Rapid Retrofit and Strengthening of Bridge Components

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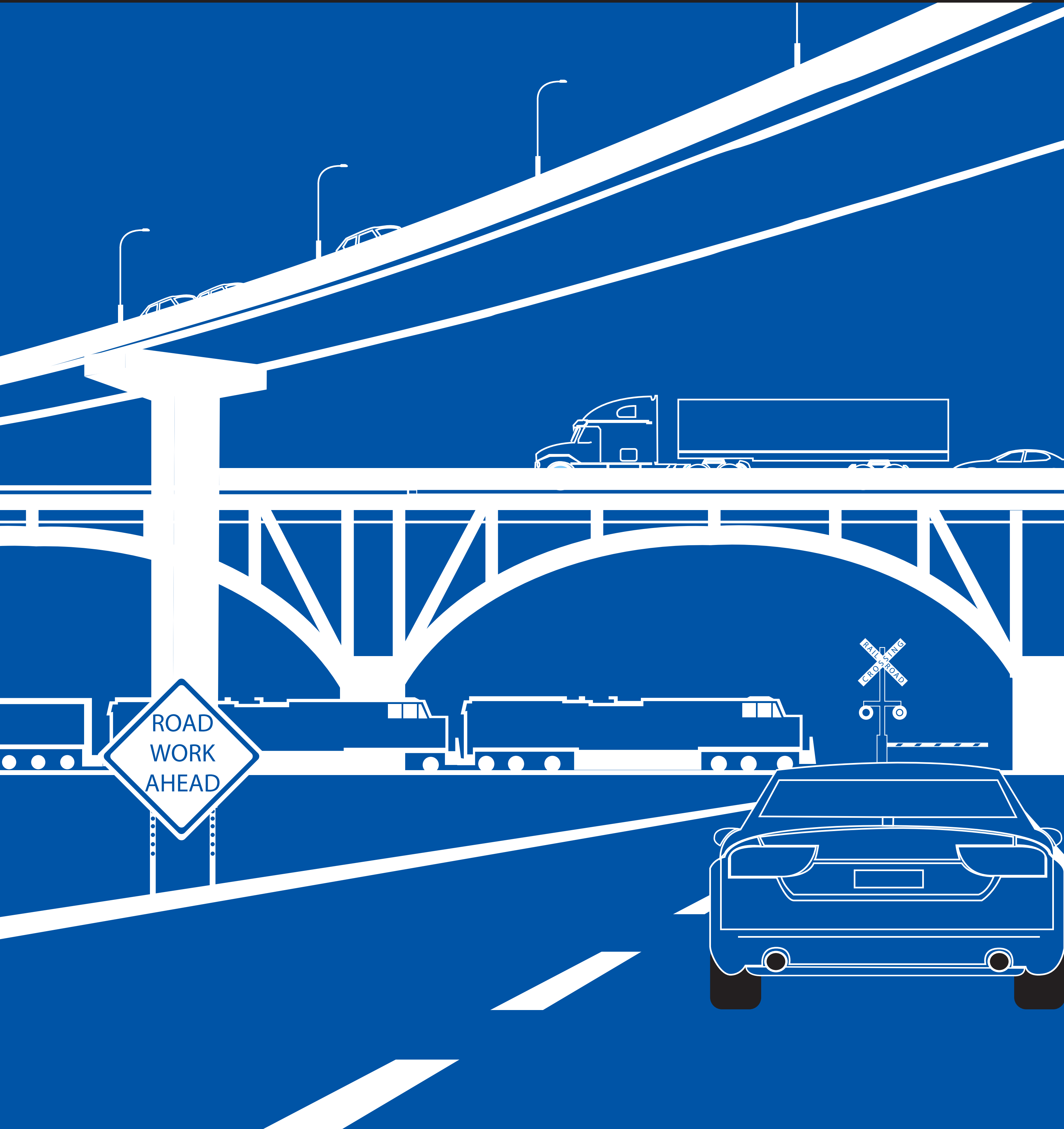

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Research Report
KTC-19-07/SPR13-465-1F

Rapid Retrofit and Strengthening of Bridge Components

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16. Abstract

Rapid repair of damaged or deteriorated concrete bridge components will prevent the entire bridge from suffering irreversible damage in the future due to gradual spalling of concrete or corrosion of exposed steel. CFRP laminates and fabrics have become popular for repairing and strengthening of concrete girders. A series of CFRP materials — branded CatStrong — specifically designed for the repair and retrofit of bridges was developed at the Kentucky Transportation Center and the University of Kentucky. These materials include the CFRP Rod Panels (CatStrong CRPs), Unidirectional and Triaxial Carbon Fabric (CatStrong UCF and TCF), and Triaxial Carbon Wrap (CatStrong TCW).

This study documented the implementation of CFRP materials to rapidly repair/strengthen six bridges in Kentucky. Three of the retrofit projects utilized CatStrong CRPs for strengthening reinforced concrete bridge girders. Because the CRPs have modular construction, they can easily be applied by a by a single worker, eliminating the need for extensive scaffolding/access equipment and a large work force. As such, the construction costs related to panel application is less than those for other retrofit measures. CatStrong TCW, combined with CatStrong TCF, was deployed for the repair and strengthening of deteriorated timber piles. The remaining two projects involved the use of CatStrong UCF and TCF for strengthening cracked prestressed concrete girder ends and strengthening a cracked bridge pier cap. Each bridge retrofit project was carried out by Kentucky Transportation Cabinet bridge maintenance crews. The crews were trained on the use and application of the new material. Design and construction specifications for the CatStrong CRPs were also developed as part of the study. This study will implement these new CFRP materials to rapidly repair/strengthen six selected bridges in Kentucky. Three of the retrofit projects utilized CatStrong CRPs for strengthening Reinforced Concrete (RC) bridge girders. The modular construction of the CRPs allows for easy application by a single worker without the need for extensive scaffolding/access equipment and a large work force. Consequently, application of the panels reduces construction costs when compared with other FRP retrofit measures. The CatStrong TCW, combined with CatStrong TCF, was deployed for the repair and strengthening of deteriorated timber piles. The remaining two projects involved the use of CatStrong UCF and TCF for strengthening cracked Prestressed Concrete (PC) girder ends and strengthening a cracked bridge pier cap. Each bridge retrofit project was carried out by the Kentucky Transportation Cabinet (KYTC) bridge maintenance crew of the respective KYTC district. The crews were trained on the use and application of the new material. Design and Construction Specifications for the CatStrong CRPs were also developed as part of the study.

17. Key Words
bridge retrofit, CFRP, CRP, girder strengthening, pier cap, timber piles, rapid repair

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Table of Contents

List of Figures

List of Tables

1. Introduction

Highway infrastructure in Kentucky and throughout the United States (US) is aging. When the American Society of Civil Engineers (ASCE) rated the nation's infrastructure in 2017, the rating for Bridges was a C+. Out of more than 600,000 bridges across the US, over 9 percent are structurally deficient, while 40 percent are 50 years or older. This latter figure is expected to double by 2030 without adequate bridge replacement. Over the last decade the Federal Highway Administration (FHWA) estimated budget needs have been growing at a much faster rate than the appropriations provided to the highway bridge program.

While the need for more investment in the nation's overstressed infrastructure is paramount, effective upkeep of existing infrastructure will minimize future funding requirements. The rapid retrofit, strengthening, and repair of structurally deficient bridges extend their service life, while letting them carry larger loads — sometimes at higher frequencies — than they were initially designed for. The use of novel high-performance materials for bridge retrofit is one strategy to extend the service lives of aging bridges. High-performance materials can have very high strength-to-weight ratios and are suitable for efficient structural repair of deficient bridge members. The ability for rapid placement and the use of minimal labor is one of the many advantages that these materials offer. Fiber reinforced polymer (FRP) composite materials — especially carbon fiber reinforced polymers (CFRP) — initially developed in the aerospace and automobile industry have become popular for strengthening bridge components.

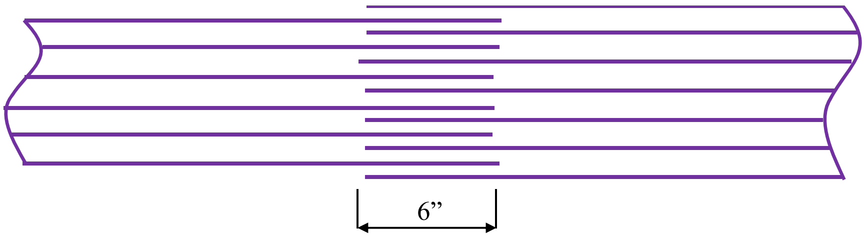
Rapid repair of impacted, damaged, or deteriorated concrete bridge components prevents irreversible damage to the structural integrity of the bridge in the future due to gradual spalling of concrete or corrosion of exposed steel. A series of CFRP materials — branded CatStrong — specifically designed for the repair and retrofit of bridges, was developed at the Kentucky Transportation Center (KTC) at the University of Kentucky. These materials include CFRP Rod Panels (CatStrong CRPs), Unidirectional and Triaxial Carbon Fabric (CatStrong UCF and TCF), and Triaxial Carbon Wrap (CatStrong TCW). CatStrong CRP and TCW are produced at the University of Kentucky; the UCF and TCF carbon fabric is procured specifically for bridge strengthening applications. Because of the CRPs modular construction, they can easily be applied by a by a single worker, eliminating the need for extensive scaffolding/access equipment and a large work force. As such, the construction costs related to panel application is less than those for other retrofit measures.

Over a six-year period, this study deployed these CFRP materials to rapidly repair/strengthen six bridges in Kentucky. Three retrofit projects used CatStrong CRPs for strengthening reinforced concrete (RC) bridge girders. CatStrong TCW, combined with CatStrong TCF, was deployed for the repair and strengthening of deteriorated timber piles. The remaining two projects involved the use of CatStrong UCF and TCF for strengthening cracked prestressed concrete (PC) girder ends and the strengthening of a cracked bridge pier cap. Each bridge retrofit project was carried out by district-level Kentucky Transportation Cabinet (KYTC) bridge maintenance crews. Crews were trained on the use and applications of the new material. Design and construction specifications for CatStrong CRPs were also developed as part of the study.

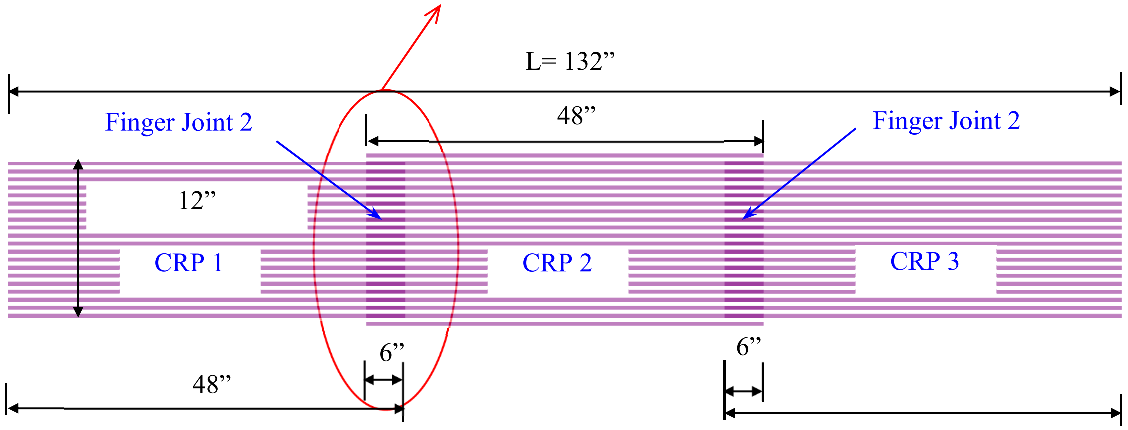
2. High-Performance Material

2.1 CatStrong CRP

CatStrong CRPs are produced using small-diameter CFRP rods mounted on a fiberglass backing. The spacing between individual rods is greater than the rod diameter. Several rod sizes are used, with diameters varying from 0.078 in. to 0.156 in. The CFRP rods have a manufacturer-reported tensile modulus of 19,500 ksi and an ultimate tensile strength of 320 ksi. Each CRP is 48 in. long and has a 36 in. fiberglass backing, providing 6 in. for the finger joint on either side of the panel. Alternate panels are produced with an extra rod to establish symmetry at the finger joint. The 6 in. overlap for the finger joint was a conservative selection based on the results of double lap shear tests. Rod spacing was calculated to maintain a minimum clear distance of 0.05 in. between rods at the finger joint. Fig. 1 illustrates the CRP structure and the modular construction, including the finger joint.



(a) CRP finger joint



(b) CRP panel geometry

Fig. 1. CatStrong CRP with finger joint

CatStrong CRPs offer several advantages over traditional CFRP laminates. They eliminate the need for splice plates by using a modular retrofit construction. This allows retrofit construction to be halted after the application of any panel, provided there is no bonding structural epoxy left on the finger joint. CRPs can be applied individually in a modular fashion by a single worker, working out of one set of scaffolding or an access platform, moving along the bridge span and applying one 4 ft. CRP at a time. Table 1 summarizes data on the two CRP types that have been experimentally evaluated and deployed for bridge strengthening in Kentucky. The CRP 070, with each CFRP rod having a minimum capacity of 1.53 kips, was utilized in three of the bridge retrofit projects highlighted in this report. Additional information on the surface preparation and application of the CatStrong CRP is provided in Appendix E.

Table 1. CRP properties for two different rod sizes

Designation	**Rod Diameter, d_r in.**	**Rod Area, A_r in^2**	**Rod Spacing, s_r in.**	**Tensile Strength ksi**	**Tensile Modulus ksi**
CRP 070	0.078	4.78×10^{-3}	0.250	320	19,500
CRP 195	0.156	19.11×10^{-3}	0.375		

2.2 CatStrong UCF and TCF

Three types of CatStrong UCF CFRP fabric were used in this project. All three uniaxial carbon fabrics are made using the same carbon fibers and have manufacturer-specified tensile strength of 413 ksi and tensile modulus of 20,200 ksi. The thickest uniaxial carbon fabric — CatStrong UCF 120 — can carry 120 kips of tensile force per 1 ft. width of fabric. The fabric is ideal for flexural strengthening of girders as well as providing confinement for piers and columns. The CatStrong UCF 055 can carry over 55 kips of tensile force, while the lighter fabric CatStrong UCF 023 can carry over 23 kips of tensile force per 1 ft. width of fabric. The flexibility of both fabrics enables them to wrap around corners while providing sufficient tensile strength in the fiber direction. Table 2 summarizes the properties of these fabrics.

Table 2. Physical and mechanical properties of CatStrong CFRP fabric

CatStrong CFRP fabric type	**Fabric width (in)**	**Laminate thickness at 55% fiber volume (in)**	**Fabric weight (oz/yd^2)**	**Tensile strength (ksi)**	**Elastic modulus (ksi)**
UCF 120	12	0.030	22.3	413	20.2×10^3
UCF 055	12	0.014	9.0		
UCF 023	12	0.006	4.1		
TCF 012*	20	0.011	8.0	116	6.3×10^3

* The mechanical properties are the minimum for both longitudinal and transverse directions

The braided triaxial CatStrong TCF 012 CFRP fabric was the other type of CFRP fabric deployed. It is a quasi-isotropic CFRP fabric with braided fibers running in 0° and ±60° directions. The primary advantage of this fabric is that it provides approximately the same tensile capacity along any direction in the plane of the fabric. The triaxial CFRP fabric used in the retrofit projects has a tensile capacity of 12 kips per 1 ft. width of fabric in all directions. This proved ideal for arresting multi-directional cracking and providing shear strength and confinement. Appendix F contains additional information on the surface preparation and application of CatStrong UCF/TCF fabric .

2.3 CatStrong TCW

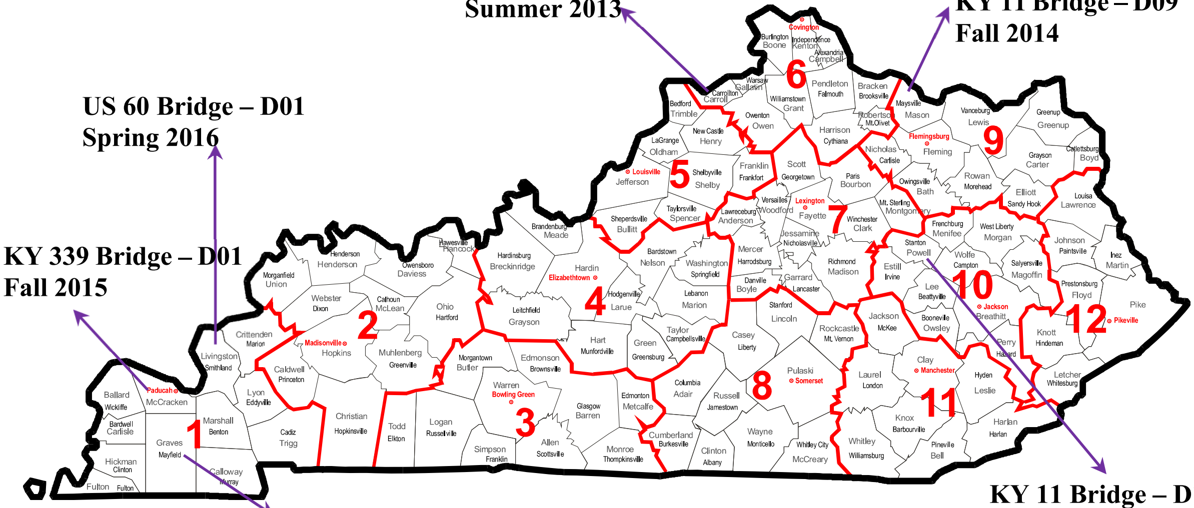
The CatStrong Triaxial Carbon Wrap (TCW) is a pre-cured CFRP laminate made from the CatStrong TCF 012 fabric. These were produced as the University of Kentucky for use as jackets to strengthen deteriorated steel/concrete/timber piles. The fiber orientation of the CatStrong TCF 012 fabric provides the necessary strength for the jacket in the axial and hoop directions. Because CFRP is a non-corrosive material, CatStrong TCW is an ideal material for applications near marine environments. TCWs are wrapped around the damaged piles/columns with spacing between the pile/column surface and the TCW. The length of the wrap is calculated based on the diameter of the pile/column, the spacing required between the pile/column and the TCW, and the required overlap for the wrap to bond with itself. Once the wrap is in place, an epoxy mortar or non-shrink grout is placed between the damaged pile/column and TCW. If a section being strengthened is below the water surface, a grout that cures underwater can be used. Additional information on the preparation of the pile/column and the application of the CatStrong TCW is in Appendix G.

3. Retrofit Projects

A primary goal of this project was training KYTC district bridge maintenance personnel in the application of CFRP material. As several Cabinet district bridge crews already had experience with the material through other retrofit projects, the current project focused on KYTC districts where CatStrong products had not been deployed. Originally seven districts were identified, out of which four district crews were trained through the six projects. The remaining three district crews will be trained through a separate research project. The six projects were carried out over a three-year period (Fig. 2).

The following list notes the CatStrong materials used to carry out each bridge retrofit:

1. CatStrong CRP (and CatStrong TCF)
    - KY 55 over Majors Run Creek – Carroll Co., D06
    - KY 11 over Cat Creek – Powell Co., D10
    - KY 80 over I-69/Purchase Parkway – Graves Co., D01
2. CatStrong UCF/TCF
    - KY 11 over CSX Railroad and Strodes Run – Mason Co., D09
    - US 60 over Cumberland River – Livingston Co., D01
3. CatStrong TCW (and CatStrong TCF)
    - KY 339 over Massac Creek – McCracken Co., D01



KY 55 Bridge – D06
Summer 2013

KY 11 Bridge – D09
Fall 2014

US 60 Bridge – D01
Spring 2016

KY 339 Bridge – D01
Fall 2015

KY 80 Bridge – D01
Summer 2013

KY 11 Bridge – D10
Fall 2013

Fig. 2 CatStrong projects in KYTC districts

4. KY 55 Over Majors Run Creek

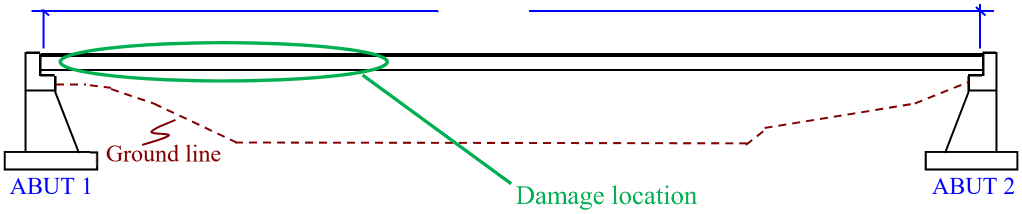
4.1 Bridge Location

The KY 55 bridge over Majors Run creek (021B00020N) is located in Carrol County, Kentucky (KYTC District 06).

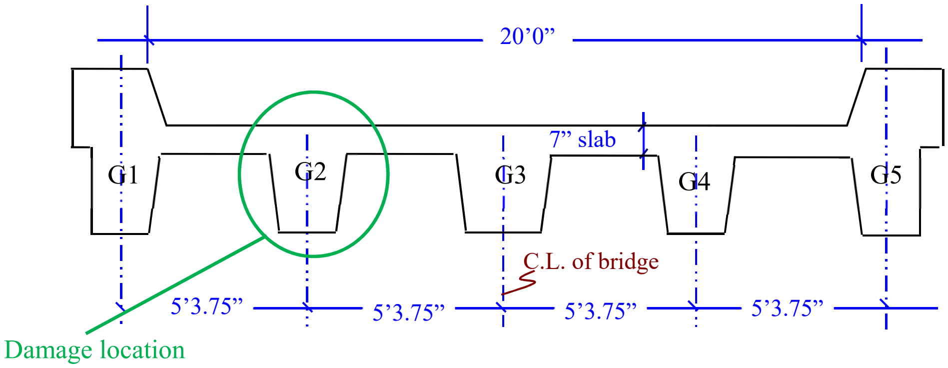
Fig. 3. Location of KY 55 over Majors Run Creek in Carrol County, Kentucky

4.2 Bridge Details

The single span reinforced concrete deck girder bridge was built in 1924 and has a 24 ft. span. The primary load bearing members are five reinforced concrete girders with a 7 in. deck on top (Fig. 4(b)).



(a) General layout of the bridge



(b) Cross section of bridge

Fig. 4. Layout of KY 55 over Major Run Creek

4.3 Damage Details

The initial damage observed was spalled concrete and corroded reinforcement near one end of Girder G2 (Fig. 5(a)). Over 50% section loss was observed in several rebars. Longitudinal cracking was also observed on the bottom of other girders (see Fig. 5(b)), indicating the rebar within them may be corroded. During the initial retrofit construction, it was found that the remaining girders also had section loss due to corrosion and required strengthening.

(a) Damage observed in girder G2 (b) Longitudinal cracks in girder G1

Fig. 5. Typical damage to concrete girders

4.4 General Retrofit Plan

Fig. 6 shows the general retrofit plan for the strengthened girders. The primary retrofit material was the 12 in. wide CatStrong CRP 070 panels. The panels were applied to the bottom and sides of the girders. CatStrong TCF 012 fabric U-wraps were applied over the CatStrong panel finger joints to provide anchorage. As many shear stirrups were also corroded, the CatStrong TCF 012 fabric provides additional shear strength to the girders. Additional details regarding the retrofit design can be found in Appendix A.

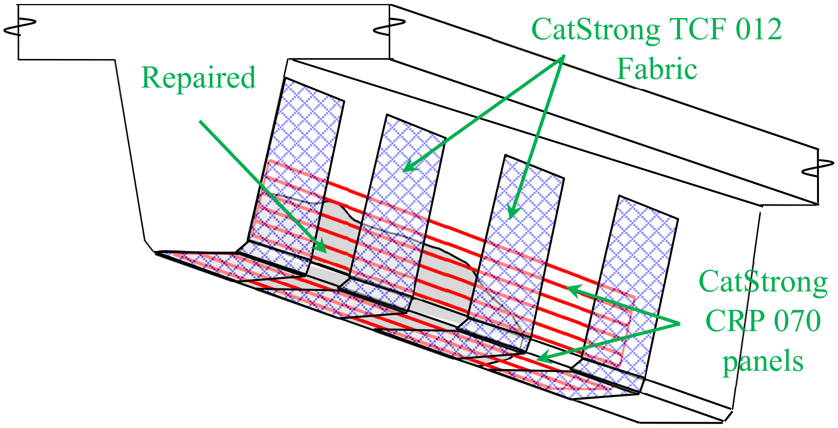


Fig. 6. Retrofit diagram of KY 55 over Majors Run Creek

4.5 Retrofit Construction

KYTC District 06 bridge maintenance personnel carried out the retrofit in June 2013. Initially, all loose concrete was removed from cracked regions of the girders. Crew members used pneumatic chipping hammers to remove the material and expose at least one inch of non-corroded reinforcing steel (Fig. 7(a)). The steel was then sandblasted to remove rust, and a zinc primer was applied with a brush after wiping it with a solvent (Fig. 7(b), (c)). Wooden forms were erected to ensure the repair mortar cured appropriately to provide the original shape of the beam (Fig. 7(d)). The forms were removed once the repair mortar had cured. A mechanical grinder was used to remove any in-plane variations between the repair mortar and pre-existing concrete.

(a) Concrete removed to expose rebar

(b) Sandblasting rebar

(c) Zinc primer brushed onto rebar

(d) Wood framework and repair mortar application

Fig. 7. Repair Process of KY 55 over Major Run Creek

A two-part epoxy was applied to the clean concrete and the CatStrong CRP 070 was placed over the epoxy and pressed into it by hand (Fig. 8(a)). This was carried out in a modular fashion, moving from one panel to the next. Each panel was connected to the next using the finger joint connection. Once rod panels were in place along the vertical and bottom faces of the girder, additional epoxy was applied over the finger joint area all the way to the top of the girders, and the CatStrong TCF 012 was placed over top of the CRP 070 using a dry layup process. All air pockets and irregularities were smoothed out of the fabric with laminating rollers (Fig. 8(b)). Fig. 9 depicts the bridge following the completed retrofit. The retrofit underwent periodic inspections in the three years following the construction — no defects were observed.

(a) CRP 070 applied with epoxy (b) TCF application with laminating rollers

Fig. 8. CRP and TCF application on KY 55 over Majors Run Creek

Fig. 9. Repairs complete on KY 55 over Majors Run Creek

5. KY 11 Over Cat Creek

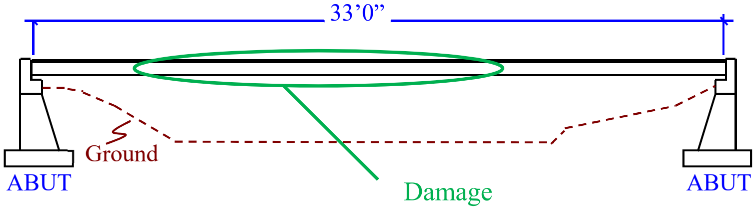
5.1 Bridge Location

The KY 11 bridge over Cat Creek (099B00034N) in Powell County, Kentucky, is located in KYTC District 10.

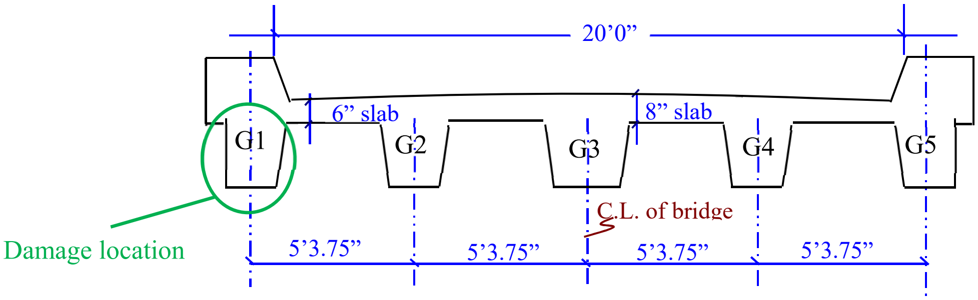
Fig. 10. Location of KY 11 over Cat Creek in Powell County, KY

5.2 Bridge Details

The single span reinforced concrete deck girder bridge was built in 1923 and has a 33 ft. span. The primary load bearing members are five reinforced concrete girders (Fig. 11(b)). The reinforced concrete deck slab is 6 in. thick over the outside girders and increases to 8 in. over the center girder.



(a) General layout of the bridge

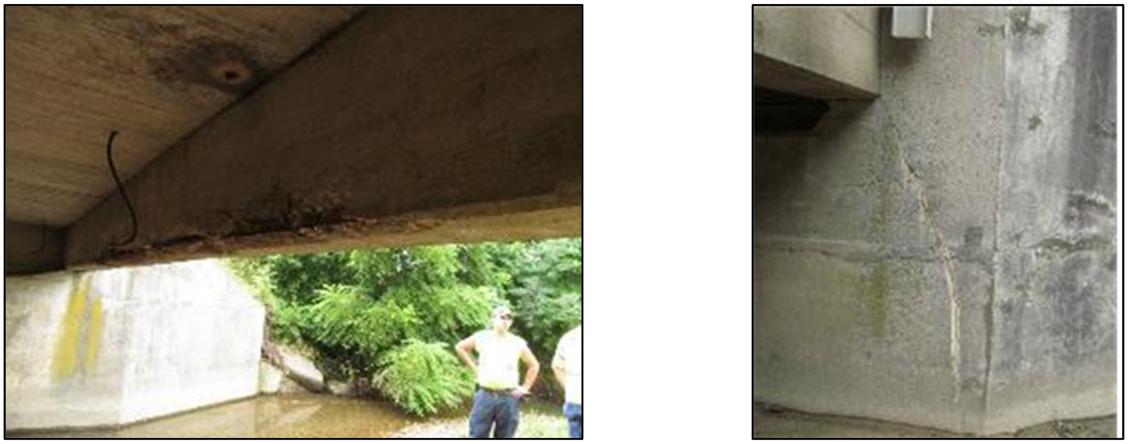


(b) Cross section of the bridge

Fig. 11. Layout of KY 11 over Cat Creek

5.3 Damage Details

The primary damage observed was spalled concrete and corroded reinforcement along the length of Girder G1 (Fig. 12(a)). In addition, two vertical cracks (Fig. 12(b)) were observed on the abutment walls.


(a) Damage to girder G1

(b) Damage to abutment wall

Fig. 12. Damage to concrete girders and abutment

5.4 General Retrofit Plan

The general retrofit plan for the girders was similar to the KY 55 bridge in KYTC D06. The primary retrofit material was 10 in. wide CatStrong CRP 070 panels. Panel width was restricted to 10 in. due to the width of the bottom surface of the exterior girder. The panels were applied to the bottom and sides the girders. CatStrong TCF 012 fabric U-wraps were applied over the CatStrong panel finger joints to provide anchorage. Additional details on the girder, as well as the abutment retrofit design, can be found in Appendix B.

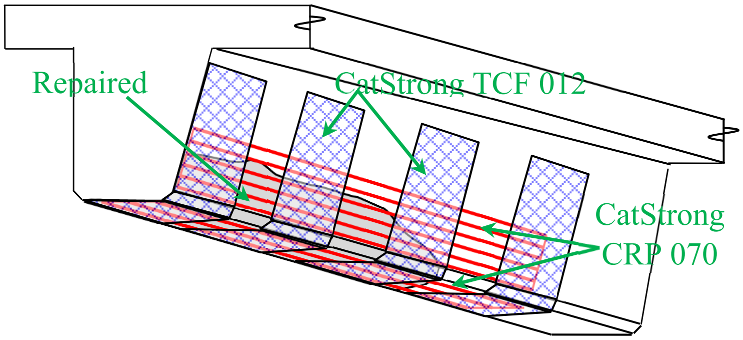


Fig. 13. Retrofit diagram of KY 11 over Cat Creek

5.5 Retrofit Construction

The retrofit was carried out by the KYTC District 10 Bridge Maintenance personnel in September 2013. Initially, all loose concrete was removed from the damaged regions of the exterior girder. Crew members used pneumatic chipping hammers to remove the material and expose at least one inch of non-corroded reinforcing steel (Fig. 14(a)). The steel was then sandblasted to remove rust, and a zinc primer was applied with a brush after wiping it with a solvent (Fig. 14(b)). Wooden forms were erected to ensure the repair mortar cured appropriately to provide the original shape of the beam (Fig. 14(c)). The forms were removed once the repair mortar had cured. A mechanical grinder was used to remove any in-plane variations between the repair mortar and pre-existing concrete.

(a) Concrete removed to expose rebar

(b) Sandblasting rebar

(c) Wood formwork and repair mortar application

(d) Repair of abutment crack

Fig. 14. Repair process of KY11 over Cat Creek

Crack injection ports were mounted, and the exterior of the abutment cracks was covered using a trowel-grade epoxy (Fig. 14(d)). Following the exterior epoxy's curing period, a crack-injection epoxy was introduced, starting from the bottom-most port and gravity fed in to the cracks. After the crack-injection epoxy had cured, the crack injection ports and excess epoxy over the cracks were ground off.

The same two-part epoxy used on the KY 55 bridge in KYTC District 06 was applied to the concrete; the CatStrong CRP 070 was placed over the epoxy and pressed into it by hand. This was carried out in a modular fashion, moving from one panel to the next (Fig. 15(a)). Each panel was connected to the next using the finger joint connection. Once rod panels were in place along the vertical and bottom faces of the girder, additional epoxy was applied over the finger joint area to the top of the girders, and the CatStrong TCF 012 was placed atop the CRP 070 using a dry layup process. The same epoxy was applied over the cracks in the abutment, and 13 in. wide CatStrong TCF 012 fabric was centered over the cracks (Fig. 15(b)). Fig. 16 shows the bridge following the completed retrofit. The retrofit underwent periodic inspections in the three years following the construction — no defects were observed.

(a) CRP 070 applied with epoxy

(b) TCF application over abutment crack

Fig. 15. CRP and TCF application on KY11 over Cat Creek

Fig. 16. Completed repairs on KY11 over Cat Creek

6. KY 80 Over I-69/Purchase Parkway

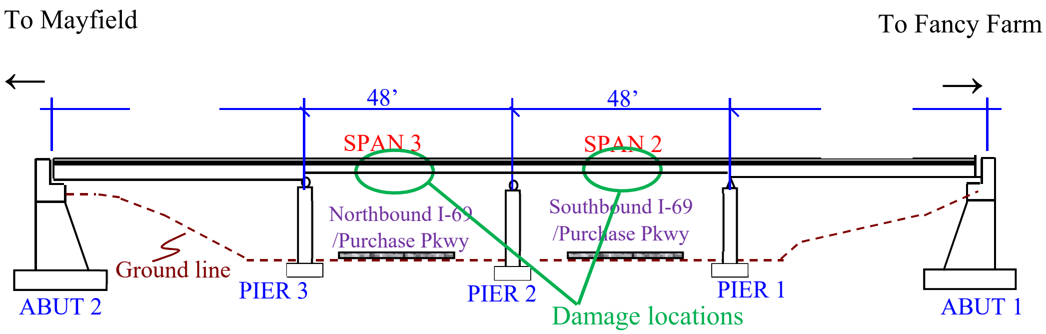
6.1 Bridge Location

The KY 80 bridge over I-69/Purchase Parkway (042B00106N) in Graves County, Kentucky, is located in KYTC District 01.

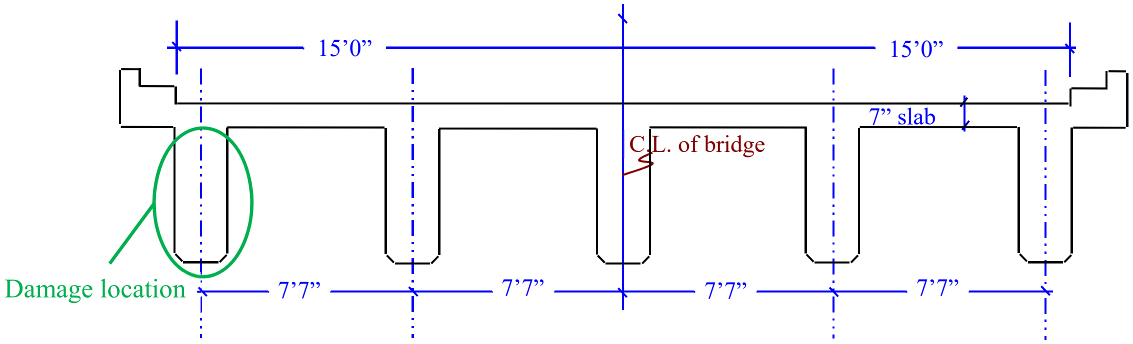
Fig. 17. Location of KY 80 over I-69 in Graves County, KY

6.2 Bridge Details

The RC bridge is a four-span (56’- 48’- 48’- 56’) bridge constructed in 1961. It is 30 ft. wide with a 7 in. deep continuous deck. The general layout of the bridge and a typical cross section is given in Figs. 18(a) and 18(b), respectively.



(a) General layout of the bridge



(b) Cross section of the bridge (span 2 and 3)

Fig. 18. Layout of the KY 80 over I-69

6.3 Damage Details

The exterior girders on the north side of the southbound and northbound lanes of I-69/Purchase Parkway suffered damage from over-height truck impacts. The impacts damaged rebars and led to concrete spalling. Several of the interior girders also exhibited concrete spalling and minor rebar damage from the over-height impacts.

Fig. 19. Damage to concrete girders

6.4 General Retrofit Plan

The retrofit plan included use of a 12 in. wide CatStrong CRP 070 panel for flexural strengthening and CatStrong TCF 012 CFRP fabric U-wraps for confinement (Fig. 20). The CRP 070 panels were applied to the bottom and sides of the girders. CatStrong TCF 012 fabric strips that were 26 in. wide were applied over the CatStrong panels with a 4 in. overlap between strips to confine the concrete and prevent it from spalling in the event of a future over-height impact. Additional details regarding the girder retrofit design can be found in Appendix C.

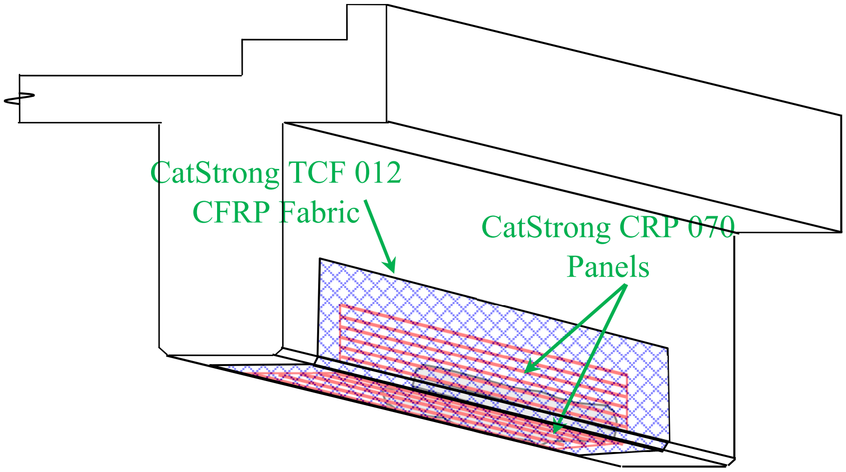


Fig. 20. Retrofit design of KY 80 over I-69

6.5 Retrofit Construction

KYTC District 01 Bridge Maintenance personnel carried out the retrofit in August 2013. One lane of the two-lane north and south bound interstate was closed during construction and the damaged areas were accessed via a scissor lift. Crew members used pneumatic chipping hammers to remove loose material and expose at least one inch of non-corroded reinforcing steel (Fig. 21(a)). The steel was then sandblasted to remove rust, and a zinc primer was applied with a brush after wiping it with a solvent (Fig. 21(b)). Wooden forms were erected to ensure the repair mortar cured appropriately to provide the original shape of the beam (Fig. 21(c)). The forms were removed once the repair mortar had cured (Fig. 21(d)). A mechanical grinder was used to remove in-plane variations between the repair mortar and pre-existing concrete.

(a) Concrete removed to expose rebar

(b) Zinc primer brushed onto rebar

(c) Wood formwork and repair mortar application

(d) Bridge girder with applied repair mortar

Fig. 21. Repair process of KY 80 over I-69

A two-part epoxy was applied to the concrete; the CRP 070 panels were placed and pressed into the epoxy by hand. Construction proceeded in a modular fashion with the application of one panel after the other; the scissor lift was moved after the application of each panel. Because the impact-damaged section spanned both lanes of the northbound I-69/Purchase parkway, the last CRP panel applied near the centerline had the finger joint left void of epoxy (Fig. 22(a)). This allowed the crew to shift traffic and start construction on the adjoining lane the following day. Once the rod panels were in place along the vertical and bottom faces of the RC girders, the CatStrong TCF 012 CFRP fabric was placed atop the CRP 070. Air pockets and irregularities were smoothed out of the fabric with laminating rollers. The completed retrofit of two girders over the northbound lanes is shown in Fig. 23.

(a) Finger joint of CRP 070 left void of epoxy (b) TCF application over CRP

Fig. 22. CRP and TCF application on KY 80 over I-69

Fig. 23. Completed repairs on KY 80 over I-69 with UV protective coating

7. KY 11 Over CSX Railroad and Strodes Run Pike

7.1 Bridge Location

The KY 11 bridge over CSX Railroad and Strodes Run (081B00049N) in Mason County, Kentucky, is located in KYTC District 09.

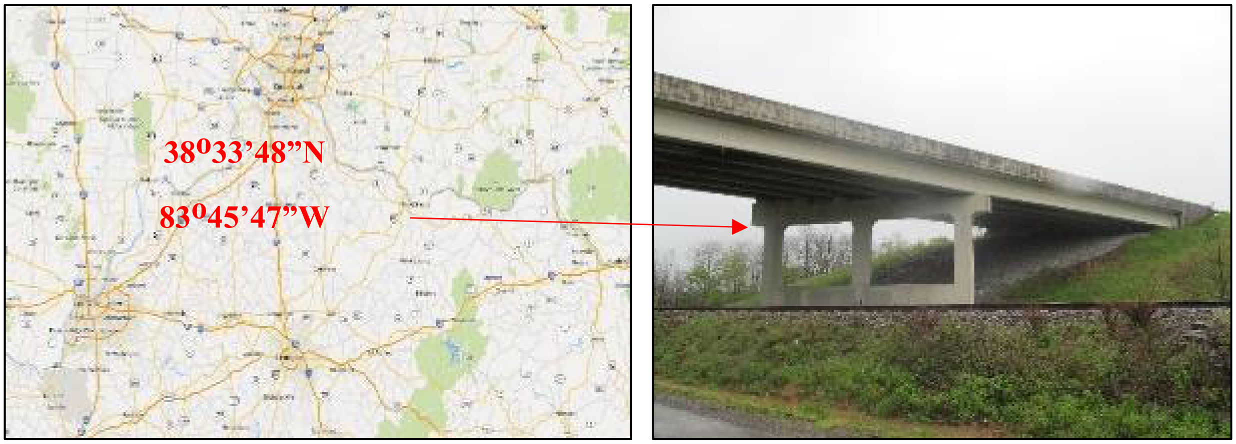
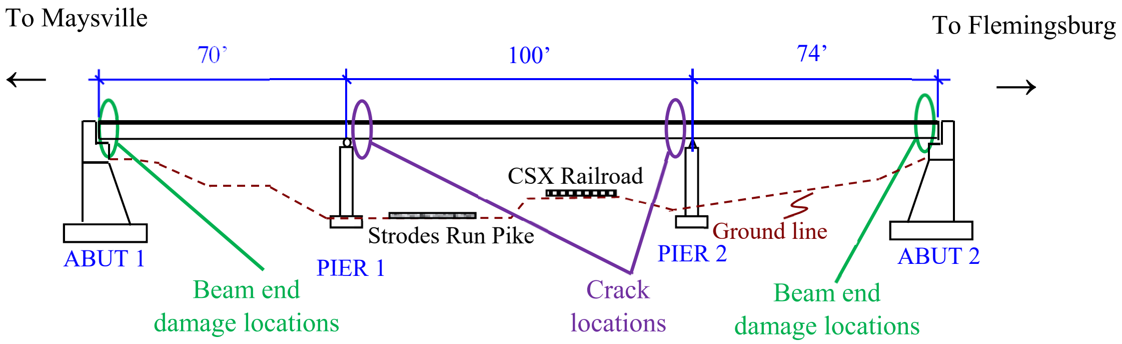


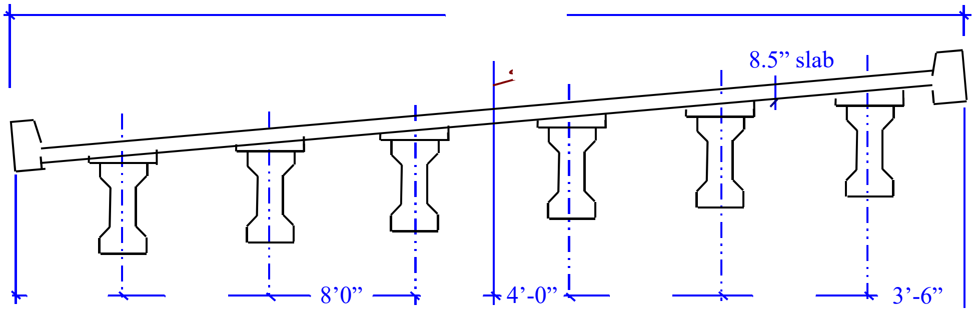
Fig. 24. Location of KY 11 over CSX railroad and Strodes Run Pike in Mason County, KY

7.2 Bridge Details

Constructed in 1979, the PC I-girder bridge has three spans (70’-100’-74’); the center span is over the CSX railroad and Strodes Run Pike. It is 47 ft. wide and has six prestressed AASHTO Type IV I-beams per span with an 8.5 in. deep continuous deck. The general layout of the bridge and a typical cross section are given in Figs. 25(a) and 25(b), respectively.



(a) General layout of the bridge



(b) Cross section of the bridge

Fig. 25. Layout of the KY 11 over CSX Railroad and Strodes Run Pike

7.3 Damage Details

The observed damage to the AASHTO Type IV PC girders included cracks at the girder ends at 10 locations, similar to Fig. 26(a). The cracks were primarily located at the ends of the girders within the center span. In addition, concrete spalling and exposed prestressing tendons were identified at the girder ends at six locations over the two abutments, similar to Fig. 26(b).

(a) Cracks at PC girder ends (b) Damage to PC girder ends over abutment

Fig. 26. Damage to beam ends and cracks in beams

7.4 General Retrofit Plan

The retrofit plan included the use of CatStrong UCF 055 CFRP and fabric strips and TCF 012 CFRP fabric U-wraps for strengthening the PC I-girder ends (Fig. 27). Additional details regarding the girder retrofit design can be found in Appendix D.

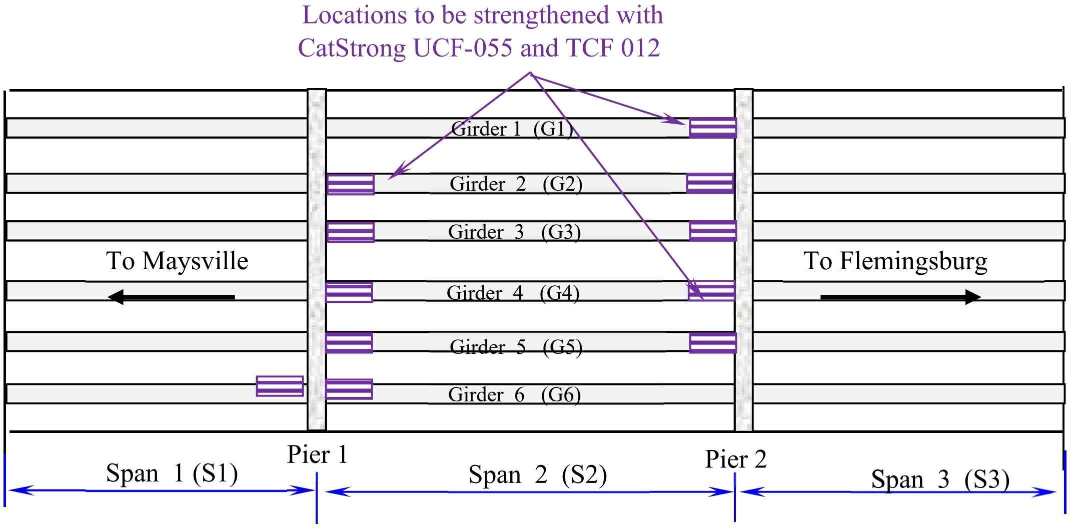


Fig. 27. UCF-055 and TCF-012 retrofit locations on KY 11 over CSX Railroad and Strodes Run Pike

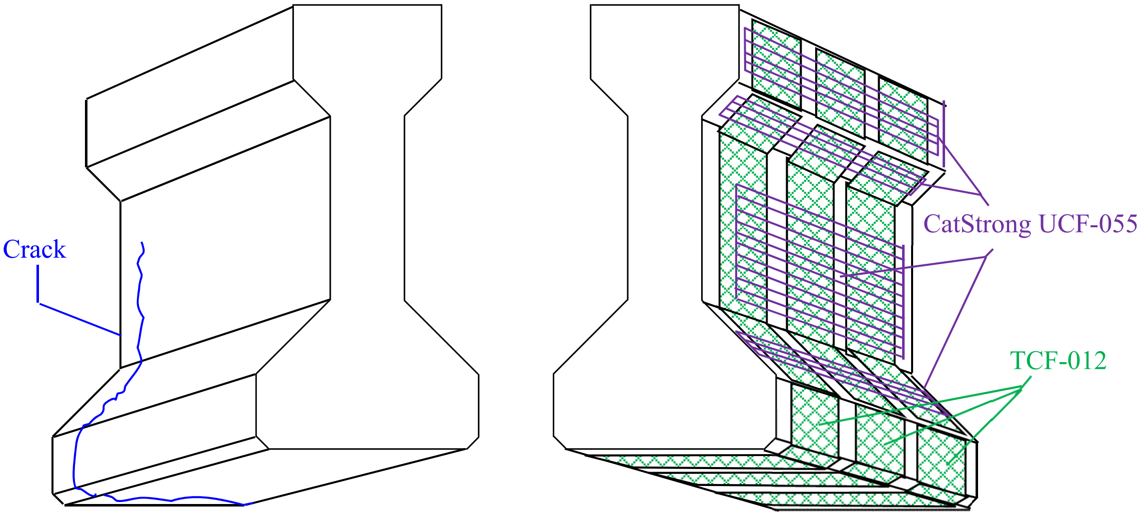


Fig. 28. Retrofit diagram of KY 11 over CSX Railroad and Strodes Run Pike

7.5 Retrofit Construction

KYTC District 09 Bridge Maintenance Personnel carried out the retrofit during July and August 2014. Loose concrete was removed from the damaged end regions of the PC I-beams over the abutments. Pneumatic chipping hammers were used to remove additional concrete and expose at least one inch of non-corroded prestressing steel. They were cleaned of rust using a mechanical brush (Fig. 29(a)). Wooden forms were erected to ensure the repair mortar cured appropriately to provide the original shape of the beam ends (Fig. 29(b)). Forms were removed once the repair mortar had cured.

(a) Cleaning damaged areas of PC beam ends

(b) Wood formwork and repair mortar application

Fig. 29. Beam end repair process

The cracks at the PC I-girder ends were too small to be injected with crack filling epoxy. The ends were blast cleaned using a pressure washer and, once dried, the CatStrong UCF 055 and/or TCF 012 application was carried out. A two-part saturating epoxy was used to impregnate the fabric prior to the application. Once the UCF 055 was applied, the TCF 012 U-wraps were placed over them. Small strips of UCF 055 were used as anchor strips for the TCF 012 U-wraps. For several girders on which the cracks were quite small, the CatStrong TCF 012 U-wraps were the primary strengthening material. After the epoxy had cured, a UV protective coating was applied over the retrofit areas on the exterior girders.

(a) Modular CRP application process

(b) TCF application over CRP

Fig. 30. CRP and TCF application on KY 11 over CSX Railroad and Strodes Run Pike

Fig. 31. Completed repairs on either side of Pier 1 following application of protective coating

8. KY 60 Over Cumberland River

8.1 Bridge Location

The US 60 bridge over Cumberland River (070B00017N) in Livingston County, Kentucky, is located in KYTC District 01.

Fig. 32. Location of KY 60 over Cumberland River in Livingston County, KY

8.2 Bridge Details

The steel truss main span and the 14 approach spans of the US 60 bridge over the Cumberland River were constructed in 1931. The approach spans are composed of two steel plate girders that span the supporting RC piers. Fig. 33 provides the general layout of the bridge and pier details,

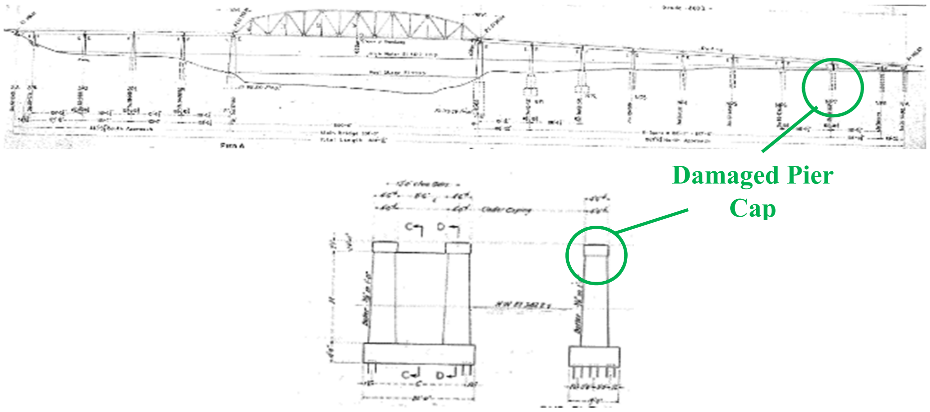


Fig. 33. Layout of KY 60 over Cumberland River

8.3 Damage Details

The pier cap on one of the approach span piers had a large vertical crack (Fig. 34). The crack originated under the bearing plate, propagated down the pier cap, and extended into the pier column. Several smaller cracks were seen on the opposite side of the pier cap.

Fig. 34. Typical damage to pier cap in US 60 bridge over Cumberland River

8.4 General Retrofit Plan

The retrofit plan included the use of 12 in. wide CatStrong UCF 115 carbon fabric for confinement of the pier cap and pier column (Fig. 35). It can carry over 115 kips of tensile force per foot width of fabric and is a very similar to the CatStrong UCF 120 in Table 2, but with a slightly lower laminate thickness and weight. The CatStrong UCF 115 was anchored to the pier wall using CatStrong UCF 023 carbon fabric strips.

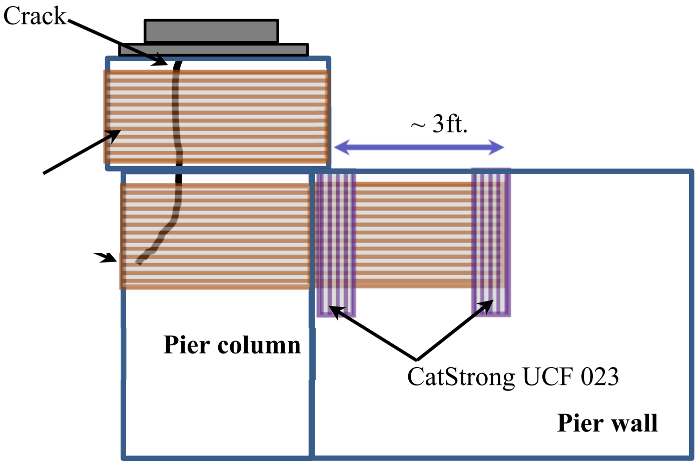


Fig. 35. Retrofit diagram of pier cap in US 60 bridge over Cumberland River

8.5 Retrofit Construction

The retrofit was carried out by the KYTC District 01 bridge maintenance crew in April 2016. Loose concrete was removed and the crack filled prior to the CatStrong carbon fabric application. The damaged area was filled with repair mortar to return the column to its original shape (Fig. 36(a)). Once cured, the repair mortar was ground to remove in-plane variations between the repair mortar and pre-existing concrete. In addition, the CatStrong fabric bond surfaces were cleaned using a mechanical grinder to provide a good bond surface.

(a) Repair mortar application

(b) Surface preparation for CatStrong UCF 115

Fig. 36. Repair process of KY 60 over Cumberland River

Once the surface was ready for carbon fiber application, a primer coating was applied to the concrete surface to prevent the saturated carbon fabric from sliding under its own weight. The CatStrong UCF 115 was impregnated with a two-part saturating epoxy and wrapped around the pier cap (Fig. 37(a)) and column (Fig. 37(b)). All air pockets and irregularities were smoothed out of the fabric with laminating rollers.

(a) Wrapping UCF 115 around column (b) UCF 115 application onto pier wall

Fig. 37. CRP and TCW application on KY 60 over Cumberland River

Twelve inch wide CatStrong UCF 023 anchor strips were applied over the CatStrong UCF 115 carbon fabric at the termination point as well as the transition point between the Pier column and Pier wall. The completed retrofit following the application of the UCF 023 anchor strips is shown in Fig. 38.

Fig. 38. Completed repairs to US 60 over Cumberland River bridge pier

9. KY 339 Over Massac Creek

9.1 Bridge Location and Details

The KY 339 bridge over Massac Creek (073B00058N) in McCracken County, Kentucky, is located in KYTC District 01. The 40 ft. center span of the three-span bridge is comprised of side-by-side PC box beams resting on two RC pier caps on either side. The pier caps on either side of the center span sit on seven timber piles (Fig. 39).

Fig. 39. Location of KY 339 over Massac Creek in McCracken County, KY

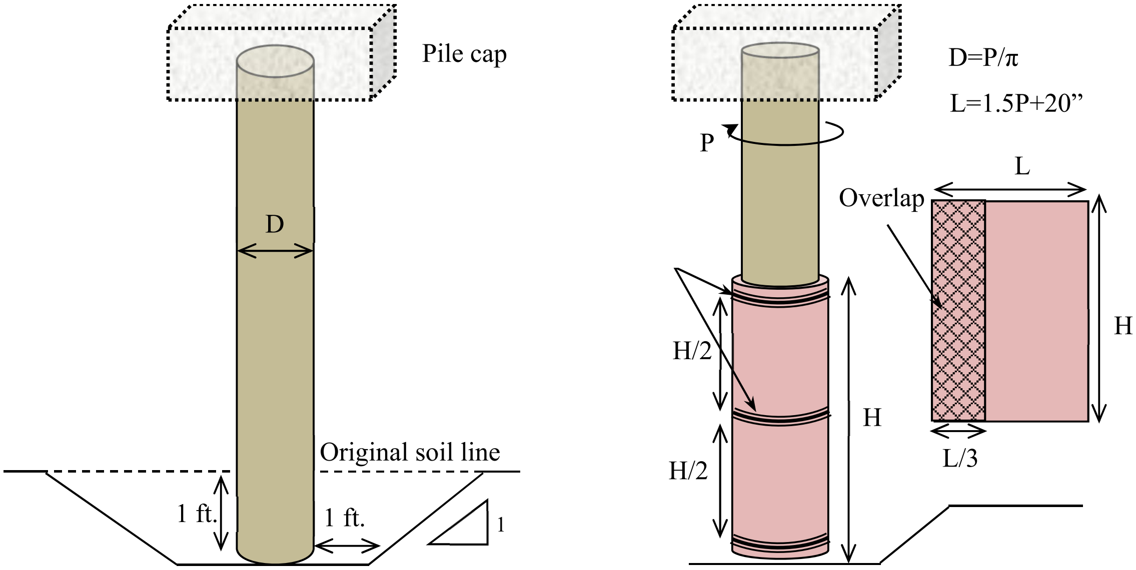
9.2 Damage Details

Many of the timber piles had deteriorated, especially near the splash zones from normal stream flow levels. Several piles had been spliced previously by KYTC bridge maintenance personnel using concrete cast around the joint between the new pile section and the old pile protruding above the ground.

Fig. 40. Typical damage to KY 339 timber pile supports

9.3 General Retrofit Plan

Two deteriorated timber piles were chosen for retrofit using CatStrong TCW 012 wraps. The wraps were to encase the deteriorated piles, with a uniform gap between the pile and the TCW 012 wraps. The installation of the wraps called for trenching a minimum of 1 ft. around the pile (Fig. 41). Then, the wrap was to be bonded onto itself using the overlap length shown in the figure. Ties/tape can be used to maintain the CatStrong TCW 012 jacket in place around the pile. A rapid set epoxy mortar is then inserted into the space between the pile and the wrap. The epoxy mortar encapsulates the timber pile; the epoxy penetrates into the deteriorated timber and strengthens the pile while preventing any future deterioration. The overall section size of the pile is increased by application of the pile wraps and the epoxy mortar. In addition, any undamaged areas of the pile above the CatStrong TCW 012 wrap would be strengthened by wrapping CatStrong TCF 012 carbon fabric around the timber pile.



Prepared Area

Application of Pile Wrap

Fig. 41. Timber pile retrofit using CatStrong TCW 012

9.4 Retrofit Construction

KYTC District 01 Bridge Maintenance personnel carried out the retrofit in November 2015. Earth surrounding the base of the damaged timber was cleared with shovels (Fig. 42(a)). Spacers were attached into the timber pile (Fig. 42(b)) to maintain 2 in. of spacing between the timber pile surface and the CatStrong TCW 012 to accommodate the epoxy mortar. As seen in Fig. 42(c), the CatStrong TCW 012 overlap was coated in a structural epoxy, wrapped around the spacers, and secured with adhesive tape. Epoxy mortar was then mixed and placed between the timber pile and the TCW 012.

(a) Clearing area around base of timber piles

(b) Drilling metal spacers

(c) Wrapping TCW 012 around spacers

(d) Filling space with epoxy mortar

Fig. 42. CatStrong TCW 012 retrofit of KY 339 over Massac Creek timber piles

The timber pile above the CatStrong TCW 012 application area was mechanically cleaned to bond the CatStrong TCF 012. A two-part primer epoxy was applied to prevent the saturated carbon fabric from sliding down under its own weight (Fig. 43(a)). The CatStrong TCF 012 was impregnated using a two-part saturating epoxy and then wrapped around the timber pile (Fig. 43(b)). Fig. 44 shows the completed retrofit of the two timber piles.

(a) Coating timber pile in primer epoxy (b) Wrapping TCF 012 around timber pile

Fig. 43. CatStrong TCF 012 application

Fig. 44. Completed retrofit of KY 339 over Massac Creek timber piles

10. CatStrong CRP Design Guide

10.1 AASHTO Design

CatStrong CRP retrofit designs rely on AASHTO's *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements* (AASHTO 2012). The design guide primarily deals with FRP laminates and fabric. It does not directly address the use of CFRP rod panels. With the information presented here, practitioners can use the AASHTO design guide (AASHTO 2012) to design external reinforcements with CatStrong CRP for reinforced and prestressed concrete flexural members. This chapter includes a numerical example for the retrofit of a damaged reinforced concrete girder due to over-height truck impact.

When evaluating if CRP can be utilized for external strengthening, AASHTO design guides restrict the capacity of the damaged girders that can be retrofitted using externally bonded CFRP (EB-CFRP) to the limits identified in Equation 1 (AASHTO Eq. 1.4.4-1). These code-based restrictions limit the likelihood of catastrophic failure due to deficiencies in the retrofit or debonding of the FRP due to accidental overloading.

$$R_r = \eta_i[(DC + DW) + (LL + IM)] \qquad (1)$$

where:

R_r = factored resistance computed in accordance with AASHTO LRFD Section 5

η_i = 1.0

DC = force effects due to components and attachments

DW = force effects due to wearing surface and utilities

LL = force effects due to live loads

IM = force effects due to dynamic load allowance

While the typical failure limits for concrete and steel may govern the ultimate design load, for certain instances of using FRP to externally strengthen concrete, the governing failure mode tends to be debonding of the retrofit material from the concrete substrate. The debonding strain (ε_{fd}) — based on AASHTO guidance — is fixed at 0.005 in./in. at the FRP material-concrete interface. Because the individual rods that make up the CRP are embedded in a layer of structural epoxy, CRPs are expected to have a greater surface area for bonding to concrete compared to traditional EB-CFRP (Peiris and Harik, 2018).

10.2 CRP Design Considerations

Equation 2 can be used to conservatively estimate the amount of CFRP material (A_f) required when replacing the capacity lost by damaged or deteriorated rebars, based on the failure mode governed by debonding strain, and provided the EB-CFRP is applied to the bottom surface of the RC girder (below the steel rebar).

$$A_f \geq \frac{A_{s-d} f_y}{f_d E_f} \tag{2}$$

where:

f_y = Yield strength of steel rebar (psi)

A_{s-d} = Damaged rebar area (in.^{2})

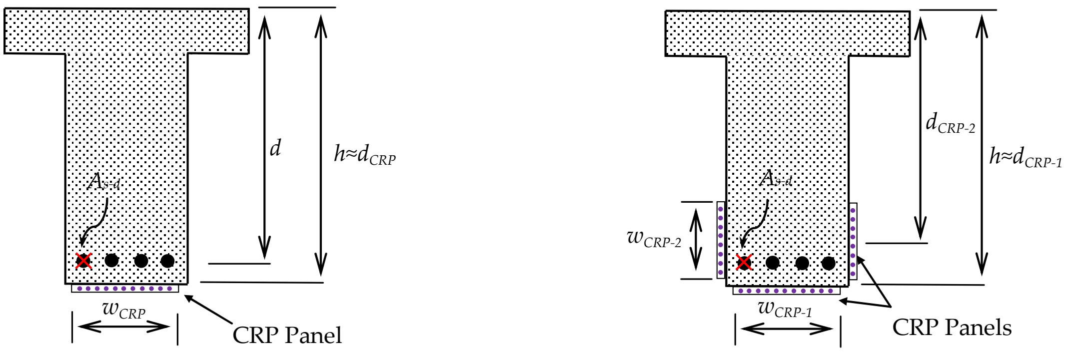
For pultruded CFRP laminates, the required strip width can be calculated by dividing the FRP area calculated from Equation 2 by commercially available laminate thicknesses. For CRPs, however, both the area of individual rods and their spacing must be considered. The required width of a CRP panel [w_{CRP} in Fig. 45(a)] can be calculated using the information on CRPs provided in Table 1 and Equation 3. The information in Table 1 applies to CFRP rods that have been experimentally evaluated by the authors. Note that the use of higher modulus CFRP rods and/or larger diameter rods would reduce the required panel width.

$$w_{CRP} \geq \frac{A_f S_r}{A_r} \tag{3}$$

where:

S_r = Rod spacing of CRP panel (in.)

A_r = CFRP rod area (in.^{2})



(a) On bottom surface

(b) On bottom surface and sides

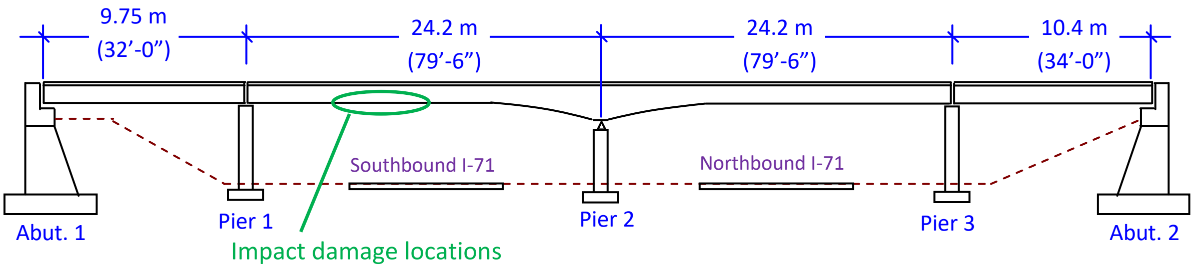
Fig. 45. CRP application locations

Because the strain on the CRPs away from the bottom surface is less than the debonding strain, the required panel widths should be estimated using Equation 4. It is practical to use the same size CFRP rods for both the bottom surface and sides (i.e. $A_{r-1} = A_{r-2}$, $s_{r-1} = s_{r-2}$). Given that the panel width at the bottom is known, the equation yields a relationship between the width of the panels on the sides ($w_{CRP\text{-}2}$) and the depth ($d_{CRP\text{-}2}$) at which they are applied.

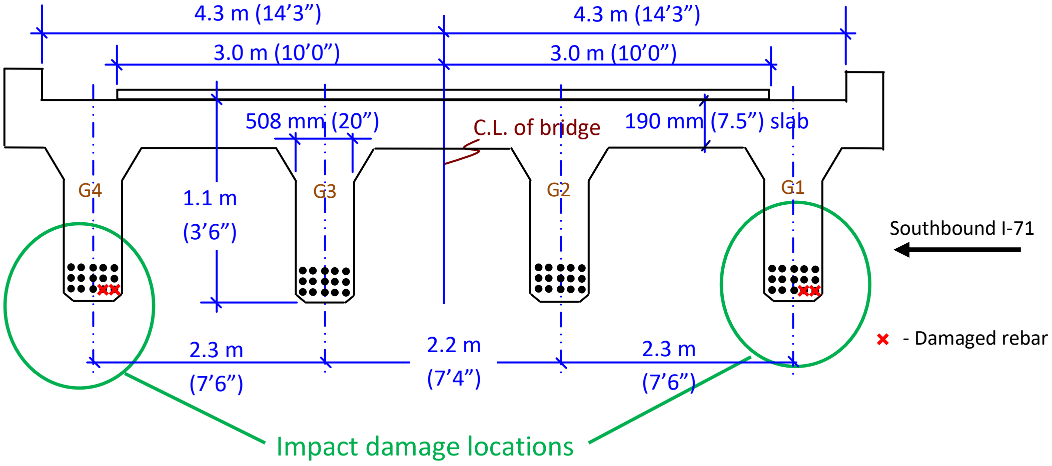
$$\frac{w_{CRP-1}A_{r-1}}{s_{r-1}} + 2\left(\frac{w_{CRP-2}A_{r-2}}{s_{r-2}}\right)\frac{d_{CRP-2}}{h} \geq \frac{A_{s-d}\, f_y}{f_d\, E_f} \qquad (4)$$

10.3 CRP Design Example

A four span RC deck-girder bridge over I-71 damaged by an over-height truck impact is used for the numerical example. The span with the damage is 79.5 ft. long, of which 54 ft. is of a constant depth of 3.5 ft., and the remainder of variable depth up to 7 ft. The damage occurred within the constant depth region. Fig. 46 depicts the cross section of the span at the damage location, showing the damaged rebar in both exterior girders. Based on the design stresses listed in the bridge plans, the concrete compressive strength was taken as 3,000 psi and the yield strength of the steel rebar was taken as 40 ksi.



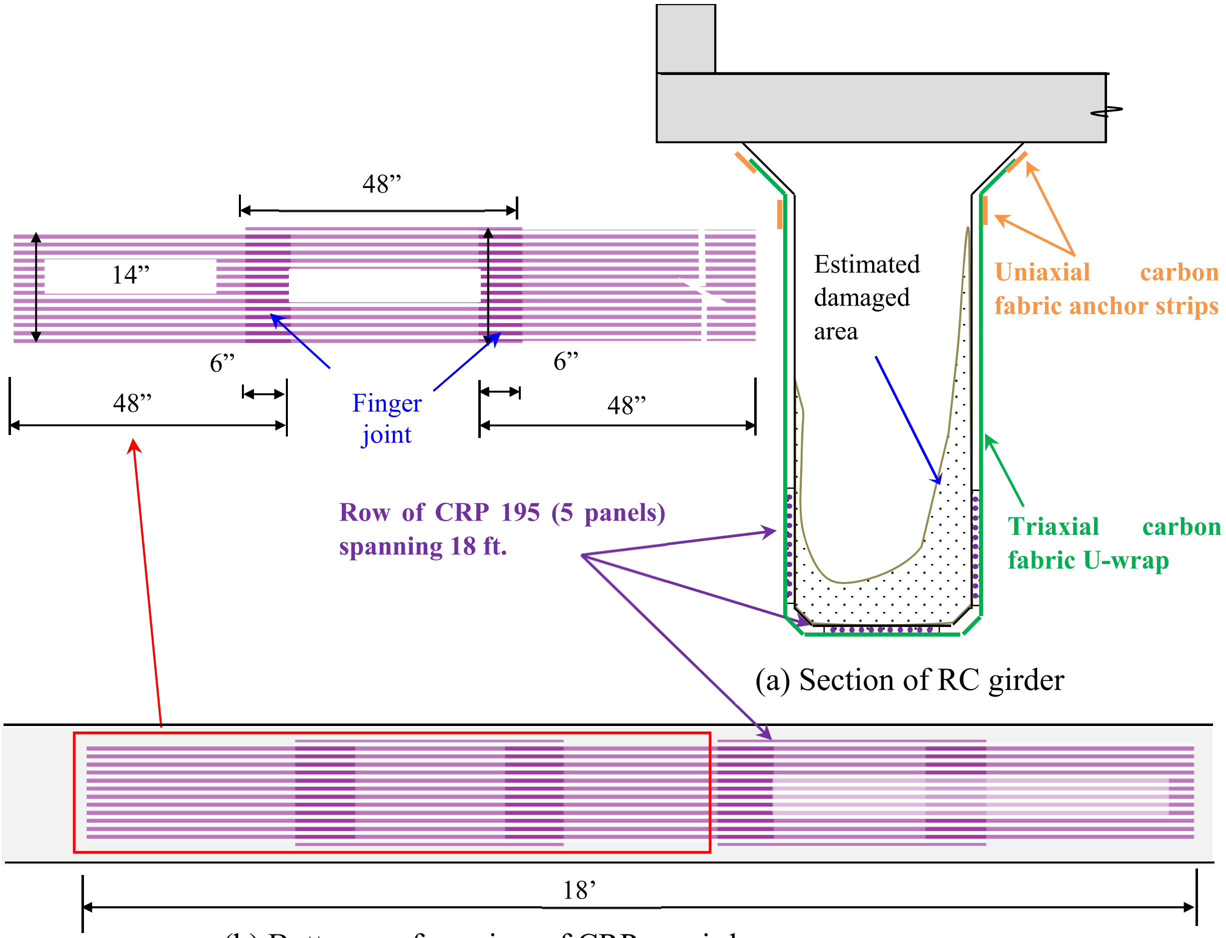
(a) General layout of the bridge



(b) Cross sectin of the bridge at impact location

Fig. 46. Impact damaged bridge details

Both exterior girders (G1, G4) over the right lane were impacted, producing spalled concrete and bent rebars. At the point of impact, the bottom rebar mat of both RC girders consisted of five #11 rebars (diameters of 1.41 in.), of which two were bent and yielded. The damaged reinforcement represented 13.3 percent of the total reinforcing steel available to resist positive bending. Girder 4 incurred the most damage, with concrete spalling spread across approximately 12 ft. Based on Equations 2, 3, and 4 it is clear that even when using the larger capacity CRP 195, the panels would need to be placed along the girder's vertical faces (Fig. 45(b)) to achieve the desired strengthening. CRP 195 panels with a width of 14 in. are selected for the final design. Based on the initial damage inspection, five panels of CRP 195 were to be applied on the bottom surface and sides of the RC girder (Fig. 47). Following deployment, the five panels have a length of 18 ft. The panels extend a minimum distance of 6 in. beyond the damaged areas. Fig. 47(a) shows CFRP U-wraps of a triaxial braided quasi-isotropic (0°, +/- 60°) carbon fabric. The U-wraps increase the CRP bond strength and provide additional capacity beyond that required by the AASHTO design guide. As concrete cover delamination was the observed failure mode for CRPs, the CFRP U-wraps are expected to increase the capacity of the CRP strengthening system by anchoring the CRP panel ends.



(a) Section of RC girder

(b) Bottom surface view of CRP on girder

Fig. 47. CRP retrofit design

Table 3 presents the flexural design calculations for the retrofitted RC girders. CFRP rod panels (CRP) are used for the retrofit and the beam analysis is based on AASHTO EB-CFRP guidelines. The ACI guide (ACI, 2017) and NCHRP Report 655 (NCHRP, 2010) for externally bonded FRP are referred to when supplementary guidance is necessary. The compressive steel reinforcing is ignored in the calculations. The application of AASHTO’s concrete stress-strain model is only practical for girders with rectangular cross sections. While the damaged RC girders were flanged sections, the method is still applicable because the neutral axis was within the flange.

Table 3. CRP retrofit design for impact damaged RC girder

Girder and Section Properties of Damaged Girder	**Value**
Clear span of girder (l)	79.6 ft.
Effective width of deck (b_e)	90 in.
Height of deck (h_d)	7.5 in.
Height of girder (including deck) (h_c)	42 in.
Cracked section moment of inertia (I_{cr})	132678 $in.^4$
Depth to cracked section N.A (kd)	10.05 in.
Girder section area (A_c)	1165 $in.^2$
Area of (remaining) steel (A_s)	20.28 $in.^2$
Depth to centroid of (remaining) steel (d)	34.4 in.
Total FRP area of CRP (A_f) Three 356 mm (14") panels contain 38 rods each. Each rod is 12 mm^2 (0.019 in^2)	2.18 $in.^2$
Equivalent depth to centroid all CRP (d_f) The two side panels are placed 25 mm (1 in.) above the bottom surface to account for the chamfer.	36.7 in.

Material Properties	**Value**
Concrete modulus of elasticity (E_c)	3,320 ksi
Concrete compressive strength (f'_c)	3000 psi
Steel modulus of elasticity (E_s)	29,000 ksi
Yield stress of steel (f_y)	40 ksi
CRP FRP modulus of elasticity (E_f)	19500 ksi
Ultimate FRP tensile strength (f_{fu}^*)	320 ksi
Ultimate FRP rupture strain (ε_{fu}^*)	0.0164 in./in.

Loading at Impact Location	**Value**
Dead load moment (including barrier wall) (M_{DL})	520 k-ft
Live load moment (edge beam) (M_{LL})	729 k-ft
Impact Factor	0.244

Design	**Value**
Step 1: Calculate CRP design material properties Since the CRP retrofit is on the bridge's edge girder and will be directly exposed to the elements, an environmental reduction factor of 0.85 is used. (ACI – Table 9.4) $f_{fu} = 0.85 f_{fu}^*$ $\varepsilon_{fu} = 0.85\varepsilon_{fu}$	**272 ksi** **0.0139 in./in.**

Step 2: Existing state of strain at FRP installation (ε_{bi}) Assuming that the beam is uncracked and only dead loads exist at the time of FRP application, the existing strain at the bottom of the girder (ε_{bi}) is calculated. $\varepsilon_{bi} = \frac{M_{DL}(d_f - kd)}{E_c I_{cr}}$	**0.00038 in./in.**
Step 3: Estimate depth to neutral axis (c) An initial assumption of the neutral axis depth (c) is taken as the height of the deck. $c = h_d$	**7.5 in.**
Step 4: Determine effective level of strain in CRP (ε_{fe}) The maximum strain that the CRP can reach is governed by the strain limits due to either concrete crushing (ε_{cu}= 0.003), FRP rupture or FRP debonding. <u>Debonding (AASHTO Section 3.2)</u> $\varepsilon_{fd} = 0.005$ <u>FRP strain at concrete crushing</u> $\varepsilon_{fe} = \frac{\varepsilon_{cu}(d_f - c)}{c} - \varepsilon_{bi}$ <u>FRP strain at rupture</u> $\varepsilon_{fu} = 0.0139$ The effective level of strain in the CRP (ε_{fe}) is the lesser of the debonding strains (ε_{fd} = 0.005 mm/mm), FRP strain at concrete crushing (ε_{fu} = 0.097 mm/mm), and the rupture strain (ε_{fu}= 0.0139 mm/mm) from the material properties. Therefore, the effective level of strain is: $\varepsilon_{fe} = \varepsilon_{fd}$	**0.005 in./in.** **0.0113 in./in.** **0.0139 in./in.** **0.0050 in./in.**
Step 5: Calculate the stress in the CRP (f_f) The stress is calculated based on linear stress-strain relationship: $f_f = E_f \varepsilon_{fe}$	**97.5 ksi**
Step 6: Calculate the strain in the concrete (ε_c) The strain in the concrete is calculated using similar triangles: $\varepsilon_c = (\varepsilon_{fe} + \varepsilon_{bi}) \frac{c}{(d_f - c)}$	**0.00138 in./in.**

Step 7: Calculate the strain in the steel (ε_s) The strain in the steel rebars is calculated using similar triangles: $\varepsilon_s = (\varepsilon_{fe} + \varepsilon_{bi})\frac{d-c}{(d_f - c)}$	**0.00496 in./in.**
Step 8: Calculate the stress in the steel (f_s) The stress is calculated based on a bi-linear stress-strain relationship: $f_s = E_s\varepsilon_s \le f_y$	**40 ksi**
Step 9: Calculate the equivalent concrete compressive stress block parameter (β_2) This factor is used to check the internal force equilibrium. The strain (ε_o) at f'_c is calculated: $\varepsilon_o = 1.71\frac{f'_c}{E_c}$ (AASHTO Eq. 3.2-2) The average stress block parameter is calculated from the parabolic stress-strain relationship for concrete: $\beta_2 = \frac{ln\left[1+\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right]}{\left(\frac{\varepsilon_c}{\varepsilon_o}\right)}$ (AASHTO Eq. 3.4.1.1-4)	**0.00154 in./in.** **0.657**
Step 10: Calculate the internal force resultants and check equilibrium The calculated value is checked with the assumed value of *c* in Step 3. (Note: The concrete strength is calculated based on NCHRP Report 655 Section 3.2.2.) $c = \frac{A_s f_s + A_{CRP} f_{CRP}}{0.9 f'_c b_e \beta_2}$	**6.4 in.**
Step 11: Adjust *c* until force equilibrium is satisfied The value for *c* in Step 10 is within the deck ($c \le h_d$) and differs from the value assumed in Step 3. Iterate starting from Step 3 until equilibrium is reached. Note: The AASHTO specifications may not be practical for the application of flanged sections when the neutral axis falls outside of the flange.	**6.83 in.**

Step 12: Calculate flexural strength components The contributions from the reinforcing steel and CRP to the beam flexural strength are calculated. The multiplier for locating the resultant of the compression force in the concrete (k_2): $k_2 = 1 - \frac{2\left[\left(\frac{\varepsilon_c}{\varepsilon_o}\right) - \tan^{-1}\left(\frac{\varepsilon_c}{\varepsilon_o}\right)\right]}{\beta_2\left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2}$ Reinforcing steel component (M_{ns}): $M_{ns} = A_s f_s (d - k_2 c)$ (AASHTO Eq. 3.4.1.1-3) FRP component (M_{nf}): $M_{nf} = A_f f_f (d_f - k_2 c)$	**0.367** **2,156 k-ft** **605 k-ft**
Step 13: Calculate flexural strength (*M_r*) An additional reduction factor, φ_{frp} = 0.85, is applied for the CRP's contribution to flexural strength (AASHTO Section 3.4.1.1): $M_r = M_{ns} + \phi_{frp} M_{nf}$	**2,671 k-ft**
Step 14: Calculate design flexural strength (*ϕM_r*) Design flexural strength (ϕM_n) with ϕ=0.9 reduction factor: $\phi M_r = \phi M_{ns} + \phi_{frp} M_{nf}$ (AASHTO Eq. 3.4.1.1-1) Note: The ϕ factor is only applied to the steel component	**2,030 k-ft**

11. CatStrong CRP Construction Specifications

The surface CatStrong CRP is being applied to must be prepared similarly to any other surface on which externally bonded FRP is applied.

11.1 Repair of any existing Concrete Damage

If concrete damage exists, the following steps must be carried out to repair the damaged area:

1. Remove all loose concrete and debris from damaged area. A pneumatic or electric chipping hammer can be used to remove all loose concrete.
2. For irregular shapes, use a concrete saw to cut a simple geometric shape to repair.
3. If steel is exposed to the elements, at least one inch of non-corroded reinforcing steel must be exposed. Sandblast the steel to remove rust and apply a zinc primer with a brush or spraying equipment.
4. If required, new rebar can be spliced or damaged rebar replaced.

(a) Removing loose concrete

(b) Saw cuts to create simple geometric shapes

(c) Sandblast exposed steel rebar

(d) Constructed wooden formwork

Fig. 48. Steps for preparing damaged RC girders – part 1

5. If needed, construct wooden formwork to facilitate the application of repair mortar. A bonding agent may be beneficial for overhead applications. Apply repair mortar to return the damaged area to its undamaged state. Vibrate the mortar to prevent voids.
6. Once the mortar sets, grind away excess mortar to remove any in-plane variations between the mortar and pre-existing concrete to a precision of 1/32 in.

(a) Setup formwork (b) Application of bonding agent

(c) Application of repair mortar (d) Grinding excess repair mortar

Fig. 49. Steps for preparing damaged RC girders – part 2

11.2 Application of CatStrong CRP

The concrete surface should be clean, dry, and free of contaminants before the CatStrong CRP is applied. Wipe the surface with a mineral solvent before applying CRP. Once the surface is repaired and cleaned, adhere to the following directions when applying the CatStrong panels:

1. Mix the structural epoxy according to manufacturer specifications.
2. Apply the mixed epoxy to the concrete surface with a trowel or spatula to a depth equal to the diameter of the CatStrong rods. Use a V-notched trowel to achieve uniform epoxy thickness. The CatStrong CRP must span a minimum of 6 in. beyond the concrete repair area. Only apply sufficient epoxy at a given time to accommodate *a single* CatStrong panel.
3. Place the CatStrong panel on the applied epoxy layer. Press it into the epoxy until the epoxy seeps out and is flush with the top of the panel. Spread excess epoxy over the top of the panel.

4. Apply epoxy for the adjacent panel. Connect the adjacent panel and the previously panel using the overlapping finger joint. CatStrong panels are designed to alternate between ‘+’ and ‘-’ panels.
5. Apply an outer layer of epoxy to the panels. Smooth the epoxy along the entirety of the strengthened area. When CFRP fabric is applied over the CRPs it should be centered over the finger joints.
6. Let the epoxy fully cure before applying a protective UV coating.

(a) Applying coat of epoxy to concrete surface

(b) Placing CatStrong over epoxy layer

(c) Alignment of plus to minus to facilitate mesh

(d) Applied coat of epoxy over CatStrong fabric

Fig. 50. Steps for CatStrong application

12. Summary and Conclusions

Rapid repair of damaged or deteriorated concrete bridge components will prevent the entire bridge from suffering irreversible damage in the future due to gradual spalling of concrete or corrosion of exposed steel. CFRP laminates and fabrics have become popular for repairing and strengthening of concrete girders. A series of CFRP materials — branded CatStrong — specifically designed for the repair and retrofit of bridges was developed at KTC and the University of Kentucky. Included among these materials are CFRP Rod Panels (CatStrong CRPs), Unidirectional and Triaxial Carbon Fabric (CatStrong UCF and TCF), and Triaxial Carbon Wrap (CatStrong TCW).

This study documented the implementation of these CFRP materials to rapidly repair/strengthen six bridges in Kentucky. Three of the retrofit projects utilized CatStrong CRPs for strengthening RC bridge girders. Because the CRPs have modular construction, they can easily be applied by a single worker, eliminating the need for extensive scaffolding/access equipment and a large work force. As such, the construction costs related to panel application is less than those for other retrofit measures. CatStrong TCW, combined with CatStrong TCF, was deployed for the repair and strengthening of deteriorated timber piles. The remaining two projects involved the use of CatStrong UCF and TCF for strengthening cracked PC girder ends and strengthening a cracked bridge pier cap. Each bridge retrofit project was carried out by KYTC bridge maintenance crews. The crews were trained on the use and application of the new material. Design and construction specifications for the CatStrong CRPs were also developed as part of the study.

13. References

AASHTO (2012) *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements* , American Association of State Highway and Transportation Officials, Washington, D.C.

ACI (2017) *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, ACI 440.2R-17, American Concrete Institute, Farmington Hills, MI.

NCHRP (2010) *Recommended Guide Specification for the Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*, Report 655, Transportation Research Board, Washington, D.C.

Peiris, A. and Harik, I.E. (2018) CFRP rod panels for strengthening concrete bridges, *Adv. Struct. Eng.*, *21*, 557–570.

Appendix A

KY 55 Over Majors Run Creek – Carrol Co.

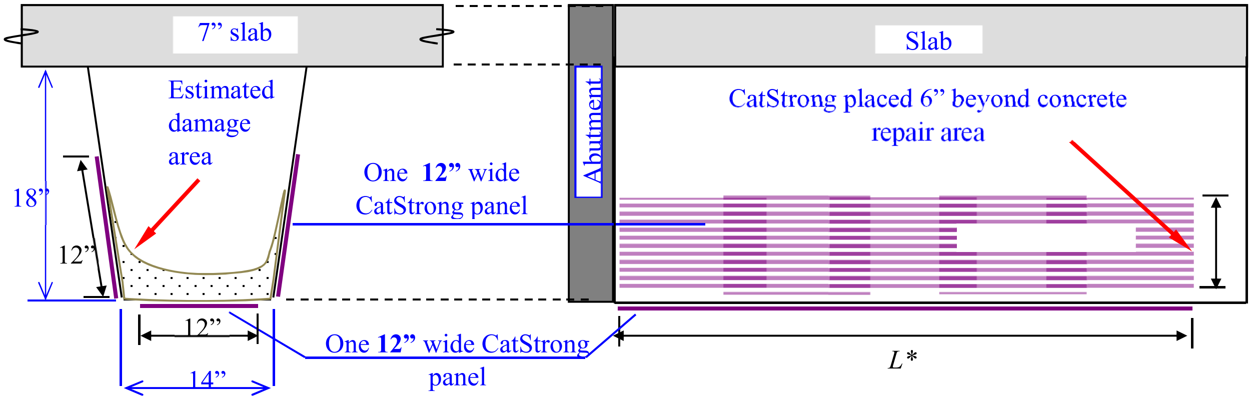


Fig. A1. Typical placement of CatStrong panels on KY 55 over Majors Run Creek

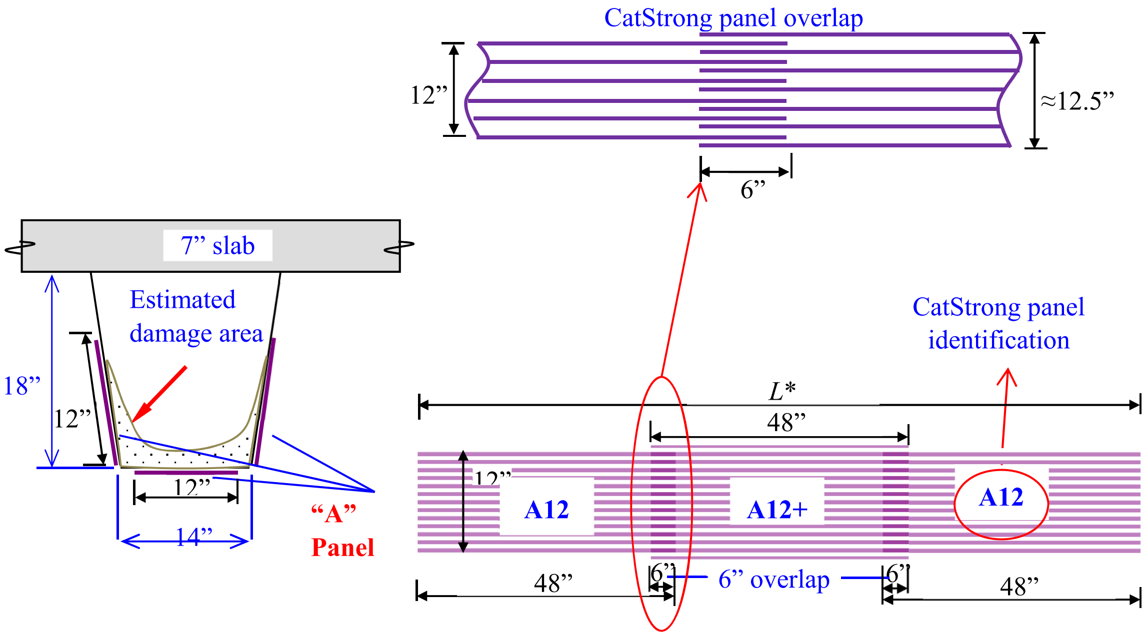


Fig. A2. Typical cuts for CatStrong panels

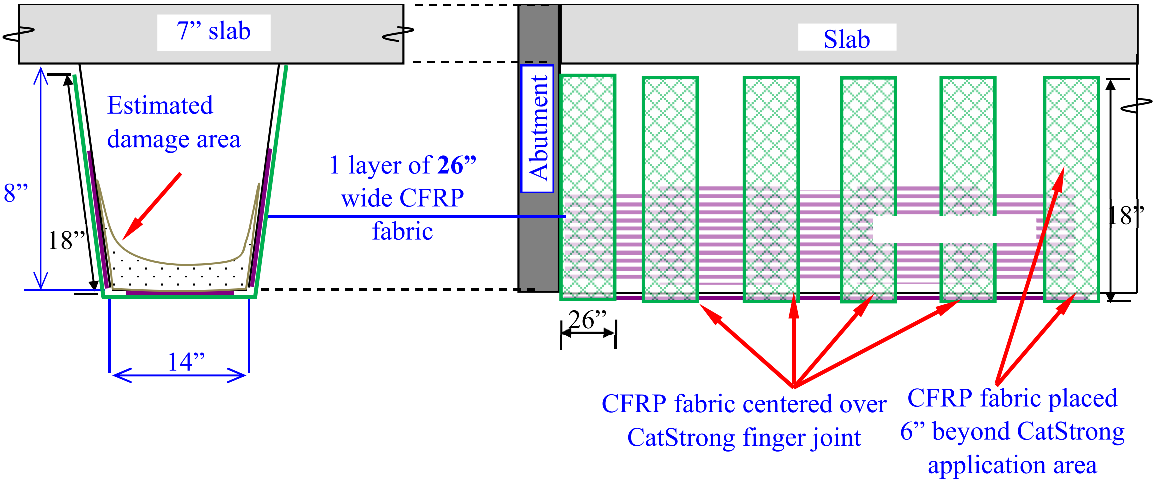


Fig. A3. Typical placement of the CFRP fabric on KY 55 over Majors Run Creek

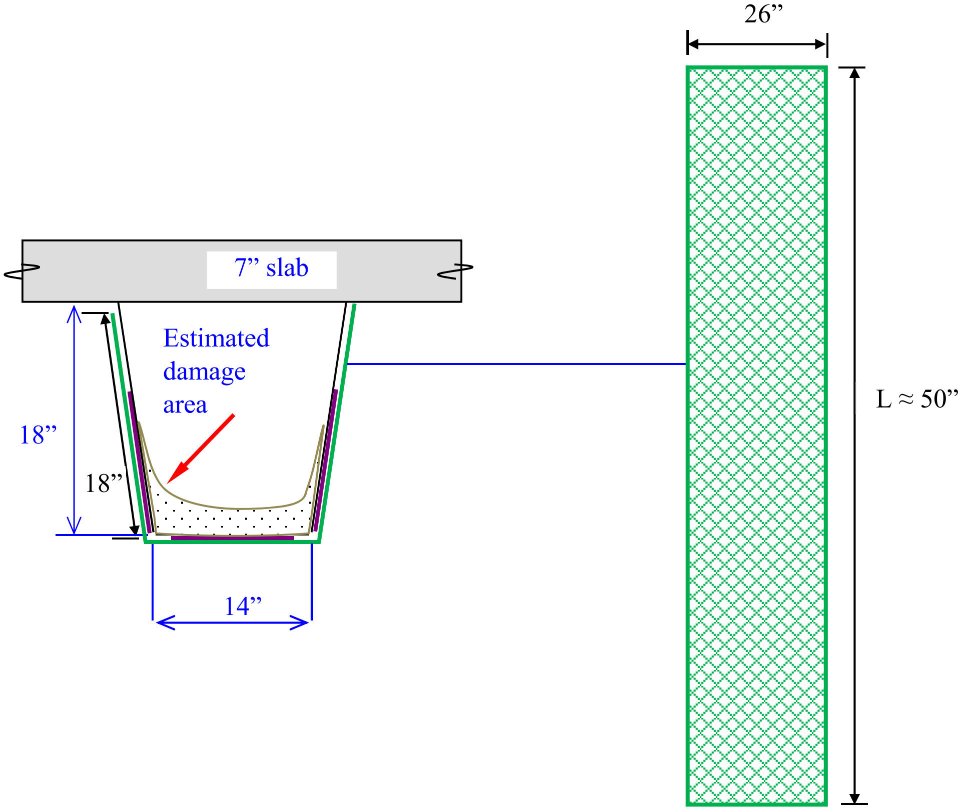


Fig. A4. Typical cut for the CFRP fabric

Appendix B

KY 11 Over Cat Creek – Powell Co.

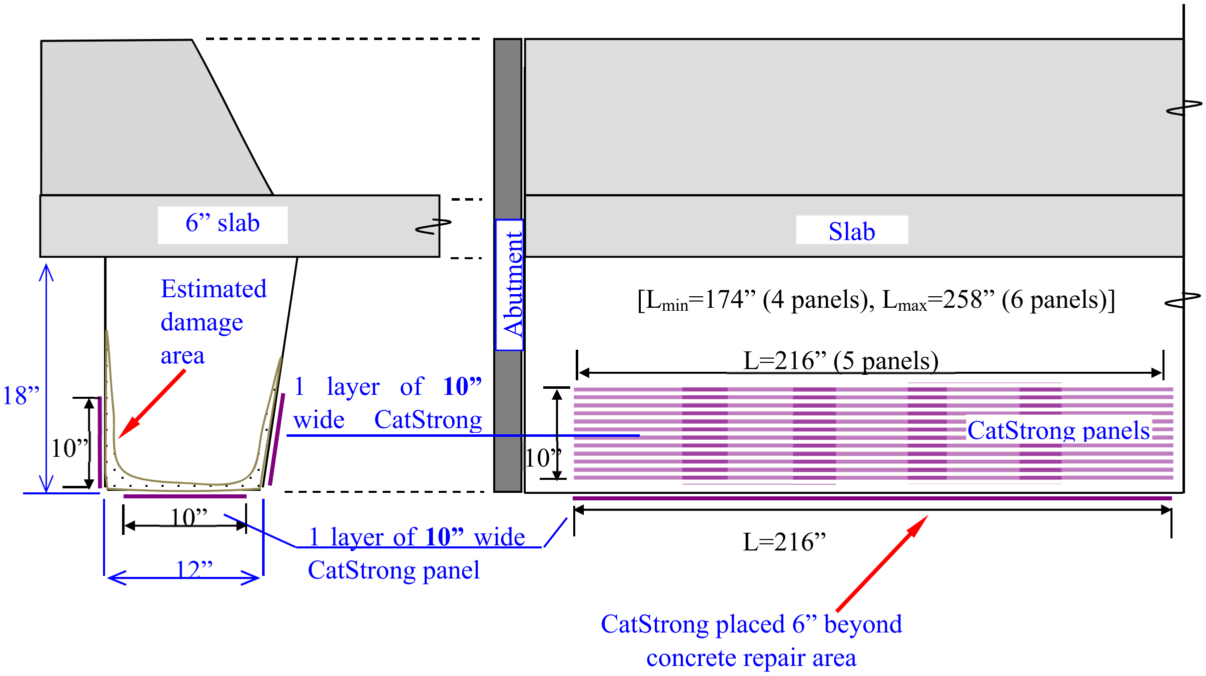


Fig. B1. Typical placement of CatStrong panels on KY 55 over Majors Run Creek

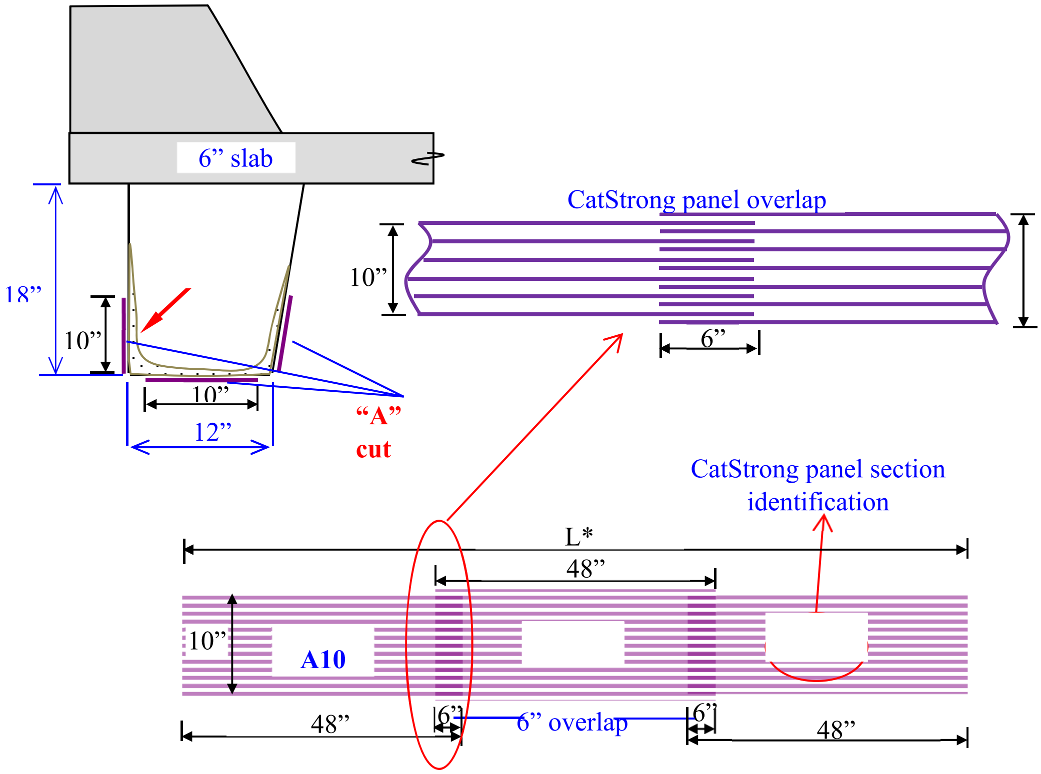


Fig. B2. Typical placement of CatStrong panels on KY 55 over Majors Run Creek

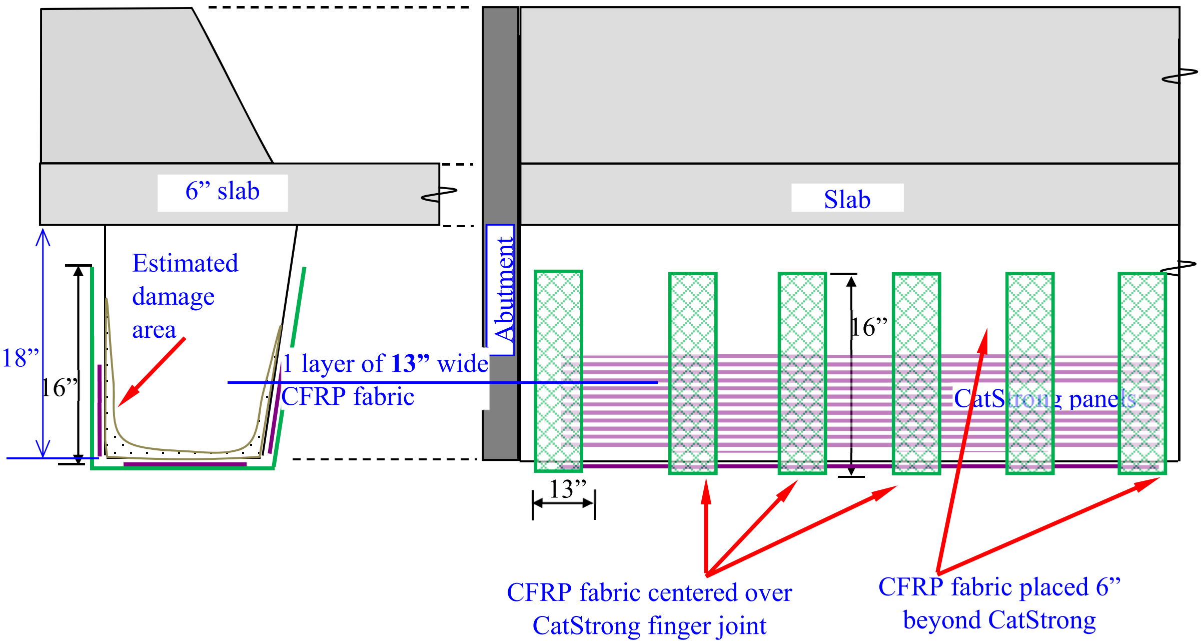


Fig. B3. Typical placement of CFRP fabric on KY 11 over Cat Creek

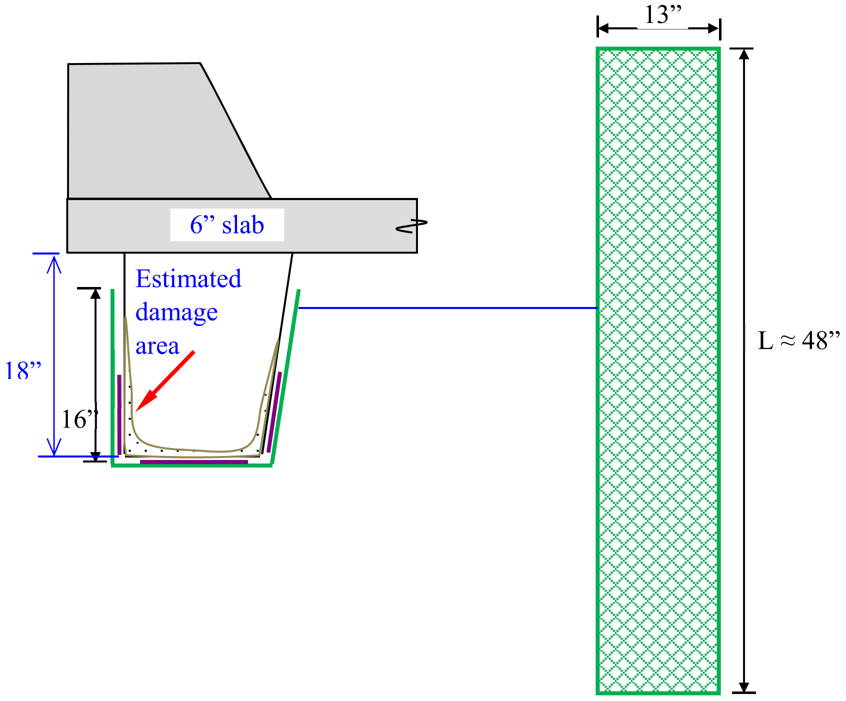


Fig. B4. Typical cut for CFRP fabric

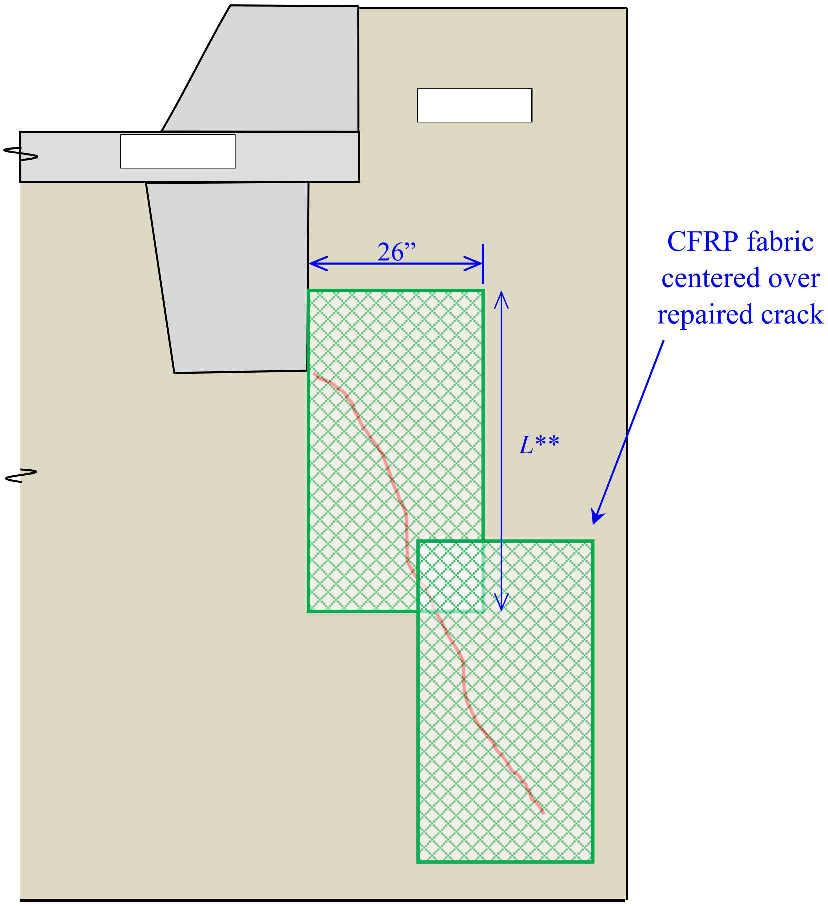


Fig. B5. Typical placement of CFRP fabric on cracked abutment under KY 11 over Cat Creek

Appendix C

KY 80 Over I-69/Purchase Parkway – Graves Co.

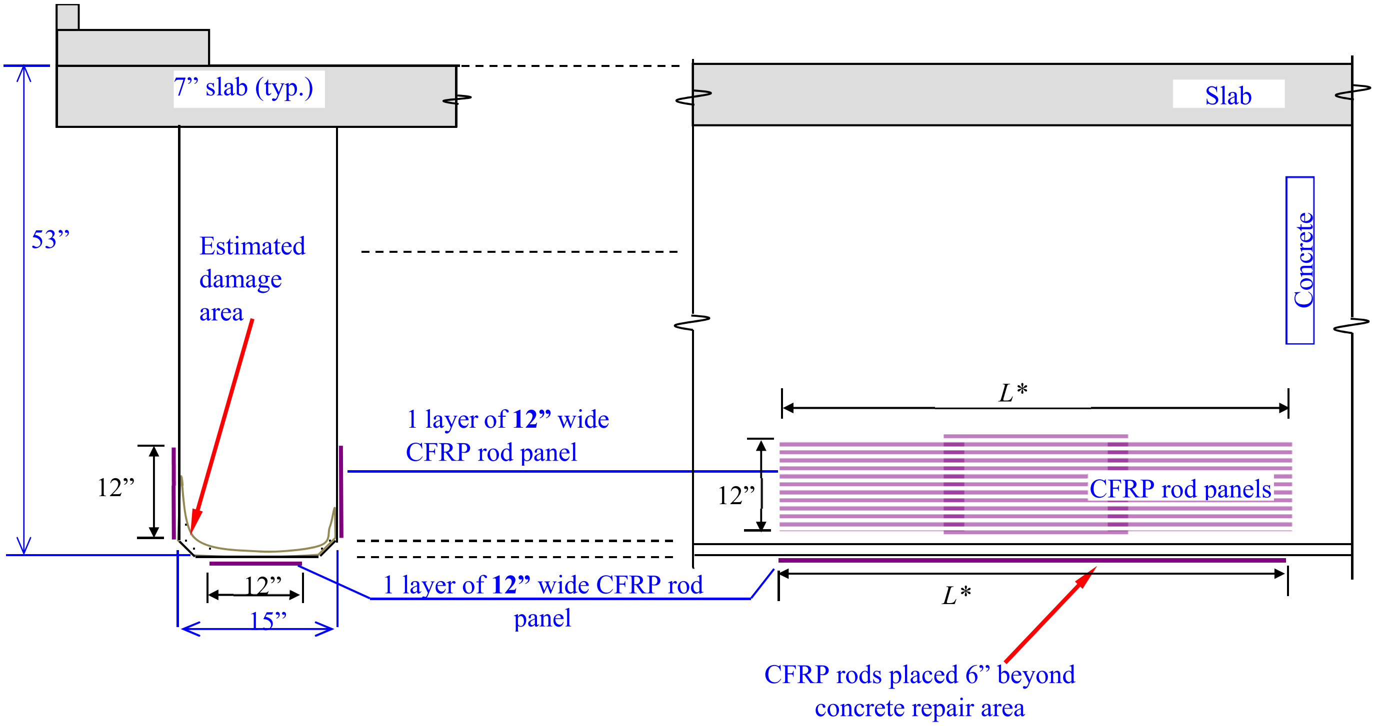


Fig. C1. Typical placement of CatStrong panels on KY 80 over I-69/Purchase Parkway

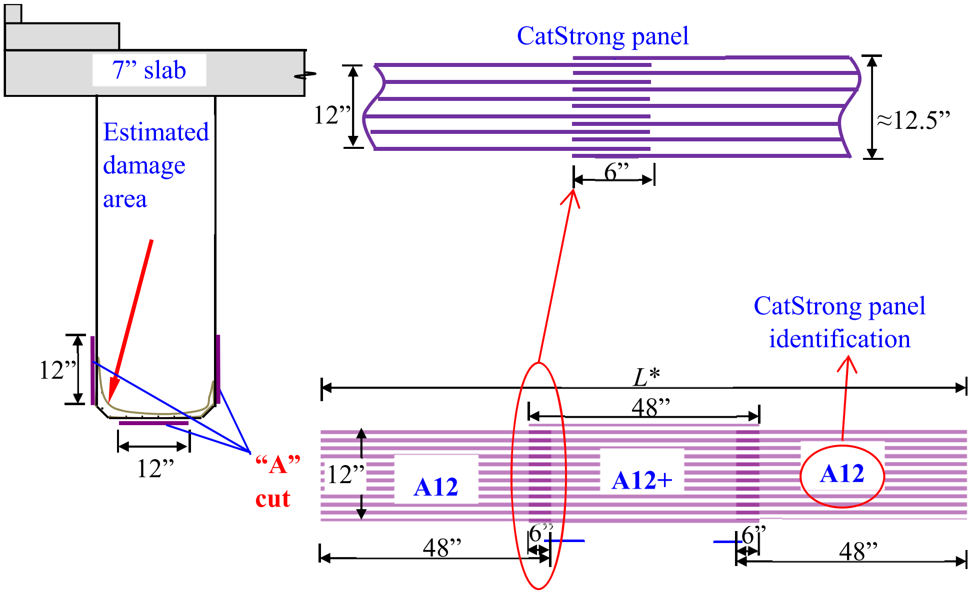


Fig. C2. Typical cuts for CatStrong panels

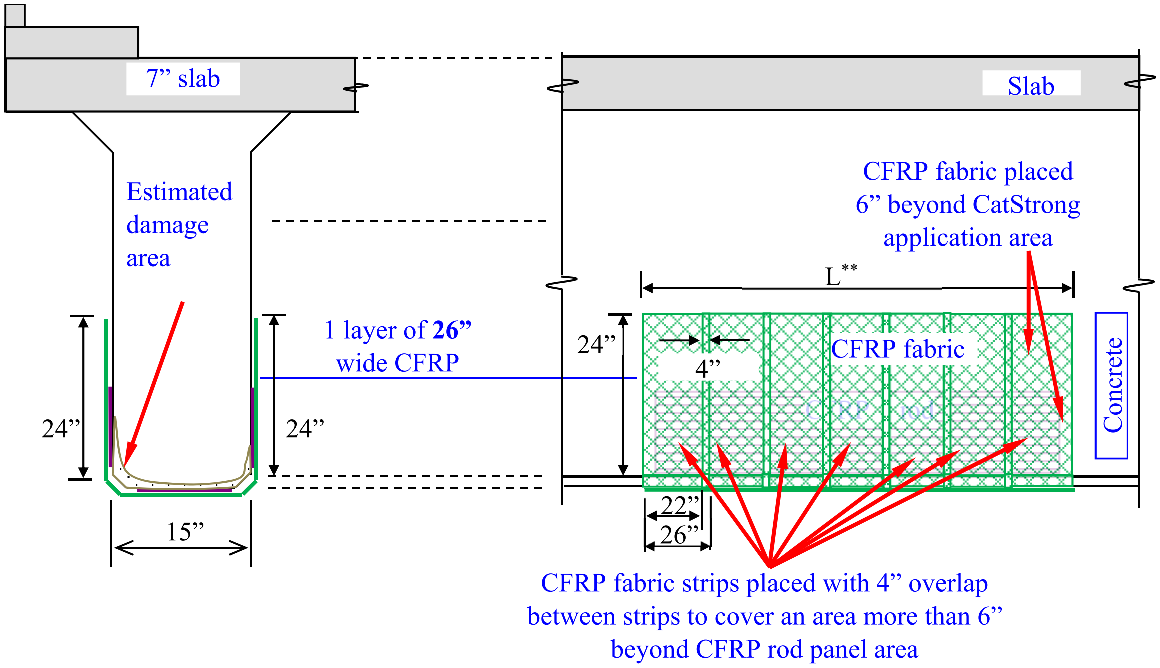


Fig. C3. Typical placement of CFRP fabric on KY 80 over I-69/Purchase Parkway

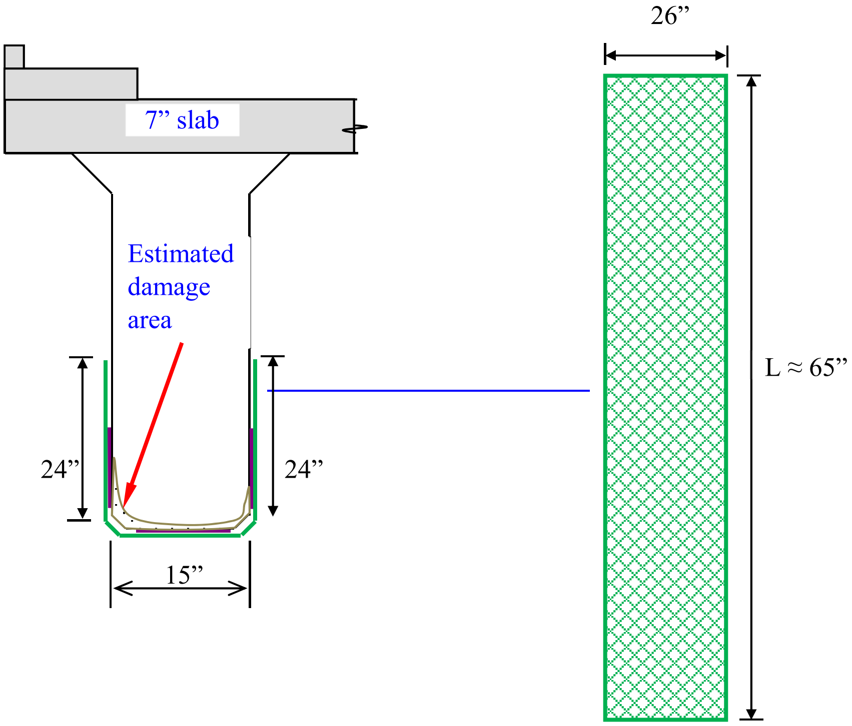


Fig. C4. Typical cut for CFRP fabric

Appendix D

KY 11 Over CSX Railroad and Strodes Run – Mason Co.

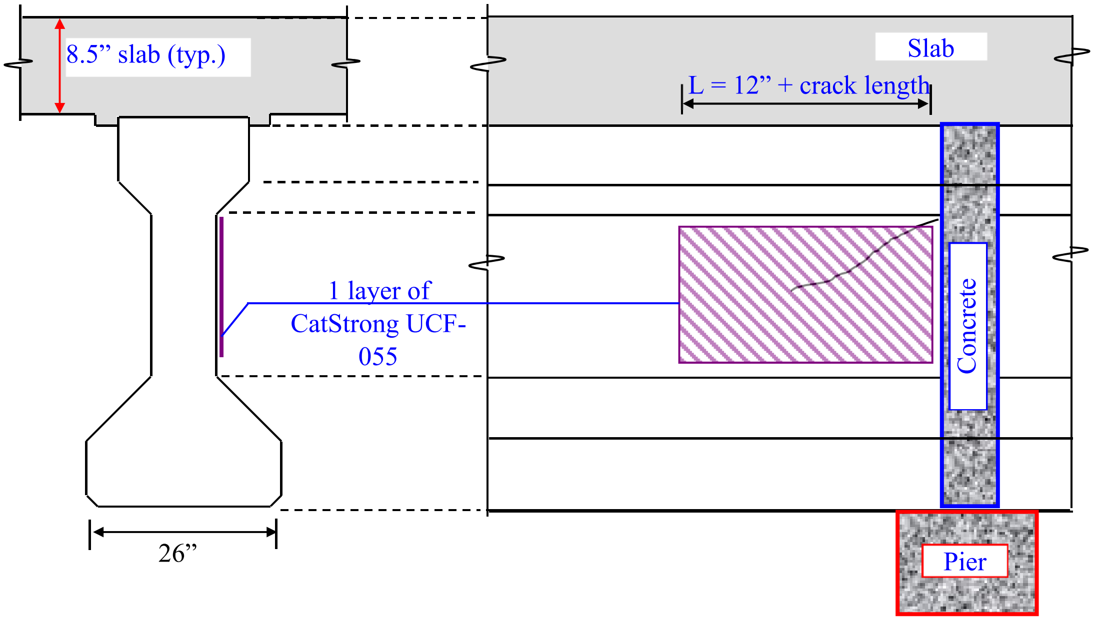


Fig. D1. Typical placement of CatStrong fabric on KY 11 over CSX Railroad and Strodes Run

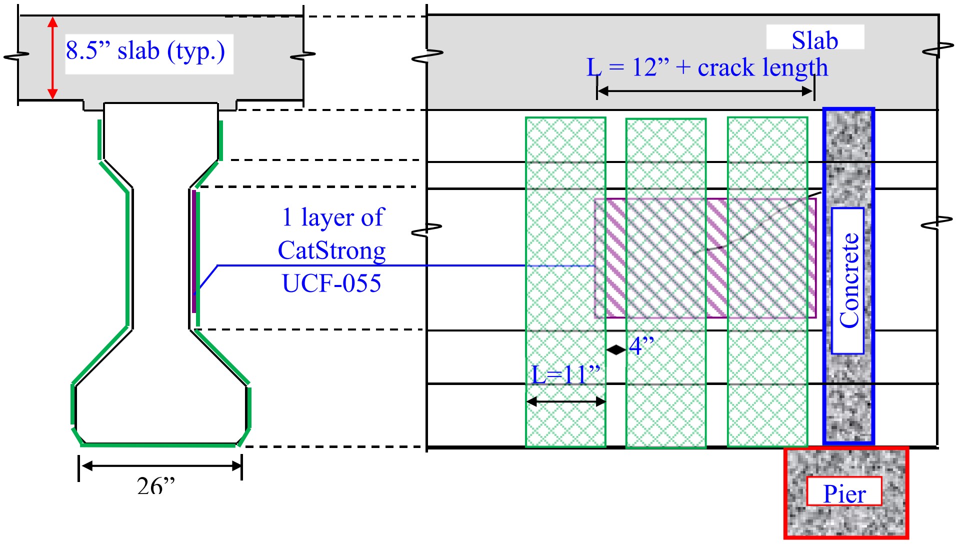


Fig. D2. Typical placement of CatStrong fabric on KY 11 over CSX Railroad and Strodes Run

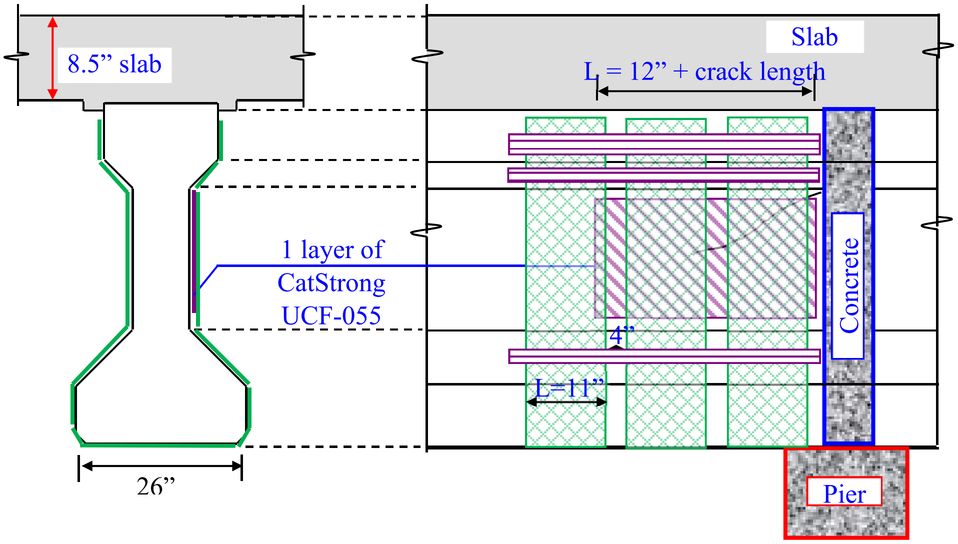


Fig. D3. Typical placement of CatStrong fabric on KY 11 over CSX Railroad and Strodes Run

Appendix E

Installation of CatStrong CRP

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Installation of CatStrong CRP

Step 1: Surface Preparation for CatStrong

1.1 If concrete damage exists, refer ‘Repair of RC & PC Concrete Members’ pamphlet for details.

1.2 Concrete should be blast cleaned, or cleaned by some other mechanical means, to leave a concrete surface profile with out-of-plane variations less than 1/32”. Surface should be clean, dry and free of any contaminants.

Step 2: Application of Epoxy

2.1 Per manufacturer’s instructions, follow mix procedure for epoxy.

(e.g. FX-778, Sikadur 30)

Note: If using two-part epoxy, premixing of each component might be necessary.

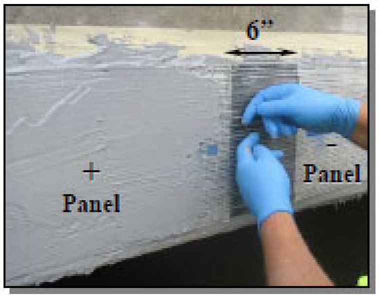
2.2 Apply mixed epoxy (e.g., FX-778, Sikadur 30) onto concrete surface with a trowel or spatula to a depth of approximately 1/8” (3.0 mm) more than the diameter of the CatStrong Rods. Check depth using depth gauge.

Step 3: Application of CatStrong

3.1 Place CatStrong panel on applied epoxy layer and press panel into the epoxy until epoxy seeps out to be flush with the top of panel. Smooth out any excess epoxy.

Note 1: CatStrong panels should span a minimum of 6” beyond the concrete repair area.

Note 2: Adjacent CatStrong panels should be alternated between ‘+’ and ‘-’ panels, brought together with a 6 inch finger joint.



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3.2 **Apply outer layer of epoxy to CatStrong panel and smooth paste along entirety of panel. Remove any excess adhesive.**

Note: If CFRP fabric is to be applied over the CatStrong CRP, center the fabric over the finger joints.

3.3 **Allow epoxy to set per manufacturer's recommendations.**

Note: Once cured the epoxy that is exposed to direct sunlight, should be painted over to protect from UV degradation.

Apply Outer Layer of Epoxy

FX-xxx **– Fox Industries:** http://www.foxind.com/
Sika XXX **– Sika Corporation:** http://usa.sika.com/

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Appendix F

Installation of CatStrong TCF

Kentucky Transportation Center

Installation of CatStrong TCF

Step 1: Surface Preparation for CatStrong TCF

1.1 If concrete damage exists, refer 'Repair of RC & PC Concrete Members' pamphlet for details.

1.2 Concrete should be blast cleaned, or cleaned by some other mechanical means, to leave a concrete surface profile with out-of-plane variations less than 1/32". Surface should be clean, dry and free of any contaminants.

Blast Clean Concrete

Step 2: Application of Epoxy

2.1 Per manufacturer's instructions, follow mix procedure for impregnating resin.

(e.g. FX-778, Sikadur 330)

2.2 Using a trowel or squeegee as recommended by the manufacturer, apply resin to prepared area at a rate that sufficiently covers the surface. (40-50 sq.ft./gallon for FX-778)

Note: For larger projects, impregnation should be completed using a mechanically driven saturator. For smaller projects, manual saturation by a roller will suffice.

Apply Epoxy

Step 3: Application of CatStrong TCF

3.1 Carefully place the CatStrong TCF on the applied epoxy and smooth out using a roller to remove creases and air pockets.

Note 1: CatStrong TCF should span a minimum of 6" beyond the concrete repair area.

Application of Carbon Fabric

Note 2: If CatStrong CRP (or other) strengthening has been used, the CatStrong TCF fabric should span a minimum of 6" beyond the CatStrong CRP.

3.2 **Make sure that the epoxy squeezes out of the fabric roving when rolling. Apply an outer layer of epoxy over the exposed fabric.**

Note 1: If required the fabric can be saturated with epoxy before placement.

Note 2: If overlapping is required, have a minimum of 4 inch overlap between adjacent fabric strips.

3.3 **If needed, apply additional layers of fabric to area while saturated epoxy is still tacky. Roll out any irregularities on this layer as well.**

Note: Once cured the epoxy that is exposed to direct sunlight, should be painted over to protect from UV degradation. (e.g. Sikagard 550W)

Apply Outer Layer of Epoxy

FX-xxx – Fox Industries http://www.strongtie.com//
Sika XXX – Sika Corporation http://usa.sika.com/

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Appendix G

Installation of CatStrong Wrap

Installation of CatStrong Wrap

Timber Pile strengthening with small section loss

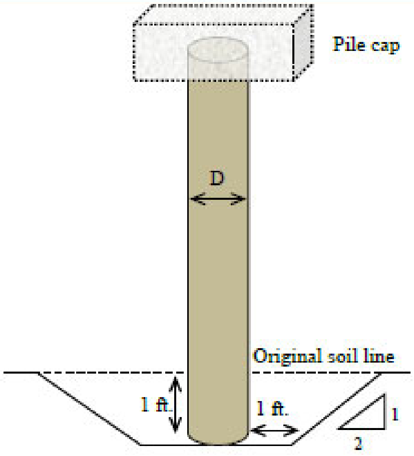
Step 1: Damage Area Preparation prior to Retrofit

1.1 Remove any loose material and debris from pile surface by pressure washing or mechanical means (wire brush etc.).

1.2 Create a trench around the pile a minimum of 1 ft. deep and 1 ft. wide with 2:1 slope.

1.3 Clean and dry pile surface by blowing compressed air and wipe down with a solvent.

1.4 Place a drop cloth at the base of the pile covering the trench surface to prevent any soil contamination of the retrofit material



Prepared Area

Step 2: Application of CatStrong Pile Wrap

2.1 Fix spacers or screws on the pile at the bottom, H/2 and H distance from the bottom to provide a 1" gap between wrap and pile.

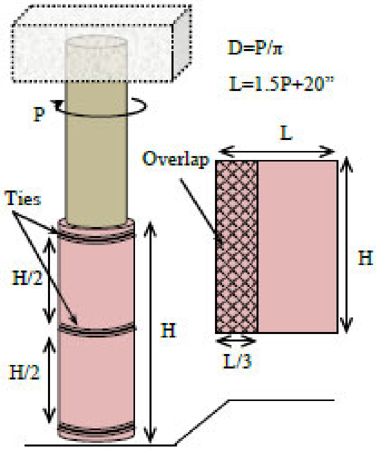
2.2 Measure perimeter of pile (P), and cut the CatStrong Wrap to a length L = 1.5P+20".

2.3 Per manufacturer's instructions, follow mix procedure for bonding epoxy. (e.g. Sikadur 330, FX-778)

2.4 Using stiff-bristled brush or roller, apply thick coat to the CatStrong Wrap overlap surface (L/3).

2.5 Wrap the CatStrong Wrap around the pile to be 'snug' with the spacers.

2.6 Wrap ratchet ties or duct tape at a distance 0, H/2 and H from the bottom.



Application of Pile Wrap

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Step 3: Application of Epoxy Mortar

3.1 Per manufacturer instructions, follow mix procedures for the epoxy mortar. (e.g. Sikadur 35 Hi-Mod LV LPL)

3.2 After initial mixing of 3-4 minutes add dried coarse aggregate (4-5 parts by loose volume with maximum aggregate size ½” or less).

Note 1: The mix is ready when all the coarse aggregate is completely wetted with the epoxy.

Note 2: The amount of prepared mix should be for pours up to 1ft. deep.

Apply epoxy mortar in layers

3.3 Pour epoxy mortar uniformly from the top of the pile wrap and vibrate gently from the outside after each pour.

Note 1: Add epoxy mix to the top of the pour to penetrate into any voids in the pile or mix.

Note 2: Begin next pour when epoxy is seen to pond on top of previous layer.

Vibrate each layer

FX-xxx – Fox Industries products http://www.foxind.com/
Sika XXXX – Sika Corporation products http://usa.sika.com/

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