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Strengthening of Off-System Bridges with Mechanically Fastened Pre-Cured FRP Laminates

by A. Rizzo, N. Galati, and A. Nanni

Synopsis: The Mechanically Fastened-FRP (MF-FRP) strengthening system has recently emerged as a practical alternative for strengthening RC structures. It consists of pre-cured FRP strips having high longitudinal bearing strength attached to the concrete surface using closely spaced steel fasteners in the form of nails or concrete wedge anchors. Resin can be used as gap filler between the concrete, the strip and the fastener. This paper presents the application of MF-FRP composites to strengthen several rural bridges with flexural deficiencies located in Missouri. The efficiency of the strengthening technique was demonstrated in terms of structural performances, and costs, labor and time savings.

Keywords: FEM; flexural strengthening; load rating; MF-FRP system; RC structures

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RESEARCH SIGNIFICANCE

The field validation of mechanically fastened FRP systems for the strengthening of rural bridges is presented. This technology is proven to be fast and economical and its effectiveness is demonstrated through field testing and FEM analysis.

INTRODUCTION

The Federal Highway Administration classifies 32 percent of rural bridges as structurally deficient: much of the problems with local bridges are due to age, obsolete design and improper execution of the work. The high cost associated with bridge replacement keeps communities from addressing many bridges. Even the cost to repair bridges is expensive with conventional bridge repairs, including removing bridge surfaces and adding new beams to strengthen spans. Maintaining and upgrading transportation infrastructure is a challenge for rural regions because of the sparse density of residents and number of roads and bridges running throughout the area. The low Average Daily Traffic (ADT) on most rural bridges makes the cost for bridge replacement seem ineffective. Low-volume bridges make it difficult for rural areas to compete for grant funding to assist with bridge replacements because rural areas are in competition with larger metropolitans. Rural areas are at a disadvantage because more populated areas can incorporate additional aspects of transportation, such as public transit and major economic impact, in grant proposals. Therefore, the strengthening of these bridges seems to be essential in order to remove or significantly increase load postings allowing for more access from county roads to major routes and directly impacting the economic development potential of the region. But, since conventional bridge repairs are not convenient, the possible application of new composites technologies has to be taken in consideration.

Fiber-reinforced polymer (FRP) materials have emerged as a practical alternative for construction, renovation and strengthening of bridges with significant cost and time savings over conventional methods. Advantages of FRP materials are that they resist corrosion, long outlive conventional materials, and have high strength-to-weight ratio. It has been shown that in this technical area nowadays the engineer has different tools available in order to find the optimal solution to each problem: manual lay-up FRP and SRP laminates, adhered pre-cured FRP laminates, near surface mounted (NSM) FRP bars and, finally, MF-FRP laminates (Lopez et al. 2004).

The MF-FRP laminates consist of pre-cured FRP strips having high transverse bearing strength attached to the concrete surface using closely spaced steel fasteners (Borowicz et al. 2004) in the form of nails or concrete wedge anchors (Bank et al. 2004; Rizzo 2005). Unlike the well known bonded methods, where adhesion is used to transfer the load to and from the reinforcement, the MF-FRP technique requires minimum surface preparation because the mechanism of load transfer to and from the composite laminate is provided by fasteners. The surface preparation includes removal and patching of unsound concrete area, elimination of concrete surface irregularities and form lines, and abrasive sandblasting in order to clean the concrete surfaces (dust, dirt, laitance, oil and any curing substance could compromise the bond) and obtain the optimal surface roughness. All these operations are labor intensive and time consuming, while major concrete deterioration beneath slabs and girders of rural bridges could prevent the application of any bonded strengthening system (see Fig. 1). In this case, the MF-FRP method may be very effective being, at the same time, a rapid and economical strengthening. Three structurally deficient bridges were strengthened using MF-FRP during the period of January-May 2004 and load tested in order to demonstrate the efficiency of this new strengthening system in terms of structural performances, and costs, labor and time savings.

DESCRIPTION OF THE BRIDGES AND OBJECTIVES

Selected Bridges

Three bridges were selected from a list of structurally deficient off-system bridges in the counties of Phelps, Dent, Crawford and Washington (Missouri, USA). The choice criteria were primarily based on the type of the structural deficiency, then on the size, the accessibility, the feasibility of the strengthening, and the importance/priority of the bridge. Therefore, among the structures with flexural deficiencies, those chosen were simply supported or continuous on two/three short spans in order to limit the labor/time/cost of strengthening. On the other hand, too short bridges were considered not feasible having a shear span improper to the anchoring of the laminates (the use of closely spaced fasteners was considered inefficient). Accessibility was another important factor since, being a pilot strengthening program, comfortable conditions were preferred to ease installation and monitoring. The importance/priority of each bridge was evaluated according to each county needs and on the Average Daily Traffic (ADT). Fig. 2 reports some geometrical details and the as built steel reinforcement of each bridge.

Bridge No. 1330005 (see Fig. 2a) is located on Route 3560 over a dry branch of the Meramec River in Phelps County, Missouri, USA. The total length of the bridge is

7925 *mm* and the total width of the deck is 6680 *mm*. The span of the bridge consists of four RC girders monolithically cast with a 152 *mm* deep deck. It can be assumed as simply-supported by the abutments. The bridge was load posted to a maximum weight of 9.07 *ton*.

Bridge No. 3855006 (see Fig. 2b) is located on Route 3855 (Industrial Drive) over a branch of Dry Creek in the City of St. James, Phelps County, Missouri, USA. The total length of the bridge is 7874 *mm* and the total width of the deck is 6756 *mm*. The structure is a 2-span continuous beam and each span consists of three RC girders monolithically cast with a 190 *mm* deep deck. The bridge was not load posted at the time of the strengthening.

Bridge No. 2210010 (see Fig. 2c) is located on County Road 6120 over Corn Creek in Phelps County, Missouri, USA. The total length of the bridge is 9754 *mm* and the total width of the deck is 6325 *mm*. The structure is a 3-span 229 *mm* deep deck: one span is simply-supported while the other two are continuous. The bridge was load posted to a maximum weight of 10.89 *ton*.

Conditions of the Bridges

From in-situ inspections, concrete spalling along the longitudinal edges of the superstructures was observed and, in some area, steel bars were found exposed and corroded in decks as well as in girders (see Fig. 3). As a consequence of the insufficient amount and layout of the longitudinal reinforcement (such as the not proper positioning of the steel reinforcing bars during the building of the bridge, see Fig 2b), girders and deck were visibly cracked mostly at mid-span (see Fig. 4). Due to the inadequate transversal reinforcement, decks also presented longitudinal cracks running close to the middle of the width or located halfway between adjacent girders (see Fig. 5a). Abutments appeared to be in good condition except for some vertical cracks running down from the bottom of the superstructures across the entire height of the abutments (see Fig 5b). As a consequence of the insufficient amount of vertical reinforcement, a mid-height horizontal crack was found on the West abutment of the bridge No. 2210010, probably due to the soil active pressure and the live loads surcharge (see Fig 5c).

The details of the three off-system bridges reinforcement and material properties were unknown at the time of strengthening due to the unavailability of plans. As a consequence, at the onset of the project, these properties were determinate in-situ, based on visual and Non Destructive Testing (NDT) evaluation. For each bridge, at least three concrete cores were drilled and tested in compliance with ASTM C39 and ASTM C42 (see Table 1). The location of the steel reinforcement was accurately detected with a rebar locator and, when necessary, concrete cover, number and size of flexural and shear reinforcement for girders were determined by chipping off concrete at different locations (see Fig 2 and Fig. 6). The steel mechanical properties were determinate by testing three specimens cut from exposed bars according to ASTM A615 and ASTM A955see Table 1.

Objectives

The layout and amount of longitudinal reinforcement is responsible for the cracking phenomena observed on the bridges superstructure. Thus, the primary objectives of the project were to analyze the bridges superstructure and to provide the design calculations for their strengthening using a MF-FRP in order to recover the loss of strength due to the corrosion of the bars and, eventually, remove the load posting.

MF-FRP STRENGTHENING SYSTEMS

The MF-FRP laminates system consisted of pre-cured FRP strips (see Fig 7a), trademarked under the name SafStrip™ (Lamanna 2002), having high transverse bearing strength attached to the concrete surface using concrete wedge anchors (see Fig. 7b). The laminate is a glass and carbon hybrid pultruded strip embedded in a vinyl ester resin. Its thickness and width are $3.175\ mm$ and $101.6\ mm$, respectively. Table 2 summarizes the mechanical properties of the pre-cured laminate (Rizzo 2005).

The use of the powder-actuated fastening FRP system was found efficient for low compressive strength concrete in lab (Borowicz 2002; Lamanna 2002) and field (Arora 2003) application. Nevertheless, during the installation of the FRP strengthening on field it was found that occasionally, fasteners did not fully penetrate the concrete substrate due to the presence of obstructions (such as large aggregates), and pockets of poor consolidation and/or deteriorated concrete (factors that can be easily controlled in a lab environment) caused loosening of nails. On the other hand, in cases of compressive concrete strength higher than $17.2\ MPa$, the fastening method resulted in concrete spalling and cratering which were considered not acceptable for the full engagement of the laminate. Therefore, the fastening method developed by Bank and Lamanna was modified for bridges, such as the Missouri off-system ones, with high compressive concrete strength and/or with large hard aggregates.

The chosen fastening system consisted of $9.525\ mm$ diameter concrete wedge anchors having a total length of $57.0\ mm$ (see Fig 7b). Resin was used as gap filler between concrete, strips and fasteners. Shear bond tests on the FRP-fastener connection showed that at the ultimate conditions, the applied load is uniformly distributed between all the fasteners: the strength of each connection was found to be $14.0\ kN$ for a concrete having a compressive strength of $27.6\ MPa$ and an embedment depth of $38\ mm$ (Rizzo 2005). For design purposes, the safety factor was set equal to 1.25. Under these assumptions, the minimum number of fasteners to anchor each FRP strip, thus failure of the FRP controls, can be obtained by dividing the load that the FRP experiences at ultimate conditions by the strength of a single connection.

DESIGN OF THE STRENGTHENING

Since it was not possible to guarantee the flexural continuity across the central supports, the deck of the bridges was conservatively modeled as slab simply-supported over consecutive girders, for bridge No. 1330005, and concrete walls, for the other two. Bridge No. 3855006 was structurally modeled as a slab supported by the abutments, since the girders did not have sufficient longitudinal flexural reinforcement and no shear reinforcement.

The analysis of the bridges was performed according to the MoDOT Bridge Manual: the assumed load configurations were consistent with the AASHTO Specifications (AASHTO 2002). The design of the MF-FRP strengthening was computed according to the experimental results attained at the University of Wisconsin-Madison (Bank et al. 2002; Lamanna 2002) and at the University of Missouri-Rolla (Rizzo 2005), and in compliance with ACI 440.2R-02, where applicable.

The structural analysis of the bridges was performed using design truck and lane loads having geometrical characteristics and weight properties as suggested in AASHTO, 2002 Article 3.7.4. An H15-44 truck and an HS20-44 truck loads were considered for bridges No. 1330005 and No. 3855006, and bridge No. 2210010, respectively. The choice of the design load was done picking the maximum load configuration compatible with the shear capacity of the structure: in fact, the MF-FRP system can only be used to increase the flexural capacity. Table 4 summarized the mechanical properties of the sections used for design. Table 4 reports the suggested strengthening for the three bridges. The bolts pattern was then verified at the ultimate and service conditions in order to avoid having any section in which the moment demand was greater than the moment capacity. During this step, the position of the bolts was optimized according to the procedure described in Rizzo (2005). Fig 8 and Fig. 9 show partial plans of the strengthening and the relative pattern of the fasteners for the bridges No. 1330005 and No. 3855006: more details about the MF-FRP strengthening of the off-system bridges can be found in Rizzo et al. (2004).

APPLICATION OF THE STRENGTHENING

The application of the MF-FRP strengthening system consisted of several steps that sometimes were strictly interconnected: fasteners selection, FRP laminates preparation (cutting and pre-drilling), setup for application, surface preparation (just removal of sizeable protrusion such as form lines, concrete offshoots, residual pieces of form, and calcium stalactites), layout and temporary fixing of the FRP laminates, drilling and cleaning of the holes in the concrete, filling of the holes with epoxy, fasteners insertion and FRP laminates clamping, cleaning of the site. Fig. 10 and Fig. 11 show some steps of the application of the MF-FRP system.

FIELD VALIDATION AND FEM ANALYSIS

In order to validate the behavior of the bridges prior to and after strengthening, static load tests were performed with legal trucks. The positions of the trucks were chosen in order to have loading configurations that maximize stresses and deflections at mid-span of deck panels and girders. Different passes were determined and, for each of them, two or three stops were executed. For each stop, the truck rear axle was centered over the marks on the deck. During each stop, the truck was stationary for at least two minutes before proceeding to the next location in order to allow stable readings.

Displacements in the longitudinal and transverse directions were measured using Linear Variable Differential Transducers (LVDTs). Strains in the strengthening material were monitored by means of strain gages. The data were acquired by a portable data acquisition system, “Orange Box”, capable of recording 32 high-level channels of data, 16 strain channels, and 32 thermocouple channels.

As an example, Fig. compares, for the bridge No. 1330005, the results prior to and after strengthening relative to Pass #3 corresponding to the rear axle of the truck at the mid-span. The experimental results were normalized by dividing displacements to the weight of the truck used for testing. The performance of the structure prior to and after the strengthening was determined by comparing the normalized experimental results prior to and after strengthening. In both cases, the bridge performed well in terms of overall deflection. In fact, the maximum deflection measured during the load test is below the allowable deflection prescribed by AASHTO, 2002 Article 8.9.3 ($\delta_{\max} \leq L/800$). As one can see from Fig. 12, the strengthening provided a slight increase of the stiffness of the bridge while the slope of the deformation line remains unchanged. For these reasons, the ratio between the stiffness K_p and K_a, prior to and after the strengthening respectively, could be estimated as the ratio between the normalized displacements prior to and after the strengthening: on average, for bridge No. 1330005, it results $K_a/K_p \cong 1.23$.

Fig. 13 reports the reading of the strain gages applied to the FRP strengthening, relative to Pass #3 Stop #3 of the load tests on the Bridge No. 1330005. The strain readings (between 120 and 170 $\mu\varepsilon$) for the most loaded girders indicate a satisfactory performance of the FRP laminates. The distribution of the strain is not symmetric as one might expect from a symmetric load condition. The difference between the strain readings in girders G2 and G3 can be attributed to the fact that the laminate on girder G3 was less engaged. This kind of behavior is typical of the non-bond critical strengthening systems where the strengthening needs relatively large deformations of the structure before being completely engaged.

FEM analysis models were developed in order to interpret the experimental data prior to and after the strengthening. For this purpose, a commercially available finite element program ANSYS 7.1 was used. The element SOLID65 was chosen to model the concrete and the FRP laminates. For this project, the material properties of concrete were assumed to be isotropic and linear elastic, since the applied load was relatively low with respect to the ultimate load condition. The modulus of elasticity of the concrete was based on the measured compressive strength of the cores obtained from the slabs according to the standard equation of AASHTO (2002) Article 8.7.1. The Poisson’s ratio was set to 0.19 . In order to take into account the presence of the cracks in girders and decks, as a result of a parametric analysis, the modulus of elasticity was reduced properly in the elements corresponding to the cracks as shown in Fig. 14 for the bridge No. 1330005. The depth of the cracks was chosen according to the data collected during the in-situ inspection while the width was assumed to be equal to the elements dimensions. Different elements were used to optimize the model and decrease the computation time. The chosen shape and size in the longitudinal and transverse cross sections allowed locating more accurately the steel reinforcing bar, to properly connect the FRP laminates to the surface of the concrete and to reduce the number of the elements in the “secondary” parts of the model, such as curbs. The modulus of the elasticity and the Poisson's ratio for the steel reinforcement were assumed as $200.0\ GPa$ and 0.3, respectively. The connections between the FRP laminates and the concrete surface were modeled as rigid, neglecting any form of non-linearity due to a potential initial non-perfect engagement of the strengthening. The modulus of the elasticity in the carbon fiber direction and the Poisson's ratio for the FRP laminates were assumed to be $60.6\ GPa$ and 0.3, respectively.

The loads were assumed as uniformly distributed over $508 \times 254\ mm$ areas as specified in AASHTO (2002) Section 4.3.30. Such loads were applied at the top of the deck simulating, in such way, the truck wheel prints. The uniform load was concentrated at the nodes corresponding to the truck wheel print and each force was determined by dividing the total load for the number of nodes.

In the cases of the bridges No. 3855006 and No. 2210010, during the tests it was observed that decks deflected like continuous slabs over two spans while for design purposes the continuity of the superstructure over the central pier was conservatively neglected. Therefore, when the longitudinal tensile steel reinforcement over the central support was unknown, a parametric analysis was performed varying the moment transferred on the central support in order to calibrate the models.

Fig. 12 reports the experimental and analytical mid-span displacements, relative to Pass #3 when the rear axle of the truck is in the mid-span of the Bridge No. 1330005. The graph shows a good match in deflections between experimental and analytical results. Fig. 13 compares experimental and analytical strains on the FRP for the same loading condition. The graph shows a good match in strains between experimental and analytical results for girders G1 and G2. The mismatch for girders G3 and G4 can be explained with the incomplete engagement of the FRP laminates to the concrete. This kind of behavior is typical of the non-bond critical strengthening systems where the strengthening needs relatively large deformations of the structure before being completely engaged. More detailed results of the load tests performed on the off-system bridges can be found in Rizzo et al. (2004).

CONCLUSIONS

Conclusions based on the retrofitting of the bridges utilizing FRP materials can be summarized as follows:

- the mechanically fastened FRP system showed to be a feasible and convenient solution for the flexural strengthening of bridges deck and girders. It may be very effective being, at the same time, a rapid and economical strengthening;
- in-situ load testing has proven to be useful and convincing;
- the FEM analysis has shown good match with experimental results demonstrating the effectiveness of the strengthening technique;
- as a result of FRP strengthening, the load posting of the bridges were removed.

It is important to underline that, while it is well known the long term behavior of the FRP materials, the MF-FRP strengthening systems need to be investigated in the next years by means of future inspections and load testing in order to quantify the effects of continued corrosion.

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Table 1 -- Material Properties Used for the Design of the FRP Strengthening

Bridge No.	*Concrete*	*Steel*	
	Compressive Strength $[MPa]$	Yield Strength $[MPa]$	Modulus of Elasticity $[GPa]$
1330005	46.6	344.7	200.0
3855006	41.4	455.0	
2210010	23.2	344.7	

Table 2 -- Mechanical Properties of the FRP Materials

Properties[a]	*Reference*	SafStrip™
Stress at Failure, MPa	ASTM D 3039	836
Modulus of Elasticity, GPa	ASTM D 3039	62.0
Open Hole Tensile Strength[b, c], MPa	ASTM D 5766	836
Unconstrained Bearing Capacity[b, d], kN	ASTM D 5961 Procedure A	235

[a] Properties measured in the longitudinal direction. They are fiber related in the case of the CFRP fabric.

[b] Properties related to a $9.525\ mm$ nominal diameter of the hole.

[c] Stress calculated on the net area. To be noted that, due to the particular failure mode of the pre-cured laminate (more details are available in Rizzo, 2005), the stress at failure for open hole specimens is the same as for the full section specimen.

[d] This value can be reached only if the edge distance is higher than $25\ mm$.

Table 3 -- Mechanical Properties of the Sections Used for Design

Bridge No.	*Element*		*Cross Section*		*Tensile Steel Area*	
			Thickness $[mm]$	*Width* $[mm]$	*Area* $[mm^2]$	*Effective Depth* $[mm]$
1330005	Girder	Web	406.4	355.6	854	473.1
		Flange	152.4	1803.4		
1330005	Deck		152.4	457.2	292	108.0
3855006	Deck		190	203.0	108	130
2210010	Deck		228.6	609.6	1013	209.6
2210010	Abutment		203.2	355.6	168	101.6

Table 4 -- Summary of the Strengthening for the Off-System Bridges

Bridge No.	*Element*	*Strengthening Scheme* (No. of Plates and Spacing on Center)	*Design Capacity* ϕM_n		*Moment Demand* M_u
			Un-Strengthened	*Strengthened*	
1330005	Girder	*Bottom of Girders:* 3 Plates *Sides of Girders:* 2 Plates	158.01[1]	408.1[1]	420.2[1]
1330005	Deck	*Spans of the Deck*: 1 Plate @457 *mm*	3.4[2]	17.4[2]	17.1[2]
3855006	Deck	1 Plate @ 203 *mm*	18.7[2]	114.8[2]	113.0[2]
2210010	Deck	1 Plate @ 610 *mm*	162.4[2]	233.1[2]	223.0[2]
2210010	Abutment	1 Plate @ 457 *mm*	12.5[2]	70.2[2]	55.6[2]

[1] The dimension is $kN \cdot m$.

[2] The dimension is $kN \cdot m/m$.

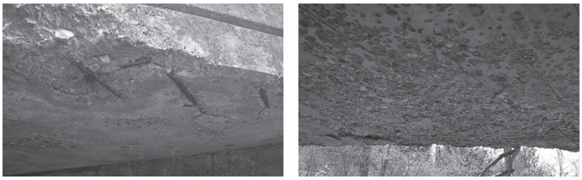
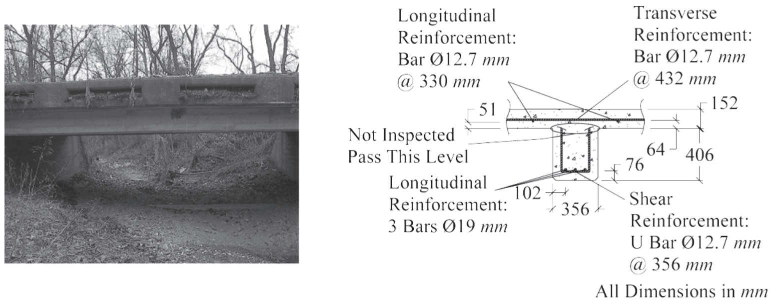
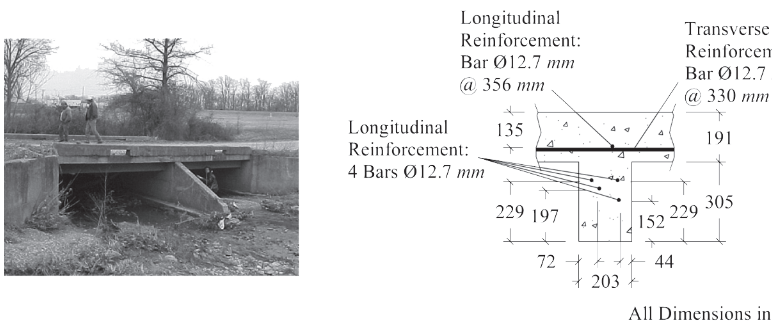


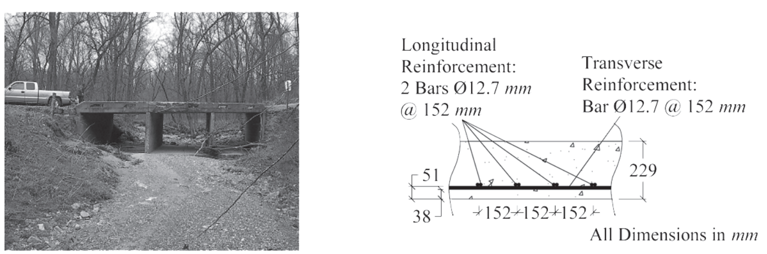
Fig. 1 — Cases of Major Concrete Deterioration



a) Bridge No. 1330005 in Phelps County



b) Bridge No. 3855006 in Phelps County



c) Bridge No. 2210010 in Phelps County

Fig. 2 – Bridges Strengthened with MF-FRP Systems in Missouri - USA

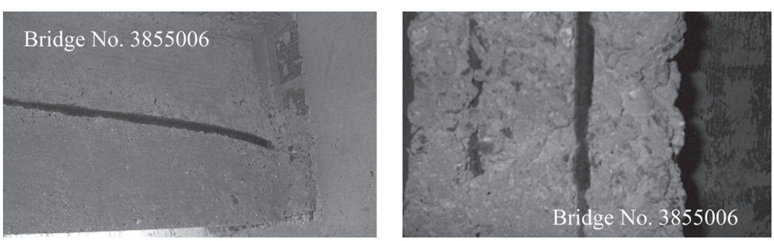


Fig. 3 — Exposed Bars in the Lateral Side of Decks and Girders

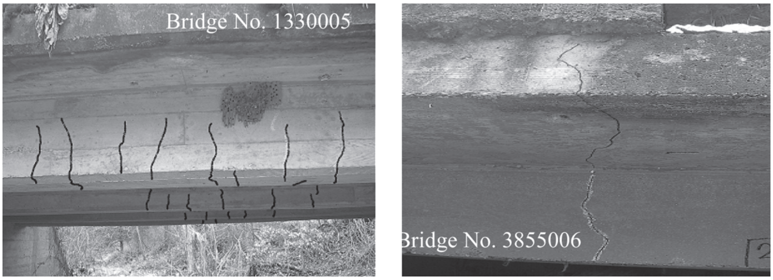
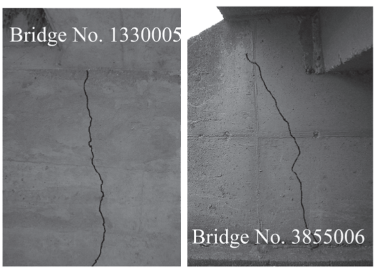
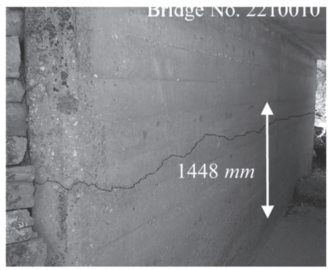


Fig. 4 — Transverse Cracks in Superstructures

a) Longitudinal Cracks in Decks



b) Vertical Cracks in Abutments from Girder Edges and Top of Superstructures



c) Horizontal Crack across the Retaining Abutment Downhill

Fig. 5 — Cracks in Superstructures and Abutments

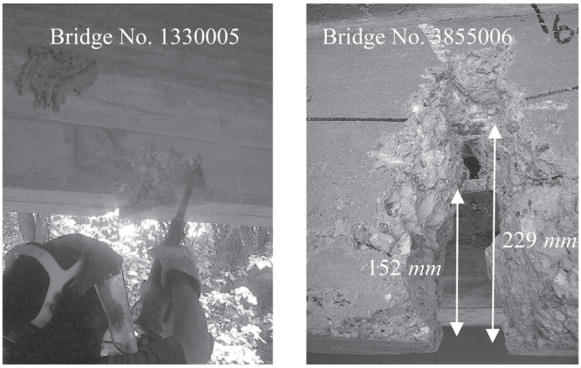
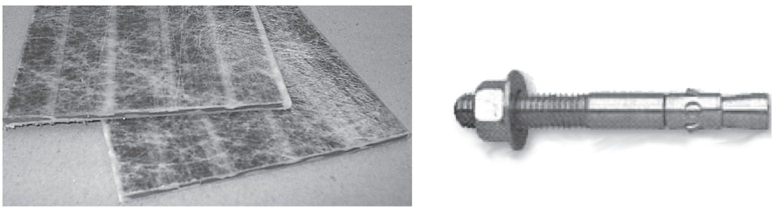


Fig. 6 — Concrete Chipped Off to Find Longitudinal and Shear Reinforcement



a) Pre-Cured FRP Laminate SafStrip™ b) Concrete Wedge Anchor

Fig. 7 — Materials Used in MF-FRP Strengthening System

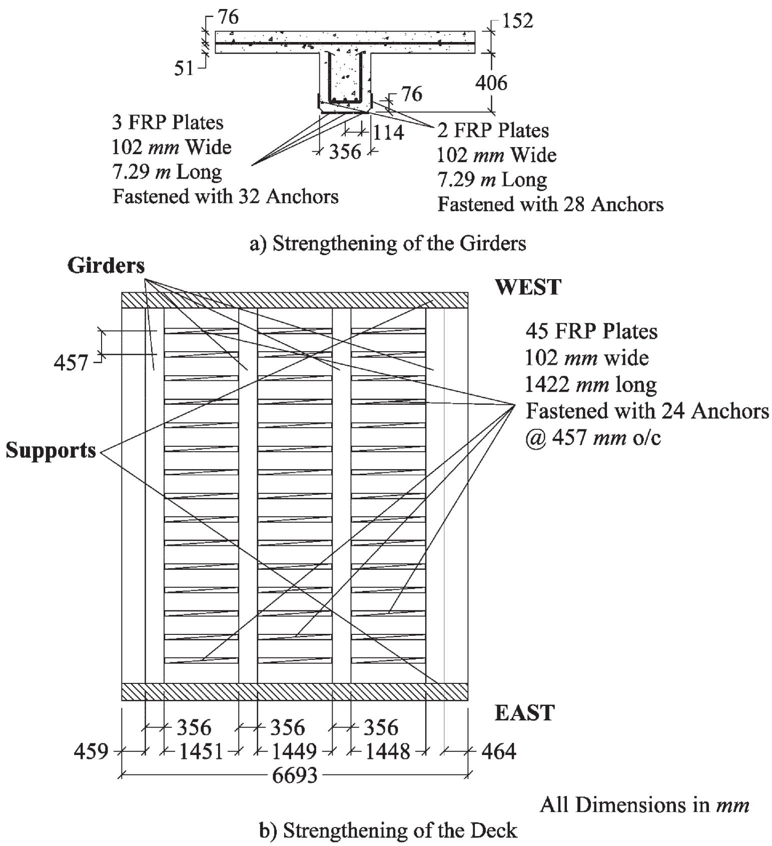


Fig. 8 — Strengthening Layout of the Bridge No. 1330005

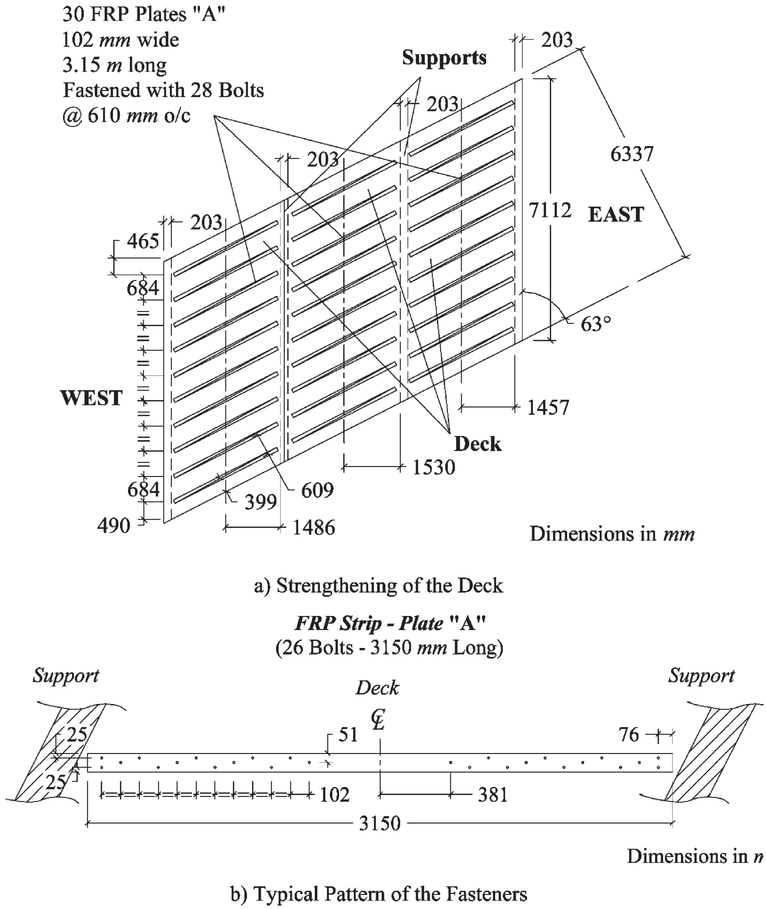
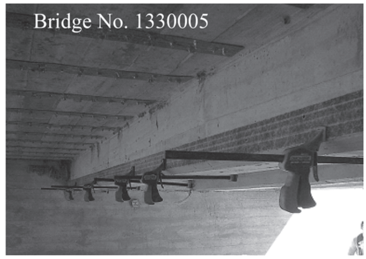
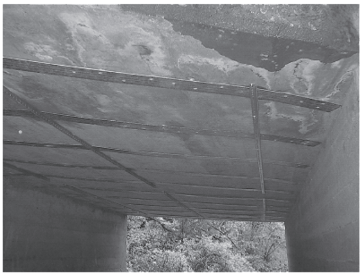


Fig. 9 — Strengthening Layout of the Bridge No. 3855006

a) Laminates Pre-Drilling

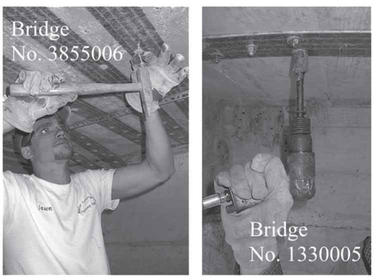


b) Temporary Fixing with Clamps



c) Temporary Fixing with Aluminum Angular

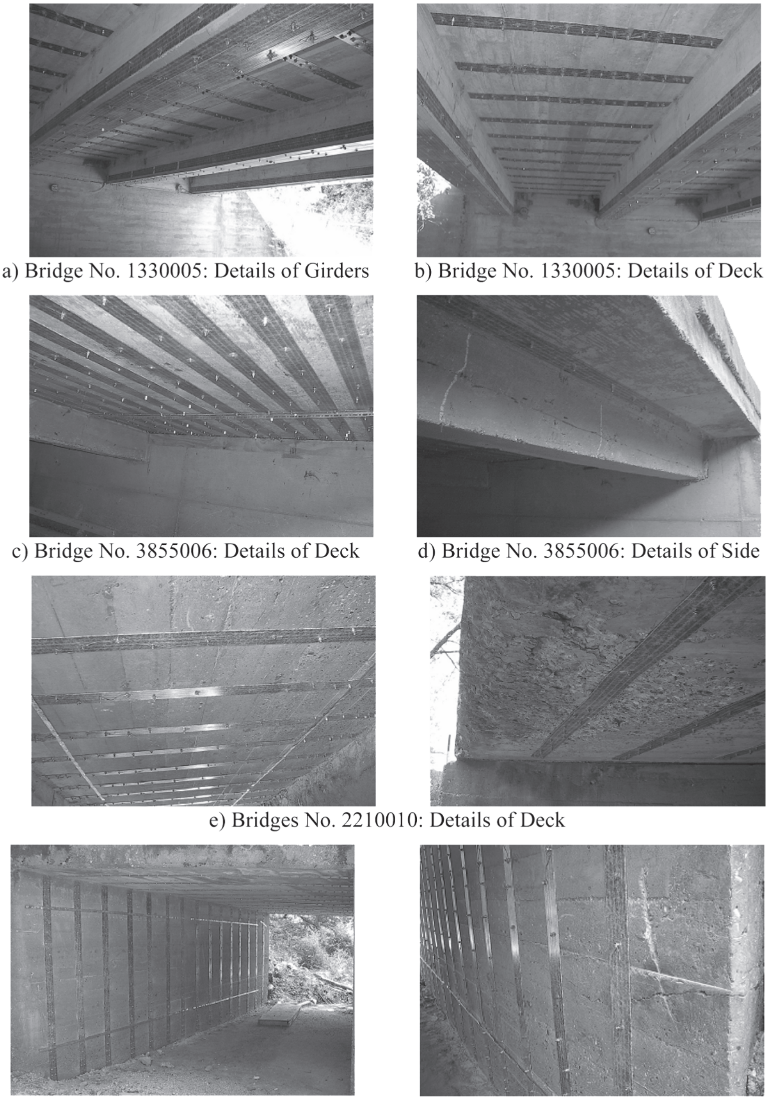
d) Injection of the Epoxy into the Holes



e) Manual and Pneumatic Hammering

f) Fastening of the Anchors

Fig. 10 — Application of the MF-FRP Strengthening System



a) Bridge No. 1330005: Details of Girders
b) Bridge No. 1330005: Details of Deck
c) Bridge No. 3855006: Details of Deck
d) Bridge No. 3855006: Details of Side
e) Bridges No. 2210010: Details of Deck
f) Bridge No. 2210010: Details of the West Abutment

Fig. 11 — Off-System Bridges after Strengthening

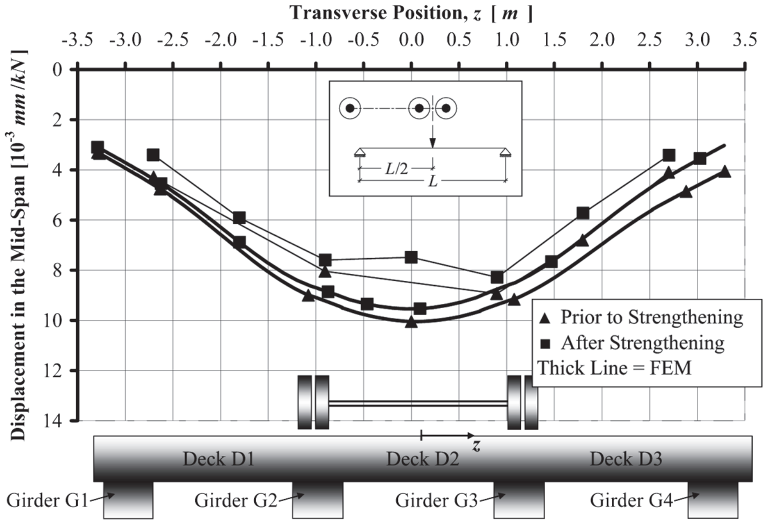


Fig. 12 — Mid-Span Displacement, Pass #3 and Rear Axle in the Mid-Span of Bridge No. 1330005 (Comparison of Experimental and Analytical Results)

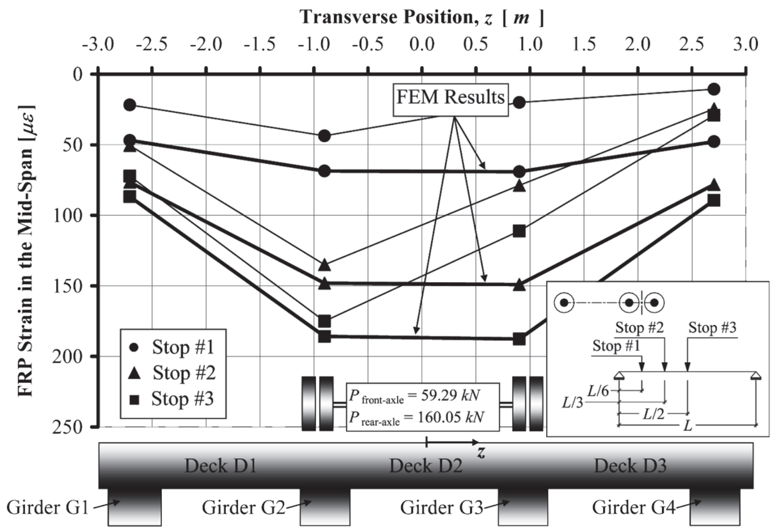
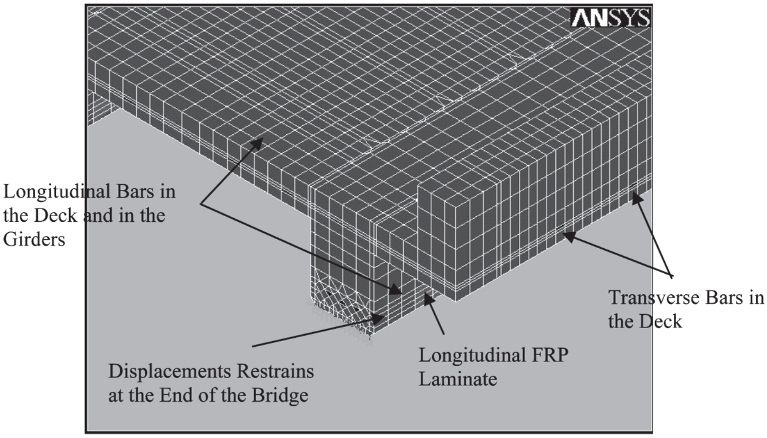
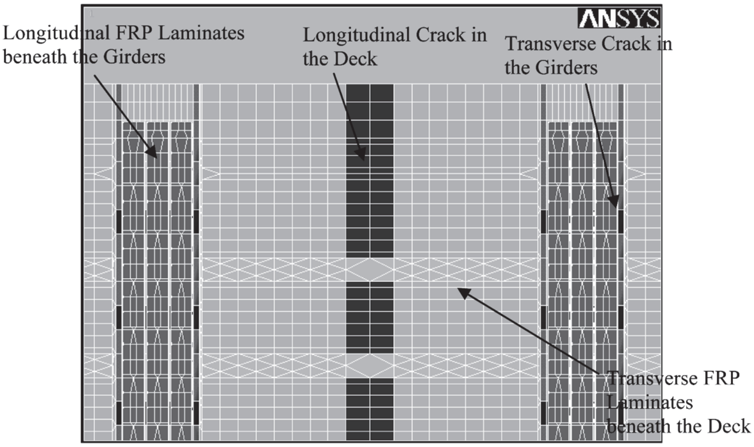


Fig. 13 — Mid-Span Strain in the FRP Fastened on the Bridge No. 1330005 Girders at Mid-Span, Pass #3 (Comparison of Experimental and Analytical Results)



a) Details of the Steel Reinforcement and Boundary Conditions



b) Details of the FRP Strenghtening (Bottom View)

Fig. 14 — FEM Model Geometry of Bridge No. 1330005