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SHEAR REPAIR OF P/C BOX BEAMS USING CARBON FIBER REINFORCED POLYMER (CFRP) FABRIC

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Research Report
KTC-06-01/FRT114-01-1F

Shear Repair of P/C Box Beams using Carbon Fiber Reinforced Polymer (CFRP) Fabric

by

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in cooperation with

Transportation Cabinet
Commonwealth of Kentucky

and

Federal Highway Administration
U.S. Department of Transportation

January 2006

1. Report No. KTC-06-01/FRT114-01-1F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Shear Repair of P/C Box Beams using Carbon Fiber Reinforced (CFRP) Fabric**		5. Report Date January 2006
		6. Performing Organization Code
7. Author(s): Jim Simpson, Issam Harik, and Choo Ching Chiaw		8. Performing Organization Report No. KTC-06-01/FRT114-01-1F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, Kentucky 40506-0281		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. FRT114
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet State Office Building Frankfort, Kentucky 40622		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code

15. Supplementary Notes
     Prepared in cooperation with the Kentucky Transportation Cabinet and the U.S. Department of
     Transportation, Federal Highway Administration.

16. Abstract

   The report documents the retrofit work carried out on the KY3297 Bridge over Little Sandy River in Carter County, Kentucky. Field investigation and evaluation revealed that the bridge superstructure was deficient in shear. The repair work was carried out using externally bonded carbon fiber reinforced polymer (CFRP) fabric system.

   The repair, using externally bonded fiber system, offers the following benefits: (1) the use of light construction equipment, hand kits and tools, (2) minimal traffic disruption as all lanes were open to traffic while work was being performed underneath the bridge, and (3) cost saving; the cost for the repair and 3-years monitoring was USD $105,000.00 compared to the estimated superstructure replacement cost of USD $600,000.00.

   The repair began in June 2001 and was completed in October 2001. After the repair, crack gauges were used to monitor all shear cracks that existed in the bridge. Inspection of the bridge was carried out at specific intervals from October 2001 to July 2005. No crack movement has been observed during the inspections. This indicates that the retrofit was a success.

17. Key Words Bridge, carbon fiber reinforced polymer (CFRP) fabric system, shear crack, repair and strengthen		18. Distribution Statement Unlimited with approval of Kentucky Transportation Cabinet	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 39	22. Price -

Form DOT 1700.7(8-72)   **Reproduction of Completed Page Authorized**

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EXECUTIVE SUMMARY

This report details the retrofitting work carried out on the KY3297 Bridge over Little Sandy River in Carter County, Kentucky, using advanced fiber reinforced polymer (FRP) composites. The main objectives of the research were to repair and partially restore the capacity of the bridge's superstructure and to strengthen the superstructure with advanced FRP materials. More specifically, the FRP materials were intended to correct and prevent any structural damage due to shear deficiency of the several girders along the bridge span. The strengthening of the supporting girders was accomplished by employing a high-strength, yet flexible, carbon fiber reinforced polymer (CFRP) fabric system produced by the Mitsubishi Chemical Corporation. This Kentucky Transportation Cabinet Project was the first of it kind in the state, and funding was provided by the Federal Highway Administration.

The bridge, which initially had an estimated remaining life expectancy of three to five years, is now expected to last twenty years or longer. The application of light-weight CFRP fabric systems only required the use of light construction kits and tools; no heavy machinery was used throughout the entire process. One positive aspect of this particular project was that the impact on daily traffic was kept to a minimum while work was being performed underneath the bridge. The cost for the repair and 3-years monitoring was USD $105,000.00 compared to the estimated superstructure replacement cost of USD $600,000.00.

The repair began in June 2001 and was completed in October 2001. After the repair, crack gauges were used to monitor all shear cracks that existed in the bridge. Inspection of the bridge was carried out at specific intervals from October 2001 to July 2005. No crack movement has been observed during the inspections. This indicates that the retrofit was a success.

ACKNOWLEDGEMENTS

1.0 INTRODUCTION

According to the National Bridge Inventory (NBI) database (FHWA 2003), an estimated 28 percent of the nation's 600,000 bridge structures are classified as either "*structurally deficient*" or "*functionally obsolete*". These bridges are in need of repair or replacement.

The Innovative Bridge Research and Construction (IBRC) Program (FHWA 2002) established by the Federal Highway Administration with the passage of TEA-21 has this main objective: to provide funds for repair, rehabilitation, replacement or new construction of bridges and other highway structures using innovative materials and material technologies. The premise of the objective is to emphasize the role of these high-performance materials and construction techniques in reducing the maintenance and life-cycle costs of the nation's bridge infrastructure.

1.1 Bridge Description

The KY3297 Bridge over Little Sandy River is located in Carter County, KY. It is a three-span [68-98-42 ft (21-30-13 m)] composite, precast prestressed spread box-beam bridge (Fig. 3.1).
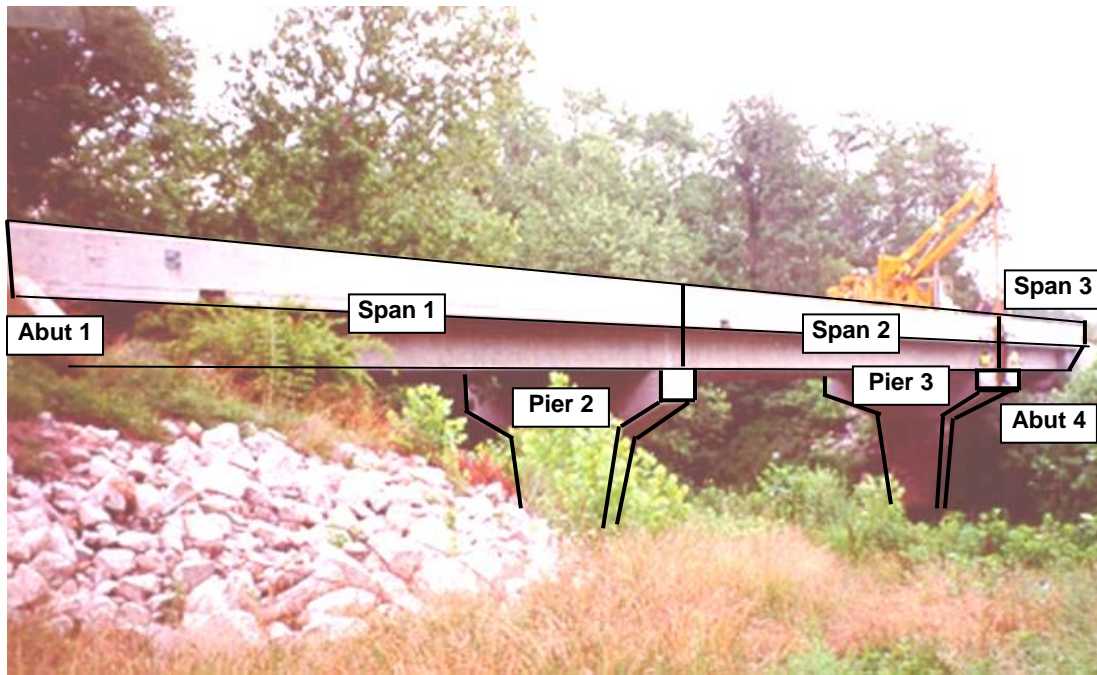
Fig. 1.1. The KY3297 Bridge over Little Sandy River, Carter County, KY.

The bridge was accepted into Kentucky Bridge Inventory (Bridge Number B00144) in April of 1993. The first inspection, made in 1993, revealed that the bridge was in very good condition without any defects. The bridge was then given a rating of 8 based on a FHWA Bridge Scale of 0 – 9, with 9 being the highest rating.

1.2 Bridge Inspection and Evaluation

Upon completion, the KY3297 Bridge was inspected on a regular basis. During a routine inspection conducted in 1996, significant shear cracks were noted in the 98' (30m) center span. The following chronicles the bridge inspection process and results during the 1996 – 1998 period:

- April 1996. Shear cracks in all four box-girders of the bridge center span. Cracks were estimated to be 1/8" wide and 6 to 8 feet long.

- June 1996. A special in-depth snooper inspection was performed. All cracks in the center span were measured and documented.
- June 1997. Annual inspection scheduled and performed.

- June 1998. Annual inspection scheduled and performed. Following this inspection, it was determined that the shear cracks in the center span (Span 2) had continued to grow in magnitude and number. New shear cracks were also discovered in Spans 1 and 3. Typical shear cracks are shown in Figs 1.2 and 1.3.

Fig. 1.2. Typical shear cracks in bridge girder.

Fig. 1.3. Shear crack with exposed shear reinforcement.

2.0 CARBON FIBER REINFORCED POLYMER FABRIC SYSTEM

2.1 Introduction

FRP composite materials have a high strength-to-weight ratio and have excellent attributes (e.g. non-corrosiveness, excellent fatigue resistance, etc.) that are immune to most harsh environment. Due to their light-weight nature, the construction techniques used for FRP composites can greatly speed many construction or repair processes. Since most repair work involving FRP composites generally requires the use of hand-tools, this process eliminates or minimizes the interruption of traffic traversing highway structures during a repair.

The carbon fiber reinforced polymer (CFRP) fabric system – Replark® System – manufactured by Mitsubishi Chemical Corporation (2000), Japan, used for this specific project will be briefly introduced herein.

2.2 CFRP Fabric System – Replark® System

The Replark® CFRP Fabric System selected for this project consists of four components: unidirectional CFRP fabric, primer, putty, and saturating resin.

- Carbon fiber reinforced polymer fabric – The main component of the Replark® System is the unidirectional CFRP fabric. The Replark 30 used for this project is manufactured using a high strength carbon fiber. The stress/strain characteristic of this fabric is linearly-elastic up to the point of failure, no yield characteristic is exhibited. Typical properties of Replark 30 are as follows:

Table 2.1 Properties of Replark 30 CFRP Fabric

PRODUCT	REPLARK 30
Fiber Area Weight	0.061 lb/ft^2 (300 g/m^2)
Thickness	0.0066 in (0.167 mm)
Tensile Strength, f_{fu}	555 x 10^3 psi (3,820 MPa)
Tensile Modulus, E_f	33.4 x 10^6 psi (2.3 x 10^5 MPa)
Standard Width	10 in (25 cm), 13 in (33 cm), 20 in (50 cm)
Standard Length	328 ft (100 m)

- Primer – The Replark® primer is a two-component epoxy system consisting of a main agent and a hardener to be mixed in a 2:1 weight ratio. It is designed to penetrate concrete pores. The primer is designed to strengthen the concrete bonding surface and to improve adhesion between the concrete surface and the CFRP fabric. See Table 2.2 for primer properties.

- Putty – The Replark® L525 putty is also a two-part system consisting of a main agent and a hardener to be mixed in a 2:1 weight ratio. It is intended to fill small voids or to repair surface irregularities up to ¼ inch (6mm) after the application of the primer. Application of putty provides a smooth surface for bonding of CFRP fabric to concrete. See Table 2.2 for putty properties.

- Saturating resin – The saturating resin is also a two-part epoxy consisting of a main agent and a hardener to be mixed in a 2:1 weight ratio. The resin is used to fix the CFRP fabric onto the concrete surface. The resin provides an effective mean of load transfer to and/or from the fabric and the concrete. See Table 2.2 for resin properties.

Table 2.2 Primer, Putty, and Resin Properties

PRODUCTS		*PRIMER[1]*	*PUTTY*	*RESIN[2]*
Appearance (2-part system)	*Main*	Pale Yellow Liquid	White Putty	Green and Thixotropic Liquid
	Hardener	Brown Liquid	Black Putty	Brown Liquid
Mix Proportion (by weight)	*Main*	2	2	2
	Hardener	1	1	1
Specific Gravity @ 77°F	*Main*	1.11	1.49	1.13
	Hardener	0.97	1.44	0.99
Adhesive Strength @ 73°F to Concrete		> 200 psi (> 1.5 MPa)	> 200 psi (> 1.5 MPa)	> 200 psi (> 1.5 MPa)

[1] *Primer PS401 for warm season (68°F – 95°F)*
[2] *Resin L700S-LS for warm season (59°F – 95°F)*

3.0 RETROFIT ANALYSIS AND DESIGN

3.1 Bridge Background

The KY-2001-01 Project – Repair of the KY3297 Bridge over Little Sandy River using FRP bonded Reinforcement – was one of the IBRC projects awarded to the Kentucky Transportation Cabinet. The scope of the project included:

- Repair of existing shear cracks in the precast prestressed box beams
- Strengthening of existing beams with carbon fiber reinforced polymer (CFRP) fabric
- Monitoring of the Retrofit

The restoration process of the bridge began in June 2001 and was completed in October 2001.

3.2 Bridge Analysis

Following the in-depth snooper inspection in 1996, a detailed evaluation of the bridge was carried out by the Division of Bridge Design, Kentucky Transportation Cabinet. The evaluation confirmed that the bridge was indeed deficient in shear reinforcement as depicted in Figs. 3.1 – 3.6. It is apparent, as demonstrated in Figs. 3.2 and 3.3, that the major deficiencies in shear are indeed in the center span (Span 2) while Span 3 shows little of such problem (Figs. 3.5 and 3.6). Detailed computations are tabulated in Appendix I.
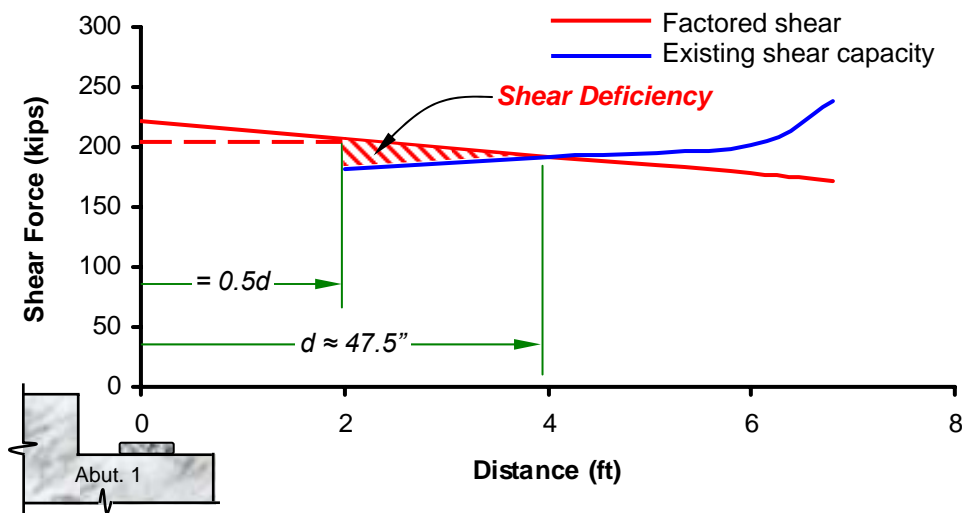
Fig. 3.1. Shear strength evaluation near Abutment 1 of Span 1.
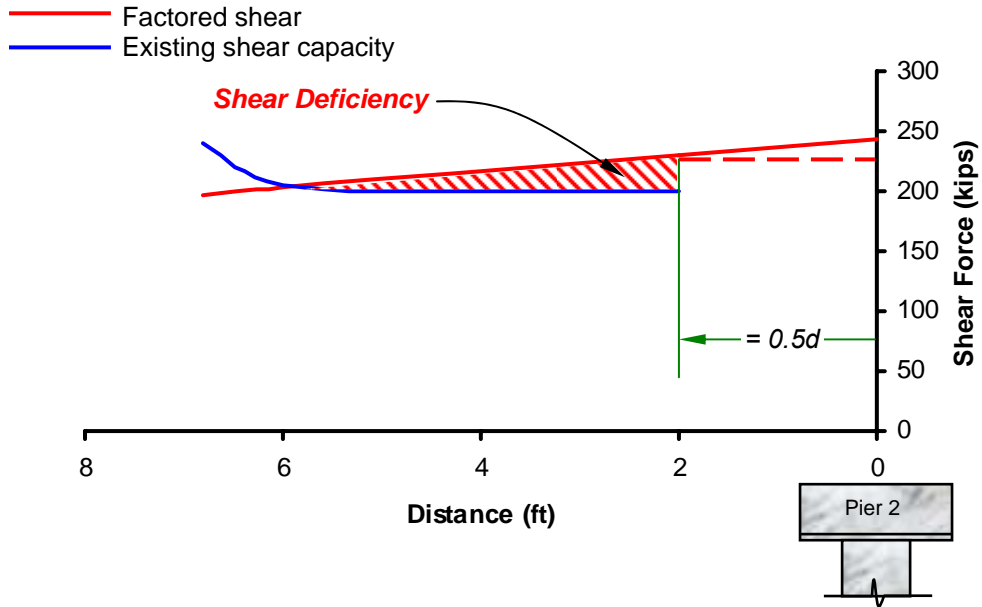
Fig. 3.2. Shear strength evaluation near Pier 2 of Span 1.
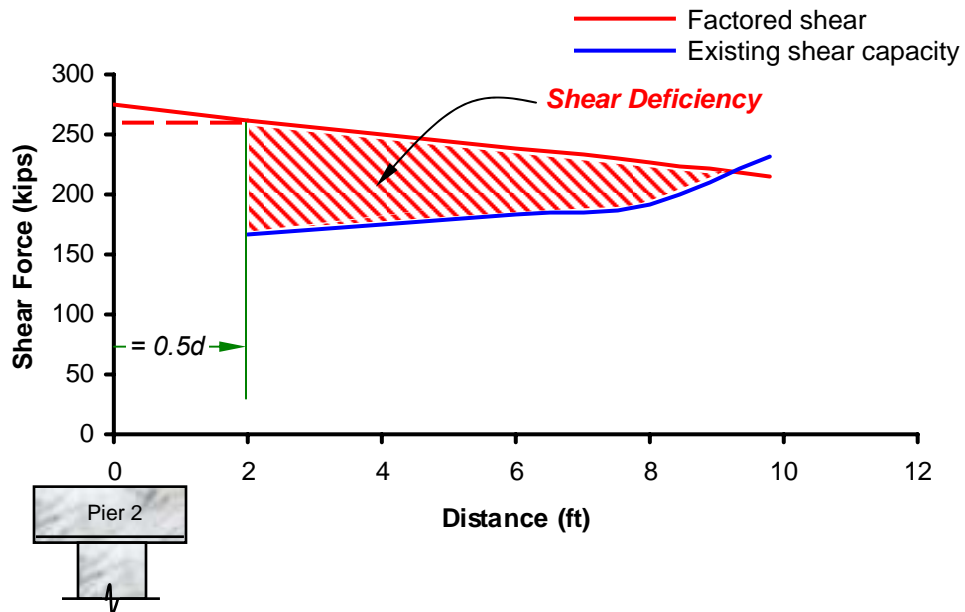
Fig. 3.3. Shear strength evaluation near Pier 2 of Span 2 (Center span).
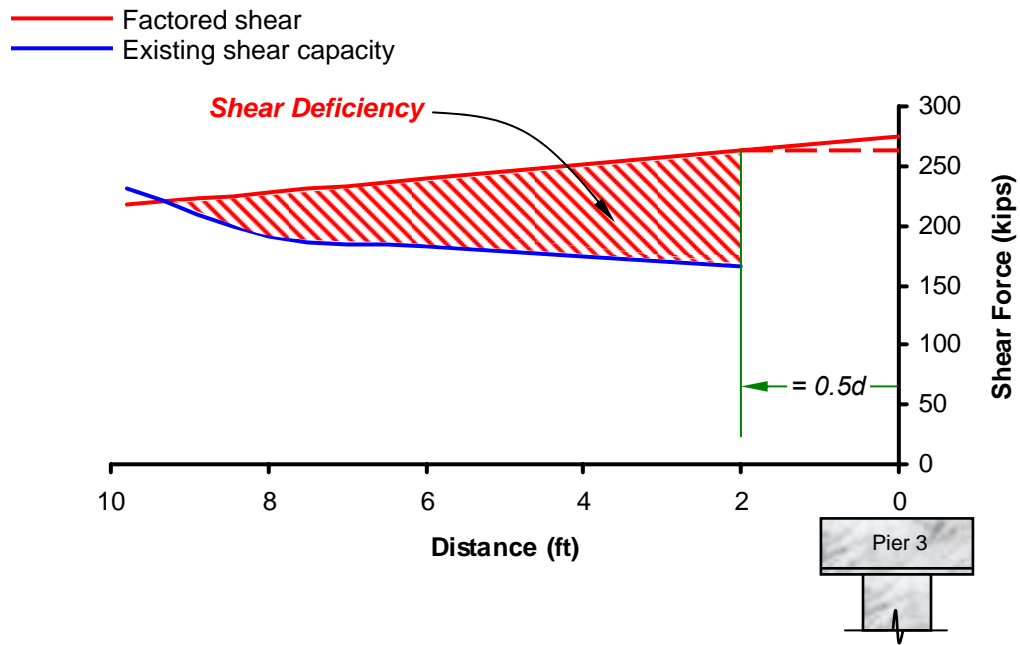
Fig. 3.4. Shear strength evaluation near Pier 3 of Span 2 (Center span).
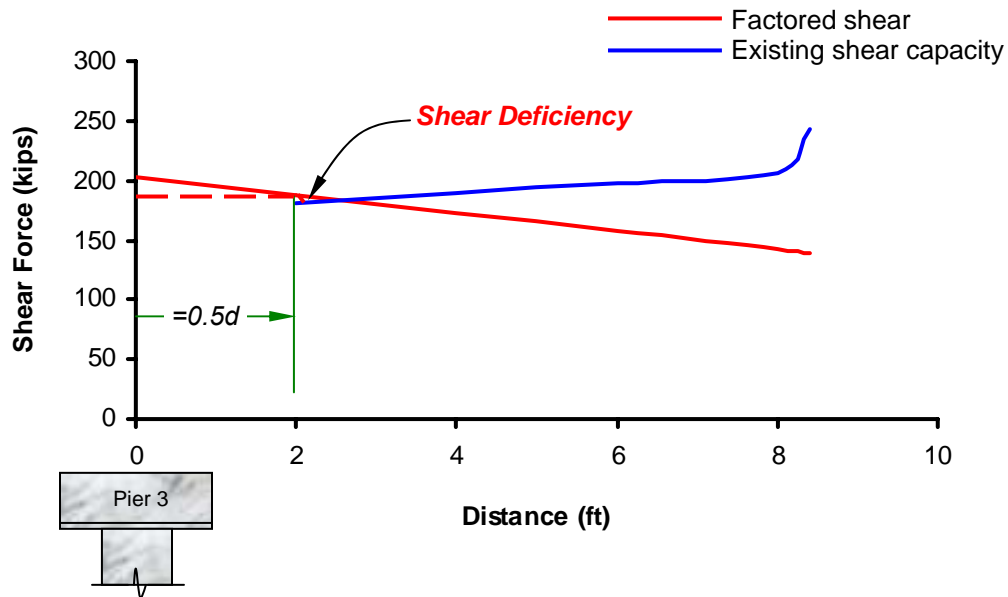
Fig. 3.5. Shear strength evaluation near Pier 3 of Span 3.

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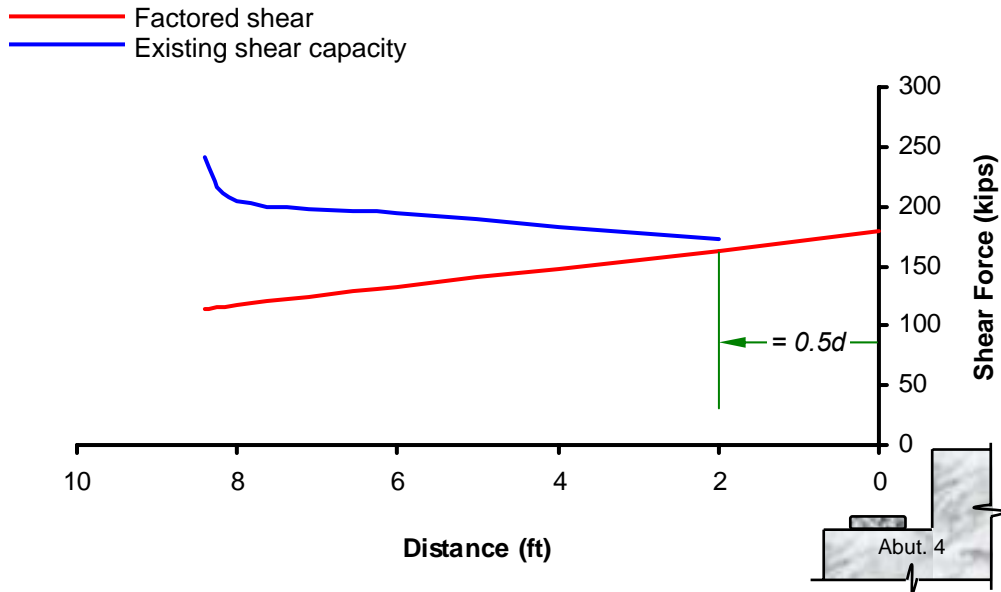
Fig. 3.6. Shear strength evaluation near Abutment 4 of Span 3.

3.3 Bridge Retrofit Plan

As described in previous sections, the shear strength of the existing box-girders was increased with the use of CFRP composites. It has been determined from the analytical results that Spans 1 and 3 needed to be strengthened with one-sheet/layer of Replark® 30 CFRP fabric while Span 2 with three-sheets/layers of the same material. Fig. 3.7 shows a schematic of the design layout for a single layer of CFRP fabric. Detailed calculations of the design are presented in Appendix I.

Replark® CFRP Fabric:
1-layer (Oriented at 45°)
    (**For Spans 1 & 3**)
3-layers (Oriented at 45°, 90°, & 45°)
    (**For Span 2**)

Slab

Haunch

Side
View

1'-9"

7'-10" (**For Spans 1 & 3**)

11'-0" (**For Span 2**)

Bottom View
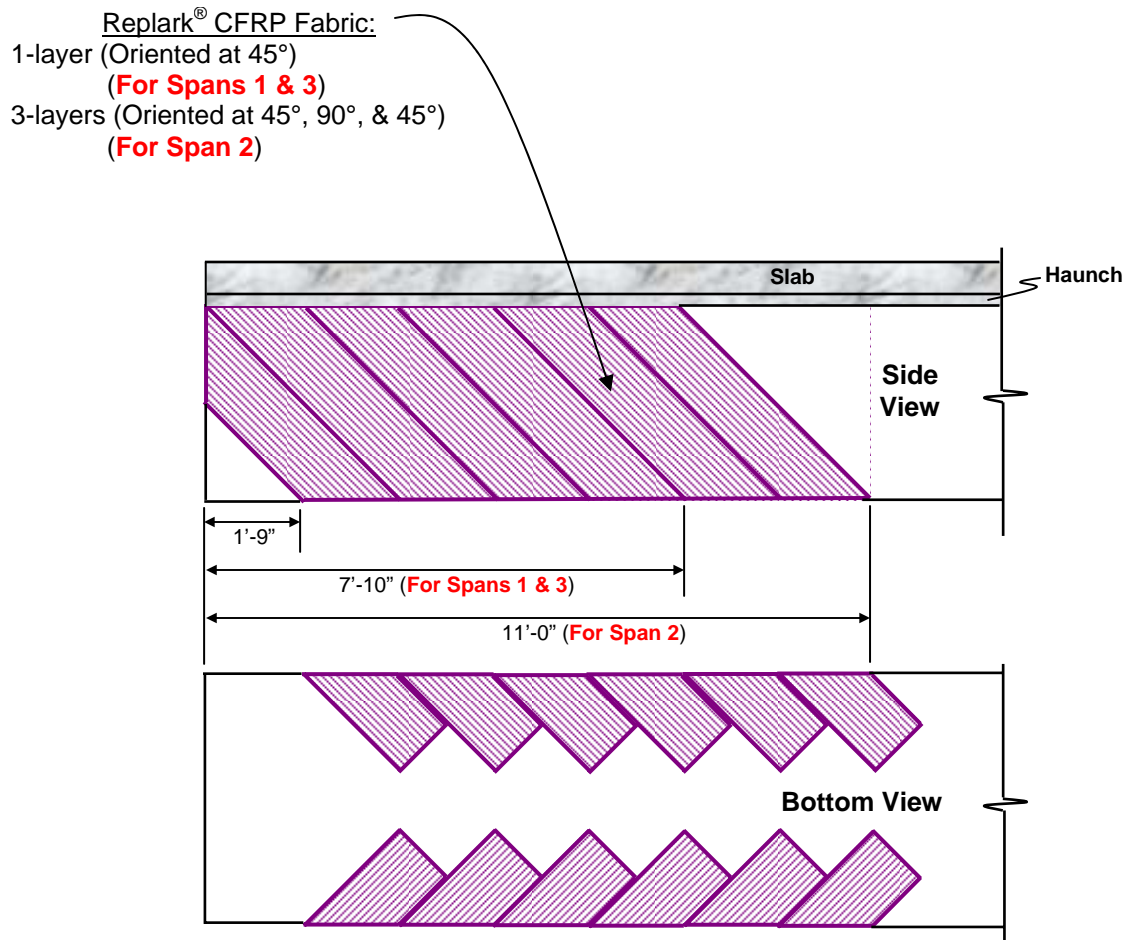
Fig. 3.7. Typical shear strengthening layout with a single layer of CFRP fabric placed at 45° with respect to the beam axis.

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4.0 REPAIR OF KY3297 BRIDGE

4.1 Introduction

Work on precast prestressed box girders was carried out in the following orders:

- Repair of existing shear cracks in the precast prestressed box beams
- Strengthen of existing beams with carbon fiber reinforced polymer (CFRP) fabric

Since the bridge was built over a waterway, typical scaffolding and/or lifts from the ground were not feasible. As a result, access to the bridge beams was made possible by the use of the Swing-Lo® 48" Wrap-A-Round Parapet Scaffolding System (see Figs. 4.1.a and b). The system was mounted on the New Jersey Barriers, and was completely adjustable and moveable along the bridge with a 48" walk board as shown in Fig. 4.1.b.

(a)

48" walk board

(b)

Fig. 4.1. Swing-Lo® Scaffolding System.

4.2 Repair of Shear Cracks

The surface of the box beams was properly cleaned and grinded (Figs. 4.2 and 4.3) before starting the crack repair process. This particular step was to ensure the removal of contaminants and all loose concrete particles and debris. This enabled a solid bond between the beams and the CFRP fabric.

Fig. 4.2. Power washing of concrete surface.

Fig. 4.3. Surface grinding.

The cracks were subsequently repaired by using the HILTI® CI 060 Epoxy Injection System. The goal of this process was to partially restore the beam's capacity. The application followed these steps: (1) mounting of injection ports. Injection ports were spaced approximately 6-inch (150 mm) apart from one another (Fig. 4.4); (2) seal

cracks (Fig. 4.5), which requires 24 hour curing time; (3) injection of CI 060 epoxy resin (Fig. 4.6); and (4) grinding off the injection ports and excess crack sealant to achieve a smooth finish (Fig. 4.7). Detailed information about the HILTI® CI 060 EP Injection System can be found in Appendix II.

Fig. 4.4. Mounting of injection ports.

Fig. 4.5. Sealed cracks.

Fig. 4.6. Epoxy injection process.

Fig. 4.7. Repaired surface with grinded off injection ports and excess sealant.

4.3 Application of the Replark® 30 CFRP Fabric System

The application of the Replark® 30 CFRP fabric system followed these five steps:

- Step 1 – Primer application:
  To improve the strength of the concrete, a coat of primer (PS401) was applied (Fig. 4.8). The primer was also intended to improve the bonding between the concrete and the CFRP fabric.

Fig. 4.8 – Primer application.

- Step 2 – Putty application:
  This step was necessary after the discovery of numerous voids and/or cavities on the surface of the beams (see Fig. 4.9). Voids and/or cavities can cause air

bubbles to form during the CFRP fabric application process which can negatively affect the performance of the CFRP system. The Replark® L525 putty was used to fill these voids and/or cavities as shown in Fig. 4.10.
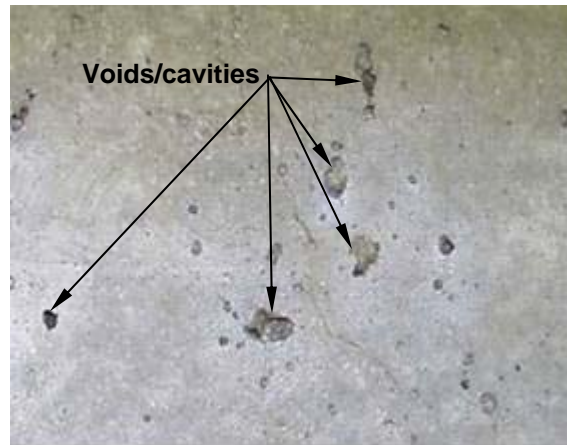
Fig. 4.9 – Voids and cavities on the beam surface.

(a) Mixing putty

Fig. 4.10 – Putty application process.

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(b) Putty application

Fig. 4.10 (Cont.) – Putty application process.

- Step 3 – Resin undercoat:
  To bond the CFRP fabric to the concrete, a resin undercoat (L700S-LS) was applied. This resin undercoat was applied to the side and to the bottom of the beam, as shown in Fig. 4.11, where the CFRP fabric would be affixed.
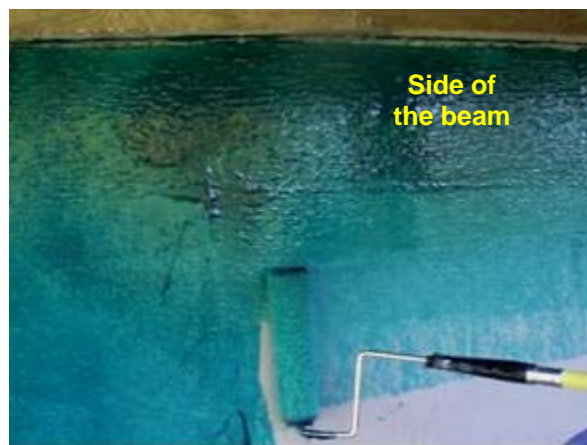
(a) Resin undercoat to side of the beam.

Fig. 4.11 – Resin undercoat application.

(b) Resin undercoat to bottom of the beam.

Fig. 4.11 (Cont.) – Resin undercoat application.

- Step 4 – CFRP fabric application:
  Immediately after the application of resin undercoat, CFRP fabric was placed onto the wet resin with the use of a roller brush as shown in Fig. 4.12.

(a) Placement of CFRP fabric onto concrete surface.

Fig. 4.12 – Placing CFRP fabric onto the concrete surface.
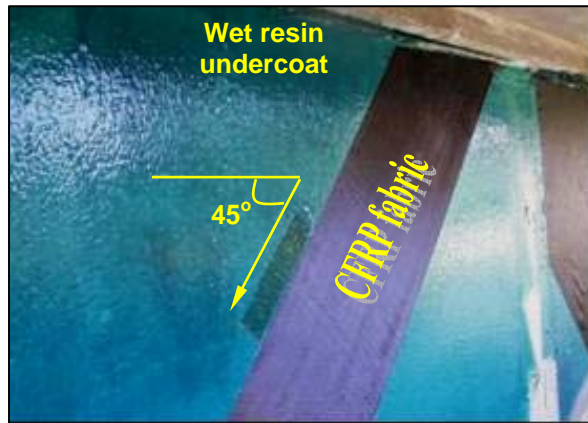
(b) CFRP fabric place at 45°.

Fig. 4.12 (Cont.) – Placing CFRP fabric onto the concrete surface.

- Step 5 – Resin overcoat and finish coat:
  To offer additional protection to the CFRP fabric, a resin overcoat (L700S-LS) was applied. Note that the resin undercoat – CFRP fabric application – resin overcoat process was completed in the same day. For aesthetic reasons, some of the repaired beams, in particular the exterior ones, were painted with a standard concrete paint. The 'before' and 'after' pictures are shown in Fig. 4.13.
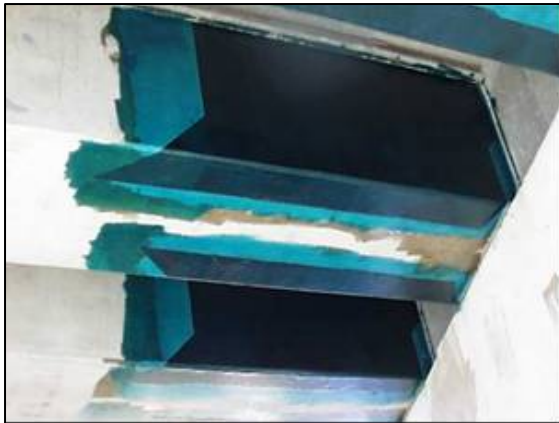
(a) Before painting

(b) After painting

Fig. 4.13 – Repaired box girders.

5.0 BRIDGE MONITORING

During the application of the Carbon Cloth, approximately thirty 3″ X 12″ windows were cut to expose critical areas, where cracks had developed on the beams. Avongard crack monitoring gauges (Fig. 5.1) were mounted directly to the beams over the repaired cracks. These gauges can record movement of less than 1mm in any direction. These gauges were read every 30 days for the first three months. The inspection cycle was extended to every 90 days.

The project was completed in October 2001. As of July 25, 2005, no crack movement has been observed. Also, there is no evidence of new cracks developing. This indicates that the retrofit was a success.
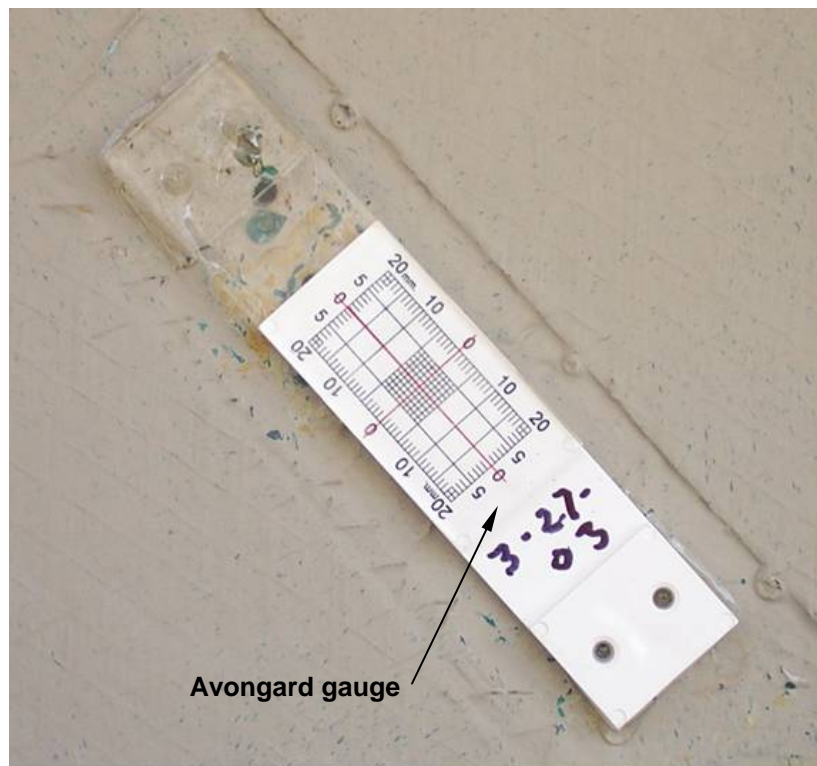
Fig. 5.1 – Crack monitoring gauge affixed to repaired crack location.

6.0 SUMMARY AND CONCLUSION

The shear repair and strengthening of the KY3297 was the first field application on an in-service bridge in Kentucky that employed fiber reinforced polymer (FRP) composites. For this particular project, the carbon fiber reinforced polymer (CFRP) fabric system – Replark$^®$ 30 (manufactured by the Mitsubishi Chemical Corporation), was used. The Replark$^®$ 30 CFRP fabric is a unidirectional carbon fiber sheet that offers high-strength and tremendous flexibility.

Based on the experience of this project, it was observed that the use of CFRP fabric system offered the following benefits:

- Light weight construction – No heavy machinery was involved during the entire retrofitting process. Work was completed successfully with the use of light construction hand kits and tools.
- Minimal traffic disruption – All lanes were open to traffic while work was being performed underneath the bridge. As a result, the CFRP rehabilitation project has virtually no or minimal impact on daily traffic.
- Cost saving – The repair cost, using externally bonded CFRP system including the 3-years of monitoring, the Kentucky Transportation Cabinet USD $105,000.00. This results in a saving of approximately USD $495,000.00, with the estimated superstructure replacement cost at USD $600,000.00.
- Extended service life – The bridge was predicted, initially, to have a remaining life expectancy of 3 – 5 years. With the repairs made, the bridge now is expected to last 20 years or longer.

Currently, thirty percent of the 13,000 bridges on the Kentucky Bridge Inventory list are either *structural deficient* or *functionally obsolete*. It is believed that a number of these bridges could potentially benefit from this type of repair. Steps should be taken to identify potential bridge candidates and to implement this repair technique statewide.

References

FHWA. "National Bridge Inventory." Bridge Technology – Infrastructure, United State Department of Transportation, Federal Highway Administration. 2003.

FHWA. "Innovative Bridge Research and Construction (IBRC) Program." Bridge Technology – Infrastructure, United State Department of Transportation, Federal Highway Administration. 2003

Mitsubishi$^©$ Chemical Corporation. "Replark© System, Design Guide". Rev. 2.0. 2001.

Appendix I

Bridge Data and Sample Calculations for KY3297 Bridge over Little Sandy River in Carter County, Kentucky.

Prestressed Box Beam Description (Span 1):
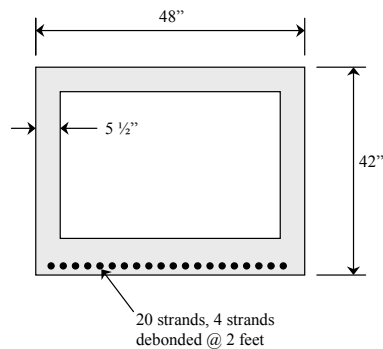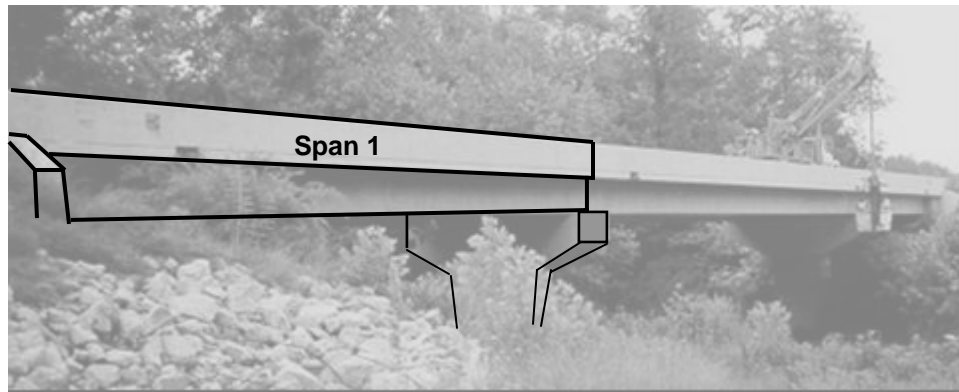
Fig. I.1 – Schematic of box beam cross section of Span 1.

Span length, L_s = 68 ft
Beam cross sectional area, A_b = 887 in^2
Concrete strength, $f_c{}'$ = 6,000 lb/in^2
Steel yield strength, f_y = 60 x 10^6 lb/in^2
Diam. of shear reinf., D_v = 0.5 in (#4 rebar)
Shear reinf. area/LF, A_v = 0.24 in^2
Shear reinf. spacing, s = 20 in C.C.
Number of prestressing strands   = 20
Number of draped strands   = 0
Number of debonded strands   = 4
Diam. of strands, D_{ps} = 0.5 in
Area of stands, A_{ps} = 0.153 in^2
Tensile strength of strands, f_{ps} = 270 x 10^3 lb/in^2
Top of slab to strand centroid, d = 47.5 in

Prestressed Box Beam Description (Span 2):

Fig. I.2 – Schematic of box beam cross section of Span 2.

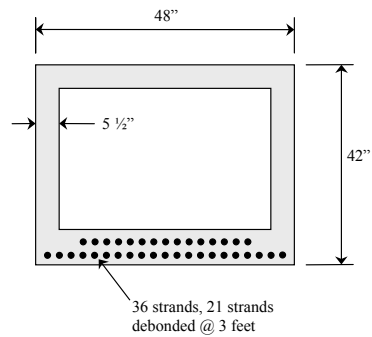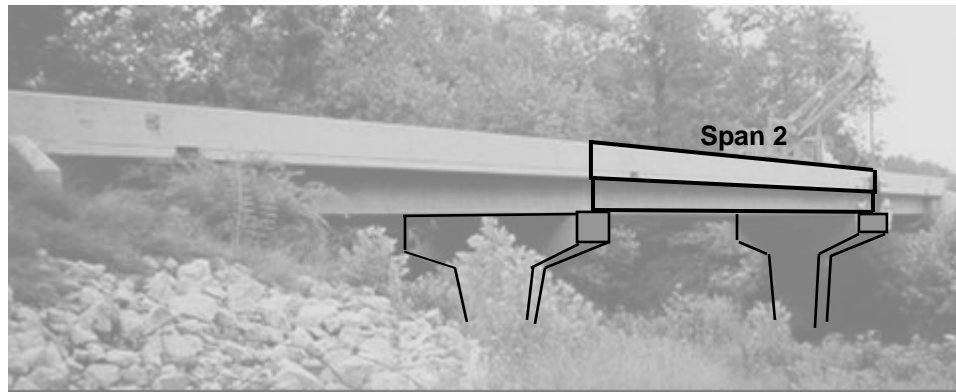|	
Span length, L_s	= 98 ft
Beam cross sectional area, A_b	= 887 in^2
Concrete strength, f_c'	= 6,000 lb/in^2
Steel yield strength, f_y	= 60 x 10^6 lb/in^2
Diam. of shear reinf., D_v	= 0.5 in (#4 rebar)
Shear reinf. area/LF, A_v	= 0.24 in^2
Shear reinf. spacing, s	= 20 in C.C.
Number of prestressing strands	= 36
Number of draped strands	= 0
Number of debonded strands	= 21
Diam. of strands, D_{ps}	= 0.5 in
Area of stands, A_{ps}	= 0.153 in^2
Tensile strength of strands, f_{ps}	= 270 x 10^3 lb/in^2
Top of slab to strand centroid, d	= 46.7 in

Prestressed Box Beam Description (Span 3):
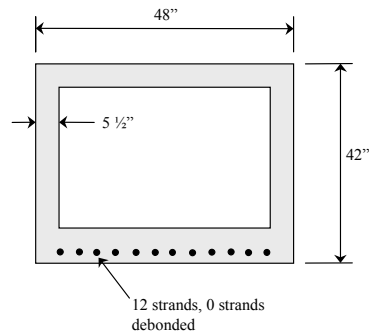
Fig. I.3 – Schematic of box beam cross section of Span 3.

Span length, L_s = 42 ft
Beam cross sectional area, A_b = 887 in^2
Concrete strength, f_c' = 6,000 lb/in^2
Steel yield strength, f_y = 60 x 10^6 lb/in^2
Diam. of shear reinf., D_v = 0.5 in (#4 rebar)
Shear reinf. area/LF, A_v = 0.24 in^2
Shear reinf. spacing, s = 20 in C.C.
Number of prestressing strands = 20
Number of draped strands = 0
Number of debonded strands = 4
Diam. of strands, D_{ps} = 0.5 in
Area of stands, A_{ps} = 0.153 in^2
Tensile strength of strands, f_{ps} = 270 x 10^3 lb/in^2
Top of slab to strand centroid, d = 47.5 in

Shear Strength and Force Evaluations:

Due to the number and severity of the cracks in the beams, it was concluded that without significant repair to the beams, no shear capacity could be given to the existing concrete ($V_c = 0$). Following a successful repair, it was assumed that at least 75% of the original shear capacity was restored. Also, it was assumed that 90% of the original capacity was restored at the extreme ends of the cracks, where the cracks were smaller (see Table I-1). The factored shears, V_u, shown in similar tables, were generated using KYBEAM 2000.

Table I-1: Shear strength and factored shear calculations.

Span 1 of KY3297 Bridge					
Dist. From support (ft)	V_c (kips)	Percent reduction (%)	$V_{c(reduced)}$ (kips)	V_s (kips)	V_u (kips)
0.0	-	-	-	-	221.51
2.0	197.0	75	147.7	34.2	207.01
4.0	209.7	75	157.3	34.2	192.51
6.0	222.4	75	166.8	34.2	178.01
6.8	227.4	90	204.7	34.2	172.21
6.8	229.1	90	206.2	34.2	197.48
6.0	226.9	75	170.2	34.2	202.79
4.0	221.4	75	166.1	34.2	216.07
2.0	221.3	75	166.0	34.2	229.34
0.0	-	-	-	-	242.62

Span 2 of KY3297 Bridge					
Dist. From support (ft)	V_c (kips)	Percent reduction (%)	$V_{c(reduced)}$ (kips)	V_s (kips)	V_u (kips)
0.0	-	-	-	-	274.22
2.0	176.9	75	132.6	33.6	262.20
4.0	188.0	75	141.0	33.6	250.18
6.0	199.2	75	149.4	33.6	238.16
8.0	210.4	75	157.8	33.6	226.13
9.8	220.5	90	198.4	33.6	215.31
9.8	220.5	90	198.4	33.6	217.93
8.0	210.4	75	157.8	33.6	228.51
6.0	199.2	75	149.4	33.6	240.26
4.0	188.0	75	141.0	33.6	252.02
2.0	176.9	75	132.6	33.6	263.77
0.0	-	-	-	-	275.52

Table I-1 (Cont.): Shear strength and factored shear calculations.

Span 3 of KY3297 Bridge					
Dist. From support (ft)	V_c (kips)	Percent reduction (%)	$V_{c(reduced)}$ (kips)	V_s (kips)	V_u (kips)
0.0	-	-	-	-	203.26
2.0	195.4	75	146.6	34.2	188.11
4.0	206.6	75	155.0	34.2	172.96
6.0	217.8	75	163.4	34.2	157.81
8.0	229.0	75	171.8	34.2	142.66
8.4	231.3	90	208.1	34.2	139.63
8.4	229.7	90	206.8	34.2	113.64
8.0	226.9	75	170.2	34.2	116.73
6.0	212.8	75	159.6	34.2	132.21
4.0	198.7	75	149.0	34.2	147.69
2.0	184.6	75	138.5	34.2	163.17
0.0	-	-	-	-	178.65

Shear Strengthening using CFRP Fabric System:

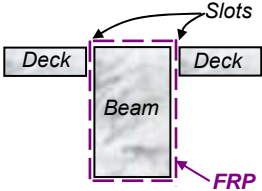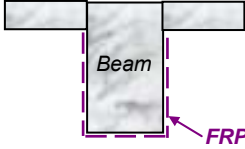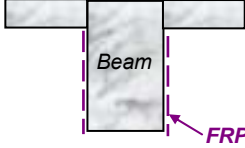The shear strength of the CFRP fabric system for KY3297 Bridge was calculated as follows (Mitsubishi Chemical Corporation 2000):

Design shear strength of CFRP fabric system = $\psi_f V_f$ (Eq. I-1)

, and $V_f = \dfrac{A_{fv} f_{fe} (\sin\beta + \cos\beta) d_f}{s_f}$ (Eq. I-2)

ψ_f = shear reduction factor (Table I-2)

Table I-2: Shear reduction factors, ψ_f.

Type of Wrapped		ψ_f factors
CASE 1: Completely Wrapped		0.95
CASE 2: 3-Sded U-Wrap		0.85
CASE 3: 2-Sided Bonded Face Plies		0.85

Where:
A_{fv} = area of FRP shear reinforcement, in^2
f_{fe} = effective tensile stress in FRP reinforcement (lb/in^2 or ksi)
d_f = depth of FRP shear reinforcement, in (Fig. I-4)
s_f = spacing of FRP reinforcement, in (Fig. I-4)
β = angle between principal fiber orientation and longitudinal beam axis (Fig. I-4)

The area of FRP shear reinforcement, A_{fv}, crossing a shear crack on *both* sides of a beam, can be determined as

$$A_{fv} = 2\, n\, t_f\, w_f \qquad\qquad \text{(Eq. I-3)}$$

Where:

n = number of FRP plies

t_f = thickness of one ply of FRP reinforcement, in

w_f = width of the FRP plies, in (Fig. I-4)
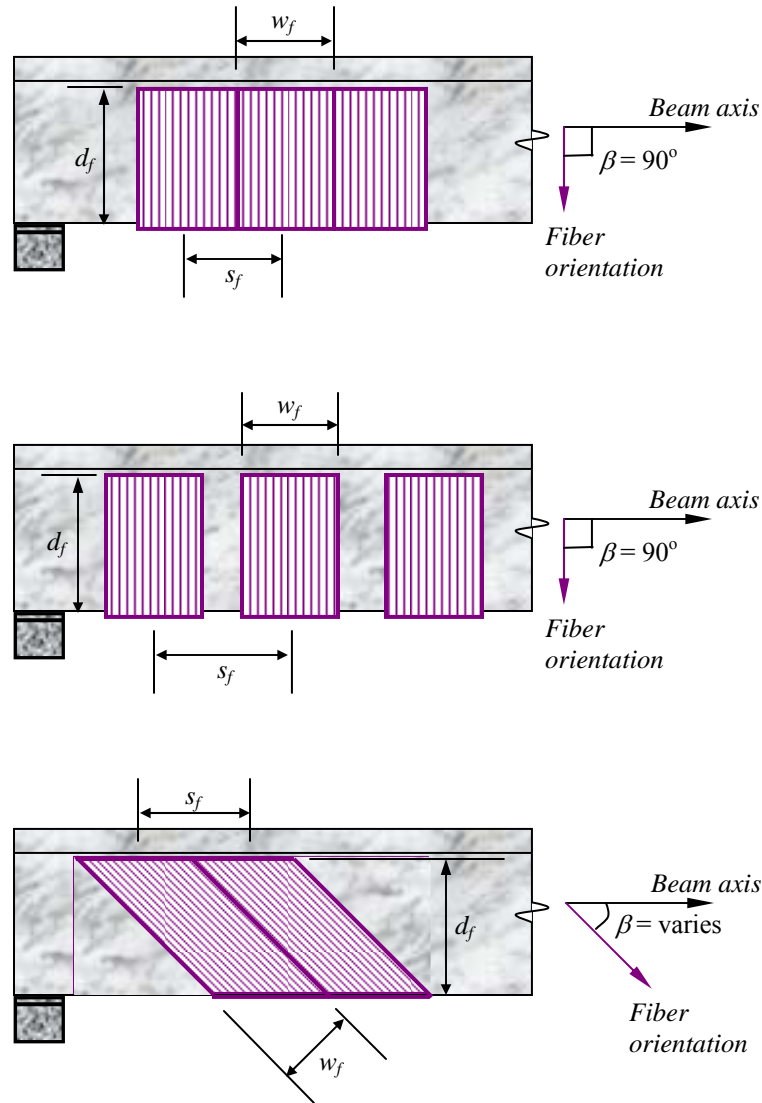
Fig. I-4 – Different wrapping configurations and fiber orientations in shear.

The effective tensile stress, f_{fe}, of Eq. I-2 can be calculated from the following equation:

$$f_{fe} = \varepsilon_{fe} \, E_f \qquad \text{(Eq. I-4)}$$

Where:

E_f = elastic modulus of the FRP in tension (ksi)

ε_{fe} = effective strain in the FRP reinforcement

For U-wraps and 2 sided face wrap (Cases 2 & 3 in Table I-2) without additional anchorage, failure is usually governed by debonding of FRP wrap from the concrete surface. In this case, the effective strain, ε_{fe}, shall be determined from the following expression:

$$\varepsilon_{fe} = \kappa_v \, \varepsilon_{fu} \leq 0.004 \qquad \text{(Eq. I-5)}$$

Where:

ε_{fu} = ultimate tensile strain of the FRP

$$\kappa_v = \frac{k_1 k_2 L_e}{468\varepsilon_{fu}} \leq 0.75 \qquad \text{(Eq. I-6)}$$

, and $L_e = \dfrac{2,500}{\left(n t_f E_f\right)^{0.58}}$ \qquad (Eq. I-7)

$$k_1 = \left(\frac{f_c'}{4,000}\right)^{\frac{2}{3}} \text{ (in which } f_c' \text{ is in lb/in}^2\text{)} \qquad \text{(Eq. I-8)}$$

$$k_2 = \frac{d_f - L_e}{d_f} \text{ (for U-Wraps)} \qquad \text{(Eq. I-9.a)}$$

or $k_2 = \dfrac{d_f - 2L_e}{d_f}$ (for 2-Sided Bonded) \qquad (Eq. I-9.b)

Design Example – Shear Strengthening of a Beam:

Say one ply of Replark® 30,
t_f = 0.0066 in
E_f = 33,400 ksi
w_f = 13 in
ε_{fu}^* = 0.017 in/in

Assume ourdoor exposure, the guaranteed tensile strain, ε_{fu}^*, is then reduced by a C_E factor of 0.85 to obtain the ultimate tensile strain.
ε_{fu} = $C_E \cdot \varepsilon_{fu}^*$ = 0.85·0.017 = 0.0144 in/in

For one ply of CFRP fabric, the area of FRP reinforcement
A_{fv} = 2 n $t_f w_f$ = 2·1·0.0066·13 = 0.176 in^2

The depth of shear reinforcement,
d_f = $d - t_{slab} - t_{haunch}$ = 36.50 in (for Spans 1 & 3)
= 35.67 in (for Span 2)

where t_{slab} and t_{haunch} are 8 and 3 inches, respectively, for the box girders.

The spacing is calculated as

$$s_f = \frac{w_f}{\sin \beta}$$

If $\beta = 45°$, then $s_f = 18.38$ in (for $w_f = 13$ in).

Concrete strength of the box girders, $f_c' = 6{,}000$ psi:

L_e = 1.99 (see Eq. I-7)

k_1 = 1.3104 (see Eq. I-8)

k_2 = 0.891 for Spans 1 & 3 (see Eq. I-9.b)
   = 0.888 for Span 2

κ_v = 0.345 for Spans 1 & 3 (see Eq. I-6)
   = 0.344 for Span 2

Since, for both cases (Spans 1 & 3 or Span 2), the calculated ε_{fu} is greater than 0.004, the limiting value of 0.004 will be used as the effective tensile strain.

The effective tensile strength or stress, f_{fe}

f_{fe} = $\varepsilon_{fe} E_f = 0.004 \cdot 33{,}400$ ksi = 133.6 ksi

The shear capacity of the one-ply CFRP fabric system,

$$V_f = \frac{A_{fv} f_{fe} (\sin \beta + \cos \beta) d_f}{s_f} = 66.04 \text{ kips (for Spans 1 \& 3)}$$

$$= 64.53 \text{ kips (for Span 2)}$$

The shear strength of the one-ply CFRP fabric system,

$\psi_f V_f$ = 56.134 kips (for Spans 1 & 3)
     = 54.851 kips (for Span 2)

A summary of shear strengths of the CFRP fabric system is provided in Table I-3:

Table I-3: Shear strengths provided by CFRP fabric systems.

Span Number	Number of layer with 2-sided bonded fabric at 45°			
	1	2	3	4
1	56.134 kips	112.268 kips	168.402 kips	224.536 kips
2	54.851 kips	109.702 kips	164.553 kips	219.404 kips
3	56.134 kips	112.268 kips	168.402 kips	224.536 kips

APPENDIX II

Technical Data Sheets of the HILTI® CI 060 EP Injection System for Girder Repair.

CI 060 EP Crack Injection System

8.2.1.1 PRODUCT DESCRIPTION

CI 060 EP is a 100% solid epoxy resin that is packaged in a self-contained cartridge with resin and hardener. The CI 060 EP is designed for repairs of thin cracks less than 1/4" (6mm) in concrete base material.

Product Features

- Low viscosity, penetrates cracks as narrow as 0.002" (0.051mm)
- No shrinkage, no solvent fumes
- Bonds to both concrete and steel
- Excellent resistance to water, salt water, alkali and many chemicals
- Forms strong, permanent, water-proof bonds

Listings/Approvals

- Meets requirements of ASTM C-881, Type IV, Grade 1, Class B

8.2.1.2 MATERIAL SPECIFICATIONS

Property	CI 060 EP Injection Resin	Quick-Set Sealing Cpd	CI 070 EP Sealing Cpd
Storage	Resin and hardener have an 18 month shelf life from the date of manufacture when stored below 80°F	Resin and hardener have a one year shelf life from the date of manufacture when stored below 80°F	Resin and hardener have a one year shelf life from the date of manufacture when stored below 80°F
Recommended Application Temp. Range	50°– 113°F	40°– 90°F	40°– 90°F
Working Time (approximate)	90 minutes at 50°F 35 minutes at 73°F 20 minutes at 90°F	3-4 min at 70°F	2¼ hours at 50°F 1 hour at 68°F 20 minutes at 86°F
Curing Time	Minimum curing time at 68°F = Approx 24 hours	30 min at 70°F	1 hour at 77°F
Compressive Strength	10,150 psi		11,100 psi
Tensile Strength	7,975 psi		6,900 psi
Compressive Modulus	265,000 psi		293,000 psi
Mix ratio (Volume)	4:1 Part A : Part B	1:1 Part A : Part B	2:1 Part A : Part B

8.2.1.3 INSTALLATION DATA

Basic Use

CI 060 EP is a heavy duty, low viscosity resin, designed to make repairs in cracked concrete structures. CI 060 EP offers no shrinkage, no solvent fumes and bonding to concrete and steel. Cracks as narrow as 0.002" to 1/4" wide can be repaired. CI 060 EP forms strong, permanent waterproof bonds that provide excellent resistance to water, salt water, alkali and many chemicals.

Coverage

- 1 tube CI 060 EP Injection resin and hardener = 14.3 in³ (234 cm³)
- One can CI 070 EP Surface Sealing resin and hardener = 58 cu in. (32 fl oz, 950 cm³). Covers approx. 50-70 ft of crack.

Limitations

- Minimum crack width 0.002" to maximum crack width 1/4".
- Do not use CI 060 EP system at less than 40°F base material temperature.
- Do not use CI 060 EP in cracks with flowing or standing water.
- Sealing only one side of a crack may cause the loss of epoxy resin.
- Tool: Use CI 060 EP with cap nut type dispenser only

8.2.1.4 INSTALLATION INSTRUCTIONS

1. Clean surface along the crack. Blow out crack with dry and oil-free compressed air.
2. Bond injection ports with CI 070 EP Crack Sealing Compound. Port spacing approximately 6-12" with wider spacing for thinner slabs.
3. Seal the crack with CI 070 EP in strips of minimum 2" wide, 1/8" deep.

4. A light tap with a hammer to the rear end of the cartridge breaks the glass cylinder releasing the hardener. Mix by see-saw motion for approx. 30 motions—do not shake.

5. Puncture the seal of the cartridge tip. Then screw on connection hose. Remove foil from rear of cartridge.
6. Plug connection hose to bottom port. Tighten union nut, insert air relief stopper at next port above (non-return valve is opened—entrapped air can escape). Use only cap nut type dispensers

7. Inject CI 060 EP resin until it appears visibly in the next port above. Remove air relief stopper (non-return valve is now closed) and insert into next port. Continue injecting into original port until the port will accept no more resin when normal hand pressure is used on the dispenser.
8. Detach connection hose from port and plug to the next higher port. Repeat operating steps 6 and 7 up to the end of the crack.

9. After the injection resin has set—generally overnight—the ports and the sealing compound can be removed with a flat chisel. If required, the surface can be ground even.

Economical

- No expensive pumps or motors
- Minimal mobilization charges
- Low cost per linear foot of repair

Easy to Use

- New, self-contained cartridge with resin and hardener in a single package
- Anti-backflow valves in ports and hoses help prevent spillage of epoxy
- No drilling required for injection port installation
- No power source required
- No equipment to clean; all parts disposable
- Portable

8.2.1.5 ORDERING INFORMATION

Description	Item No.	Size	Quantity
CI 060 EP Kit	00220244		1 Kit*
CI 070 EP Crack Sealing Compound	00225491	1 quart (950 cm³)	1
CI 070 EP Crack Sealing Compound	00225493	1 quart (ea) (950 cm³)	4 (case)
Quick-Set Sealing Compound	Special Order	1 quart	1
Non return ports	00020132	—	30
Connection hoses	00020133	—	6
Air relief stoppers	00020134	—	4

* Kit Includes: 172 in³ injection epoxy, 30 ports with non-return valves, 6 connection hoses with non-return valves, 4 air relief stoppers

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