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OVERVIEW OF TESTING TO FAILURE PROGRAM OF A HIGHWAY BRIDGE STRENGTHENED WITH FRP COMPOSITES

Antonio Nanni, Tarek Alkhrdaji, Genda Chen, Michael Barker,
Xinbao Yang, and Randy Mayo

Synopsis:

This paper presents an overview of a research program aimed at validating the effectiveness of strengthening highway bridges with FRP composites. The validation is carried out by performing load tests to failure on the decks and piers of an existing bridge. The selected bridge is a solid slab reinforced concrete structure and is representative of bridges constructed in Mid-America during the first half of this century. Two of the three decks were strengthened with externally bonded unidirectional carbon FRP sheets and near-surface mounted carbon FRP rods. Elastic tests were conducted on the decks using a moving vehicle. These tests were conducted prior to and after strengthening as well as after cutting the bridge parapets. The decks were tested to failure under static loads. At different stages of damage, as caused by the static loads, the decks were subjected to the dynamic force applied by a shaker in an attempt to correlate dynamic signature to the level of damage. The piers, originally designed for gravity loads, were seismically upgraded. Piers were strengthened using near–surface mounted carbon FRP rods as well as jackets made of continuous FRP sheets. The piers were tested to failure under cyclic static loading. The research program results indicate that FRP materials can effectively be used for strengthening reinforced concrete bridge structures.

Keywords: bridges, carbon fibers, decks, flexure, FRP, glass fibers, jacketing, load testing, piers, seismic upgrade, strengthening

Antonio Nanni, FACI, is the V & M Jones Professor of Civil Engineering and Director of the University Transportation Center (UTC) at the University of Missouri-Rolla. Dr. Nanni is interested in construction materials, their structural performance, and field application. Antonio Nanni is an active member in the technical committees of ACI, ASCE, ASTM and TMS.

Tarek Alkhrdaji, ACI member, received his MS in 1997 from the University of Missouri-Rolla where he is currently a Ph.D. Candidate in the Department of Civil Engineering. In 1997, he received the ACI-Missouri Chapter Graduate Student Award. Tarek Alkhrdaji is a member of ASCE and EERI.

Genda Chen, an assistant professor in the Department of Civil Engineering at the University of Missouri-Rolla, specializes in structural earthquake engineering. He received his Ph.D. degree in 1992 from the State University of New York at Buffalo. He is presently a registered Professional Engineer in the State of California. Dr Chen is a member of ASCE and EERI.

Michael Barker is an associate professor in the Department of Civil Engineering at the University of Missouri-Columbia. He received his BS and MS from Purdue University and his Ph.D. from the University of Minnesota in 1990. Dr. Barker has conducted research projects in the experimental testing, analysis, and design of steel girder, and concrete bridges.

Xinbao Yang is a Ph.D. candidate in the Department of Civil Engineering, University of Missouri-Rolla. He obtained his BS and MS degrees from Shanghai Institute of Railway Technology in China. His research fields include seismic assessment and retrofit of bridges, structural vibrations, and health monitoring. He is a member of EERI.

Randy Mayo is currently an Area Engineer for the Missouri Department of Transportation. He has over 21 years of bridge design, inspection, and construction experience. He received his BS degree in civil engineering from the University of Missouri-Rolla in 1979.

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INTRODUCTION

Many reinforced concrete (RC) solid slab bridges in Missouri and surrounding states were constructed in the first half of this century. These bridges were designed to accommodate traffic loads smaller than currently permitted and with no consideration to seismic vulnerability. At present, many of these structures have not deteriorated but are structurally deficient. Solutions for the upgrade of these bridges using economical and reliable techniques are of great interest. To this effect, advanced composite materials made of fiber reinforced polymers (FRP) have a great potential (1).

Bridge J857 (see Figure 1), located on Route 72 in Phelps County, Missouri, was scheduled for demolition during the fall of 1998. The bridge provided an excellent opportunity to demonstrate the effectiveness of FRP systems for structural upgrade. The bridge was built in 1932 and consists of three simply supported decks made of 18 in. (460 mm) thick solid reinforced concrete slabs with an original roadway width of 25 feet (7.6 m). Each simply supported deck spans 26 ft (7.9 m). The original plans of the bridge shows that deck slabs are reinforced with #8 (25 mm) deformed steel bars at 5 in. (127 mm) spacing in the longitudinal direction and #4 (13 mm) deformed steel bars at 18 in. (457 mm) spacing in the transverse direction. Two abutments and two bents support the bridge decks. Each abutment consists of two piers connected at the top by a cap beam. The bents are at a 15-degree skew. The piers have a 2 by 2 ft (0.6×0.6 m) square cross-section and are reinforced with four #6 (19 mm) deformed steel bars located at the corners of the cross section. The transverse reinforcement is made of #2 (6 mm) steel ties at 18 in. (457 mm) spacing. Contrary to dimensions shown in the original drawings, the actual height of the piers was found to vary from 6 to 11 ft (1.8-3.4 m). The piers are supported by spread footings with the following dimensions: 4 by 4 by 2.5 ft ($1.2 \times 1.2 \times 0.75$ m). The reinforced concrete parapet walls are approximately 2.5 ft (0.75 m) high and run the entire length of the bridge. Bridge dimensions were verified through field inspection. Steel reinforcement size and spacing and concrete cover thickness were verified using a bar locator. In general, the condition of the bridge was good and no major damage (e.g., corrosion of reinforcement, or concrete spalling) was observed. The material properties used in the preliminary analysis were based on the values recommended by MoDOT database (2).

The main objective of this research program was to investigate the effects of different strengthening techniques on stiffness, structural performance, ductility, and mode of failure of decks and piers. In addition, it was possible to investigate other bridge engineering issues such as the effects of parapets on stiffness, effect of skew on deck performance, and correlation of dynamic signature of the bridge decks to the induced level of damage**.**

Figure 1. Bridge J857 after strengthening

BRIDGE STRENGTHENING

The bridge was strengthened while in service. Compared to other strengthening techniques, the application of FRP is rapid and does not interrupt traffic flow. Two systems were used in strengthening the bridge decks and piers: externally bonded FRP sheets and near-surface mounted FRP rods. Externally bonded FRP sheets installed by wet lay-up are currently and successfully used worldwide (1). Near-surface mounted FRP rods embedded in pre-made grooves and bonded in place with an epoxy-based paste is a more recent method. This technique provides benefits similar to those of FRP sheets. An additional advantage of this technique is the possibility of anchoring the reinforcement into adjacent RC members. The application of near-surface mounted reinforcement requires minimal surface preparation work and installation time. For this project, CFRP rods with surface roughened by sandblasting were used. The mechanical properties of the FRP sheets and rods used in the project are given in Table 1.

Bridge Deck Strengthening

Two of the three bridge decks were strengthened to the same level of nominal capacity using either externally bonded FRP sheets or near-surface mounted FRP rods. 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 HS20-

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modified truck load. This level of strengthening would also provide a clear differentiation between strengthened and un-strengthened decks. Table 2 shows the current and upgraded flexural capacity of the bridge decks.

Table 1. Mechanical properties of FRP reinforcement

FRP Type	Dimension (in) [mm]	Design Strength (ksi) [MPa]	Design Strain (in/in or mm/mm)	Tensile Modulus (ksi) [Gpa]
Glass sheets*	Thickness t_f = 0.0139 [0.353]	220 [1520]	0.021	10,500 [72]
Carbon sheets*	Thickness t_f = 0.0065 [0.165]	550 [3800]	0.017	33,000 [228]
Carbon rods**	$D = {}^{7}/_{16}$ [11]	180 [1240]	0.0105	17,200 [119]

* Fiber properties ** Rod properties

Table 2. Current and upgraded flexural capacity of the bridge decks

Computed Capacity (k-ft) [KN-m]	Required Nominal Capacity (k-ft) [KN-m]		Desired Flexural Capacity (k-ft) [KN-m]
	HS 20	HS 20 mod.	
78.5 [106.4]	91.1 [123.5]	101.6 [137.8]	101.7 [137.9]
Required Strengthening	16%	29%	30%

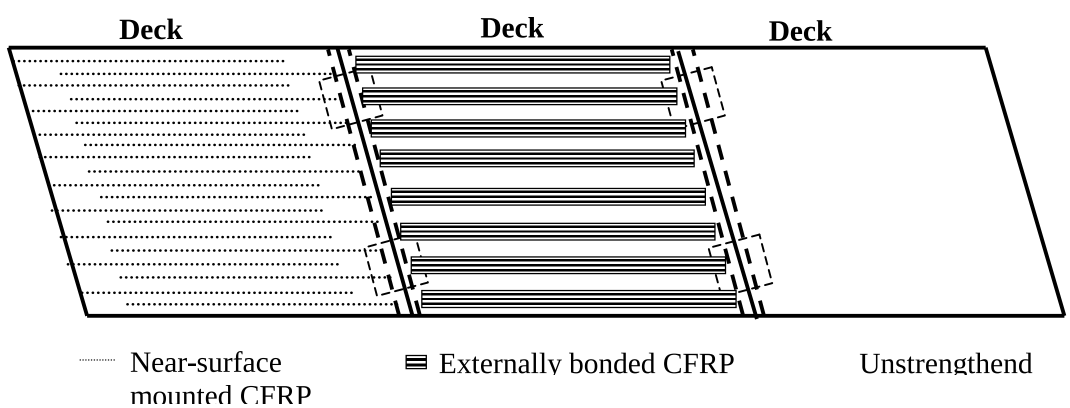

Figure 2. Bridge deck-strengthening schemes

The design was achieved using a procedure for ultimate state conditions in which the classical approach of equilibrium and compatibility requirements was used to obtain a failure mode based on steel yielding followed by FRP rupture (3). The design of externally bonded sheets called for eight, 20-in (500 mm) wide, single-ply of CFRP strips on the deck soffit. The strips were evenly spaced over a width of 25 ft (8.2 m) and ran the entire length of the slab, as shown in Figure 2. A certified specialty contractor applied the FRP sheets in accordance to manufacturer's specifications (4). Similarly, the required number of near-surface mounted reinforcement was determined to be 20 rods spaced at 15 in. (375 mm). The FRP rods were staggered such that at least 50% of the area of FRP reinforcement extended to the support, as shown in Figure 2. The rods were embedded in 20 ft (6.6 m) long, ¾" (19 mm) deep, and $^{9}/_{16}$" (14 mm) wide grooves cut onto the soffit of the bridge deck parallel to its longitudinal axis. The rods were grouted in place using a viscous epoxy paste. Appropriately spaced wedges were used to hold the rods in place until the epoxy cured.

Pier Strengthening

Design for the seismic upgrade of the piers was conducted with consideration to current code requirements. Both the ductility and strength of the piers were addressed in the seismic upgrade. Seismic performance category (SPC) B was selected for this project since it is representative of existing bridges in Missouri. A preliminary investigation indicated that the piers were adequate for resisting the shear forces induced by an earthquake while a deficiency existed in ductility and flexural capacity. Table 3 summarizes the current and upgraded flexural and shears capacities of the bridge piers. The flexural strengthening design of bridge piers was achieved using compatibility and equilibrium approach.

Three of the four bridge columns were strengthened. The un-strengthened column was used as a benchmark. One column was externally jacketed with glass FRP sheets to study the effect of concrete confinement on column ductility. The jacket consisted of six plies of glass FRP sheets installed by wet lay-up. The jacket was applied in 20 in. (500 mm) sections and covered the entire height of the column. The fiber direction was perpendicular to the column axis.

The other two columns were strengthened with near-surface mounted CFRP rods to increase the flexural capacity of the columns. The rods were anchored to the footing to ensure that the full capacity of the strengthened section is attained at the base of the column. The intended levels of flexural strengthening were such that two different failure modes would be achieved. One controlled by rupture of the CFRP reinforcement (3 rods on each face of the column) and one by crushing of concrete (7 rods on each face of the column). The rods were mounted on two opposite faces of the columns in a similar manner to that discussed for the decks and were fully anchored (minimum 15 in., 375 mm) into the footings. For this, 16-in (400 mm) deep holes were drilled into the footings, aligned with the grooves on the column sides. The grooves and the drilled holes were filled with a viscous epoxy grout. Finally, the columns were wrapped with 4-ply, 20 in. (500 mm) wide, CFRP jacket to improve the ductility. The jacket covered the entire height of the columns. The fiber direction was perpendicular to the column axis.

Table 3. Current and desired flexural and shear capacities of bridge piers

Current Capacity		Required Capacity Based on SPC B		Desired Flexural Capacity		
Shear (kips) [KN]	Flexure (k-ft) [KN-m]	Shear (kips) [KN]	Flexure (k-ft) [KN-m]	0 Rods (k-ft) [KN-m]	6 Rods (k-ft) [KN-m]	0 Rods (k-ft) [KN-m]
76 [338]	140 [190]	36 [178]	360 [488.2]	140 [190]	283 [383.7]	388 [526.1]

TESTING PROGRAM

Destructive and Non-Destructive Testing of Bridge Decks

Non-Destructive Testing: The three bays of the bridge were field tested elastically prior to any strengthening work using a field test system consisting of two main units. The data acquisition unit, which is a self-supporting vehicle equipped with devices capable of measuring up to 100 channels of strain and 25 channels of deflection. The loading unit is a flatbed truck that can be loaded with up to 75,000 lb (34 tons). For this test, the flatbed truck was loaded with steel weights to simulate an H20 vehicle. The total weight of the truck was approximately 42 kips (19 tons). Once the strengthening work was completed, the three bays of the bridge were once again elastically tested using the same equipment, as shown in Figure 3. A third load test was carried after cutting the parapet walls of the bridge (see Figure 4) and cleaning bridge deck joints to determine their contribution to bridge stiffness.

Concrete cores and steel reinforcement samples were obtained for laboratory characterization. Pull-off tests were conducted on the FRP sheets as quality control tests to ensure adequate bond with the concrete. In addition, pull-out tests were conducted in the laboratory on CFRP bars to determine the required development length (5).

Static Load Testing: Each of the three spans was tested to failure by applying a quasi-static load cycles. Four 200-kips (90-tons) hydraulic jacks were used to apply the static load (See Figure 5). The jacks rested on the bridge deck and pulled against two steel spreader beams located under the deck. Each spreader beam was made of two standard W14×90 steel shapes. The spreader beam transfers the load to a steel girder made of two W36×150 steel shapes, which reacts against the cap beams as shown in Figure 5. 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.

Dynamic Load Testing: Dynamic tests were conducted on each of the three slabs. A dynamic shaker mounted on top of each slab was used to induce the dynamic force. The shaker was placed at mid-span to generate the first mode of vibration of the bridge slab. The shaker was operated at several frequencies until resonance in slab was achieved. A dynamic test was conducted in-between some static load cycles. Accelerations and deflections of each deck were recorded at different locations as a function of time.

Testing of Bridge Piers

The piers were tested to failure by applying cyclic lateral loads to the pier cap beams. To achieve this, the central portion of the cap beam was removed and a hydraulic jack was inserted in the gap. A second hydraulic jack was attached to a reaction frame as shown in Figure 6. The two jacks were used alternately to create a cyclic loading condition. A 10-in strip of each deck was saw-cut along the longitudinal axis of the bridge to allow for the relative displacement of the piers. Column displacements, rotation, steel strain, and strain in CFRP and GFRP sheets were measured at different locations.

Figure 3. Elastic load test

Figure 4. Cutting bridge parapet walls

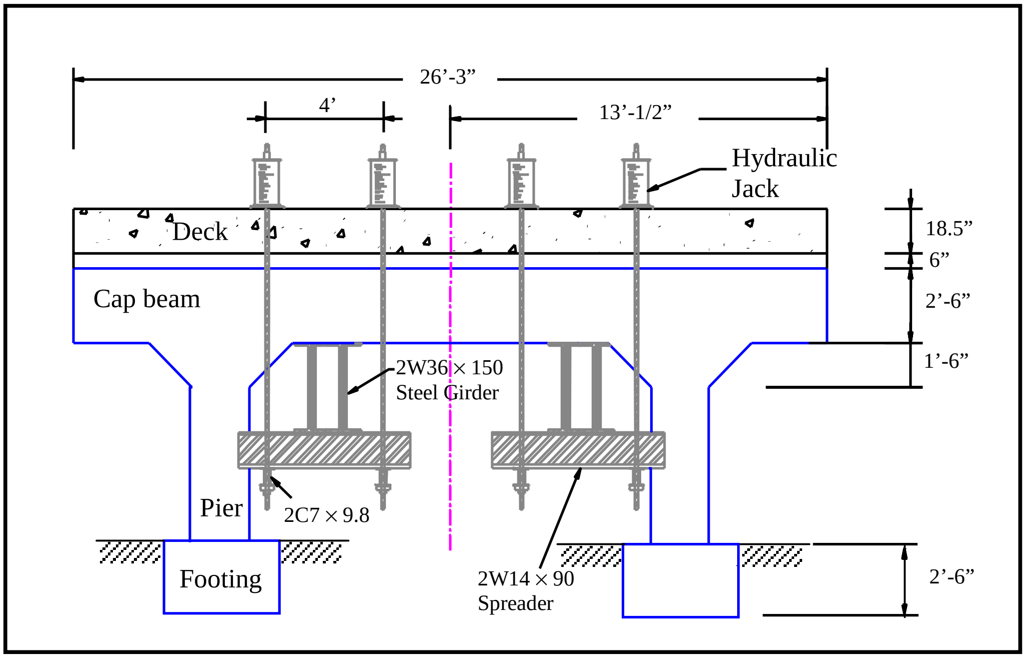

Figure 5. Static load test setup for bridge decks (1 in. = 25 mm)

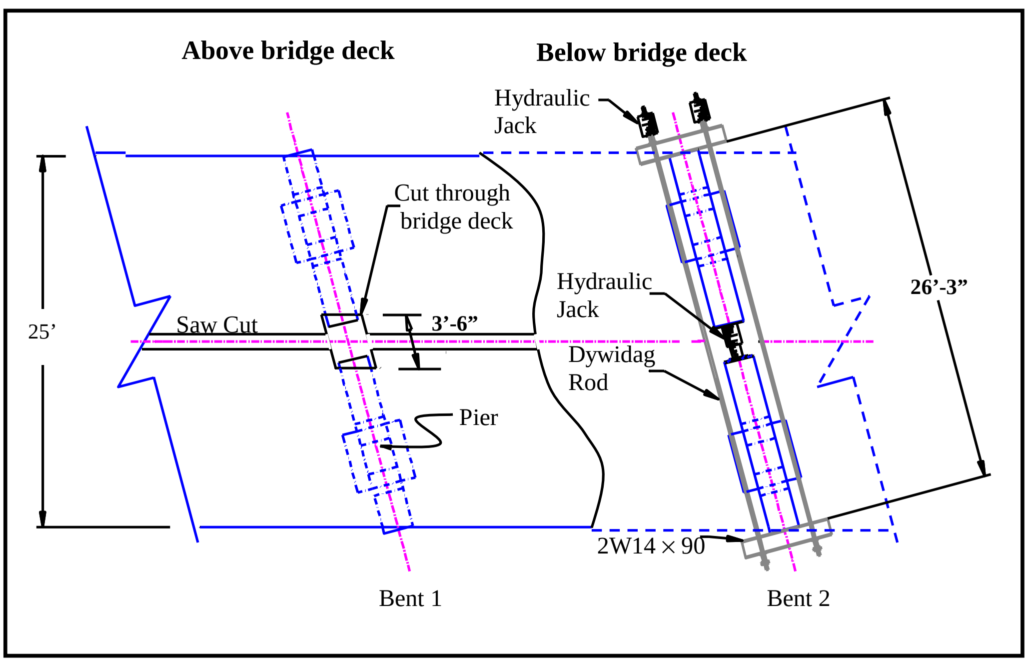

Figure 6. Configuration of cyclic loading mechanism for bridge piers (1 in. = 25 mm)

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TEST RESULTS AND CONCLUSION

Preliminary examination of the test results clearly indicates the good performance of the strengthened decks with ultimate strength capacities exceeding DOT requirements. The nominal capacity of the three decks at failure and the associated mode of failure are given in Table 4. In general, the strengthened decks had smaller deflections at ultimate than the un-strengthend deck. Failure loads of bridge piers exceeded in magnitude the predicted loads. This behavior is related to the effect of superstructure/substructure interaction and the skew effect on the lateral load capacity of the piers. Test results obtained during this research program are used to validate the effectiveness of strengthening bridge components using FRP composites.

The elastic tests are used to (1) determine how superstructure accessories affect bridge stiffness and (2) determine the effect of FRP materials on the elastic response of the strengthened structure. The destructive tests on the decks are used to (1) determine the mode of failure of the structural member with and without strengthening and (2) determine the effect of skew on deck behavior and failure mode. The dynamic tests are used to (1) correlate dynamic signature with the level of damage induced by quasi-static loading and (2) determine if dynamic signature is a viable method to assess strengthening. The destructive tests on piers are used to(1) determine the ultimate capacity and modes of failure of piers with and without strengthening and (2) confirm/calibrate analytical models for behavior of concrete columns under lateral loads

Table 4. Moment capacities and failure modes of tested bridge decks

Strengthening Type	None	Externally bonded sheets	Near-surface mounted rods
Capacity (k-ft) [KN-m]	(114.6) [155.4]	(134.1) [181.8]	(147.4) [200]
Failure Mode	Crushing of concrete	Peeling of CFRP sheets	Rupture of CFRP rods

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