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VALIDATION OF FRP COMPOSITE TECHNOLOGY THROUGH FIELD TESTING

Strengthening of Bridge T-0530
Crawford County, MO

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Strengthening of Bridge T-0530

CRAWFORD COUNTY, MODOT DISTRICT 9

EXECUTIVE SUMMARY

This report presents the materials and construction for flexural strengthening of the reinforced concrete (RC) bridge T-0530, Dallas County, Missouri, using externally bonded reinforcements. The report makes reference to two other documents: a) Master Materials and Construction Specifications, written in AASHTO language, and b) Manufacturer's Literature, that contains the tech data sheets for the materials used in this research program. This document explains the concrete repairs, surface preparation, materials specification, storage, handling, etc, for the five different technologies used in this research program, namely: manual lay-up carbon FRP laminates; near surface mounted (NSM) carbon FRP bars; adhered pre-cured carbon FRP laminates; steel reinforced polymer (SRP) laminates; and mechanically fastened carbon FRP laminates.

Bridge T-0530 is one of five existing RC bridges, located in three districts, which were strengthened using composite materials. Five different strengthening techniques were used in the entire program but only two were used for bridge T-0530: manual lay-up carbon FRP laminates and pre-cured carbon FRP laminates.

This project was conducted under a joint MoDOT – UMR University Transportation Center – Private Sector funding initiative. The five existing concrete bridges will be monitored twice a year over five years, including repeated load tests. The data, information, and understanding from this validation are used in the drafting of design and construction specifications to be written in AASHTO language for future FRP-related bridge-strengthening projects.

The strengthening schemes were designed in compliance with the ACI 440.2R-02 Design Guide for Externally Bonded FRP Materials where applicable. Both FRP strengthening techniques were easily implemented and showed satisfactory initial performance. The strengthening of this bridge was carried out during seven weeks in July to September of 2003. The structure has five spans (47 ft = 14.33 m each), each with three RC girders monolithically cast with a 6 in (15 cm) slab. The FRP system consisted of manual lay-up for spans 1, 3 and 5, numbered North to South, and pre-cured carbon FRP laminates. FRP laminates were U-wrapped on all longitudinal girders to anchor the flexural reinforcement and increase the shear capacity.

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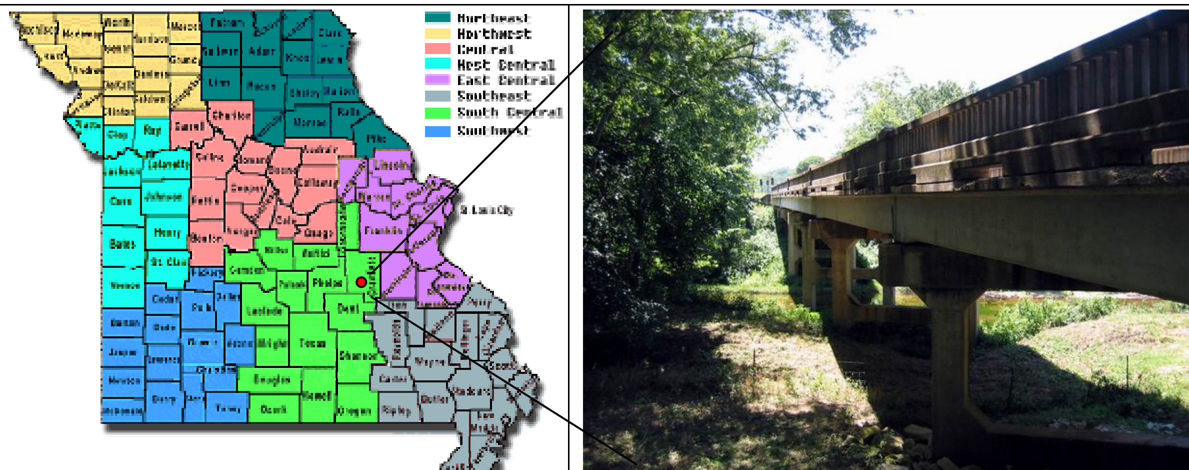
1. INTRODUCTION

1.1 General description

Bridge T-0530 is located in Crawford County, MoDOT District 9. The structure has five equally-spaced spans (47 ft, 14.33 m), each with four RC girders monolithically cast on a 6 in (15 cm) slab (see Table 1, Figure 1, Figure 2 and Figure 3). The total bridge length is *237 ft* (72.23 m) and the total width of the deck is *23 f t*(7 m). Each span has one transversal beam with the same depth as the main girders (Figure 2).

Table 1- Summary Information

BRIDGE T-0530	
	
District: 9	**County:** Crawford
Year Built: 1937	**Feature Intersected:** Crooked Creek
Main Spans Construction: RC T-Beam	**Number of Main Spans:** 5
Total Length: 237 ft (72.2 m)	**Rating (Deck/Sup/Sub):** 5/5/5
Load Posting: Trucks over 21 ton (19.05 tons in SI units), 15 mph (24.14 km/h) on the bridge	
BRIDGE FEATURES	
Geometry • Height of the bridge is 23 ft (7 m). Total width of deck is 23 ft (7 m). • Deck consists of four RC beams spaced 78 in (2m) on centers. All spans have also a transverse beams (Figure 2). The thickness of the slab is 6 in (15 cm).	
Concrete Condition before Strengthening • Some spalling of concrete along the edges of the bridge was evident. Concrete in beams and deck was in good condition. Minor cracking noticed; however, injection was not needed. • Piers and abutments were in good condition. Some deterioration exists in the bents due to steel corrosion (Figure 3).	

Two FRP system technologies were used for the flexural strengthening of this bridge. The FRP system consisted of manual lay-up for spans 1, 3 and 5, numbered North to South, and pre-cured carbon FRP laminates. FRP laminates were U-wrapped on all longitudinal girders to anchor the flexural reinforcement and increase the shear capacity.

Figure 1. Approach to the bridge

Figure 2. Longitudinal and transversal beams

Figure 3. Condition of bents

2. MATERIALS

2.1 Material Properties

Two commercially-available external composite systems were adopted: (1) externally bonded CFRP laminates installed by manual wet lay-up and (2) pre-cured carbon FRP laminates. The main difference between these two techniques is the preparation necessary during the application of the strengthening. FRP have been applied following the Master Materials and Construction Specifications.

The properties of the composite materials used in the design are summarized in Table 2 and 3, as reported by the manufacturers (see Manufacturer's Literature).

Table 2 – Properties of CFRP Laminate Constituent Materials

Material	Ultimate tensile strength f^*_{fu} ksi [MPa]	Ultimate strain ε^*_{fu} in/in [mm/mm]	Tensile modulus E_f ksi [GPa]	Nominal thickness t_f in [mm]
Primer	2.5 [17.2]	0.03	104 [0.7]	-
Putty	2.2 [15.2]	0.07	260 [1.8]	-
Saturant	8.0 [55.2]	0.035	440 [3.0]	-
High Strength Carbon Fiber	550 [3790]	0.017	33,000 [228]	0.0065 [0.1651]

Table 3– Properties of pre-cured CFRP laminate Constituent Materials.

Material	Ultimate tensile strength f^*_{fu} ksi [MPa]	Ultimate Strain ε^*_{fu} [in/in]	Tensile modulus E_f ksi [GPa]	Cross Sectional Area in^2 [mm^2]	Dimensions in×in [mm×mm]
Epoxy Adhesive	4.5 [31]	0.04	-	-	-
Pre-cured laminates	350 [2,400]	0.017	19,000 [131]	0.2204 [140]	4×0.055 [100×1.4]

2.2 Summary Bill of Material (As Built)

Table 4 and Table 5 presents a summary of materials as used. Table 4 shows the break up for the various reinforcement types.

Table 4– Summary of Bill of Reinforcement as Built

FRP Type	Reinforcement	Member Location	Span	Quantity	
Manual Lay-up Laminates	Flexural	Slab	1, 3, 5	921 ft^2	86 m^2
		Interior Girder	1, 3, 5	592 ft^2	55 m^2
		Exterior Girder	1, 3, 5	216 ft^2	20 m^2
		Total		**1729**	161 m^2
	Shear	Interior Girder	All	658 ft^2	61 m^2
		Exterior Girder	All	527 ft^2	49 m^2
		Total		**1185** ft^2	110 m^2
Pre-cured Laminates	Flexural	Slab	2, 4	883.6 *ft*	269 m
		Girder	2, 4	475 *ft*	145 m
		Total		***1,359 ft***	414 m

Table 5– Summary of Bill of all Material as Built

Manual Lay-up Laminates	Sheet	**2,914** ft^2	**271** m^2
	Primer	**2424** ft^2	**225** m^2
	Putty	**2424** ft^2	**225** m^2
	Saturant	**4,430** ft^2	**412** m^2
	Coating	**2424** ft^2	**225** m^2
Pre-cured Laminates	Laminate	**1,359** ft	**414** m
	Resin	**1,359** ft	**414** m
	Coating	**379** ft^2	**35** m^2

The detailed compilation for the bill of materials reported in the Tables above is given at the end of this report as Appendix 1.

3. STRENGTHENING

3.1 Substrate Repair

The performance of a composite system depends not only on the quality and strength of the concrete substrate but also on the bond between the composite and substrate. A clean and sound substrate is essential for composite repair systems. Unsound concrete, concrete which emits a relatively dead or hollow sound when its surface is tapped with a metal tool, was removed and patched. Holes through the deck were filled; all concrete surfaces to be strengthened were thoroughly prepared according to the minimum requirement defined in the Master Materials and Construction Specification.

The concrete repair work consisted of the following parts:

- Partial-depth repairs of deteriorated concrete on deck and bents
- Removal of sound concrete along the deck and girders to establish a suitable surface profile

In order to place CFRP on the underside of the bent system, repair work was done by removing 10 cubic feet (0.28 m^3) of concrete from the deteriorate areas on deck, cleaning this area, installing repair materials, finishing and texturing (Figure 4).

Figure 4. Repair of deteriorated areas on deck.

3.2 Surface Preparation

To promote continuous intimate contact between concrete and FRP, several important issues had to addressed in the surface preparation: concrete surface irregularities, fins, and/or sharp angles that may result in separation and delamination of carbon laminate from the concrete and/or in localized stress concentration. Concrete surface irregularities were removed and smoothed to less than 1 mm (see Figure 5)

Figure 5. Leveled of surface

Rounding of corners using grinders reduces stress concentration and results in improved bond between the FRP and concrete surface. The concrete angles were rounded to no less than 1/2-inch (12.7 mm) (see Figure 6)

Figure 6. Rounding of corners on girder

Abrasive sandblasting was used to clean the concrete surfaces of dust, dirt, laitance, oil and any curing substance. Concrete surface roughness was equivalent to CSP 3 (Concrete Surface Profile number 3) as defined by the International Concrete Repair Institute. The sandblasting must be applied prior to CFRP. All loose particles, oil, dust, cement, paint and other contaminants were contained in accordance with State regulation (Figure 7)

Figure 7. Preparation of appropriate roughness by sandblasting

3.3 Externally Bonded Composite Reinforcement

Spans 1, 3 and 5, numbered from North to South, were strengthened with manual lay-up laminates. Spans 2 and 4 were reinforced with pre-cured laminates. The installation process for each technology will be described in the following sections.

3.3.1 Manual Lay-up CFRP Laminates

The carbon fabric for the manual lay-up system consists of uni-axial carbon fiber sheets for strengthening the positive moment and shear region of reinforced concrete. In this instance, a high strength carbon fiber was used (Table 2)

3.3.1.1 Primer Application to Fill Voids

Two-component epoxy primer (Table 2) was used to fill voids in the concrete surface. All surfaces to receive the carbon fiber fabric were primed with the penetrating primer (Figure 8)

Primer was mixed in accordance with the manufacturer’s recommendations (See Manufacturer’s Literature) using brushes and rollers. The volume of primer to be prepared at one time was such that could be applied within its pot life. Primer was thoroughly mixed with a hardener at the manufacturer’s specified ratio.

Application was uniform in a sufficient quantity to fully penetrate the concrete and produce a non-porous film in the surface after full penetration. A four-way method, application in all four directions, was used. When necessary, a second coat was applied after the first coat penetrated into the concrete.

Figure 8. Filling of voids and defects by primer and putty collocation

3.3.1.2 Epoxy Filler/Surfacer

Remaining minor surface irregularities and defects were corrected using epoxy filler/surfacer or putty. It is not desirable that the epoxy putty filler cover the entire concrete surface.

A trowel was used to apply the putty in order to fill any surface defect (Figure 8). The material properties of the primer and putty that were used are listed in Table 2.

3.3.1.3 Application of Carbon Fiber Sheets

The carbon fiber sheets were cut beforehand into prescribed sizes using scissors and a simple made-in-place device (Figure 9).

A saturant coating (Table 2) was applied with a medium nap roller after application of the primer and putty. Afterward, the pre-cut fiber sheets were attached according to Contract drawings.

Figure 9. Cutting process of CFRP sheet

The carbon fiber sheets were installed by manual lay-up method (Figure 10). The sheets were properly aligned and set into the surface saturant. The fiber plies were aligned on the structural member according to the Contract Documents. Any deviation in the alignment more than 5˚ (approximately 87 mm/m or 1 in/ft) was not acceptable. The sheets were saturated by rolling out the external surface. This operation also removed excess of saturant and bubbles (Figure 11). After appropriate time (10 minutes), a second saturant application over the carbon fiber sheets were applied to a complete impregnation (Figure 12).The saturant was applied in strict accordance with the manufacturer's recommendations (Manufacturers Literature).

Figure 10. Manual lay-up CFRP sheet installation.

Figure 11. Squeezing of air bubbles and saturation over laminates

The process must allow sufficient working time for the rolling of the carbon fiber sheet and saturant to produce a uniform system that is completely free of voids and trapped air. It must be completed within the limits of saturant pot-life.

Because saturant is susceptible to temperature, special care shall be taken to minimize the elapsed time between mixing and application of the saturant. This must be applied to the sheet at least 15 minutes prior to any thickening.

In order to avoid vibrations during the installation, traffic control was used (see Figure 12). Speed of the car was limited to 15 mph (24.14 km/hr). Finally, a topcoat was applied to the sheet to provide a cosmetic finish and environmental protection (see Figure 12)

Figure 12. Traffic control and topcoat protection

3.3.2 Pre-cured CFRP Laminates

The carbon/epoxy composite (CFRP) pre-cured laminate consists of carbon fiber strips, epoxy primer, and epoxy adhesive. The material properties of the pre-cured laminates and epoxy paste that have been used are listed on Table 3.

Installation of pre-cured FRP systems is generally similar to single ply wet lay-up. Repair of concrete substrate and surface preparation to provide an open roughened texture are procedure similar as described in sections 3.1 and 3.2 of this report.

Advantage over the manual lay-up comes from the fact no saturant and so no work for a full impregnation is needed.

Pre-cured system strips were cleaned and cut in length specified in contractor drawing and placed into wet adhesive within the pot life of adhesive (See Figure 13). The applied pre-cured carbon FRP system was not disturbed before the adhesive fully cured.

Figure 13. Installation of Pre-cured laminates

Figure 14. Installation of Pre-cured laminates

In order to avoid vibrations during the installation, traffic control was used. Speed of the car was limited to 15 mph (24.14 km/hr). Finally, a topcoat was applied to the sheet to provide a cosmetic finish and environmental protection.

4. ACCEPTANCE TESTING.

A direct pull-off test based on ASTM D 4541-93 was used by the contractor in this project. This test allows to check the quality of the installation of the FRP. It consists in gluing an aluminum square plate on the strengthened part to be checked; afterwards, a core is drilled close to the aluminum plate through the laminate strip into the concrete substrate, providing an isolated test location for attachment of the pull-off tester (Figure 15). The tester records the force causing the failure, which, if divided by the core cross sectional area, will result in tensile strength (psi). Upon failure of the core specimen, a visual examination of the failure plane location reveals whether the failure occurred at the bond line or within the substrate. Failure of the concrete and not at the bond line was the only acceptable failure. The tensile bond strength must be more than 200 psi (1.4 MPa). One pull-off test was performed every 200 ft^2 (20 m^2) of area strengthened with carbon fiber strip system or once every deck span.

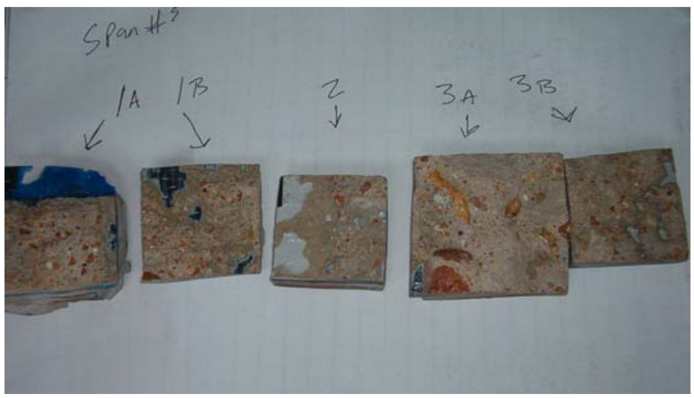


Figure 15. Pull-off test

The results of single tests made on all spans are summarized in table 7. They show values of tensile bond strength bigger than the minimum required. Based on these results and that all failures occurs in the concrete and not at the bond line, installation of FRP was considered successful.

Table 6. Results of direct pull-off test for Crawford County bridge T-0530

Test #	Test Results (psi) [MPa]	Description	Work Area	
1	700 [4.9]	Carbon Fiber	Deck	Span 1
2	600 [4.2]	'	Girder Shear	
3	650 [4.55]	Pre-cured Laminates	Interior girder	Span 2
4	700[4.9]	'	Deck	
5	500 [3.5]	Carbon Fiber	Deck	Span 3
6	500 [3.5]	""	Girder	
7	550 [3.85]	Pre-cured Laminates	Deck	Span 4
8	500 [3.5]	""	U Wrap Ext Girder	
9	600 [4.2]	Carbon Fiber	Deck	Span 5
10	400 [2.8]	""	U Wrap Int Girder	

APPENDIX 1

Detailed Bills of Materials (as Built)

1 Pre-cured carbon FRP laminates

1.1 FLEXURAL REINFORCEMENT

1.1.1 Slab

1.1.1.1 Spans 2 & 4

$$(2)(2)\cdot(13 + 16 + 18)(4.7\text{ft}) = 883.6\text{ft}$$

1.1.2 Interior Girder

1.1.2.1 Spans 2 & 4

$$(2\cdot 2)\cdot(3\cdot 25.6\text{ft}) = 307.2\text{ft}$$

1.1.3 Exterior Girder

1.1.3.1 Spans 2 & 4

$$(2\cdot 2)\cdot(3\cdot 14.0\text{ft}) = 168\text{ft}$$

2 Manual Lay-up Laminates

2.1 FLEXURAL REINFORCEMENT

2.1.1 Slab

2.1.1.1 Spans 1, 3 & 5

$$(2)(3)(13\cdot 3\cdot 9\text{in} + 11\cdot 4\text{in})(56\text{in}) = 921.7\text{ft}^2$$

2.1.2 Interior Girder

2.1.2.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot(25\text{ft} + 8\text{in} + 24\text{ft} + 8\text{in} + 23\text{ft} + 8\text{in} + 12\text{ft})(16\text{in}) = 688\text{ft}^2$$

2.1.3 Exterior Girder

2.1.3.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot(14 + 13)\,\text{ft}\cdot 16\text{in} = 216\text{ft}^2$$

2.2 SHEAR REINFORCEMENT

2.2.1 Interior Girder

2.2.1.1 All spans

$$(10)\cdot(31\text{in} + 17\text{in} + 31\text{in})(2\cdot 5\cdot 1\text{ft}) = 658\text{ft}^2$$

2.2.2 Exterior Girder

2.2.2.1 All spans

$$(10)\cdot(31\text{in} + 17\text{in} + 31\text{in})(2\cdot 4\cdot 1\text{ft}) = 527\text{ft}^2$$

3 Resins Application (Pre-cured laminates)

3.1 FLEXURAL REINFORCEMENT

3.1.1 Slab

3.1.1.1 Spans 2 & 4

$$(2)(2)\cdot(13+16+18)(4.7\text{ft}) = 883.6\text{ft}$$

3.1.2 Interior Girder

3.1.2.1 Spans 2 & 4

$$(2\cdot 2)\cdot(3\cdot 25.6\text{ft}) = 307.2\text{ft}$$

3.1.3 Exterior Girder

3.1.3.1 Spans 2 & 4

$$(2\cdot 2)\cdot(3\cdot 14.0\text{ft}) = 168\text{ft}$$

4 Primer, Putty and Topcoat Coating ((Manual Lay-up)

4.1 FLEXURAL REINFORCEMENT

4.1.1 Slab

4.1.1.1 Spans 1, 3 & 5

$$(2)(3)(13\cdot 3\cdot 9\text{in} + 11\cdot 4\text{in})(56\text{in}) = 921.7\text{ft}^2$$

4.1.2 Interior Girder

4.1.2.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot(25\text{ft} + 8\text{in})(16\text{in}) = 205.3\text{ft}^2$$

4.1.3 Exterior Girder

4.1.3.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot(14)\,\text{ft}\cdot 16\text{in} = 112\text{ft}^2$$

4.2 SHEAR REINFORCEMENT

4.2.1 Interior Girder

4.2.1.1 All spans

$$(2)(10)\cdot(31\text{in} + 17\text{in} + 31\text{in})(5\cdot 1\text{ft}) = 658\text{ft}^2$$

4.2.2 Exterior Girder

4.2.2.1 All Spans

$$(2)(10)\cdot(31\text{in} + 17\text{in} + 31\text{in})(4\cdot 1\text{ft}) = 527\text{ft}^2$$

5 Saturant Application (Manual Lay-up)

5.1 FLEXURAL REINFORCEMENT

5.1.1 Slab

5.1.1.1 Spans 1, 3 & 5

$$(2)(3)(2\cdot 13\cdot 3\cdot 9in + 2\cdot 11\cdot 4in)(56in) = 1843.3ft^2$$

5.1.2 Interior Girder

5.1.2.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot((2\cdot 25ft + 2\cdot 8in + 24ft + 8in + 23ft + 8in + 12ft))(16in) = 893.3ft^2$$

5.1.3 Exterior Girder

5.1.2.1.1 Spans 1, 3 & 5

$$(2\cdot 3)\cdot(14\cdot 2 + 12)\,ft\cdot 16in = 320ft^2$$

5.2 SHEAR REINFORCEMENT

5.2.1. Interior Girder

5.2.1.1 All Spans

$$(2)(10)\cdot(31in + 17in + 31in)(2\cdot 5\cdot 1ft) = 1317ft^2$$

5.2.2 Exterior Girder

5.2.2.1 All Spans

$$(2)(10)\cdot(31in + 17in + 31in)(2\cdot 4\cdot 1ft) = 1053ft^2$$