Strengthening Highway Bridges with CFRP Composites

By Tarek Alkhrdaji

The future growth of nations and their economical prosperity are closely related to the potency of their transportation infrastructures. Bridges, in particular, are one of the most important components of these infrastructures. The vast majority of bridges in the United States were built in the second half of 20th century, after World War II. Many of these bridges were constructed with reinforced concrete using older standards and an anticipated service life of about 50 years. For many of these bridges, the design loads are smaller than what are currently permitted and include no consideration for seismic vulnerability. A recent survey by the National Cooperative Highway Research Program (NCHRP) indicated that 63% of North American transportation agencies anticipate a need to increase the live load capacity of existing highway bridges.

Also, the Transportation Research Board reported in 1998 that, in the United States, there are approximately 590,000 structures in the National Bridge Inventory database. Approximately 80% of these (475,850) are classified as bridges with spans of 20 ft or longer. Of this number, approximately 50,000 are classified as structurally deficient, 89,000 are functionally obsolete, and 54,000 are both structurally deficient and functionally obsolete. Many of these structures have exceeded their design life and carry loads in excess of their original design. These excess loads, in conjunction with fatigue and deterioration from chlorides used indeicing operations, have left many bridges in need of repair, strengthening, or replacement. With these concerns in mind, the condition of the United States' infrastructure needs to be addressed, and major action on this issue needs to be taken. A major rehabilitation program will have to be implemented to keep these bridges in service, which could cost the financially strapped transportation agencies millions of dollars.

Economically, it is not feasible to replace every outdated bridge across the country. In addition, constructing new bridges takes longer than rehabilitation and can cause inconvenient traffic disturbances. A more economical and rapid solution is to retrofit these bridges using new technologies that allow for upgrading with minimal or no disturbance to their use. Fiber-reinforced polymer (FRP) materials provide an excellent and economical solution to the structural upgrade of bridge components due to their lightweight, corrosion-resistant, and high tensile-strength properties. The most important characteristic of FRP in highway structure repair and strengthening applications is the speed and ease of installation. The higher material cost is typically offset by reduced labor, use of heavy machinery, and shut-down costs, making FRP strengthening systems very competitive with traditional strengthening techniques.

In Missouri, the first strengthening project using FRP composites was conducted in 1998 for Bridge G270, located on Route 32 in Iron County. The bridge has a load restriction posting that limits truck weights for single-axle trucks to 19 tons and all other trucks to 34 tons. The Missouri Department of Transportation (MoDOT) selected this bridge for upgrading because of its restricted load posting and location near the Doe Run lead mines, which generate heavy truck traffic. In addition, in 1999, MoDOT funded a research program aimed at validating the design and analysis procedure through the full-scale FRP strengthening and load-testing to failure of the three decks of Bridge J857, located on Highway 72 in Phelps County, after strengthening with FRP composites. These research projects demonstrated the collaboration between the government (MoDOT), industry (Structural Preservation Systems) and academia (University of Missouri-Rolla, UMR) supporting analysis and design as well as instrumentation. Out of a number of cases of strengthening of bridges using FRP composites in the last several years, this study presents a project that used FRP upgrading of three bridges located in Boone County, MO. The project background, description of these bridges, FRP strengthening design and application, and in-situ load testing are presented, and laboratory and field-testing results are discussed.

Bridge G270

Bridge G270, located on Route 32 in Iron County, MO, is a 20-ft solid reinforced concrete slab, built in 1922 with an original roadway width of 18 ft. The bridge currently carries a traffic volume of 1600 vehicles per day. Recent rating calculations showed that Bridge G270 requires strengthening in order to carry the current traffic loads.

Rating results indicated that the bridge was approximately 9% overstressed. However, bridge strength calculations were based on "as-built" plans that assumed no section losses. From a field inspection, the bridge decks were found to have 1 to 2 in. of concrete deterioration at the interface of the concrete deck and the asphalt-wearing surface. Compensating for the loss in effective depth requires approximately a 20% increase in moment capacity.

Laboratory Experimentation

Since Bridge G270 had to remain in service, testing to verify capacity improvement was not an option. Instead, test beams were built to mimic the existing bridge dimensions and reinforcement. The beams were constructed at a length of 20 ft and a depth of 18.5 in. to replicate a strip of the bridge. A width of 15 in. was chosen to provide an adequate surface area for the application of FRP. Test beams were constructed with 1.5 in.^{2} of tension steel and a concrete strength of 5770 psi. The objective of this test was to produce an increase in moment capacity equal in percentage to that required in the field.

Two beams were built for laboratory testing. For a baseline, one beam was without strengthening. The second beam was strengthened using one ply of carbon fiber-reinforced polymer (CFRP), 12 in. wide. The design of externally bonded FRP strengthening was achieved using CFRP reinforcement that has a design strength of 550 ksi, a modulus of 33,000 ksi, an ultimate strain at failure of 0.017 in./in., and a thickness of 0.0065 in. The load-deflection curves, shown in Figure 1, demonstrate the good agreement between the theoretical and experimental results. The curves also show that the design methodology used that was based on strain compatibility, force equilibrium, and laws of the constituent material, was effective in predicting the strength and failure modes of the beams. The failure modes, as predicted, were the yielding of steel reinforcement, followed by the crushing of the concrete (unstrengthened) or the rupture of the CFRP (strengthened).

Field Application of FRP

The soffit of the bridge slab had grout lines left from the original construction. These were flattened with hand grinders. In addition, the surface of the concrete was prepared prior to CFRP application using sandblasting to remove loose concrete and other particles that may have hindered the development of adequate bond. Since bond is the main shear-transfer mechanism between the concrete and the CFRP system, achieving a composite behavior in the upgraded member is very sensitive to surface preparation and application of the system. The CFRP sheet layout pattern consisted of eight sheets of CFRP, 20 in. wide, bonded to the bottom side of the slab using the wet lay-up process. The wet lay-up systems were saturated and cured in place, and therefore, were analogous to cast-in-place concrete. A saturating resin, along with the compatible primer, was used to bond the FRP sheets to the concrete surface (Figure 2). The strengthening process was rapid with no interruption to traffic flow, and the entire process was completed in two days.

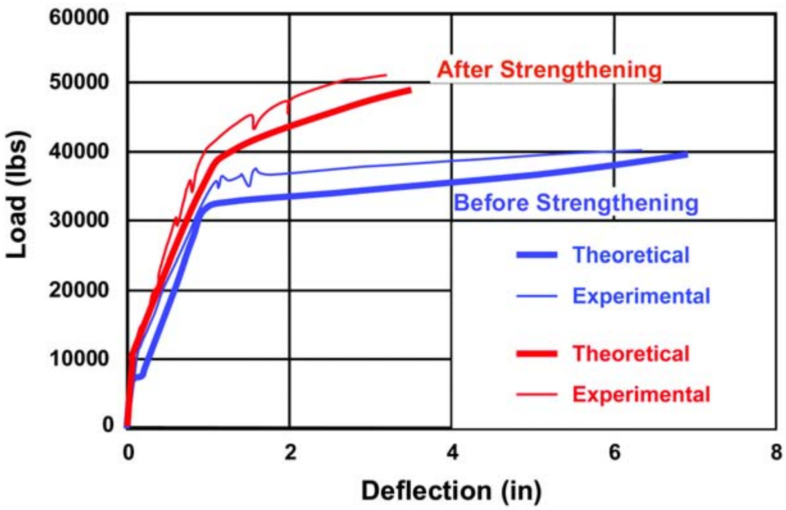

Figure 1: Experimental results of test beams

Figure 2: CFRP reinforcement bonded to the underside of Bridge G270

Bridge J857

The main objective of the Bridge J857 testing program was to investigate the effects of different strengthening techniques on the structural performance, ultimate capacity, and mode of failure of the bridge spans. The bridge was located on Route 72 in Phelps County, MO, as shown in Figure 3. Due to the realignment of Route 72, the bridge was decommissioned in December 1998 and scheduled for demolition. The bridge was built in the 1930s

Figure 3: Bridge J857

Figure 4: Strengthening of Bridge J857 spans

(a) Installing CFRP rods

(b) Installing CFRP sheets

and consisted of three simply supported spans made of 18 in.-thick solid reinforced concrete slabs with an original roadway width of 25 ft. Each simply supported deck spanned 26 ft. 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 spans of the bridge were strengthened to the same level of nominal flexural capacity. Two FRP systems were used in strengthening the deck slabs: externally bonded FRP sheets, and near-surface mounted (NSM) FRP rods, as shown in Figure 4. The latter consists of FRP bars embedded in premade grooves and bonded in place with an epoxy-based paste. The NSM reinforcement used in this project consisted of CFRP rods with surfaces roughened by sandblasting. From a design point of view, a 29% increase in the nominal moment capacity would have been sufficient to upgrade the bridge decks to carry an HS20-modified truck loading. This level of strengthening would also provide a clear differentiation between performance of the strengthened and unstrengthened spans. Based on this approach, the design of externally bonded sheets called for eight 20-in. wide, single-ply CFRP strips bonded on the deck soffit using the wet lay-up procedure. Similarly, the required number of NSM rods of reinforcement was 20 rods, spaced at 15 in. on centers. The rods were embedded in 20 ft-long grooves cut into the soffit of the bridge deck parallel to its longitudinal axis.

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 quasistatic load cycles using four 200-kip hydraulic jacks. The jacks rested on the bridge deck and pulled against two steel spreader beams located under the deck. 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.

For the span with NSM rods, the rupture of some CFRP rods at the location of the widest crack, which occurred at midspan, initiated deck failure. The failure mode of the span strengthened with CFRP sheets was a combination of rupture and peeling of the sheets. As for the reference span, the classical mode of failure of yielding of steel reinforcement, followed by the crushing of concrete, was attained. The span strengthened with NSM rods showed the highest capacity with a flexural strength of 147.1 kips-ft (per foot width), while the span strengthened with CFRP sheets had a capacity of 134.1 kips-ft, and a capacity of

114.6 kips-ft for the unstrengthened span. For all three spans, the experimental values exceeded the theoretical predictions. Figure 5 shows the load-deflection curves for the three spans.

Comparing the performance of unstrengthened decks, the increase in the moment capacity for decks strengthened with CFRP sheets and NSM CFRP rods was 17 and 27%, respectively. However, test results indicate that the measured ultimate capacity of the unstrengthened deck is about 46% higher than initial prediction. Testing of concrete cores and steel coupons indicated that the actual concrete strength was 8147 psi compared to 2300 psi from the initial assumption, whereas for steel, the actual yield strength was 43,333 ksi compared to 30,000 ksi from the initial assumptions. Hence, the lower-than-anticipated percentage increase in the ultimate capacity was related to the higher actual strength of the original deck.

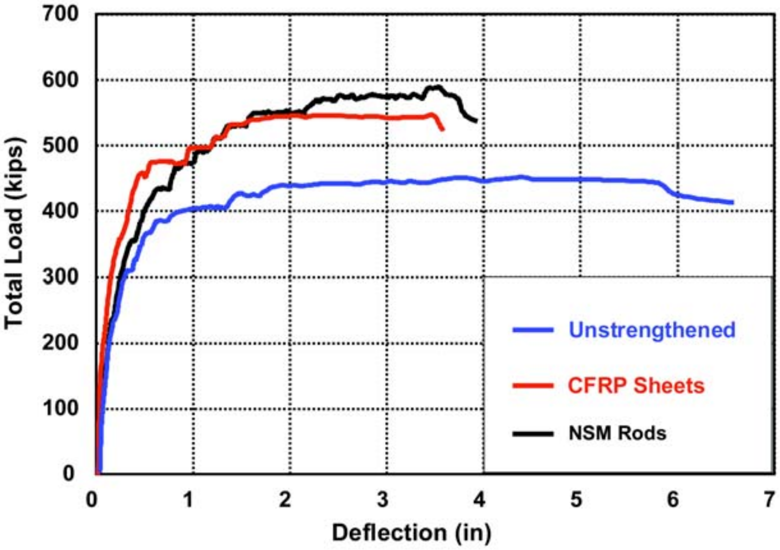

Figure 5: Full-scale testing results for Bridge J857

Application of CFRP for Bridge Strengthening

Three bridges (Brown School Road Bridge, Creasy Springs Bridge, and Coats Lane Bridge) were constructed between 1970 and 1976. Each bridge consists of a single-span, simply supported deck with precast reinforced concrete (RC) channel sections, with a 4 in.-thick slab that runs the entire span of the bridge. Each channel has RC diaphragms spaced at 6 ft-3 in. that connect the two stems. The precast channels are tied together through the stems with 1 in.-diameter steel bolts and fasteners for composite action. In 1986, the lanes of Brown School Road Bridge were widened with two 18 in.-thick and 50 in.-wide RC slabs, one on each side of the deck. The edge slabs were designed for HS20 truck loading. The Creasy Springs and Brown School Road bridges are located on roads with a high traffic count. The Coats Lane Bridge is located on a gravel county road. Figure 6 shows a typical underside seen on these bridges. The three bridges were designed according to the standards of the American Association of State Highway and Transportation Officials (AASHTO). All bridges were evaluated in 1979, and a 15-ton load limit was determined based on load-posting criteria used at that time and based on the available information.

Approximately 3600 vehicles per day cross the Creasy Springs and Brown School bridges with an estimated 10% truck usage. The Coats Lane Bridge is used by approximately 160 vehicles per day. Due to increasing traffic counts and use from heavier traffic, the bridges required strengthening to remove the posted loads. Upgrading these bridges would provide greater accessibility for industry and emergency vehicles to reach area residents and avoid a 6-mile detour. The current AASHTO code indicated that the RC channels require upgrading their flexure and shear capacity to carry the new truck loading.

Figure 6: The underside of Coats Lane Bridge

The initial cost estimate of deck strengthening for all three bridges, using conventional upgrade methods, was approximately $220,000. Replacement of these three bridges was not an option. The option of upgrading with FRP composites was investigated and found to be a feasible one. Due to the novelty of these strengthening systems, and to ensure proper application and quality control of the FRP system, the County Public Works Department decided to award this project in a design/build scenario. Following a field investigation and condition survey, and a review of bridge

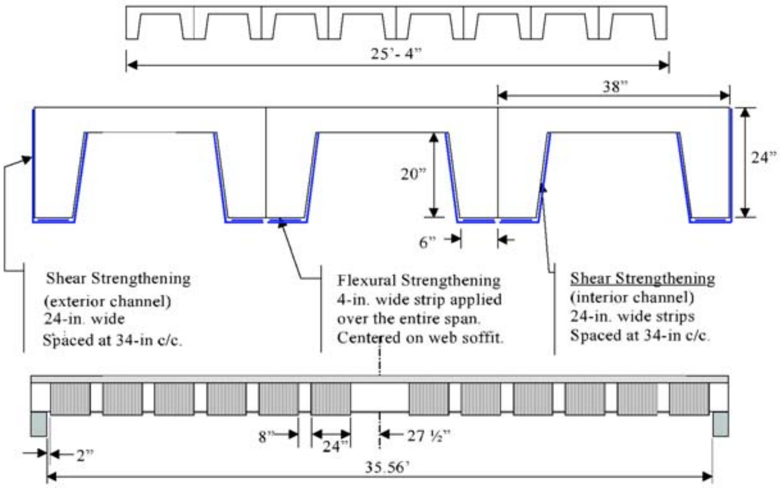

Figure 7: Details of CFRP strengthening for Coats Lane Bridge

Figure 8: Application of CFRP strengthening

plans, the initial estimate of structural upgrade of the three bridges was approximately $65,000, resulting in a savings of $155,000. To allow for load posting removal, MoDOT requested a full-scale load testing of at least two of the bridges before and after strengthening.

Although the original design concrete strength was 3000 psi, field tests using a Schmidt-Hammer yielded a concrete strength of approximately 9000 psi. However, it was decided to use a concrete strength of 5000 psi for analysis and strengthening design. A steel yield strength of 40 ksi was used. The capacity of the three bridges was calculated according to AASHTO specifications. Accordingly, the bridges needed flexural and shear strength upgrades that varied for the three bridges, with maximum values of 20 and 22% for flexure and shear, respectively.

The design of externally bonded FRP strengthening was achieved using the same CFRP reinforcement. A typical CFRP layout is shown in Figure 7. The CFRP strengthening system was applied using the wet lay-up procedure, as shown in Figure 8. Figure 9 shows the Coats Lane Bridge before and after strengthening with CFRP.

Elastic In-Situ Load Testing

Four load tests (two tests per bridge) were performed on the Coats Lane Bridge and the Brown School Bridge to assess their performance before and after strengthening. The objective of the load tests was to investigate the performance of the strengthened bridges to allow for load posting removal. The load test did not seek to evaluate the safety or the ultimate load-carrying capacity of the entire structure. The in-situ load testing procedure involved applying vehicular loading to the bridges using two H20 trucks, as shown in Figure 10. The response of each bridge was monitored during the test and used to evaluate its performance. The effect of impact was not physically examined during the load testing.

Each of the four load tests was performed in a similar manner. The Linear Variable Differential Transducers (LVDTs) were installed to measure the horizontal strain at the midspan of three channel-members. In addition, three LVDTs were placed at three locations on the midspan (one lane only) to measure vertical displacements. Result comparisons presented in the following are based on live-load effects only. In-situ testing clearly indicates the improved deflection behavior due to FRP strengthening, with smaller deflections measured after CFRP strengthening. In addition, the measured strains indicated that, for the same load level, the internal stresses in the original member have been reduced from those before strengthening, thus increasing their load-carrying capacity.

Effect of Strengthening on Bridge Load Rating

Load rating a bridge is achieved by calculating a rating factor (RF), using the method outlined by AASHTO in the *Manual for Condition Evaluation of Bridges*. If the RF is greater that 1, then the bridge can be rated safe for the target rating. The inventory ratings of the bridges based on flexure varied from 1.04 to 1.11, and those based on shear, from 1.05 to 1.08. These rating values are based on an HS20 truck load (34-ton load rating). As seen in these tables, the applied strengthening for the three bridges has the effect of increasing the rating factor, allowing for a higher bridge rating. Based on theoretical predictions and the observed response of the bridge during load testing, it was concluded that the overall goal of removing the 15-ton load rating has been accomplished.

Field Application of Research

The outcome of current research programs indicates that the strength of bridge decks can be increased using surface bonded FRP composites. The two strengthening techniques that were investigated, namely sulfate mounted FRP rods and externally bonded FRP sheets, were found to be very effective in increasing the capacity of solid RC deck slabs. The performance of the strengthened slabs was verified through laboratory testing as well as full-scale in-situ testing to failure.

Utilizing the economical and structural benefits of externally bonded composites, the use of FRP reinforcement was employed for upgrading single-span bridges. Externally bonded CFRP composites provided the most economical solution for flexure and shear upgrade of three highway bridges located in Boone County, MO. The lower upgrade cost resulted from speed and ease of composite system application. Each bridge was closed for approximately one week, which resulted in a minimal disruption to traffic. Due to its light weight, installation of the CFRP system was achieved by a crew of four workers and did not involve the use of any heavy machinery. Results of in-situ load testing of the strengthened bridges suggests that CFRP application improved the stiffness and the strength of the bridge deck.

Based on the results of the analytical calculations of the structural components, as applied to the AASHTO rating equation and the validation by load testing, a recommendation to remove the load posting can be substantiated. For both bending moment and shear, the load-rating factor was increased to a value of over 1.0 for each bridge member.

The design/build approach that was used in this project and the quality control of the specialized contractor was essential to achieve a successful upgrading with externally bonded FRP reinforcement.

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(a)

(b)

Figure 9: Coats Lane Bridge before (a) and after (b) strengthening

Figure 10: Bridge in-situ load testing