Quality Control Test For Carbon Fiber Reinforced Polymer (CFRP)
Anchors For Rehabilitation

by

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The Thesis committee for Guillermo Huaco
Certifies that this is the approved version of the following thesis:

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APPROVED BY
SUPERVISING COMMITTEE:

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James O. Jirsa, Supervisor

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Oguzhan Bayrak
Dedication

To the memory of my beloved father (†),
who passed away when I started my master studies here.
He always has encouraged me to become a PhD.
His love I always carry with me.

To my beloved mother,
who always believe on my capacities,
and gives me her love and tenderness on my whole life.

To my brother,
for his protection in my childhood

To Karina,
(T.A.K.)
Acknowledgements

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December 3, 2009
Quality Control Test For Carbon Fiber Reinforced Polymer

(CFRP) Anchors For Rehabilitation

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Different strategies can be used to repair, rehabilitate and strengthen existing structures. Techniques based on Fiber Reinforced Polymer (FRP) materials appear to be innovative alternatives to traditional solutions because of their high tensile strength, light, weight, and ease of installation. One of the most common and useful FRPs is Carbon Fiber Reinforced Polymer (CFRP) used in sheets and anchors attached on the concrete surface to strengthen the section through addition of tensile capacity. The purpose of this study was develop a technique for assesses the strength of anchors for quality control purpose.

However, to transfer tensile capacity to a concrete surface, the sheets are bonded to the surface with epoxy adhesive. As tension increase, CFRP sheets lose adherence of the epoxy from the concrete surface and finally debond. To avoid this failure, CFRP anchors are applied in addition at the epoxy. The CFRP anchors allow the CFRP sheets to utilize their full tensile capacity and maximize the material efficiency of the CFRP retrofit. The number and size of anchors play a critical role. However the capacity of CFRP anchors has not been investigated extendedly.
A methodology for assessing the quality of CFRP anchors was developed using plain concrete beams and reinforced externally with CFRP sheets attached with epoxy and CFRP anchors. Applying load to the beam, allowed the development a tensile force in the CFRP sheets and a shear force on the CFRP anchors. The shear forces in the CFRP anchors were defined by the load applied to the beam and compared with forces based on measured stress in CFRP sheets.
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CHAPTER 1
Introduction- Background Information

1.1 INTRODUCTION:

Despite the good tensile performance of Carbon Fiber Reinforced Polymer (CFRP) and the potential for improvement of the capacity of RC retrofitted members, anchorage between CFRP and reinforced concrete (RC) members is a weak link that determines the performance of retrofitted RC members. CFRP sheets debond from the face of reinforced concrete member. The epoxy adhesive used to connect the CFRP sheet with the concrete the strength of the concrete substrate, and the surface preparation (Fig. 1.1) limits the tension force that can be developed in the sheet.

![Figure 1.1 Debonding of CFRP sheet before strength of sheet is reached (Kim 2006)](image_url)

The use of CFRP anchors to avoid delamination of the CFRP sheet is one solution. CFRP anchors allow the CFRP sheets to utilize their full tensile capacity and maximize the material efficiency of the CFRP retrofit (Fig. 1.2). The number and size of anchors must be carefully selected to achieve this result.
1.2 OBJECTIVES:

1. Develop a test specimen to study the variables influencing anchor performance and to use as a quality control technique.

2. Propose specimen size, and materials, based on a standard test for concrete material strength evaluation but modified for this purpose.

1.3 METHODOLOGY:

Perform axial and bending tests of concrete blocks and beams with CFRP sheets attached and CFPR anchors installed. For this purpose, the standard test for flexural strength of concrete, ASTM C 293 – 07 (Fig. 1.3), was chosen. Some modifications were made, such as depth-span ratio.

Figure 1.2 CFRP sheet rupture when anchor used. (Kim 2006).
Table 1.1 Parameters specified in ASTM C293 and proposed modifications for CFRP anchor quality control

As shown in Fig.1.3 the ASTM C293 involves a concrete beam is loaded at midspan. In the modified beam, CFRP sheets and anchors are installed on bottom side of the beam.

The modified beam is proposed for quality control of CFRP anchors, (Fig. 1.4). Based on adjustments to ASTM C293 shown above, a proposal for a procedure to test the shear capacity of CFRP anchors is presented
Figure 1.4 Proposed test for quality control of CFRP anchors.

1.4 CFRP as Material for Rehabilitation:

Different strategies can be pursued in repair, rehabilitation and strengthening of existing structures. Innovative techniques based on Fiber Reinforced Polymer (FRP) materials appear to be promising alternatives to traditional solutions. Composite materials are light and easy to install, their application does change the geometry of the structure. In some cases, it can be installed without interrupting the use of the structure. Installations are shown in Figure 1.5.

The use of CFRP sheets in the construction industry has increased in recent years, especially for seismic retrofit applications
1.4.1 CFRP Anchor

A CFRP anchor is shown in Fig. 1.6. It consists of a small CFRP sheet that is inserted into the concrete and splayed out over the CFRP sheet (Fig. 1.7). Details of an anchor installation are shown in Fig. 1.8.
1.4.2 Debonding

While the high tensile strength of CFRP provides tremendous benefits to strengthen structural elements, lack of sufficient bond between the CFRP and its substrate may pose design challenges because of the potential delamination of CFRP prematurely.
Generally debonding occurs in the support materials that are characterized by a lower tensile strength, bond strength is strictly related to the tensile strength of the support material and to the bond stress distribution at the interfaces, which depends on stiffness of adhesive and fibers. Cracks and irregularities of the surface could represent weak points for bond behavior due to concentration of stresses. (Ceroni 2006)

There are some experiments which have been published, that indicate that the types of load and surface did not affect the values of bond strength (Guimaraes 2007).

1.4.3 Temperature

Temperature may affect the bond properties of the epoxy. Forces developed in CFRP appear to be lower for higher environment temperatures (90-120\(^\circ\)C) and a given external load. High temperature reduced the stiffness of the epoxy, as consequence, the stress in the concrete and the deformation increased. (Klamer 2005). For example, if the structure is an industrial building (foundries), it is necessary to consider the high temperature of the environment for design of retrofit scheme.

1.5 ACI 440 GUIDE FOR DESIGN AND CONSTRUCTION OF EXTERNALLY BONDED FRP SYSTEMS FOR STRENGTHENING CONCRETE STRUCTURES:

ACI 440 provides provisions for the use of FRP materials, including CFRP. However, it has no guidance for CFRP anchors.

The report is divided into 5 parts:
1. General: Scope, notation and definition, background information
2. Materials: Constituent materials and properties
3. Recommended Construction Requirements: shipped, storage and handing; installation, inspection, evaluation, and acceptance; maintenance and repair.
4. Design Recommendations
5. Design examples

Of most interest to this study is the material in parts 2 and 3, especially chapter 5, 6 and 7 of ACI 440.

In chapter 5 of this document, recommendations for construction requirements have been given, such as: shipping to conform to packaging regulations; storage conditions and shelf life, safe storage of the CFRP components need recommendations are also given for handling, use of material safety data sheets, for safe and clean work areas, and handling instructions.

Chapter 6 includes valuable guidance on installation including the following items:
- Contractor competency (must demonstrate experience working with CFRP);
- Environment conditions such as temperature,
- Humidity and moisture considerations, specially on the surface of the concrete.
- Installation in hot and cold environment cases procedures, are discussed considering specifications from the manufacturer; such as “The transmission of moisture vapor from a concrete surface through the uncured resin materials typically appears as surface bubbles and can compromise the bond between the CFRP system and the substrate.”(ACI 440.2R 2008)

Chapter 7 ACI 440 focuses on quality control by inspection and evaluation of all aspects of an application, such as, the ability of the contractor, the quality of the materials (coupons of CFRP sheets tests), compression test of concrete. Currently ACI 440 is developing the quality control guidance for CFRP anchors, especially methods for capacity of CFRP sheets for flexural strengthening. ACI 440 suggests that “the degree of QC and the scope of testing, inspection, and record keeping depends on the size and complexity of the project”(ACI 440.2R 2008).

In Chapter 8 periodical maintenance of the CFRP installed on the structures is discussed. Repair of the CFRP system by damage after installation is covered on this.
Chapter 9 and further chapters give considerations for design, considering the different effects of external loads.

1.6 QUALITY CONTROL

The contractor must demonstrate experience in repair and rehabilitation projects, and where possible, on similar large-scale concrete structures which have to be rehabilitated. The contractor should demonstrate specific knowledge in the use of CFRP materials (sheets and anchors).

![Figure 1.9 Installation of CFRP sheets (Paul 2007)](image)

Quality control for use of CFRP materials begin with the preparation of qualification patches constructed and tested to demonstrate the properties of the materials and the efficiency of the procedures.

Achieving long-term durability requires high quality materials along with the proper installation. Quality control is mandatory for rehabilitation projects. Quality control should begin with the selection of the contractor and materials.
CFRP sheets have a tensile strength of 4000MPa and more than 0.10% strain at rupture. Quality control has to be carried out in accordance with the procedures outline in ACI 440. Tension tests of CFRP sheets must be conducted during the installation process.

To assure high quality installation CFRP sheet, the concrete surface must be properly prepared as ACI 440 suggests. Rounding, correction of all defects, sand blast cleaning (if necessary) must be inspected before CFRP installation. The installation must to be inspected to verify that the epoxy is properly cured to avoid voids between CFRP and concrete.

![Interface bond test](image)

*Figure 1.10 Interface bond test (Paul 2007)*

1.6.1 Quality of implements before installation

Good condition of installation tools is very important for realizing the inherent strength of CFRP materials (Fig. 1.11).
An appropriate procedures for preparing the materials (epoxy and CFRP elements), clean instruments, and time of installation (pot life) to use are issues to considering (Fig. 1.12).

Figure 1.11 Installation tools

Figure 1.12 Preparation of the epoxy

a) Mixing of the epoxy component  
b) Epoxy ready to use.
Poor quality of epoxy (older than expiration date on material) is likely to result in poor performance of the retrofitted section (anchor for/ sheet failure interface failure) as shown Fig. 1.13.

Figure 1.13 Anchor fan debonding
CHAPTER 2

Previous Research

Several research projects to on the behavior of concrete and CFRP sheets have been reported. A brief review of select projects is presented.

2.1 KOBAYASHI ET AL. (2001)

Kobayashi investigated application of CFRP anchors to a CFRP wrapped column with wing walls (Fig. 2.1). Due to wing walls, the CFRP sheet can not be wrapped around the column continuously. The CFRP anchor can provide continuity of semi-closed CFRP sheet through the wing wall. He investigated the stress transfer mechanism of the CFRP anchor and factors that influence the capacity of CFRP anchor. (Kobayashi 2001)

![Figure 2.1 CFRP Anchors for CFRP Wrapping of a Column with Wing Walls](image)

Figure 2.1 CFRP Anchors for CFRP Wrapping of a Column with Wing Walls

(Kobayashi et. al.2001)
Kobayashi (2001) studied the effects of fan angle on the force transfer from CFRP sheet to CFRP anchor as Figure 2.2 shows. He concluded that the angle should be less than 90 degrees in order to achieve good force transition between the sheet and the anchor.

![Figure 2.2 Fan opening angle studied by Kobayashi (Kobayashi 2001).](image)

### 2.2 Ozdemir & Akyuz (2005)

The effect of concrete compressive strength, anchorage diameter and depth, amount of fibers on the tensile strength of CFRP anchors, was studied by Ozdemir and Akyuz (2005). Tensile capacity of the CFRP anchor (Fig. 2.3) increased linearly until the depth reached an effective bond length of 100mm as embedment depth increased. Beyond this length the tensile capacity did not increase.
They concluded that compressive strength of the concrete did not effect the tensile capacity of the CFRP anchor if its embedment depth was less than 50mm. However, the effect of concrete compressive strength became more important as embedment depth increased.

### 2.3 Kim (2008)

Tests of beams using different types of anchorage, carried out by Kim are summarized in Table 2.1

The behavior of the different anchors is shown in Fig.2.4. The strength and deformation capacity increased as anchorage improved. The CFRP sheet developed its full tensile capacity with a combination of CFRP anchors and U-wraps. The force and displacement increased more than 100% over the beam without anchors.
### Figure 2.4 Load-Deflection Relationships (Kim 2007)

![Graph showing load-deflection relationships for different types of anchorage.](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Configuration of CFRP Materials</th>
<th>Number of Layers of CFRP Sheet</th>
<th>Type of Anchorage</th>
<th>Failure Mode</th>
<th>Maximum Applied Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 layer None Delamination of CFRP sheet</td>
<td>1 layer</td>
<td>None</td>
<td>Delamination of CFRP sheet</td>
<td>14.57 kip</td>
</tr>
<tr>
<td>2</td>
<td>2 layers CFRP U-wrap Delamination of CFRP U-wrap</td>
<td>2 layers</td>
<td>CFRP U-wrap</td>
<td>Delamination of CFRP U-wrap</td>
<td>15.38 kip</td>
</tr>
<tr>
<td>3</td>
<td>2 layers CFRP Anchor Concrete Failure around Anchor Holes</td>
<td>2 layers</td>
<td>CFRP Anchor</td>
<td>Concrete Failure around Anchor Holes</td>
<td>25.78 kip</td>
</tr>
<tr>
<td>4</td>
<td>2 layers CFRP Anchor &amp; CFRP U-wrap Fracture of CFRP Sheet</td>
<td>2 layers</td>
<td>CFRP Anchor &amp; CFRP U-wrap</td>
<td>Fracture of CFRP Sheet</td>
<td>31.94 kip</td>
</tr>
</tbody>
</table>

*Location of the anchors and U-wraps are the same as specimen No. 2 and No. 3.

### Table 2.1 Characteristics of type of anchorage on Beams (Kim 2008)
Kim (Kim 2008) studied methods for strengthening lap splices in square and rectangular reinforced concrete columns using combinations of CFRP jackets and CFRP anchors for structures damaged by earthquakes. Three square columns (460 mm x 460 mm x 2970 mm) and one rectangular column (460 mm x 910 mm x 2970 mm) column were fabricated and rehabilitated using CFRP jackets only or by a combination of CFRP jackets and CFRP anchors. Both damaged and undamaged columns were strengthened and tested.

---

Figure 2.5 Column tested by Static Cyclic Forces. (Kim 2008).

Figure 2.5 shows a column that has been retrofitted using CFRP jackets. There are CFRP anchors on two opposites faces of the rectangular section of column. Two Cyclic Static tests have been performed to the column, in two different directions; one where one side of column, which doesn’t have any anchor, make to work the CFRP sheets; and the other direction, where CFRP anchors worked.
Figure 2.6 Results of Column tested by Static Cyclic Forces. It is noticed that Side retrofitted with CFRP anchor has more capacity (Kim 2008).

Figure 2.7 Column tested by Static Cyclic Forces. Side without anchor used (left) and using anchor (right)(Kim 2008)

CFRP Anchors coupled with CFRP sheets to resulted in the splices reaching higher capacity. The number and size of anchors played a critical role (Fig. 2.6 and 2.7).
Including CFRP anchors, improved the deformation capacity of displacement increase. Columns as indicated on Fig. 2.8.

Figure 2.8 Results of Column tested by Static Cyclic Forces. It is noticed that Side retrofitted with 16 CFRP anchors has more capacity (Kim 2008)

2.4 ORTON (2008)

Orton tested concrete blocks joined with CFRP materials (sheets, U wraps and anchors shown in Fig. 2.9) The tests consisted of two rectangular blocks of concrete connected only by a CFRP sheet. The connected blocks were loaded as a simple beam with a point load at midspan, thereby putting tension in the CFRP sheet. The blocks were either of the same height (to simulate providing continuity through the negative moment
reinforcement) or had a height difference (to simulate providing continuity of the positive moment reinforcement through a beam-column joint).

Orton found that unanchored CFRP sheets utilized less than 40% of their tensile capacity before debonding (Fig. 2.10). U-wraps allowed the CFRP sheet to reach its full tensile capacity, but required much greater amounts of material when the anchors were used (Fig. 2.11). CFRP anchors allowed the CFRP sheet to reach its full tensile capacity. Finally, a greater number of smaller and more closely spaced anchors were found to be more effective, and each of several rows of anchors was effective in transferring tensile forces into the concrete.(Orton 2007)

![Figure 2.9 Results of tests by Orton (Orton 2007)](image_url)
<table>
<thead>
<tr>
<th>Test #</th>
<th>Slope height difference</th>
<th>Type of Fabric</th>
<th>Anchorage</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
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<td>none</td>
<td>SCH-35</td>
<td>none</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-ns1</td>
<td>none</td>
<td>SCH-35</td>
<td>none</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-us1</td>
<td>none</td>
<td>SCH-35</td>
<td>U wraps 6&quot; wide at 5&quot; and 19&quot;</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-us2</td>
<td>none</td>
<td>SCH-35</td>
<td>Double U wrap 6&quot; wide at 5&quot; and 19&quot;</td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-2s1</td>
<td>none</td>
<td>SCH-35</td>
<td>2 3/8&quot; anchor at 3&quot;</td>
<td><img src="image5.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-2s2</td>
<td>none</td>
<td>SCH-35 sheet SCH-41 anchors</td>
<td>5/8&quot; anchor at 5&quot; and 19&quot;</td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-4g1</td>
<td>none</td>
<td>SCH-35</td>
<td>2 3/8&quot; anchor at 3&quot; and 6&quot;</td>
<td><img src="image7.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-4s1</td>
<td>none</td>
<td>SCH-35</td>
<td>2 3/8&quot; anchor at 5&quot; and 19&quot;</td>
<td><img src="image8.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-4s2</td>
<td>none</td>
<td>SCH-35 sheet SCH-41 anchors</td>
<td>Two 1/2&quot; anchors at 5&quot; and 19&quot;</td>
<td><img src="image9.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-4s3</td>
<td>none</td>
<td>SCH-35 sheet SCH-41 anchors</td>
<td>2 3/16&quot; anchors at 5&quot; and 19&quot;</td>
<td><img src="image10.png" alt="Diagram" /></td>
</tr>
<tr>
<td>00-6s1</td>
<td>none</td>
<td>SCH-35</td>
<td>3 3/8&quot; anchors at 5&quot; and 19&quot;</td>
<td><img src="image11.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 2.10 Beam with the CFRP sheets installed.**

**Figure 2.11 Types of reinforced by CFRP sheet used (Orton 2008)**

Orton presented simple design recommendations for the use of CFRP sheets to provide continuity to reinforced concrete beams.
2.5 **LE PHAM 2009**

Pham (Kim 2008) studied the importance and relevance of the effects of bend radius on performance of CFRP anchors, using 6 beams as proposed earlier for quality control of CFRP anchors. Pham found that the capacity of an anchor increased when the fillet radius increased. He also recommended more tests on anchor hole geometry.

2.6 **JSCE (1997)**

Japanese Society of Civil Engineers (JSCE) research committee (1997) provide the following equation to estimate the reduction in capacity of CFRP elements due to a bend.

\[
\frac{f_a}{f_u} = 0.09 \frac{r}{d} + 0.3
\]

Here \(f_a\) is the stress capacity of the bent CFRP element, \(f_u\) is the ultimate capacity of the straight element, \(r\) is the radius of the bend, and \(d\) is diameter of the element. According to this equation, a 0.5-in anchor with 0.5-in bend radius will have 39% of the capacity of a straight element.
CHAPTER 3
Experimental Program

3.1 **PROJECT OVERVIEW:**

Kim (2008) recommended tests using concrete beams for quality control tests of CFRP sheets. The beams had CFRP sheets attached on their bottom face. A flexural test is conducted by applying a midspan load on the beam.

To find a reliable methodology for the quality control of CFRP anchors, six sets of specimens were developed and tested. Each set of beams was designed using the results and behavior of the previous set. In each set, a different parameter was varied; strength of the concrete, internal reinforcement, type of connection and condition of the epoxy.

3.2 **FEATURES OF SPECIMENS AND TEST SETUP:**

3.2.1 **Specimen Size**

Pham (2009) studied the effect of specimen size, on previous research. His results were used to define the test in this study as shown in Fig. 3.1

The width of CFRP sheets used in the tests varied from 1.2 to 4 inches. The length of CFRP sheet was selected so that the sheet extended 2 in beyond the center of the anchor holes.
Figure 3.1 Selection of width and length of CFRP strengthening sheets.

To produce failure by fracture of the CFRP sheets, the width of the strips used to make anchors was varied. Pham (2009), based his tests on data from tests of the same type of CFRP anchors tested by Kim (2008). The widths of the CFRP anchors used in this study were 130% to 150% of the width of the CFRP strengthening sheet used by Pham (Pham 2009). For the last set, the widths of CFRP anchors have been reduced to find the anchor shear failure. The length of the anchor was equal to the depth of the hole plus the fan length plus 0.5 in. The CFRP anchor consists of a CFRP sheet folded as shown in Fig. 3.2.

A CFRP anchor width of 0.6in means: one strip folded to provide two layers of 0.6in width each. (2 x 0.6 in)
The fan should be good enough to ensure sufficient bond area between the anchor and the strengthening sheet. Pham (2009) concluded that the fan angle affected the force transfer from the CFRP to the anchor.

Patches were used on the anchors of beams. The patches consist of small CFRP sheets which cover the CFRP anchor as shown in Fig. 3.2b. Fig. 3.2b shows the location of the patch. The dimension of the patches were based on the width of CFRP sheet being anchored.

![Figure 3.2 Strip of CFRP anchor before installation (a) and patch over the CFRP anchor (b).](image)

3.2.2 Test Setup and Procedure

All the tests were performed on a universal compression machine. The beam is supported by roller and pin as shown in Fig. 3.3. A roller was placed to transmit the
applied load to the beam. Steel plates were attached to the surface of the concrete at support and load locations in some tests. Deflection at the beam midspan was measured. Strain gages were used applied to the CFRP sheets.

The load was slowly increased. Although deformation control is preferable, the specimen was quite stiff and displacement was very sensitive to small changes in load.

The testing machine had two settings. First, increase load was monitored so that any decrease in load was not recorded. Second, the machine measured both increasing and decreasing the loads under cyclic loading.

Figure 3.3 Specimen in test machine.
3.3 **Test Program:**

3.3.1 Set 1

3.3.1.1 *Features of specimens*

Set 1 was tested by Pham (2009) following recommendations of Kim (2008). Pham (2009) begin to make specimens similar to those of ASTM C293. Pham proposed preliminary sizes of beams and CFRP sheets for those tests, as shown in Fig. 3.4. The specimens on Set 1 had preformed or drilled holes. He also found that the fillet on the holes was a critical parameter for connections using CFRP anchors (Set 2), even when failure was initiated by shear. (Pham 2009) To delay premature shear failure in the test, transverse reinforcement in the form of wire mesh was placed in the beam at the location of the anchor holes.

The principal features of this set are:

- No steel plates between load or support rollers. Concrete beam was in direct contact with steel rod supports and point of loading.

- No patch on the CFRP anchor applied

- Preformed holes (for CFRP anchors).

Table 3.1 contains details of the specimens in Set 1.
For all the specimens on Set 1, the test machine measured increasing load only as indicated by the flat curves at deflections between 0.03 and 0.07 in. Therefore, the response of the beams shows only increasing loads (Fig. 3.5). The specimens exhibited elastic behavior up to about 8 kips load. The strength of concrete was the same for all the
specimens. Specimen S1-2.5-2x3.5-0.625-4-0.25, which had more CFRP material than others, also has the biggest capacity (13.84kips).

Figure 3.5 Load-Deflection response of Set 1 specimens

Table 3.2 Capacity of Set 1 specimens

<table>
<thead>
<tr>
<th>SET 1</th>
<th>Specimen</th>
<th>Strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Initial cracking of concrete</td>
<td>Failure</td>
</tr>
<tr>
<td>f'c=4.8ksi</td>
<td>S1-2-2 x 3-0.625-4-0.25</td>
<td>no gage</td>
<td>7.81</td>
<td>10.83</td>
</tr>
<tr>
<td></td>
<td>S1-2-2 x 3-0.5-4-0.25 a</td>
<td>no gage</td>
<td>7.75</td>
<td>11.04</td>
</tr>
<tr>
<td></td>
<td>S1-2-2 x 3-0.5-4-0.25 b</td>
<td>no gage</td>
<td>9.49</td>
<td>12.42</td>
</tr>
<tr>
<td></td>
<td>S1-2.25-2 x 3-0.625-4-0.25</td>
<td>no gage</td>
<td>8.43</td>
<td>10.31</td>
</tr>
<tr>
<td></td>
<td>S1-2-2 x 3-0.5-4-0.25</td>
<td>no gage</td>
<td>8.13</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td>S1-2.5-2 x 3.5-0.625-4-0.25</td>
<td>no gage</td>
<td>7.90</td>
<td>13.84</td>
</tr>
</tbody>
</table>

Pham (2009) observed; anchor failure in two tests. First cracking occurred at loads less than 8 kips, however the force at ultimate capacity ranged from 11 to 14 kips.
3.3.2 Set 2

3.3.2.1 Features of specimens

- No steel plates used at bearing areas. Concrete beam in direct contact with steel pin of supports and at point of load application.

- No patch on the CFRP anchor applied.

- Objective was influence of fillet as shown in Fig 3.6.

Figure 3.6 Sketch of the specimens and setup for Set 2

Table 3.3 contains details of the 6 tests in Set 2.
The test machine was set to measure cyclic loads. So the lath decreasing and increasing loads could be recorded as shown in Fig. 3.7. For S2-2.66-2x2.22-0.5-4-0a, the initial portion of load deflection curve was lost. When the beam cracks, there is a drop in the load as the tension force is transferred from the concrete to the CFRP sheet. The highest load was carried by specimen S2-2.66-2x2.22-0.5-4-0.5b which had the 0.5 in fillet radius. (Table 3.4)
Figure 3.7 Load-deflection response of Set 2 specimens.

Table 3.4 Capacity of Set 2 specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0 a</td>
<td>no gage</td>
<td>4.70</td>
<td>8.96</td>
</tr>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0 b</td>
<td>no gage</td>
<td>-</td>
<td>8.97</td>
</tr>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0.25 a</td>
<td>no gage</td>
<td>5.59</td>
<td>10.42</td>
</tr>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0.25 b</td>
<td>no gage</td>
<td>6.97</td>
<td>10.71</td>
</tr>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0.5 a</td>
<td>no gage</td>
<td>6.39</td>
<td>10.82</td>
</tr>
<tr>
<td>S2-2.66-2 x 2.22-0.5-4-0.5 b</td>
<td>no gage</td>
<td>7.09</td>
<td>11.23</td>
</tr>
</tbody>
</table>
3.3.3 Set 3

3.3.3.1 *Features of specimens*

- Contaminated epoxy
- No patch on the CFRP anchor applied
- Use of steel plates at supports point of loading.
- Constant fillet radius of $\frac{1}{2}$”
- High compression strength of concrete: $f'c = 11.4$ ksi. To avoid shear failure that was observed in Set 1 and 2, high concrete strength (11.4ksi) was used with no internal mesh.

The specimen is shown in Fig.3.8 and details of the three tests of Set 3 are given in Table 3.5. Load-deflection response is shown in Fig.3.9 and CFRP strains are plotted against load in Fig.3.10.
Figure 3.8 Sketch of the Set 3 specimens.

Table 3.5 Properties of the Set 3 specimens

<table>
<thead>
<tr>
<th>SET 3</th>
<th>SPECIMEN</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC=11.4ksi epoxy contaminated condition</td>
<td>S3-2-2 x 4-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 4</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>S3-3-2 x 6-0.5-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>3</td>
<td>2 x 6</td>
<td>0.5</td>
<td>4</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>S3-4-2 x 8-0.75-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>4</td>
<td>2 x 8</td>
<td>0.75</td>
<td>4</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.9 Load-deformation response of Set 3 specimens

Figure 3.10 Strain behavior of CFRP sheet
Table 3.6 Capacity of Set 3 specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33-2 x 4-0.25-4-0.25</td>
<td>0.0063</td>
<td>7.22</td>
<td>Anchor debonding</td>
</tr>
<tr>
<td>33-3 x 6-0.5-4-0.25</td>
<td>0.0055</td>
<td>7.52</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>33-4 x 8-0.75-4-0.25</td>
<td>0.0043</td>
<td>9.71</td>
<td>Concrete shear failure</td>
</tr>
</tbody>
</table>

Three different widths of CFRP sheets and anchors were used. However the epoxy was contaminated and it was found that the shelf life had been exceeded. As a result, the quality of the bond between the CFRP sheet and the concrete surface was reduced and failures by debonding were observed.

The maximum strain observed was 0.6%, less than 0.8% average from CFRP coupon tests (see Appendix 1), and less than 1% as indicated in manufactures specifications. The failures present were anchor debonding or shear at concrete as indicated in Table 3.6. The CFRP sheets did not fracture.

Specimen S3-4-2 x 8-0.75-4-0.25, which had more CFRP material installed, then the other, should have had the biggest failure load than the others, as shows at Fig.3.9, debonding of the anchor (Fig.3.10) occurred before the capacity of the CFRP was reached.

Figure 3.11 Bad performance of the epoxy. Anchor fan debonded.
3.3.4 Set 4

Considering the influence of the epoxy condition, new epoxy was used for the beams of Set 4. This set had the same features for comparison with results Set 3. Installation of the CFRP materials was supervised by a commercial FRP installer, who suggested adding patches of CFRP over the anchor. Some patches were applied to the anchor that were already installed.

The specimens in Set 4 are divided into 2 groups: (A) repeat of set 3 with new epoxy materials, (B) same as (A) but with a groove cut into the beam to create a failure plane at the midspan.

3.3.4.1 Set 4 A

Set B specimens are shown in Fig. 3.11 and details are provided in Table 3.2.

Figure 3.12 Sketch of the Set 4A specimens
Table 3.7 Properties of Set 4A specimens

<table>
<thead>
<tr>
<th>SET 4 A</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>new epoxy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4A-2-2 x 4-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 4</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>S4A-3-2 x 6-0.5-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>3</td>
<td>2 x 6</td>
<td>0.5</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>S4A-4-2 x 8-0.75-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>4</td>
<td>2 x 8</td>
<td>0.75</td>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Load-deflection and load-strain relationships are plotted in Figs. 3.13 and 3.14.

Figure 3.13 Load deformation response of Set 4A specimens
The setup of the test machine was calibrated to measure increasing load on the specimens with 2 and 4 in width of CFRP sheets and results in the plot curves shown.

As with Set3 results, specimen with more CFRP material (S4A 4-2x8-0.75-4-0.25) had more capacity (Fig 3.12).

CFRP fracture was observed for 2in wide sheet (strain at failure was 1%, more than 0.8% from coupon tests – see appendix 1); shear failure occurred in the other two specimens (0.5% strain in the CFRP sheet). For specimens with bigger CFRP sheet width, the type of failure was shear concrete failure, value of maximum strain were lower than 0.8%. Elastic behavior force was at most 10.48kips, and at failure 13.78kips. A summary of the results is provided in Table 3.8 and failure are shown in Figs 3.15 and 3.16.

Figure 3.14 Beam load-strain behavior of CFRP sheet
Table 3.8 Capacity of Set 4 A specimens

<table>
<thead>
<tr>
<th>SET 4A</th>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>new epoxy</td>
<td>S4A-2 x 4-0.25</td>
<td>0.0101</td>
<td>8.67</td>
<td>11.34 CFRP sheet fracture</td>
</tr>
<tr>
<td></td>
<td>S4A-3 x 6-0.5</td>
<td>0.0048</td>
<td></td>
<td>11.34 Concrete shear failure</td>
</tr>
<tr>
<td></td>
<td>S4A-4 x 8-0.75</td>
<td>0.0049 0.0049</td>
<td>10.48 13.78</td>
<td>Concrete shear failure</td>
</tr>
</tbody>
</table>

**Figure 3.15** 2in wide CFRP sheet fracture.

**Figure 3.16** Shear failure in concrete (Set 4A)
3.3.4.2 Set 4B

The specimens in set 4B (Table 3.9) include a 3in deep cut at midspan as shown in Fig. 3.17. A transverse cut at the midspan (width 0.02in) was added prior to testing to lower the cracking moment. New epoxy also was used.

**Table 3.9 Properties of Set 4B specimens**

<table>
<thead>
<tr>
<th>SET 4 B</th>
<th>SPECIMEN</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td>S4B-2-2 x 4-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 4</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>S4B-3-2 x 6-0.5-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>3</td>
<td>2 x 6</td>
<td>0.5</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>S4B-4-2 x 8-0.75-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>4</td>
<td>2 x 8</td>
<td>0.75</td>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 3.17 Sketch of Set 4B specimens

Load-deflection and load-strain relationships are plotted in Fig.3.18 and Fig.3.19.

41
Figure 3.18  Load-deformation response of specimens

Figure 3.19  Beam load-strain behavior of CFRP sheet
Maximum values of strain presented are less than 0.8% (ultimate average strain from coupon test). The predominant failure was shear in concrete.

The response is largely nonlinear, without pronounced charge in stiffness. The section cracked under very load because of the transverse cut at midspan. The maximum shear capacity of the section was 17.12kips. (Table 3.10) (Fig.3.19).

Although shear failure of the concrete occurred, one specimen failed at load of 17.2kips
3.3.5 Set 5

For Set 5 two groups of specimens were tested: group A had 2in wide CFRP sheets and anchor widths were made using 3, 2 and 1in wide sheets; group B had 1.2 in wide CFRP sheets and anchor widths of 3, 2 and 1in.

To avoid shear failure in the concrete the CFRP sheet widths were reduced in Set5.

3.3.5.1 Set 5 A

- CFRP Sheet: 2in
- CFRP anchor width 3, 2, 1 in
- $f'_{c} = 11.4$ ksi

Set 5A specimens are shown in Fig. 3.20 and details are given Table. 3.11

Figure 3.21 Sketch of the Set 5A specimens
Table 3.11 Sketch of Set 5A specimens

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSA-2-2 x 3-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 3</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>SSA-2-2 x 2-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 2</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
<tr>
<td>SSA-2-2 x 1-0.25-4-0.25</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 1</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Load displacement and load-strain curves are plotted in Fig.3.22 and Fig.3.23. As before, there was a sharp drop in the curves when the concrete cracked in flexure.

Figure 3.22 Load-deflection of Set 5A
Fracture of CFRP sheets was observed in 2 of 3 tests. No fracture of anchors occurred. One specimen failed in shear as indicated in Table 3.12. maximum beam load was 12.99 kips. For a specimen with a 2 in anchor, the load reached 13 kips. With a 3 in anchor width, the CFRP sheet ruptured at a strain of 1.3% while a 1 in wide anchor fractured at 0.8% strain. The appearance on specimen with sheet fracture is shown in Fig. 3.23.

Table 3.12 Capacity of the specimens Set 5 A

<table>
<thead>
<tr>
<th>SET 5 A</th>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIFFERENT ANCHOR SIZES</td>
<td>SSA-2-2 x 3-0.25-4-0.25</td>
<td>0.0130</td>
<td>8.23</td>
<td>9.34</td>
</tr>
<tr>
<td>SSA-2-2 x 2-0.25-4-0.25</td>
<td>0.0091</td>
<td>9.23</td>
<td>12.99</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>SSA-2-2 x 1-0.25-4-0.25</td>
<td>0.0080</td>
<td>8.69</td>
<td>11.46</td>
<td>CFRP sheet fracture</td>
</tr>
</tbody>
</table>
3.3.5.2  **Set 5 B**

- CFRP Sheet: 1.2in
- CFRP anchor width 3, 2, 1 in
- $f_c = 11.4$ ksi

Details of the specimens in Set 5B are given in fig. 3.25 and Table 3.13
Figure 3.25 Sketch of the Set 5B specimens

Table 3.13 Properties of Set 5B specimens

<table>
<thead>
<tr>
<th>SET 5B</th>
<th>SPECIMEN</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIFFERENT ANCHOR SIZES</td>
<td>5SB-1.2-2 x 3-0.375-4-0.375</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>1.2</td>
<td>2 x 3</td>
<td>0.375</td>
<td>4</td>
<td>0.375</td>
</tr>
<tr>
<td>5SB-1.2-2 x 2-0.375-4-0.375</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>1.2</td>
<td>2 x 2</td>
<td>0.375</td>
<td>4</td>
<td>0.375</td>
<td></td>
</tr>
<tr>
<td>5SB-1.2-2 x 1-0.375-4-0.375</td>
<td>8</td>
<td>No</td>
<td>Drilled</td>
<td>Yes</td>
<td>1.2</td>
<td>2 x 1</td>
<td>0.375</td>
<td>4</td>
<td>0.375</td>
<td></td>
</tr>
</tbody>
</table>

Load-displacement and load-strain curves are shown in Fig. 3.26 and Fig. 3.27.
Figure 3.26  Load-deformation response of specimens

Figure 3.27  Beam load-strain behavior of CFRP sheet
Fracture of the CFRP sheets (flexural failure) occurred in all the specimens (Table 3.14). No anchor fracture occurred. There was debonding of CFRP sheets near midspan (Fig. 3.28). The maximum beam load presented was 7.37 kips. An interesting observation was the low strain at failure (0.53%) in two tests with wide anchors. This may indicate that the CFRP anchors have an influence on the CFRP sheets behavior.

<table>
<thead>
<tr>
<th>SET 5B</th>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f’c=11.4ksi</td>
<td>S5B-1.2x2 x 3-0.375-4-0.375</td>
<td>0.0053</td>
<td>8.97</td>
<td>7.37</td>
</tr>
<tr>
<td></td>
<td>S5B-1.2x2 x 2-0.375-4-0.375</td>
<td>0.0055</td>
<td>8.26</td>
<td>5.64</td>
</tr>
<tr>
<td></td>
<td>S5B-1.2x2 x 1-0.375-4-0.375</td>
<td>0.0120</td>
<td>8.12</td>
<td>6.06</td>
</tr>
</tbody>
</table>

Figure 3.28 CFRP sheet failure with debonding near midspan
3.3.6  Set 6

Adjustments were made to the specimens in order to produce failure in the CFRP anchors. Previous results showed that some of the CFRP anchors fractured. For Set 6 specimens, the width of CFRP sheets was 2in and the width of for CFRP anchors was less than 1in. so that anchor failure would occur before the concrete failed in shear or the CFRP sheet ruptured. Additionally half of Set 6 specimens had plastic wrap between concrete surface and CFRP sheets. The purpose of the plastic wrap was to prevent any transfer of force by adhesive bond. The entire tensile force in the CFRP sheets was carried by the CFRP anchors.

3.3.6.1  Set 6 A

- CFRP Sheet: 2in
- CFRP anchor 0.8 in (CFRP sheet’s width)
- Plastic WRAP used in one of the specimens.
- $f'c=11.4\text{ksi}$

Details of the specimen with with plastic wrap one show in Fig.3.29. Load-displacement and load-strain curves are shown in Fig. 3.30 and Fig.3.31. Maximum loads are strain are shown in Table 3.16.

<table>
<thead>
<tr>
<th>Table 3.15 Properties of Set 6 A specimens.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SET 6</td>
</tr>
<tr>
<td>f'c=11.4ksi</td>
</tr>
<tr>
<td>No plastic WRAP</td>
</tr>
<tr>
<td>Plastic WRAP</td>
</tr>
</tbody>
</table>
Figure 3.29 Sketch of specimens using plastic wrap

Figure 3.30 Load-deformation behavior of Set6A specimens
The response of both tests are similar. Plastic wrap does not have an important influence on the capacity of the system. The strains, at anchor failure were quite different even though the loads were the same. The maximum strain values measured were less than 1% (ultimate strain value given by manufacturer). Since the sheets did not rupture, in a short narrow strip of CFRP strain measurements may not be very accurate because its eccentricities that develop debonding of the CFRP occur.
In both cases anchor failure was observed at nearly the same beam load. The results indicate that plastic wrap was not needed to ensure that all the force was transferred to the anchor. Without the plastic wrap, debonding occurred and created the same condition.

Anchor failures are shown in Fig.3.32 and Fig.3.33.

Figure 3.32  CFRP anchor fracture. With no plastic wrap

Figure 3.33  CFRP anchor fracture. With plastic wrap
3.3.6.2 Set 6B

- CFRP Sheet: 2in
- CFRP anchor 0.6 in (CFRP sheet’s width)
- Plastic WRAP used in one of the specimens.
- \( f'c = 11.4\text{ksi} \)

Details of the tests in Set 6B are given in Fig. 3.34 and Table 3.17.

**Table 3.17 Properties of Set 6 B specimens**

<table>
<thead>
<tr>
<th>SET 6 B</th>
<th>SPECIMEN</th>
<th>Width, in</th>
<th>Wire mesh</th>
<th>Holes</th>
<th>Bearing plates</th>
<th>Width of FRP sheets, in</th>
<th>CFRP Anchor width, in</th>
<th>Hole diameter, in</th>
<th>Embedment depth, in</th>
<th>Fillet radius, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>No plastic WRAP</td>
<td>S6A-2</td>
<td>8</td>
<td>No Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 0.6</td>
<td>0.375</td>
<td>4</td>
<td>0.375</td>
<td></td>
</tr>
<tr>
<td>Plastic WRAP</td>
<td>S6B-2</td>
<td>8</td>
<td>No Drilled</td>
<td>Yes</td>
<td>2</td>
<td>2 x 0.6</td>
<td>0.375</td>
<td>4</td>
<td>0.375</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3.34 Sketch of specimens, using plastic wrap](image)

55
Load-deflection and load-strain curves are plotted in Fig.3.35 and Fig. 3.36. Strains and loads at failure are presented in Table 3.18.

**Figure 3.35 Load deformation response of specimens**

**Figure 3.36 Beam load-strain behavior of CFRP sheet**
Table 3.18  Capacity of Set 6 B specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6A-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0056</td>
<td>7.32</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0058</td>
<td>8.34</td>
<td>Anchor failure</td>
</tr>
</tbody>
</table>

Similar to Set 6A, anchor failures were observed. There is little difference in loads at failure, once again indicating that plastic wrap was not important for achieving anchor failure of the 2 x 0.6in width of CFRP anchor. The maximum strain measured was close to 0.6% and was less than 0.8% average ultimate strain from coupon tests.

The appearance of the specimen after fracture is shown in Fig.3.37 and Fig.3.38. All four tests in Set 6 at failure are shown in Fig. 3.39.

Curves of load-deflection response are quite different. Plastic wrap may influence the specimen behavior. This has one pick, which it is the load at initial cracking of concrete. For the other specimen without plastic wrap, the behavior was similar to previous set specimens.

![View of anchor](image1.jpg)  ![View of CFRP sheet](image2.jpg)

Figure 3.37  CFRP anchor fracture. With no plastic wrap
Figure 3.38 CFRP anchor fracture. With plastic wrap

Figure 3.39 The failure of all Set 6 tests was by fracture of CFRP anchors

A summary of all tests is given in Table 3.19.
Table 3.19 Summary of results

(*) SET 1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Initial cracking of concrete</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1-2-2 x 3.0-625-4-0.25</td>
<td>no gage</td>
<td>7.81</td>
<td>10.83</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>S1-2-2 x 3.0-5-4-0.25 a</td>
<td>no gage</td>
<td>7.75</td>
<td>11.04</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S1-2-2 x 3.0-5-4-0.25 b</td>
<td>no gage</td>
<td>9.49</td>
<td>12.42</td>
<td>Shear failure</td>
</tr>
<tr>
<td>S1-2.25-2 x 3.0-625-4-0.25</td>
<td>no gage</td>
<td>8.43</td>
<td>10.31</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>No internal reinf.</td>
<td>S1-2-2 x 3.0-5-4-0.25</td>
<td>no gage</td>
<td>8.13</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td>S1-2-2 x 3.5-625-4-0.25</td>
<td>no gage</td>
<td>7.90</td>
<td>13.84</td>
</tr>
</tbody>
</table>

(/**) SET 3

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Initial cracking of concrete</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1-2-2 x 4-0.25-4-0.25</td>
<td>0.0063</td>
<td>7.22</td>
<td>11.8</td>
<td>Anchor debonding</td>
</tr>
<tr>
<td>S3-3-2 x 6-0.5-4-0.25</td>
<td>0.0055</td>
<td>7.52</td>
<td>14.24</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>S3-4-2 x 8-0.75-4-0.25</td>
<td>0.0043</td>
<td>9.71</td>
<td>13.43</td>
<td>Concrete shear failure</td>
</tr>
</tbody>
</table>

(*** SET 4

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Initial cracking of concrete</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4A-2-2 x 4-0.25-4-0.25</td>
<td>0.0101</td>
<td>8.67</td>
<td>11.34</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S4A-3-2 x 6-0.5-4-0.25</td>
<td>0.0048</td>
<td>8.81</td>
<td>11.34</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>S4A-4-2 x 8-0.75-4-0.25</td>
<td>0.0049 0.0049</td>
<td>10.48</td>
<td>13.78</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>S4B-4-2 x 8-0.75-4-0.25</td>
<td>0.0062 0.0054</td>
<td>8.40</td>
<td>17.12</td>
<td>Concrete shear failure</td>
</tr>
</tbody>
</table>

(*** SET 5

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Initial cracking of concrete</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5A-2-2 x 3-0.25-4-0.25</td>
<td>0.0130</td>
<td>8.23</td>
<td>9.34</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S5A-2-2 x 2-0.25-4-0.25</td>
<td>0.0091</td>
<td>9.23</td>
<td>12.99</td>
<td>Concrete shear failure</td>
</tr>
<tr>
<td>S5A-2-2 x 1-0.25-4-0.25</td>
<td>0.0080</td>
<td>8.69</td>
<td>11.46</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S5B-1-2-2 x 3-0.375-4-0.375</td>
<td>0.0053</td>
<td>8.97</td>
<td>7.27</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S5B-1-2-2 x 2-0.375-4-0.375</td>
<td>0.0055</td>
<td>8.26</td>
<td>5.64</td>
<td>CFRP sheet fracture</td>
</tr>
<tr>
<td>S5B-1-2-2 x 1-0.375-4-0.375</td>
<td>0.0120</td>
<td>8.12</td>
<td>6.06</td>
<td>CFRP sheet fracture</td>
</tr>
</tbody>
</table>

(*** SET 6

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Max. strain in CFRP (in/in)</th>
<th>Beam load (kips)</th>
<th>Initial cracking of concrete</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>f'c=11.4ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S6A-2-2 x 8-0.375-4-0.375</td>
<td>0.0084</td>
<td>7.61</td>
<td>9.83</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>S6B-2-2 x 8-0.375-4-0.375</td>
<td>0.0053</td>
<td>7.18</td>
<td>8.25</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>S6A-2-2 x 0.6-375-4-0.375</td>
<td>0.0056</td>
<td>7.32</td>
<td>9.06</td>
<td>Anchor failure</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-375-4-0.375</td>
<td>0.0058</td>
<td>8.34</td>
<td>7.17</td>
<td>Anchor failure</td>
</tr>
</tbody>
</table>

(*/*)Performed by Pham (2008)
(/**)Performed by Pham and Guillermo Huaco (2009)
(***)Performed by Guillermo Huaco (2009)
CHAPTER 4
Calculation of Shear Force on CFRP Anchor

4.1 Evaluation of Case with Plastic Wrap

For the beam shown in Fig. 5.1, the forces transferred to the anchor can be determined from the measured CFRP strain and compared with the force computed using measured beam loads.

![Figure 4.1 Beam used in calculations](image)

4.2 Force from StrainMeasured on CFRP Sheet

Two values of elastic modulus of the CFRP were used: (E manufacturer = 13900ksi) and by the results of coupon tests (E test = 11400ksi). (see appendix 1)
Formulation:
Ultimate strain at failure of CFRP anchor $\varepsilon$:
$\varepsilon \times E$ (young modulus of CFRP) = Stress in CFRP sheet = $\sigma$
$\sigma \times A$ (area of CFRP Sheet) = Tension force on CFRP sheet (considering linear behavior of CFRP sheets, as coupons shows)
Tension force transmitted force to anchor
Shear Force CFRP anchor = Tension force on CFRP sheet
Then: (from CFRP sheet properties)
$\varepsilon \times E \times $ Area CFRP sheet = Shear Force CFRP anchor

Table 4.1 Shear force on anchors calculated using $E$ manufacturer

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>MAX. STRAIN MEASURED (in/in)</th>
<th>STRESS CALCULATED (ksi)</th>
<th>TENSION FORCE (kips) SHEAR FORCE IN ANCHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6A-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0056</td>
<td>77.84</td>
<td>6.23</td>
</tr>
<tr>
<td>S6A-2-2 x 0.8-0.375-4-0.375</td>
<td>0.0084</td>
<td>116.76</td>
<td>9.34</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0058</td>
<td>80.62</td>
<td>6.45</td>
</tr>
<tr>
<td>S6B-2-2 x 0.8-0.375-4-0.375</td>
<td>0.0053</td>
<td>73.67</td>
<td>5.89</td>
</tr>
</tbody>
</table>

Table 4.2 Shear force on anchors calculated using $E$ coupon tests

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>MAX. STRAIN MEASURED (in/in)</th>
<th>STRESS CALCULATED (ksi)</th>
<th>TENSION FORCE (kips) SHEAR FORCE IN ANCHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6A-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0056</td>
<td>63.84</td>
<td>5.11</td>
</tr>
<tr>
<td>S6A-2-2 x 0.8-0.375-4-0.375</td>
<td>0.0084</td>
<td>95.76</td>
<td>7.66</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-0.375-4-0.375</td>
<td>0.0058</td>
<td>66.12</td>
<td>5.29</td>
</tr>
<tr>
<td>S6B-2-2 x 0.8-0.375-4-0.375</td>
<td>0.0053</td>
<td>60.42</td>
<td>4.83</td>
</tr>
</tbody>
</table>
4.3 Using Values of Measured Beam Load $P$

Considering that the most reliable data is the measured load, the force transferred to the anchor can be determinate from the load. The moment in the beam is

$$M = \frac{PL}{4}$$

Since $C = T$

And $a (0.85)f'c b = C = T$

$$M = \frac{PL}{4} = C(h + 0.02 - \frac{a}{2})$$

Figure 4.2 Stress on beam due $P$ load

Where:
- $P$: Vertical point load
- $L$: span of the beam
- $C$: Compression Internal Force
- $T$: Tension Internal Force
- $f'c$: Compression Strength of Concrete
- $b$: width of beam on compression
- $h$: Depth of beam
- $a$: depth on Whitney compression rectangular block

Substituting, the following equations are developed
 Quadratic equation can be solved

Solution:

\[ a = \frac{-B + \sqrt{B^2 - 4C}}{2} \]

And

\[ a = \frac{-B - \sqrt{B^2 - 4C}}{2} \]

Where

\[ B = -2 \ (h + 0.02) \]

\[ C = \frac{PL}{2(0.85)(f'c) \ (b)} \]

Then:

\[ T = a \ (0.85) f'c \ b \]

T = Tension Force on CFRP sheet, which is transmitted directly to CFRP anchor

Then: \( T = \text{Shear Force CFRP anchor} \)

Using formulations developed lines above, and the measured load, the computed values of shear force at the anchors is as shown in Table 4.3:
Table 4.3 Shear force calculated by measured beam load

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>Measured load beam at failure of CFRP anchor (Kips)</th>
<th>a (in) = c / 0.65</th>
<th>Shear Force on anchor calculated (kips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6A-2-2 x 0.6-0.375-4-0.375</td>
<td>9.06</td>
<td>0.102</td>
<td>7.97</td>
</tr>
<tr>
<td>S6A-2-2 x 0.8-0.375-4-0.375</td>
<td>9.83</td>
<td>0.111</td>
<td>8.65</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-0.375-4-0.375</td>
<td>7.17</td>
<td>0.080</td>
<td>6.29</td>
</tr>
<tr>
<td>S6B-2-2 x 0.8-0.375-4-0.375</td>
<td>8.25</td>
<td>0.093</td>
<td>7.25</td>
</tr>
</tbody>
</table>

Differences between the test value and the calculated value using beam load are relatively close (about 10 – 15% lower) to the computed values using measured strains as indicated in Table 4.4.

Table 4.4 Comparison among shear force on anchor

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>calculated by measured beam load (kips)</th>
<th>computed by strain measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>calculated using E manufacturer (kips)</td>
<td>using E coupon tests (kips)</td>
</tr>
<tr>
<td>S6A-2-2 x 0.6-0.375-4-0.375</td>
<td>7.97</td>
<td>5.11</td>
</tr>
<tr>
<td>S6A-2-2 x 0.8-0.375-4-0.375</td>
<td>8.65</td>
<td>7.66</td>
</tr>
<tr>
<td>S6B-2-2 x 0.6-0.375-4-0.375</td>
<td>6.29</td>
<td>5.29</td>
</tr>
<tr>
<td>S6B-2-2 x 0.8-0.375-4-0.375</td>
<td>7.25</td>
<td>4.83</td>
</tr>
</tbody>
</table>

Using the maximum measured strain and the E values from the manufacturer and the coupon tests indicates that E from the coupon tests is too low.
CHAPTER 5
Conclusions and Recommendations

The use of CFRP sheets in the construction industry has increased in recent years, especially for seismic retrofit applications. The mechanical properties of CFRP allow an engineer to improve the performance of inadequate members. In addition, CFRP sheets are light weight and highly workable.

The tests conducted in this study demonstrated how CFRP anchors improve the use of CFRP sheets to strengthen reinforced concrete members. ACI 440 provides design recommendations, for use of CFRP sheets and for the quality control of rehabilitation projects that are CFRP.

Quality control for CFRP installations is necessary for rehabilitation projects.

Studies were performed to improve understanding of CFRP materials, especially when used for anchors.

Poor quality materials (such as contaminated epoxy) resulted in premature debonding. However the influence on load capacity is low.

The size of CFRP sheets and anchors, and/or strength of concrete were studied in order to find a reliable procedure for quality control of CFRP anchors. It was possible to develop anchor fracture using less material in the anchor than in the sheet thereby eliminating the variables associated with sheet fracture and concrete fracture.

A Test specimen was developed to study the variables influencing anchor performance. The specimen size and materials, by making changes to the specimen used in ASTM C293A, commonly used to evaluate concrete material strength.

For future research, more beams tests are needed with different material properties, and geometric.
APPENDIX A

CFRP Coupons

Coupons indicate that behavior of CFRP sheets is linear basically as Fig A.1 shows. (Pham 2009)

By coupons test, values of Ultimate stress, ultimate strain and Young modulus have been obtained, as Table A.1 shows. Results were used in chapter 4.

![Figure A.1 Behavior of strain on CFRP coupons (Pham 2009)](image)

**Table A.1 Summary of results of tests performed**

<table>
<thead>
<tr>
<th>Coupon</th>
<th>Width</th>
<th>Thickness</th>
<th>Ultimate load</th>
<th>Ultimate stress</th>
<th>Ultimate strain</th>
<th>Average E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in</td>
<td>in</td>
<td>Kip</td>
<td>ksi</td>
<td>in/in</td>
<td>ksi</td>
</tr>
<tr>
<td>C2-1</td>
<td>2</td>
<td>0.04</td>
<td>8.4</td>
<td>105.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C2-2</td>
<td>2</td>
<td>0.04</td>
<td>8.94</td>
<td>111.75</td>
<td>0.0091</td>
<td>12280</td>
</tr>
<tr>
<td>C2-3</td>
<td>2</td>
<td>0.04</td>
<td>8.05</td>
<td>100.63</td>
<td>0.0091</td>
<td>11058</td>
</tr>
<tr>
<td>C2-4</td>
<td>2</td>
<td>0.04</td>
<td>6.26</td>
<td>78.25</td>
<td>0.0072</td>
<td>10868</td>
</tr>
<tr>
<td>C2-5</td>
<td>2</td>
<td>0.04</td>
<td>9.6</td>
<td>120.00</td>
<td>0.0076</td>
<td>15789</td>
</tr>
<tr>
<td>C2-6</td>
<td>2</td>
<td>0.04</td>
<td>8.85</td>
<td>110.63</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C2-7</td>
<td>2</td>
<td>0.04</td>
<td>9.19</td>
<td>114.88</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Average 106.00 0.00825 11402
Figure A.2 Test setup

Figure A.3 Failure of coupon
Figure A.4 . Coupons after tests
## APPENDIX B

**CFRP material properties**

*Table B.1 CFRP sheets properties provided by the manufacturer*

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Method</th>
<th>Typical Test Value</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength (ksi)</td>
<td>D-3039</td>
<td>143</td>
<td>121</td>
</tr>
<tr>
<td>Elongation at crack failure</td>
<td>D-3039</td>
<td>1.00%</td>
<td>0.85%</td>
</tr>
<tr>
<td>Tensile modulus (ksi)</td>
<td>D-3039</td>
<td>13900</td>
<td>11900</td>
</tr>
<tr>
<td>Laminate thickness (in)</td>
<td>D-3039</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>
APPENDIX C
Properties of epoxy used on installation of CFRP materials

Table C.1 Epoxy properties provided by the manufacturer

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Method</th>
<th>Typical Test Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength (ksi)</td>
<td>D-638, Type 1</td>
<td>10.5</td>
</tr>
<tr>
<td>Tensile modulus (ksi)</td>
<td>D-638, Type 1</td>
<td>461</td>
</tr>
</tbody>
</table>
APPENDIX D

Concrete Blocks

Test with 2 blocks were performed, shown in Fig.2 shows. Installation was difficult, and: torsion effects due to unintended eccentricity resulted in premature failure of the sheets.

*Figure D.1 Concrete Blocks joined by CFRP sheets and CFRP anchors.*

*Figure D.2 Eccentricity was one of the problems presented of tests.*
APPENDIX E

Installation of CFRP sheets and anchors

The following photos provide a description of installation procedures.

Figure E.1  CFRP sheets and anchors to be installed on beams.

Figure E.2  Cleaning of the concrete surface before installation of CFRP materials.
Figure E.3  Application of the epoxy by roller on the surface of concrete beam

Figure E.4  Application of the epoxy into drilled holes for CFRP anchor
Figure E.5 Application of epoxy to CFRP materials

Figure E.6 Elimination of excessive epoxy on CFRP sheets using tubes
Figure E.7 Installation of CFRP sheet on concrete beam

Figure E.8 Installation of CFRP anchor in concrete beam.
Figure E.9  . Spreading out of the CFRP anchor fan.

Figure E.10  Wire of CFRP anchor is cut before patch installation
Figure E.11 Application of the patch on the CFRP anchor and final pass of roller with the epoxy on CFRP materials
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American Concrete Institute, (2008). “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08).” Farmington Hills, Michigan, USA.


Pham, L.T.;(2009) “Development of a Quality Control Test For Carbon Fiber Reinforced Polymer Anchors” M.S.E. Thesis The University of Texas at Austin. USA, 84pp

VITA

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During the following years he was employed as a teacher and research assistant at the National University of Engineering in Lima, Peru. He also spent time as an engineer at Fenix South America Consulting, Steel Deck Enterprises and SC Engineering in Lima Peru. In January, 2008, he entered the Graduate School at the University of Texas at Austin.

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