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16. Abstract

The objective of the implementation study was to

- Provide guidance for installation of strengthening systems
- Provide training materials for personnel carrying out construction and inspection for shear strengthening of concrete beams using CFRP anchors and sheets on concrete beams.
- Suggest QA/QC procedures
- Provide design recommendations and specifications for projects

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THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

Procedures for the Installation and Quality Control of Anchored CFRP Sheets for Shear Strengthening of Concrete Bridge Girders

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1. Guidance for Installation of Strengthening Systems

The research team and the Project Panel worked with the San Antonio District to select a structure on which a trial field installation could be carried out. After a visit to the San Antonio District, a bridge was selected. The bridge is located at the intersection of Loop 1604 and O'Connor Road and is shown in Figure 1. The site selected was considered to have less traffic than the other potential sites and provided easy access to the girders as well as working space that would not interfere with traffic.

Figure 1: View of bridge selected for trial installation

A session was organized to prepare the Special Bridge Maintenance Team in the San Antonio District for installing a carbon fiber reinforced polymer (CFRP) strengthening scheme. The key feature of the selected bridge was that it consists of I-beam girders that can be strengthened only if CFRP anchors are used with CFRP sheets. For the CFRP sheets to carry shear forces, anchors are needed at the re-entrant corners to prevent the CFRP sheets from pulling away at the corners, as Figure 2 depicts.

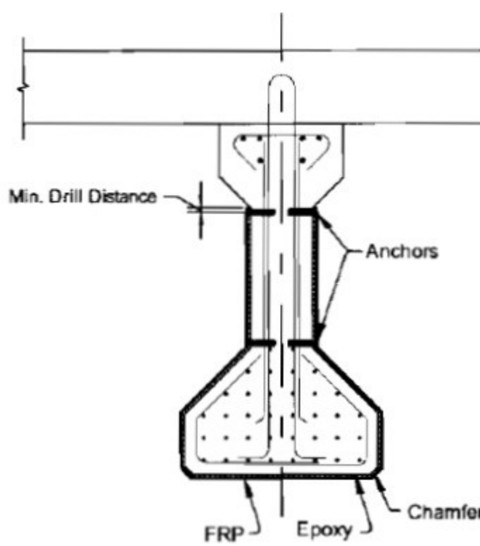


Figure 2: Arrangement of CFRP sheets and anchors for I-girder

Details of the training session and materials prepared for the demonstration session are presented in Appendix A. The session was organized so that the Special Bridge Maintenance Team from the San Antonio District could observe installation procedures demonstrated by the research team and then practice installation firsthand.

2. Field Installation

On May 31, 2012, the CFRP shear strengthening technique was installed on the selected bridge. The following series of photos chronicles the installation sequence (Figures 3–19). Two installation procedures were used: wet layup and dry layup. Wet layup involves saturating the CFRP sheets prior to placement on the concrete surface. Dry layup involves placing dry sheets on a surface wetted with epoxy and then coating the sheets, working the epoxy into the dry sheet.

Figure 3: Site of installation

Figure 4: Maintenance vehicles in position

Figure 5: Work platform in position

Figure 6: Preparation of concrete surface

Figure 7: Hole with rounded edge for anchor

Figure 8: Work area for preparation of CFRP sheets

Figure 9: Saturation of CFRP sheets with epoxy (wet layup)

Figure 10: Application of epoxy to concrete surface, including holes, and placement of saturated sheets

Figure 11: Installation of anchors

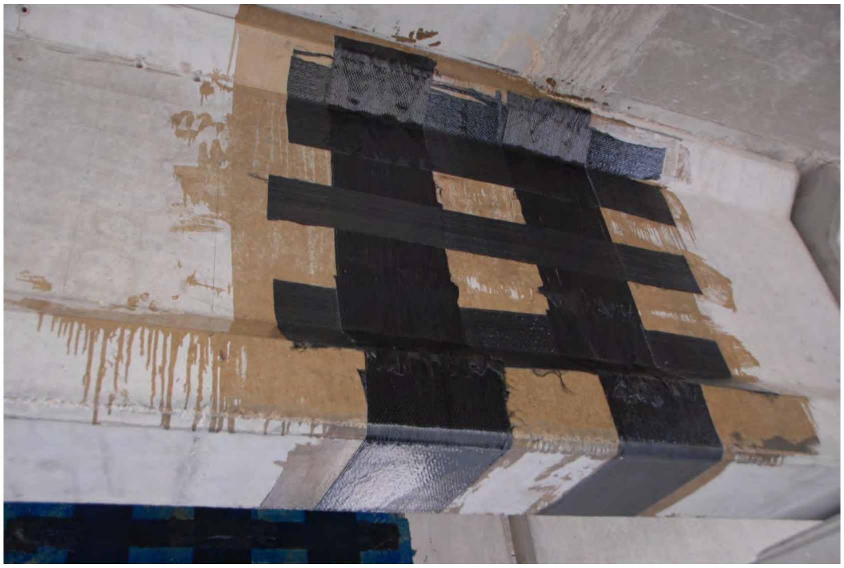


Figure 12: Completed wet layup installation

Figure 13: Preparation of CFRP sheets (dry layup)

Figure 14: Application of primer epoxy coat

Figure 15: Application of epoxy to concrete surface and anchor holes

Figure 16: Installation of dry CFRP sheets on epoxy coated surface

Figure 17: Saturation of dry sheet with epoxy

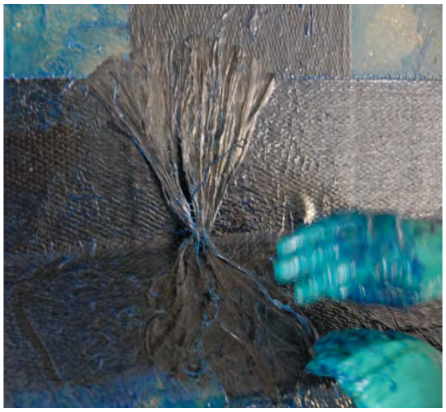


Figure 18: Installation of anchor at re-entrant corner

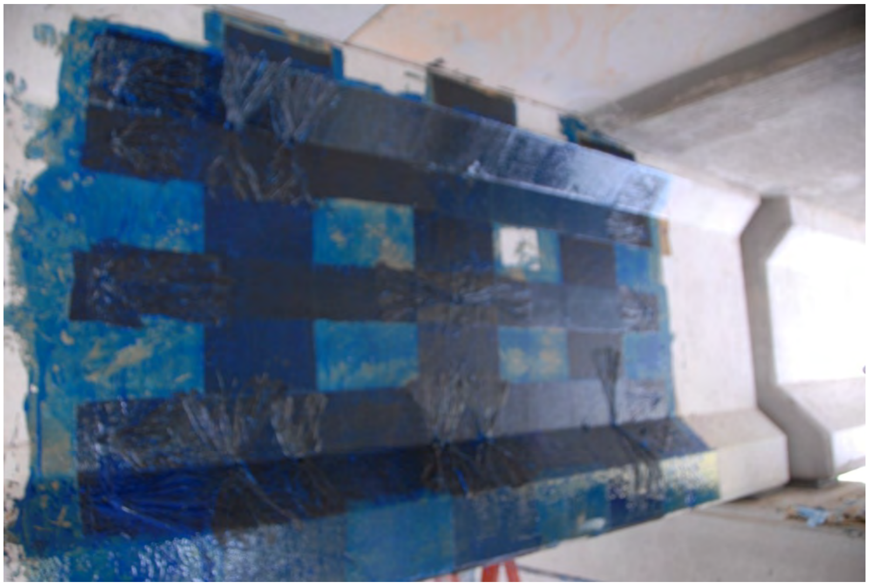


Figure 19: Completed dry layup installation

Shortly after the field installation was completed, the research team met with the Special Bridge Maintenance Team in San Antonio to discuss the procedures with the personnel who carried out the installation. The research team wanted to get input regarding the adequacy of the training session and the materials that had been prepared prior to installation. A key point in the discussion was suggestions for improving the installation procedures. It should be noted that the day of installation was rather cool compared with normal temperatures in San Antonio in late May. Had the temperature been higher, the working time for the epoxy would have been shorter and could have created problems during installation. The Maintenance Team suggested placing the epoxy in a larger bucket containing ice water to keep the material at a lower temperature after the two components were mixed. The Maintenance Team had some problems locating the holes for the CFRP anchors after the sheets were placed. Several suggestions were made but no agreement was reached as to the best procedure. The merits of the wet and dry layup procedures were discussed and participants generally agreed that the wet layup process seemed to be better when placing the CFRP materials in an elevated position and on the sides of girders that had a complex geometry.

Some special procedures for consideration in field operations are presented in Appendix B.

3. QA/QC Procedures

The need for quality control procedures is twofold. First, the materials must be handled and used properly. Manufacturers' recommendations may provide this information but they are not standardized and may be confusing. Second, the installation techniques can be evaluated only by a test that will provide information on the performance of the CFRP anchor/sheet installation.

As part of Project 0-6306, a beam test shown below (Figure 20) was studied for quality control purposes. Under this implementation study (5-6306), some additional quality control specimens were constructed and tested to help define the procedures to be utilized in the field work and in the development of the training materials. The details of the QA/QC test specimen and the test procedure are included in Appendix C.

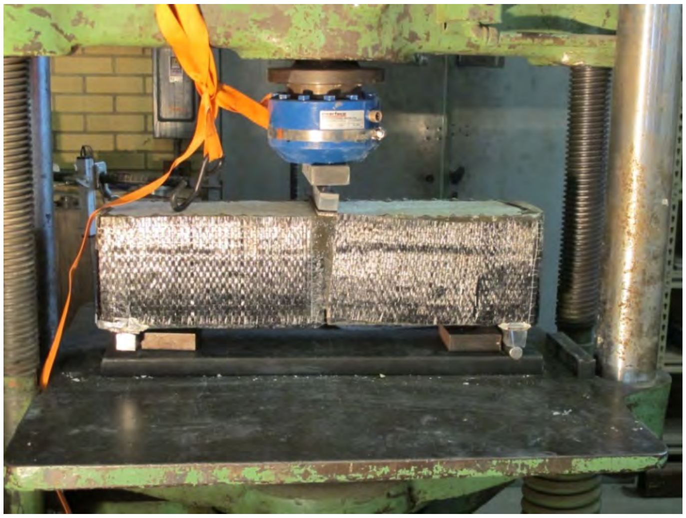


Figure 20: QA/QC Test

4. Design Details for Use of CFRP in Shear Strengthening

Specifications for CFRP Anchors

The following parameters are most influential to the strength of CFRP anchor installations:
1) anchor layout,
2) anchor inclination,
3) depth of anchor hole,
4) anchor hole chamfer radius,
5) area of anchor hole,
6) amount of CFRP material in anchors,
7) anchor fan length,
8) anchor fan angle, and
9) anchor reinforcement.

Figures 21 and 22 illustrate typical CFRP anchor and strip details.

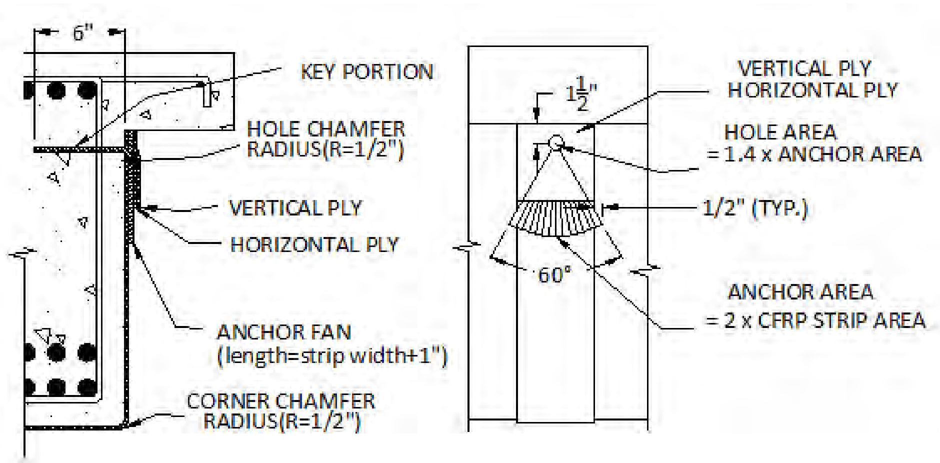


Figure 21: Recommended details of CFRP anchors

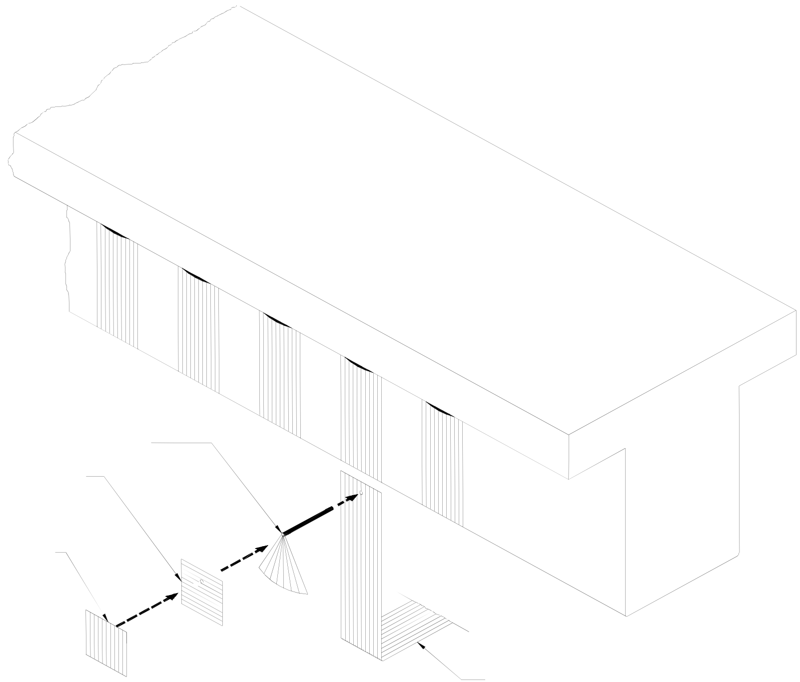


Figure 22: Isometric view of U-wrap with CFRP anchorage system

Based on work performed in this project and TxDOT project 0-6306, the following CFRP anchor details are recommended for use in shear strengthening applications.

1. Anchor layout

In general, it is *better to increase the number of anchors and the number of strips* across the critical section to provide more redundancy and reduce stress concentrations. However, increasing the number of anchors increases installation time. A balance between adding redundancy and reducing construction time should be achieved.

One CFRP anchor per width of CFRP strip is recommended. However, *if the width of a CFRP strip exceeds $d_f/4$, multiple anchors should be considered* to reduce stress concentrations at the anchor fan and key; (d_f = effective CFRP length = distance from anchor to tension chord of beam). For a continuous sheet, the number of CFRP anchors is determined by the width of CFRP to be covered by each anchor. It is recommended that this width not exceed $d_f/4$.

Anchors should be placed such that the effective CFRP length (d_f) is maximized (i.e., as close to the top of a beam as possible). Anchors should always be placed within the concrete core; i.e., within the volume of concrete enclosed by transverse reinforcement.

CAUTION: recommended anchor details are provided for use with single-layer CFRP applications. These details did not provide acceptable performance in the imited work done using multi-layer CFRP applications.

2. Anchor hole inclination from axis perpendicular to surface

Anchor holes were investigated with up to 10 degrees of inclination from the perpendicular to the concrete surface. Inclinations of that amount did not show any adverse effects on anchor performance.

We recommend providing anchor holes that are perpendicular to the concrete surface or bisect the angle created by concrete surfaces at re-entrant corners (e.g., at the intersection of the flange and web in an I-girder). *A deviation of less than 10 degrees from that preferred angle direction did not affect the performance of anchors.*

We recommend performing non-destructive testing to locate steel bars in concrete members prior to drilling so as to minimize drilling into bars. If, however, a steel bar is intersected while drilling, the anchor hole can be kept at the same location and inclined 10 degrees to either side of the bar without any adverse effect on its performance.

<u>3. Depth of anchor hole</u>

A *6 in. hole depth* was used in all test specimens of Project 0-6306 and is recommended to ensure that the anchor engages the concrete core. A *4 in. hole depth* was used in the San Antonio I-girder webs, which were only 6 in. thick. We recommend specifying anchor holes that are *6 in.* deep wherever possible, but never shallower than *4 in.*.

<u>4. Area of anchor hole</u>

An *anchor hole area that is 1.4 times the area of the CFRP anchor* is recommended. Hole diameter should be determined from that area and rounded up to the nearest $1/16^{th}$ of an inch. Holes that are either smaller or larger can reduce anchor performance. A small hole makes it difficult to insert the anchor and a large hole requires more epoxy to fill the space.

<u>5. Anchor hole chamfer radius</u>

An *anchor hole chamfer radius of 0.5 in.* was found to perform well and is recommended. This chamfer can be achieved by using a grinder to grind the edge of the hole at the beam surface to the desired radius. Alternately, a drill bit with a diameter larger than the hole can serve as a "countersink" bit.

<u>6. Amount of CFRP material in anchors</u>

We recommend using an *area of CFRP material in anchors that is at least twice as large as the material area in the CFRP strips* that are developed.

<u>7. Anchor fan length</u>

We recommend using an *anchor fan length of at least 6 in.* in all applications. Longer lengths may be needed to ensure a minimum of a ½ in. overhang of the fan on either side of the strip being developed (see Figure 21 for illustration).

<u>8. Anchor fan angle</u>

A *fan angle of 60 degrees* is recommended in all applications.

<u>9. Anchor reinforcement</u>

Two additional patches in perpendicular directions should be attached over the CFRP anchors (Figures 21 and 22). Patches should be square with sides equal to the strip width.

5. Design of Anchored CFRP Shear Strengthening Systems

Design guidelines for shear strengthening of RC beams using externally bonded and anchored CFRP systems are presented in this section. The guidelines are closely based on ACI 440.2R-08 shear strengthening provisions for externally bonded FRP systems. The guidelines are based on work done in TxDOT project 0-6306 and do not apply to prestressed members or to members with a shear span-to-depth ratio smaller than 2.0. Two options are provided for designing such systems:

- Option 1: A direct use of ACI 440.2R-08 provisions that utilizes the effective strain value for completely wrapped applications in anchored applications.
- Option 2: A modified version of ACI 440.2R-08 provisions that introduces two factors that account for transverse steel and CFRP interactions.

The first option is presented because it is easy to use and familiar to designers of CFRP shear strengthening systems. This method, however, does not take into account the interactions between transverse steel and CFRP and is very conservative. The second option modifies ACI 440.2R-08 provisions to take into account the interactions between steel and CFRP. It provides more accurate estimates of shear strength than the first option.

Option 1: Equivalent to ACI 440.2R-08 Provisions for Completely Wrapped Systems

ACI 440.2R-08 is the most widely used guideline for externally bonded FRP systems. The design recommendations in ACI 440.2R-08 are based on limit-states design principles and are compatible with ACI 318-05. Three types of FRP wrapping schemes are treated in ACI 440.2R-08 for shear strengthening: completely wrapped systems, U-wrap systems, and side bonded systems. Note that anchored systems are not currently treated in the document.

The design equations for FRP shear strengthening in ACI 440.2R-08 are adapted from shear strength equations of ACI 318-05. FRP shear contribution is evaluated in the same manner as for steel except that an effective FRP stress is used instead of a yield stress. The effective stress used is based on an effective strain that can be developed in the FRP sheets and depends on the wrapping scheme. Schemes that can develop the full capacity of the FRP and produce a mode of failure that involves fracture of the CFRP sheet/strip rather than debonding of the FRP are given the highest effective strain values. One important thing to note about these provisions is that the effective strain for completely wrapped CFRP is set at 0.004. This limit on effective strain was placed to preclude large tensile strains across the critical shear crack that can result in loss of aggregate interlock and weakening of the concrete shear transfer mechanism.

Figure 23 illustrates certain geometric variables used in the proposed guidelines. The proposed shear design guidelines for externally applied and anchored CFRP systems are summarized in Figure 24. Essentially, properly anchored CFRP U-wrap systems are treated in the proposed guidelines as ACI 440.2R-08 treats completely wrapped systems. A small modification is introduced to the factor ψ_f for anchored systems. The ψ_f factor is an additional strength reduction factor that accounts for the relative reliability of each application system. This factor is given as 0.95 for completely wrapped systems that are quite reliable in their application. The factor is given as 0.85 for the less reliable U-wraps and side bonded applications. A value of 0.90 is chosen here for anchored U-wrap systems as their reliability is deemed to be intermediate between the other two cases. The effective depth to be used for CFRP anchored systems (d_{fv} in Figure 23) is the distance from the anchor to the extreme tension fiber of the section.

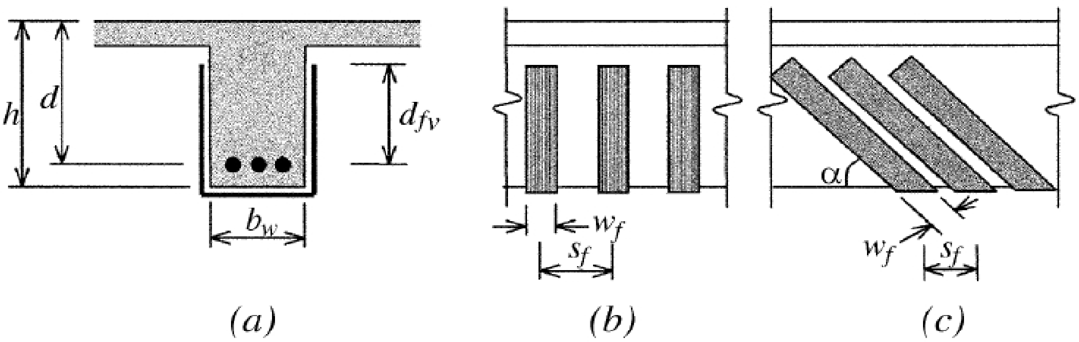


Figure 23: Description of the variables used in FRP shear strengthening calculations

$$V_n = \phi(V_c + V_s + \psi_f V_f)$$

where V_c, V_s, V_f = concrete, steel, and CFRP shear contributions

ϕ = strength reduction factor = 0.75

ψ_f = additional reduction factors for CFRP shear reinforcement

0.90: U-wraps with anchorage

$$V_c = 2\sqrt{f_c'}b_w d$$

$$V_s = \frac{A_{sv} f_{sy}(\sin \alpha s + \cos \alpha s)d}{s}$$, αs = inclination of stirrups from axis of member

$$= \frac{A_{sv} f_{sy} d}{s}$$ for αs = 90°

$$V_f = \frac{A_{vf} f_{fe}(\sin \alpha + \cos \alpha) d_{fv}}{s_f}$$, α = inclination of CFRP fibers from axis of member

$$= \frac{A_{vf} f_{fe} d_{fv}}{s_f}$$

$A_{vf} = 2t_f w_f$, $f_{fe} = \varepsilon_{fe} E_f$

where d_{fv}, s_f, w_f, α are illustrated in Figure 23

f_c' = concrete specified compressive strength (psi)

b_w = section web width

d = section effective depth

A_{sv} = area of transverse reinforcements spaced at s

f_{sy} = yield strength of transverse reinforcements

s_f = center to center spacing of CFRP strips

d_{fv} = distance from anchor to section extreme tension fiber

t_f = nominal thickness of one ply of CFRP reinforcement

w_f = width of CFRP reinforcing plies

E_f = tensile modulus of elasticity of CFRP

ε_{fe} = effective strain level in CFRP reinforcement attained at failure

ε_{fe}= 0.004 ≤ 0.75ε_{fu} (U-wraps with anchorage)

ε_{fu} = ultimate strain capacity of CFRP reinforcement

Figure 24: Proposed shear design equations—Option 1
(Adapted from ACI 440.2R-08)
In bold are modifications to the ACI 440.2.R-08 provisions.

All other provisions of ACI 440.2R-08 apply to the proposed guidelines. These include provisions for reinforcement limits, FRP strip spacing, and existing substrate strains.

Reinforcement limits

The total shear strength provided by reinforcement should be taken as the sum of the contribution of the FRP shear reinforcement and the steel shear reinforcement. The sum of the shear strengths provided by the shear reinforcements should be limited to prevent concrete crushing. ACI 440.2R-08 refers to ACI 318-05, which defines the limit as the following:

$$\boldsymbol{V_s + V_f \leq 8\sqrt{f'_c}\, b_w d}$$

<u>*FRP strip spacing*</u>

For external FRP reinforcement in the form of discrete strips, the center-to-center spacing between the strips should not exceed the sum of *d*/4 plus the width of the strip. This limitation reflects the requirement that a minimum number of FRP strips cross the critical section.

<u>*Existing substrate strain*</u>

ACI 440.2R has a limitation on existing substrate strain. Unless all loads on a member, including self-weight and any prestressing forces, are removed before installation of FRP reinforcement, the substrate to which the FRP is applied will be strained. These strains should be considered initial strains and should be excluded from the strain in the FRP. The initial strain level on the bonded substrate can be determined from an elastic analysis of the existing member, considering all loads that will be on the member during the installation of the FRP system. The elastic analysis of the existing member should be based on cracked section properties.

Option 2: Modified ACI 440.2R-08 Provisions Including Interaction Terms

A second design option is presented here that improves shear strength estimates of beams reinforced with CFRP. Similarly to Option 1, the proposed Option 2 is based on the shear design provisions of ACI 440.2R-08. In fact, Option 2 builds on the modifications of Option 1 on ACI 440 by introducing two new factors that account for the interactions between CFRP and transverse steel. Figure 25 summarizes the proposed shear design equations. The two additional factors, k_s and k_f, are introduced to modify the ACI 440.2R-08 defined shear contributions of steel (termed here as V_{s0}) and CFRP (termed here as V_{f0}) respectively.

<u>*Steel ($\boldsymbol{k_s}$) and CFRP ($\boldsymbol{k_f}$) interaction factors*</u>

As observed experimentally, the efficiency of the CFRP shear strengthening depends on the amount of CFRP and the amount of transverse steel reinforcements. In essence, steel stirrups and CFRP strips are sharing the shear load across a critical shear crack. The more CFRP material that is provided, the stiffer the CFRP strips will be and the more load they will attract. Conversely, the more steel stirrups that are present for a given amount of CFRP, the less shear load the CFRP will take. The shear contributions of CFRP and steel are not, however, directly related to the amounts of materials. Other factors, such as changes in the inclination of the critical shear crack, also influence the contribution of each material to shear strength.

An empirical approach was taken to determine the interaction factors k_s and k_f. For simplicity, the rational function form shown below was considered to define both k_s and k_f factors.

$$y = \frac{a}{b+x}$$

Through trial and error, the following equations were found to fit experimental data well while providing simple and transparent equations for designers. The factors are a function of the ratio of steel and FRP contributions to concrete contribution. Both factors thus decrease as larger amounts of steel and FRP are used.

$$k_s = \frac{8}{4+\frac{V_{s0}+V_{f0}}{V_c}} = \frac{8V_c}{4V_c+V_{s0}+V_{f0}} \;,\; k_f = \frac{6V_c}{4V_c+V_{s0}+V_{f0}}$$

$$\phi V_n = \phi(V_c + V_s + \psi_f V_f)\;,\; \mathbf{(0 \le V_{s0} + V_{f0} \le 4V_c)}$$

where V_c, V_s, V_f = concrete, steel, and CFRP shear contributions

V_s, V_f = steel and CFRP shear contributions considering interactions between materials

V_{s0}, V_{f0} = steel and CFRP shear contributions without considering interactions between materials; same equations as ACI 440.2R-08

ϕ = strength reduction factor = 0.75

ψ_f = additional reduction factors for CFRP shear reinforcement

0.90: U-wraps with anchorage

$$V_c = 2\sqrt{f_c'}b_w d$$

$$\boldsymbol{V_s = k_s V_{s0}}$$

$$\boldsymbol{V_f = k_f V_{f0}}$$

$$V_{s0} = \frac{A_{sv} f_{sy}(\sin\alpha s+\cos\alpha s)d}{s} = \frac{A_{sv} f_{sy} d}{s}$$

$$V_{f0} = \frac{A_{vf} f_{fe}(\sin\alpha+\cos\alpha)d_{fv}}{s_f} = \frac{A_{vf} f_{fe} d_{fv}}{s_f}$$

$$A_{vf} = 2t_f w_f \quad \text{(5-8)} \qquad f_{fe} = \varepsilon_{fe} E_f$$

where

$\boldsymbol{\varepsilon_{fe}}$**= 0.004 ≤ 0.75**$\boldsymbol{\varepsilon_{fu}}$ **(U-wraps with anchorage)**

$\boldsymbol{k_s}$**: steel interaction factor** $\boldsymbol{k_f}$**: CFRP interaction factor**

$$\boldsymbol{k_s = \frac{8V_c}{4V_c+V_{s0}+V_{f0}}} \quad \text{(5-10)}, \qquad \boldsymbol{k_f = \frac{6V_c}{4V_c+V_{s0}+V_{f0}}}$$

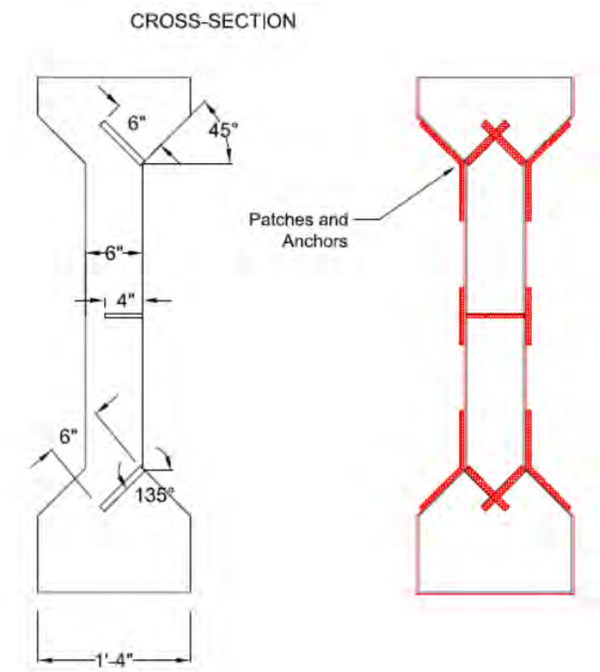
Figure 25: Proposed shear design equations—Option 2

(Adapted from ACI 440.2R-08)

In bold are modifications to ACI 440.2.R-08 provisions (see Figure 24 for term definitions).

6. Drawings and Specifications for Projects

The following drawings and specifications were presented to the TxDOT bridge maintenance crew for installing the anchored CFRP sheets on the San Antonio bridge (Figures 26 to 29). They are presented here to illustrate how CFRP sheets and anchors can be specified on drawings.



Vertical Strips:
75" Length (Including 16 " lap splice at the bottom)
12" Width
6 Total

Horizontal Strips:
78" Length
4 - 12" Width
2 - 6" Width
6 Total

Anchor Patches
12 - 12" by 12"
8 - 6" by 6"
10 - 12" by 6" (Fibers in 6" Direction)
10 - 6" by 12" (Fibers in 12" Direction)

Two Way Anchors:
22" Length (4" Embedment, 7" Fan)
Area of Anchor 0.264 in^2

One Way Anchors:
26" Length (6" Embedment, 7" Fan)
Area of Anchor 0.132 in^2

Two Way Anchor Holes:
6" Depth
1 1/16" Diameter Holes
Bisect surface angles as shown; slight angle to the right to avoid intersecting holes drilled from both sides of the web

One Way Anchor Holes:
4" Depth
½" Diameter Holes
Holes in the flange: perpendicular to the surface
Holes in the web: slight angle to the right to avoid intersecting holes drilled from both sides of the web

Figure 26: San Antonio I-Girder cross section and CFRP sheets and anchors

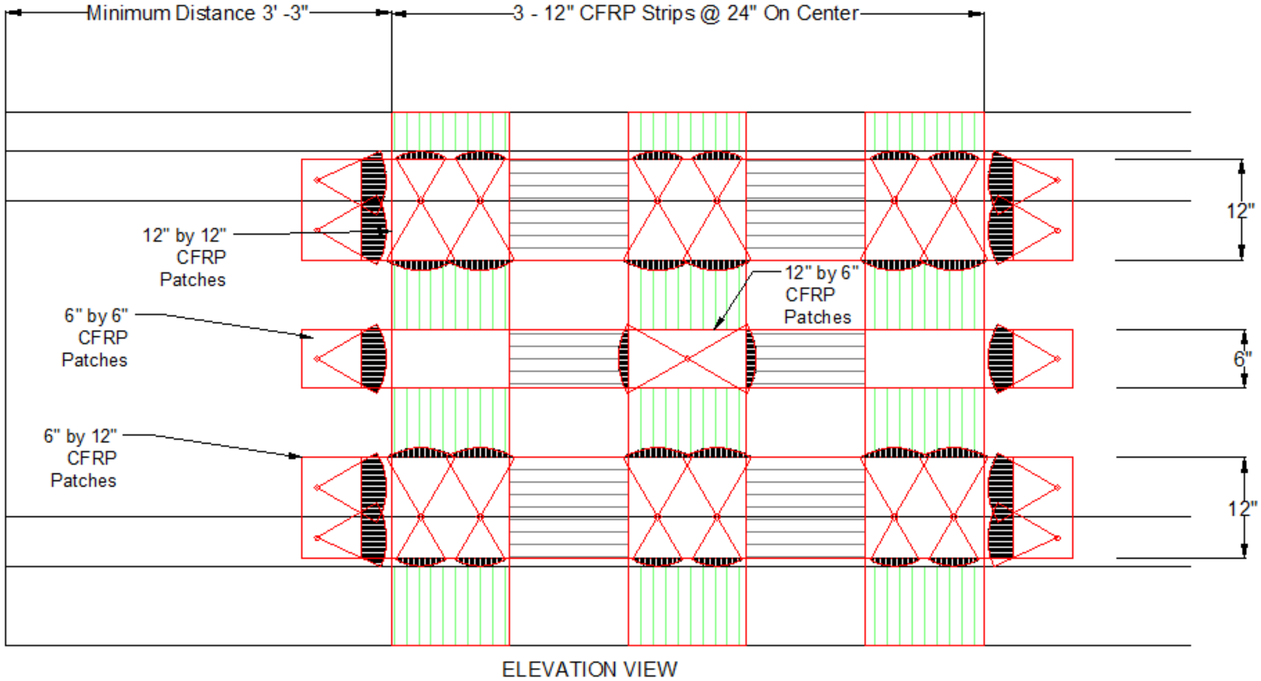


Figure 27: San Antonio I-Girder elevation view with all CFRP sheets and anchors

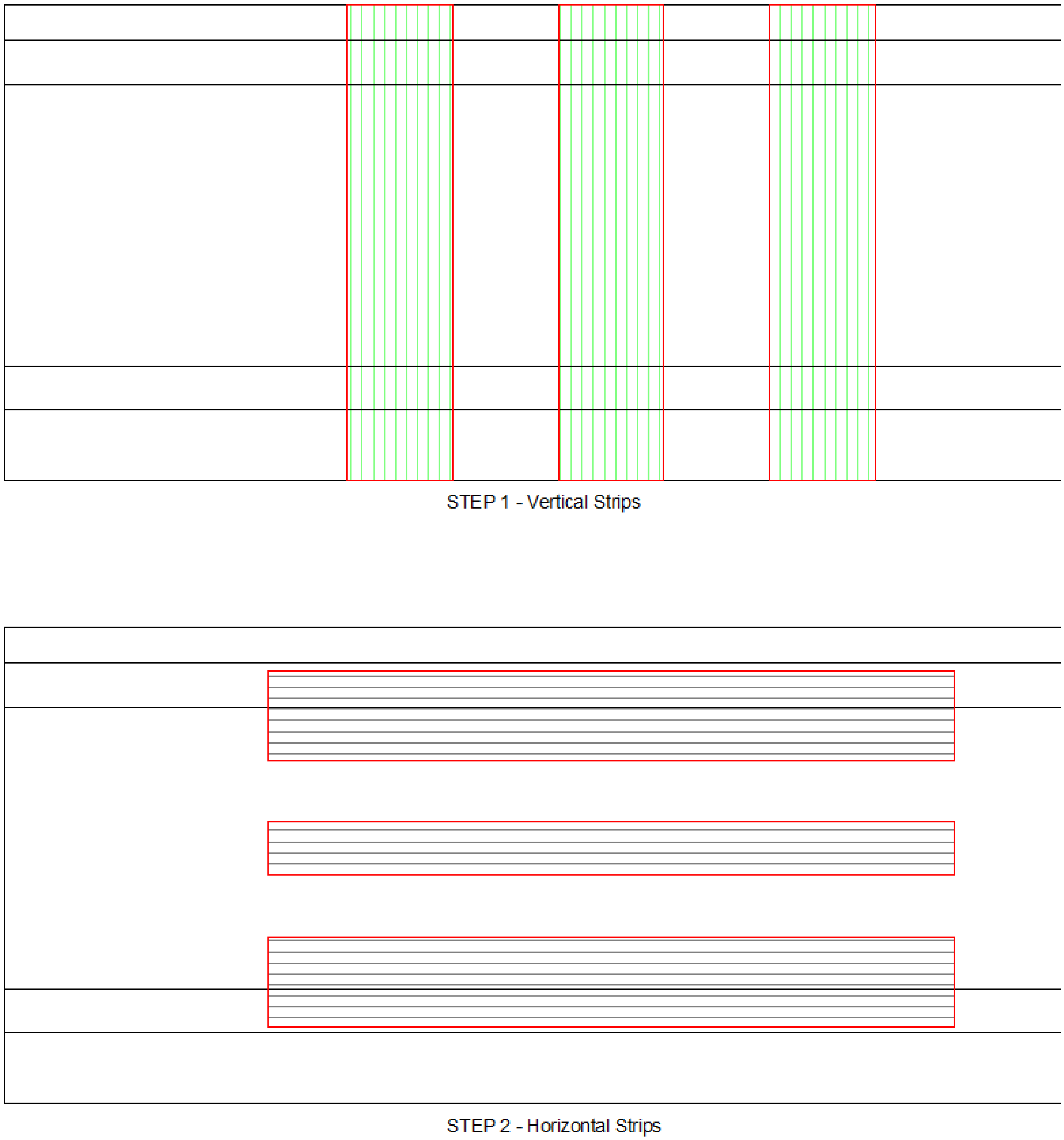
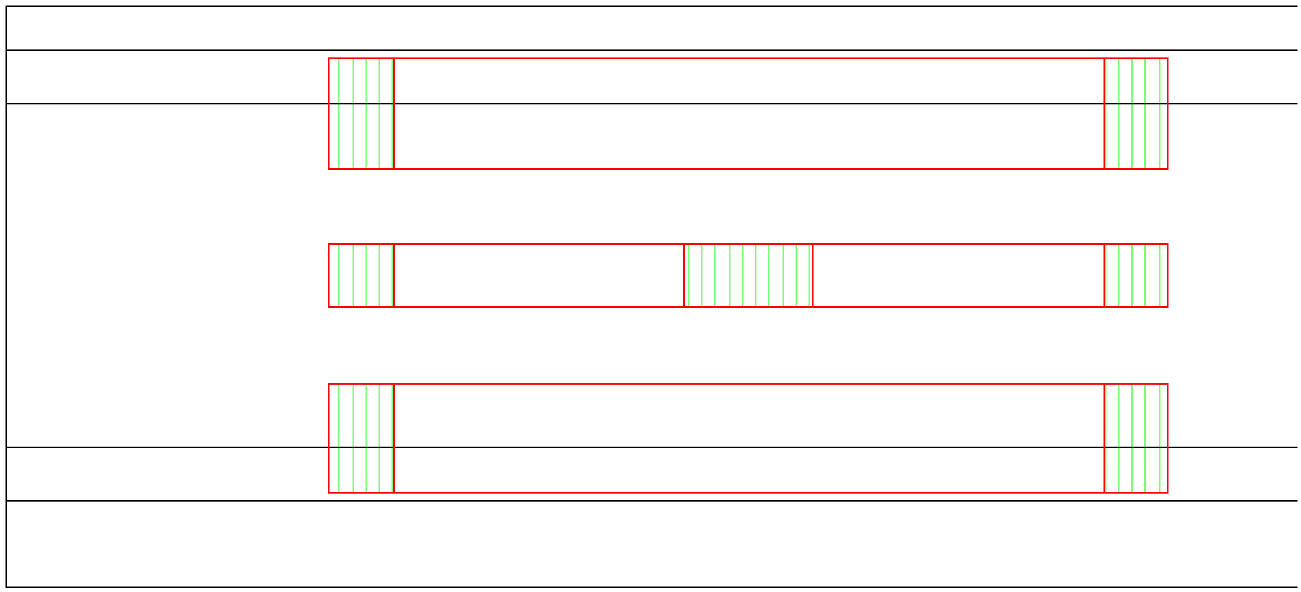


Figure 28: San Antonio I-Girder elevation view with first two installation steps



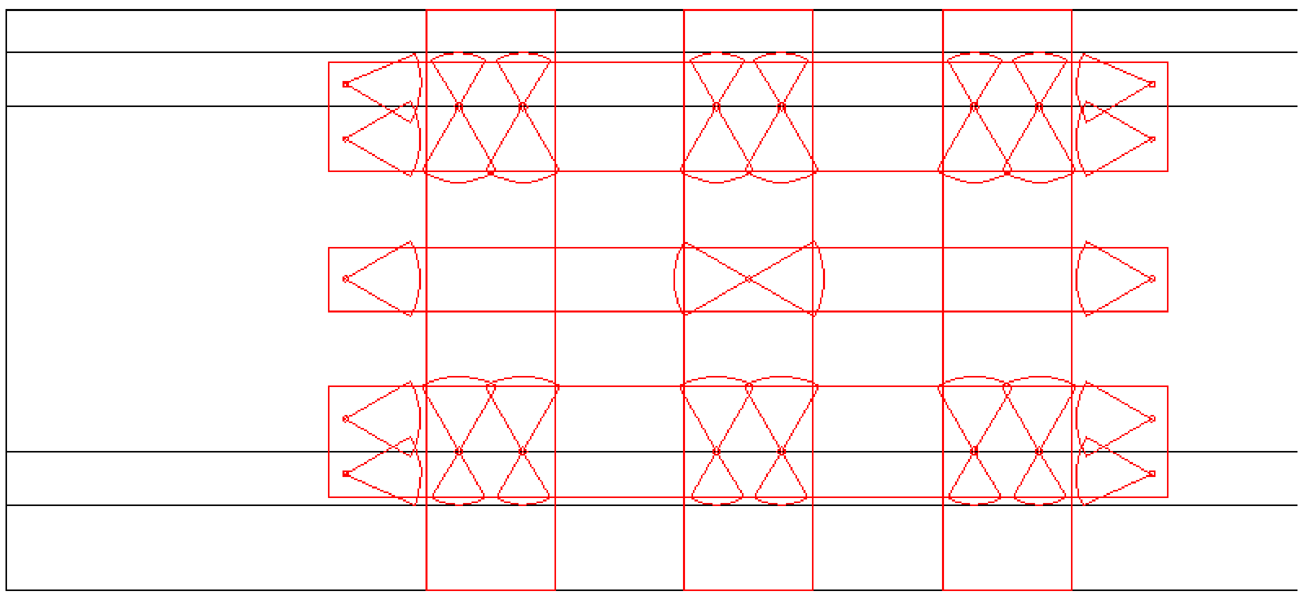
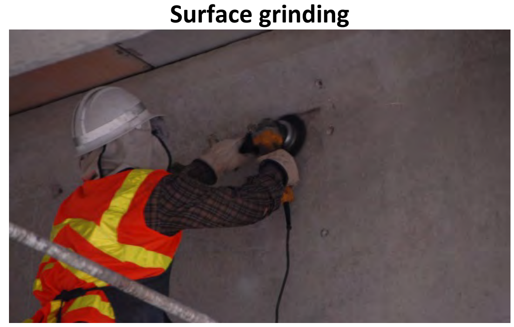


Figure 29: San Antonio I-Girder elevation view with last installation steps

Appendix A. Guide for the Installation of Externally Bonded and Anchored CFRP

This appendix provides step-by-step instructions for the installation of CFRP sheets and anchors in shear strengthening applications, addressing both wet and dry layup applications. Only two tasks differ between wet and dry layup. Commentary and illustrative pictures accompany the instructions.

TASKS	COMMENTARY
1. Prepare the concrete surface a. Smooth surface using light surface grinding. b. Grind edges that CFRP anchors have to bend around to a minimum chamfer radius of ½”. c. Clean surface with DRY compressed air. d. Mark location of CFRP strips and anchors. 	Since anchors provided in this project are able to fully develop the ultimate strength of the CFRP sheets, bond between CFRP and concrete is not essential structurally. Surface preparation for anchored CFRP applications can therefore be simplified compared to surface preparation for unanchored bond-critical CFRP applications. For anchored applications, the concrete surface should be smooth, clean, dry, and free of any loose material (i.e., limited roughness and no protrusions). ACI 440.2R-08 recommends that all 90° corners be rounded to a minimum radius of 0.5” to minimize stress concentrations in the CFRP at the corners. **Surface grinding** 
2. Prepare the anchor holes a. Drill anchor holes to specified size and depth i. If a rebar is encountered, angle the drill hole at the same location such that it avoids the rebar but not more than 10° from the original perpendicular line. b. Round the edge of the hole to a minimum radius of ½”. The anchorage holes need to be rounded only to the required radius along the edge that contacts the anchorage fan. c. Clean hole either with a vacuum or dry compressed air.	Drilling the hole to the specified depth and radius is essential. Holes that are too narrow will hinder the insertion of anchors and holes that are too wide may compromise the anchors’ strength. Holes that are too deep will make the portion of the anchor sticking out too short. Holes that are too shallow may compromise the strength of the anchor. In most cases where anchor failure was noted in experiments, failure was observed at the anchor bend at the edge of the hole. The rounding of the hole and the chamfer radius are essential in preventing a premature anchor failure. ***CAUTION:*** Do not use compressed air with oil or other particles as the oil or particles may interfere with the bond between anchor and concrete.

Step a

Step b

Final clean hole

Sample hole pattern for I-girder

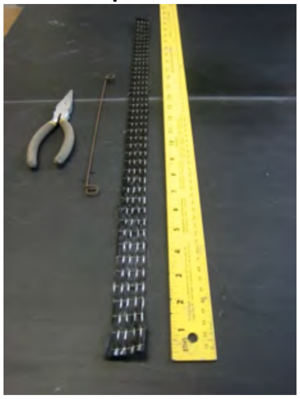
3. Construct CFRP anchors

CFRP anchors may be purchased from manufacturers. If that option is not available, use the following steps to fabricate the CFRP anchors.

a. Anchors may be produced on or off site.
b. Cut CFRP sheets to the desired width (perpendicular to the fibers) and length (parallel to the fibers) for each anchor.
c. Fold each cut sheet once along the length.
d. Attach a tie wire to the CFRP anchor sheet at mid length.
e. Fold the anchor at the tie.

CAUTION: Carbon fiber can cause allergic reactions. Use gloves and wear respiratory protection during this task.

steps b and c



steps d and e

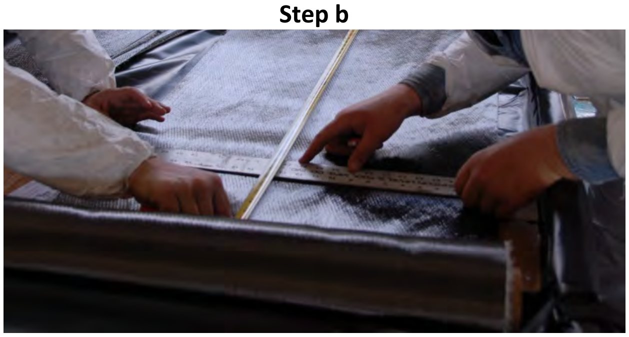
Final anchor

4. Cut CFRP sheets and patches

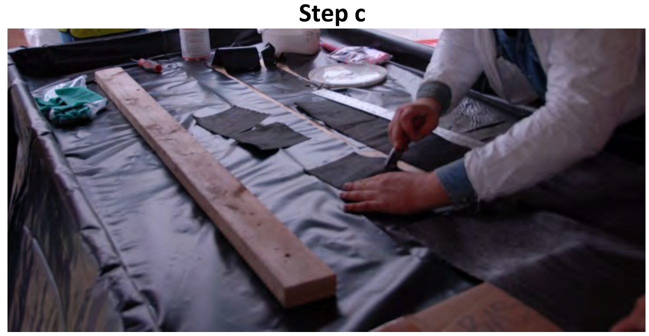
a. CFRP sheets can be cut off site or on site.
b. Cut CFRP sheets into strips of specified length (along the CFRP fibers) and width (perpendicular to the CFRP fibers).
c. Cut CFRP sheets into patches that will be used to reinforce the anchors.

Carbon fibers can cause allergic reactions. The use of gloves and wear respiratory protection is recommended during this task.

Step b



Step c



5. Wear protective gear

a. Wear body suit.
b. Wear hair cover.
c. Wear gloves.
d. Shoe covers are recommended.

Applying CFRP to concrete can be very a messy process. **NOTE:** Once the epoxy sets, removing it from clothing item, hair, or skin is virtually impossible. Typically all items exposed to epoxy during installation are discarded at the end of the job.

6. Divide the job into workable batches

a. Estimate total installation time.
b. Evaluate the epoxy’s workable time.
c. Divide job into parts that can be accomplished each within the epoxy’s working time.

Estimate the amount of time the epoxy will be workable from manufacturer specifications. Working time is highly dependent on temperature. During hot days, extend the working time by dipping the epoxy container in a larger bucket containing ice water. Typical working times are 1 to 3 hours depending on temperature.

CAUTION: Each CFRP sheet and its anchors must be installed in the same batch. Don’t let the sheet dry before installing the anchors that connect to it.

7. Mix epoxy

Manufacturers typically provide the two components that make up the epoxy in pre-measured buckets.

a. Pour the two components into a larger container and mix thoroughly with an electric mixer.
b. Mix to the manufacturer-specified duration.

Epoxy used in CFRP applications typically comes in two components that need to be mixed on site. One component consists of a high-strength resin and the other component is a chemical hardener that reacts with the resin, causing the epoxy to set.

Vapors from one component can react with the second component and initiate setting. **Keep the two components separate until they are ready for use.**

CAUTION: The strength of the epoxy can be compromised in adverse climate conditions. When high humidity, wetness, or extreme temperatures are present, CFRP installation may not be possible. Please refer to manufacturer climate restrictions.

Steps a and b

8. Saturate concrete surface and holes

a. If the manufacturer requires a primer, saturate the anchor holes and concrete surface where CFRP sheets will be placed with the primer.
b. Saturate the anchors holes with epoxy.
c. Saturate the concrete surface with epoxy where CFRP sheets will be placed. For dry layup, be sure to provide a generous coating so that it may be worked into the fabric.

Saturation of anchor holes can be done using a brush or a saturated anchor. If an anchor is used for saturation, discard it after saturation and do not install that anchor. The surface is saturated in much the same way that paint is applied.

Step a

Step b

WET LAYUP

9. Saturate CFRP sheets

Repeat for each CFRP strip.

a. Place strip on a plastic sheet.
b. Apply epoxy liberally using a roller.
c. Flip the CFRP sheet to the other side.
d. Apply epoxy liberally using a roller. Make sure that the sheet is fully saturated with epoxy.

Some manufacturers sell machines to saturate the CFRP strips. In the absence of such machines, this simple procedure can be used.

Steps a and b

10. Apply CFRP strips to the concrete surface

Repeat for each strip.

a. Place the CFRP strip in its final location.
b. Using a trowel, remove excess epoxy and air voids from the strip. **TIP:** Start away from the strip ends and work towards the end so that air bubbles are pushed out.

This step is one of the most critical in the application process. Inadequate installation of the strips will result in a compromised strength. **The CFRP must be in full contact with the concrete, with no air voids or separations**.

It may be useful to roll sheets around a wide roller once saturated and then unroll then unto the surface.

The epoxy is typically viscous enough to allow the sheet to stick to the surface without needing to be held on manually.

Step a

Step b

DRY LAYUP

9. and 10. Apply CFRP strips to the concrete surface

Repeat for each strip.

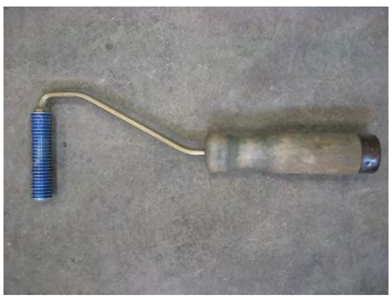
a. Place the CFRP strip in its final location over the epoxy.
b. Work the epoxy with a serrated roller until the epoxy come through the fabric. Make sure to remove all air voids in the process.
c. Apply a second coating of epoxy on the sheet and work into the fabric using the roller. Make sure to remove all air voids in the process

This step is one of the most critical in the application process. Inadequate installation of the strips will result in a compromised strength. **The CFRP must be in full contact with the concrete, with no air voids or separations**.

TIP: Start away from the strip ends and work towards the end so that air bubbles are pushed out.

The epoxy is typically viscous enough to allow the sheet to stick to the surface without needing to be held on manually.

Roller



Step b

ALL APPLICATIONS

11. Install CFRP anchors

Repeat for each anchor.

a. Place a CFRP patch centered at the anchor hole with fibers running perpendicular to the fibers of the strip.
b. Spread the fibers at the hole location to allow for insertion of the anchor.
c. Saturate the anchor with epoxy.
d. Insert the anchor into the hole. Make sure the anchor is inserted through the entire depth. Fan out the portion of the anchor CFRP that extends beyond the hole in the direction(s) specified. Make sure the fan angle and extension of the fan beyond the edge of the strip are as specified.
e. Cut the rebar tie that held the anchor as close to the surface as possible.
f. Place a CFRP patch centered at the anchor hole with fibers running in the same direction as the fibers of the main strip.

TIP: The best way to spread the fibers is to use a gloved finger.

CAUTION: Do not use sharp objects such as scissors to spread the fibers at anchor hole (due to the risk of cutting fibers in the main strip).

For a bi-directional anchor that requires fanning in two directions, make sure to keep both halves of the anchor separate during insertion so that each could be fanned independently and avoid entanglement.

Typical fan angle is about 60°; fans should extend at least ½" beyond the edge of a sheet

Step a

Step b

Step c

Step d

Step e

Step f

12. Apply final coat of epoxy a. Apply a final coat of epoxy on all CFRP surfaces.	This task is meant to smooth the surface and ensure full saturation of the CFRP with epoxy.

Information provided in the installation guidelines will be used to produce short videos and a presentation for the training sessions we are committed to delivering to TxDOT as part of this project.

Appendix B. Special Considerations for Installation of CFRP on an In-Service Bridge

A TxDOT maintenance crew performed a field installation to evaluate and improve the practical aspects of installing externally bonded and anchored CFRP sheets on bridge sections. The following table outlines topical considerations when exploring repairs of in-service bridges.

Topic	COMMENTARY
1. Site evaluation Several factors need to be assessed to ensure quality installation of CFRP. a. *Accessibility:* the surface of the sections that need to be repaired or strengthened must be accessible for the installation b. *Surface conditions:* the surface of the concrete on which CFRP is to be attached should be free of large cracks and protrusions. c. *Moisture:* sections should be dry for the application. CFRP should not be used on sections that contain significant absorbed water.	If the surface is damaged, grouting or epoxy injection may be necessary prior to installing CFRP. In all cases, CFRP coverage should always allow the concrete section to exchange moisture with the ambient air without impediment. Discrete strips are therefore recommended over continuous CFRP coverage.
2. Concrete condition a. Concrete surface should be smooth, clean, dry, and free of any loose material (i.e., limited roughness and no protrusions). b. Concrete in the section should have limited cracks and crack widths.	Since the anchors provided in this project are able to fully develop the ultimate strength of the CFRP sheets, bond between the CFRP and concrete is not essential structurally. Surface preparation for anchored CFRP applications can therefore be simplified (compared to surface preparation for unanchored bond-critical CFRP applications). However, a smooth surface free of protrusions is still required and can be typically achieved using light grinding. CFRP can be placed over a limited number of cracks of up to 0.016” in width. Wider cracks or extensive crack patterns should be epoxy-injected prior to application.
3. Material safe handling When handling and cutting CFRP: a. Wear gloves. b. Wear respiratory protection. c. Wear eye protection. When handling epoxy: d. Cover equipment and surfaces that may come into contact with epoxy. e. Wear body suit. f. Wear hair cover. g. Wear gloves. h. Shoe covers are recommended.	Carbon fiber can cause allergic reactions. Use gloves and wear respiratory and eye protection when handling or cutting CFRP. Applying CFRP to concrete can be very a messy process. **NOTE:** Once the epoxy sets, removing it from clothing item, hair, or skin is virtually impossible. Typically all items exposed to epoxy during installation are discarded at the end of the job.

Appendix C. Quality-Control Beam Tests

Beam specimens consist of 6in. x 6in. x 24in. unreinforced concrete beams that are tested under bending through three-point loading (Figure C1). The beams are reinforced with an anchored CFRP strip at their tension face. Additional CFRP sheets are wrapped around the sides to ensure failure of the strip at the tension face and preclude shear failures of the beam (see the drawings in Section C.1).

An adequate anchor installation will result in the fracture of the anchored CFRP strip (Figure C2). The strength of the CFRP laminate can be evaluated from the ultimate strength reached in the test. Thus, the beam tests not only allow the validation of the quality of anchor installation, they also allow the evaluation of the CFRP laminate strength.

Please note that the details of the test beams are preliminary at this stage. Further testing is being conducted as part of TxDOT project 0-6783 through which final beam design and testing methodology will be produced.

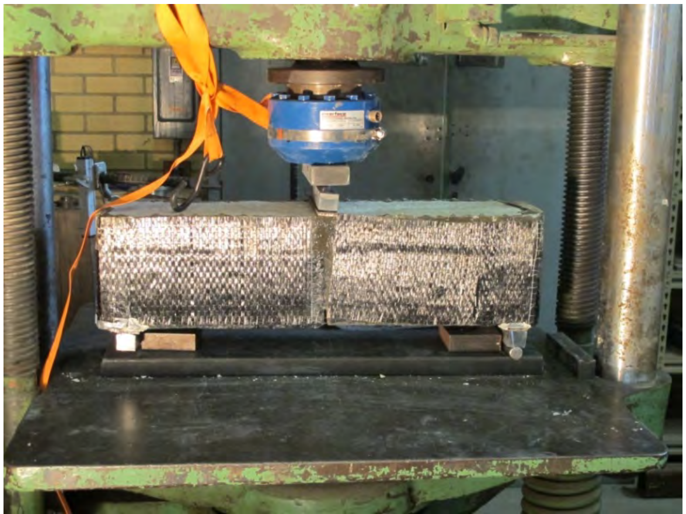
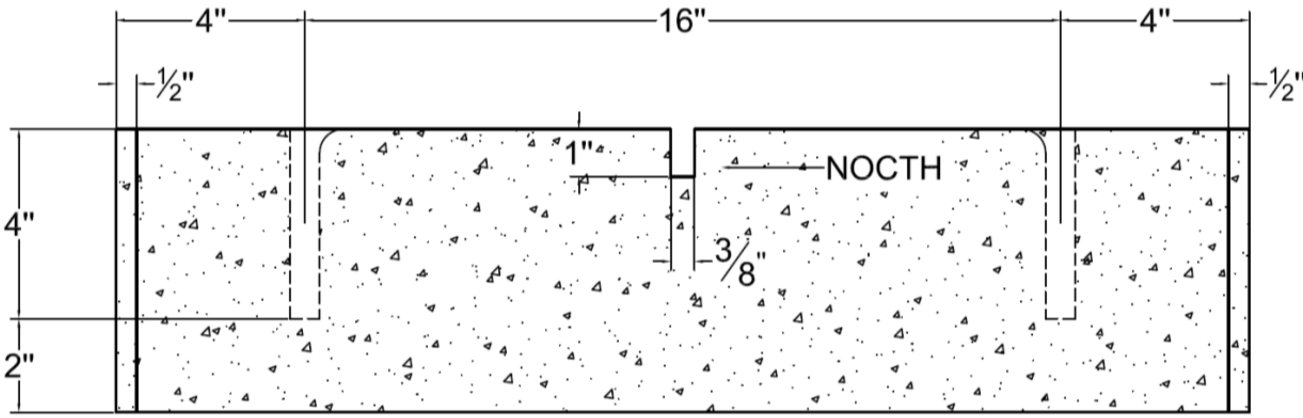


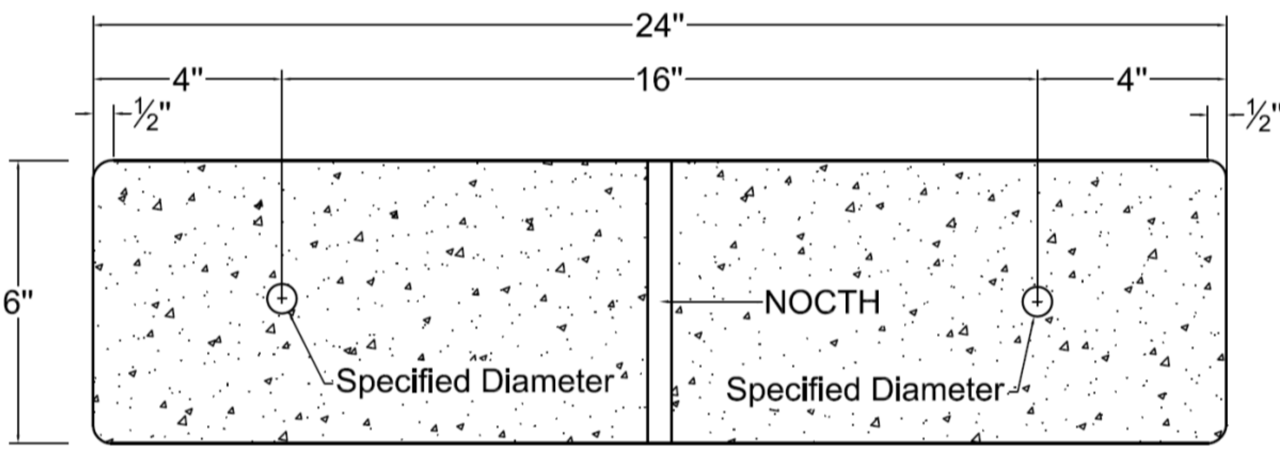
Figure C1: Beam in test rig

Figure C2: Successful test with CFRP sheet fracture

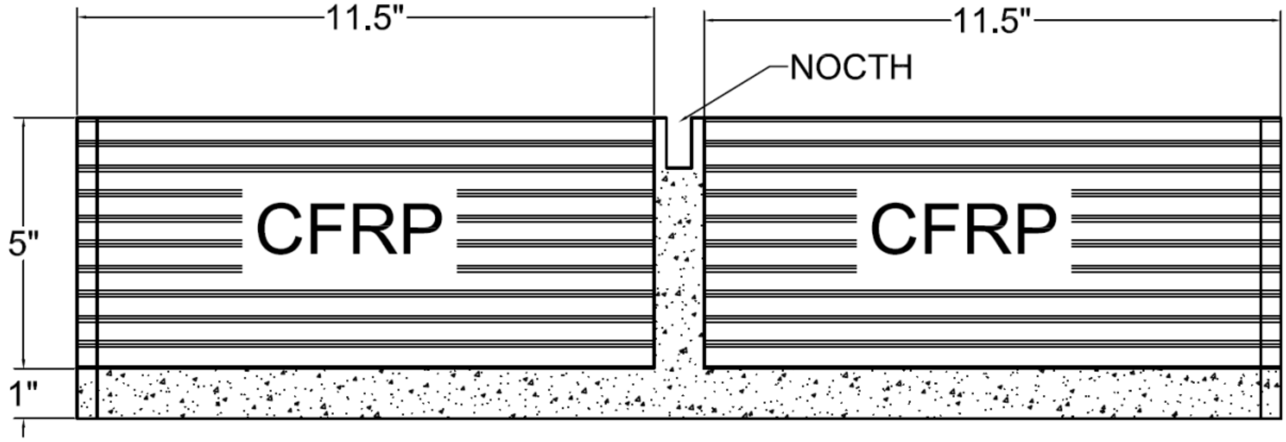
C.1 Drawings



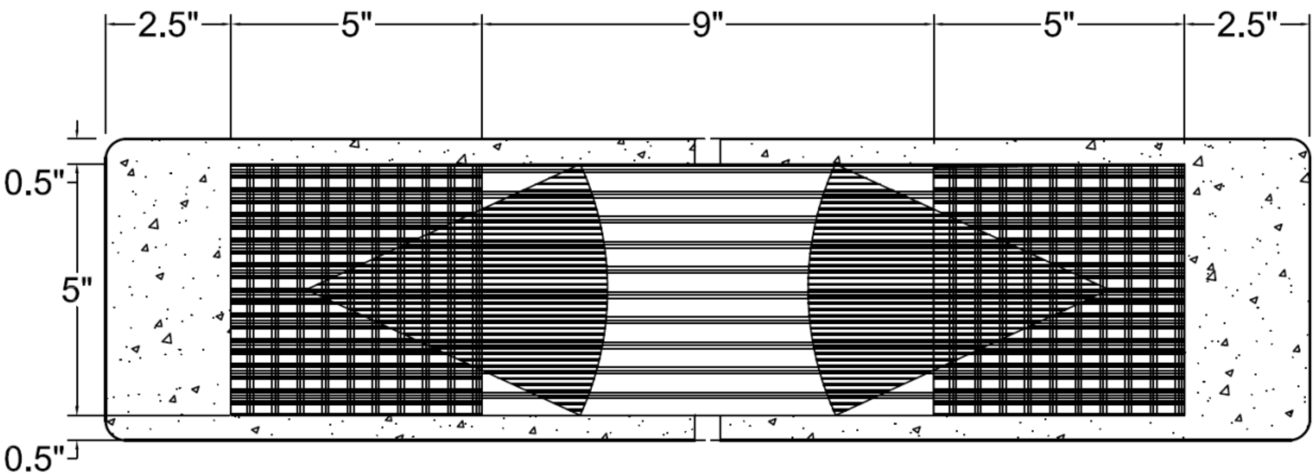
Side View without CFRP



Bottom View without CFRP



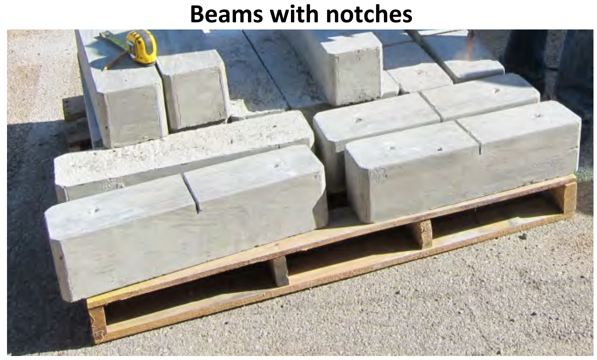
Side View with CFRP



Bottom View with CFRP

C.2 Guide for the Construction of Quality-Control Beam Specimens

This section presents step-by-step instructions for the installation of CFRP sheets and anchors for the quality control beam tests.

TASKS	COMMENTARY
1. Cast the beam specimen a. Forms for standard beams used for three-point loading tests can be used. Chamfer the vertical edges of the forms a minimum of 0.5”. Inserts can be used to round the edges. b. Cast the concrete using the specified concrete mix. c. Cure the concrete for the time required to reach the desired concrete strength.	If the beam tests are used to qualify installation or materials for a particular structure, the specified concrete mix of the beams and the structure should be the same. **Beam forms showing chamfer** 
2. Saw cut a notch in the beam a. Saw cut a notch in the beam at mid span of the bottom face. The notch should be approximately 1” deep and 3/8” wide.	**Beams with notches** 
3. Prepare the anchor holes a. Drill TWO anchor holes to the specified diameter and a 4” depth. Center the holes at the bottom face of the beam, spaced at 16” on center. b. Round the edge of the hole to a minimum radius of ½”. The anchorage holes need only be rounded to the required radius along the interior-facing edges that contact the anchorage fans. c. Clean holes either with a vacuum or dry compressed air.	Drilling the holes to the specified depth and radius is essential. In most cases where anchor failure was noted in experiments, failure was observed at the anchor bend at the edge of the hole. The rounding of the hole and the chamfer radius are essential in preventing a premature anchor failure. ***CAUTION:*** Do not use compressed air with oil or other particles, as the oil or particles may interfere with the bond between anchors and concrete.

Step a

Step b

Final clean hole

Beams with anchor holes

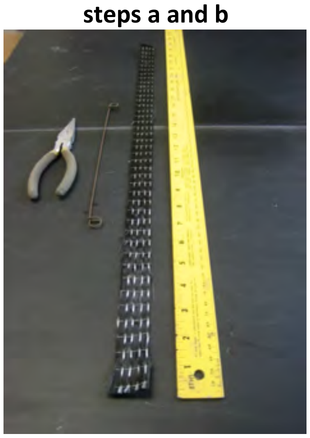
4. Construct CFRP anchors

CFRP anchors may be purchased from manufacturers. If that option is not available, use the following steps to fabricate CFRP anchors.

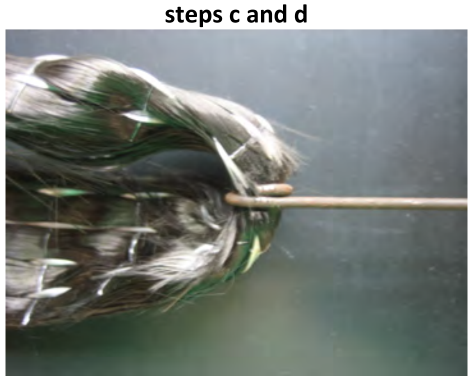
a. Cut CFRP sheets to the desired width (perpendicular to the fibers) and length (parallel to the fibers) for each anchor.
b. Fold each cut sheet once along the length.
c. Attach a tie wire to the CFRP anchor sheet at mid length.
d. Fold the anchor at the tie.

CAUTION: Carbon fiber can cause allergic reactions. Use gloves and wear respiratory protection during this task.

steps a and b



steps c and d



final anchor

5. Cut CFRP sheets and patches a. Cut CFRP sheets into THREE strips with the following dimensions: ***1 strip: 5” wide x 19” long*** ***2 strips: 5” wide by 29” long*** b. Cut CFRP sheets into FOUR patches that are 5x5” square.	The width dimension is perpendicular to fibers. The length dimension is parallel to fibers. ***CAUTION:*** Carbon fiber can cause allergic reactions. Use gloves and wear respiratory protection during this task.
6. Wear protective gear a. Wear body suit. b. Wear hair cover. c. Wear gloves. d. Shoe covers are recommended.	Applying CFRP to concrete can be very a messy process. **NOTE:** Once the epoxy sets, removing it from clothing item, hair, or skin is virtually impossible. Typically all items exposed to epoxy during installation are discarded at the end of the job.
7. Mix epoxy Manufacturers typically provide two components that make up the epoxy in pre-measured buckets. a. Pour the two components into a larger container and mix thoroughly with an electric mixer. b. Mix to the manufacturer specified duration. ***CAUTION:*** The strength of the epoxy can be compromised in adverse climate conditions. When high humidity, wetness, or extreme temperatures are present, CFRP installation may not be possible. Please refer to manufacturer climate restrictions.	Epoxy used in CFRP applications typically comes in two components that need to be mixed on site. One component consists of a high-strength resin and the other component is a chemical hardener that reacts with the resin, causing the epoxy to set. Vapors from one component can react with the second component and initiate setting. **Keep the two components separate until they are ready for use**. **Steps a and b** 

8. Saturate concrete surface and holes

a. If the manufacturer requires a primer, saturate the anchor holes and concrete surface where CFRP sheets will be placed with the primer.
b. Saturate the anchors holes with epoxy.
c. Saturate the concrete surface with epoxy where CFRP sheets will be placed. For dry layup, make sure to provide a generous coating so that it may be worked through the fabric.

Saturation of anchor holes can be done using a brush or a saturated anchor. If an anchor is used for saturation, discard it after saturation and do not install that anchor. The surface is saturated in much the same way that paint is applied.

Step a

Step b

WET LAYUP

9. Saturate CFRP sheets

Repeat for each CFRP strip.

a. Place the strip on a plastic sheet.
b. Apply epoxy liberally using a roller.
c. Flip the CFRP sheet to the other side.
d. Apply epoxy liberally using a roller. Make sure that the sheet is fully saturated with epoxy.

Some manufacturers sell machines to saturate the CFRP strips. In the absence of such machines, this simple procedure can be used.

Steps a and b

10. Apply CFRP strips to the concrete surface

Repeat for all three long strips.

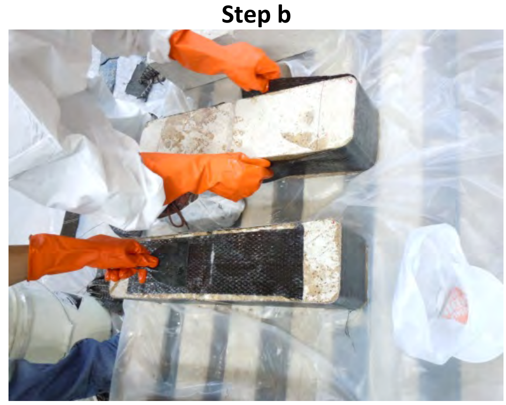
a. Place the CFRP strip in its final location.
b. Using a trowel, remove excess epoxy and air voids from the strip.

This step is one of the most critical in the application process. Inadequate installation of the strips will result in a compromised strength. **The CFRP must be in full contact with the concrete, with no air voids or separations**. **TIP:** Start away from the strip ends and work towards the ends so that air bubbles are pushed out.

The epoxy is typically viscous enough to allow the sheet to stick to the surface without needing to be held on manually.

Step a

Step b



DRY LAYUP

9. and 10. Apply CFRP strips to the concrete surface

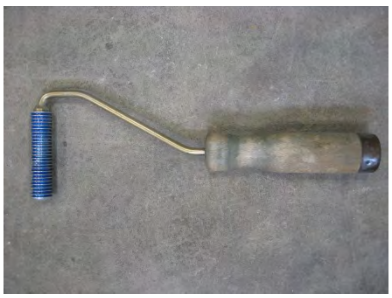
Repeat for all three long strips.

a. Place the CFRP strip in its final location over the epoxy.
b. Work the epoxy with a serrated roller until the epoxy come through the fabric. Make sure to remove all air voids in the process.
c. Apply a second coating of epoxy on the sheet and work into the fabric using the roller. Make sure to remove all air voids in the process.

This step is one of the most critical in the application process. Inadequate installation of the strips will result in a compromised strength. **The CFRP must be in full contact with the concrete, with no air voids or separations**. **TIP:** Start away from the strip ends and work towards the ends so that air bubbles are pushed out.

The epoxy is typically viscous enough to allow the sheet to stick to the surface without needing to be held on manually.

Roller



Step b on an I-girder

ALL APPLICATIONS

11. Install CFRP patches and anchors

Repeat for each anchor.

a. Place a CFRP patch centered at the anchor hole with fibers running perpendicular to the fibers of the strip.

b. Spread the fibers at the hole location to allow for insertion of the anchor.

c. Saturate the anchor with epoxy.

d. Insert the anchor into the hole. Make sure the anchor is inserted through the entire depth of the hole.

e. Fan out the portion of the anchor CFRP that extends beyond the hole towards the center of the beam. Make sure the fan angle is 60° and the fan extends to the edge of a sheet.

f. Cut the rebar tie that held the anchor as close to the surface as possible.

g. Place a CFRP patch centered at the anchor hole with fibers running in the same direction as the fibers of the main strip.

TIP: The best way to spread the fibers is to use a gloved finger.

CAUTION: Do not use sharp objects such as scissors to spread the fibers at anchor hole due to the risk of cutting fibers in the main strip.

Step a

Step b

Step c

Step d

Step e

Step g

12. Apply final coat of epoxy

a. Apply a final coat of epoxy on all CFRP surfaces.

b. Make sure there are no voids or air bubbles between the CFRP sheets and the concrete.

This task is meant to smooth the surface and ensure full saturation of the CFRP with epoxy.

Final Product (with 3” wide side CFRP sheets)