

Field Applications of FRP Reinforcement: Case Studies



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Sami Rizkalla
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PREFACE

The field application of fiber-reinforced polymer (FRP) composite materials as reinforcement for concrete structures has been growing rapidly in recent years, mostly with interest in alternatives to steel reinforcing bars and for strengthening concrete structures. FRP products provide options and benefits not available using traditional materials.

In 2001, ACI Committee 440 published ACI 440.1R-01, “Guide for the Design and Construction of Concrete Reinforced with FRP Bars,” as the first document in the Emerging Technology Series (ETS) adopted by ACI. ETS documents provide recommendations on the use of new technologies based on available test data, technical reports, and limited experience with field application. Based on the intense research that has been conducted worldwide, the committee revised and updated this report in 2003 (ACI 440.1R-03).

FRP systems have been used extensively for strengthening concrete structures as an alternative to traditional strengthening techniques. In 2002, ACI Committee 440 published ACI 440.2R-02, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.” This was the second document in the ETS series published by ACI.

As a result of the extensive use of FRP as internal and external reinforcement for new structures and strengthening concrete structures, respectively, the committee organized three technical sessions on “Field Application of FRP Reinforcement—Case Studies” with a total of 21 papers presented at the ACI Fall 2003 Convention, in Boston, Massachusetts. All papers dealt with case studies and demonstration projects to provide clear evidence of the practicality, credibility, and maturity attained by this technology.

This volume includes the papers presented during the Fall 2003 Convention, plus five additional papers that augment the range of field applications and case studies. The goal of this document is to help practitioners implement FRP technology, while providing testimony that design and construction with FRP material systems is rapidly moving from emerging to mainstream technology.

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CHAPTER 1

FRP COMPOSITES FOR INTERNAL REINFORCEMENT

FRP Reinforced Concrete in Texas Transportation—Past, Present, Future

by T. E. Bradberry and S. Wallace

Synopsis: Fiber reinforced polymer (FRP) materials can be used in concrete infrastructure elements to achieve short-term and long-term construction and performance goals that cannot be met with traditional steel reinforcement. Like other states, Texas is faced with materials-based transportation infrastructure challenges including: deterioration of concrete due to the corrosion of steel reinforcement, bridge girders damaged by vehicle impacts, concrete bridges that have no visual signs of distress but are load-posted or otherwise deficient in load rating, girders and bent caps that have inadequate shear reinforcement by current standards or that exhibit service cracking, and even a need to provide reinforcement that does not interfere with vehicle imaging loops requiring magnetic/electrical isolation near turnpike toll plazas. This paper reports on Texas transportation infrastructure construction and maintenance projects where FRP materials have been implemented as a means to meet each of these challenges. Included herein are descriptions of selected Texas Department of Transportation (TxDOT) construction and maintenance projects involving concrete internally and externally reinforced by FRP materials. These projects are either completed or will soon go to contract. Most of these projects have been carried out on a trial or experimental basis but they serve to provide a brief glimpse into the probable future of FRP reinforcement in Texas transportation projects.

Keywords: corrosion-induced concrete deterioration; fiber reinforced polymer composites; FRP repair; FRP strengthening; impact damage; infrastructure; rehabilitation; structural concrete; transportation

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INTRODUCTION

With the recent publication of design guidelines for the application of FRP internal and external reinforcements to reinforced concrete, design engineers now have tools with which to meet challenges, which steel reinforcement has not satisfactorily met in the past. Not the least of these challenges has been that presented by the aging and deterioration transportation infrastructure of the United States. To a significant degree these same challenges face engineers at the Texas Department of Transportation (TxDOT). Fiber-reinforced-polymer (FRP) reinforcement has been used in Texas to meet such challenges on a number of projects in recent years. Some applications, such as using FRP as internal reinforcement for the purpose of eliminating electrochemical corrosion of reinforcement and subsequent corrosion product induced deterioration of surrounding concrete, have limited application in Texas. This is because, other than in marine environments, concentrations of chlorides in concrete exceeding corrosion threshold levels are not as prevalent in Texas as they are in jurisdictions to the north. Other applications, such as externally bonded FRP strengthening of bridge elements, whose original design strength is now substandard making otherwise healthy looking concrete bridges load rate below acceptable levels for widening or other rehabilitation, are likely to be more widely employed. Externally bonded FRP fabrics used in the repair of impact damaged bridge girders are fast becoming an accepted practice by TxDOT bridge maintenance engineers and thus shows promise for more widespread use in Texas. Yet another emerging application for FRP internal reinforcement exploits the non-magnetic property of GFRP reinforcement to provide reinforced concrete that does not interfere with vehicle imaging loops requiring magnetic/electrical isolation near turnpike toll plazas. Examples of these projects plus an application where FRP reinforcement is used to correct a design flaw are presented in this paper. Finally, the future of FRP reinforcement in Texas transportation infrastructure is briefly considered.

RESEARCH SIGNIFICANCE

This paper demonstrates the increasing use of FRP reinforcement by TxDOT transportation engineers in the construction and repair of transportation infrastructure for

the state of Texas. All the projects presented have been designed by TxDOT transportation engineers or TxDOT consultants who, presented with a structural or material problem, solved the problem by using FRP reinforcement. These projects indicate that FRP reinforced concrete is considered by TxDOT engineers to be a viable option to traditional steel reinforced concrete in environments and situations where steel reinforced concrete has not performed well or cannot be effectively used.

FRP REINFORCEMENT

Although FRP is a new material for reinforcing concrete in the transportation infrastructure industry, it has been a primary material in the aerospace, automotive, and recreational equipment industries for years. Because of its reduced weight, superior corrosion resistance, and magnetic transparency, FRP reinforcement in concrete elements may offer longer life and more versatile application than traditional steel reinforcement, particularly for transportation infrastructure. In Canada, where reinforced concrete bridge decks deteriorate due to corrosion of steel reinforcement and are replaced approximately every twenty years, the Ontario Ministry of Transportation is using FRP composite reinforcement for extending bridge deck service life to 75 years (1). In the United States FRP reinforcement is also being used in transportation infrastructure, with the first application of internal reinforcement being the fully GFRP bar reinforced concrete deck of a bridge in McKinleyville, West Virginia, built in 1996 (2).

Transportation design engineers in the United States have been reluctant to employ FRP reinforcement largely because of their perception that design and construction standards or guidelines are not available and because of the challenges to reinforced concrete design philosophy presented by FRP reinforced concrete. In fact, domestic state governments and engineering associations worldwide are cooperating to standardize workable national and international design parameters and specifications. In addition, the composites industry is forging critical associations with the civil engineering community and organizations such as the American Concrete Institute (ACI) and the Civil Engineering Research Foundation (CERF) (3). CERF alone has funded approximately \$4,000,000 of research in this effort as of 2002. In May of 2001, ACI Committee 440, "Fiber Reinforced Polymer Reinforcement", published an emerging technology series document offering guidance to engineers in the design and construction of concrete reinforced with FRP bars (4). In October of 2002, ACI Committee 440 published a second emerging technology series document, one that includes recommendations on the engineering and construction of concrete strengthened with externally bonded FRP systems (5). FRP strengthening systems use FRP composite materials such as laminates and fabrics as supplemental externally bonded reinforcement. Development of these and similar design and construction documents backed by good research data and demonstrated field experience are essential to overcoming the individual and corporate reluctance of infrastructure designers to employ FRP reinforcement in transportation projects.

USE OF FRP REINFORCEMENT IN TEXAS

The Texas Department of Transportation (TxDOT) supports the use of FRP reinforcement and is increasingly employing it to meet challenges such as the following:

- Concrete deterioration caused by steel reinforcement corrosion.
- Rapid repair of overheight vehicle or payload impact damage to bridge superstructure elements such as prestressed concrete bridge girders.
- Rehabilitation of bridges whose current load rating is inadequate because they were built before implementation of the HS-20 design live-loading.
- Strengthening or repair of girders and bent caps that have inadequate shear reinforcement by current standards or exhibit service cracking that is aesthetically undesirable and may be of structural concern, such as the cracking that often occurs at the reentrant corners of inverted tee bent caps.
- Reinforcement that will not interfere with vehicle imaging loops requiring magnetic or electrical isolation near the planned toll plazas of the Texas Turnpike Authority's central Texas (Austin District) toll roads.

Repair and Strengthening Using Externally Bonded FRP Fabrics and Laminates

Three completed projects are reported to illustrate the use of externally bonded FRP fabrics and laminates in the repair and strengthening of Texas transportation infrastructure projects:

- The repair of an impact-damaged bridge superstructure using a carbon FRP (CFRP) system.
- The strengthening of a pan girder bridge using CFRP systems to increase its load rating.
- The repair and strengthening of the ends of inverted-tee bent caps having cracked reentrant corners, using a CFRP system.

Solution for Corrosion-Induced Concrete Deterioration

In the Texas panhandle, frequent use of chloride-containing deicing agents has pushed the chloride concentration at the level of reinforcement in many concrete bridges past the steel corrosion threshold, resulting in corrosion-induced deterioration of the reinforcement and deleterious cracking of the surrounding concrete. One completed Texas project illustrates use of glass FRP (GFRP) internal bar reinforcement as an alternative to epoxy-coated steel reinforcement for preventing corrosion-induced concrete deterioration in a bridge deck.

Solution for Magnetic Transparency Needs of Vehicle Imaging Loop Detectors

A recent realized transportation application of FRP reinforcement is its use in central Texas as reinforcement for pavement and bridge deck sections on area toll roads. Loop detectors embedded in concrete riding surfaces generate magnetic fields that enable them to detect characteristics of vehicles as they pass through toll plazas. For the system to function properly, magnetic fields must not be allowed to generate electrical current that could result in cross-talk between adjacent and remote loop detectors. GFRP reinforcement's unique, non-magnetic, non-conductive properties meet this challenge. One Texas project currently awaiting construction illustrates this unique application.

Past Project: GFRP Reinforcement in a New Concrete Bridge Deck

Background—Corrosion of metallic reinforcement accelerated by the use of chloride containing deicing agents is a primary cause of concrete bridge deck deterioration. A potential innovative solution to this problem is to eliminate this corrosion by using electrochemically inert FRP bars in lieu of steel reinforcement. However, because FRP bars are linearly elastic to failure TxDOT engineers have been hesitant to use them. Nonetheless, TxDOT engineers requested funds through the TEA-21, Innovative Bridge Research and Construction Program (IBRCP) for a proposal to use FRP bars as reinforcement in a concrete bridge deck. The IBRCP required TxDOT to use the FRP bars as an innovative material before performing companion research. This is due to a requirement that the innovative material be incorporated into a construction project which encumbered the funds in the same fiscal year in which they were awarded; a time frame within which the contracting and completion of a companion research program was not possible. The IBRCP facilitated the design and construction of a TxDOT bridge that incorporated FRP bars in its concrete deck by providing funds for field monitoring, comprehensive laboratory companion testing, and the estimated increased cost of the FRP bar reinforced deck over what a conventionally designed and constructed bridge deck would cost. An important factor contributing to the success of the project in light of the restrictions the program placed on obtaining and using the findings of companion research was the transfer, during the project design phase, of preliminary consensus design guidelines to the design engineer by members of ACI Committee 440. This sharing of design technology occurred prior to the publication of ACI 440.1R-01 (4).

Project Overview—In the year 2000, TxDOT used GFRP bars as top mat reinforcement in the concrete deck of the Sierrita de la Cruz Creek Bridge constructed near Amarillo, Texas. Placed in service in January 2001, the phase-constructed bridge carries an estimated 1,650 vehicles per day (including approximately 300 trucks, many of which are fully loaded gravel trucks) along a portion of Ranch-to-Market Road 1061 (RM 1061) situated in Potter County, Texas. The bridge is the first Texas transportation application of internal FRP reinforcement.

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The project bridge design engineer performed the complete bridge design, including the GFRP-bar reinforced concrete deck (6), consulting extensively with various members of ACI Committee 440 because the Committee's ACI 440.1R-01 (4) document had not yet been published. The bridge design engineer assumed the Westergaard theory of slab behavior to determine the distribution of wheel load effects to the design forces to the deck (7). In current Texas practice, concrete bridge decks are typically supported on prestressed concrete beams having no end or interior diaphragms (see Figure 1); therefore, arch slab behavior relying on the development of compressive membrane forces and restraint of beam top flange movements cannot be fully achieved—thus internal reinforcement of the bridge decks is required. The resulting design was governed by serviceability considerations with the estimated crack width being the controlling parameter. For a detailed treatment of the design procedure see Reference 6.

The bridge deck design accommodated the properties of all the GFRP bars that were available in North America in 1999, the year the project was designed. The design team developed special specifications for the GFRP bar reinforced concrete slab and the contractor selected the product which met the special specification. The contractor, who was awarded the contract through the competitive bid process, chose GFRP bars produced by Hughes Brothers, Inc. of Seward, Nebraska.

Figure 2 shows concrete being placed on the GFRP-bar mat, which is chaired off the precast, prestressed concrete subdeck. These panels are reinforced with conventional active steel prestressing strands in the span direction (perpendicular to the beams) and passive steel bars in the orthogonal direction. The panels provide the critical positive-moment reinforcement for all bays (the region of slab between adjacent beams) except the bay where the two phases of construction meet. For that bay, epoxy-coated steel bars provide positive-moment bottom reinforcement.

The specific gravity of GFRP bars is about one fourth that of steel reinforcement. Although the savings in mass (weight) of the finished bridge deck is minimal, the transportation cost for the reinforcement is less and the placement cost, as measured by the ease with which the “iron workers” are able to place the bars in the formwork, is also less for GFRP bars as compared with epoxy-coated steel bars. This was the experience of the contractor for this project.

The new structure replaced a functionally obsolete reinforced concrete pan-girder structure that had exhibited significant loss of concrete cover due to corrosion-induced deterioration of the reinforcement. The all new 13.8-m (45.28-ft) overall-width bridge consists of seven 24.0-m (78.74-ft) prestressed concrete girder spans, two of which have top mat GFRP-bar reinforced concrete decks. The remaining five spans have top mat epoxy-coated-steel reinforced concrete decks for performance comparison with the GFRP-bar reinforced concrete decks.

Research and Technology Transfer—Two related research studies are associated with the Sierrita de la Cruz Creek Bridge.

The federally funded (IBRCP) TxDOT Research Project No. 9-1520, “FRP Reinforcing Bars in Bridge Decks”, conducted by a consortium of three research agencies—Texas Transportation Institute (TTI) at Texas A&M University, The University of Texas at

Arlington (UTA), and Texas Tech University (TTU)—serves as the bridge deck monitoring and companion test research program. The scope of this project includes evaluation and documentation of the performance of FRP bars used as internal top mat reinforcement in bridge decks and the development of AASHTO type design recommendations for their application. The study involves a literature search to document the state-of-the-art, laboratory companion tests to establish material and structural behavior, full-scale prototype crash testing, and field monitoring of the prototype FRP reinforced concrete bridge deck system during construction and early service life. This project is still underway, having been extended ten months to complete the last of the required testing. Two interim research reports have been published (8, 9).

The Texas funded TxDOT Research Project No. 0-4138, “Full-Scale Crash Tests of FRP Bar Reinforced Bridge Rails,” conducted by TTI grew directly out of the IBRCP funded project in order to investigate the crash worthiness of fully FRP reinforced concrete bridge rails. This project addresses the behavior of such concrete bridge rails on concrete deck slab structures where both rail and slab are reinforced with GFRP bars when the rail/slab system is subjected to full-scale vehicle crash tests in accordance with the requirements of NCHRP 350, Test 3-11. This project has been completed and the final and summary reports approved for publication (10, 11).

TxDOT has also sponsored UTA’s participation in the bond test portion of the “ConFibreCrete” European research network, Federation of Concrete (FIB) Task Group 9.3, and ISIS Canada jointly organized “Round Robin Tests for FRP Reinforcement” (12, 13).

To demonstrate and generate interest in the IBRCP project, the Federal Highway Administration (FHWA) sponsored a half-day innovation showcase on July 25, 2000, in conjunction with the July 26, 2000 placing of the concrete for the first phase of the bridge deck. Also, the bridge design engineer has received and filled requests for technical information about this project. The requests came from several interested state DOTs who were considering, planning or designing their own FRP bars in bridge deck projects as well from Dr. Brahim Benmokrane was designing such a project to be build in Canada.

Past Project: Externally Bonded CFRP System for Repair of an Impact Damaged Bridge Girder

Background—Occasionally in Texas an overheight truck, or its payload, hits a bridge superstructure and causes enough damage that a structural repair is warranted. For prestressed concrete beam superstructures, depending on the degree of severity of the impact damage, three classes of repair procedures and materials are employed in compliance with TxDOT Special Specification Item 4421, “Repair of Impact Damaged Prestressed Concrete Bridge Beams” (*Appendix “A”*), with Category I repair being that class of repair required for the most severely damaged beams. Since the development of this special specification TxDOT research has provided guidance on damage assessment and repair protocols (14). More recently, it has become common practice for the Bridge Division bridge construction and maintenance engineer charged with the design of such

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repairs to use externally bonded FRP fabric as a little “extra insurance” or, in a recent case not reported herein, as a fully designed and explicit load carrying element.

Project Overview—An over-height vehicle struck the Farm-to-Market 1927 (FM 1927) bridge over eastbound IH 20 in Ward County in the Odessa District on January 17, 2002, severely damaging an external beam. The four-span precast prestressed concrete beam bridge was built in 1964. The simply supported superstructure consists of two 13.72-m (45-ft) end spans and two 18.29-m (60-ft) interior spans with four beams at 2,438 mm (8-ft) center to center in each span. The damaged beam is a Type C beam in the 18.29-m (60-ft) span over eastbound IH 20, and it required closing of a lane of IH 20 during the inspection and repair. The beam’s web and the bottom flange near the middle of the span between two diaphragms were fractured into several pieces as shown in Figures 3 and 4. However, based on visual inspection and “sounding” of the forty-four 13-mm (3/8-in) diameter prestressing strands, all but one were in good condition and seemed to have retained the “lion’s share” of their pre-impact tension, in spite of the loss of surrounding concrete. The one exception was a strand which had been severed in a previous impact. The concrete deck, the top flange, and the rest of the beam were in good shape.

After careful evaluation, TxDOT engineers concluded that the damaged beam was repairable. Because a large area of concrete in the web of the beam was severely fractured, the Bridge Division bridge maintenance engineer proposed one layer of CFRP composite in addition to the normal repair method to restore the shear strength and the integrity of the beam. The CFRP composite wrap was not rationally designed to carry a particular level of stress but rather was assumed desirable for enhancing the integrity of the repair. The damage assessment described above and the subsequent repair procedures described below were informed by TxDOT sponsored research (14).

TxDOT engineers provided details and specifications for the repair work. Repairs to the prestressed concrete beam were in accordance with Special Specification Item 4421, “Repair of Impact Damaged Prestressed Concrete Bridge Beams,” Category I repair (*Appendix “A”*). Category I repairs are targeted at damaged prestressed concrete beams with significant spalling, section loss, and cracking. The special specifications give the engineer authority to require that a loaded 9.17-cu m (12 yard) dump truck or other loaded vehicle, as approved by the engineer, be placed on the bridge over the damaged beam to keep the beam loaded while the repair material cures. The benefits of this preloading prior to repair are numerous and include 1) restoration of beam profile and precompression, 2) facilitation of the removal of damaged concrete, 3) improved penetration of injected epoxy into cracks opened by preloading, 4) restoration of a portion of the effective prestress of the strands, and 5) precompression of the patching material providing a hedge against subsequent cracking under service loads (14). TxDOT engineers recommended that the loaded trucks stay on the span until the patched concrete cured for at least 24 hours and reached 27.58 MPa (4,000 psi) using high early strength concrete. After completing the concrete repair, including the injection of epoxy to seal cracks and the removal of the loaded truck from the deck, the contractor wrapped the repaired area between two adjacent diaphragms with a single layer of CFRP composite fabric. TxDOT engineers specified that the CFRP installation be performed by a

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subcontractor who specialized in the work following the manufacturer's instruction and with approval of the Engineer. The direction of the longitudinal fiber was perpendicular to the longitudinal beam axis (vertical on the web) because the CFRP was intended for shear strengthening.

The Bridge Division construction engineer estimated the costs of two alternative repairs as follows:

- *Estimated Cost to Repair the Beam*—\$26,445 (including the use of the CFRP) plus the cost of mobilization and traffic-handling during an estimated seven days of construction time.
- *Estimated Cost to Replace the Beam*—\$54,866 plus the cost of mobilization and traffic-handling during at least 20 days of construction time and 10 days of fabrication and delivery time for the new Type C Beam.

The work included concrete repair using rapid-set non-shrink multipurpose grout and rapid set non-shrink concrete mix with a gravel size of 9.52-mm (3/8-in), epoxy injection, and installation of a CFRP-composite wrap made by Sika, consisting of a unidirectional carbon-fiber fabric and a compatible epoxy adhesive.

Patching of the concrete and the epoxy injection took four days; CFRP composite installation took one day. The total cost was \$47,000, which included \$22,000 for concrete repair and \$25,000 for CFRP composite installation. The area of CFRP installation was about 13.94-sq m (150-sq ft). This small area of CFRP and the cost of mobilization may be the primary reasons this job was so costly on a unit basis. After completion of all repair work, all lanes under the bridge were opened to traffic in April of 2002 (see Figure 5).

Past Project: Externally Bonded CFRP Systems for Increasing the Load Rating of a Bridge

Background—Brena, et al (15, 16) conducted TxDOT sponsored research to investigate the feasibility of using externally bonded FRP composite material to increase the load rating of bridges in order to make them eligible for widening¹. The research testing program involved two phases—first, static and dynamic tests on a total of thirty

¹A bridge widening project requires that the portion of the bridge to remain have a load capacity high enough to justify widening over replacement. This capacity is quantified through various load ratings that are normally based on the original bridge plans and material specifications but sometimes include such items as mill test reports to get a better idea on the “real” material properties. However, assessment of this load rating involves other information on the bridge along with engineering judgment. As a rule of thumb, a proposed bridge widening will not be approved unless the load rating of the remaining portion of the bridge after widening is at least H-20 (operating level) and no less than about HS-17 (inventory level). The number shown for the H rating is the allowable weight of the vehicle in tons, and the number shown for the HS rating is the rating factor multiplied by 20. Thus, a rating factor of 1.0 would result in a rating of HS 20, a rating factor of 1.25 would result in an inventory rating of HS 25, and a rating factor of 0.75 would result in an inventory rating of HS 15.

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(30) beams, and subsequently, tests on four (4) full-scale strengthened bridge specimens. The thirty (30) beam tests identified the failure mechanisms and were instrumental in the determination of the appropriate size and spacing of transverse straps used to delay the onset of debonding of the FRP fabrics and/or pultruded plates from the concrete surface. The full-scale bridge specimens included both reinforced concrete tee-girders (for the Texas pan-girder type bridge) and flat-slabs (for the Texas FS-slab type bridge—curbs removed after slab strengthening). The pan-girder specimen was selected and dimensioned to reproduce key features of the expected behavior of a portion of the prototype pan-girder bridge. The full-scale bridge specimen is a reproduction of an interior section of the prototype bridge and was used to demonstrate that the strengthening system would provide the desired load capacity with the requisite level of ductility. The CFRP composites selected for the pan-girder test specimens were designed to increase the inventory rating for the bridge specimen from HS-10 to HS-20. Shown in Figures 6 through 8 are the pan-girder bridge specimens during testing and after debonding failure of the external CFRP laminate system.

Overview of the TxDOT Research Implementation Program—TxDOT has a policy encouraging the implementing of all “field ready” results from its research programs as well as from that of other agencies or even private entities such as transportation product manufacturers. In this policy, implementation is defined as the adoption of a product for use, including technology transfer activities that promote adoption, such as the following:

- **Information Dissemination**—includes the development, packaging and distribution of brochures, manuals, articles, reports, videos, and other materials which provide product descriptions and instructions to enable and promote use.
- **Training**—includes training course development and conduct necessary to enable and promote use.
- **Demonstration**—the placing of a product into TxDOT’s operational environment to demonstrate its use, which includes the following:
 - **Deployment**—the initial procurement and dissemination of a product to users, and
 - **Implementation Field Testing**—the demonstration and/or verification of product performance in TxDOT’s operational environment, including District/Division/Office (D/D/O) or National Experimental and Evaluation Program (NEEP) projects.

Overview of the Implementation Project—A demonstration type project was approved for implementation of the research results of Brena, et al (15, 16). The research results were implemented in the widening of a bridge carrying Farm-to-Market Road 1632 (FM 1362) traffic over Sue Creek in Burleson County. The original bridge is a two-span reinforced concrete pan-girder structure—a very common bridge type in Texas that was issued as a standard for various pre HS-20 design loading bridges built between 1948 and 1964. The two simply supported spans are each 9.14-m (30-ft) long, and the overall width of the bridge is 6,553-mm (21.5-ft), with proposed widening out to 9,754-mm (32-ft).

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Because this was a research implementation project, TxDOT engineers used both of the strengthening systems determined as viable by the researchers for this application. Therefore, each of the structure's two spans had its own CFRP strengthening system. The first span was strengthened with longitudinally oriented CFRP fabric produced by Master Builders as the primary strengthening reinforcement and transverse CFRP fabric straps produced by Master Builders as the secondary reinforcement used to control debonding of the longitudinal reinforcement (see Figure 9). The second span was strengthened with longitudinally oriented CFRP pultruded laminates produced by Sika Corporation as the primary strengthening reinforcement and transverse CFRP fabric straps produced by Sika Corporation as the secondary reinforcement used to control debonding of the longitudinal reinforcement (see Figure 10). The CFRP application took less than a week per span to complete. The CFRP strengthening systems were designed to bring the bridge load rating up to at least H-20, which is the same load level as HS-20 for this short span structure.

In accordance with the recommendations of the two CFRP systems manufacturers the contractor used a combination of sand blasting and grinding to prepare the surface to receive the CFRP materials. Grinding was mostly used to smooth out the bottom of the girders. A scaffold was used to provide easy access to the beam stems where the FRP materials were applied.

The construction costs for the project are detailed as follows:

<u>Item</u>	<u>Sub-cost</u>	<u>Cost</u>
Roadway.....		\$207,907
Bridge.....		\$162,092 (\$84.42/ft)
• Strengthening (FRP appl.).....	\$63,500 (\$33.07/ft ²)	
• Repairs (epoxy injection, etc.)	\$15,000 (\$7.81/ft ²)	
• Widening.....	\$83,592 (\$43.54/ft ²)	
Project Total.....		\$369,999

TxDOT widened the bridge at a cost of \$908.69/m² (\$84.42/ft²) rather than replacing it for between \$377/m² and \$484/m² (\$35/ft² and \$45/ft²). However, the project did not have a high enough priority to compete for federal bridge replacement funds, and thus was not eligible for widening without first being strengthened. TxDOT's solution allowed the use of federal funds to increase the capacity of the structure and funded the implementation of research findings in an area of great potential value to TxDOT and other transportation agencies. Replacement, if the bridge load rating had warranted it, would have required either acquisition of the additional right-of-way to build a detour during bridge demolition and reconstruction or use of phasing to handle traffic during construction. This would have complicated the project design and construction, lengthening the project development and construction time, adding both construction cost and highway user cost to the total cost of the bridge replacement project.

Work on this bridge was completed on August 8, 2002. TxDOT engineers have not categorically recommended or dismissed the use of CFRP for strengthening of such bridges. The strengthening alternative must compete against all the other alternatives regarding managing an existing bridge that is in some way deficient. Each such project is evaluated on a case-by-case basis with regard to hydraulic issues, project location, right-

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of-way need and cost, traffic handling, overall cost, and funding. Ideally the alternative which best meets these diverse needs is selected.

Past Project: Externally Bonded CFRP System for Strengthening the Shear Capacity of the Ends of Inverted Tee Bent Caps

Background—The design procedure for inverted tee bent caps in Texas is based on the research of Furlong and Mirza (17-20). That procedure, in part, involves detailing web stirrups that act as hangers that effectively deliver the concentrated loads applied to the bent cap flanges (inverted-tee ledges) into the body of the web (inverted-tee stem). The effect of these “hangers” is easily visualized by considering a section through an inverted tee bent cap (Figure 11) where the hangers function to prevent the flanges from separating (cracking) excessively from the web and peeling open from the reentrant corner. This reentrant corner is often cracked in structures that are in service, especially when the exterior beam is near the end of the cap. If sufficient hanger steel is not provided in this region the aesthetically displeasing reentrant corner crack could be transformed into a crack which compromises the safety of the structure.

In such a scenario, one method of fixing the structural deficiency is to use an externally bonded FRP system to compensate for the insufficiency of the size and/or number hanger bars provided near the end of the cap. This was the choice made by the Houston District bridge design engineer who was faced with this problem after such an inverted tee bent cap had already been constructed. The engineer’s design methodology was loosely based on guidance from the April 1999 working draft of the now published ACI Committee 440 document *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (5) and the ASCE document *Structural Plastics Design Manual* (21). The design engineer employed a strength-based approach to determine the amount and direction of carbon fiber reinforcement, relying on strength reduction factors to limit strain across the expected crack and included superstructure dead load in the analysis because the beams had not yet been erected. An ongoing University of Houston conducted research project, TxDOT Research Project 0-1854, “New Method for Serviceability Design of Inverted ‘T’ Bent Cap Ledges”, to develop serviceability criteria for inverted tee bent caps, provided cracked specimens for use in testing the repair methodology. A specimen was wrapped using the same CFRP materials as planned for the strengthening and then loaded to failure. This test showed that the CFRP materials are forgiving in terms of workmanship and that the design approach employed to remedy the hanger bar deficiency was conservative (Figures 12 through 14).

Project Overview—During construction, the ledge reinforcement of the inverted tee bent caps for a bridge being built to carry State Highway 249 (SH 249) traffic over Spring Cypress Road in Houston was determined to be deficient. It was considered deficient because the inverted tee bent cap and beams to be supported were flush-framed—meaning the beams’ edges were nearly flush with the end of the cap—and the hanger reinforcement provided was not adequate to prevent excessive corner cracking. This geometry results in fewer hanger bars resisting the forces tending to separate the ledge of the inverted tee from the stem, producing a higher risk of excessive reentrant corner cracking. While visible crack width in the reentrant corner at the end of

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such inverted tee bent caps is a common problem, in this case such cracking could lead to more than just aesthetic impact because the behavior of this disturbed stress region is not well understood. After consideration of various options to strengthen the ledges or recast the bent caps, the District determined externally bonded CFRP reinforcement to be a highly cost effective and reliable approach to control the risk of large crack development. A District bridge design engineer designed the CFRP strengthening using the guidance mentioned above in the relevant background section. Figure 15 is an engineering sketch showing the order of application of the eight separate CFRP fabric strips on the end of the bent cap.

District engineers developed a special specification for the strengthening project, using a combination of draft consensus and proprietary specifications as a guide. District inspectors and contractor personnel thoroughly documented the construction process for the benefit of future projects. The completed strengthening is shown in Figure 16 for the ends of adjacent inverted tee bent caps. The cost of the strengthening was \$45,000 for 20.44-sq m (220-sq ft) or \$2007/sq m (\$205.00/sq ft). The work, completed in September 1999, was highly effective, being transparent to the untrained eye, and controlled cracking in the flush-framed, inverted tee bent cap. Figure 17 show a typical flush framed inverted tee bent cap in its completed configuration.

Present Project: Externally Bonded CFRP System for Repair of an Impact Damage Bridge Girder

The IH 10 Overpass carrying IH 10 traffic over SH 304 in Gonzales County was hit by an overheight vehicle in October 2002 causing significant damage to two girders and slight damage to a third. Engineers proposed repair procedures similar to those used for the FM 1927 structure. For the exterior beam, which sustained the most damage, CFRP wrapping around the entire bottom flange and beam webs has been detailed; the adjacent less-damaged beam will only have CFRP fabric wrapped around the bottom flange and halfway up the bottom beam chamfers. The repair work for these two beams is Category I in accordance with the Special Specification Item 4421, "Repair Impact Damaged Prestressed Concrete Bridge Beams" (*Appendix "A"*). The classification of the repair for the third damaged beam drops to a Category II because the damage is less extensive. Figures 18 and 19 show some of the details that have been developed for the repair of this impact damage. As of April 2003, this maintenance project was pending.

Present Project: Internal GFRP Reinforcement to Achieve Magnetically Transparent Pavement and Bridge Deck Sections

Background—The Texas Transportation Authority (TTA), a division of TxDOT, is currently extending the north end of Loop 1 to connect with SH 45, a new highway along the border of Travis and Williamson Counties in central Texas. Both the segments of Loop 1 and SH 45 will be built as toll roads, requiring toll plazas at certain ingress and egress points as well as points across the main lanes. Each toll plaza will include traffic loop detectors embedded in the concrete roadway surface. The loop detectors generate magnetic fields that enable them to detect characteristics of vehicles passing through the toll plazas.

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For the loop detectors to operate properly, a horizontal zone around them equal to approximately twice the area of the loop detector grids must be free of metallic reinforcement to a depth of 7-in. The presence of magnetic, conducting reinforcement such as steel reinforcement in these non-magnetic zones would provide paths for electrical interaction between loop detectors, introducing noise that would mask each loop detector's contribution to the magnetic image of the vehicle, making the entire system inoperable or unreliable. Therefore, use of traditional steel reinforcement is precluded in these zones.

Magnetically Transparent Pavement Sections—The highway alignments call for thirteen Loop 1/SH 45 designated toll plazas at at-grade ingress and egress ramps and three barrier plazas across highway main lanes to be built along the eastbound and westbound SH 45 and northbound and southbound Loop 1 alignments. The loop detectors will be embedded in the continuously reinforced concrete pavement (CRCP) of the ramps and main lanes. TTA, working closely with TxDOT pavement engineers and the bridge design engineer of the Sieritta de la Cruz Creek Bridge mentioned above, has developed a standard drawing titled “Concrete Pavement Details: Fiber Reinforced Polymer Bars Reinforced Concrete” for use on central Texas area toll road projects. The standard drawing shows a GFRP reinforcing ratio, which is approximately 255% greater than that typically used in steel reinforced CRCP.

Magnetically Transparent Bridge Deck Sections—One Loop 1/SH 45 toll plaza will be placed on the Loop 1 Southbound Entrance Ramp Bridge. This structure was originally designed as a typical Texas prestressed concrete girder bridge. The completed construction plans were of 24.38-m (80-ft) long spans comprised of Type C girders spaced 2560-mm (8.399-ft) apart. The 203-mm (8-in) thick concrete deck included 914-mm (3-ft) overhangs along each edge. The entire superstructure rested on concrete inverted tee bent caps. After completion of the original design, TTA requested that traffic loop detectors be embedded at four locations in the concrete bridge deck around the toll plaza area. This required a new deck design for those areas.

The top mat of reinforcing in the required non-magnetic zones around the loop detectors must have at least 76-mm (3-in) of clear cover to leave room for the loop detectors at the surface of the concrete. To meet these requirements, TTA requested that the designer provide a top mat of GFRP bars in all required non-magnetic zones because GFRP bars are non-conductive and non-magnetic. This creates unique requirements for the bridge at the southbound entrance:

- It needs to accommodate a toll plaza.
- It must not use traditional steel reinforcing in the top mat of the concrete deck.
- It must not have reinforcing bars of any kind in the top 76-mm (3-in) of the deck.

TTA contracted with Carter & Burgess to change the original design to accommodate the loop detectors and to provide full-width GFRP-reinforced sections of the deck extending along the end 25% of each span in the plaza area. The typical section will be a 254-mm (10-in) thick slab with a top mat of GFRP reinforcing with 76-mm (3 in) of clear cover. The bottom mat will have traditional steel reinforcing. The deck will transition from the

GFRP reinforced concrete deck to the standard (steel reinforced) TxDOT deck outside the non-metallic loop detector zones. Unique design issues introduced by the use of GFRP reinforcing include limited flexural ductility, potential for creep rupture, crack width controlled design, and overly conservative shear capacity formulation. Design issues considered which GFRP reinforced concrete shares in common with other structural materials include control of deflection and the limitations imposed by fatigue considerations. The design of and construction specification for these GFRP reinforced bridge deck sections were developed with the aid of technology transferred from the design and construction of the Sierrita de la Cruz Creek Bridge and from related Reference 6.

Future Projects

Future Texas transportation infrastructure projects involving FRP reinforced concrete are a certainty although none beyond one or two over-height vehicle impact damaged prestressed concrete bridge beam repairs are currently scheduled for design and construction. Such projects await an attempt to eliminate corrosion-induced deterioration of a concrete bridge deck in a severe corrosive environment, the next over-height vehicle impact on a prestressed concrete girder bridge, the opportunity to keep an existing bridge in service by increasing its load capacity, the need to strengthen or repair bridge elements where shear strength is in question, a decision to provide magnetic transparency in bridge deck or pavement sections of toll plazas requiring magnetic transparency, or possibly an as yet unconceived application to solve some sort of transportation infrastructure problem.

Design and performance issues need to be addressed before wholesale use of FRP reinforcement in Texas transportation infrastructure can be approved. Design guidelines must address questions about the structural implications of the reduction in ductility that use of FRP reinforcement creates, giving designers mitigation options for dealing with design-limiting ramifications. Questions about long-term residual material properties, especially with regard to internal reinforcement, are a significant barrier to general acceptance of FRP by practicing engineers.

SUMMARY AND CONCLUSIONS

This paper shows that engineers responsible for design, rehabilitation and repair of Texas transportation infrastructure have so far had a positive experience with FRP reinforced concrete, with FRP reinforcement offering performance or application that exceeds the performance or applicability of traditional steel reinforcement. Although TxDOT has not sanctioned the wholesale use of FRP reinforcement, the TxDOT projects described in this paper demonstrate that FRP reinforcement is emerging as a viable option for the repair and strengthening of existing concrete and for reinforcement of new concrete transportation infrastructure in Texas. The use of externally bonded CFRP systems for repair of over-height vehicle impact damaged prestressed concrete bridge beams is stated as having already becoming common practice in Texas. Using externally bonded CFRP systems for increasing the load ratings of reinforced concrete bridges has been implemented on one bridge in Texas and thereby has become a rehabilitation alternative

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that may now be considered. Additionally, internal GFRP reinforcement planned for installation in central Texas toll roads will result in pavement and bridge deck sections having regions of magnetic and electrical isolation near the planned toll plazas, meeting the unique need of “magnetic transparency” that is required for vehicle imaging loop detectors to function properly.

Although most TxDOT engineers are unfamiliar with FRP materials today, this paper demonstrates that these engineers will likely be learning and hearing more and more about the structural applications and application limits of FRP materials and may be called upon to use FRP reinforcement to solve common and unusual problems. If this happens many will realize the benefits of reduced weight, will appreciate the absence of corrosion-induced deterioration in FRP-reinforced concrete elements, will select externally bonded CFRP systems as practical and aesthetic alternatives for critical concrete repair and strategic concrete strengthening, and will find that concrete reinforced with GFRP bars exhibits the magnetic transparency required for vehicle imaging loop detectors to function properly. A few transportation infrastructure design engineers in the United States, though reluctant to employ FRP reinforcement because of a perception that design and construction standards or guidelines are not available and because of the challenges to reinforced concrete design philosophy FRP reinforced concrete presents, have nonetheless been required to solve both simple and complex structural concrete problems using FRP materials. In so doing, many of these individuals have found, as a result, that they have increased their knowledge and understanding of structural design and behavior.

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SPECIAL SPECIFICATION

4421

Repair of Impact Damaged Prestressed Concrete Bridge Beams

1. **Description.** This Item shall govern for the repair of impact damaged prestressed concrete beams as specified herein and/or as directed by the Engineer.
2. **Materials.** All materials that become part of the final product will be furnished by the Contractor. All tools, equipment, labor, scaffolding, incidentals and safety equipment shall be furnished by the Contractor.

Materials to be used in the repair of the structural concrete members shall be submitted to the Engineer for approval. For proprietary materials, this submission shall include all manufacturer's recommendations and material application instructions. The Contractor's work shall be done in accordance with these instructions and recommendations unless otherwise authorized by the Engineer. Concrete for repair shall contain Grade 1 fine aggregate, Grade 7 coarse aggregate and a minimum of seven (7) sacks of cement per cubic yard. All concrete repair material, or proprietary repair material submitted for approval, shall have a minimum 28-day Compressive Strength of 5000 psi or as shown on the plans.

All materials shall conform to the pertinent requirements of the following Items:

- Item 420, "Concrete Structures"
- Item 421, "Portland Cement Concrete"
- Item 431, "Pneumatically Placed Concrete"
- Item 440, "Reinforcing Steel"
- Special Specification "Epoxy and Adhesives"

If requested by the Engineer, the Contractor shall be required to prepare trial mixes of patch and/or crack injection material to ensure their ability to perform the work as required.

3. **Scope of Work.** The damaged prestressed concrete beams shall be returned to their original geometric section. The beams to be repaired may require one or more of the basic repair methods listed below and will be so categorized elsewhere on the plans as follows:

Category I: Significant spalling, section loss and cracking

Category II: Surface spalling only

Category III: Crack injection only

(1) General.

- (a) If directed by the Engineer, the Contractor shall furnish and place, on the bridge deck, a vehicle such as a loaded 12 yard dump truck or other

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loaded vehicle as approved by the Engineer, to load the bridge span until the completion of the curing.

- (b) Upon completion of curing, any repaired areas found defective shall be removed and repaired at the expense of the Contractor.
- (c) The Contractor shall repair any damaged diaphragms, only if shown on the plans. This work will not be measured or paid for directly, but shall be considered subsidiary to this Item.
- (d) The Contractor shall replace any damaged Bridge Protective Assembly, only if shown on the plans. This work will not be measured or paid for directly, but shall be considered subsidiary to this Item.

(2) Repair of Spalls or Areas of Section Loss.

- (a) Remove all loose or delaminated concrete in the damaged beam. All spalled and/or fractured concrete shall be removed to sound material. Feather edges shall be eliminated by saw-cutting and/or chipping a perpendicular or undercut face, as approved by the Engineer, around the periphery of the area to be repaired. The minimum depth of repair shall be 1/2 inch.
- (b) In areas where the depth of repair is greater than two (2) inches, the Contractor shall drill and epoxy anchors into the beam. Anchors may be 3/8-inch diameter bolts, No. 3 U-shaped rebar or other devices as approved by the Engineer. Anchors shall be inserted a minimum of three (3) inches into the exposed surface and provide a minimum of one (1) inch clear cover in the patch region. One (1) anchor device shall be installed for each one (1) square foot of patch area. Anchors shall be placed so as to miss the existing strands and reinforcing steel in the beam. Supplemental reinforcing may be required for the patch as directed by the Engineer. Such reinforcing may be reinforcing bars, welded wire fabric or other approved material. Welded wire fabric shall be held securely approximately 3/4 inch out from the surface to be covered. Steel drive pins, driven to a penetration of one (1) inch or 1/4 inch hook bolts, installed per the manufacturer's recommendations, shall be used to attach the wire fabric. The wire fabric shall be fastened securely to each pin or bolt.
- (c) Any cracks which extend further into the beam once the loose material, described in Section (a) above, has been removed shall have 3/8 inch diameter polyethylene tubes placed perpendicular to the surface at six (6) inch spacing for the entire length of the crack. The purpose of these tubes is to allow for epoxy injection into the beam interior once the exterior patch has been placed.

The tubing segments shall be drilled, inserted and epoxied a minimum of 1/2 inch into the surface of the spalled area and routed to the side or bottom of the beam as directed by the Engineer. Each section of tubing

shall extend at least six (6) inches beyond the exterior of the repaired beam.

- (d) The surface of the area to be patched shall be cleaned by sandblasting or other means as approved by the Engineer to remove all loose particles, dirt, deteriorated concrete or other substance that would impair the bond of the patch material. Exposed reinforcing steel and prestressing stands shall be cleaned of old concrete and corrosion. Final cleaning of the concrete surface and reinforcing steel shall be accomplished by high pressure air blast.

Air lines shall be equipped with a filter designed to remove all oil from the air.

Surfaces to be patched with concrete or mortar shall be saturated surface dry (SSD). Surface preparation and/or bonding agents for proprietary patch materials shall be in accordance with the manufacturer's recommendations.

- (e) Concrete, as defined previously, shall be used for repair areas with depths of one (1) inch or greater. Mortar, conforming to the requirements of Item 421, "Portland Cement Concrete", shall be used for repair of areas less than one (1) inch in depth. Epoxy mortar or proprietary patch materials may be used in lieu of concrete or mortar for repair, if approved by the Engineer.

Replacement of concrete may be accomplished in accordance with Item 431, "Pneumatically Placed Concrete", or other approved alternate methods. A satisfactory demonstration of the adequacy of any alternate method may be required by the Engineer. If so required, the Contractor is responsible for performing said demonstration.

For small areas, the Contractor may mix the concrete or mortar in a small motor-driven mixer using the volume method of measuring the ingredients. The methods used to measure ingredients and the mixing procedure shall be approved by the Engineer. The method used to mix proprietary materials shall follow the manufacturer's recommendations.

Placement of concrete or mortar will not be permitted when the atmospheric temperature (taken in the shade away from artificial heat) is below 50 F. The minimum temperature of the concrete or mortar at the time of placement shall be 60 F. For proprietary materials, the manufacturer's recommendations shall be followed with regard to temperature at time of application and placement methods.

- (f) Concrete or mortar repairs shall be water-cured in accordance with Item 420, "Concrete Structures", for a period of four (4) days. Pneumatically placed concrete repairs shall be cured in accordance with Item 431, "Pneumatically Placed Concrete". Epoxy mortar and proprietary material repairs shall be cured in accordance with the manufacturer's

recommendations. Care shall be taken to prevent freezing of the repair material during the curing period.

(3) Epoxy Injection of Cracks.

- (a) Epoxy injection of cracks shall be done after all concrete patching operations have been completed. The epoxy used for sealing the surface of cracks prior to injection shall be an epoxy adhesive capable of bonding to wet or dry surfaces and shall be gray in color. It shall have adequate strength and adhesion to confine the injection material in the cracks being injected until the injection material has cured.

The epoxy used for injection shall be a two-component epoxy conforming to Department Materials Specification D-9-6100, Type IX or other material as approved by the Engineer. The viscosity of the epoxy shall be adjusted as necessary to obtain penetration and retention into the cracks. Where there is considerable variation in crack widths, it may be necessary to use more than one (1) epoxy formulation. The epoxy shall contain no solvents and no solvents shall be added at any time. The mixing ratio of the components in terms of volume and weight shall be clearly stated. Proprietary crack injection systems may be used subject to approval by the Engineer.

- (b) The cracks to be injected will be as designated by the Engineer and an approximate length of repair may be shown on the plans for informational purposes only. Unless otherwise approved by the Engineer, injection will not be permitted unless the concrete temperature is above 50 F and the air temperature is above 50 F and rising.

The top surface of cracks to be injected shall be cleaned free of dust, dirt, oil, grease or other material that would interfere with the bond of the surface sealer. The interior of the cracks should also be cleaned as much as possible with compressed air prior to sealing. Entry ports for epoxy injection shall be provided, spaced far enough apart to assure that when the epoxy shows at the adjacent port, it has completely filled the crack to its full depth. Entry ports may be either surface mounted or drilled into the cracks. Ports shall be placed along cracks a maximum of 12 inches on center and usually determined by the tightness of the crack and the depth of penetration. Spacing is generally between four (4) inches and 10 inches. When drilling cracks for port installation, care should be used to avoid over drilling the crack. There should be no evidence of any dust or debris remaining in the drilled holes, which would be detrimental to the injection process. The injection ports shall be epoxied in place with the surface seal epoxy being careful not to seal the ports from resin flow.

- (c) The epoxy shall be injected with automatic two-component proportioning and mixing equipment. The two (2) components shall be mixed by the machine just prior to injection. The machine must be capable of proportioning the materials to within plus or minus five (5) percent of the

ratio stated by the epoxy supplier. The mixing head must be designed so that an intimate mix of the two (2) components will be obtained. Dwell time in the mixing head shall not exceed 10 seconds.

Injection of the epoxy into a given crack shall, unless permitted by the Engineer, begin first at the lowest entry port and progress upward as the epoxy begins to flow out of the adjacent ports. Injection pressure shall be kept as low as possible and shall not exceed 30 psi. After injection at a given port has been completed, this port shall be sealed and injection started at the next adjacent port. Where exceptionally wide cracks are encountered (greater than 1/4 inch), the injection epoxy may be modified by the addition of an approved filler provided it can be demonstrated that the modified epoxy will readily penetrate the full depth of the crack without void inclusions and will flow from the entry port adjacent to that in which the modified epoxy is injected.

Before beginning injection, and at selected intervals during the injection work, a small sample of the mixed epoxy will be taken from the injection gun. Should these samples show any evidence of improper proportioning or mixing, injection work shall be suspended until the equipment or procedures are corrected.

The surface of the crack herein treated shall be finished flush with the adjacent concrete surfaces and show no indentations or evidence of port fittings.

4. **Quality of Work.** The overall quality of the work will be judged by the Contractor's ability to achieve a repair with no voids remaining in the beam and full epoxy penetration into all cracks.

In case of question as to the quality of the work, the Engineer may have core samples taken from the completed work and access the completeness of the patch and/or crack injection. The cores will be taken at locations determined by the Engineer. The expense of taking and testing core samples will be borne by the Department.

In general, core samples indicating 90 percent or more epoxy penetration into the crack will signify acceptable work. Work not considered acceptable will not be paid for unless satisfactorily corrected by the Contractor. In evaluating core samples for compliance, the Engineer will take into account the presence of foreign matter that was not amendable to removal by usual crack cleaning processes required herein.

5. **Measurement.** This Item will be measured by the each individual beam to be repaired, of the category specified. The approximate linear feet of epoxy injection to be used may be shown on the plans for the Contractor's information only.
6. **Payment.** The work performed and the materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit bid price for "Prestressed Concrete Beam Repair", of the category specified. This price shall be full compensation for repairing damaged prestressed concrete beams including furnishing and placing all materials, removing all loose or defective

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concrete, saw-cutting as required, cleaning reinforcing steel and/or strands, epoxy crack injection, for furnishing and placing new reinforcing steel, anchor devices, drive pins, studs or expansion bolts, and for all labor, equipment, tools and incidentals necessary to complete the work.

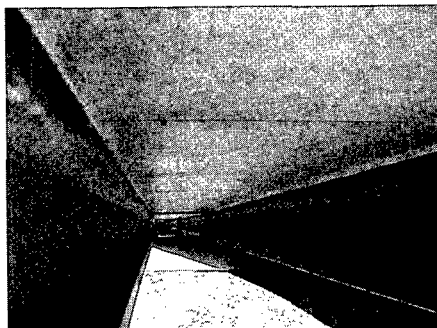


Figure 1: Typical Texas construction practice—no permanent diaphragms provided.

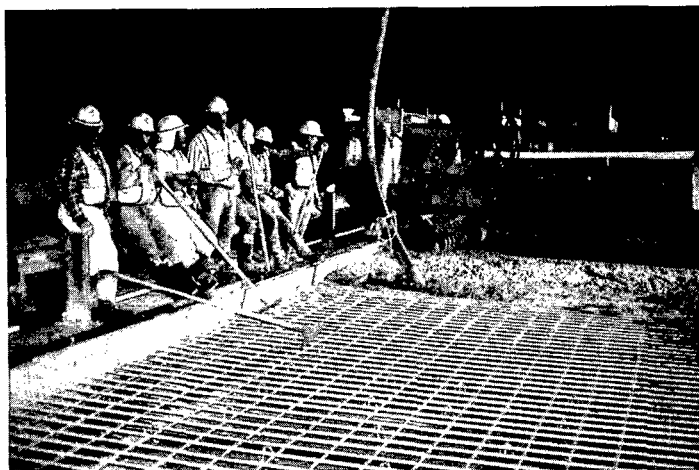


Figure 2: Concrete placement in the GFRP reinforced concrete deck of the Sierrita de la Cruz Creek Bridge.

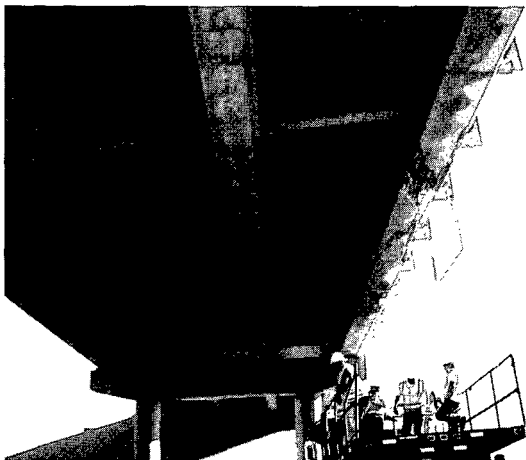


Figure 3: Exterior Girder Bottom Flange after Impact with Overheight Vehicle/Payload.



Figure 4: Interior Face of External Girder after Impact with Overheight Vehicle/Payload.

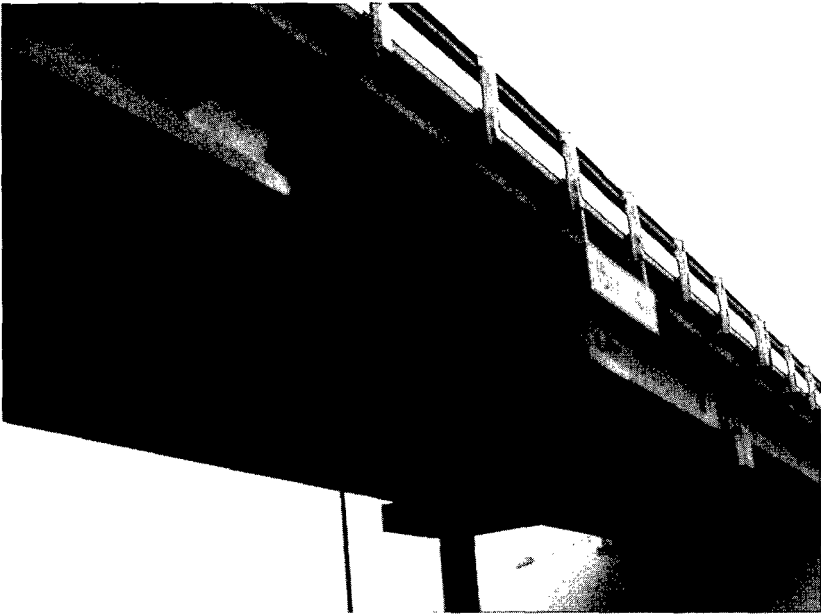


Figure 5: Damaged External Girder after Completed Repair Work.

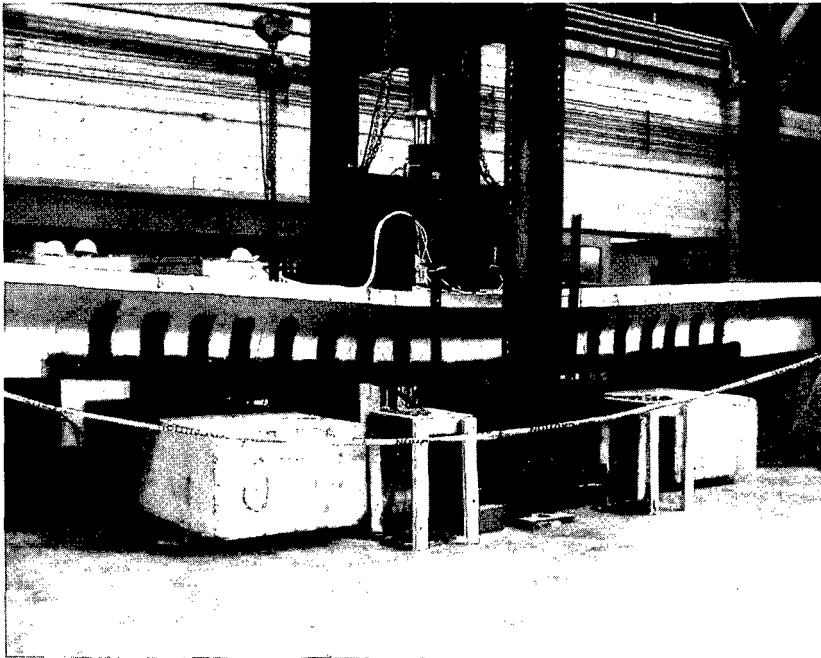


Figure 6: Externally Strengthened CFRP Laminate Pan Girder Specimen During Laboratory Load Testing.

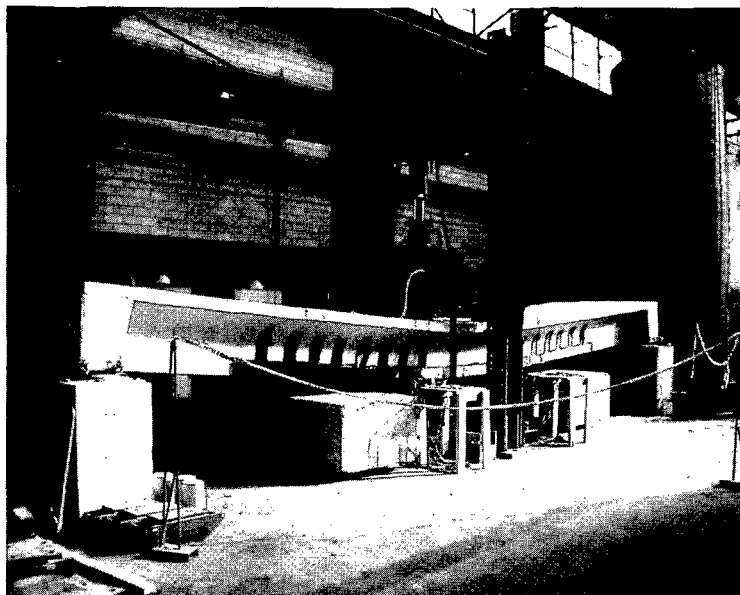


Figure 7: Externally Bonded CFRP Laminate Strengthened Pan Girder Specimen After Partial Debonding of CFRP Laminate.



Figure 8: Externally Bonded CFRP Laminate Strengthened Pan Girder Specimen Immediately After Full Debonding of the CFRP Laminate System.



Figure 9: Pan Girder Span Strengthened with Externally Bonded Longitudinal CFRP Fabric Anchored by Transverse Straps of CFRP Fabric.



Figure 10: Pan Girder Span Strengthened with Externally Bonded Longitudinal CFRP Extruded Laminate Anchored by Transverse Straps of CFRP Fabric.

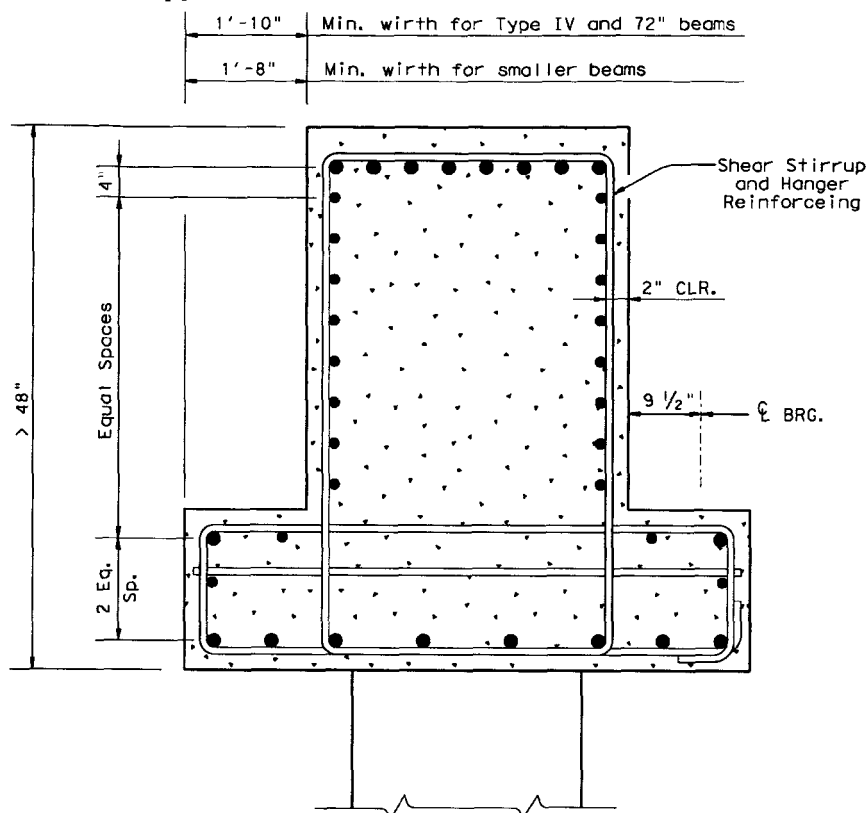


Figure 11: Section Through Inverted Tee Showing Basic Dimensions And Reinforcement Pattern and Identifying Shear Stirrup and Hanger Reinforcing.

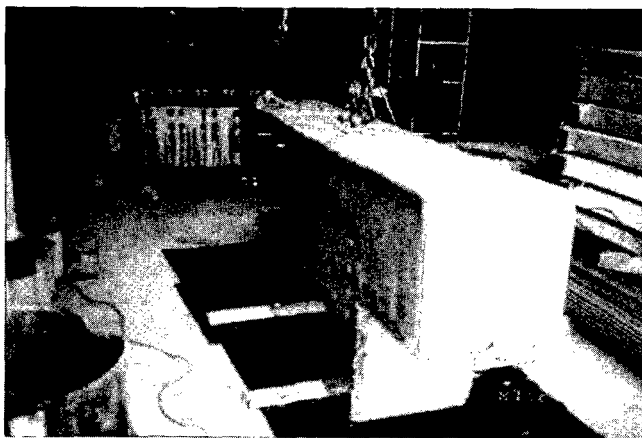


Figure 12: Inverted Cracked Inverted Tee Test Specimen Prior to Application of the Externally Bonded CFRP Repair System Being Tested.

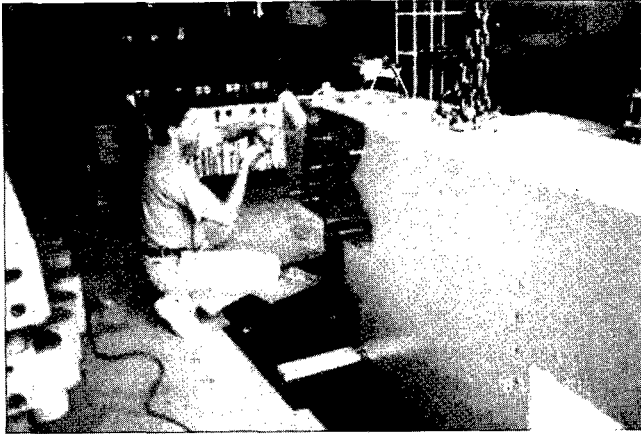


Figure 13: Application of Externally Bonded CFRP Repair System to the Inverted Cracked Inverted Tee Test Specimen.



Figure 14: CFRP Fabric Strengthened Inverted Tee Test Specimen Loaded to Failure.

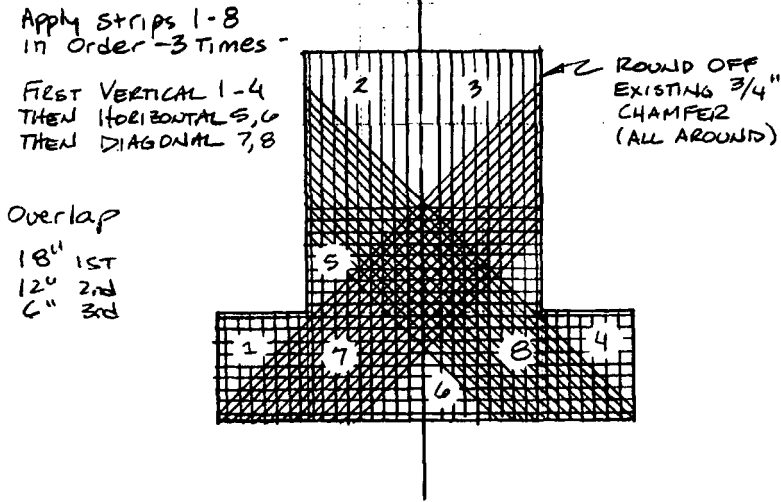


Figure 15: Design Sketch Showing the Order the Application of the CFRP Fabric Strips to the End of the Inverted Tee Bent Cap.

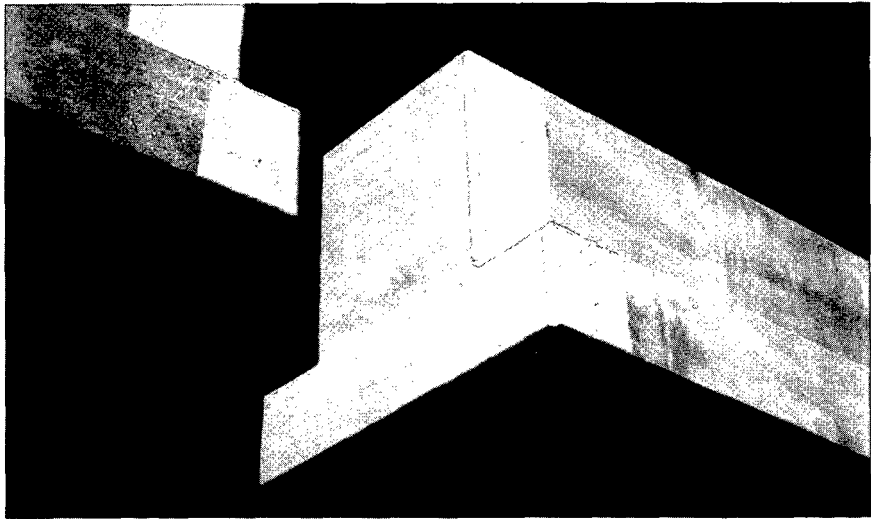


Figure 16: CFRP Fabric Strengthened Adjacent Inverted Tee Bent Caps

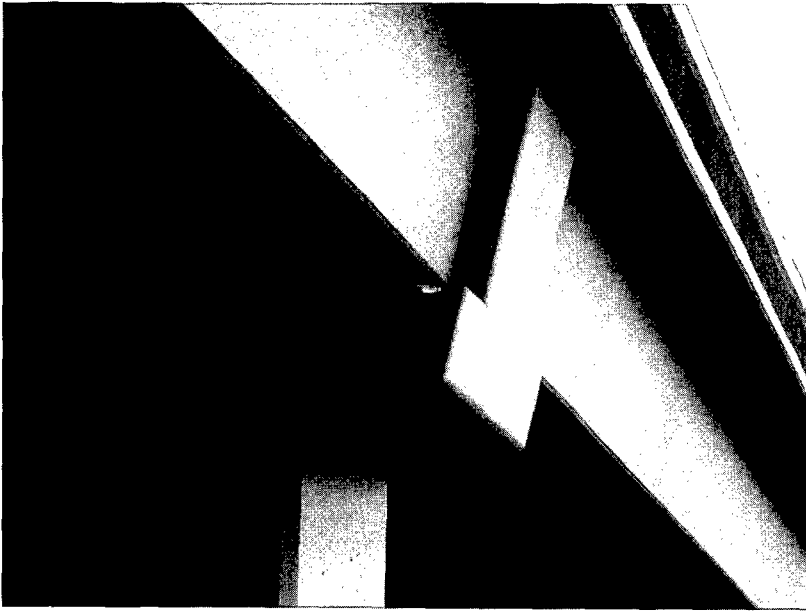


Figure 17: Girders Flush Framed With An Inverted Tee Bent Cap

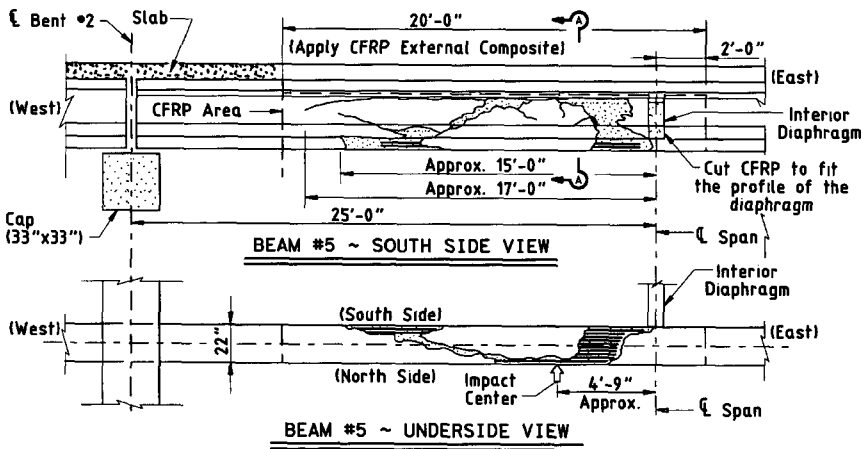


Figure 18: Prestressed Concrete Beam Repair Details IH 10 Overpass at SH 304 Showing Approximation of Extent of Damage to Exterior Beam

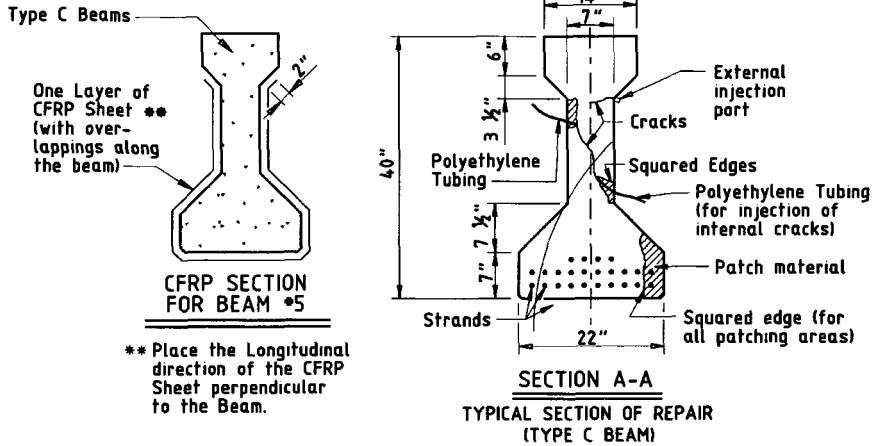


Figure 19: Prestressed Concrete Beam Repair Details IH 10 Overpass at SH 304 Showing Approximation of Extent of Damage to Exterior Beam Cross Section along With Repair Instructions, Including CFRP Wrap

Design and Testing of a Highway Concrete Bridge Deck Reinforced with Glass and Carbon FRP Bars

by E. El-Salakawy and B. Benmokrane

Synopsis: A new highway bridge was constructed using FRP bars as reinforcement for the concrete deck slab. The bridge, located on highway 55 North over the Magog River (Quebec, Canada), is a girder type with a total length of 83.7 m and five main steel girders continuously supported over three spans. The two end spans are 26.2 m each and the middle one is 31.3 m. The deck is a 220-mm thickness concrete slab continuous over four spans of 2.845 m each with an overhang of 1.352 m on each side. One full end span (26.2 m) was totally reinforced with FRP bars in top and bottom mats. The other two spans of the bridge were reinforced with galvanized steel. The steel reinforced concrete deck slab was designed according to Section 8 of the New Canadian Highway Bridge Design Code, CHBDC (CAN/CSA-S6-00 2000). The steel reinforcement was then replaced with FRP bars according to Section 16 of CHBDC (CAN/CSA-S6-00 2000). This design resulted in using glass FRP bars (No.16 - 15.9 mm-diameter) in all directions except in the transverse direction on the bottom mat where carbon FRP bars (No.10 - 9.5 mm-diameter) were used. The construction of the bridge was completed on September 2002 and opened for traffic during the second week of October 2002. Before opening to the traffic, the bridge was tested for service performance using standard truckloads as specified in the new CHBDC (CAN/CSA-S6-00 2000). During all load tests, strains in FRP and steel reinforcements and deflections of FRP and steel reinforced spans (slabs and girders) were recorded. Design, construction details, and the results of this first series of field tests are discussed in this paper.

Keywords: bridges; concrete deck slabs; controlled load test; fiber reinforced polymer (FRP); field application

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INTRODUCTION

Bridge deck deterioration is one of the most common deficiencies in a bridge system. Concrete bridge decks deteriorate faster than any other bridge component because of direct exposure to the environment, de-icing chemicals, and ever-increasing traffic loads. The magnitude of deck cracking and delamination due to corrosion is a major problem when measured in terms of rehabilitation costs and traffic disruption. To overcome corrosion-related problems, the steel reinforcement should be protected from corrosion, or be replaced with alternative non-corroding materials. One of these alternatives is fiber reinforced polymer (FRP) composite reinforcement, which has been used successfully in many industrial applications and more recently has been introduced as concrete reinforcement in bridge decks and other structural elements. The use of the non-corrosive FRP composite bars as reinforcement for concrete bridge decks provides a potential for increased service life, cost-effectiveness, and environmental benefits (Rizkalla et al. 1994 and 1998; Saadatmanesh and Ehsani 1996; GangaRao et al. 1997; Japan Concrete Institute 1997; Benmokrane and Rahman 1998; Hassan et al. 1999; Humar and Razaqpur 2000; Khanna et al. 2000; Benmokrane et al. 2001, Steffen et al. 2001; Benmokrane and El-Salakawy 2002). The new Canadian Highway Bridge Design Code (CAN/CSA-S6-00 2000) includes a new section (Section 16) for using FRP composite bars as non-prestressed and prestressed reinforcements for concrete bridges (slabs, girders, and barrier walls). Furthermore, several codes and design guidelines for concrete structures reinforced with FRP bars have been recently published (ACI 440.1R-01 2001; CAN/CSA-S806-02 2002; ISIS-M03-01 2001).

Through the NSERC research chair in FRP reinforcements for concrete structures, which started in 2000 at the Department of Civil Engineering, Université de Sherbrooke (Quebec, Canada), a collaboration with the Ministry of Transportation of Quebec (MTQ) was established to develop and implement FRP reinforcement in concrete bridges. After

the development/improvement of new carbon/glass composite bars and the satisfactory results obtained in the laboratory on concrete deck slab prototypes reinforced with these bars (Benmokrane et al. 2002; El-Salakawy et al. 2003), field applications became a requirement to move forward with this technology. The first and successful field application of these new bars was Wotton Bridge (Benmokrane and El-Salakawy 2002; El-Salakawy et al. 2002). Wotton Bridge is located in the Municipality of Wotton on the 6th Road west, Western Bank, over the Nicolet-Center River in Québec. The bridge is a girder type with four main girders (Standard Type IV AASHTO pre-stressed concrete beams) simply supported over a single span of 30.60 m. The deck is a 200-mm thickness concrete slab continuous over three spans of 2.65 m each with an overhang of 1.15 m. The top reinforcement layer of the deck slab for half the bridge was made of glass FRP composite bars. Within the same half of the bridge, a 5-m width portion of the bottom layer of the deck slab was reinforced with carbon FRP composite bars. While the other half of the bridge was reinforced with conventional steel. More details about this bridge including the FRP reinforcement configuration and field test results can be found elsewhere (Benmokrane and El-Salakawy 2002; El-Salakawy et al. 2002).

Magog Bridge, presented in this paper, is the second application, which is different from Wotton Bridge. Magog Bridge is larger in size, has different structural system, is exposed to heavier traffic and harsher environment (located on a highway). Upon the successful construction of this highway bridge during summer 2002, a field test was conducted to evaluate the service performance under wheel truckloads before the opening of the bridge to traffic. This paper presents the design, construction details, and field test results of Magog Bridge.

RESEARCH SIGNIFICANCE

The paper presents a new and innovative field application of FRP bars as reinforcement for the concrete deck slab of highway bridges. The new Canadian Highway Bridge Design Code, which includes a new section on using FRP composite bars, has been used to design the concrete deck slab. This field application contributes to the validation/improvement of the existing design codes and guidelines, establishes construction details, and evaluates the performance of FRP reinforcement under real service loading and environmental conditions.

MAGOG BRIDGE ON HIGHWAY 55 NORTH

The bridge presented in this paper is located over Magog River on Highway 55 North (Québec, Canada) in the vicinity of Magog City near the US/Canadian border. The bridge is a girder type with a total length of 83.7 m and five main steel girders continuously supported over three spans (Figure 1a). The two end spans are 26.2 m each and the middle one is 31.3 m. The deck is a 220-mm thickness concrete slab continuous over four spans of 2.845 m each with an overhang of 1.352 m on each side (Figure 1b). Clear concrete covers of 35 and 60 mm at bottom and top, respectively were used. The

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concrete bridge deck slab was replaced, while the other main supporting elements (steel main girders, abutments, and the two middle piers) were in good condition and were kept without changes. The concrete deck slab of south end span (the first span of the bridge according to the direction of traffic – 26.2 m) was reinforced with FRP composite bars. The other two spans of the bridge were reinforced with galvanized steel bars.

Material Properties

The bridge deck slab was constructed using normal-weight ready-mixed concrete (Type V MTQ). The concrete compressive strength was 52 MPa, which was obtained based on the average values from the tests performed on three 150 × 300-mm cylinders. The tensile strength of the concrete was 3.5 MPa as determined by performing the split cylinder tests. Two hundred and sixty cubic meter of concrete were cast into the bridge deck slab through a 12-hour period (started at 7:00 p.m. and finished 7:00 a.m. the following day). The properties of the newly developed sand-coated carbon and glass FRP bars used in reinforcing the deck slab are listed in Table 1.

Design of the Concrete Bridge Deck Slab

The design of the bridge deck slab reinforced with FRP composite bars was originally made with steel bars using the flexural design method according to the new Canadian Highway Bridge Design Code (Clause 8.18 – CAN/CSA-S6-00). The steel reinforcement was then replaced by FRP reinforcement according to Clause 16.8.7 (CAN/CSA-S6-00). According to this Clause of the Code, the steel replacement is based on equivalent stiffness for bottom reinforcement layer (ρ_{sB}) and based on equivalent strength for top reinforcement (ρ_{sT}). The FRP reinforcement ratios, ρ_{fB} and ρ_{fT} , were determined using equations 1 and 2.

$$\rho_{fB} = \frac{\phi_s E_s}{\phi_f E_f} \rho_{sB} \quad \text{for bottom reinforcement} \quad (1)$$

$$\rho_{fT} = \frac{\phi_s f_y}{\phi_f f_f} \rho_{sT} \quad \text{for top reinforcement} \quad (2)$$

where f_y , E_s , and ϕ_s are the yield strength, the modulus of elasticity, and the resistance factor of steel reinforcement, f_f , E_f , and ϕ_f are the tensile strength, the modulus of elasticity, and the resistance factor of FRP reinforcement. The resistance factor ϕ is taken as 0.75, 0.85, and 0.9 for glass FRP, carbon FRP, and steel bars respectively (Clause 16.5.3 and 8.4.6 – CAN/CSA-S6-00). The design moments given in Table 2 were based on a wheel load of 87.0 kN with the associated load factor of 1.7 (Clause 3.5.1 – CAN/CSA-S6-00), a dynamic load allowance of 0.4 (Table 3.5.1a – CAN/CSA-S6-00) and a load combination factor of 0.9 (Clause 3.8.4.5.3 – CAN/CSA-S6-00). This design approach led to the use of glass FRP bars (No.16 - 15.9 mm) in all directions except in the bottom transverse direction where carbon FRP bars (No.10 - 9.5 mm) were