Advanced Composites for Rehabilitation/Improvement of Existing Bridges

John M. Hooks [1]

Abstract

Almost 30 percent of the 592,000 bridges, culverts and tunnels in the United States (US) are rated deficient. This includes bridges with main members that are deteriorated or damaged by impact as well as main members that are under strength. The deficiencies related to structural capacity or performance include deteriorated concrete bridge decks, corrosion damaged or cracked concrete bridge pier caps and columns, beams with deteriorated concrete and/or excessive cracking, beams damaged by vehicular impact and concrete or steel beams with reduced or substandard load carrying capacity. Certain types of these structural deficiencies are amenable to rehabilitation and/or strengthening using bonded repairs with fiber reinforced polymer (FRP) composite laminates or post-tensioning with FRP composite tendons. Highway agencies in the US have several years of experience in applying FRP materials for applications such as: rehabilitating and strengthening pier columns and pier caps; repairing cracked concrete box girders and increasing shear strength; increasing flexural strength of concrete tee-beams, concrete box girders and steel truss members; and strengthening bridge piers for seismic loads. Examples of successful bridge rehabilitation with FRP composites are described along with methods of evaluating performance and durability of the bonded repairs.

Background

The Federal Highway Administration (FHWA) maintains a National Bridge Inventory and in this database there are records on approximately 478,000 bridges plus 114,000 tunnels and culverts. The total deck area of these bridges 3.2 billion square feet (297.3 million square meters). The age of these bridges ranges from over 100 years to just opened to service. Figure 1 shows that the majority of structures in the US were built during the interstate construction “boom”. The mean ages of concrete and steel (superstructure material) bridges are virtually the same - 46 years old; prestressed bridges were not utilized until the 1950’s and the mean age of prestressed concrete bridges is 26 years old. The mean age of all bridges is 43 years.

Since other factors such as environment, traffic volumes, heavy vehicle loading conditions and maintenance history are also very important, the age of a bridge alone is not a definitive indication of current condition or capacity of the bridge. However, age is still a useful indicator when examining a bridge population for trends in bridge deficiencies.

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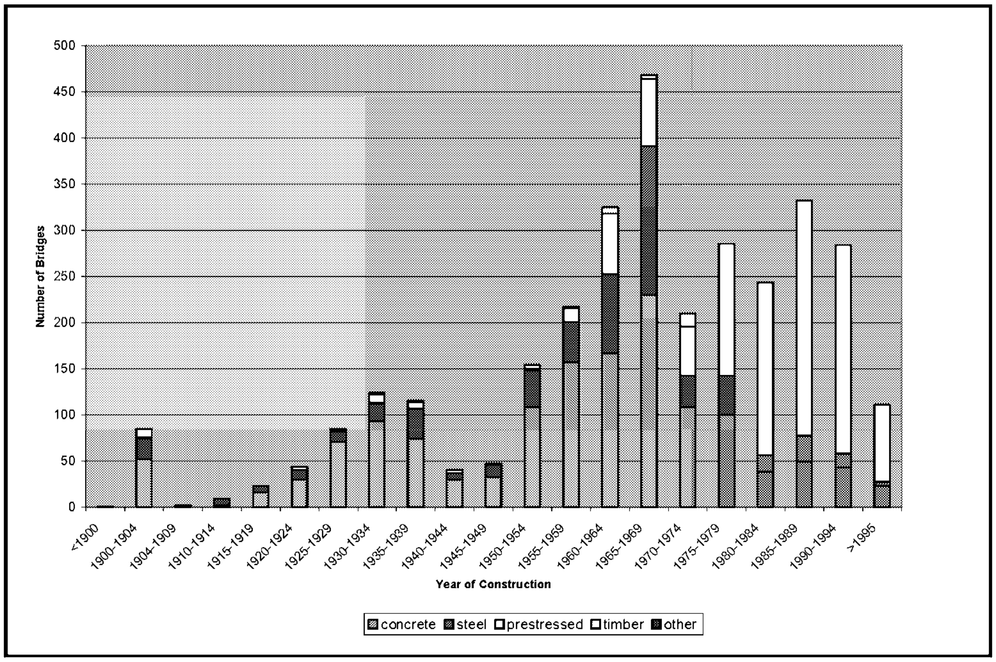


Figure 1 – Age Distribution of All Bridges in the United States - 2001

In the United States, the FHWA maintains data on deficient bridges based on the following definitions: a structurally deficient bridge is one that (1) has been restricted to light vehicles only, (2) is closed, or (3) requires immediate rehabilitation to remain open; a functionally obsolete bridge is one which the deck geometry, load carrying capacity (comparison of the original design load to the current State legal load), clearance, or approach roadway alignment no longer meets the usual criteria for the system of which it is an integral part. In addition to other causes, bridges are rated structurally deficient if the condition rating for the deck, superstructure and/or substructure condition ratings are less than or equalto 4 (this rating is from a rating a scale of 0 to 9 with 4 indicating poor condition – advanced section loss, deterioration, spalling or scour); or if the bridge receives a low Structural Appraisal Rating. The structural evaluation appraisal rating is assigned based on the inventory load capacity ratings and the average daily traffic. Structural Appraisal Ratings less than or equal to 2 (defined in the FHWA Recording and Coding Guide as a “basically intolerable condition requiring high priority of replacement”) indicate structural deficiency.

Based on recent data, almost 30 percent of the bridges in the United States are rated deficient. The number one cause of bridge deficiency is related to deck geometry – essentially a bridge with a roadway too narrow for the traffic volumes currently using the bridge. After deck geometry, there are several leading causes of bridge deficiencies including: deck condition rating, substructure condition rating, structural evaluation rating and superstructure condition rating. Figure 2 shows the numbers of bridges rated deficient on the basis of various poor condition ratings or appraisal ratings.

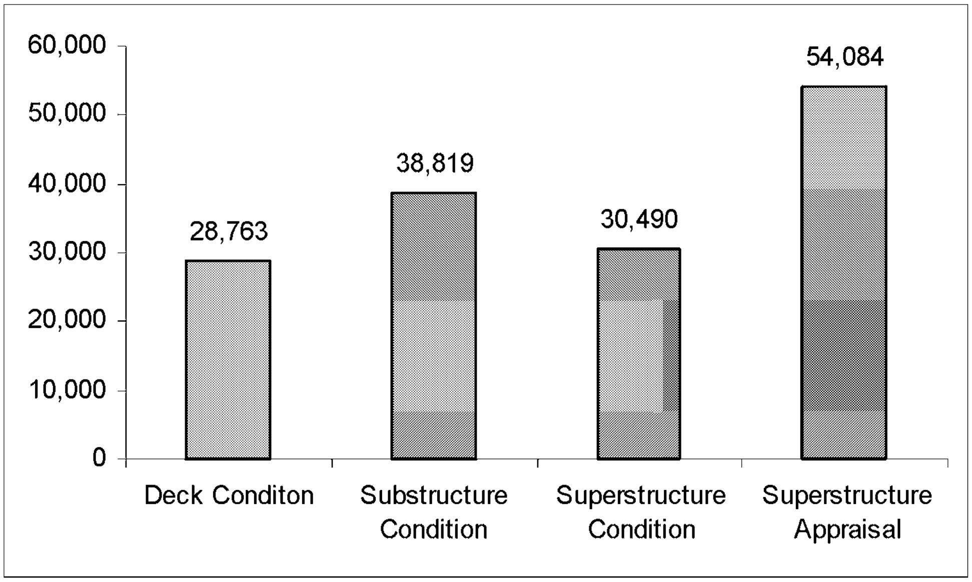


Figure 2 – Major Causes of Bridge Deficiencies

Specific situations that result in low ratings on bridges include the following scenarios:

- main load carrying members (girders) where structural steel is corroded and section loss is significant and members where concrete sections are deteriorated because of corrosion of internal reinforcing and/or prestressing - the load capacity of the bridge is reduced and the conventional solution would be establishing load restrictions or closing the bridge and replacing it or simply taking the bridge out of service;
- main load carrying members (girders) that have been struck by overheight vehicles and damaged to the point that restoration of the structural capacity is required;
- concrete pier capbeams that are deteriorated and/or exhibiting shear and/or flexural cracks - the load capacity of the bridge is reduced and again, the conventional solutions would be establishing load restrictions, closing the bridge, replacing the substructure or replacing the bridge;
- concrete pier columns that are deteriorated with significant loss of concrete through delaminations and spalling – column capacity is diminished and conventional solutions would include shotcrete repairs, steel jackets or replacement of the columns;

- structural decks where the concrete is badly deteriorated because of corrosion of the reinforcing steel and subsequent delamination and spalling of the concrete slab
- concrete or steel main members which were originally designed for a live load standard that is inadequate for legal live loads today - - the load capacity of the bridge is reduced and the conventional solutions would be establishing load restrictions, closing the bridge or replacing the bridge.

Deficient bridges have a direct negative impact on mobility and congestion and represent potential safety issues: narrow bridge roadways, lane closures, load limitations, speed & volume restrictions at work zones, bridges out of service, bridge failures and collapses (though rare) and accidents related to bridge geometries and deck riding qualities. The FHWA is committed to eliminating deficient bridges and reducing the "down time" necessary to complete maintenance, repair or rehabilitation projects. This is a major challenge because bridge and highway agencies continually operate under severe budgetary constraints and funds are not available to replace or even upgrade all deficient bridges in a timely manner. The FHWA is aggressively promoting a policy of system preservation, i.e., prolonging the life of bridges through preventive maintenance and upgrading to forestall the more costly actions of partial or full replacement of the bridge.

Meeting the Challenges - Fiber Reinforced Composite Polymers

One way to meet the challenge to reduce deficiencies and minimize the impact of rehabilitation work involves development and utilization of significantly improved bridge materials such as high performance steels and concretes. Beginning in recent years the bridge engineering community has been experimenting with a material that is relatively new to the civil infrastructure community: fiber reinforced polymer (FRP) composites. FRP materials have been used extensively in the aerospace industry but only recently are they being applied on highway bridges. Among other properties, FRP materials have a high strength to weight ratio and excellent resistance to attack from chemicals including road salts. In addition, easy prefabrication of FRP bridge elements and comparatively short installation times make FRP materials excellent candidates for bridge applications.

In June 1998, the United States Congress passed the Transportation Efficiency Act for the 21st Century (TEA-21). This landmark legislation authorized funds for a new major initiative intended to improve the condition, durability, and capacity of bridges. The Innovative Bridge Research & Construction (IBRC) Program was created to support the development and deployment of innovative materials and technologies to repair, rehabilitate or replace bridges. Over the life of the of the IBRC program, 288 projects utilizing innovative materials have been funded.

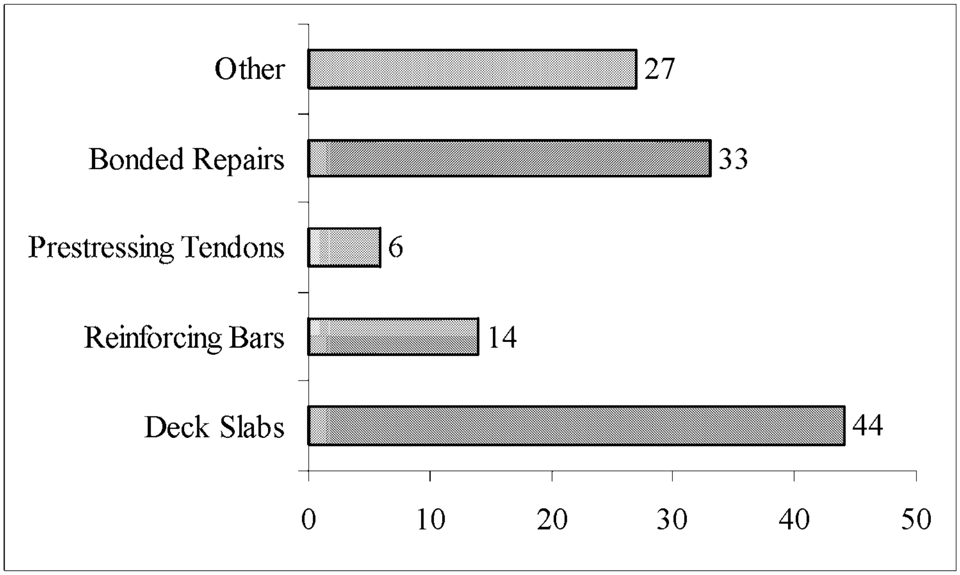


Figure 3. IBRC Projects, 1998 – 2003 Using FRP Composites in Highway Structures

One hundred and twenty-four of these projects involve the use of FRP composites applications including bridge decks, concrete reinforcement, prestressing tendons, column wrapping or bonded sheets to increase bridge strength. Figure 3 shows the distribution of types of IBRC projects using FRP composites for bridge repair rehabilitation or new construction.

Improving Bridges Using FRP Composites

The following examples summarize some early experiences from ongoing or completed IBRC projects where FRP composites were used to rehabilitate and/or strengthen a bridge. These project have recently been completed and further evaluation will be done to assess long term performance. All of the solutions are considered successful based on short term results.

Steel I-Girder Bridge Strengthened with Carbon FRP Rods (Wipf et al, 2003)

Iowa bridge number 3903.0S 141, designed and built in 1955, carries Iowa State Highway 141 over Willow Creek in Guthrie City, Iowa. As seen in Figure 4, this bridge is a three span continuous rolled shape steel girder-bridge, 210 feet (64.0 meters) in length and 26 feet (7.9 meters) wide. The bridge consists of two end spans of 64 feet (19.5 meters) and a center span of 82 feet (25.0 meters) with four beams spaced at 8 feet & 3 inches (2.5 meters) on center. The roadway width carries two traffic lanes and a narrow shoulder. The interior beams are wide flange (WF) 33 X 141 and the exterior beams are WF30 X 116. The bridge is currently rated with an HS 11.0 Inventory Rating and an HS 18.7 Operating Rating. This bridge is rated structurally deficient due to a low Structure Appraisal Rating but is otherwise in good condition. The bridge is currently considered borderline for load posting and is representative of the status of many similar bridges in other states.

4 (a) Side view

4 (b) Road way

Figure 4. State Highway 141 bridge over Willow Creek (Wipf et al, 2003)

This bridge is typical of many older, rural highway bridges that were designed for lower standards and now need to be load posted and restricted to loads less than the State's legal limit. Since the economic consequences of load restrictions and detours can be significant, especially in rural areas where detours are long, bridge owners are searching for economical methods to increase the load carrying capacity of the bridge without the expense of complete replacement of the superstructure or the entire bridge. The chosen solution was to install Carbon Fiber Reinforced Polymer (CFRP) post-tensioning rods in the positive moment regions of the exterior girders of each span as a method of strengthening the steel I-girders.

Anchorage assemblies (Figure 5) were bolted to the webs of the exterior girders at the ends of the positive moment regions above the bottom flanges of the I-girders. CFRP rods were chosen due to their outstanding mechanical characteristics and non-corrosive properties. The post-tensioning system consists of 3/8 inch (9.5 millimeter) diameter CFRP rods, steel tube anchors, 1 inch (25.4 millimeter) couplers and 1 inch (25.4 millimeter) x 30 inch (25.4 millimeter) all threads with nuts, and 1 inch (25.4 millimeter) diameter high-strength bolts and 5 x 5 x ¾ x 0 feet-7 inch (127 x 127 x 19.1 millimeter x 177.8 millimeter angles with ½ inch (12.7 millimeter) thick stiffeners for the anchorage assemblies. Each post-tensioning bracket connects four CFRP rods to the web of the beam with 1 inch (25.4 millimeter) diameter bolts. A total of 12 kips (53.4 kilo-newtons) was applied to all rods (four rods per location).

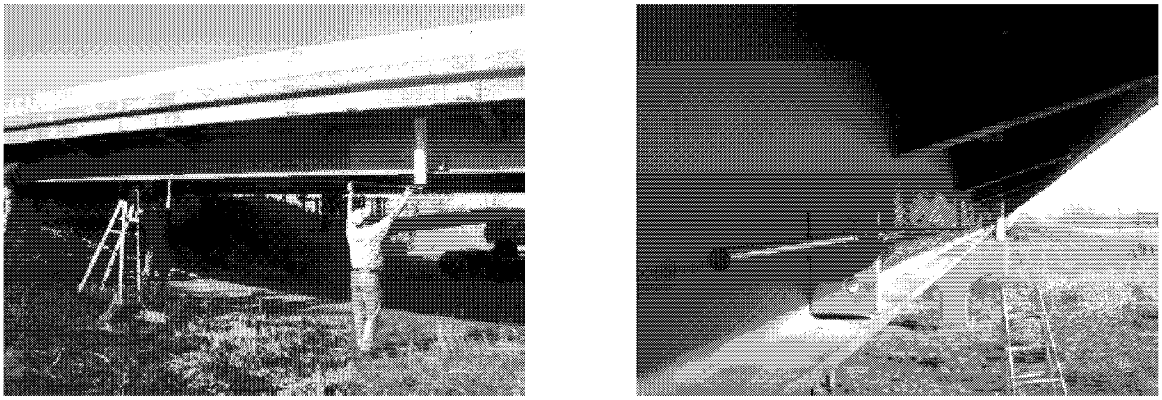
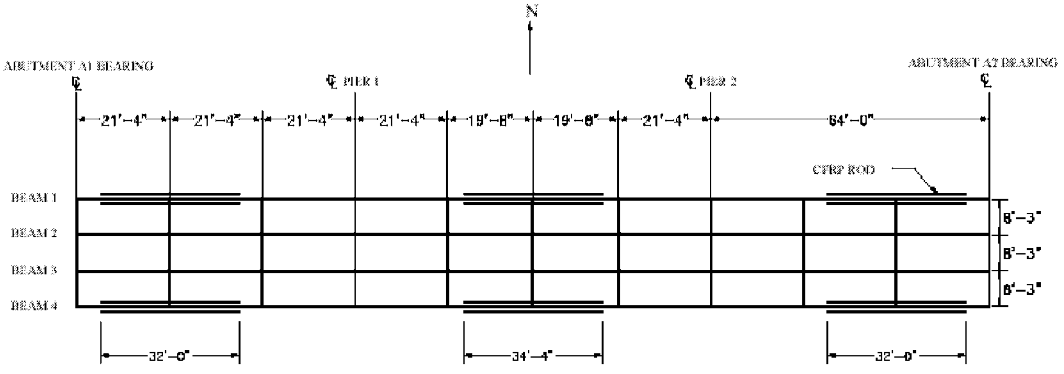
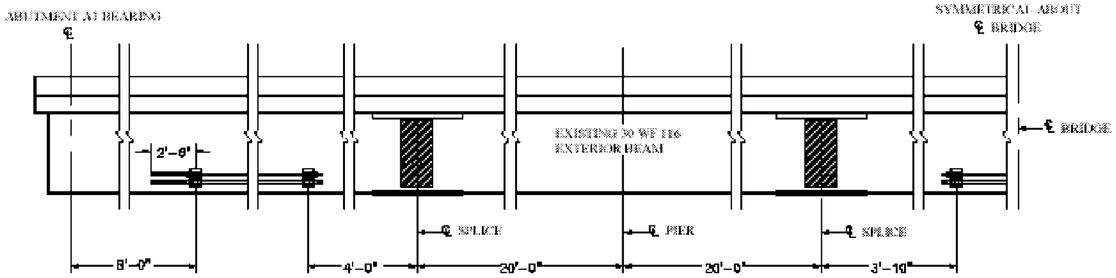


Figure 5. Placement of the CFRP rod (Wipf et al, 2003)



6 (a) Plan View



6 (b) Side View

Figure 6 – Location of Post-tensioning System (Wipf et al, 2003)

A diagnostic load test was conducted prior to installation of the post-tensioning system to establish a baseline behavior of the unstrengthened structure. Strain gages were placed on the guardrails, on the CFRP rods, and the bottom surface of the top flange and the bottom surface of the bottom flange of the beams. Due to the symmetry of the bridge structure, only a half of the bridge was instrumented. During the installation of post-tensioning rod hardware and stressing of the system, both the bridge and post-tensioning system were monitored. A second and a third diagnostic load test were conducted immediately after installation of the post-tensioning system and one year of service to assess the effectiveness of the retrofit system.

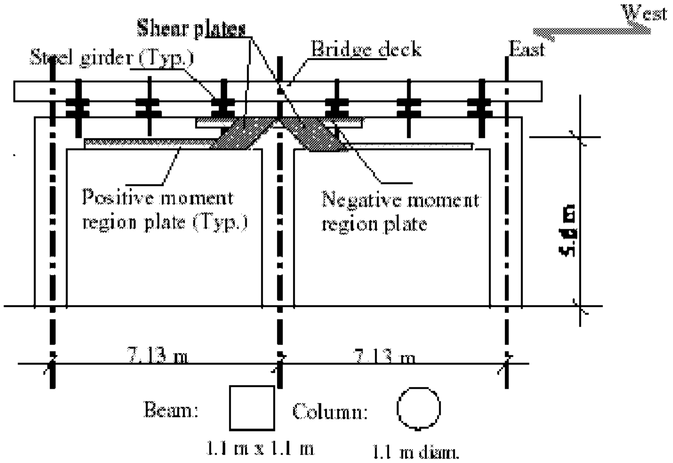
Strengthening of a Pier Capbeam Using Bonded FRP Composite Plates (Hag-Elsafi et al, 2002)

The East Church Street bridge in Elmira, New York was built in 1954 and carries traffic on State Route 352 over State Route 17, the Southern Tier Expressway and future Interstate 86. The bridge is a four-span, multi-stringer steel structure, with a total length of about 220 feet (67 meters). It has two 12-foot (3.66-meter) wide lanes, and two 3.5-feet (1.07-meter) wide and 9-inch (230-millimeter) high curbs. The average daily traffic counts on Routes 352 and 17 are about 9,000 and 20,000 vehicles, respectively. An inspection in 1997 revealed excessive cracks at the capbeams of Piers 2 and 3 of the bridge. The two piers and photos of the cracks at Pier 3 capbeam are shown in Figure 7. Each of the capbeams has a 3.6-foot (1.1-meter) x 3.6-foot (1.1-meter) square cross-section, and is supported by three 3.6-foot (1.1- meter) diameter circular piers. An increase in dead load, as a result of recent additions of deck overlays and a median concrete barrier, was a suspected cause of the cracking. The structure, which was originally built with an 11.5-inch (292-milimeter) thick concrete deck and no barrier, now has a 12.5-inch (318 millimeter) thick deck and a median concrete barrier weighing about 820 pounds per linear foot (12 kiloNewtons per linear meter). A preliminary analysis indicated possible capbeams' deficiencies in both moment and shear capacities under current service loads.

If left unrepaired, the bridge would be considered for load posting or for replacement because of the inability to safely carry current legal loads. The former option is a significant restriction for a bridge carrying heavy traffic in an urban area. Funds were not available for the latter option, replacement, which is a drastic option for an otherwise sound bridge. An alternative solution that was less costly, faster and less disruptive to traffic was chosen. This project will evaluate and demonstrate the feasibility and cost-effectiveness of using bonded FRP repair materials to strengthen cracked capbeams .

Figure 7. Flexure and shear plates for FRP repairs (Hag-Elsafi, 2002)

The targets for improvement were an increase of 10 percent in the capbeam's shear capacity and an increase of 20 percent in the capbeam's moment capacity. Flexural and shear plates, made of carbon/glass hybrid and glass materials, respectively, were used for strengthening of the Pier 3 capbeam (Figures 7a and 7b). The flexural plates are 0.5 inches (13 millimeters) thick, 10 inches (254 millimeters) wide, and 17 feet (5.18 meters) long. The shear plates are .27 inches (7millimeters) thick, 3.6 feet (1.1 meters) wide, and 5.6 feet (1.7 meters) long, shaped as seen in Figure 7. The FRP plates were bonded to the capbeam surfaces (Figure 8) by an epoxy resin. Surface preparation was a simple power washing to remove loose debris and concrete. Two different methods were used to ensure adequate contact while the resin was curing. On one side, anchor bolts applied clamping force and on the other side, a wooden clamping frame was used to apply a more uniform clamping force.



Notes: 1. All plates applied on both beam sides. 2. Moment plates are 254 mm x 13 mm. 3. Shear plates are 6-mm thick.

Figure 8. FRP Strengthening system (Hag-Elsafi et al, 2002)

To determine if design assumptions were correct and to see if the bonded plates did reduce the live load stresses in the reinforced concrete capbeam, 2 sets of load tests were run before and after the application of the FRP plates. The results of the load test showed a reduction of about 10 percent in shear stresses and about 6 percent in flexural stresses. The neutral axis of the repaired capbeam did shift downward slightly when compared to the unrepaired capbeam.

This project demonstrated that FRP composite plates could be used in a cost-effective bridge retrofit technique. Compared to conventional repair methods, the retrofit system used in this project proved to be a cost-effective solution ($18,000 for the FRP solution vs. $150,000 for the conventional repair). The system was relatively easy to install and caused minimal interruption to traffic. These are important features which make it attractive to bridge owners, specially for similar applications in highly populated metropolitan areas.

Strengthening of a Concrete T-beam Bridge (Hag-Elsafi et al, 2002)

The bridge carries State Route 378 over the Wyantskill Creek in the City of South Troy, Rensselaer County, New York. This simple span, reinforced concrete, T-beam structure was built with an integral deck in 1932. The bridge is 40 feet (12.19 meters) long, about 120 feet (36.58 meters) wide, and is supported by a total of 26 beams spaced at 4.5 feet (1.37 meters) center to center. A cross-section of a typical beam is shown in Figure 9. The bridge has been open to traffic without weight-limit restrictions and has an average daily-traffic volume of approximately 30,000 vehicles. It has 5 traffic lanes, and is a vital route linking the City of South Troy with areas west of the Hudson River. During routine inspection, excessive moisture and salt infiltration was observed in the bridge superstructure. Many of the beams had large areas covered with efflorescence, freeze-thaw cracking, and a few beams showed signs of concrete delamination. Concerns about section loss of the reinforcing steel to corrosion and overall safety of the structure was heightened by the absence of any documentation containing complete information needed for reliable evaluation or load rating of the bridge structure. The New York State Department of Transportation (NYSDOT) elected to rehabilitate the structure as opposed to replacing it or posting the bridge for less than legal load limit. An FRP-laminate strengthening system was selected based on its application being the least intrusive with traffic and the most practical. Rehabilitation work, including erection of a full-size platform underneath the bridge, surface preparation, and installation of the laminates was conducted between August and November of 1999.

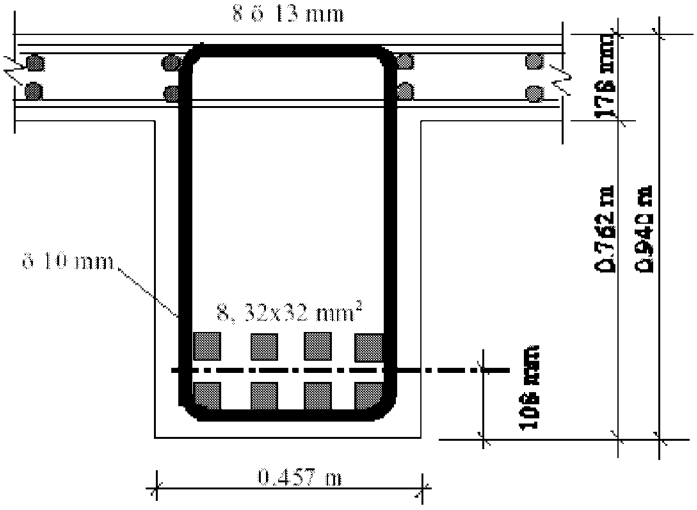


Figure 9. Typical interior beam section (Hag-Elsafi et al, 2002)

The objectives of this study were to evaluate effectiveness of the FRP strengthening system used in this project and investigate its influence on the bridge structural behavior, using results from load tests conducted before and after installation of the system.

Surface preparation and laminate installation were performed according to the procedures recommended by the laminate manufacturer. Areas of the beams with visible cracking were first repaired (by removing loose concrete and replacing it with new patching concrete, and filling the cracks with a cement based grout material) and those with uneven surfaces ground to a smooth finish. Sharp edges around the beam corners were then rounded, and the bridge underneath was sand-blasted and pressure washed with water to remove any loose surface materials that could lead to debonding of the laminates. A primer was applied followed by a putty at the locations where the FRP laminates were to be installed. The primer is expected to penetrate the concrete surface, increase its strength, and improve laminate bonding to the surface. An epoxy resin was applied to the surface, followed by placement of the laminates.

Before and after load testing with trucks of known weight with strain gages placed on concrete surfaces, reinforcing steel and the laminates (after repair testing). Results were found to be inconclusive but did indicate that:

1. Under service live load, after the laminates were installed, main rebar stresses were moderately reduced, concrete stresses (flexural and shear) moderately increased, and transverse live-load distribution to the beams slightly improved. Although the laminates participated in load

carrying, compatibility of strains was not satisfied at some locations, attributed to the level of precision in strain measurements and/or a lack of full bond development at the time of the testing.

2. Unintended fixity of the beam ends was discovered, which substantially reduced anticipated live load moments.

3. As expected, after the laminates were installed, the neutral axis migrated downwards, but effective flange width remained almost unchanged for all truck positions.

This experience indicated significant promise for repairs with FRP composite sheets and demonstrated the potential cost savings of $300,000 for the repair as done versus an estimated cost for replacement of $1,200,000.

Strengthening of a Concrete Box Beam for Shear Stresses

The bridge carries Kentucky Route 3297 over Little Sandy Creek in Carter County, Kentucky. The bridge is designed as a spread, pre-tensioned box beam in 3 spans that are simple for non-composite dead loads and continuous for composite dead loads and traffic live loads. Over time, shear cracks have developed in the box beams and the cracks have widened since they were first identified. Figure 10 shows the wide shear cracks that are evidence of a deficiency in shear strength. The situation was deemed serious enough to require replacement of the bridge unless the beams could be strengthened for shear stresses. Replacement was estimated to cost $450,000 and would have required the complete closure of the bridge for several months. The Kentucky Transportation Cabinet, in conjunction with the Kentucky Transportation Center developed an alternative solution that had two major advantages: 1) the impact of the work on the traffic using the bridge would be minimal except for limiting access to heavy trucks; and 2) the total cost of the strengthening was $105,000, less than one quarter of the cost for replacement.

After surface preparation of injecting cracks and filling voids, fabric was placed on 45 degree angle (Figure 11)

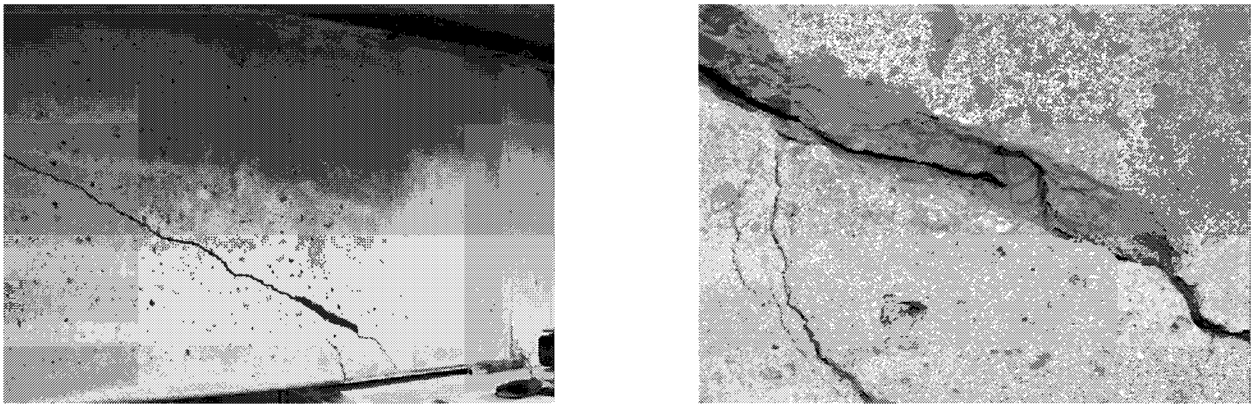


Figure 10(a). Shear Crack Location Figure 10(b). Shear
Crack Opening

Figure 10. Shear Cracks in Concrete Box Beams

Figure 11 – Placing Carbon Fabric on Beams

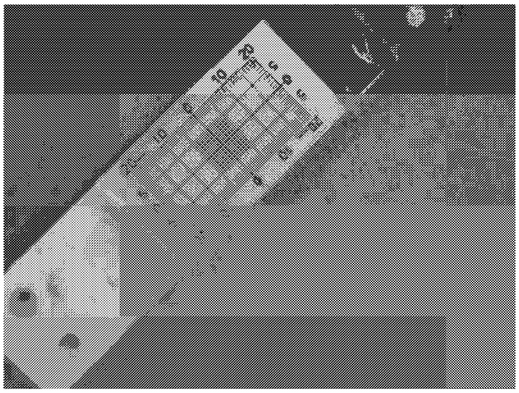


Figure 11. Crack Monitor for Measuring Movement in Shear Cracks

The repairs to shear cracks in the concrete box beams have been in service since October 2001. In order to monitor the performance of the CFRP repairs, crack monitors were placed on the surface of the repaired beams and crack width opening is periodically monitored.

Summary & Conclusions

The United States has an extensive and modern highway system that supports a vital and growing economy and active lifestyle for it citizens. The public assumes a seamless highway system and bridges play a critical role in that system; many bridges are in need of repair, rehabilitation or strengthening in order to provide and ensure adequate levels of service for current and future traffic. Neither the federal government nor state and local highway agencies have sufficient funds to pay for extensive rehabilitation or replacement of all deficient structures. The use of FRP composite materials is being demonstrated as a cost-effective alternative solution to other feasible actions such as load posting, replacement of substructure, replacement of the bridge as well as other more conventional repair methods. The IBRC program is still ongoing and some results are still considered preliminary, but following conclusions can be reached:

- FRP composites can be successfully bonded to steel and concrete surfaces of main load carrying bridge members; FRP composite tendons can be used to externally post-tension bridge beams
- FRP composite laminates can be designed to provide additional flexural and/or shear strength
- FRP composites can be installed quickly and with minimum traffic disruption
- Rehabilitation or strengthening with FRP materials can be very cost-effective when compared to more conventional solutions
- Using FRP materials allows the bridge owner to defer more costly rehabilitation and eventual replacement
- Replacement of concrete bridge decks with FRP composite panels is a method of very rapid rehabilitation which also allows the live load rating of older bridges to be increased.

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