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Upgrading Missouri Transportation Infrastructure: Solid RC Decks Strengthened with FRP Systems

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ABSTRACT

Over 40 percent of the bridges in the United States need repair, strengthening, or replacement. Due to limited funds, many states are forced to post load restrictions on their bridges as a temporary measure. Recently, fiber reinforced polymers (FRP) have emerged as a practical solution for repair/strengthening of highway bridges. Since there are no nationally accepted specifications for design and construction with bonded FRP reinforcement, the Missouri Department of Transportation (MoDOT) has funded a research program aimed at validating the design and analysis procedure through strengthening and testing to failure of bridges under realistic highway loading and conditions. Two bridges, Bridge G270 and Bridge J857, were selected for this demonstration. Both bridges are solid reinforced concrete slab bridges. Bridge G270 was strengthened to increase its load carrying capacity using externally bonded carbon FRP and is still in service. Two of the three deck slabs of Bridge J857 were strengthened with FRP composites. Elastic tests were conducted on Bridge G270, before and after strengthening. Laboratory and field tests were conducted to validate the analytical model and design capacity. The decks of Bridge J857 were tested to failure under static loads. Test results indicate that FRP strengthening can increase the capacity of solid-slab bridge decks. Strength and failure modes can be predicted using the classical approach for RC design and analysis, based on equilibrium and compatibility. This paper reports on the research program, strengthening techniques, test results, and modes of failure of the tested bridge decks.
INTRODUCTION

The National Research Board (1) reports that in the United States, there are approximately 590,000 structures in the National Bridge Inventory database. Over 40 percent of these bridges need repair, strengthening, or replacement. Fatigue and deterioration from chlorides used in de-icing operations have accelerated deterioration rates of many bridge decks and increased the need of repair, strengthening or replacement of these structures. In addition, many bridges may be deficient because they have exceeded their design life and carry loads in excess of their original design (2). Due to budget constraints, the cost to repair or replace all of these structures is beyond the financial means of many state DOTs. Hence, they have resorted to temporary solutions such as posting load restrictions until more funds become available.

Recently, advanced composites made of fibers embedded in a polymeric resin, also known as fiber-reinforced polymer (FRP) materials, have emerged as an alternative and practical solution to steel reinforcement and its inherent corrosion problems. FRP materials are corrosion resistant and exhibit several properties suitable for their use as structural reinforcement (3,4).

Pioneering work on strengthening of concrete structures with FRP composites took place in the 1980’s, in Switzerland, where the first on-site repair by externally bonded FRP took place in 1991 (5). Since then, strengthening by externally bonded FRP has been studied and implemented worldwide (6). Currently, there are no nationally accepted specifications for design and construction control of FRP composite materials for structural repair and strengthening. The database for performance of FRP strengthened RC members is based on laboratory tests that are usually conducted on small-scale specimens that do not account for real boundary conditions and site effects. Field tests, on the other hand, can demonstrate the actual behavior of a structure and can lead to a better understanding of the performance of the system as a whole. Although the short-term behavior of these applications has been experimentally evaluated, research into their
long-term performance is incomplete, and durability issues have not been addressed comprehensively. For example, carbon fibers may pose a galvanic corrosion problem when in contact with a less noble material such as reinforcing steel in the presence of a conductive environment. FRP’s used in highway bridges are expected to perform in service for very long times. Therefore, practitioners need to be able to predict the long-term behavior of these materials and the resulting effects on the performance of the strengthened structures. To ensure the quality and performance of FRP repair/strengthening, the Federal Highway Administration is currently sponsoring research programs to develop model specifications for repair/strengthening of existing bridges using FRP composites.

In response to the need for field verification of this new technology, the Missouri Department of Transportation (MoDOT) has funded a research program aimed at validating the design and analysis procedure through laboratory and in-situ testing of a highway bridge strengthened with FRP composites. The objective of this demonstration was to bridge the gap between and small-scale experiments and the real-life behavior of FRP strengthened bridge decks for capacity verification. In addition, monitoring of the field-performance of strengthened deck provides valuable information on durability of FRP composites. Properties of the FRP materials used in this research program are given in Table 1. The same FRP materials were used for both bridges.

**BRIDGE RATING**

A wide range of rating values can be achieved for the same bridge based on the level of complexity of the analysis used in the rating process (7). The proper identification of the material properties and the incorporation of its boundary conditions influence the reliability of bridge deck ratings. The rating is usually done using the recommended material properties, which in most
cases may result in a quite conservative rating. Since the rating of a bridge is ultimately linked to its decommission, careful consideration should be given to the factors that can unnecessarily cut short the service life of the bridge.

According to MoDOT’s current load rating guidelines, any structure built, rehabilitated, or reevaluated shall be rated using the Load Factor Method (8). Bridges are rated at two load levels, the maximum load level called the Operating Rating and a lower load level called the Inventory Rating. The Operating Rating is the maximum permissible load that should be allowed on the bridge. Exceeding this level could damage the bridge. The Inventory Rating is the load level the bridge can carry on a daily basis without damaging the bridge. The Operating Rating is based upon the appropriate ultimate capacity using current AASHTO specifications. Load posting is established using the H20 and 3S2 vehicles at 86% of the Operating Rating. The legal load in Missouri is 204 kN (23 tons) for H20 vehicles and 356 kN (40 tons) for 3S2 vehicles. See Figure 1 for typical axle loads and spacing for rating vehicles.

In many cases, the deficiency in demand is only a small percentage of the capacity of the bridge. Therefore, using economical techniques for upgrading these bridges can provide savings for state DOTs and lead to the removal of many load posting signs.

Bridge G270 has a load restriction posting of 169 kN (19 tons) for H20 trucks and 302 kN (34 ton) weight limit for all others. Externally bonded carbon FRP reinforcement (CFRP) was selected to increase the load carrying capacity of this bridge. Externally bonded FRP sheets are installed by wet lay-up, a relatively common strengthening technique already implemented in many projects worldwide (9).

DESIGN OF FRP STRENGTHENING
The strengthening design of externally bonded FRP sheets was achieved using the limit state approach. According to this method, the flexural capacity of the critical section is calculated by combining force equilibrium, strain compatibility, and constitutive laws of the materials at failure (10,11). An initial strain at the extreme tension concrete fibers, $\varepsilon_i$, is calculated based on cracked section properties and considering only the self-weight of the deck. The non-linear stress distribution in the concrete is replaced by Whitney’s rectangular stress block. The equivalent stress block factors, $\alpha_i$ and $\beta_i$, can be determined for any value of concrete strain at the extreme compression fiber by the numerical integration of the stress strain diagram. For concrete, a parabolic constitutive law equation is simple and practical for design consideration (12). Based on this approach, the values of $\alpha_i$ and $\beta_i$ are expressed as follows:

\[
\beta_i = \frac{4\varepsilon_i - \varepsilon_c}{6\varepsilon_i - 2\varepsilon_c}
\]

\[
\alpha_i = \frac{3\varepsilon_c - \varepsilon_c^2}{3\beta_i - \varepsilon_c^2}
\]

In which $\varepsilon_c$ is the concrete strain corresponding to the ultimate concrete strength, $f'c$, and can be taken as (13):

\[
\varepsilon_c = \frac{1.71f'_c}{E_c}
\]

Considering force equilibrium requirements, the equations for forces and moments are established as follows:

\[
\alpha f_{c} b c = A_{s} f_{s} + R A_{f} f_{f}
\]

\[
M_{n} = A_{s} f_{s} \left( d - \frac{\beta_{1} c}{2} \right) + R A_{f} f_{f} \left( h - \frac{\beta_{2} c}{2} \right)
\]

In which \( R \) is a reduction that for the current investigation was taken as 0.85. Also considering the compatibility of strains, the following equations can be derived:

\[
\varepsilon_{s} = \varepsilon_{c} \left( \frac{d - c}{c} \right)
\]

\[
\varepsilon_{f} = \varepsilon_{c} \left( \frac{h - c}{c} \right) - \varepsilon_{i}
\]

Equations (1) through (7) are used to predict stresses in concrete, steel and bonded FRP at any load level. Because of the number of variables involved, the solution is achieved by assuming an initial concrete strain and then calculating the stress in steel and FRP through iteration. This process is terminated when either the concrete reaches a strain of 0.003 mm/mm or the FRP reaches its ultimate strain.

Deficient bridge decks may require an increase in capacity in the range of 10 to 30% for which the rupture of FRP typically governs. This was also the case for the two bridges of this project. Checks were made to ensure that the shear strength requirements meet the upgraded load capacity. Since the amount of FRP is small compared to the area of concrete and steel, the increase in stiffness at service level is negligible. Accordingly, it is recommended that serviceability checks be performed without accounting for the effect of FRP addition.
Bridge G270 is located on Route 32 in Iron County. The bridge is a 6.10 m (20 foot) solid reinforced concrete (RC) slab built in 1922 with an original roadway width of 5.49 m (18 feet). Figure 2 shows a photo of the bridge. The bridge currently carries a traffic volume of 1,600 vehicles per day. Around 1990, the original baluster handrails were removed and replaced with a thrie-beam guardrail that expanded the roadway width to approximately 6.10 m (20 feet). The bridge has a load restriction posting that limits trucks over 124.6 kN (14 tons) to 24.14 km/h (15 mph) on the bridge. The posting also limits truck weights for single axle trucks to 169.1 kN (19 tons) and all other trucks to 302.6 kN (34 tons). MoDOT selected this bridge for evaluation because of its restricted load posting and location near the Doe Run lead mines which generates heavy truck traffic.

Based on the bridge rating analysis using HS20 truck loading, the new service loads will produce a maximum positive bending moment of $M_s = 186.9$ kN-m/m (42 kip-ft/ft), and an ultimate moment of $M_u = 267.0$ kN-m/m (60 kip-ft/ft). The capacity of the deck was based on conservative material properties established by MoDOT [$f'_{c} = 16.3$ MPa (2,363 psi) and a yield strength for the mild steel of $f_y = 207$ MPa (30,000 psi)]. From field observations, it was evident that some concrete deterioration and reinforcement corrosion has taken place. From past experience, bridge decks of this age with an asphalt overlay experience 2.54 to 5.08 cm (1 to 2 inches) of concrete deterioration thus reducing section effective depth. This reduction in effective depth results in a 6 to 9 percent loss in moment capacity. Strengthening design of the bridge deck called for one 330-mm (13.0-inches) ply of CFRP per one meter (3.3 foot) width of the deck slab.

Laboratory Experimentation
Since bridge G270 needed to remain in service, testing to failure was not an option therefore it was decided to construct two full-scale RC beams that could be tested in the laboratory to failure. One was used as a control beam and the other was strengthened with externally bonded CFRP laminates.

Because of the impossibility of exactly reproducing the material properties of the existing deck, specimens were fabricated with MoDOT Class B concrete and steel reinforcement with a yield strength of 414 MPa (60 ksi). The estimated concrete strength of the two beams determined by standard cylinder breaks was 39.8 MPa (5,770 psi).

To verify design approach and capacity improvement, the beam was strengthened with externally bonded CFRP laminates to achieve a 20% increase in flexural capacity. This would be the equivalent increase in strength needed in the existing structure to remove the load posting.

The test beam was strengthened using one ply of CFRP 300 mm (12 inches) wide. The dimensions of the test beams were chosen to mimic the existing bridge length of 6.10 m (20 feet) and the slab depth of 470 mm (18.5 inches). A width of 0.380 mm (15 inches) was chosen to provide an adequate surface area for the application of CFRP.

Test beams were instrumented with strain gauges attached to the reinforcing steel at mid-span and to the compression concrete. Deflection measurements were recorded with linear variable displacement transducers (LVDTs) placed at the supports, quarter points and at mid-span.

The load deflection curves, shown in Figure 3, demonstrate the good agreement between the theoretical and experimental results. These curves show that the design methodology used is effective in determining the strength and failure modes of the beams. The failure modes, as predicted, were yielding of steel reinforcement followed by the crushing of the concrete (unstrengthened beam) or the rupture of the CFRP (strengthened beam) (14).
Field Application of FRP

The soffit of the bridge slab had grout lines left from the original construction. These were flattened with hand grinders and the entire slab was lightly sand blasted to remove any loose material. The CFRP sheets layout pattern consisted of eight sheets of CFRP, 500 mm (20 inches) wide. FRP sheets were applied using the wet lay-up process according to the manufacturer specifications (15). Strengthening process was rapid with no interruption to traffic flow and the entire process was completed in three days including instrumentation and elastic testing. Figure 4 illustrate the application of externally bonded CFRP sheets to the deck soffit.

Elastic Load Testing

The University of Missouri-Columbia provided the load testing equipment used in the initial tests to determine the elastic deflection response. The equipment consisted of a self-supporting data acquisition vehicle with the capabilities of monitoring 100 channels of strain and 25 channels of deflection.

The vehicle used to load the bridge consisted of a flatbed truck loaded with steel weights. The load test vehicle, totalling 188 kN (21.14 tons), had known axle weights of 45 kN (10.2 kip) front, 72 kN (16.3 kip) and 70 kN (15.8 kip) for the rear. The data was collected with five LVDTs placed at quarter points both longitudinally and transversely.

A load test was performed on the bridge before and after the application of FRP. Deflection tests were performed by driving the loaded truck over the bridge. The test truck made six passes over the bridge. The truck drove forward and backward on the South side, North side and
centerline of the bridge. Each time the truck passed over the bridge the deflection readings were measured and recorded.

A second load test was performed on August 19, 1999 after the application of FRP. This test was conducted to investigate the effects of time on the performance of the system. Deflection tests were performed by driving the loaded dump truck over the bridge. The test truck made three passes over the bridge. The truck drove forward on the South side, centerline, and North side of the bridge. Each time the truck was positioned at the 1/4, 1/2, and 3/4 span points over the bridge. The truck was stopped for two minutes while the deflection readings were measured and recorded. Table 2 shows the results of the measured bridge deck deflections at the centerline of the bridge and on the transverse direction at mid-span for the three elastic tests. The results of the second load-deflection tests clearly show the FRP sheets continue to carry tensile stresses. The deflections are virtually the same as those taken on May 21, 1998 just after the FRP was applied.

Long Term Monitoring

As a part of the research program for bridge G270, in-situ corrosion measurements were planned. The aim of this monitoring is to detect any possible reactions between the steel reinforcement and the carbon fibers. The first approach included corrosion potential measurements. In addition, with use of a portable potentiostat, electrochemical impedance spectroscopy tests (EIS) were conducted. With this technique, it was possible to monitor the electrochemical degradation occurring on the steel and on the CFRP. Measurements were taken at two locations, one set near the North edge of the slab and the other set in the middle of the slab. Each set consisted of four points at 0.6 m (2 feet) intervals along each reinforcing bar. The South edge had good surface integrity, while the North edge had some damage due to corrosion of the steel reinforcement. The
first set of data was collected on May, 1998. Corrosion potential measurements, polarization resistance and EIS measurements were conducted. The bridge was re-visited on May, 1999. The results are indicative of moderate corrosion rates (14).

**BRIDGE J857**

The main objective of Bridge J857 testing program was to investigate the effects of different strengthening techniques on the stiffness, structural performance, ultimate capacity, and mode of failure of the bridge decks. The bridge was built in the 1930s and was located on Route 72 in Phelps County, Missouri. Due to the realignment of Route 72, the bridge was decommissioned in December 1998 and scheduled for demolition. The bridge consisted of three simply supported decks made of 460 mm (18 inches) thick solid reinforced concrete slabs with an original roadway width of 7.6 m (25 feet), as shown in Figure 5. Each simply supported deck spanned approximately 7.9 m (26 feet). Bridge decks were supported by two abutments and two bents. Each bent consists of two columns connected at the top by a RC cap beam. The bents were at a 15-degree skew. In general, the condition of the bridge was good and no major damage (e.g., corrosion of reinforcement, or concrete spalling) was observed.

**Bridge Deck Strengthening**

Two of the three decks of the bridge were strengthened to the same level of nominal capacity while the bridge was in service. Two FRP systems were used in strengthening the decks: externally bonded CFRP sheets and near-surface mounted (NSM) CFRP rods. The latter consists
of FRP bars embedded in pre-made grooves and bonded in place with an epoxy-based paste.

NSM rods offer the advantage of feasibility of anchoring the rods into members adjacent to the one to be strengthened, do not require surface preparation work, and require minimal installation time. This technique can be used to increase the flexural capacity of decks, beams, walls and columns and can be used to strengthen shear walls.

In order for the bridge to carry an HS20 truck, its nominal moment capacity should not be less than 417 kN-m/m (93.7 kip-ft/ft). Comparing these values with the deck capacity of 352 kN-m/m (79.2 kip-ft/ft), the required level of strengthening was established as 18% and 37%. Since a capacity increase of 18% may not provide a clear differentiation between the flexural behaviors of the strengthened and unstrengthened decks, it was decided to strengthen the decks by approximately 30%. The mounted rods were staggered such that 50 percent of the rods extended to deck supports.

Similar to Bridge G270, the design was achieved using a procedure for ultimate state conditions to obtain a failure mode based on steel yielding followed by FRP rupture. Based on this approach, the design of externally bonded sheets called for eight, 500 mm (20-in) wide, single-ply CFRP strips on the deck soffit. Similarly, the required number of NSM rods reinforcement was 20 units spaced at 375 mm (15 inches). The rods were embedded in 6.6 m (20 feet) long, 19 mm (0.75 in) deep, and 14 mm (0.56 in) wide grooves cut onto the soffit of the bridge deck parallel to its longitudinal axis.

To apply the NSM rods, the grooves were filled half way with epoxy paste. The FRP rods were placed in the groove and lightly pressed, as shown in Figure 6. The grooves were then filled with more paste and the surface was leveled. Appropriately spaced wedges were used to hold the rods in place until the epoxy cured. Externally bonded CFRP sheets were installed in the manner outlined earlier for bridge G270.
Load Testing to Failure

Testing to failure was achieved after the bridge was closed to traffic. Each of the three spans was tested to failure by applying quasi-static load cycles. Four 90-tonnes (200-kip) hydraulic jacks were used to apply the static load. The jacks rested on the bridge deck and pulled against two steel spreader beams located under the deck. The spreader beams transferred the load to two steel girders, which reacted against the cap beams as shown in Figure 7. The magnitude of the maximum load used in each successive load cycle was incremented until failure of the deck was achieved. Deck deformations as well as strain in the steel bars, CFRP bars and CFRP sheets were measured at different locations.

Experimental Results

As expected, experimental results indicated that the addition of FRP reinforcement had insignificant contribution to the elastic stiffness of strengthened decks. This is due to the relatively small amount of FRP added to the section compared with the area of existing steel reinforcement. The stiffness of strengthened decks reduced after the yielding of the steel reinforcement whereas the unstrengthened deck had no stiffness after steel yielding. Figure 8 shows the load mid-span deflection curves for the three decks. This figure indicates that a trade off exists between the deck capacity and the maximum mid-span deflection.

The experimental capacity of the bridge decks were higher than anticipated from initial calculations. Initial strengthening design using NSM CFRP rods and externally bonded CFRP sheets was based on conservative material strengths. Concrete cores and steel coupons were
obtained after the bridge was closed to traffic, which occurred after strengthening was completed.

The actual material strengths determined from laboratory testing were significantly higher that the assumed values.

The measured response of the decks from testing to failure indicated that some level of restraint existed even though the joints between the decks were cut clean prior to testing. By attempting to match experimental and analytical results using the measured deflections and strains, the end fixity level for the two external and internal decks was estimated to be 16% and 12%, respectively. A strengthening design based on the assumption of simple supports is therefore conservative.

Based on more representative material properties, the moment capacities for the deck strengthened with NSM rods, bonded sheets, and the unstrengthened deck were 661, 627, and 485 kN-m/m (149, 141, and 109 kip-ft/ft), respectively. Based on the estimated fixity levels the experimental moment capacities were 661, 627, and 536 kN-m/m (149, 141, and 120 kip-ft/ft), in the same order. Experimental capacities of the strengthened decks correlated well with the theoretical values. The higher experimental capacity of the unstrengthened deck was related to the influence of strain hardening of the steel reinforcement. Accordingly, the approach utilized in this study for design/analysis of RC deck strengthened using the investigated FRP systems is satisfactory.

The mode of failure of each deck was dependent on the strengthening scheme. For the deck with NSM rods, failure was initiated by the rupture of some CFRP rods at location of wider cracks. The failure mode of the deck strengthened with CFRP sheets was a combination of rupture and peeling of CFRP sheets. As for the reference deck, the classical mode of failure of yielding of steel reinforcement followed by the crushing of concrete was attained.

Comparing the field performance of strengthened vs. unstrengthened decks, the increase in the moment capacity was 24% and 18% for decks strengthened with NSM CFRP rods and CFRP
sheets, respectively. However, it should be noted that the experimental capacity of the unstrengthened deck is about 52% higher than its initial prediction.

CONCLUSIONS

This paper reports on a research program aimed at demonstrating, through in-situ testing the performance of bridge decks upgraded using FRP composites. Two bridges were considered to demonstrate the feasibility of using CFRP materials as a mean to upgrade RC bridge decks.

Two FRP strengthening techniques were investigated in this program, namely near-surface mounted FRP rods and externally bonded FRP sheets. Both were found satisfactory in terms of constructability and capacity improvement. Capacity of strengthened decks can be predicted with good accuracy using the classical approach that utilizes equilibrium and compatibility requirements. Since the area of bonded FRP is usually small compared to the area of steel, the increase in deck stiffness prior to steel yielding is negligible. Durability data is now being generated from continuous monitoring of Bridge G270. This information will be useful for more accurate prediction of the long-term performance of the strengthening systems.

ACKNOWLEDGEMENTS

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TABLE 1  Mechanical Properties of FRP Reinforcement

<table>
<thead>
<tr>
<th>FRP Type</th>
<th>Dimension mm [in]</th>
<th>Design Strength MPa [ksi]</th>
<th>Design Strain mm/mm or in/in</th>
<th>Tensile Modulus GPa [ksi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon sheets*</td>
<td>t_f = 0.165 [0.0065]</td>
<td>3800 [550]</td>
<td>0.017</td>
<td>228 [33,000]</td>
</tr>
<tr>
<td>Carbon rods**</td>
<td>D = 11 [7/16]</td>
<td>993 [144]</td>
<td>0.0105</td>
<td>119 [17,200]</td>
</tr>
</tbody>
</table>

* Fiber properties    ** Rod properties
TABLE 2  Measured Deflection from Elastic Testing

<table>
<thead>
<tr>
<th>Distance* (m)</th>
<th>Deflections (mm)</th>
<th>% of Original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>May-98</td>
</tr>
<tr>
<td>1.53</td>
<td>0.178</td>
<td>0.170</td>
</tr>
<tr>
<td>3.05</td>
<td>0.231</td>
<td>0.229</td>
</tr>
<tr>
<td>4.58</td>
<td>0.175</td>
<td>0.168</td>
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</table>

Transverse Direction at Mid-span

<table>
<thead>
<tr>
<th>Distance** (m)</th>
<th>Deflections (mm)</th>
<th>% of Original</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>May-98</td>
</tr>
<tr>
<td>1.56</td>
<td>0.249</td>
<td>0.218</td>
</tr>
<tr>
<td>3.13</td>
<td>0.231</td>
<td>0.229</td>
</tr>
<tr>
<td>4.69</td>
<td>0.203</td>
<td>0.203</td>
</tr>
</tbody>
</table>

*distance from the support  ** distance from the edge at midspan

Note: 1 m = 0.328 ft; 1 mm = 0.04 inch

FIGURE 1 Bridge G270
FIGURE 2  3S2 and H20 Vehicles used for bridge rating in Missouri.
FIGURE 3 Experimental load-deflection curves from lab testing (1 in. = 25 mm, 1 kip = 4.448 kN.)
FIGURE 4  Application of CFRP sheets to Bridge G270.
FIGURE 5  Bridge J857.
FIGURE 6  Application of NSM CFRP rods to Bridge J857.
FIGURE 7 Static load test setup for bridge J857 decks (1 ft = 0.305 m, 1 in. = 25 mm).

FIGURE 8 Experimental and theoretical load-deflection curves for J857 bridge decks (1 in. = 25 mm, 1 kip = 4.45 kN).