Casting the cap in place allows the cross slope to be provided during forming. One major disadvantage to this method of construction is that the cast-in-place portion of work is elevated. Therefore the caps require very heavy self-supporting forms. These heavy forms will often need to be assembled and the concrete placed at hazardous elevations.

4.3.4 Summary

Regardless of which option is chosen, precasting any part of the substructure system should speed up construction time and reduce site disruptions when compared to an all cast-in-place substructure system. Both systems offer improved durability for the columns through post-tensioning. Prestressed caps would be less permeable and therefore more durable than non-prestressed caps. Both precast and cast-in-place caps could be prestressed (pretensioned and post-tensioned for precast caps and post-tensioned for cast-in-place caps). Precasting would provide higher quality control in fabrication with a resulting less permeable concrete.

4.4 Summary

Substructure design provides an opportunity for creative design with short and moderate span bridge systems. New technologies and new materials can be applied for attractive and economical results. Substructures can be constructed using methods of precasting, casting in place or a combination of the two. This chapter has presented a precast substructure system for standardization. A geometrically similar system may be cast-in-place or be a combination of both precast and cast-in-place elements.

The proposed precast substructure system is a versatile system that can be used for a wide variety of bridge widths and heights. This system can be used with standard precast girder superstructure systems and offers a new alternative to substructure design that can increase construction speed thereby reducing costs associated with traffic delays and re-routing. The precast system of match-casting with epoxy joints has provided excellent durability for structures in the past. The combination of precasting and using high performance concrete results in more durable and more attractive construction (Figure 4.50).

Precast substructures are not an entirely new form of construction but have been used successfully in the past. Such a system will be most useful at first in Texas for large projects in highly visible locations where construction efficiency (speed of construction) and final appearance are particularly important. An initial investment in forms for a large project will lead to future savings when the forms may be re-used for similar or smaller projects. Over time and with high re-use, new standard shapes for substructures may be developed to provide TxDOT designers with even more alternatives for attractive substructure design.

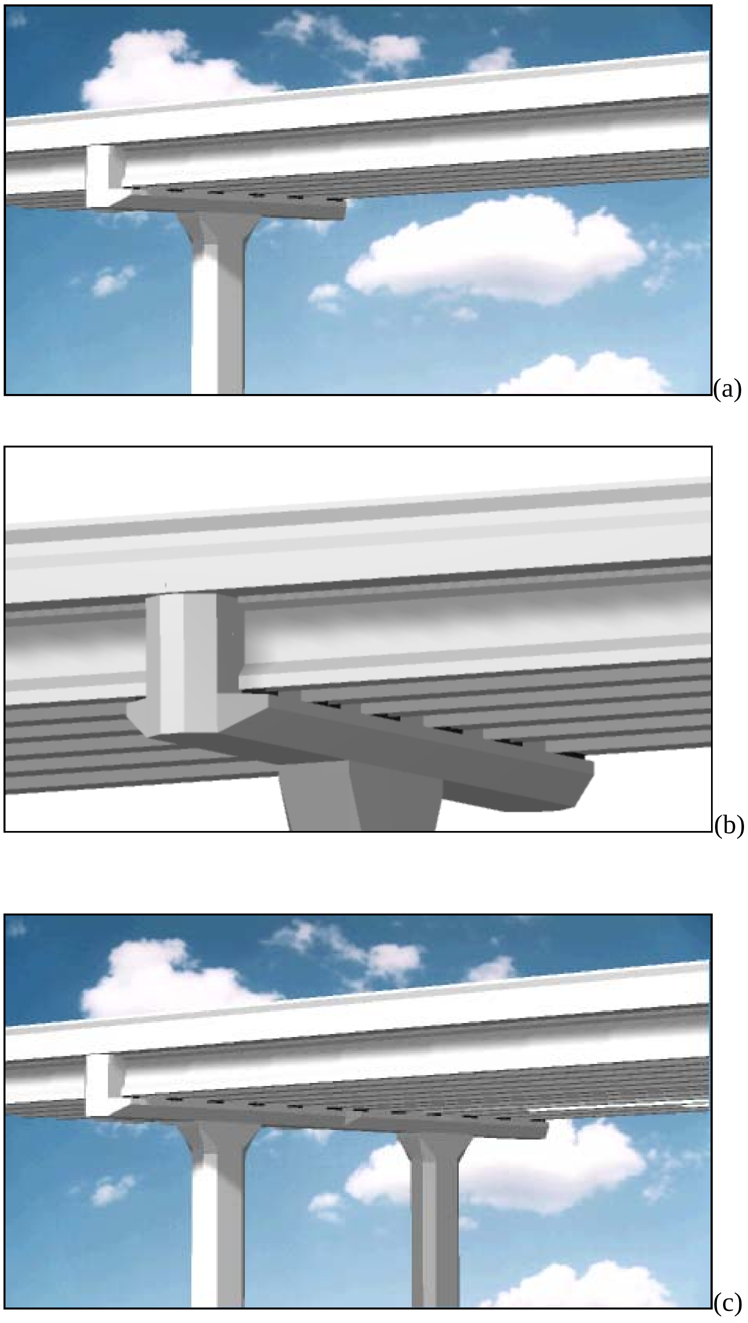


Figure 4.50 Computer aided renderings of a hammerhead (a,b) and frame (c) bent using the proposed precast substructure system

CHAPTER 5
ALTERNATE SUBSTRUCTURE DESIGN - CAST-IN-PLACE CONCRETE OPTIONS

5.1 Introduction

Cast-in-place concrete requires formwork to be assembled in the field. Formwork can be fabricated to accommodate almost any shape the designer chooses (Figure 5.1). Such a wide variety of shapes are possible because of concrete’s flowing quality. The engineer’s challenge is to find new forms and new shapes that are attractive and within reasonable economic limits.

Savings can be achieved with cast-in-place concrete through standardization of formwork. Unfortunately, in Texas such standardization has stalled with the use of just a few shapes - circular or rectangular columns with prismatic caps (Figure 5.2). This system typically results in an ugly forest of columns in any setting. The limited variety of substructure shapes in Texas has been maintained for the sake of economics yet allows for very little creative expression.

This Chapter explores new options for cast-in-place concrete substructure design. In particular, ideas are presented that are compatible with precast concrete superstructure design. The goal of this Chapter is to spark the creativity of engineers designing short and moderate span bridges. Ideas are presented that can be implemented in certain design situations without excessive cost increases. A general guideline is to keep cost increases within 2-5% of the project cost.

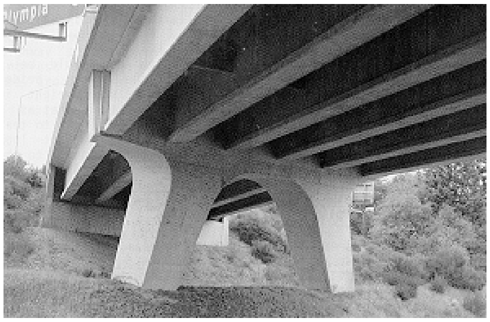


Figure 5.1 Cast-in-place substructure

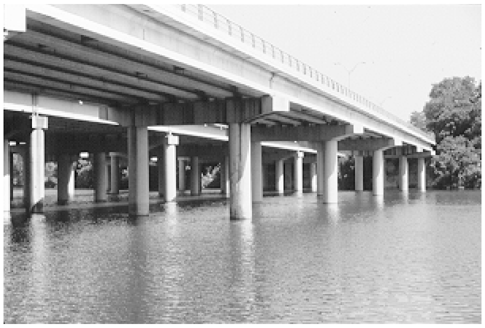


Figure 5.2 Typical cast-in-place substructure system in Texas

5.2 Alternative Cast-in-place Substructure Systems

A few substructure shapes outside of the predominantly used circular and rectangular columns have been experimented with in Texas. Even more shapes can be found in other States and countries. Section 5.2.1 reviews the basic substructure systems used throughout Texas. Sections 5.2.2-5.2.6 discuss a variety of alternative shapes including previously used shapes and new ideas for substructure design. Ideas for enhancing substructure design through non-structural details such as concrete texture and color, and the shaping of bent cap ends are also explored. The cast-in-place options presented are discussed in terms of their aesthetic appeal or drawbacks as well as their economic feasibility for TxDOT.

5.2.1 Substructure Systems

The substructure systems most widely used in Texas include individual columns, walls, hammerhead bents and multi-column bents. Each system is presented and illustrated below. (Although all of the systems presented can be found in Texas, illustrations 5.6 and 5.11 are not Texas bridges.)

Individual Columns

Individual columns may be used *without bent caps* to support individual girders (Figures 5.3-5.6). Individual columns are most appropriate when supporting the spines of segmental box girders or under individual trapezoidal box or U-beam superstructures (Figures 5.5-5.7). Trapezoidal box beam and U-beam superstructures require fewer longitudinal beams. As a result, it is often possible to use fewer individual supports for a given bridge width than traditional box beams or I-girders would require. Individual supports for traditional I-girders will typically create a cluttered "forest of columns." Widely spaced, large I-girders and/or girders on heavy skews however, may warrant individual columns with a less congested appearance resulting. Individual columns may be efficiently precast or cast in place. Individual columns minimize substructure clutter the most when used with a box girder superstructure (Figure 5.7).

Figure 5.3 Individual columns used to support individual beams

Figure 5.4 Individual columns supporting individual cast-in-place continuous beams

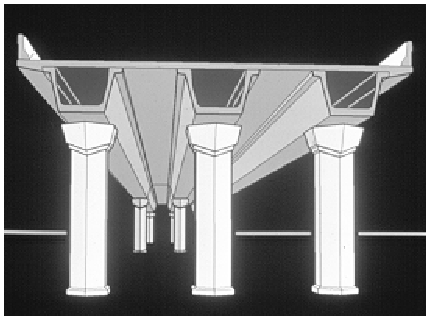


Figure 5.5 Individual columns supporting individual precast U-beams

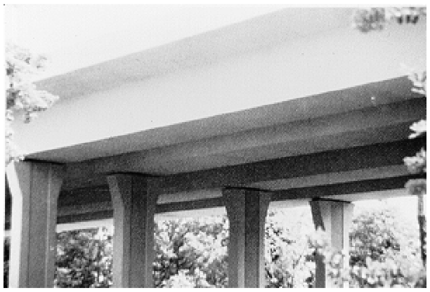


Figure 5.6 Individual columns supporting individual trapezoidal box girders

Figure 5.7 Individual columns supporting a single box girder bridge

Walls

Wall substructures are supports that are generally as wide as the superstructure which they support (Figure 5.8). Walls are typically used in rivers for minimizing blockage from debris (Figure 5.9a) or for crash protection in railroad crossings (Figure 5.9b). Wall substructures obstruct visibility through a bridge when viewed from most angles, particularly if they are closely spaced (Figure 5.9a). However, when walls are used in connection with increased span lengths, the walls may add to a simple, elegant appearance (Figure 5.10). Walls are typically cast-in-place and can therefore be economically cast with tapers or other interesting shapes (Figure 5.11).

Hammerhead Bents

Hammerhead bents (T-shaped single-column bents) are common for narrow bridges and bridges in locations where visibility through the structure is desired. Hammerhead bents may be a variety of shapes. They may be entirely underneath the superstructure (Figures 5.12-5.13) or partially or fully integrated with the superstructure (Figures 5.14-5.15). Circular columns are difficult to integrate visually with rectangular bent caps (Figure 5.12b, 5.14b). Rectangular columns can be integrated with rectangular bent caps more easily with attractive results (Figures 5.12a, 5.14a) Hammerhead bents may be have tapered caps and/or columns where structurally appropriate for increased efficiency and expression of the flow of forces (further discussed in Section 5.2.2).

Multi-Column Bents

Multi-column bents are common for wide bridges or in locations where the area underneath the bridge needs to be straddled. Multi-column bents are often the most economical solution for any bridge width yet typically give a bridge a cluttered appearance (Figure 5.16). As with hammerhead bents, circular columns are more difficult to visually integrate with prismatic bent caps than are rectangular columns (Figures 5.17-5.18). Multi-column bent caps may be entirely underneath the superstructure as seen in Figure 5.17 or they may be partially or entirely integrated with the superstructure (Figure 5.18). Bent caps may be haunched or tapered where structurally appropriate for increased efficiency and expression of the flow of forces.

5.2.2 Alternative Shapes - Structural Expression, Curves, Tapers

There are numerous possibilities for attractive substructure design. The substructures may be designed to express visually the flow of forces from the superstructure to the foundation. This is

Figure 5.8 A wall substructure unit used for a highway overpass

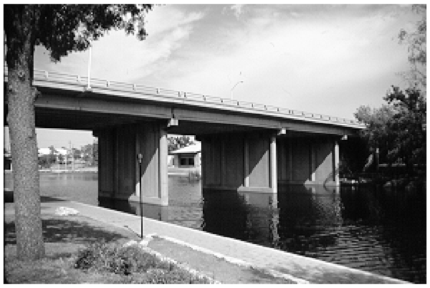


Figure 5.9a Wall substructure units for a water crossing

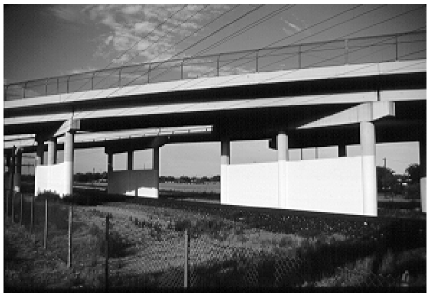
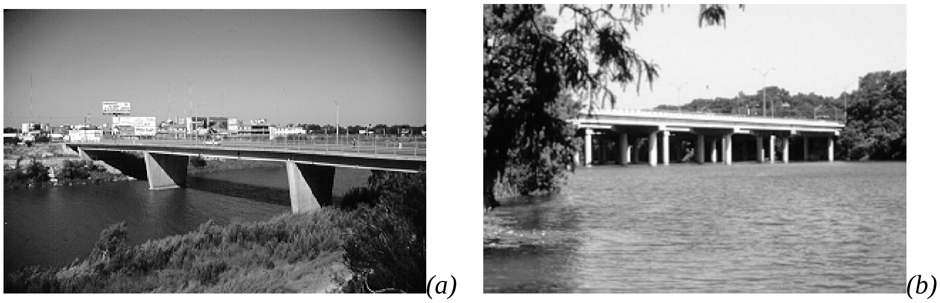


Figure 5.9b A combination multi-column and wall substructure for a railroad crossing



Two single tapered walls with long spans (a) increase visibility through the river crossing whereas multi-column bents with shorter spans (b) block visibility

Figure 5.10 Visibility through the substructure

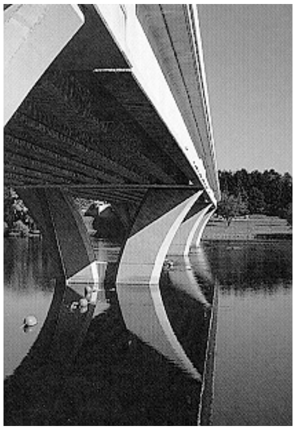
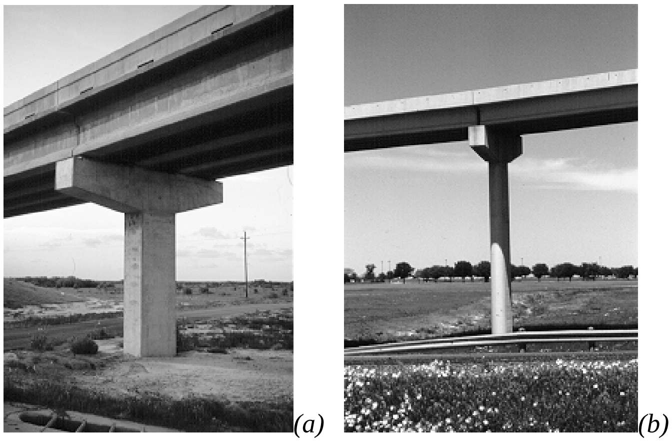


Figure 5.11 Cast-in-place substructures can be easily curved or tapered

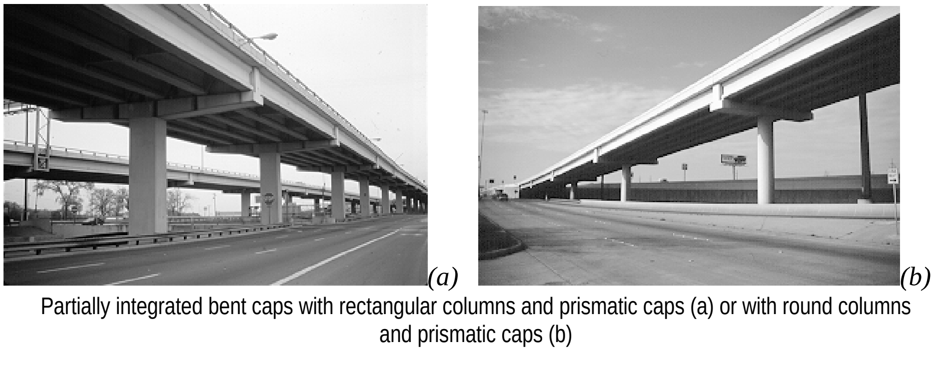


(a) *(b)*

A rectangular column and prismatic cap (a) and a rounded column joining a prismatic cap (b).

Figure 5.12 Hammerhead bents types

Figure 5.13 Hammerhead bents entirely underneath the superstructure



(a) *(b)*

Partially integrated bent caps with rectangular columns and prismatic caps (a) or with round columns and prismatic caps (b)

Figure 5.14 Bent cap integration with superstructure

Figure 5.15 A hammerhead bent cap fully integrated into the depth of the superstructure through the use of dapped girders

Figure 5.16 Cluttered multi-column bents create "forests" of columns

Figure 5.17 Circular columns with a rectangular bent cap entirely underneath the superstructure

Figure 5.18 Rectangular columns joining a prismatic inverted T cap

referred to as structural expression - a direct connection between the structural form and the structural function. Examples include deepening sections at points where larger resistance for higher moments is required or tapering columns down to pinned ends. For instance, the tapered hammerhead bent shown in Figure 5.19 is structurally expressive of the flow of forces under static loading conditions.

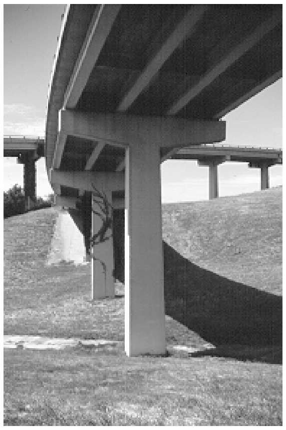
Figure 5.20 shows a pier that has a fixed connection at the base and a pinned connection under the superstructure. The form is structurally expressive in that the lack of moment transfer at the top of the column is expressed visually with the narrowing of the pier section towards the top. The fixed connection at the bottom is expressed by the widening of the pier towards the base. Other examples are shown in Figures 5.21a&b.[78] Structurally expressive forms must be true to their purpose. Exaggerated forms may appear contrived (Figure 5.22) while other expressive forms may be disconcerting (Figure 5.23).

To display the flow of forces between the caps and columns of substructure units, the edges of these two elements should be continuous from one to another. Elements with abrupt changes in size whose edges do not line up give the substructure a clumsy, “building block” appearance (Figures 5.24-5.25). Attention to the integration of the different parts will result in a more attractive form, one that demonstrates the smooth flow of forces from the superstructure to the foundation (Figures 5.26a&b).

Expression of the construction process is another alternative for structural expression. For example, construction joints can be accented with chamfers. Accented joints however, interrupt the smooth lines expressive of concrete's quality of monolithically following any shape or form. Instead accented joints may make concrete appear like its structural material predecessor, masonry (Figure 5.27).

Simple curves can enhance a substructure’s appearance particularly for bridges in highly visible settings. Large wall supports can be curved to minimize their often heavy appearance (Figure 5.28). Incorporating curves into substructure design softens the visual flow from one element to another. Rather than appearing as a set of building blocks, the elements flow together.

Subtle tapers can easily be used for attractive results. A two span overpass with a single tapered column is more elegant than a three span bridge with two multi-column standard Texas bents (Figures 5.29a&b). A single tapered pier (Figure 5.30a) is more handsome than a stepped circular pier (Figure 5.30b).



The tapered cap and column of this hammerhead bent is structurally expressive of the increased moment resistance required at the cap/column intersection and at the column base under critical loads

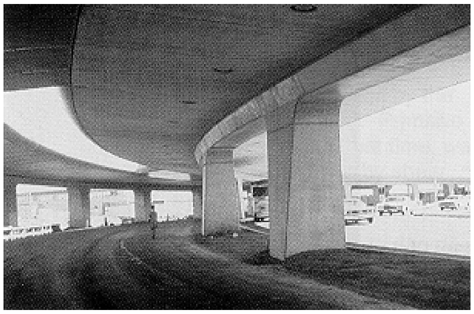
Figure 5.19 Structural expression in substructure design

The clear expression of a continuous girder on pinned supports shows the lack of moment transfer between the super- and substructure

Figure 5.20 Structural expression in substructure design

These tall piers are more fixed at the base than at the top. Under critical lateral loads, the point of inflection is located at about two-thirds the height from the base, allowing the columns to taper in at that location of minimum moment.[78]

Figure 5.21a Structural expression in substructure design



The tapers in these piers vary in both the longitudinal and transverse directions. In the transverse direction, the columns are vertical cantilevers - fixed at the base and pinned at the top. In the longitudinal direction, the columns are pinned at the base to relieve shrinkage and creep stresses in the post tensioned deck and are "fixed" at the top to provide continuity between the super- and substructure.[78]

Figure 5.21b Structural expression in substructure design

Extreme tapering in short substructure units exaggerates the flow of forces and appears contrived

Figure 5.22 Extreme tapering

A flared column that stops short of the outer girders leaves the viewer with a sense of uneasiness about the support of the superstructure

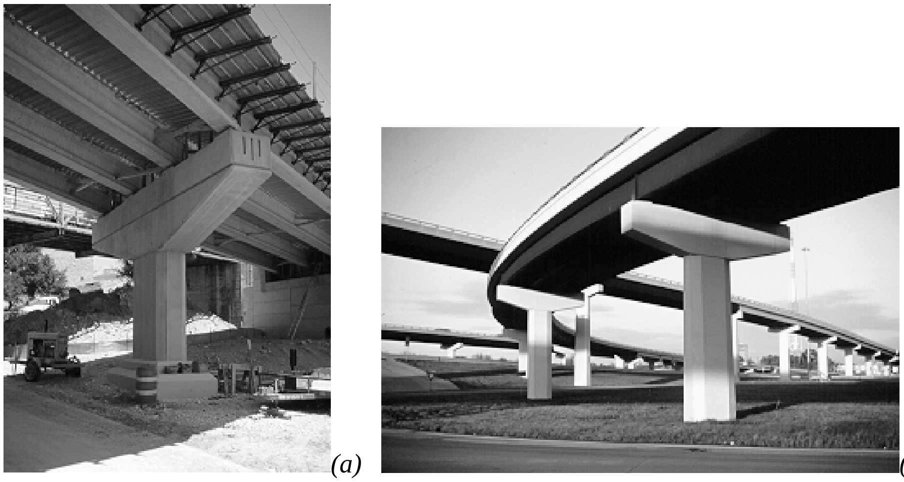
Figure 5.23 Disconcerting design

The wide and heavy cap taper does not integrate well with this narrow column

Figure 5.24 A lack of integration

A large cap end wall contrasts strongly with narrow columns and gives the structure a weak and clumsy appearance

Figure 5.25 An awkward appearance



(a) (b)

Figure 5.26 Attractive integration of the cap and column through simple column chamfers and cap tapers (a & b)

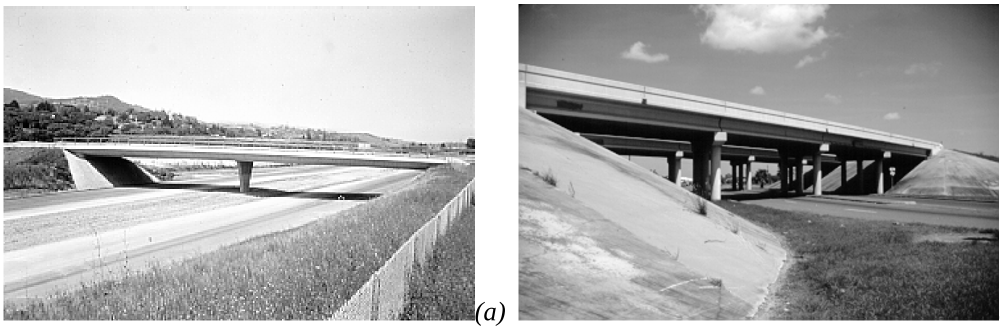
(a) (b)

Accented joints give the appearance of a masonry structure (a). A smooth surface (b) shows off concrete's ability to perform its structural task in a flowing form.

Figure 5.27 Effect of accenting joints

Curved tapers on these large wall supports are an elegant alternative to the typically massive appearance of wall substructures

Figure 5.28 Reducing massive appearance



(a) (b)

Figure 5.29 A simple tapered single support (a) is a more elegant solution than a series of multi-column bents (b) for a standard overpass

(a) (b)

Figure 5.30 A subtle column taper (a) is more attractive than abrupt changes in cross section (b) for tall columns

5.2.3 Improving Visibility Through the Bridge

Multi-column bents on short span bridges allow for limited visibility through their “forest” of columns (Figure 5.31a). Where more openness, light and visibility are desired, fewer substructure elements should be used (Figure 5.31b). This can best be carried out through the use of hammerhead bents or multi-column bents with no more than two columns. Bent caps with more than two columns are generally cluttered and should be avoided (Figures 5.32-5.35). Where possible, an exceptionally wide bridge could be split into two bridges each with a two-column substructure (Figure 5.36). Using two smaller bents in place of one larger one allows more light to reach underneath and through the bridge thus avoiding any dark tunnel effects. As well, two smaller frame bents may be used rather than one larger bent with many columns. When two-column bents are combined with longer spans, a lighter, more transparent bridge will result. This is a particularly good solution for congested urban areas, crime-ridden areas or park settings.

Fewer substructure elements may result in larger elements. Therefore it is important to keep in mind the size of elements when minimizing the number of elements. Large columns may appear as walls and block visibility from certain angles. In such cases, using two smaller columns in place of one wall-like column may be used.

Visibility through the bridge is also effected by the type of bent cap chosen. Bent caps may be fully integrated, partially integrated or entirely underneath the substructure (Figures 5.13-5.15). Compared with fully and partially integrated bent caps, caps that are entirely underneath the superstructure lead to the most obstruction of visibility through the bridge (Figure 5.13). Partially integrated bent caps such as inverted T caps, place the mass of the cap between the beams so that only the ledge supporting the beams is visible. Therefore visibility through the bridge is improved with partially integrated caps (Figure 5.14). Fully integrated caps allow for the cleanest profile. Substructure clutter is greatly reduced allowing for the maximum visibility through the bridge (Figure 5.15).

Visibility is often impaired by the use of skewed bents. In particular, a mixture of skewed and normal multi-column bents leads to a confusing design and one that is often visually "incoherent" (Figures 5.37a&b). Such mixtures should be almost always avoided. In general, unless stream or traffic flows make them essential, skews should be avoided all together. While skewed bridges may minimize span lengths, they are typically more difficult to construct and skewed abutments often lead to increased costs.[11] Alternate solutions should be investigated (Figures 5.38a&b, Figure 3.67). Where skews cannot be avoided, substructure shapes should be chosen that can accommodate

Bridges of similar superstructure and roadway width with a forest of columns (a) or a single elegant tapered column (b)

Figure 5.31 Visibility through substructure

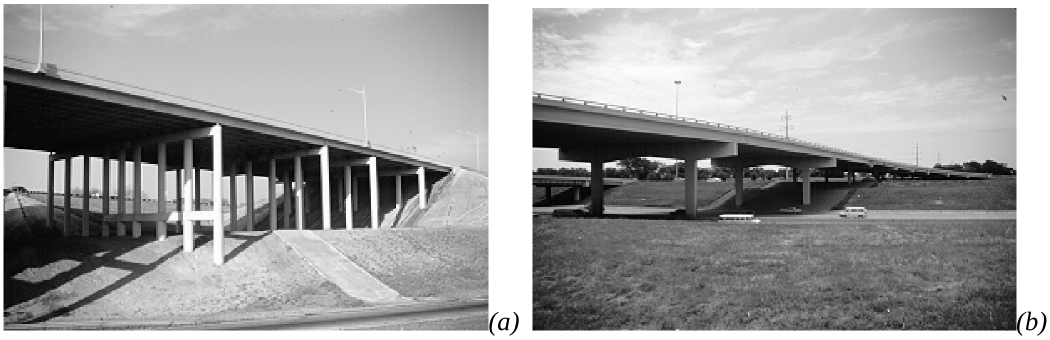


Figure 5.32 Cluttered multi-column bents (a) replaced with more open two-column frame bents (b)

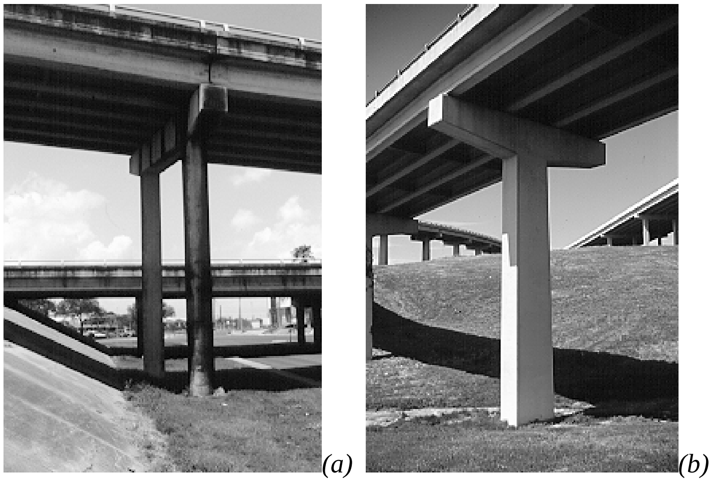
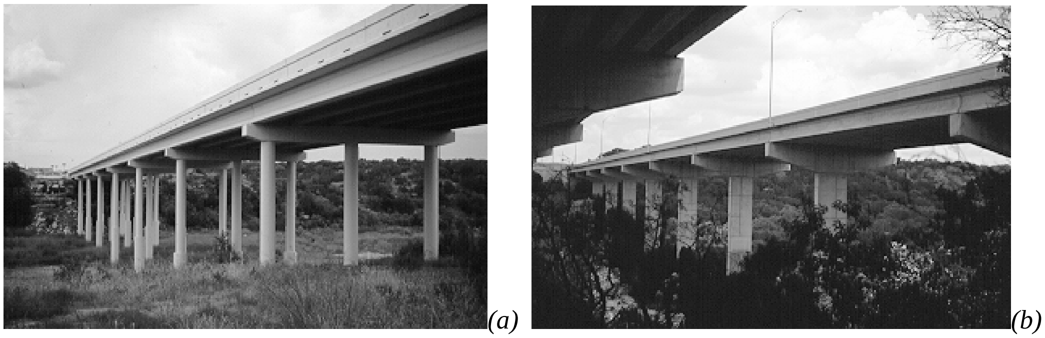
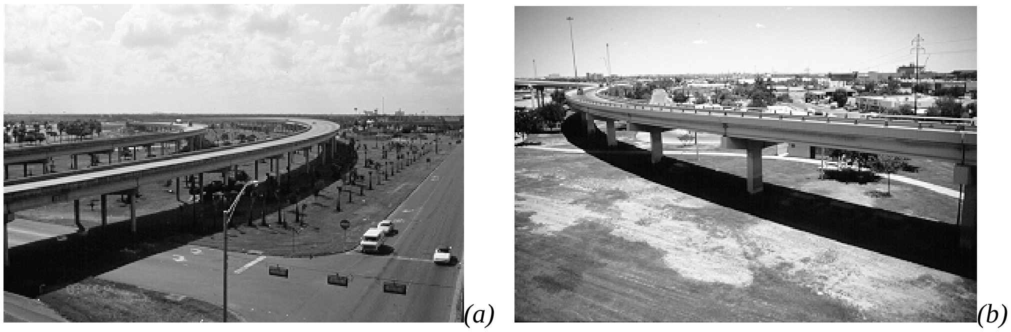

(a) (b)

Figure 5.33 A narrow two-column bent vs. a single column hammerhead bent (b)


(a) (b)

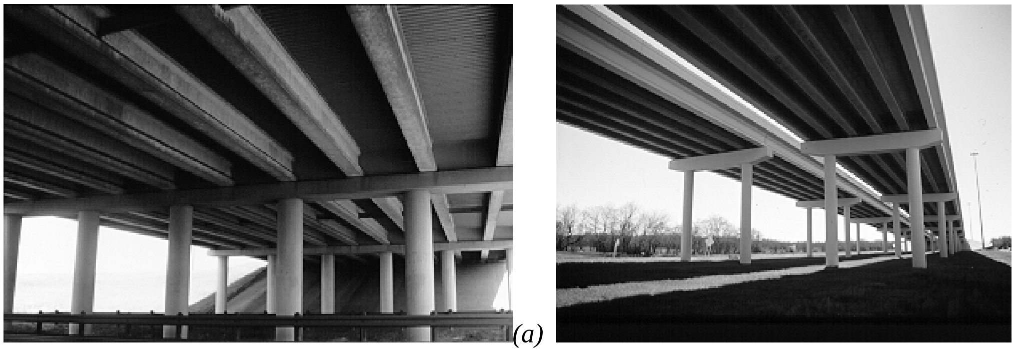
Replacing multi-column bents (a) with single column hammerhead bents (b) creates a cleaner more rhythmic appearance

Figure 5.34 Multi-column bents vs. hammerhead bents


(a) (b)

Replacing multi-column bents (a) with single column hammerhead bents (b) creates a neater, more open substructure area. The proportions of large single columns blend better with precast girder superstructures than the thin columns of multi-column bents.

Figure 5.35 Multi-column bents vs. hammerhead bents



(a) (b)

A wide roadway (a) can be split into two separate structures with fewer columns (b). This allows more light to reach the underside and increases visibility through the bridge.

Figure 5.36 Separating wide bridges

(a) (b)

Skewed bents result in confusing designs that are visually incoherent and unattractive (a&b)

Figure 5.37 Skewed bents

both the deck and skew directions such as octagonal piers (Figure 5.39). (Circular columns are another option but as stated before, do not integrate well when used with rectangular bent caps and are not recommended.)

5.2.4 Integrated Designs

Designs that integrate the superstructure and substructure are another attractive alternative that has been used occasionally in Texas and extensively in the pacific northwest. In the latter areas, such integration is often required structurally to resist earthquake loads. However in any location, a moment connection between the superstructure and substructure will allow for longer spans thus potentially decreasing the number of foundations and substructure elements required and often increasing the visual slenderness of the bridge.

Integrating the superstructure and substructure do not require a moment connection. Fully integrated caps are the most direct way to visually integrate the substructure with a simply supported superstructure. Here, inverted T bent caps would be used to support simply supported dapped beams. This leads to the cleanest connection with the least amount of substructure clutter (Figures 5.40,5.15,5.31b).

Exposed and partially exposed bent caps may be shaped to express the flow of forces from the superstructure to the foundations as discussed in Section 4.3.2. Such shaping visually integrates the elements, provides visual interest to the user or passerby and imparts a feeling of stability and safety.

5.2.5 Variety with Standards

Many suggestions for improved substructure designs may require unique formwork that would not be feasible for projects with tight budgets. For such projects, standard substructure forms will almost always be required. Although not the case in Texas at this time, there can certainly be variety and appeal in standard forms. Two simple details that could add visual interest and be standardized are column chamfers and column flares.

Chamfering is a technique used to remove the sharp corners of rectangular columns (Figures 5.41-5.42). The angle of the chamfer can be chosen by the designer and will be effected by the reinforcement layout and overall structural design. Chamfering can minimize or enhance the relative proportion between the columns and different elements of the bridge.

Figure 5.40 A fully integrated cap provides a clean transition between the superstructure and substructure

Figure 5.41 Small chamfers on a rectangular column

Figure 5.42 A large chamfer makes these rectangular columns appear slender

When designing different sized chamfered columns on the same project, chamfers may change proportionally with the column size or remain the same (Figure 5.43). Particularly for columns of varying height, Option II is a more attractive solution than Option I as the chamfers change in proportion with the column section (Figure 5.44a). Keeping chamfers in proportion with the column sizes creates a smoother visual transition from one size of column to the next. Small chamfers may be attractive on tall columns, but when the same cross section is used for a shorter column, it will appear more like a stocky wall (Figure 5.44b). Column chamfers can easily be incorporated into standard designs with attractive and economical results.

Simple flares can be incorporated into standards as well. The California Department of Transportation has over 40 standard column shapes most with flares (Figure 5.45).[79] Over the years, as the standards have been used more regularly, they have become more and more economical. Thus new standard shapes could be developed to broaden the range of standard substructure options.

5.2.6 Enhancement of Substructure Designs using Non-structural Details

Non-structural details such as texture and color can be used in substructure design to enhance structural qualities. Attractive shaping of bent cap ends is another non-structural detail that can improve substructure and overall bridge appearance.

Texture and color selections may be used to accent slenderness and form but are by no means necessary for attractive substructure design. Texture and color should never be used to decorate a substructure or to cover up dull forms.

There are numerous different finish options. To avoid monotony, different projects should incorporate different finishes according to the design concept of that project. However, similar textures and colors should be used throughout a large project for coherence. Appendix B in Volume II gives an outline of many textures, colors and formliners available including their advantages and limitations in terms of appearance, maintenance and cost.

Texture

Different types of concrete texture include exposed aggregate, sand-blasted surfaces, rubbed finishes, relief and surface patterns obtained from formliners.

Exposed aggregate may be used to reflect the local geological materials particularly when the aggregate color matches that of natural rock surroundings. Exposed aggregate is not only an

attractive finish but it may act as a graffiti deterrent (Figure 5.46). To avoid monotony from one project to the next, the numerous types of exposed aggregate finish available should be explored. Sand blasting and rubbed concrete are two other concrete finish options that have successfully enhanced good projects in the past (Figure 5.47).

Relief may be provided to accent different structural members. Vertical grooves in piers accent height and give piers a taller and thus more slender appearance (Figures 5.48-5.49). Horizontal accents on vertical members give a heavier, more massive or cut stone-like appearance (Figures 5.50-5.51).

A wide variety of formliner patterns are available for use on bridge projects. A single formliner pattern can be used effectively as a harmonizing element throughout a project (Figure 5.52).

The use of texture to make concrete appear as another material should be restricted to locations where the structure is meant to replicate local structures. However, in general, concrete is best employed expressing the sculptural material that it is, capable of being formed in countless shapes. Rather than imitating other structural materials (Figure 5.53), concrete is most artistically used in its own unique ways (Figures 5.54-5.55).

Color

Color may be incorporated in concrete designs by adding pigments to a concrete mix, or by staining or painting the surface (Figures 5.56-5.57). Color is incorporated in steel bridges through self-weathering steel or painting the steel.

Experience in Texas has shown that painted concrete typically peels within a few years of application. Painting of concrete therefore results in the additional maintenance needs incurred by repainting whereas concrete colored through staining does not (Figure 5.58). Colored concrete whether painted or stained, may be made to match the local natural or built environment. This technique is typically used for architectural projects. A nice example is found in Austin where retained earth wall colors are made to resemble the pink granite of the State Capitol (Figure 5.59).

As mentioned in the previous chapter, graffiti and staining from dirty run-off water are common problems that plague bridges, particularly the substructure. Painted concrete can be repainted to cover unwanted staining or graffiti. Stained concrete can be sand-blasted to remove unwanted staining and graffiti. A wide variety of concrete stain colors are available today and virtually any color can be chosen to paint concrete.

Figure 5.46 Exposed aggregrate finishes may be less likely to attract graffiti than plain concrete.

Figure 5.47 An attractive pier with a rubbed concrete finish

Figure 5.48 Vertical relief enhances the slenderness of this pier.

Figure 5.49 Vertical grooves give this wide pier a more slender appearance.

Figure 5.50 Horizontal grooves make concrete appear like masonry.

Figure 5.51 Horizontal accents give tall piers a stockier appearance.

Figure 5.52 Similar formliner patterns used for the railing and the end of the bent cap

Figure 5.53 Concrete piers formed to appear like stone are foreign to the modern superstructure and urban location.

Figure 5.54 An attractively shaped pier showing off concrete's moldable quality

Figure 5.55 An elegantly tapered pier with exposed aggregate used to accent slenderness

Figure 5.56 The concrete for these piers was stained to blend with the local rock coloring.

Figure 5.57 Concrete painted with an earthtone to integrate with the landscape.

Figure 5.58 Unattractive peeling of painted concrete

Figure 5.59 Low concrete retaining walls colored to match local building materials

Bent Cap Ends

The ends of bent caps are typically highly reflective surfaces. As a result, they call attention to themselves and often detract from the overall bridge appearance. In many cases, bent cap ends stick out like sore thumbs (Figure 5.60). Shaping the ends can prevent these eyesores. Shaping can soften bulky proportions or can accent the smooth horizontal line of the bridge.

Angling the end of a bent cap to put it in a shadow will cause attention to focus on the reflective superstructure thereby accenting the horizontal flow of the structure (Figure 5.61). A more sculptural, chamfered end will add interest and may be desirable for a structure emphasizing the relationship between superstructure and substructure (Figure 5.62-5.63). The cap may be shaped to blend with and maintain the horizontal line of the superstructure (Figures 5.64-5.65). The result is the appearance of one long continuous beam. Designers must keep in mind that this technique is deceptive in terms of structural expression. The true structure is one of simply supported beams, not continuous beams.

For balanced proportions between caps and columns, inverted T bent caps should have stem widths equal to the column width as seen in Figure 5.66. If the inverted T stem is wider than the column, chamfering can be used as an optical correction. The bent cap end may be chamfered so that the flat reflective surface (the surface between the chamfers) is the same width as the supporting columns (Figure 5.67). Chamfering bent cap ends to complement chamfered columns is a good option for well-integrated design.

Non-structural walls such as those in Figure 5.68 are often used at the end of bent caps to cover an inverted T or any gap between two simply supported beams. These walls call attention to the joint. The emphasized joint accents the simply supported superstructure but disrupts the horizontal visual flow of the bridge. Figure 5.69 shows the halting route of the eye across a bridge with bulky cap ends. Figure 5.70 on the other hand shows how non-structural walls can result in a clean, metered appearance. If non-structural walls are desired, the walls must be kept in proportion with other elements of the bridge.

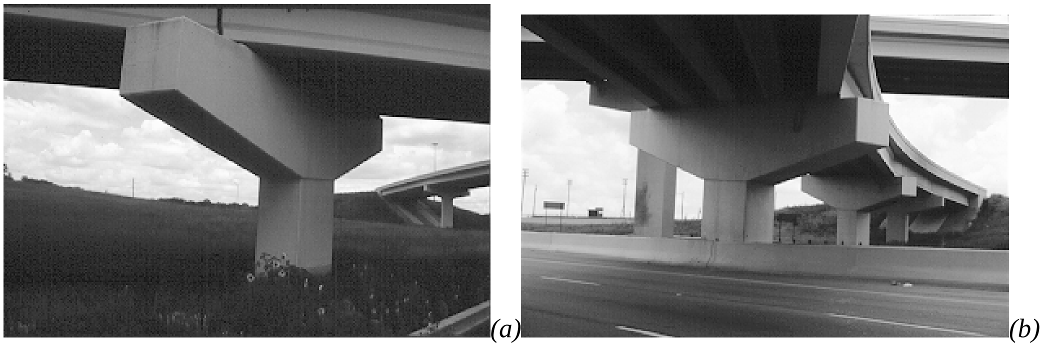


Figure 5.60 Awkward appearance of blunt rectangular bent cap ends magnified by skewed bents

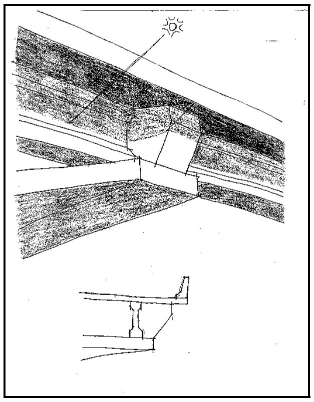
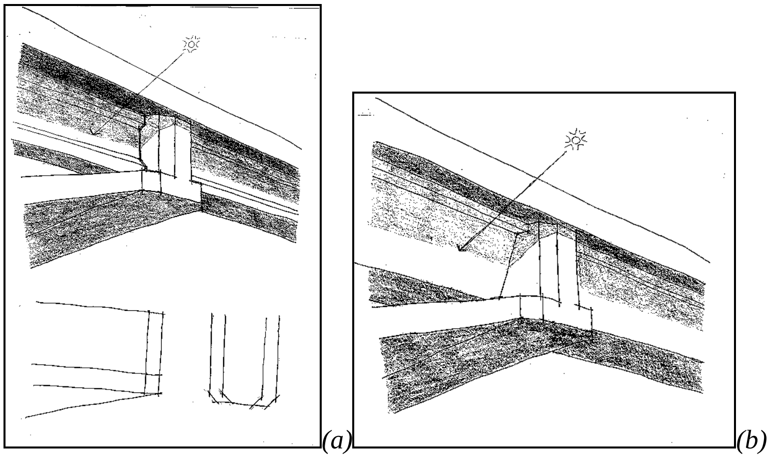


Figure 5.61 Bent cap angled back to de-emphasize its typically massive appearance



Bent cap chamfering to de-emphasize large reflective surfaces and provide sculptural transition between the superstructure and substructure.

Figure 5.62 Bent cap end chamfering

Figure 5.63 Continuation of chamfers from column to bent cap for a well-integrated form.

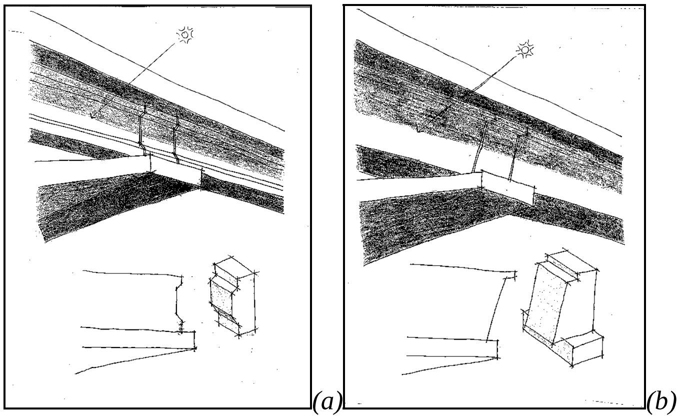


Figure 5.64 Bent cap ends formed to match the shape of concrete I-girders (a) and U-beams (b)

Figure 5.65 Inverted T bent cap stem shaped to mimic the concrete I-girders it supports

Figure 5.66 Balanced appearance of a column and bent cap stem of equal width

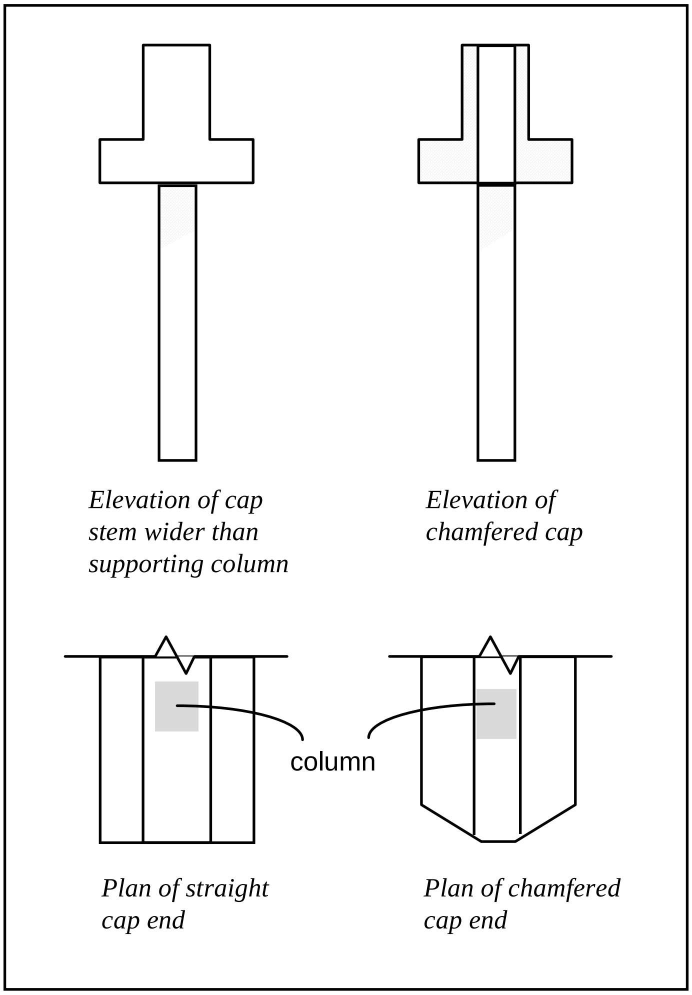
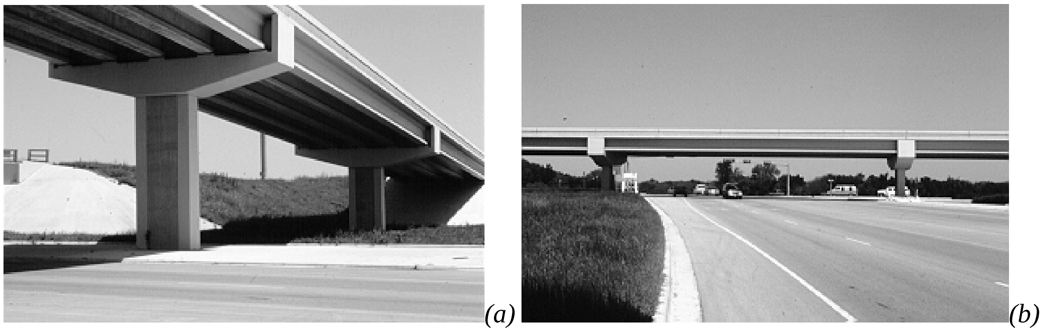


Figure 5.67 Comparison of bent cap end treatments



A thin wall at the end of a bent cap covers the gap between simply supported girders (a). The wall is unobtrusive in the oblique view (a) but gives the cap a disproportionately large appearance from the side (b).

Figure 5.68 Poor proportioning

Figure 5.69 A disrupted visual flow of the horizontal superstructure

These non-structural walls (a) are the same width as the bent columns (b) giving the superstructure/substructure transition a neat and clean appearance.

Figure 5.70 Well-proportioned non-structural walls

5.3 Summary

Designing the substructure of a bridge can be a fanciful display of creativity or a simple expression of elegance. The designer's challenge is to consider the efficiency, aesthetics and economy of the design within the project constraints. The choice of substructure system may be controlled by the superstructure span lengths chosen, support locations, column heights, foundation conditions or the superstructure width. In light of the constraints, a variety of economical substructure systems should be considered. The many standard options include individual columns, walls, and hammerhead or multi-column bents. Bent caps on piers may be rectangular or inverted-T's. Piers with fully integrated bent caps are also an option. Key issues to consider when choosing an appropriate substructure system are structural expression, visibility through the bridge, integration of the substructure to other bridge elements and the bridge site, and enhancement through attention to non-structural details. With thoughtful consideration, an attractive and well-suited substructure will greatly enhance the overall appearance of standard bridge systems.

CHAPTER 6
APPLICATIONS OF RESEARCH

6.1 Introduction

The research conducted for CTR Project 0-1410 has been applied to a number of bridge projects. The research team had the opportunity to apply the principles of the TxDOT Aesthetics & Efficiency Guidelines (Guidelines) to two current TxDOT projects, one in San Angelo, TX and one in Wichita Falls, TX. For both projects, the use of precast substructures was also explored. The Guidelines have been applied to four existing or potential bridges in Texas for a series of Examples by a member of the research team, Steve Ratchye, who has advanced degrees in both architecture and structural engineering.[10] These studies are included in a section titled Examples in the Guidelines.

This Chapter will describe the application of the research to the San Angelo and Wichita Falls projects. The resulting impact on the aesthetics and efficiency of these bridge projects will be discussed. Ratchye's Examples will be briefly described and as previously mentioned, are presented under Examples in the Guidelines. A full report on the initial version of the Examples can be found in Reference 10. The Examples were subsequently revised by the author and the project staff.

6.2 Research Application to US Highway 67 in San Angelo, TX

In November of 1994, the research team was invited to offer aesthetic recommendations for a bridge project in west Texas, US Highway 67 in San Angelo. Time was a major constraint for involvement in this project. The bridge was to be let in May 1995 requiring design plans to be finalized in January 1995. The research team's involvement was therefore limited to approximately 4 weeks.

The US 67 project had been in the planning stages for about 20 years before action was taken to finalize the design for construction. The impetus for finalizing the design came from partial federal funding to experiment with the use of high performance concrete (HPC) for pre-tensioned girders. Using high performance concrete with its higher than average compressive strength, would allow AASHTO Type IV girders to span up to 45m (150'), 6m (20') more than what similar normal strength concrete girders would span. Research Study 9-589 of the Center for Transportation Research was involved with the project to aid with the use of HPC.[80] One stipulation of this study was that attention be paid to the aesthetic impact of the bridge substructure on the Concho River park. A proposal was made to use precast caps to support the I-girders and to use concrete with a compressive strength of 55 MPa (8000 psi) in the substructure. The contractor was to be given the option to either precast the columns or cast them in place.

At the time of the research team's involvement, the preliminary Guidelines by Listavich[8] were being developed. Preliminary developments of the precast substructure system by Barnes[9] were also underway. The US 67 Project therefore was an excellent opportunity for the research team to explore the implementation of its research. Involvement in this project was a trial application of the ideas to be presented in the Guidelines and the suitability of precasting substructures for standard highway bridges.

6.2.1 Project Description

The US 67 Highway Project involved the design and construction of bridges and highway in southeast San Angelo. Of particular interest to the research team were the planned twin elevated bridge structures crossing the Concho river. These structures would also span a park along the river, ATSF railroad tracks, and US Highway 87 (Figure 6.1). The planned elevated structures were to run between the existing US 67 north and southbound highways. The existing roadways would become the new highway's frontage roads. The twin structures were to be raised up between the two existing roadways so as to span the US Highway 87 crossing (See Section A-A in Figure 6.1b). The new bridges would therefore be approximately 4.5m (15') above the existing US 67 bridges crossing the Concho River (Figures 6.2).

6.2.1.1 Site Characteristics

The research team visited and walked the site in November 1994. Photographs and site observations were recorded. Site characteristics that were particularly important to the new bridge design were the attractiveness and openness of the park area (Figure 6.3), and the diagonal crossing of the ATSF Railroad through the existing US 67 and US 87 intersection (Figure 6.1b).

The park area of this bridge site is part of a larger park that follows the Concho River winding through much of San Angelo. There is a small park road that runs beside the park and river. Pedestrian paths also run throughout the park with many picnic tables and benches along the way (Figures 6.2, 6.3a). There are a number of bridges crossing the river and park as well. The age,

character and function of these bridges varies. Each bridge seems to represent the era in which it was built. Some of the bridges exhibit older craftsmanship, typical of the WPA era (Figures 6.4-6.5). Other bridges represent the changing design trends of the Texas DOT (Figures 6.6-6.7). A few pedestrian bridges cross the river as well (Figures 6.8-6.9). Many of the engineers of these previous bridges embraced the attractive park setting by striving to enhance the park with their designs. The public too, has become actively involved with the construction of these bridges. The pedestrian bridge of Figure 6.9 is lined with plaques funded by local residents.

Another key observation made during the site visit was of danger at the intersection between the highways and the railroad at the north end of the site. The area is very open and flat. The railroad did not appear to be heavily traveled. However, the future bridge abutments to the northeast of the railroad tracks would create a wall dividing the area and restricting visibility. In particular, west bound US 67 frontage road traffic would have limited view of west bound railroad traffic with the bridge abutments in place (this is further discussed in Section 6.2.2).

The site observations gave the research team a good feel for the effect the new bridges would have on the site. The importance of the park to the city must be recognized. Attention must be given to the visual impact the future bridges will have on the site. At the same time, public safety in terms of visibility around the bridge, must be considered.

6.2.1.2 Pre-existing Design Plans

While the project was in planning stages for the past 20 years, the geometric design (roadway alignment) was completed by engineers in the San Angelo District. When the project was revived, the plans were sent to the Design Division in Austin and preliminary bent locations were established. This design, referred to herein as the original layout is shown in Figure 6.10.

With the joining of CTR Project 9-589, span lengths of up to 43m (140’) were designed for experimentation with AASHTO Type IV HPC girders. These HPC girders were to span the river to avoid foundation and substructure construction in the water, and to span US 87. Type IV girders of varying span lengths were to be used throughout the project except for the spans over the railroad tracks where increased vertical clearance requirements dictated the use of shallower AASHTO Type C girders.

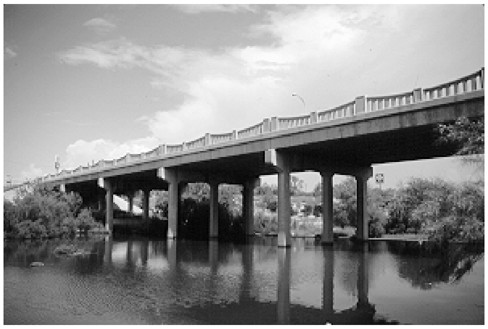


Figure 6.4 One of the older bridges crossing the Concho River in San Angelo

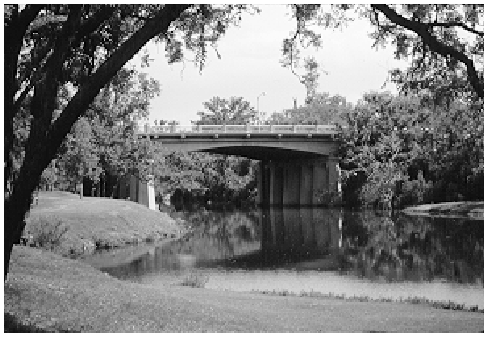


Figure 6.5 One of the older bridges crossing the Concho River in San Angelo

Figure 6.6 A cast in place slab bridge crossing the Concho River

Figure 6.7 A precast prestressed concrete I girder bridge crossing the Concho River

Figure 6.8 One of many pedestrian bridges across the Concho River

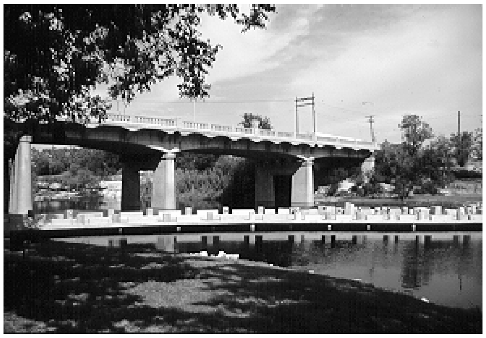


Figure 6.9 A low pedestrian bridge across the Concho River

6.2.2 Application of Aesthetics Guidelines Principles

While involvement on this project occurred before the completion of the TxDOT Aesthetics & Efficiency Guidelines (Guidelines) many of the ideas and principles addressed throughout the development of the Guidelines were applied to the US 67 Project. The proposed improvements will be presented here in the order that such improvements should be addressed in original design. This follows the order for suggested improvements in the Guidelines (refer to Figure 3.72 and Volume II of this dissertation).

6.2.2.1 Problems Identified with the Original Layout

In balancing the observations made during the site visit with a review of the original layout, a number of problems were identified with the aesthetics and efficiency of the proposed project. Problems were identified with the layout, and with both the superstructure and substructure design. In terms of aesthetics, a number of possibilities for attractive design could be explored.

The first problem was the number of different span lengths used. Roughly five general span lengths are used for a total of 17 spans (Figure 6.10). Frontage road traffic traveling alongside the bridge will experience these varying span lengths as a disharmonious jumble. In particular, rhythm is visually disrupted by the random location of bents. Another layout problem was the location of the bridge abutments. The western abutments were directly up against the park road, looming over and dominating the otherwise open riverside park. On the eastern side, the abutments ran directly alongside the railroad tracks. The combination of this skewed abutment wall and the skewed bents would create a dark tunnel ("Thug Alley") in this open setting (Figure 6.11). The large abutment created a dangerous intersection as it restricted the views of westbound US 67 frontage road traffic and westbound train traffic.

The skewed bents in the layout also creates aesthetic problems with the superstructure and substructure design. In elevation, skewed bents create a jumbled appearance (see Figures 5.37a&b). In the case of US 67, the skewed bents require multi-column bents whereas the rest of the project was designed for single column bents. (Single column bents were part of the original plan to improve aesthetics through minimizing substructure clutter.) The resulting clutter on one end of the project detracts from the project as a whole. It is inconsistent to be concerned with aesthetics only on one side (in this case, the park side) of a project. To have a relatively minor railroad track dictate such unattractive bridge design shows the lack of awareness to aesthetic issues (and more attractive design alternatives) that bridge engineers often seem to have in their work.

A final problem identified was the use of different depth girders to provide the increased vertical clearance required for railroad traffic. When using I-girders on inverted T bent caps, the change in superstructure depth can be particularly disruptive visually at the bent cap end (Figure 6.12).

6.2.2.2 Layout Improvements

The first proposed improvement to the layout was to use more spans of similar length throughout the project (Figure 6.13). Reducing the variety of span lengths will allow for more harmonious viewing particularly by frontage road traffic. Using consistent longer span lengths also helps solve the other problems identified. Longer span lengths can allow the abutments to be pushed back away from the park road on the western end of the project and away from the railroad on the eastern end. Increasing superstructure lengths reduces the number of substructure supports. Pushing the abutments back keeps both the park area and the railroad intersection area more open. Safety is improved with the increased visibility between westbound US 67 frontage road traffic and westbound train traffic. Lengthening the spans when combined with slightly increased bridge elevation allows the bridge to span the railroad tracks with proper vertical and horizontal clearance without using skewed bents. With this layout solution, the bridge stands on its own, unaffected by yet safely spanning the railroad. The result is a more open and harmonious design.

Using similar span lengths and avoiding skew bents removes the need for multi-column bents. Single column hammerhead bents can be used consistently throughout the project. Asymmetrical bent caps (Figure 6.12) are avoided by raising the bridge elevation to provide adequate vertical clearance for the train. In the original design, the deck elevation dictates the need for shallow beams. This in turn dictates the need for shorter spans and unattractive, uneven bent caps. All of these drawbacks are easily removed by raising the deck elevation (between 250-375mm (10-15”)) and using longer spans of similar depth to the rest of the project. An additional advantage to longer spans over the tracks is that one foundation and substructure unit is no longer required.

6.2.2.3 Superstructure and Substructure Design Suggestions

As discussed in the previous section, superstructure design is made more consistent through the use of similar span lengths and girder types. The shallow AASHTO Type C beams are no longer required thus avoiding the unattractive transition between different beam depths. Multi-column skewed bents are avoided as well.

Due to the late involvement of the research team to this project, it was recognized that the TxDOT designers were under a strict time constraint to complete the project. TxDOT seemed resistant to the proposed raising of the deck elevation and the work this would involve in order to avoid using shorter span Type C girders. As a result, the research team also explored ways to improve the appearance of the railroad crossing in the event that the designers did choose to keep skewed bents and a combination of Type IV and Type C girders.

As bent cap ends are highly reflective surfaces, unattractive asymmetrical ends are a particular eyesore. To minimize this eyesore, the research team proposed that concrete pedestals on top of the inverted T ledge be used to support the shallower beams. The bent cap itself would remain symmetrical and match the other bent caps in the project (Figure 6.14). The use of tapered pedestals would be a further improvement to the appearance of the shorter, shallower span (Figure 6.15). Another suggestion was to provide columns for the skewed bents that would correspond to both the bents orthogonal to the direction of the bridge traffic and the skewed railroad. This would help integrate the skewed bent with the rest of the bridge supports (see Figure 5.39).

Aside from calling for mostly single column hammerhead bents, the substructure design was not yet finalized before the research team became involved with the US 67 Project. The TxDOT Project Director Norman Friedman of the TxDOT Bridge Design Division in Austin designed a windowed pier for use on the San Angelo project (Figure 6.16). As mentioned previously, high performance concrete was to be used for the substructure with precast bent caps. Precasting was also an option for the columns. The research team explored a number of column shapes for precasting. These are presented in Section 5.2.3.

6.2.2.4 Non-Structural Details

There are many ways that the bridge project as a whole could be enhanced with attention to non-structural details. One suggestion was to use a consistent formliner pattern in the substructure. In particular, a pattern should be used which in combination with the substructure shape would have enough detail to provide a comfortable feeling for the park users. In such a narrow park, the large single columns could seem overwhelming without textural relief.

An open rail for the motorists above was suggested to allow for better views of the area and also to lighten the apparent slenderness of the structure from a distance (see Figure 3.22). Finally, drainage pipes should be internal to the substructure sections.

6.2.3 Potential use of Precast Substructures

The desire to experiment with high performance concrete (HPC) in the substructure made a precast option very attractive. The increased compressive strength of the HPC allowed for hollow sections which would reduce foundation costs and, if precast, allow for easy handling of the segments. Even precasting only the cap would simplify the erection process by avoiding the need for setting up cap formwork and placing concrete at the higher elevations (roughly 12m, 40ft.) over the river. The precast cap proposed at the time was too heavy to be lifted as a single unit with the cranes on site for the girders. Therefore a segmentally precast cap was proposed similar to that of Proposal I presented in Chapter 4 (Section 4.2.3). Different precasting options were explored for a basic column shape that had both a solid and a "windowed" option (Figure 6.17).

6.2.4 Final Design

A number of the suggestions offered by the research team were used for the final TxDOT design. The final layout is shown in Figure 6.18. An effort was made to standardize the span lengths of the overall bridge. This was particularly successful on the western end of the project over the park and river. However due to time constraints, TxDOT designers were indeed unwilling to change the vertical elevation of the bridge over the railroad tracks. As a result, shallower, shorter spanning Type C beams were required. This unfortunately dictated the need for skewed bents. However, pedestals to support the shallower beams were chosen in place of an asymmetrical bent cap. This will help reduce the visual abruptness of the changing superstructure depths at the cap.

Using a greater number of longer spans did allow for the removal of one substructure unit and also allowed the designers to push the abutments back from both the park road and the railroad tracks. This lightened both of these areas and improved visibility and therefore safety at the railroad/motorist intersection.

The details of a precast substructure system had not been fully worked out at the time design had to be finalized. Thus, this option was met with skepticism by TxDOT designers. As a result, the substructures were designed to be cast in place. A modified windowed pier was selected. The bottom "window" for the taller columns in the original design (Figure 6.16) was filled in to comply with flood provisions in the area. An attractive "fractured fin" formliner was chosen as an inset to the columns (Figure 6.19).

The final appearance of this bridge represents some of the newer design capabilities of its time, particularly with the long span high performance concrete I-girders. Many of the less attractive

aspects of the bridge could have been avoided with more forethought. A more developed and detailed precast substructure system could have been used with attractive results.

Figure 6.19 A windowed pier under construction for US 67

6.2.5 Economic Impact

The economic impact of the proposed improvements was examined after the project was bid. Only the proposed changes that were actually implemented were examined. The bid prices were compared to typical costs in the area for what would have been constructed had no changes been made. The three major changes examined were the trade-off between increased superstructure lengths and decreased abutment requirements, the removal of one substructure unit and the use of a windowed pier. The results are shown in Table 6.1.

Pushing the abutments back resulted in savings. The size of the retained earth wall was large enough that it's cost exceeded the cost of longer girders. Removing one substructure unit certainly resulted in savings. No adjustments were considered for foundation costs although they would most likely have decreased as well. The windowed pier was bid at a higher price than normal single column bents.

It should be recognized that bid prices are *not* necessarily a true reflection of actual cost. Rather, contractors are able to recover potential costs elsewhere in a project by adjusting bid prices. New forms of construction provide contractors with an excuse to increase bids in that area whether or not the work will cost them more. In the case of the San Angelo project, an overall savings was reflected in the bid prices for the sum of the proposed changes. While the unfamiliar substructure seemed to increase prices, improvements which resulted in increased visibility around the structure and a more harmonious layout afforded savings. The overall result was a probable savings in bridge cost of 1.6% and a savings in total project cost of 0.5%.

6.2.6 Summary

Involvement in the San Angelo project was very useful for the continuation and refinement of the research for Project 1410. The majority of the lessons learned were beneficial for further development of the Guidelines. Observations and comments on precasting of substructures provided important guidance for further development as well.

Applying principles from Listavich's Aesthetic Guidelines[8] gave the research team a better understanding of the design process. The importance of a site visit was clear. Physical constraints will need to be recognized from the outset for successful bridge design. Physical constraints must be balanced with procedural constraints (in the case for San Angelo, time and roadway elevations) so that all of the constraints become boundaries and not obstacles.

Application of Guidelines principles was seen to improve aesthetics and safety while achieving monetary savings. While certain ideas led to cost increases, the amount of the increase was very little in terms of overall bridge cost and even less in terms of overall highway project cost. The considerable improvement in aesthetics outweigh the minor cost increases. The public infrastructure appearance is improved along with the quality of life in the area. Involvement in this project demonstrated the practicality and possibilities for economical and aesthetical success which thoughtful application of the Guidelines can provide for the design of standard short and moderate span bridges.

It was also clear that any new precast substructure system would need to be carefully designed and detailed for adoption into the practice. Details of constructability - fabrication and erection - as well as workable connection details would be essential. The weight of substructure elements must be kept down to ranges that could be handled with conventional lifting equipment used for handling long girders in order to improve the efficiency of fabrication and erection. Difficulties were recognized in terms of assessing the costs of a proposed precast substructure system. The difficulty arises primarily in quantifying the benefits of minimizing environmental impact, avoiding traffic delays and improving bridge aesthetics.

6.3 Research Application to US Highway 287 in Wichita Falls, TX

In February of 1996, the research team was invited to make a presentation of Project 1410 research to the TxDOT engineers in the Wichita Falls District Office. The District office was in the planning stages for twin elevated highway structures that were to pass through a business district near downtown Wichita Falls. The current highway is heavily traveled and the stop lights in the area result in frequent traffic congestion. The research team was invited to offer comments and suggestions for the design of the planned elevated structures. Due to the businesses and parks in the area, aesthetics was an important concern of the public and of the designers. Speed of construction and avoiding extensive traffic delays or re-routing was a major concern due to the heavy traffic use and in the interest of helping the local businesses survive.

After the initial visit, a few members of the research team returned one month later to give a similar presentation at an open civic meeting. Again, the research project was presented, but with more emphasis on suitable solutions for the design of US 287. The presentation was well-received. While the audience of local engineers, politicians, businessmen and interested residents learned more about potential designs, the research team gained a better understanding of the interests of these various groups when a bridge project is developed. It was clear how important it is for engineers to be able to communicate their ideas and expertise clearly and convincingly to the public and to be sensitive to public opinion and concern in order for good bridge designs to result.

As the elevated highway ties in to a portion of interstate highway, some federal funding was available to the district. However, most of the funding for this project would come from the District's "pocket" - funding that was allocated to them by the State. Traffic projections for the future indicated that ultimately three lanes will be required for each direction. The District therefore was to decide to design three-lane structures up front or to design two-lane structures with capabilities for future widening.

At the time of the research team's involvement, Listavich's preliminary *Aesthetics Guidelines*[8] were complete and a final version, *The TxDOT Aesthetics & Efficiency Guidelines* (Guidelines), was being developed. Barnes' precast substructure system[9] (Proposal I in Chapter 4) was nearing completion with many of the fabrication and erection details worked out. The US 287 Project therefore provided a new opportunity for the research team to explore further implementation of its research. Unlike the San Angelo project involvement, this project was still in an active, open stage of development when the research team became involved. Principles from the Guidelines could be more fully applied and the feasibility and suitability of using a precast substructure system for this project could be explored.

6.3.1 Project Description

A plan of the proposed project can be seen in Figure 6.20. The portion of US Highway 287 being designed had been planned for in previous highway construction. The new construction will connect previous stretches of US 287 from the south to US 287 and IH-44 to the north. Stub-outs exist on the south end of the site where the new elevated structures will tie in (Figure 6.21). As shown in Figure 6.20b, the elevated structures being designed are separated by one wide (183m, (600')) city block. At either end of the project, the elevated structures come together side by side to join the existing highway structures.

Curved on and off-ramps to adjoining highways and to the downtown area are required as well. Fly-over ramp structures must be provided to connect this project on the south end to an east-west highway, US 82, known locally as Kell Boulevard. At the north end of the northbound structure an off ramp to the downtown area was requested by city officials. An on-ramp to the southbound structure at the north end is desired but not required at this time.

As shown in Figure 6.22, the new elevated structures will take up one of the four existing lanes of the city roads now being traveled on for US 287 (Broad St. for northbound traffic and Holiday St. for southbound traffic). The final three lane structure will overhang part of the street as well as the existing sidewalk.

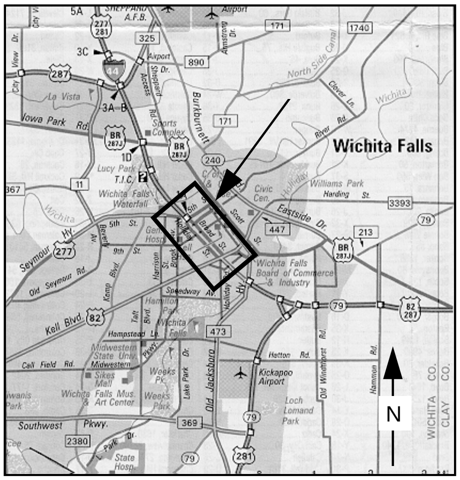


Figure 6.20a Partial map of Wichita Falls showing proposed bridge site

Figure 6.21 Stubs-outs on the south end of the US 287 project (view looking south)

6.3.1.1 Site Characteristics and Constraints

The majority of the structure runs over a city grid of 130m (430') blocks. As the north and southbound structures are separated by a wider 183m (600') city block, the possibility of these structures forming a "wall" between two sides of town is reduced (see Figure 6.39). A three-lane structure will appear lighter and allow for more light to reach underneath it than a six-lane structure would.

There is an existing park on the north end, the Harold Jones Park (Figure 6.23). Although not heavily used, a number of people were seen enjoying lunch at the park's picnic tables. At the south end is a park-like area of open land that is owned by the State (Figure 6.24). The businesses in the area seemed to be surviving but with low activity. In talking with city residents, it was discovered that while the city is making attempts to revive the downtown area to the northeast of the site, most business development is occurring southwest of the site. This strip of businesses in the area of the proposed bridges is a bit of a "no-man's land." However, there are a number of hospitals, churches and municipal buildings located among the small businesses and restaurants in the area (Figures 6.25-6.26). Due to the variety of activity, the research team felt that there was potential for this area to eventually be revived (in a span of at least 20 years) and to attract more use. It was essential therefore that an aesthetically pleasing solution be found for the bridge design, one that would enhance and not detract from the site. In particular, the bridge must be attractive from underneath and up close as the future users of the site would be pedestrians and slow-moving local traffic.

The existing right-of-way dictates that the elevated structure will have its supports on and hang over the existing streets (Figure 6.22). Therefore during construction, part of the road will need

Figure 6.23 The Harold Jones Park

Figure 6.24 Open land at the south end of the site (view from stub-out looking north)

Figure 6.25 A local church

Figure 6.26 City Hall

to be closed. For substructure construction, only one lane will need to be blocked off. However, if a precast concrete girder superstructure system is chosen, three and possibly all four of the lanes will need to be closed for periods of time to haul the girders to the site and lift them into place with the required two cranes (Figure 6.27). This work will have to originate from the existing road as the other side of the structure is taken up by local businesses. Another observation about the right-of-way was that the new structures will often be very close to some of the existing buildings including one attractive older church (Figure 6.28).

Figure 6.27a Two cranes are required to place precast concrete girders

Figure 6.27b Heavy traffic on the existing 287 will need to be re-routed during construction

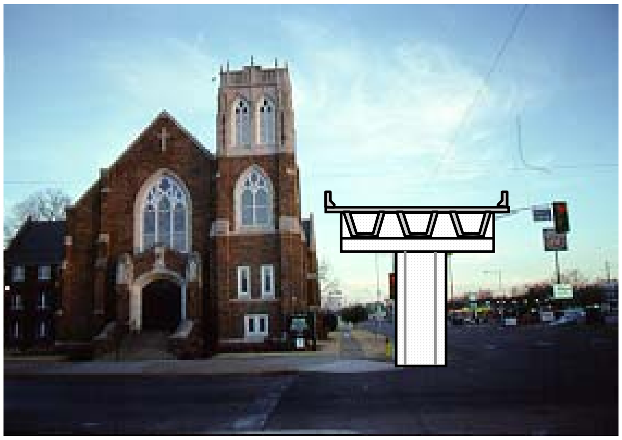


Figure 6.28 Sketch of where the new elevated highway will be relative to some of the local architecture.

6.3.2 Application of the Guidelines

Unlike the San Angelo Project, US 287 in Wichita Falls was in the beginning stages of final design when the research team was made aware of the project. This gave the team the opportunity to apply the Guidelines from an open stage of design rather than at the very end. First, a vision for the bridge was developed based on the observations made during the site visit. Three major points formed the design concept of the structure and needed to be addressed. They were,

1) The structures must enhance the site without creating a wall between the older downtown and the newer developments in the city.
2) The structures should maintain as light and open an appearance as possible to be attractive for future pedestrian use.
3) The impact of the structures both during construction and once completed should have a minimum negative impact on the local businesses.

The ideas for the design concept were then carried out in suggestions for all steps in the design process to produce a coherent design. Suggestions made at these different steps of design are presented in the following sections.

6.3.2.1 Planning & Layout

To carry out the design concept, the primary concern in planning & layout will be choosing a layout that can maximize visibility through the bridge. To do this, three primary suggestions were made.

The first suggestion for maximizing visibility through the bridge was to use single column substructures. Single columns minimize substructure clutter and keep the area underneath the bridge quite clear. An added benefit of single column bents is that they minimize construction disruptions by requiring less construction area for foundation placement than multi-column bents require. The larger elements (column and cap) do require stronger formwork.

The second suggestion for maximizing visibility was to use the longest span lengths possible to minimize the number of substructure units. Even with single column bents, a wall-like appearance may result from oblique angles if the columns are spaced too close together (Figure 6.29). The city grid allows for the simple use of even span lengths throughout the straight portions of the elevated structures. Four spans of 32.5m (107.5') or three spans of 43.3m (142') could be used

Figure 6.29 An example of closely space columns forming a wall

for each city block. The longer span lengths would increase visibility and reduce the number of foundations and substructure units required by 25%. Although stronger foundations would be required, site disruption would be decreased through fewer required excavation locations. In the end, the span lengths chosen will depend on the type of superstructure chosen. This is further discussed in the next section.

The third suggestion for improving visibility through the bridge is to keep the bottom of the superstructure between 6-7.5m (20-25') above ground rather than the minimum of 5m (16.5') originally based strictly on vehicular clearance considerations. Raising the vertical elevation of the bridge helps maintain a light appearance for the bridge. Rather than crowding the site, a slightly raised bridge allows more light to reach underneath the structure thus creating a more inviting space. This is particularly important for the continued use of the area by pedestrians.

6.3.2.2 Superstructure Design

To provide a light, long span structure, three superstructure systems were considered. These were pretensioned concrete I-girders, pretensioned concrete U-beams and a post-tensioned segmental box girder. Steel girders could also provide long spans but are considerably more expensive than the concrete alternatives and would only be considered for longer curved spans that the I-girders and U-beams could not accommodate.

Pretensioned concrete I-girders have a few advantages for this project. The first is that pretensioned I-girders are economical. The State average for pretensioned I-girder bridges in 1995 was \$310 per square meter (\$29/ft.^{2}) of roadway surface. Another advantage is that I-girder bridges can easily accommodate widening and narrowing roadways. I-girder bridges can also be easily widened in the future.

Despite the few advantages of pretensioned I-girders, their many disadvantages make this system a poor option for the Wichita Falls project. I-girder bridges are particularly unattractive from underneath. The narrow girders and wide spacing create dark cave-like voids when viewed from underneath (Figure 6.30). Diaphragms between the girders add clutter to the darkness. The sloped upper surface of the bottom flange provides a perfect spot for pigeons to roost, discouraging pedestrians from wanting to pass underneath. Pretensioned I-girders are also not suited for sharply curved alignments. The discrete chords of girders require shorter spans to fit sharp curves. Not only are span lengths limited, but substructure requirements are increased and unattractive scalloped shadows are visible on the girders during parts of the day (Figure 6.31).

Pretensioned concrete U-beams are another very economical option. They typically cost the same as pretensioned I-girder bridges. U-beams are more attractive from underneath than I-girders. Their smooth underside and angled walls reflect more light, brightening the appearance from underneath (Figure 6-32). U-beams provide no pigeon-roosting surface along their length. U-beams can accommodate a certain amount of roadway widening or narrowing but are not as flexible a system as I-girders. The reason is that one U-beam can take the place of two I-girders. For sharp transitions in plan, two wider U-beams can only be placed on 2.5m (8') centers and flare out to 4.5m (15') centers. However, four I-girders could be placed on 0.6m (2') centers to flare out to 2.5m (8') centers if necessary. In the case of the Wichita Falls project there was one area where a transition in plan could not be accommodated by U-beams. An alternative would be to use a U-beam on the exterior and I-beams on the interior to accommodate the flare (Figure 6.33). Although not particularly attractive from underneath, the continuity of the bridge elevation with U-beams could be preserved.

Another disadvantage is that similar to I-girders, U-beams are not well-suited for sharply curved alignments. U-beam bridges could be widened in the future but again, due to their larger width, are not as flexible a system for future widening as I-girders.

A segmental box girder superstructure would provide the most attractive addition to the site. The smooth underside and thin wings optimize the openness and reflected light underneath the bridge (Figure 6.34). In particular, the vertical clearance is increased for the frontage road motorists who experience the bridge for greater lengths than crossing traffic (Figure 6.35). Longer spans are easily achieved with segmental box girders and highly slender, continuous spans are possible. Segmental box girders are also very well-suited for curved alignments. The segments can be precast to fit curves. As a result, segmental box girders would provide dramatic and sweeping curved fly-

Figure 6.30 View of an I girder bridge from below

Figure 6.31 Scalloped shadows on curved bridges made up of straight girders

Figure 6.32 View of a U-beam bridge from below

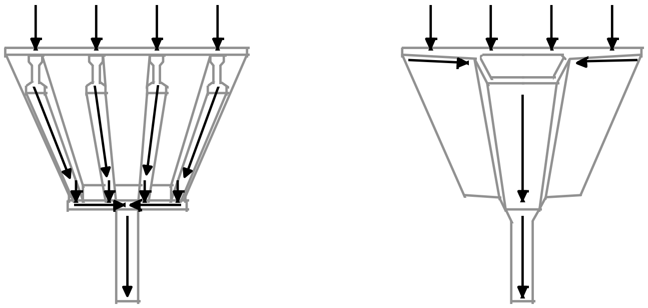
over ramps at the highly visible ends of the US Highway 287 project. The main drawback to segmental box girders is that it would be difficult to widen the girders. Thus it would make sense to construct all three lanes initially.

The main issues in choosing a superstructure system revolve around the design concept and the economics of the project. The economic impact of superstructure choices is discussed in Section 6.3.5. The final bridge must be an attractive addition to the site, maintain a light, open appearance particularly for the local traffic and pedestrians and be constructed with a minimum amount of disruption to the site. A segmental box girder superstructure would best satisfy all of these criteria. Although more expensive than an I-girder or U-beam structure, the slender and light appearance from underneath, the ability to construct the bridge from above without disrupting traffic and the dramatic elegance of the curved ramp structures make this the most attractive option. Because segmental box girders can more easily span longer distances, constructing just three spans per city block would be simple and would improve visibility through the bridge by decreasing the number of substructure supports required. I-girders and U-beams would require the use of higher strength concrete (perhaps high performance concrete) to reach these longer spans.

The importance of this bridge enhancing rather than detracting from the site warrants the additional cost of a box girder superstructure. However, if only two lanes can be constructed at first and will need to be widened in the future, or if all of the curved ramp structures could not be built at the same time, this may not be a good option. Constructing additional spans at a later date using precast segmental construction would be uneconomical and using a different superstructure system for the additional portions would be unattractive. In this case, U-beams should be used throughout the project.

6.3.2.3 Substructure Design

To provide a clean and open design, a single column substructure system should be used. With a segmental box girder superstructure, single columns without bent caps could be used. This would provide the lightest appearance. The aesthetic advantages of a box girder are apparent when the flow of forces in a box girder is compared to that of an I-beam bridge (Figure 6.36). The more efficient box girder bridge form leads to a more elegant structure. If the box girder superstructure is continuous, the supports would need to provide only a single bearing, making the design even cleaner.



Precast Prestressed I-Girders,
Inverted T hammerhead bent

Individual beams must be supported on a bent cap. Large cantilevers for caps require deep sections thus increasing required material, reducing clearances and impairing visibility

Prestressed Box Girder,
Single column support

Single spine of box girder carries loads directly to single column. This efficient flow of forces eliminates the need for bent caps, improves visibility through the bridge and clearly displays the flow of forces in a simple, well-integrated form.

Figure 6.36 Comparison of the flow of forces in two different bridge systems

If a U-beam or I-girder system is chosen, inverted T bent caps would help improve visibility through the substructure. As well, the articulation of each span at it's supports through inverted T cap ends is visually consistent with the articulation provided by the city grid of streets. The cap ends can easily be chamfered or shaped for an attractive appearance consistent with column details. Structural expression would be attractive for the hammerhead bent caps. The caps could be tapered to deepen at the column face or the columns could flare out to meet the cap. Both of these options provide structural efficiency and visual integration of the cap and column.

The appearance of the substructure will be greatly effected by whether or not the full 3-laned bridge would be built initially or whether only a 2-laned bridge would be built with a future widening option. If future widening is required and single columns are desired for the final bridge, the initial substructure must be built to support the final three lanes. An asymmetrical substructure would result if widening were to be only on one side on the bent (Figure 6.37a). This would be very awkward in appearance. With widening provisions on both sides, a symmetrical substructure can be provided initially (Figure 6.37b). However, the column supporting two lanes but designed for three lanes will be stocky. The engineers must very seriously consider the visual impact such bridges would have until they are widened (*if* they are widened).

For improved construction efficiency, the substructure units could be precast segmentally. Precasting the substructure is discussed further in Section 6.3.3.

6.3.2.4 Non-structural Details

Attention to detail at this bridge site is very important as it will be primarily a pedestrian and local traffic area. The bridges must be attractive so as not to create an urban wasteland, ruining the local businesses. Attention to detail was a concern of the public particularly near the park at the north end.

Consistent surface treatment of the columns will add an attractive and unifying touch to the large structure. Using colored concrete pavers for the walkways beneath the bridge will also enhance this area and make it more attractive and welcoming to pedestrians. The designers have numerous options for column and walkway surface treatments, many of which are presented in Appendix B of the Guidelines.

Drainage should be carefully planned and controlled. Drain pipes should be internal. Although controversial to the businesses, no signs should be permitted to hang on the structure as they would detract from the bridge form. An open impact barrier for the roadway should be used to maintain a slender appearance for distant viewers and traffic passing underneath orthogonal to the spans. Consideration of sunlight under the bridge must be made when choosing landscaping. Attractive vegetation is desirable particularly in the park areas.

6.3.3 Potential use of Precast Substructures

The US 287 project in Wichita Falls would benefit from using precast substructures. Perhaps most importantly, traffic disruptions could be minimized as fabrication would occur off site. Bridge erection would be faster as the need to set up formwork, place concrete and wait for it to cure would be eliminated. This would help relieve potential traffic delays and re-routing that the city would like to avoid. Precast substructures will have a higher quality finish which will add to the attractiveness of the final structure. A computer rendering of the proposed precast substructure system from Chapter 4 is shown on the future site in Figure 6.38.

Precasting the substructure would also be useful for a scheme where future widening must be feasible. Additional precast segments in the locations shown in Figures 6.22 and 6.37b for example, can be easily post-tensioned to the existing bent (with a method similar to that described in Section 4.2.3.3). Post-tensioning ducts would need to be provided initially. These ducts would need to be properly covered and protected until widening is desired.

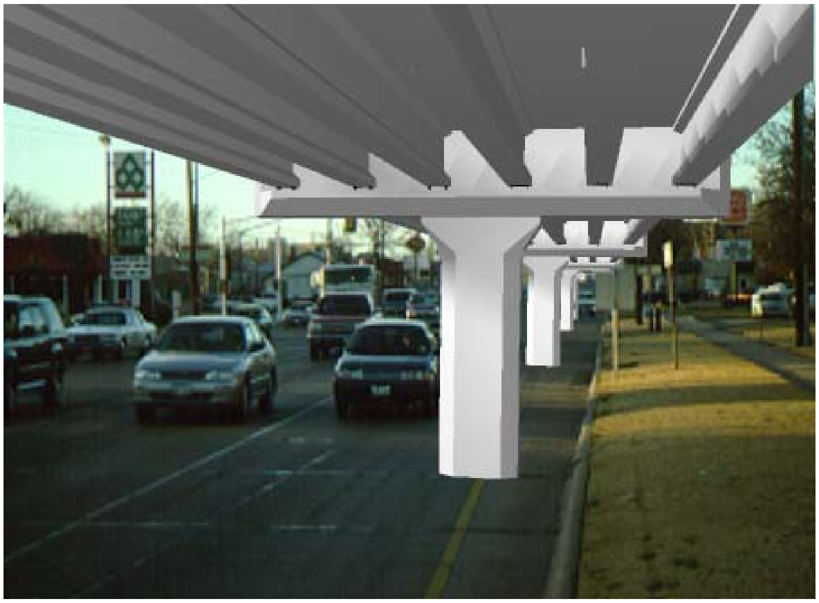


Figure 6.38 Computer rendering of the proposed precast substructure system along the right of way on Holiday St. (innermost lane to be removed)

6.3.4 City Planning Considerations

Raising the highway removes the virtual wall that traffic congestion creates during rush hour. This project lifts the fast moving traffic up and allows city traffic to flow more easily between the newer developed areas to the southwest, and the old downtown. The separation of the twin elevated structures by a 183m (600’) city block creates boundaries for the space between (Figure 6.39). There are many approaches that can be taken with the urban planning of this area to develop this space in attractive and productive ways for the city. There is potential for promenades to be developed along the frontage roads and for a district to be created within the block where the shops could be re-oriented to open towards the center. Such development could not happen overnight. Many issues would need to be addressed such as the location of some buildings directly up against the new elevated structures. However there does seem to be potential for this area to stay active. The elevated structure could provide an attractive promenade area leading people into the central district. The structure can then be seen as something that helps create an area rather than destroy it. Any city planning project such as this would be an investment over 20-30 years. Federal funding is often available in the form of tax relief for small businesses in older areas being revived and renovated.

More immediate concerns regarding city planning concern the impact of the bridge on buildings directly neighboring the new structure. As mentioned previously, some structures are very close to the location of the new bridge. This will necessitate turning some of the entrances to these buildings away from the bridge.

6.3.5 Potential Economic Impact

A major factor dictating the economics of this project will be the choice of superstructure system. In 1996, I-girders and U-beam superstructure bridges averaged \$310 per square meter (\$29/ft.^{2}) of roadway surface in Texas. As U-beams are currently only fabricated in Victoria, Texas (near Houston), the hauling costs associated with constructing such a bridge in Wichita Falls may increase the cost by a few dollars per square foot. The \$310/m^2 (\$29/ft.^{2}) cost is largely based on unattractive substructure systems. Using more attractive substructures could increase these costs to, say, \$355/m^2 (\$33/ft.^{2}) (see San Angelo project description in Section 6.2 and Table 6.1). The simply supported precast segmental box girder project for US 183 in Austin with more attractive substructure supports at the same time cost approximately \$420/m^2 (\$39/ft.^{2}) of roadway surface. This might be 20% more than an enhanced precast I or U-girder bridge. The construction equipment for US 183 in Austin or the San Antonio "Y" could be re-used for a segmental box girder bridge in Wichita Falls which would keep the costs down. However, the start up costs of a precasting yard would require the entire bridge project to be completed for it to be economical. An initially two-lane segmental box girder superstructure would be more difficult to widen in the future than an equivalent I-girder or U-beam structure. The entire three-lane bridge would therefore need to be constructed initially for this to be an economical solution. A continuous precast segmental box girder project may be higher than \$420/m^2 (\$39/ft.^{2}). However the longer spans possible with a continuous superstructure will allow for savings in substructure and foundation costs.

The Wichita Falls project is a controversial one and warrants additional costs for improving the structure's appearance. The presence of the new bridges must help to enhance the area if it is to survive economically. If the bridges detract from the area, a rift will be created in the city. The bridges would essentially create a barrier between the old downtown and the newer developments. For this reason, I girders should not be considered regardless of their probably being the lowest cost choice. They would also be the least attractive option. A segmental box girder would provide the most attractive addition particularly at the highly visible curved end portions of the project. As mentioned previously, the segmental design should not be considered if the entire three lane width cannot be built at once. The start-up costs for a precasting yard for a second phase of construction in the future will be excessively costly for a project of this size.

6.3.6 Summary

Many lessons were learned through the research team's involvement with this project. Offering suggestions for improved bridge design while the planning process was still in a fluid state proved to allow for a more realistic view of the project's constraints. Decisions could be made after many options were considered rather than strictly based on cost and speed of design (as was the case with the San Angelo project).

Again, a site visit was essential for developing a vision and design concepts for the bridge. These design concepts could then be carried out while considering many different options for layout, superstructure design, substructure design and non-structural details. It was also evident that this urban project had considerable impact on city politics. It would be difficult for engineers to consider this impact while concentrating on their primary job of bridge design. Therefore it is important for the engineers to work collaboratively with city officials. The engineers must stick to good engineering design and communicate to the city the attractive possibilities attainable with engineering design rather than allowing the city to decorate their bridges unnecessarily. The engineers must choose forms and layouts that are elegant and attractive and do not need to be covered with facades or ornamentation.

The project was still being designed at the writing of this dissertation. A decision to use U-beams where possible, and steel girders for longer curved spans was most recently proposed. A segmental box girder superstructure system was considered too expensive for the District to justify constructing.

6.4 Example Applications of Guidelines to Four Texas Sites

A number of examples were developed wherein the Guidelines were applied to four bridge projects, and the usefulness of the Guidelines evaluated. These examples were initially developed by Ratchye, an engineer and architect, and are reported in Reference 10. Ratchye's examples were modified and included in the Guidelines.

The Examples aim to offer further illustrative applications of the Guidelines and to show the range of solutions and the varied cost impact of design decisions based on aesthetics and efficiency. The first two Examples concern ongoing TxDOT projects. The last two are imaginary scenarios.

The sites for the four example bridges represent most of the typical land use patterns in Texas. Each bridge consists of a few short to medium spans. The first Example presents a bridge design for a sensitive rural location, a low water crossing near the tourist center of Salado in Bell County near Waco. The second example discusses the design of a bridge for a suburban freeway crossing in Richardson, a Dallas suburb. A highly visible urban site, the southern part of Downtown San Antonio serves as the location for the third example. The final Example concerns an environmentally sensitive site, Zilker Park in Austin.

The Examples follow the organization of the Guidelines. Each Example begins by "visiting the site" through a description, photos and a site plan. Site conditions and constraints are discussed and a vision is presented for the design of the bridge. The Example then offers design possibilities for layout, superstructure, substructure, and non-structural details. A baseline conventional design is presented for each Example. The Example then examines a few of the options illustrating application of the Guidelines in greater depth and compares price estimates for the various options. In harmony with the overall theme of these Guidelines, no single specific solution is recommended. The solution would be chosen from the available options depending on the resources available and the pressures of the project constraints. The Examples show the design possibilities and their costs and benefits. Those responsible for the project would make the final decisions in a real life context.

Price estimates appearing in the Examples are based on typical costs indicated by TxDOT personnel. The cost figures listed are not absolute and will vary by location within the state and also over time. They are typical of 1996 costs. They represent an attempt to show the relative economic effect of design decisions. The cost listed for the TxDOT Project 1410 precast substructures are further discussed in Chapter 7 of this dissertation.

6.4.1 Outcome of Examples

Much was learned from the application of the Guidelines to the Examples. In general, the Examples are a successful display of the potential impact the Guidelines can have on the aesthetics and efficiency of short and moderate span standard bridge systems. Each example resulted in the design of three different structures, all with improvements in aesthetics over the baseline conventional design.

For the low water crossing in Bell County and the suburban freeway overcrossing in Richardson, considerably improved bridges were estimated to be just 8% more expensive than the baseline options. Much of the increase in cost for the Bell County Bridge is attributed to the use of more expensive railings. For the Richardson example, the two options considered using the precast substructure system developed as Proposal II in Chapter 4 of this dissertation were less expensive than a cast in place substructure option. The decrease in cost is attributed to the faster on-site erection time and the decreased amount of material required for the substructure.

For the two imaginary scenarios in highly visible locations where public acceptance is particularly important, suggested improvements resulted in economic changes from a 16% savings to a 98% increase. For the San Antonio bridge, a very attractive structure was estimated to be 13% more expensive than the baseline option. At Zilker Park in Austin, an attractive option was estimated to be 18% above the baseline and 10% lower than an option with only minor improvements over the baseline option. While the increases in cost for these two imaginary scenarios are greater than 10%, it is safe to say that the less expensive options would in fact not be options because of their ugly appearance in such highly visible settings. A 13-18% increase in cost for an attractive bridge of standard bridge components designed with adherence to the Guidelines by the DOT should be considered a successful design.

The Examples are an essential part of the Guidelines. They give a designer a clear picture of how the Guidelines can be applied and be useful for a number of different standard bridge types and site locations. By following the design process and making suggestions at each step, they reinforce the importance of aesthetics being considered at the outset of design - a strong theme in the Guidelines. Concluding each Example with an economic analysis of proposed designs shows convincingly that following Guidelines does not require significant increases in bridge cost, particularly where aesthetics is a major concern.

6.5 Summary

Having the opportunity to implement the research while it is on-going has been valuable for this project. For the Guidelines, input from designers, precasters, form suppliers and contractors across the State and gaining insight into the design process has helped shape the Guidelines into a practical and useful manual. Through both projects, it was seen that application of the Guidelines from the outset of design will allow for the best use of the manual. With the San Angelo project, it was found that with simple layout changes, more attractive solutions could be found with economic savings. The Wichita Falls project showed the simplicity with which the Guidelines could be applied to allow for simple comparisons of design options. This project also showed how public interest in bridge aesthetics will often be involved with a design. Engineers therefore need to pay attention to the impact of their designs on the public and develop their own ideas so that they can proudly display their work rather than have the neighbors try to mask it.

Exploring the use of precast substructures helped focus the development of a more comprehensive precast substructure system for standardization. Extensive attention to fabrication, erection and connection details is necessary for adoption of this new substructure design option. The possibilities for economical and attractive use of such a system is clear. The details must be practical and the presentation convincing to inspire the industry to overcome their "prisoner of the familiar" hang-ups and further the potential for a new form of substructure design and construction.

Further application of the Guidelines will continue to be aided through examination of the Examples, initially developed as case studies by Ratchye. The Examples show designers specifically where aesthetic decisions can be made throughout the design process. Beginning with a site visit, developing a vision, and concluding with the economic consequences of suggested improvements shows convincingly the ease of application, the usefulness and the practicality of the Guidelines. The Examples also point to the future possibilities of precast substructure construction as an attractive and economical form of construction for short and moderate span bridge systems. As the Guidelines are implemented, additional applications should be developed and documented to display further the applicability of the Guidelines to more bridge types typically found throughout the State.

CHAPTER 7
IMPLEMENTATION

7.1 Introduction

The research work described in the Chapters 3-6 has direct applications for TxDOT (and other) highway planners and bridge engineers. Implementation of the two major outputs from the research will be discussed in this Chapter; The TxDOT Aesthetics & Efficiency Guidelines (Guidelines) and the precast substructure system proposed for standardization. Necessary follow-up steps are presented.

7.2 Aesthetics & Efficiency Guidelines

The TxDOT Aesthetics & Efficiency Guidelines should be distributed to highway planners and bridge engineers throughout the State. In addition to the Design Division and the District Design Offices, it is essential that highway planners in the area offices around the State receive copies of the Guidelines. Many of the decisions affecting bridge aesthetics and in particular the geometric layout, are made at the preliminary stages of design by highway planners. The Guidelines point to the importance of these decisions on the development of attractive and efficient bridges. With all parties involved in bridge design aware of the aesthetic consequences of their decisions, there can be more understanding and communication between the parties.

The successful use of Guidelines in both Maryland and Minnesota have been initiated by short courses led by the developers of their Guidelines. Short courses give engineers an opportunity to focus on how to use the manual. Typically such a short course ends with a design competition between groups of engineers working on an existing standard bridge project. These short courses have been well received and a valuable learning tool. A strong introduction in the use of Guidelines will make future use of the Guidelines easier.

The Aesthetics & Efficiency Guidelines may also be conveniently implemented during Value Engineering meetings. Value Engineering meetings are typically held for bridge projects in highly visible or highly controversial sites. Focusing on aesthetics and efficiency while striving for an economical solution will be useful for Value Engineering sessions.

7.3 Alternate Substructure System

The proposed substructure system described in Chapter 4 has been developed to facilitate adoption for standardization. This system is primarily for use with short and moderate span bridges with precast concrete girder superstructures, a highly standardized superstructure system. Standardization of short and moderate span bridge components results in economic savings primarily through highly efficient, repetitive fabrication processes and reduced design and construction time. Developing a new standard for substructure systems will be the key to the success of introducing and implementing precast substructure design for standard highway bridges.

While precast substructures are not an entirely new form of construction, they have had limited use in the past. In an effort to understand potential acceptance of a standardized precast substructure system a sampling of industry personnel were questioned about the use of precast substructures by their offices and in the future. Response comments are outlined in Section 7.3.1.

As mentioned previously, a major impetus for the development of a standardized precast substructure system is the potential savings attainable - savings in time and money particularly on site during construction. Section 7.3.2 discusses potential economic impact of a standardized precast substructure system as a result of discussions with experienced precasters and contractors in Texas.

7.3.1 Industry Comments on Precast Substructures

A number of industry personnel were questioned about the use of precast substructures in their design offices. Their direct comments are summarized here. The positive and negative comments along with concerns or reservations display a general mood in the industry concerning the acceptance of precast substructures as an upcoming form of construction. These comments point to areas needing further study or areas where misconceptions need to be addressed and clarified.

7.3.1.1 LoBuono, Armstrong & Associates

Precast substructures are an acceptable method of construction but it is not apparent to this firm that precast piers offer economical advantages over cast-in-place piers. Casting piers in place is seen as a natural progression continuing up from foundation casting. As well, the “lag” time between the notice to proceed with superstructure erection and when the superstructure elements are ready to be erected can be filled with substructure casting. Exceptions are recognized in the case of large projects or projects built in difficult to access sites, where precasting has been used advantageously in the past.

Some concerns expressed about precast substructures have involved the use of looped strands. Anchoring both ends at the top is viewed as a problem as is the ability to efficiently thread these looped tendons. Tendons anchored in the bottom may require special attention to removing water from the ducts. Post-tensioning bars are considered easier to work with but more expensive.[81]

Author's comments: A potential solution to congestion problems with looped tendon anchorages at the top is through use of high performance concrete with strengths of 56MPa (8,000psi) or higher, where smaller anchorage spacing may be permitted (see Section 4.2.5.7). Special anchorage devices must be tested in higher strength concrete before they can be used in such higher strength concrete in the field.

The case for casting substructures in place being a natural progression from cast-in-place foundations can also be used for precasting substructures. A precast substructure would facilitate the natural progression of the precast superstructure to follow.

7.3.1.2 J. Muller International

To be practical, precast substructure elements must be used on large projects where it is economically justifiable to set up a casting yard and haul the segments to the site. The size and shape of the segments must have significant redundancy for efficient casting. Precast substructures are particularly advantageous for sites that are difficult to access and for bridges built in harsh environments. For bridges in harsh environments, fabrication indoors is advantageous and the high quality control precasting offers allows for efficient use of higher quality concrete - HPC - less permeable therefore more durable.[82]

Author's comments - Another option for precast substructures to be economically justifiable is through standardization. The large volume of smaller, standard bridges exceeds the volume of many large projects.

7.3.1.3 DRC Consultants

Precast hollow box piers are considered strictly for economics and speed of construction. They have not been common in the past because projects are typically too small to gain economic advantages or because transportation costs are excessive. In a few cases, seismic criteria require a large amount of vertical post-tensioning.[83]

Author's comments - Again, precast substructures will most probably be economically justifiable through market aggregation brought about by effective standardization. Applicability of precast substructures to seismic regions is not of major interest to TxDOT but certainly is a topic worthy of further investigation.

7.3.1.4 CALTRANS

Segmental substructures have not been used in California but there does seem to be a future for segmental piers particularly in non-seismic areas. The continuity needed to satisfy the ductile design philosophy of the American seismic provisions has led CALTRANS to use cast-in-place piers with mild reinforcement. Investigations into the use of prestressing to provide continuity resulted in the conclusion that the "lack of substantial strain energy between the design load and the ultimate strength of the high strength strand could be a problem." For precast substructure design to be utilized in California, the seismic performance of such substructures will need to be further researched.[84]

7.3.1.5 Texas Department of Transportation

The Texas Department of Transportation (TxDOT) has used precast piers for at least three projects: the Neches River Bridge in Port Neches, US 183 in Austin and the Louetta Rd. Overpass on State Highway 249 in Houston. The Neches River Bridge was designed by the engineering firm of Figg & Muller. Two of the segmental piers were temporary supports that were more easily dismantled as segmental piers. The US 183 piers and the Louetta Rd. overpass piers were designed by TxDOT. For US 183, the large size of the project and high repetition of similar pier types (260 piers, 3 pier types) were reasons for proposing precast construction. The contractor chose to precast only one pier type. The decision to cast the other piers in place was based on several factors. These included the ability to quickly invoke field labor, an extreme shortage of space in the confined precast yard, extremely generous amounts of cleared right of way which could be cage and form staging areas, and a very modest economic benefit computed as a 0.38% savings over the precast option. Upon completion, the contractor's superintendent indicated construction of the precast piers was the easiest way to build piers he had experienced. The second place bidder felt they would have precast all of the piers. The Louetta Rd. piers were precast because a study mandated that 69MPa

(10,000psi) concrete be used for the substructure. To take advantage of the higher strength concrete, hollow piers were designed to be prestressed. No major problems ensued. The Louetta project was also seen as a study into the feasibility of precasting substructures in the future.[85,86]

TxDOT is open to the development of precast substructures and is clearly in support of investigating the feasibility of such systems.

Author's comments - The precast piers developed for the Louetta Rd. overpass are being used again for a current project in El Paso. Practical implementation of the proposed precast substructure system by TxDOT will require development of specific standards for the range of applications of most interest. The recommendations from this project should greatly facilitate such an effort.

7.3.2 Economic Impact

Discussions with precasters and erectors in Texas led to estimations for the cost of the proposed precast substructure system including necessary construction time. Specifically one Texas precaster and one Texas contractor were furnished with schematic plans of the proposed precast substructure system including dimensions, proposed fabrication description and erection sequence. Their cost estimates of the fabrication and erection of the system are outlined in Table 7.1. Cost estimates were based on the premise that the suggested system has been standardized by TxDOT and implemented by being specified in a fairly wide number of bridges. Therefore the prices listed assume that this substructure is already in production and that several precast plants possess the necessary formwork. Engineers would be able to specify standard precast piers just as they now specify standard I-beams or box beams. The estimate of construction time given in Table 7.1 was made by the author based on observing recent field experience in Texas. The erection of five single precast columns (the equivalent of one 5-column cast-in-place bent) for the Louetta Rd. overpass in Houston (Figure 4.12) required roughly 10 days in the field. A two-column frame bent was then estimated at requiring 4-5 full days (8-10 half days). The time estimate given in half days reflects the fact that some operations such as alignment of the first column segment and casting of the base geometry control joint may occur for more than one bent before further erection operations on one bent proceed. No cost benefits are included for the substantially reduced field construction time with possible savings in traffic control and benefits in early completion of the project.

Figure 7.1 gives a comparison of the estimated proposed precast substructure cost with current average bid prices in Texas for current cast-in-place substructures with rectangular caps and with inverted T caps. The precast substructure system with its inverted T cap would be most competitive with the cast-in-place inverted T alternative and has both aesthetic and life-cycle cost advantages (discussed further below). Although the cost per cubic meter for the precast system is higher, the overall cost of a bent will be lower in many cases. This results from the precast substructure requiring less material through the use of high performance concrete in efficient hollow shapes. A comparison of material quantities, estimated cost and estimated construction time for the three forms of construction shown in Figure 7.1 are given for a hypothetical multi-column bent in Figure 7.2. Even without including the potentially highly significant cost benefits of faster on site construction times, the proposed precast system is highly competitive.

Project to project, advantages of the system witll vary. Considering the benefits of faster on site construction time points to high potential for future success of precast substructure systems. A recent project in Texas ("Pierce elevated" in Houston) utilizing 710kN (160k) precast pier caps to speed erection time in a congested urban site resulted in the largest early-completion bonus ($1.6 million) ever offered by the Texas Department of Transportation.[89] The value of a day of construction time saved was estimated at $53,000. The project manager for the contractor remarked that using falsework to tie the cast-in-place columns with the precast caps would have required six times as long as the method they used which required no falsework. Clearly the value of construction speed in certain locations will far outweigh the construction cost differences of different substructure systems. For instance, as shown in Figure 7.2, while a precast substructure unit may cost $20,000 more than a cast-in-place multi-column bent with a rectangular bent cap, a construction time savings of two weeks in the congested urban site mentioned previously would equate to a savings of $742,000. The costs would vary depending on the size and location of the project. However, the recent experience and valuation of construction speed should give precast substructure systems in the future a highly competitive economic advantage.

Another potential economic impact of precast substructure construction is with life-cycle costs. Precasting the substructure has the advantage of higher quality control with concrete placement. The result will typically be a higher quality surface finish. The unattractive formlines and tie patterns common to cast-in-place concrete construction will be reduced with precasting. As a result, painting the surface will not be necessary to provide an attractive surface appearance. Painted concrete requires repainting roughly every five years or more often if the surface was not prepared before painting. Either way, painting concrete is a maintenance headache that should be avoided wherever possible. An attractive precast finish will reduce maintenance needs and costs.

Another savings in life-cycle costs achieved through the higher quality control of precasting is enhanced durability. Cover requirements on reinforcement are more accurately achieved and better controlled mixing, placement and curing methods can result in a better quality concrete. The combination of epoxy-coated reinforcement, adequate cover achieved with controlled plant production methods and decreased permeability through high performance concrete can provide excellent durability for a precast substructure. Enhanced durability will reduce maintenance and potential replacement costs particularly for the substructure of bridges in coastal regions and areas where de-icing salts are used on the bridge decks.

7.4 Recommendations for further research

Further research involving the Aesthetics and Efficiency Guidelines (Guidelines) should include a careful follow up of the results of using these guidelines. Projects where guidelines were implemented should be analyzed in terms of aesthetic comparisons, efficiency of material use and construction time and effort. Economic impact of using the Guidelines should be examined as well. Case studies of example applications similar to those mentioned in Chapter 6 should continue to be made and documented. Engineers will best understand and be able to implement the Guidelines with detailed examples presented.

Further research in the development of precast substructure systems is desirable. Investigations can be extended to include non-prestressed connection alternatives. Column segments may be joined with non-prestressed reinforcement spliced through grouted sleeve couplers as with the Edison Bridge discussed in Section 4.2.1.2. Potential applications of precast substructure systems should be examined for seismic regions. Such studies should be funded nationally or by concerned States.

Further study of the economic impact of more rapid on-site construction would benefit the future implementation of such a substructure system. While material and labor costs are easily estimated and over time made more accurate, the advantages of avoiding traffic delays and making new highways available to the public faster are less quantifiable but may in fact have a more

profound impact on the economics of precast substructure systems. Recent attempts to quantify motorist inconvenience such as for the "Pierce elevated" project discussed in Section 7.3.2, exemplify the importance of speed of construction. Different ways in which faster construction can benefit a community should be emphasized, observed and recorded.

The economic advantages of precasting year-round in harsh climates where the construction season is short should also be further examined.

7.5 Summary

The most important aspect of implementing the research presented in this dissertation is following the success or failures of projects in which the Guidelines or the precast substructure system are used. This research has been developed for direct application in the field and must therefore be analyzed and judged in terms of its effectiveness, usefulness and aesthetic and economic impact on actual projects.

The Guidelines should be evaluated and revised over time as new structural systems develop and new material and construction technologies are put into practice. While some of the structural systems analyzed in the Guidelines may fall out of common practice, the principles presented in the Guidelines should be applicable to new systems.

As precast substructure systems become more widely accepted and used, their aesthetic and economic impact on short and moderate span bridge design must be evaluated. Evaluations should consider both initial and life-cycle costs as well as appearance. Communication between researchers, designers and builders must remain open and cooperative for rapid and successful implementation of new ideas and for the sharing of positive and negative experiences with precast substructure systems.

CHAPTER 8
SUMMARY & CONCLUSIONS

8.1 Summary

Standard highway bridges of short and moderate spans are typically designed for economy and function alone. Although these short and moderate span bridges often dominate the highway landscape, they typically detract from rather than enhance the environment in which they are built. Such an unimaginative display of structural engineering does little to express the rapid growth and exciting developments in this profession.

The improvement of standard short and moderate span bridges through the use of aesthetic guidelines and attractive, efficient concrete substructures is reported. This research was conducted through the Center of Transportation Research at the University of Texas at Austin as Project No. 0-1410.

Aesthetics & Efficiency Guidelines were developed that were primarily intended for use by bridge and highway engineers at the Texas Department of Transportation (TxDOT). An attractive and efficient substructure system of match cast precast segmental elements post-tensioned together on site was developed for use with standard superstructure systems in Texas. Attractive cast-in-place substructures as an alternate to the current common Texas substructure practice utilizing circular columns and rectangular bent caps were also investigated. Applications of this research to two existing projects in Texas were summarized and the resulting impact reviewed. Four example applications of the Guidelines showed general approaches and varied economic benefits and/or costs. Implementation strategies for further application of the research are given.

The research presented in this dissertation includes:

- A literature review with particular focus on short and moderate span bridges (Chapter2)
- A photographic survey of short and moderate span bridge systems in Texas documenting successes and failures (Chapter 3)
- Interviews with Texas Bridge and Highway engineers to define the design process and aesthetic challenges (Chapter 3)
- Informal “face-to-face” surveys of the public’s perception of and attitude towards standard bridges as well as willingness to fund aesthetic improvements (Chapter 3)
- The development of the Aesthetics & Efficiency Guidelines (Chapter 3)
- The development of an attractive and efficient precast substructure system for use with standard short and moderate span bridges (Chapter 4)

- An investigation of new cast-in-place substructure designs (Chapter 5)
- Application of the Guidelines and the precast substructure system to two existing projects in Texas and four illustrative examples (Chapter 6) and ,
- Suggested strategies for further implementation of the research with potential impact on aesthetics, efficiency and economics (Chapter 7).

The Guidelines included in Appendix F (Volume II) are a manual that bridge designers and highway planners can refer to throughout the design process. This manual illustrates to engineers how their *engineering* decisions impact the aesthetics and efficiency of their designs. Rather than providing a book of rules with do's and don'ts, the Guidelines offer suggestions and propose questions to be asked at each step of the design process.

Three major themes are carried throughout the Guidelines, providing a framework for the design of attractive and efficient bridges. The first theme stresses the importance of balancing aesthetics, efficiency and economics with each design. Efficiency refers to both an efficient use of materials as well as efficient methods of construction. The second theme asserts that each design must be carried out according to an initial vision or design concept for the bridge. Design concepts must be developed by all parties involved in a given bridge project. The third theme maintains that designers must strive for coherence in their projects by fulfilling the design concept at each stage of the design process.

The Guidelines challenge State DOT engineers to be creative and to include aesthetics equally with the more commonly recognized engineering disciplines of economy and efficiency. Following the Guidelines as an initial step toward more creative design, designers will be able to maintain pride in their work while the public maintains pride in their State.

This study clearly showed that the appearance and efficiency of standard short and moderate span bridges can be greatly improved with more thoughtful substructure design. In the past forty years superstructure design in Texas has continually been evaluated and improved by taking advantage of new efficient structural shapes, the efficiency of higher strength materials (both steel and concrete) and the efficiency of mass production through precasting. Substructure design on the other hand has remained virtually the same utilizing the same basic shapes (circular or square columns and rectangular or inverted T bent caps) with lower grade non-prestressed steel and cast-in-place concrete.

The standard multi-column bent substructure system most often used in Texas requires labor intensive on-site construction, utilizes a relatively low quality concrete and creates an unattractive forest of columns. The majority of bridges with durability problems in Texas have deficient substructures. More efficient and more durable substructures would combine high performance materials and precasting. As a specific proposal, a precast substructure system was developed for use as an alternate substructure system in Texas.

The proposed precast substructure system is made up of segmentally match cast piers with a match cast cap that is well suited for manufacture in a precast pretensioning plant. The cap and piers would be post-tensioned together on site. The proposed system has two designated geometry control joints per pier that would require field concreting or grouting. Match cast segmental construction of the pier shafts has been proposed largely due to it's successful use for moderate and long span superstructure design in the past and its successful use for piers on several recent Texas projects. Segmental construction has proven to be a rapidly constructed, durable, and fairly economical system that minimizes traffic conflict and can reduce impact on the local environment.

The proposed precast substructure system is a versatile system that can be used for a wide variety of bridge widths and heights. Two specific design examples are presented in detail in Appendices C and D. The new system uses elements which can be handled by the types of cranes used for erecting standard girders. The precast system of match-casting with epoxy joints has provided excellent durability for structures in the past. The combination of precasting and using high performance concrete results in more durable and more attractive construction. The geometric shape of the proposed system may also be used for cast-in-place construction and is recommended as an attractive alternative to current standard cast-in-place substructures.

Numerous attractive options for cast-in-place substructure design are proposed in Chapter 5 as alternatives to the circular column, rectangular cap substructure system used most often in Texas. Key issues identified that should be considered when choosing an appropriate substructure system and shape are structural expression, visibility through the bridge, integration of the substructure with other bridge elements and the bridge site, and enhancement of substructure design through attention to non-structural details. Designing the substructure of a bridge is shown to be an opportunity to display creativity and to express the elegance possible through *engineering*. With thoughtful consideration, attractive and well-suited substructures will greatly enhance the overall appearance of standard bridge systems

The Guidelines were used to develop design options for four possible bridge projects in Texas. The results were documented in a series of Examples that show convincingly the ease of application, the usefulness and the practicality of the Guidelines. The Examples also point to the future possibilities of precast substructure construction as an attractive and economical form of construction for short and moderate span bridge systems. The Examples are reported on briefly in Chapter 6 and are presented in the Guidelines in Appendix F, Volume II of this dissertation.

Suggestions for continued implementation of this research are presented in Chapter 7. Implementation strategies include widespread distribution of the Guidelines to bridge and highway engineers across the State as well as short courses to introduce their use. The Guidelines may also be adopted for use during Value Engineering meetings. As the Guidelines are put into actual practice, additional Examples should be developed, documented, analyzed and judged in terms of the effectiveness, usefulness and aesthetic and economic impact the Guidelines have on actual projects.

Clearly, initial implementation of the proposed precast substructure system should be as part of several large projects in highly visible locations where construction efficiency (speed of construction) and final appearance are particularly important. An initial investment in forms for a large project will lead to future savings when the forms may be re-used for similar or smaller projects. Texas precasters and contractors who were asked to give cost estimates for the fabrication and erection of the proposed precast substructure system if and when standardized indicated that the proposed system will most probably be economically competitive with cast-in-place multi-column inverted T cap bents. In the future, other new standard shapes for both precast and cast-in-place substructures may be developed to provide TxDOT designers with even more alternatives for attractive substructure design.

8.2 Conclusions

8.2.1 General Conclusions

1. Current attitudes towards standardization have led to a highway landscape dominated by unattractive, unimaginative and often deficient short and moderate span highway bridges. Most problems are connected with substructures. The efficiencies and attractiveness possible with standardized bridge components are presently not being fully realized because the standard substructures widely used tend to be unattractive, have low durability, and are not always structurally efficient.
2. Aesthetics Guidelines for highway planners and bridge engineers are an essential first step towards improving bridge aesthetics for standard bridge systems and for

developing an awareness of the ways in which *engineering* decisions effect the appearance of engineered structures.

3. Developing and promulgating a design concept for a bridge is essential for attainment of coherent projects in State highway transportation offices where a single project may be designed by numerous parties in different offices over long time spans. Economic savings in terms of both material efficiency and construction speed as well as improved appearance can be achieved when a visionary design concept is developed at the outset of a project.
4. Precast substructure systems are a relatively new and versatile alternative in substructure design that offer numerous benefits for highway construction including rapid on-site construction time, reduced traffic delays, improved structural efficiency, improved overall appearance, reduced maintenance needs, and enhanced durability.
5. Precast substructure systems will be most efficient, attractive and economical when utilizing high performance concrete, standardized plant production methods, match casting and rapid field erection.
6. A prototype precast substructure system has been developed that exploits the benefits listed in Conclusion 4 and satisfies Conclusion 5. Design examples are furnished to indicate typical computations and applications.
7. Initial use of precast substructures for standard highway bridges should be for large repetitive projects where the economy of scale will minimize initial form investment costs.

8.2.2 Detailed Conclusions

1. Most literature on bridge aesthetics calls for more attention to be given to bridge aesthetics and presents generalized aesthetic principles. However, very little is written providing practical guidance on how to apply these principles with reasonably economical results.
2. While the efficient use of materials on long span bridges very often leads to the most economical design, the efficient use of materials for short and moderate span

bridges is often secondary to utilization of standardized, efficient construction methods.

3. The aesthetics of standard bridge systems is most profoundly affected by the layout of the bridge and the substructure system chosen. Non-structural bridge components cannot improve the appearance of a dull bridge form.
4. Significant aesthetic improvements can be made to standard bridges with little increase in cost (often less than 5%) and sometimes with savings.
5. Application of the Guidelines from the outset of design will allow for the best use of the manual.
6. On site construction time for precast substructures will most probably require half or less the time that current cast-in-place concrete substructure construction requires.
7. Costs incurred by traffic delays and benefits to the public as a result of faster highway construction are difficult to quantify but are an important advantage to precasting over cast-in-place construction particularly in congested areas.
8. For a precast substructure system, match cast pier segments and a template that has been match cast to the cap are the key elements for speed of construction as well as durability.
9. Strut & Tie modeling is a particularly useful tool for preliminary design where examination of the flow of forces can lead to efficient design shapes.
10. Cast-in-place substructure design should take advantage of the moldability of concrete. Incorporation of curves, tapers and column and cap shaping for structural expression and or bridge component integration should be explored in design.

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