STRENGTHENING OF OFF-SYSTEM BRIDGES USING FRP COMPOSITES

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Abstract

A significant number of Bridges in the United Stated and all over the world need rehabilitation and strengthening. Due to budget constraints, many authorities are forced not to proceed with strengthening but to post load restrictions on their bridges as a temporary measure. Fiber reinforced polymers (FRP) provides an economical and practical solution for repair/strengthening of highway bridges. Three off-system bridges in Missouri that were constructed in the 1970's had a constant increase in the traffic volume and the use of heavier trucks. Analysis of these bridges indicated that they are deficient in shear and flexure and demanded an upgrade to withstand the current (HS20) truck loading. Using FRP composites, an economical upgrade solution was achieved due to the speed and ease of their installation that involved minimum labor and traffic interruption. Load tests were conducted on two of these bridges before and after strengthening to evaluate their performance. This paper reports on the strengthening techniques, design approach, and testing of the bridges.

Introduction

The National Research Board [1] reports that in the United States (US), there are approximately 590,000 structures in the National Bridge Inventory database. Fatigue and deterioration of steel reinforcement from chlorides used in de-icing operations have accelerated deterioration rates of many bridges. As a result, over 40 percent of the bridges in the US need repair, strengthening, or replacement. In addition, many bridges have exceeded their design life and carry loads heavier than their original design loads. A recent survey indicated that sixty-three percent of the North American transportation agencies expect the need to increase the live load capacity of existing highway bridges to increase as the infrastructure continues to age [2]. Budget constraints due to shortage of available funds have forced many states Department of Transportation (DOT) to post load restrictions on deficient bridges until more funds become available. Several DOT's are using more sophisticated methods of analysis to elevate to a higher load rating. The use of full-scale in-situ load testing to evaluate existing live load capacity of questionable bridges also has been used.

The conventional methods for improving the live load capacity of bridges include section enlargement, span shortening, and the use of epoxy bonded steel plates. Corrosion-related problems and difficulty of application due to the heavy weight of steel plates have limited the use of latter technique.

Recent developments in advanced fiber reinforced polymer (FRP) materials, have shown that these materials are good alternative to steel plate bonding. Previous research studies and field applications of externally bonded FRP systems have been documented in ACI 440 [3]. Criteria for evaluating FRP systems are becoming available to the construction industry [4,5].

In the United Kingdom, the Concrete Society has recently released Technical Report No.55 "design guidance for strengthening concrete structures using fiber composite materials"[6]. The American Concrete Institute (ACI) is in the final stages of releasing a similar document to be used as a

"Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures"[7]. The Federal Highway Administration (FHWA) is currently sponsoring research programs to develop model specifications for repair/strengthening of existing bridges using FRP composites and to ensure the quality and performance of FRP strengthening. Recent publications [8, 9] show a wider acceptance and applications in industrial and other conventional problems in the United States. The development in India through the last several years indicates that there is a further scope for collaboration of technology and the available indigenous materials and application of FRP.

FRP materials provide an excellent and economical solution for 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 structures 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 the State of Missouri in the Mid-west United States, various bridges have been strengthened using FRP techniques. They demonstrated the collaboration between the government (public funding), industry (engineering and construction) and academic using sophisticated methods of 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, using FRP upgrading of three bridges located in Boone County, Missouri. Project background, description of these bridges, FRP strengthening design and application, and in-situ load testing are presented in this paper.

Bridge Description

The 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. and connecting 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 slab, one on each side of the deck. The edge slabs were designed for HS20 truck loading. Creasy Springs and Brown School Road bridges are located on roads with a high traffic count. Coats Lane Bridge is located on a gravel County road. A summary of details for these bridges is given in Table 1. Figure 1 shows a typical cross section seen on these bridges. The three bridges were designed according to 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 3,600 vehicles per day cross Creasy Springs and Brown School bridges with an estimated 10% truck usage. Coats Lane is used by approximately 160 vehicle per day. Due to increasing traffic counts and use of heavier traffic, the bridges needed strengthening to remove the posted loads. Upgrading these bridges would open up greater accessibility for industry as well as access to the emergency vehicles to reach area residents and avoiding a 6 mile detour. Current AASHTO code indicated that the RC channels require upgrading of their flexure and shear capacity to carry the new truck loading.

Table 1. Details of the Three Bridges

	Brown School	Creasy Lane	Coats Lane
Span (ft)	20.1	19.4	38.8
No. of Channels	8	8	8
Total Width (ft)	25.3	25.3	25.3
As (in^2)/channel	3.16	3.16	8.0
Effective Depth, d (in.)	16	16	14.75
As (shear) (in^2)/ft	0.196	0.196	0.196

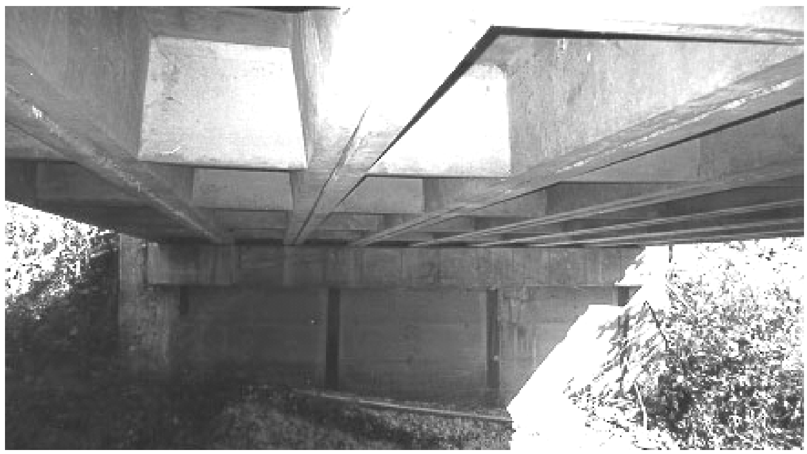

Figure 1. The Underside of Coats Lane Bridge.

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 system, 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/built scenario. The project was awarded to a specialty concrete structures repair and upgrade contractor with experience in the design and application of FRP strengthening systems. Following a field investigation and condition survey, and review of bridge plans, the initial estimate of structural upgrade of the three bridges was approximately $65,000, with $155,000 in savings. To allow for load posting removal, the Missouri Department of Transportation (MODoT), requested a full-scale load testing of at least two of the bridges before and after strengthening.

Material Characteristics

The original design concrete strength was 3,000 psi, field tests using a Schmidt-Hammer yielded a concrete strength of approximately 9,000 psi. However, it was decided to use a concrete strength of 5,000 psi for analysis and strengthening design. Steel yield strength of 40 ksi was used.

Structural Capacity

The capacity of the three bridges was calculated according to AASHTO specifications. A summary of the flexural and shear strength and design requirements based on HS20 truck loading for each bridge are given in Tables 2 and 3, respectively. The table also gives the required level of strengthening to achieve the design strength.

Table 2. Summary of Flexural Requirement

Bridge	**New Demand, M_u (ft-k)**	**Capacity, ϕM_n (ft-k)**	**Required Strengthening (%)**
Brown School Road	177.2	147.7	20
Creasy Springs	166.9	147.7	13
Coats Lane	461.8	473	0*

*Minimum flexural strengthening will be added to ensure comparable reserve strength

Table 3. Summary of Shear Requirement

Bridge	**New Demand, V_u (k)**	**Capacity, ϕV_n (k)**	**Required Strengthening (%)**
Brown School Road	43	35.8	20
Creasy Springs	41.9	35.8	17
Coats Lane	56.1	46.1	22

Design of FRP Strengthening

The design of externally bonded FRP strengthening was achieved using carbon FRP (CFRP) reinforcement. The CFRP material has design strength of 550 ksi, a modulus of 33,000 ksi and an ultimate strain at failure of 0.017 in./in. The same CFRP material was used for flexure and shear strengthening of all three bridges.

Flexure

The strengthening design of bonded FRP sheets was achieved using the limit state approach. Accordingly, flexural capacity of the critical section is calculated by combining force equilibrium, strain compatibility and constitutive laws of the materials [10]. Unlike steel, FRP materials are linear elastic up to failure and cause the strain in the outermost fibers of concrete and of the FRP to vary, depending on the section properties and reinforcement of the member. Since the concrete strain at failure is equal to or less than 0.003 in./in., the typical rectangular stress block factors, $\square_1$ and $\square_1$, defined by ACI 318 are not applicable. In lieu of the ACI definition, the equivalent stress block factors can be calculated for any value of maximum concrete strain by the numerical integration of the stress strain diagram and the nonlinear compressive stress distribution in the concrete [11]. Although strength calculations indicated that Coats Lane Bridge did not need flexural strengthening, a decision was made to apply CFRP strengthening to the bridge to ensure reserved flexural strength, as indicated in Table 4.

Table 4. Flexural CFRP Reinforcement

	No. of Plies per Stem	Ply Width (in)	Ply Length (ft)
Brown School Road	1	5	18.8
Creasy Springs	1	5	18.1
Coats Lane	1	4	35.5

Shear strengthening

Shear strengthening was based on the design approach proposed by Khalifa et al [12]. Table 6 provides a summary of requirements to correct the shear deficiency of a single bridge channel.

Table 5. Shear CFRP Reinforcement

	No. of Plies per Stem	Ply Width (in)	Strips Spacing (in)
Brown School Road	1	24	32
Creasy Springs	1	24	32
Coats Lane	1	24	32

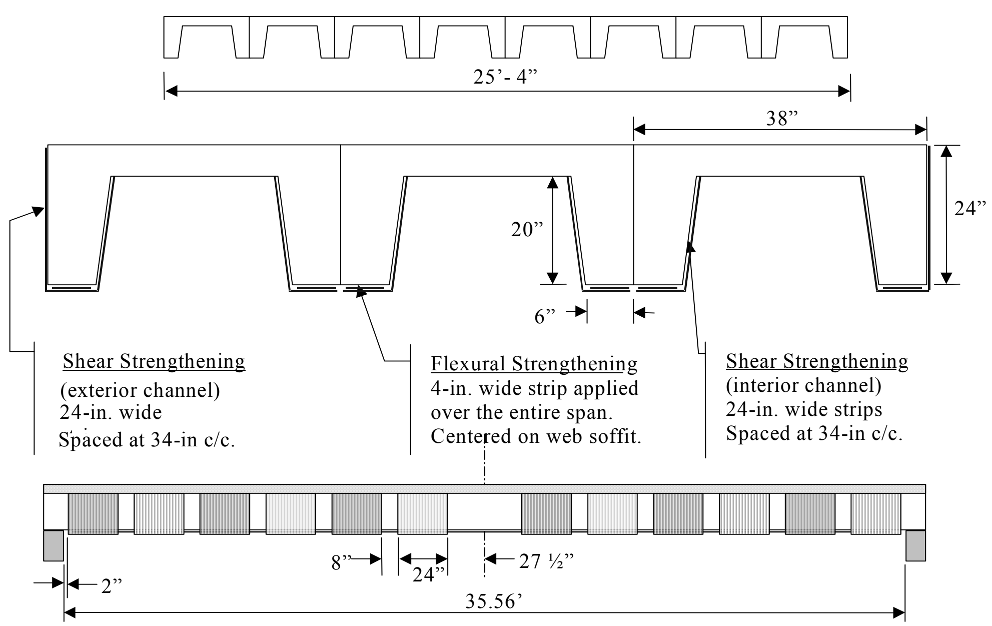

Figure 2. Details of CFRP strengthening for Coats Lane Bridge

CFRP strengthening system was applied with the wet lay-up procedure using unidirectional CFRP sheets of 0.0065-in. thickness. Wet lay-up systems are saturated and cured in-place and therefore, are 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 (see Figure 3). The surface of the concrete was prepared prior to CFRP application using sand blasting to remove loose concrete and other particles that may hinder 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 FRP system. It is therefore recommended that a contractor with experience on similar projects should be employed for FRP strengthening.

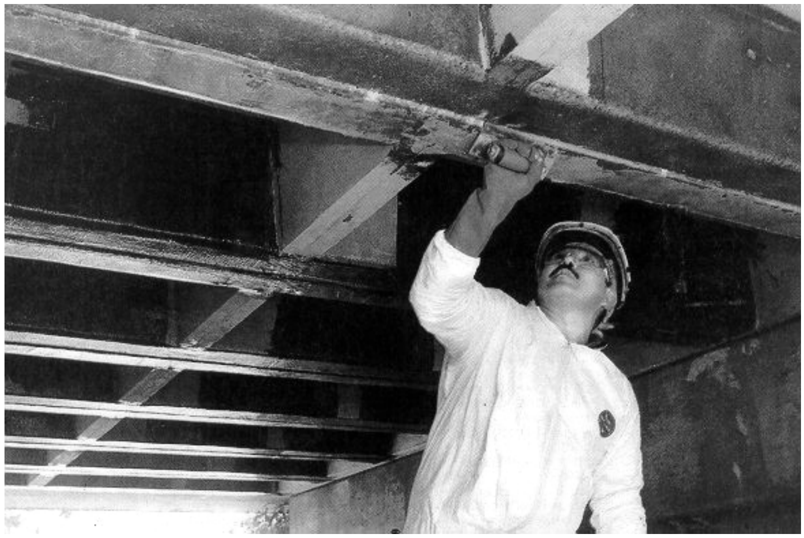

Figure 3. Application of FRP Reinforcement

Elastic In-Situ Load Testing

Four load tests (two tests per bridge) were performed on Coats Lane Bridge and 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. 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. Figure 4 shows Coats Lane Bridge before and after strengthening.

Load Test Configuration and Instrumentation

Each of the four load tests was performed in a similar manner. The LVDTs were installed to measure the horizontal strain at the mid-span of three channel-members. At the level of the steel reinforcement, the LVDTs were used measure horizontal deformations (elongation) over a 12-in. gage length. Large gage length was used in order to measure an average strain value thus, minimizing any local effects that crack opening may have on the strain distribution. On the soffit of the slab of the channel section, the LVDTs was installed to measure horizontal deformations (shortening) over a 12-in. gage length. In addition, three LVDTs were placed at three locations on the mid-span (one lane only) to measure vertical displacements (see Figure 5). During load tests performed after strengthening, strain gages were installed on the surface of the FRP reinforcement to monitor their performance.

Measurements acquired during load testing reflect only the effects of live loads. Dead weight effects cannot be measured in the field. However, deformation and strains due to dead weight effects can be theoretically estimated. In order to accurately evaluate the effects of FRP strengthening on the structural behavior of tested bridges, result comparisons presented in this study are based on live load effects only.

Figure 4. CFRP strengthening of Coats Lane Bridge

Load Testing Procedure

The two H20 trucks made two passes on the bridge. In each pass, the two trucks were driven side-by-side along the length of the span, as shown in Figure 6. The trucks were stopped with their rear (heaviest) axle positioned at five locations along the span of each of the bridges (spaced at one-sixth the span). The trucks rested at each location for approximately 2 minutes before proceeding to the next location. Once the trucks have completed all of the stops on the bridge, the physical testing of the bridges was completed.

Test Results

Figures 7 and 8 illustrate the measured response of the Coats Lane bridges in terms of deflection prior to and after strengthening with FRP composites. These figures give the real-time deflection response for two loading cycles (two truck passes). The five steps shown on each pass correspond to the five locations where the trucks were stopped. During the test, it was observed that the measured deflections for the second pass were slightly larger that those measured on the first pass. It is not clear as to why this behavior has occurred. Comparison of the two tests clearly indicates the improved deflection behavior due to FRP strengthening. The deflection at mid-span was reduced by approximately 20% after strengthening with CFRP composites. This behavior indicates some contribution of CFRP composites to the stiffness of the structure. Test results also indicated that, for the same load level, the internal stress in the original member have been reduced from those before strengthening thus, increasing their load carrying capacity.

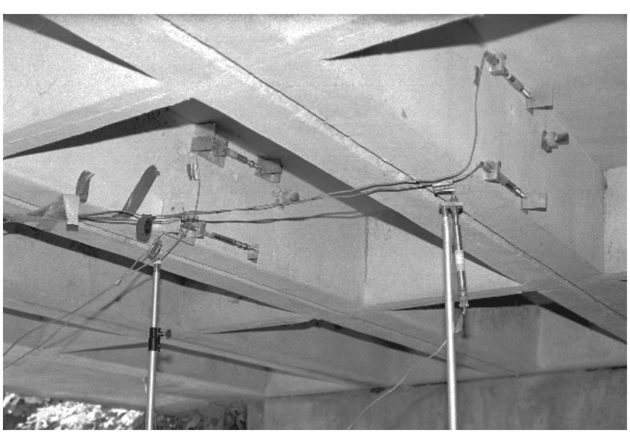

Figure 5. Load–testing instrumentation

Figure 6. Bridge In-situ load testing

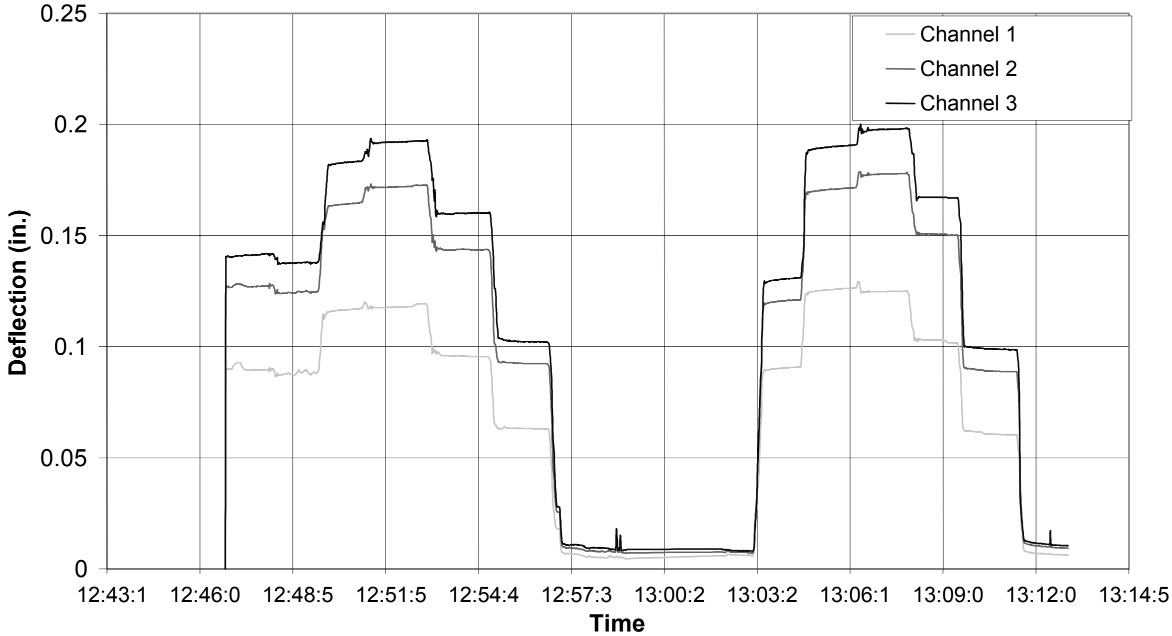

Figure 7. Deflection measured prior to strengthening

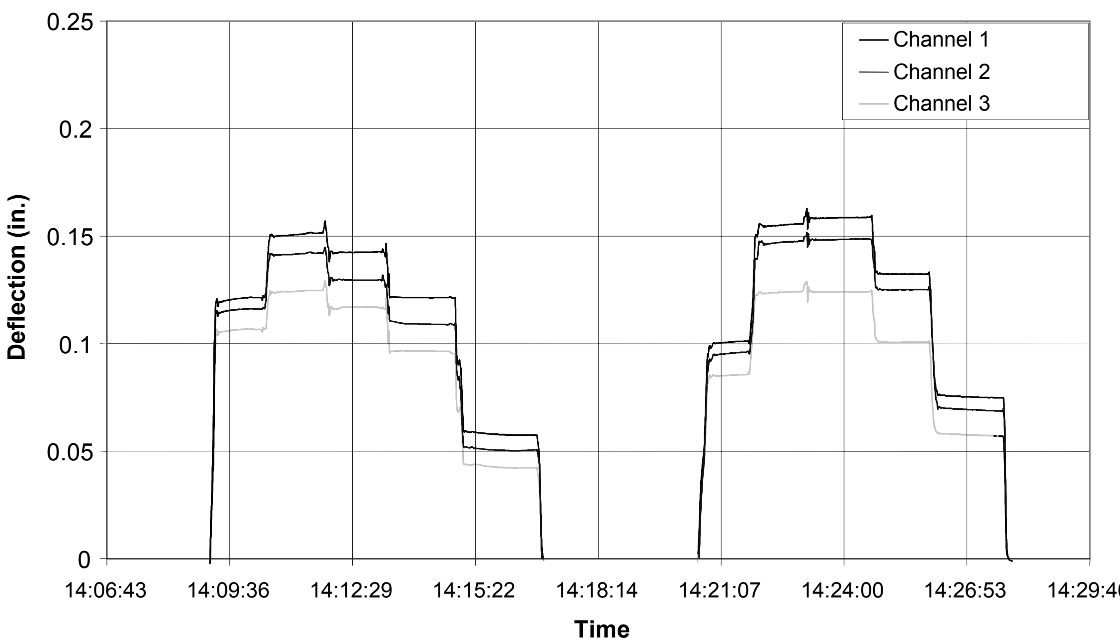

Figure 8. Deflection measured after FRP strengtheing

Figure 9 shows the moment histogram for the bridge prior to strengthening, calculated using the strain measurements and assuming linear elastic behavior. The maximum moment computed with this procedure is approximately 62.0 kip-ft. This value is smaller than the theoretical live load moment of 95.5 kip-ft based on AASHTO wheel load distribution guidelines and an H20 truck. The smaller moments measured in the field was related to the following two reasons:

- the lateral distribution of the wheel loads across the width of the bridge as proposed by AASHTO is a conservative estimate; and

- the strain data are dependent on the location of the measurement and the crack pattern present in the region of measurement.

Figure 10 shows a comparison of the load-deflection results from both before and after strengthening. The plotted moments are those that were calculated based on the AASHTO load distribution factors. The deflections are those that were recorded during the tests at each of the truck positions. It can be seen from this figure that for any given moment (or applied load) the deflection decreased after the strengthening was applied. This also reflects the increased stiffness of the member due to the addition of the FRP laminates.

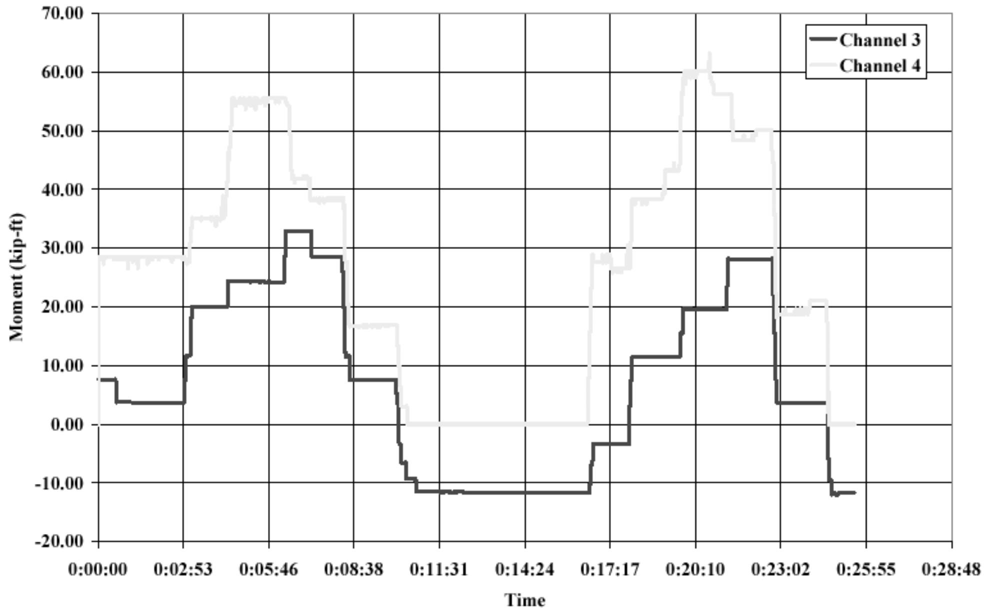

Figure 9. Moment histogram for Coats Lane Bridge (before strengthening)

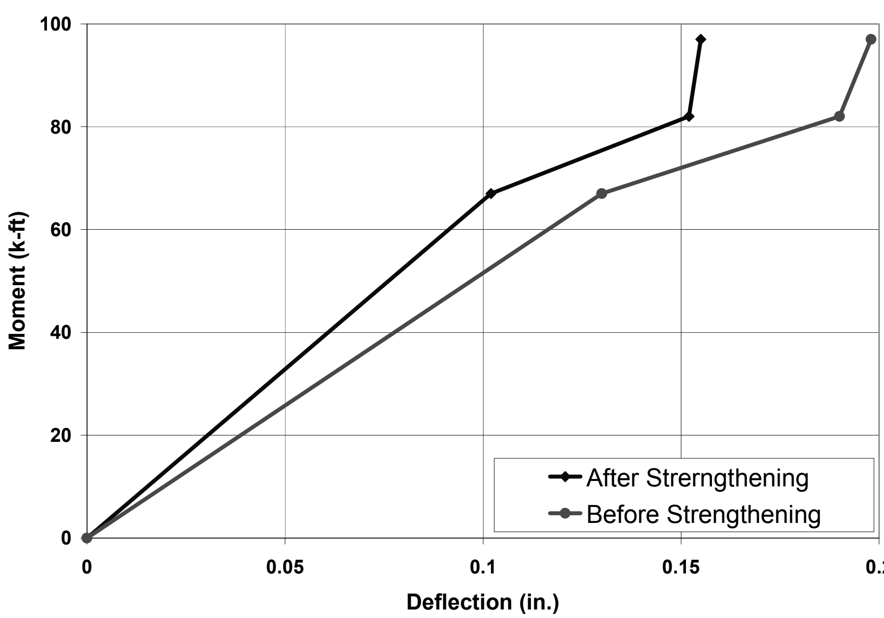

Figure 10. Comparison of moment-deflection results for Coats Lane Bridge.

Effect of Strengthening on Bridge Load Rating

In Missouri, All 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 Inventory Rating is taken as 60% of the Operating Rating. The Load Factor Rating Method for Operating Rating is based upon the appropriate ultimate capacity using current AASHTO specifications [13]. Load rating of a bridge is achieved by calculating a rating factor (RF) using the method outlined by AASHTO in the Manual for Condition Evaluation of Bridges [14]. If the rating factor (RF) is greater that 1, then the bridge can be rated safe for the target rating. The Inventory Ratings based on flexure is given in Tables 6 and that based on shear is given in Table 7. In these tables, rating is 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.

Table 6. Rating Factor for a Single Channel Section (Bending Moment).

	Rating Factor (RF)		
Bridge	**Before Strengthening**	**After Strengthening**	**Rating in Tons**
Brown School Road	0.80	1.04	20.7
Creasy Springs	0.86	1.11	22.3
Coats Lane	1.04	1.14	22.7

Table 7. Rating Factor for a Single Channel Section (Shear).

	Rating Factor (RF)		
Bridge	**Before Strengthening**	**After Strengthening**	**Rating in Tons**
Brown School Road	0.81	1.05	21.1
Creasy Springs	0.83	1.09	21.9
Coats Lane	0.78	1.08	21.6

Conclusion

Externally bonded carbon FRP composites provided the most economical solution for flexure and shear upgrade of three highway bridges located in Boone County, Missouri. The lower upgrade cost resulted from speed and ease of composite system application. Each bridge was closed for approximately one week, which resulted in minimum disruption to traffic. Due to its lightweight, installation of the CFRP system was achieved by a crew of four men and did not involve the use of any heavy machinery. Preliminary results of in-situ load testing of the strengthen 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. A single channel section was selected for each of the three bridges to determine its load rating based on an HS20 truckload. 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/ built 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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