Development of a Quality Control Test for Carbon Fiber Reinforced Polymer Anchors

by

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Development of a Quality Control Test for Carbon Fiber Reinforced Polymer Anchors

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The use of carbon fiber reinforced polymer (CFRP) materials to strengthen concrete structures has increased in recent years. In most strengthening applications, CFRP laminates are bonded to concrete members with adhesives. Studies showed that the CFRP laminate debonded from the concrete surface, causing failures when the laminate reached only 40-50% of its capacity. CFRP anchors have been developed to overcome debonding problems. While the benefits of using CFRP anchors were demonstrated, little information regarding the quality control of CFRP anchor systems has been reported in the literature. For the research program presented in this thesis, 18 specimens were tested in order to:

- Assess the importance of a quality control process for CFRP anchors,
- Investigate factors that influence the anchor performance, and
- Find a simple way to maintain quality.

The research program demonstrated that quality control is critical to maintaining reliability of CFRP anchor systems. Bend radius was shown to have significant influence on the anchor capacity. Two types of specimens were tested and compared to investigate their applicability as a quality control test. Finally, a quality control procedure for CFRP anchors was recommended.

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CHAPTER 1

Introduction

1.1 RESEARCH SIGNIFICANCE

The use of fiber reinforced polymer (FRP) to strengthen concrete structures has progressively increased since the 1980's. According to NCHRP Report 514 (Mirmiran et al. 2004), in the United States, more than 25 Innovative Bridge Research and Construction (IBRC) projects have been or are being conducted that involve FRP composites bonded to concrete structures [Mertz et al. 2003]. In addition, numerous projects have been undertaken by state DOTs and counties [Alkhrdaji et al. 2000, Mayo et al. 1999, Nanni et al. 2001, Schiebel et al. 2002, Shahawy and Beitelman 1996]. In the state of Texas, a number of prestressed concrete bridges have been repaired using Carbon FRP (CFRP) composites.

The increased use of FRP materials can be attributed to their speed and ease of installation. Compared to traditional strengthening methods using bonded steel plates, FRP systems do not require heavy equipment, avoid corrosion problems, and take less time. FRP materials also increase the likelihood of repairing damaged concrete structures instead of replacement with new structures. The advantages of FRP are particularly important for structures whose loss of use or traffic delays must be minimized.

Although possessing advantageous characteristics, externally bonded FRP systems have some disadvantages that impede their implementation. One crucial problem is debonding of FRP laminates from concrete surfaces. Several experimental studies show that CFRP sheets reached only 40-50% of the tensile strength at the time they were debonded from concrete surfaces [Bonacci and Maalej 2001, Orton et al 2008]. As a result, more than half of the material capacity can not be utilized.

In an effort to overcome debonding problems, CFRP anchors have been developed. Tests show that CFRP sheets can develop their full strength when CFRP anchors are properly installed [Orton 2007, Kim 2008]. Furthermore, the strength can be developed even if there is no bond between the CFRP sheet and concrete surface. Therefore, the need for extensive surface preparation can be reduced if adequately designed CFRP anchors are provided [Orton et al. 2008, Kim 2008].

While the benefits of CFRP anchors have been demonstrated, little information regarding the quality control of the anchors can be found in the literature. Like most FRP repair systems, CFRP anchors are deceptively simple. However, mistakes such as improper installation of the anchors or saturation of the fibers, misaligning of the fabric and inadequate preparation of the anchor holes could significantly affect the performance of CFRP anchors unless quality control is implemented.

1.2 RESEARCH OBJECTIVES AND SCOPE

The research presented in this thesis was undertaken to assess the importance of quality control in CFRP anchor applications and to find a simple way to maintain quality. The research is limited to externally bonded CFRP materials used in repair and strengthening of concrete structures. An experimental program with 18 specimens was conducted to achieve the following objectives:

- Demonstrate the need for quality control of CFRP anchor systems.
- Determine components of a quality control process for CFRP anchor systems.
- Develop a standard test that could be used to qualify a CFRP anchor system and to maintain the quality of workmanship.
- Investigate factors that affect the performance of CFRP anchors.

CHAPTER 2

Background Information

2.1 CFRP MATERIALS

2.1.1 General concept of FRP materials

Fiber reinforced polymer is a composite material that consists of two main components. The first one is high strength fibers acting as the main load carrier. The second one is resin which glues the fibers together, distributes forces among the fibers and protects the fibers.

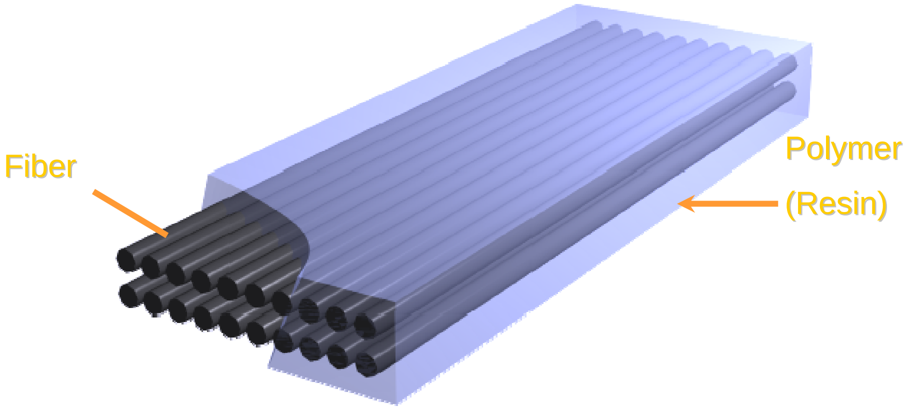


Figure 2.1 FRP composites, Courtesy of Dingyi Yang

2.1.2 Classification of FRP materials

FRP materials can be classified in several ways. The first one is based on the constituent materials. Common types of fibers include carbon fiber, glass fiber and aramid fiber. The FRP materials correspondingly are CFRP, GFRP and AFRP. Epoxy, vinyl esters, and polyesters are the most commonly used resins.

The second way to classify FRP materials is based on installation methods and forms of the materials. ACI 440 divides externally bonded FRP composites into 4 categories:

Wet layup systems—Wet layup FRP systems consist of dry fiber sheets or fabrics impregnated with a saturating resin on site.

Precured systems—Precured FRP systems consist of a wide variety of composite shapes manufactured off site. Typically, an adhesive, along with the primer and putty, is used to bond the precured shapes to the concrete surface.

Prepreg systems—Prepreg FRP systems consist of partially cured unidirectional or multidirectional fiber sheets or fabrics that are preimpregnated with a saturating resin in the manufacturer's facility. Prepreg systems are bonded to the concrete surface with or without an additional resin application, depending on specific system requirements. Prepreg systems are saturated off-site and, like wet layup systems, cured in place.

Near-surface-mounted (NSM) systems—Surface embedded (NSM) FRP systems consist of circular or rectangular bars or plates installed and bonded into grooves made on the concrete surface. A suitable adhesive is used to bond the FRP bar into the groove, and is cured in-place.

Lastly, CFRP applications can be categorized as bond-critical or contact-critical. According to ACI 440, bond-critical applications, such as flexural or shear strengthening of beams, slabs, columns, or walls, require an adhesive bond between the FRP system and the concrete. Contact-critical applications, such as confinement of columns, only require intimate contact between the FRP system and the concrete. Contact-critical applications do not require an adhesive bond between the FRP system and the concrete substrate, although one is often provided to facilitate installation.

For all experimental tests conducted in this research, wet-layup carbon fiber reinforced polymer (CFRP) with epoxy as the resin was used to make the sheets and anchors.

2.1.3 Main properties of FRP composite

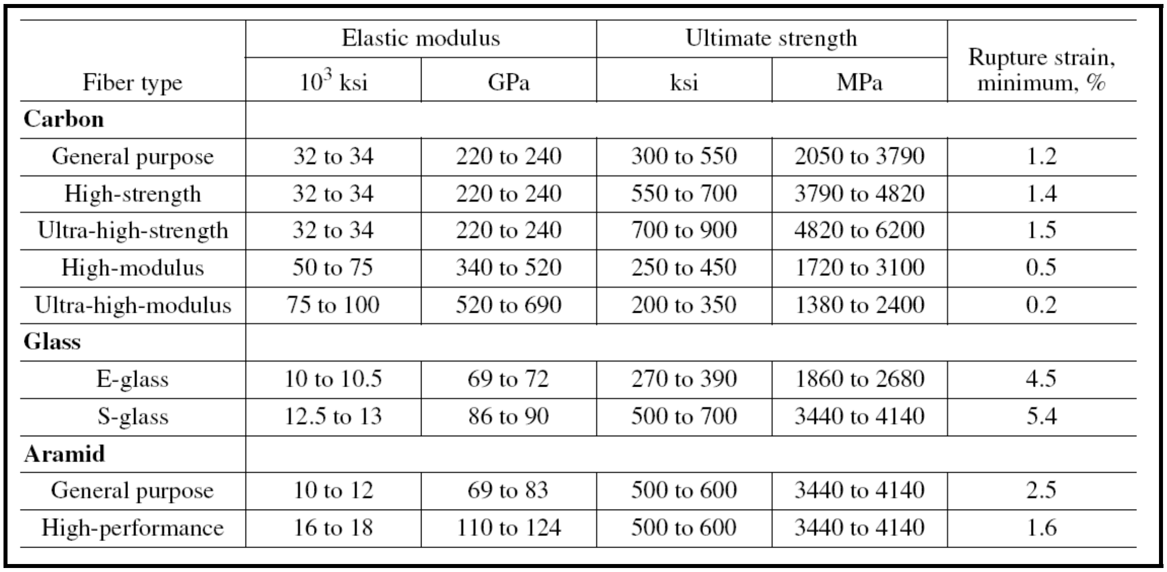
2.1.3.1 Density

FRP materials have densities ranging from 75 to 130 lb/ft3 (1.2 to 2.1 g/cm3), which are four to six times lower than that of steel [ACI 440]. The light density leads to lower transportation costs, reduces added dead load on the structure, and can ease handling of the materials on the project site.

2.1.3.2 Tensile behavior

When loaded in direct tension, unidirectional FRP materials do not exhibit any plastic behavior before rupture. The tensile behavior of FRP materials consisting of one type of fiber material is characterized by a linear elastic stress-strain relationship until failure, which is sudden and brittle [ACI 440]. Typical tensile properties of different types of fibers are provided in Table 2.1.

Table 2.1 Typical tensile properties of fibers used in FRP systems [ACI 440.2R-08]



Fiber type	Elastic modulus		Ultimate strength		Rupture strain, minimum, %
	10^3 ksi	GPa	ksi	MPa	
Carbon					
General purpose	32 to 34	220 to 240	300 to 550	2050 to 3790	1.2
High-strength	32 to 34	220 to 240	550 to 700	3790 to 4820	1.4
Ultra-high-strength	32 to 34	220 to 240	700 to 900	4820 to 6200	1.5
High-modulus	50 to 75	340 to 520	250 to 450	1720 to 3100	0.5
Ultra-high-modulus	75 to 100	520 to 690	200 to 350	1380 to 2400	0.2
Glass					
E-glass	10 to 10.5	69 to 72	270 to 390	1860 to 2680	4.5
S-glass	12.5 to 13	86 to 90	500 to 700	3440 to 4140	5.4
Aramid					
General purpose	10 to 12	69 to 83	500 to 600	3440 to 4140	2.5
High-performance	16 to 18	110 to 124	500 to 600	3440 to 4140	1.6

2.2 DEBONDING AND ANCHORAGE OF CFRP SYSTEMS

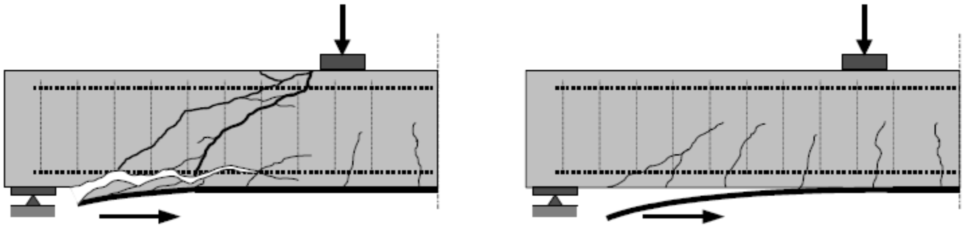
2.2.1 Debonding failures

Debonding is an important failure mode in externally bonded FRP strengthened systems. Debonding failures may occur at premature levels of load and are generally brittle [Buyukozturk and Yu 2006]. Experimental studies show that CFRP sheets reach only 40-50% of the tensile strength when they were debonded from concrete surfaces [Bonacci and Maalej 2001, Orton et al. 2008].

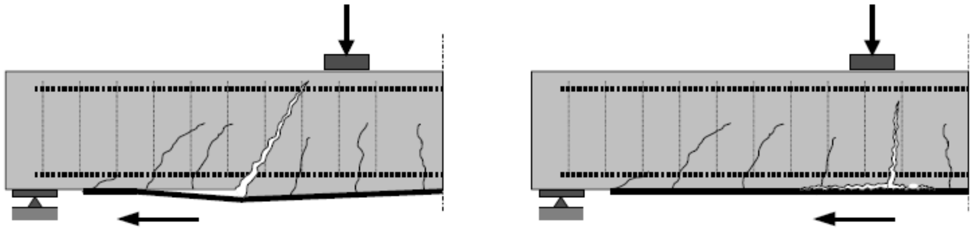
Debonding is a highly complex phenomenon. It can occur in the concrete substrate, in the FRP laminates or in the interface between concrete and FRP. Debonding depends on the quality of the concrete cover, surface preparation, type of adhesives and environmental conditions including temperature and humidity. As a result, debonding can occur in different ways as shown in Figure 2.2 and is difficult to control.

2.2.2 Anchorage for FRP systems

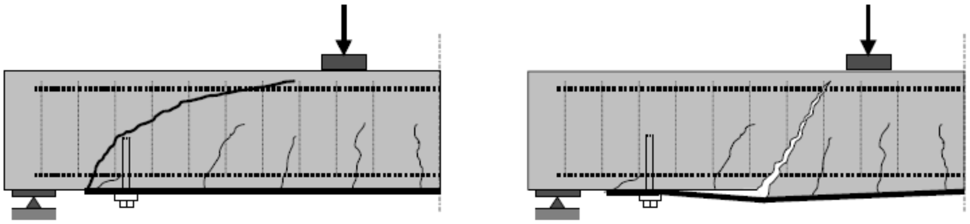
In an effort to overcome debonding problems, several anchorage systems have been developed. The anchorage of the ends of FRP sheets with steel plates and bolts is effective and can increase the shear capacity of RC members (Sato et al. 1997). For prepeg plates, the use of fasteners as anchorage (Figure 2.3) increased flexural capacity of reinforced concrete beams [Lammana et al. 2001, Lammana 2002]. Mechanical anchorages using steel plate and bolts or fasteners, may be effective in laboratory, but are not very practical in field applications due to corrosion of steel, stress concentration at bolted locations and initial cracking of concrete caused in bolting process (Figure 2.4).



(a) shear failure with concrete cover debonding (b) FRP debonding from plate end



(c) FRP debonding from flexure-shear crack (d) FRP debonding from flexural crack



(e) plate end shear failure (f) shear failure and debonding

Figure 2.2 Debonding failure mechanisms (Gunes, 2004)

Figure 2.3 Mechanically fastened prepreg CFRP plate [Lamanna, 2002]

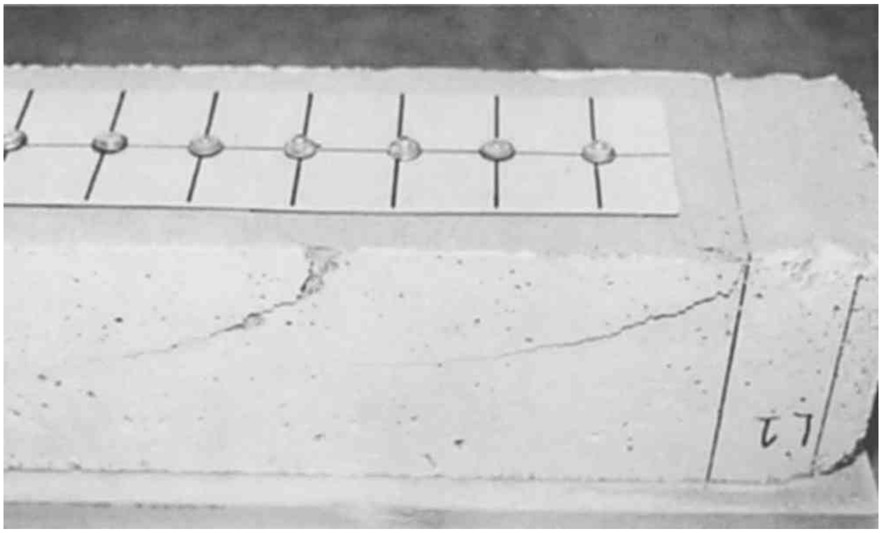
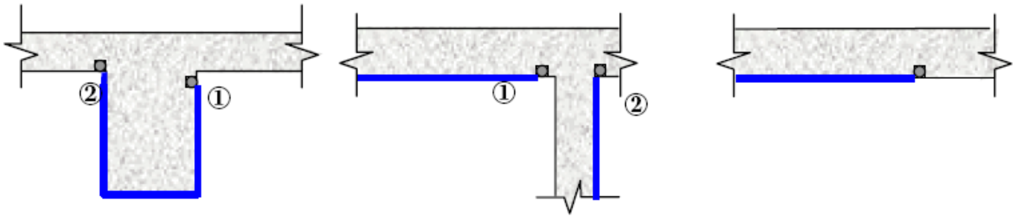


Figure 2.4 Initial cracks due to fastening [Lamanna et al. 2001]

The U-anchor (embedding FRP into preformed grooves in the concrete) was shown to increase shear capacity of FRP systems as shown in Figure 2.5 (Khalifa et al, 1999). U-anchors can reduce stress concentration but their performance is dependent on the concrete cover and therefore may not be able to carry the whole tensile force in the FRP sheets after debonding occurs.



(a) Anchor types for U-wrap shear strengthening of beams

(b) Anchor types for flexural strengthening of beam/slabs and wall/columns

(c) Plane surface anchorage for flexural strengthening of beam/slabs

Figure 2.5 Applications of U-anchors [Khalifa et al, 1999]

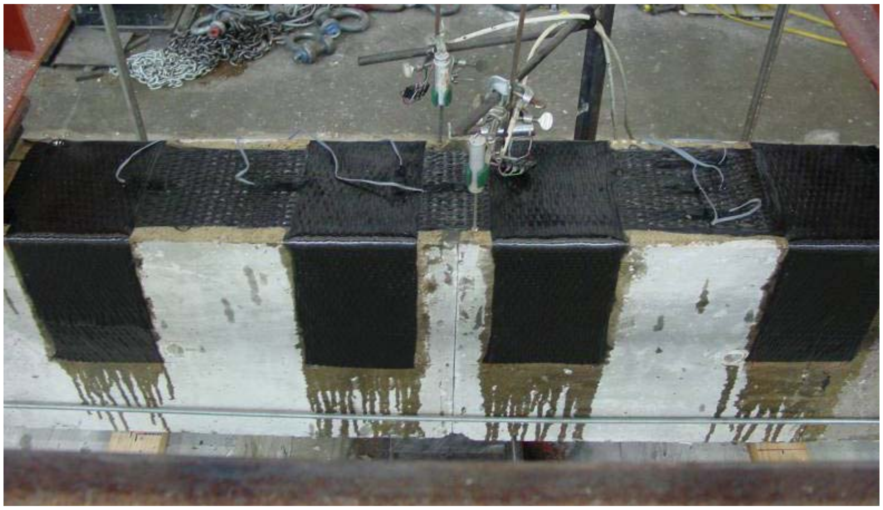


Figure 2.6 U-wrap anchorage [Orton, 2007]

Another type of anchorage for FRP systems is the use of U-wrap. U-wraps are fiber sheets installed perpendicular to the FRP sheet that provides the additional strength to the member (Figure 2.6). U-wraps increase the capacity of FRP systems by increasing the area of bonded FRP materials. Experimental research shows that with the use of U-wraps, the anchored CFRP sheet can develop its full strength though this method is not efficient with regard to the amount and cost of material effective [Orton et al. 2008]. In addition, U-wraps are not effective or applicable in certain cases, when the web of the member changes shape, such as T-beams or I-girders, or where slabs may reduce the length of U-wraps.

2.3 CFRP ANCHORS

CFRP anchors offer another way to anchor FRP sheets. A CFRP anchor is made by cutting a CFRP strip, impregnating it with resin, inserting it into a predrilled hole in the concrete and then fanning out fibers of the anchor on the CFRP sheet. The angle of the fan may be 360 degrees as in Figure 2.7 or smaller than 90 degrees as in Figure 2.8. The anchor is saturated with epoxy and installed immediately after the CFRP sheet is placed so that the sheet and anchor work as a composite unit. CFRP anchors can be applied in cases where U-Wraps are ineffective.

Tests show that CFRP sheets can develop their full strength when CFRP anchors are properly installed. Furthermore, the strength can be developed even if there is no bond between the CFRP sheet and concrete surface [Orton et al 2008]. This finding reduces the need for extensive surface preparation if CFRP anchors are adequately provided.

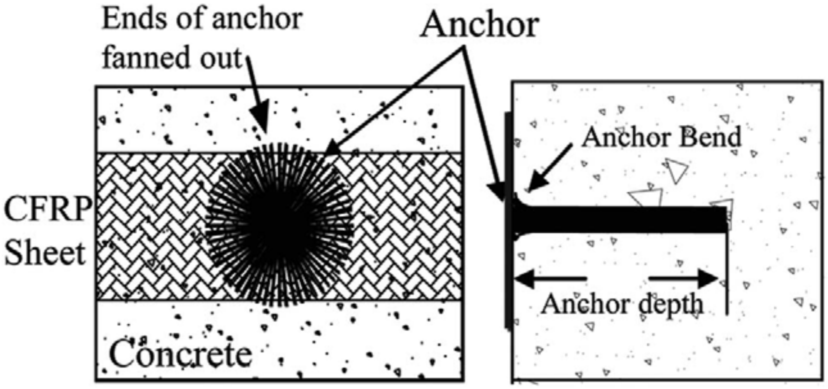


Figure 2.7 CFRP anchor with 360-degree fan [Orton et al. 2008]

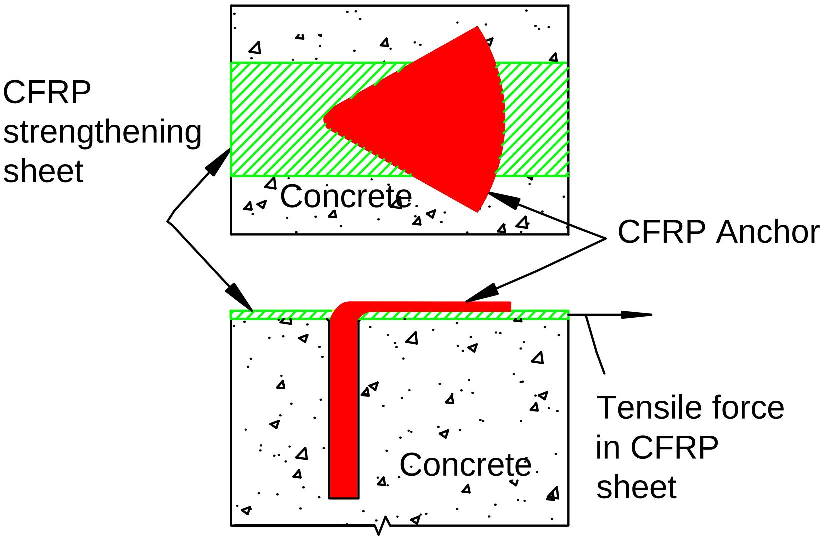


Figure 2.8 CFRP anchor fanned out in one direction

2.4 PREVIOUS STUDIES ON CFRP ANCHORS

2.4.1 Quality control tests for CFRP anchors

Little information regarding quality control of CFRP anchors could be found in the literature. Kim (2008) made an effort to find a simple qualification test for CFRP anchors. The selected specimen was based on Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Center-Point Loading (ASTM C 293-07). The 6 in. by 6 in. by 20 in. beam was simply supported and attached with one CFRP sheet on the bottom (Figure 2.9). Unfortunately, this test did not provide reliable results due to lack of shear strength of the beam.

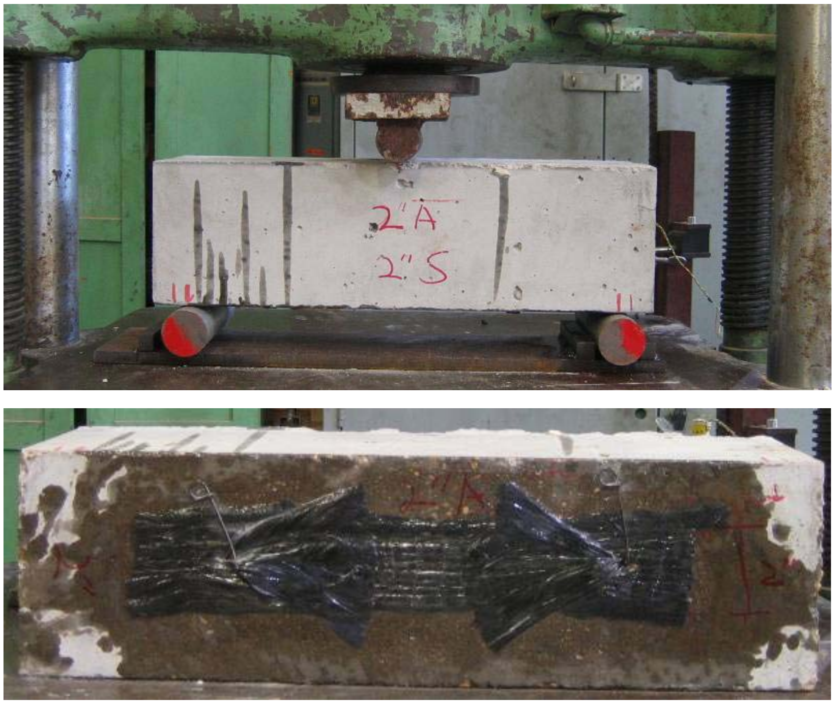


Figure 2.9 Qualification test for CFRP anchors [Kim 2008]

2.4.2 Embedment depth of FRP anchors into concrete element

From direct tension tests of CFRP anchors as shown in Figure 2.10, Akyuz and Ozdemir concluded that there is an effective depth of 10 cm, beyond which tensile capacity of the anchor no longer increases. However, these tests do not reflect the actual force transfer mechanism of CFRP anchor system in which the tensile force in CFRP sheet is transmitted through CFRP anchor mainly by shear as shown in Figure 2.8, instead of tension.

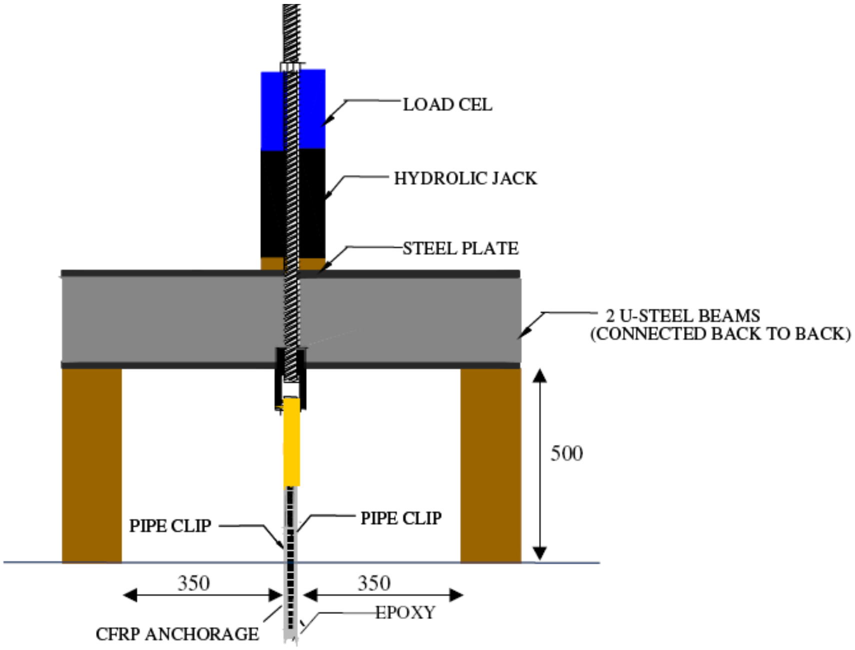


Figure 2.10 CFRP anchor [Akyuz and Ozdemir, 2004]

Orton (2008) used CFRP anchors for concrete members strengthened in flexure with CFRP sheets (Figure 2.11). She recommended that the anchors be embedded at least 2 inches into the core of the concrete. By penetrating into the core, the anchor provides a load path to flexural reinforcement in the member. The total depth of the anchors including concrete cover would be around 5 inches (Figure 2.12).

Kim (2008) used CFRP anchor systems similar to those in Orton’s tests and recommended that the depth of CFRP anchors be at least 4 inches.

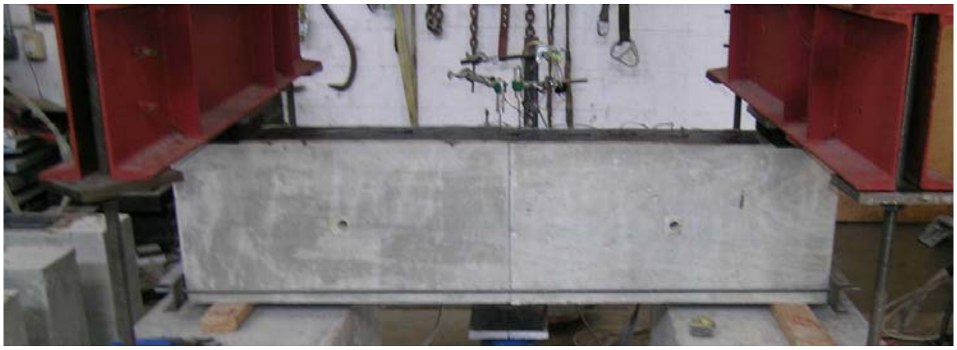


Figure 2.11 Concrete member strengthened in flexure with CFRP [Orton, 2007]

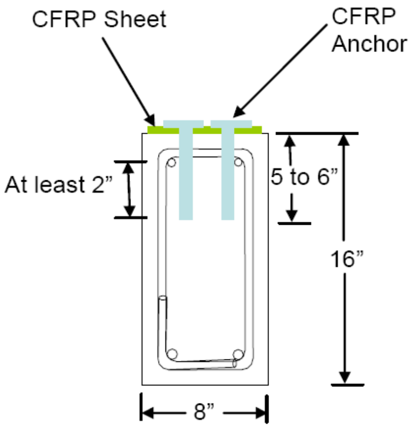


Figure 2.12 Depth of CFRP anchor [Orton et al. 2007]

Niemitz (2008) conducted shear tests for CFRP anchors. A CFRP sheet was bonded and anchored into a reinforced concrete block that was tied to the floor with steel bars (Figure 2.13). The sheet is connected to a load cell and hydraulic jack through a steel plate and pulled in tension. A 2-inch anchor depth was used for all of the tests and only one anchor pullout was observed in the studies. Niemitz concluded that the embedment depth of the anchors is not a governing parameter. However, it should be noted that the CFRP sheet was anchored to a rather large concrete block in which the force in CFRP sheet did not have to be transferred to the reinforcement in the member. In flexural strengthening such as Orton's tests, a CFRP sheet was attached to the bottom of a narrow beam with a limited width. In addition, the concrete cover is usually under tensile stresses. In this case, spalling of concrete cover is more likely to occur if the tensile force in CFRP sheet is not transferred to the reinforcement inside the concrete member.

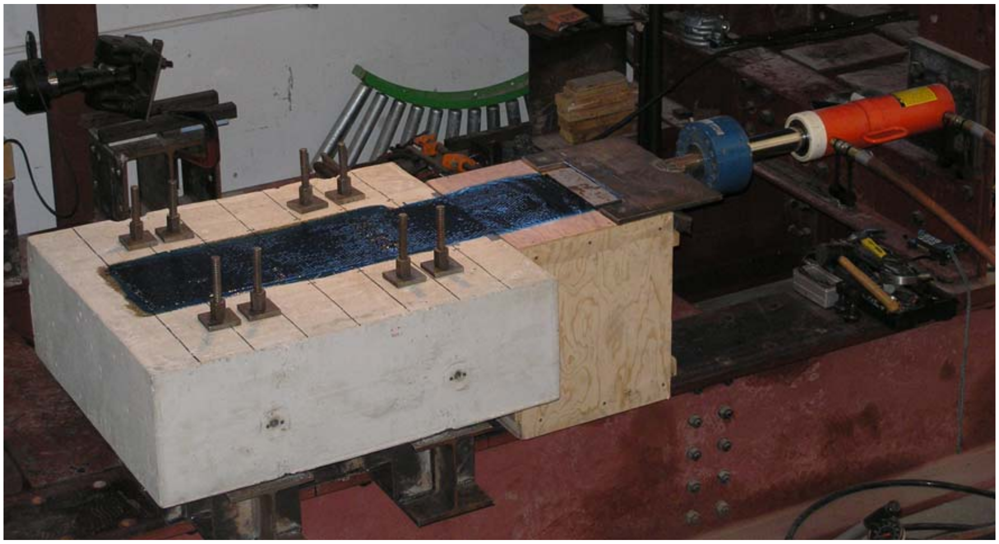


Figure 2.13 Shear test for CFRP anchors [Niemitz, 2008]

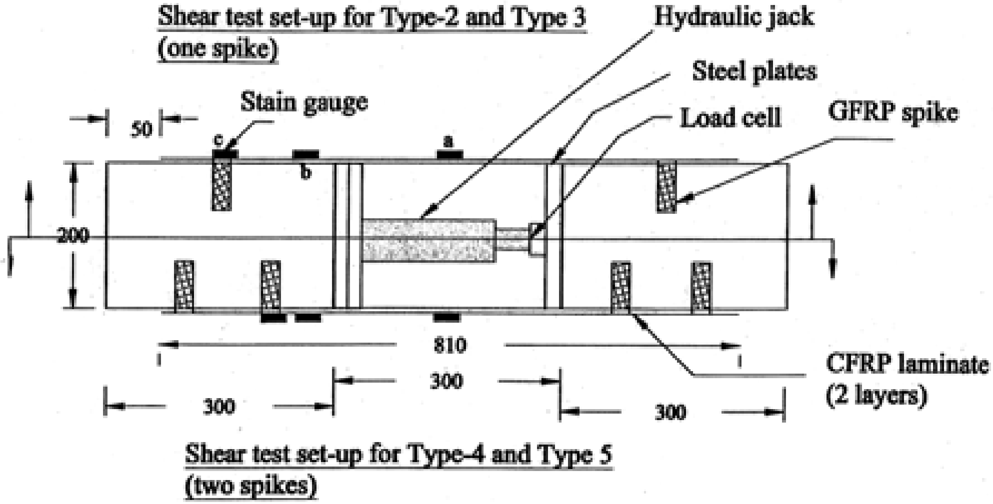


Figure 2.14 Shear test for CFRP anchors [Eshwar et al. 2008]

Eshwar (2008) implemented shear tests for anchors made of glass fibers (GFRP spike anchors) as shown in Figure 2.14. Two concrete blocks were aligned and connected with CFRP laminates on both sides. The CFRP laminates were bonded and anchored into the concrete blocks using GFRP anchors. A hydraulic jack was then placed between the two blocks. The jack pushed the two blocks away from each other and created tensile forces in the CFRP laminates. These forces were transmitted to the concrete blocks through the anchors. Eshwar recommended an embedment depth of at least 2 inches for GFRP anchors.

2.4.3 Bend radius of CFRP anchors

There has been no study on the effects of bend radius on FRP anchor performance. The effects of bend radius on FRP bars, however, were investigated by some researchers and are presented herein for reference.

Studies by Morphy (1999) on the effect of bend diameter for CFRP stirrups suggest that the radius of the bend be greater than four times the CFRP diameter. Thus, for a 0.5-inch anchor, the bend radius is 2 inches. Unfortunately, this radius is unrealistic for CFRP anchors.

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

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

Where 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% capacity of a straight element.

ACI 440.2R-08 recommends that where fibers wrap around the corners of rectangular cross sections, the corners be rounded to a minimum 0.5 in. (13 mm) radius to prevent stress concentrations in the FRP system.

2.4.4 Amount of material used in CFRP anchors

The amount of material used in CFRP anchors is an important parameter in a CFRP anchor system. If the anchor does not have enough capacity, it may fracture before the CFRP sheet can develop its full strength. Orton (2008) concluded that the cross-sectional area of CFRP anchors should be two times greater than that of CFRP strengthening sheets. It should be noted that this is only the necessary condition. Orton's studies show that when the cross-sectional area of a CFRP anchor was large, the anchor fractured before the CFRP strengthening sheet could develop its full strength. When the cross-sectional area was split into several smaller anchors, the CFRP sheet reached its full capacity.

Studies by Kim (2008) show that when the cross-sectional area of CFRP anchors is 33% more than that of CFRP strengthening sheet, the sheet can develop its full capacity. He recommended that the cross-sectional area of CFRP anchors be 50% more than that of the CFRP sheet.

2.4.5 Fan shapes for the end of CFRP anchors

Kobayashi (2001) studied the effects of fan angle on the force transfer from CFRP sheet to CFRP anchor (Figure 2.15). He concluded that the angle should be less than 90 degrees in order to achieve a good force transition between the sheet and the anchor. Fan-shaped anchors were also used by Masuo et al. 2001 (Figure 2.16), Orton (2007) and Kim (2008).

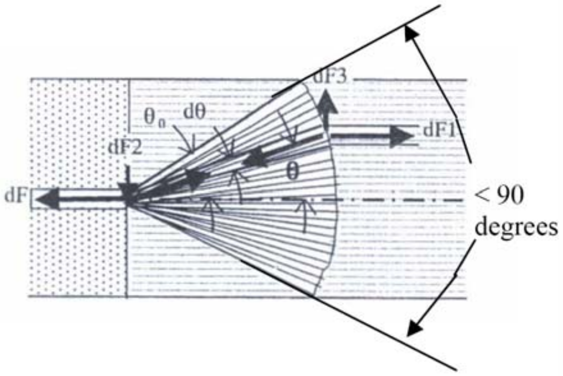


Figure 2.15 Fan opening angle studied by Kobayashi [Kobayashi et tal. 2001]

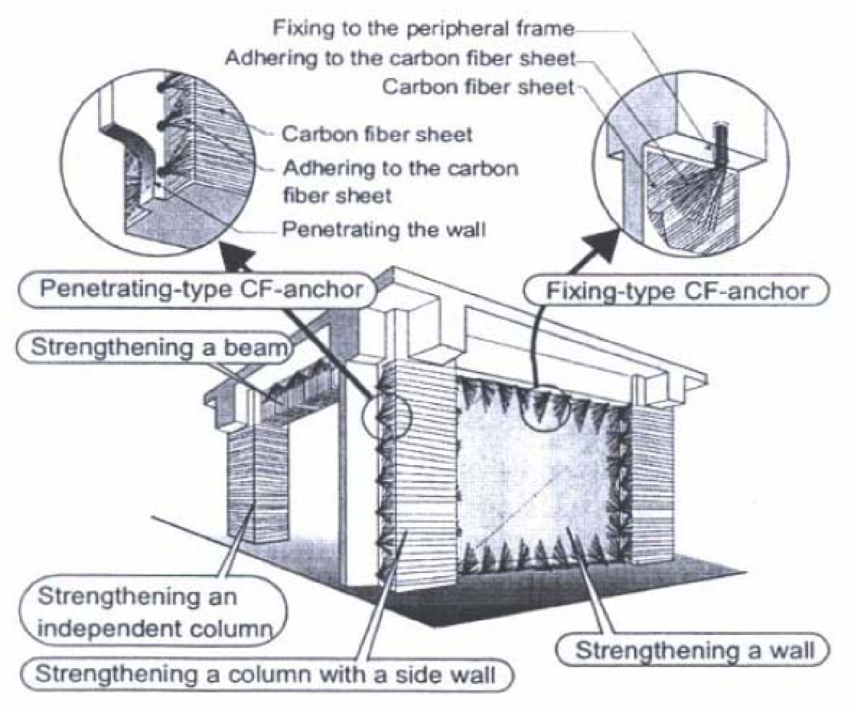


Figure 2.16 Use of anchor fans [Masuo et tal, 2001]

Niemitz (2008) and Eshwar et al. (2008) used 360-degree fans for their fiber anchors (Figure 2.17).

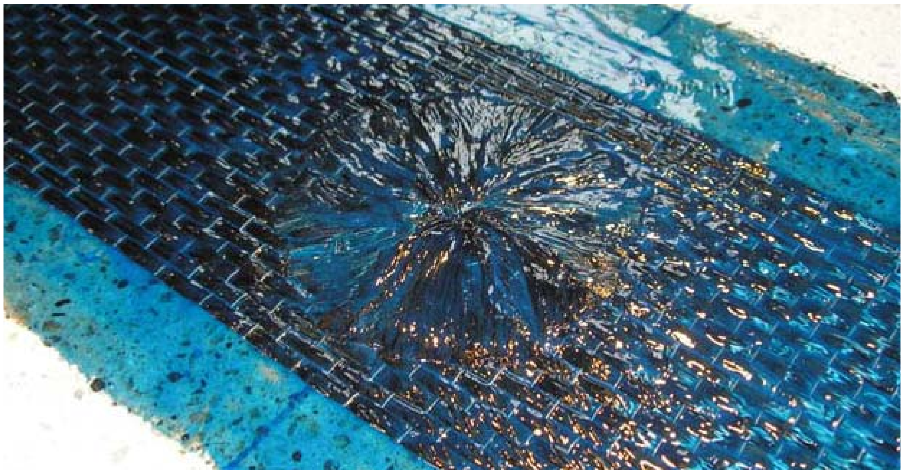


Figure 2.17 Use of 360-degree anchor fans [Niemitz, 2008]

2.4.6 Other results

Kim (2008) and Orton (2007) concluded that bonding is not critical when adequately designed CFRP anchors are provided. As a result, the need for extensive surface preparation can be reduced.

Regarding the diameter of anchor holes, Kim (2008) recommended that the cross-sectional area of anchor hole be at least 40% larger than that of the CFRP anchor. Akyuz and Ozdemir suggested that there be at least 1 or 2 mm free space in the hole for the epoxy resin.

2.5 INSTALLATION OF CFRP ANCHOR SYSTEMS

2.5.1 Preparation of specimens

Before CFRP can be installed, the concrete surface and anchor holes need to be prepared. The surface should be even and clean (Figure 2.18). It should be noted that the bonding of CFRP sheet and concrete is no longer critical due to the presence of CFRP anchors. Thus, as long as the surface is clean and flat, no grinding is required.

Holes are drilled into the concrete element to the desired depth (Figure 2.19). The edge of the holes must be rounded off to provide smooth surface (Figure 2.20). Depending on the application, the radius of the edge may need to be checked with a radius gage. Anchor holes are then cleaned with compressed air (Figure 2.21) or a bottle brush. The holes should be free of dust and oil in order to obtain a good bond between epoxy and the concrete element.

Figure 2.18 Preparing the concrete surface [Courtesy of Insung Kim]

Figure 2.19 Drilling holes into the concrete element

Figure 2.20 Rounding off the edge of the holes and checking with a radius gage

Figure 2.21 Cleaning the holes with compressed air

2.5.2 Installation of CFRP sheets and anchors

Epoxy must be prepared following the manufacturer’s instruction. The concrete surface and anchor holes are saturated with epoxy (Figure 2.22 and Figure 2.23). The CFRP sheet is saturated, rolled through two PVC pipes to remove excess epoxy and applied to the concrete surface (Figure 2.24 and Figure 2.25). The sheet should be carefully aligned and then smoothed by hand, putty knife or PVC pipe to remove any voids and/or air bubbles (Figure 2.26).

Figure 2.22 Mixing epoxy and saturating anchor holes

Figure 2.23 Saturating the concrete surface

Figure 2.24 Saturating CFRP sheets

Figure 2.25 Rolling CFRP sheet through PVC pipes

Figure 2.26 Applying and aligning CFRP sheet

CFRP anchors are saturated and inserted into predrilled holes (Figure 2.27). The protruding end of the anchors is fanned out over the sheet. Special attention should be paid to smoothing the fan in order to achieve good bond between the anchor and the sheet.

In addition to the installation procedure presented in this report, ACI-440 instructions for wet-layup systems should be followed.

Figure 2.27 Inserting CFRP anchor into the hole

Figure 2.28 Fanning the end of CFRP anchor

Figure 2.29 Finished specimen

CHAPTER 3

Experimental Program

3.1 OVERVIEW

In this experimental program, four series of tests with 18 specimens were conducted. In the first series, six beam specimens were tested in order to find a simple test that can be used as quality control test for CFRP anchor systems (Section 3.4). The selected specimen is a simply supported beam similar to the ASTM test for concrete modulus of rupture. One CFRP sheet was bonded and anchored to the bottom of the beam in order to increase its flexural capacity. The sheet was expected to fracture at failure of the specimen.

Based on findings from the first tests, another series of six beams were tested to investigate effects of bend radius on CFRP anchor behavior (Section 3.5). Although it is widely known that the bend may cause stress concentration and reduce the anchor capacity, no study on quantifying this bend effect in CFRP anchors could be found in the literature. The tests in this experimental program were conducted to quantify the effects of bend radius on CFRP anchors' capacity.

In the first two series, some specimens encountered failure of concrete behind the anchors which provided no useful information on the performance of the CFRP anchor system. In an effort to overcome this problem without increasing the sizes of the specimens, a third test series were carried out with high strength concrete (fc' = 11,500 psi). Grouted steel bearing plates were also placed at supporting and loading points to avoid eccentricity and increase shear strength (Section 3.6).

In another effort to prevent failure of concrete, three new specimens were tested. The specimens consisted of two concrete blocks connected to each other by two CFRP sheets which are anchored to the concrete on both sides (Section 3.7). The two blocks were pushed away from each other by a hydraulic jack. The jack created tension forces in the CFRP sheets and loading was increased until failure.

3.2 DEFINITIONS AND DESIGNATIONS

3.2.1 Definitions

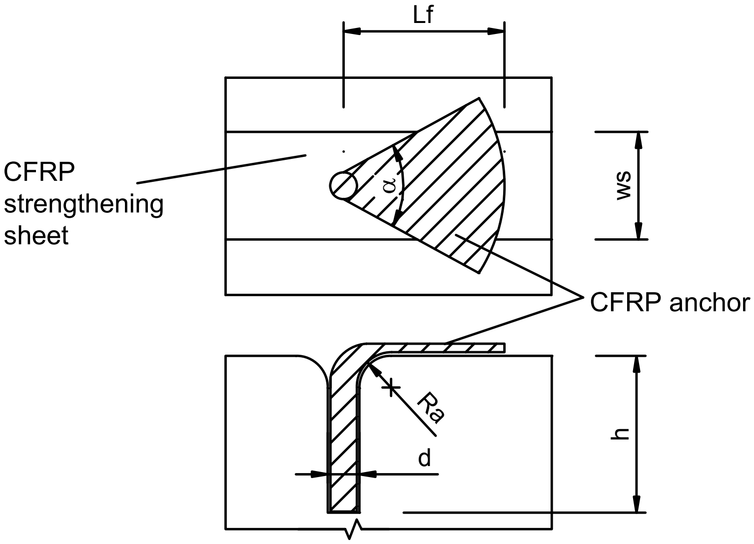


Figure 3.1 Components of a CFRP anchor system

- CFRP anchor system: The composite system consisting of CFRP strengthening sheet and CFRP anchor.

- Width of CFRP sheet (W_s): Width of the CFRP sheet used to strengthen the concrete members.

- Width of CFRP anchor (W_a): Width of the CFRP strip used to make anchor

- Embedment depth (h): Depth of the anchor embedded into the concrete element, specified by the depth of the anchor hole.

- Hole diameter (d): Inner diameter of the anchor hole

- Bend radius of the anchor (R_a): The radius obtained by grinding the edge of anchor hole.

- Fan length (L_f): Length of the fan part of the anchor

- Fan angle (α): Opening angle of the fan part of the anchor

3.2.2 Designation of specimens

C: coupon specimens (Section 3.3.1).

- 1, 2, 3...: number of the specimen.
- Example: C-1, C-2...

BM: beam specimens (Sections 3.4, 3.5, and 3.6).

- i: 1st test series, Section 3.4.
- b: 2nd series, Section 3.5.
- h: 3rd series, Section 3.6.
- 1, 2, 3...: number of the specimen.
- Example: BM-i-1, BM-h-2...

BL: block specimens (Section 3.7).

- 1, 2, 3: number of the specimen.
- Example: BL-1, BL-2...

3.3 MATERIAL PROPERTIES

3.3.1 CFRP Constituent Materials

The same type of CFRP materials were used for all the tests in this research. The composite consisted of Tyfo SCH-41 Fabric and Tyfo S Epoxy, supplied by Fyfe Co. LLC. Data from the manufacturer is presented in Table 3.1, Table 3.2 and Table 3.3. In addition, seven coupons were made and tested (Figure 3.2) in compliance with the Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM D-3029. Strain gages were installed on four coupons to measure strains under tensile forces. Stress-strain relation of CFRP laminates is basically linear as shown in Figure 3.3. It can be seen from coupon test results in Table 3.4 that the ultimate elongation and tensile modulus were closed to the design values while the average tensile strength was lower than the design one. The fact that strength and strain of some of the coupons were much lower than the others may be due to mistakes during specimen preparation and test procedure. Therefore, these results of coupon tests were not used to estimate capacity of the CFRP anchor system in this research. The design data provided by the manufacturer was used instead.

Table 3.1 CFRP laminate properties provided by the manufacturer

Property	ASTM Method	Typical Test Value	Design Value
Ultimate tensile strength, ksi	D-3039	143	121
Elongation at break	D-3039	1.0%	0.85%
Tensile modulus, ksi	D-3039	13900	11900
Laminate thickness, in	D-3039	0.04	0.04

Table 3.2 Typical dry fiber properties provided by the manufacturer

Property	Value
Tensile strength, ksi	550
Ultimate elongation	1.7%
Tensile modulus, ksi	33400
Density, lbs/in^3	0.063

Table 3.3 Epoxy properties provided by the manufacturer

Property	ASTM Method	Typical Test Value
Tensile strength, ksi	D-638, Type 1	10.5
Tensile modulus, ksi	D-638, Type 1	461

Figure 3.2 CFRP coupon test

Table 3.4 CFRP laminate properties from coupon tests

Coupon	Width	Thickness	Ultimate load	Ultimate stress	Ultimate strain	Average E
	in	in	kip	ksi	in/in	ksi
C-1	2	0.04	8.4	105	N.A	N.A
C-2	2	0.04	8.94	111.75	0.0091	12280
C-3	2	0.04	8.05	100.625	0.0091	11058
C-4	2	0.04	6.26	78.25	0.0072	10868
C-5	2	0.04	9.6	120	0.0076	15789
C-6	2	0.04	8.85	110.625	N.A	N.A
C-7	2	0.04	9.19	114.875	N.A	N.A
Average				105.875	0.00825	11402

(N.A: no strain data available)

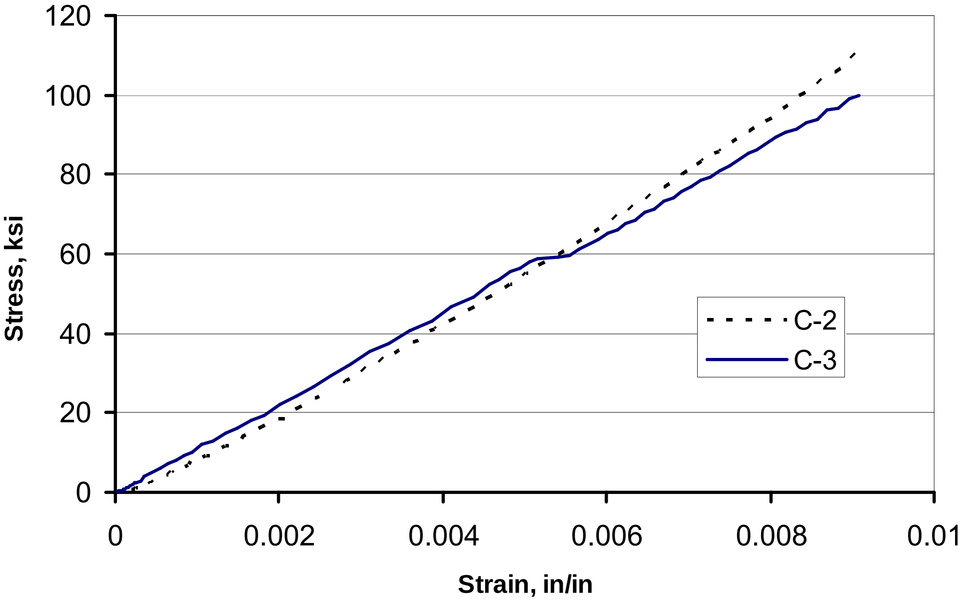


Figure 3.3 Stress – Strain relation of CFRP laminates from coupon tests

3.3.2 Concrete

For each concrete batch, three to four cylinders were made and tested according to the Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C 39/C 39M. The average concrete compressive strength at 28th day was 4,900 psi in the first series (Section 3.4), 4,500 psi in the second series (Section 3.5) and 11,500 psi in the last two series (Sections 3.6 and 3.7).

3.4 SELECTION OF BEAM SPECIMENS FOR THE QUALITY CONTROL TEST

3.4.1 Objectives

The objective of this series was to find a specimen and test setup that can be used as a qualification test for CFRP anchors. For a qualification test, the requirements were that the specimens should be small and the test should be simple to carry out. For this purpose, the test for flexural strength of concrete, ASTM C 293 – 07 (Figure 3.4), was chosen with several modifications as presented in Table 3.5.

The modified specimen as shown in Figure 3.5 is simply supported and loaded at mid-span. One CFRP sheet was attached to the bottom to strengthen the flexural capacity of the beam. The sheet was anchored at its ends into the concrete element. The amount of materials in the CFRP sheets and anchors was calculated so that the specimen failure would be due to fracture of the CFRP sheet. An anchor system that develops the full strength of CFRP sheet or the stress used in design would be considered "qualified". The selected specimen, therefore, could be used to qualify the design values and the method of installation.

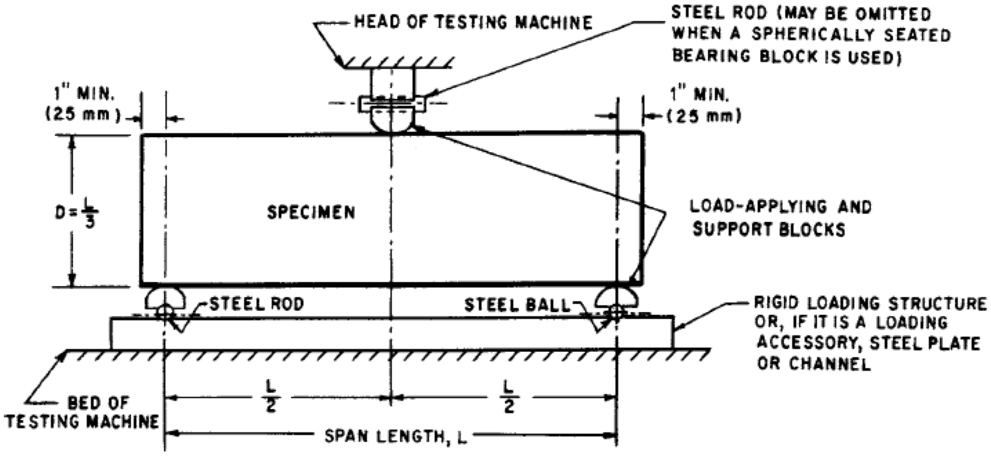


Figure 3.4 Test apparatus – ASTM C293

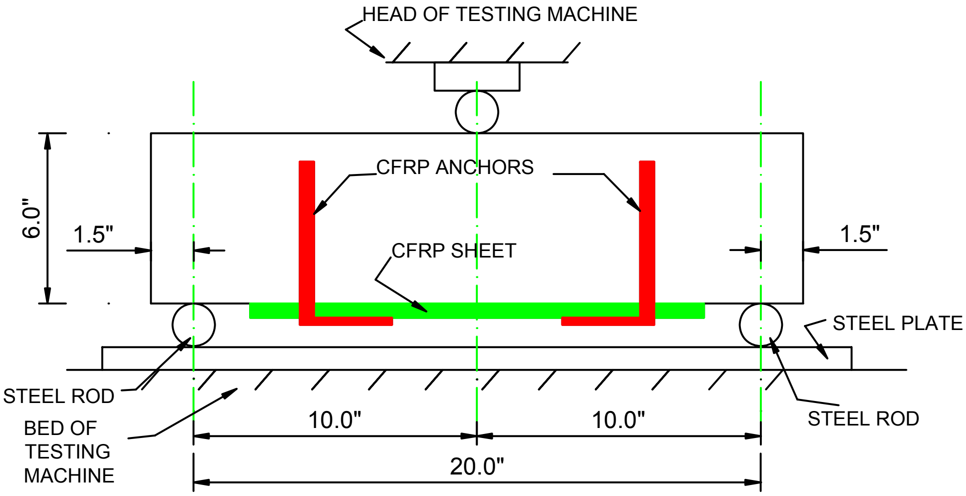


Figure 3.5 Test setup for beam specimens (section through beam)

Table 3.5 Comparison of ASTM C293 and the selected beam specimen

Parameter	ASTM C293	Selected specimen
Width	Not specified	8 in
Depth (D)	L/3	6 in
Span length (L)	3D	20 in. - 21 in.
Flexural capacity	Concrete only	Concrete and CFRP sheet

3.4.2 Selection of parameters for the CFRP anchor system

3.4.2.1 Width and length of CFRP strengthening sheets:

The width of CFRP sheets used in first test series ranged from 2 to 2.5 inches. The length of CFRP sheet was selected so that the sheet would extend 2 inches beyond the center of the anchor holes.

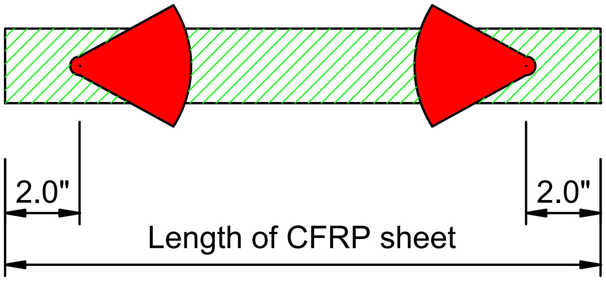


Figure 3.6 Selection of width and length of CFRP strengthening sheets

3.4.2.2 Width and length of CFRP anchors

The width of the strips used to make anchors was selected to produce failure by fracture of the CFRP sheets. Based on data from tests of the same type of CFRP anchors by Kim (2008), widths of the CFRP anchors in this series were selected ranging from 130% to 150% of the width of the CFRP strengthening sheet. The length of the anchor was equal to the depth of the hole plus the fan length plus 0.5 in.

3.4.2.3 Length and angle of the fan part of CFRP anchor

The length of fan should be long enough to ensure a sufficient bond area between the anchor and the strengthening sheet. The fan angle affects the force transfer from the CFRP to the anchor. Based on data from tests by Kobayashi (2001) and Kim (2008), the fan length was selected equal to the width of anchor and the fan angle was less than 90 degrees.

3.4.2.4 Depth and diameter of anchor holes

The depth and diameter of anchor holes were selected based on recommendations by Kim (2008). All the anchor holes were 4 inches deep. The diameter of anchor hole was selected so that the cross-sectional area of the hole is at least 140% of the cross-sectional area of the anchor.

3.4.3 Test Setup and Procedure

Figure 3.7 Testing beam specimens

The specimen was placed on one roller and one fixed support. A spherical head was attached to the loading machine to minimize eccentricity caused by uneven surfaces. The load was steadily increased until failure occurred. The loading rate was about 2-3 kips per min. A linear potentiometer was installed to measure the displacement of the test machine.

3.4.4 Results

3.4.4.1 Ultimate loads and failure modes:

In all specimens, the first crack occurred at mid span at about 8 kips. Then the crack opened and debonding occurred. Three failure modes were observed: fracture of CFRP longitudinal sheet (Figure 3.8 and Figure 3.9), fracture of CFRP anchor (Figure 3.10 and Figure 3.11) and failure of concrete behind the anchors (Figure 3.12 and Figure 3.13). The ultimate loads and failure modes of all specimens were summarized in Table 3.6.

SPECIMEN 10
Wire mesh: No
Holes: DRilled
CFRP sheet: 2"
CFRP anchor: 3"
MAX LOAD 11.04K
CFRP sheet Failure

Figure 3.8 Fracture of CFRP sheet

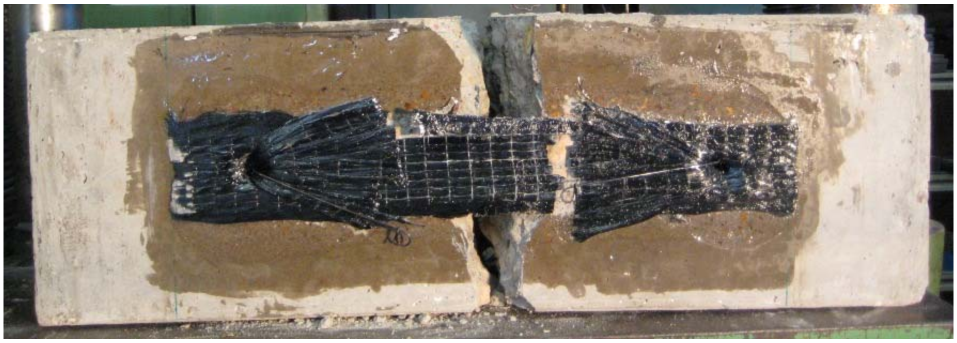


Figure 3.9 Detail of fractured CFRP sheet

Figure 3.10 Fracture of CFRP anchor

Figure 3.11 Detail of fractured CFRP anchor

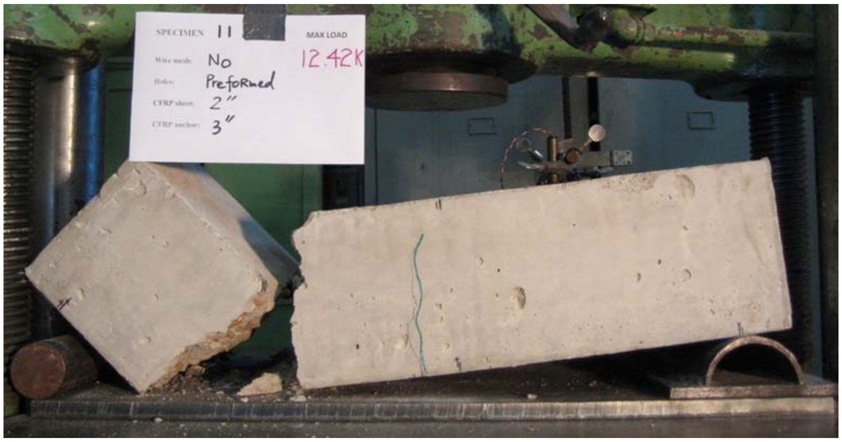


Figure 3.12 Concrete failure

Figure 3.13 Detail of concrete failure

Table 3.6 Result summary of initial tests

Specimen	Width of CFRP sheets	Width of CFRP anchors	Diameter of anchor holes	Embedment depth	Failure load	Failure mode
	in	in	in	in	kip	
BM-i-1	2	3	0.625	4	10.83	Anchor fracture
BM-i-2	2	3	0.5	4	11.04	CFRP sheet fracture
BM-i-3	2	3	0.5	4	12.42	Concrete failure
BM-i-4	2.25	3	0.625	4	10.31	Anchor fracture
BM-i-5	2	3	0.5	4	11.25	CFRP sheet fracture
BM-i-6	2.5	3.5	0.625	4	13.84	Concrete failure

3.4.4.2 Load – Deflection behavior:

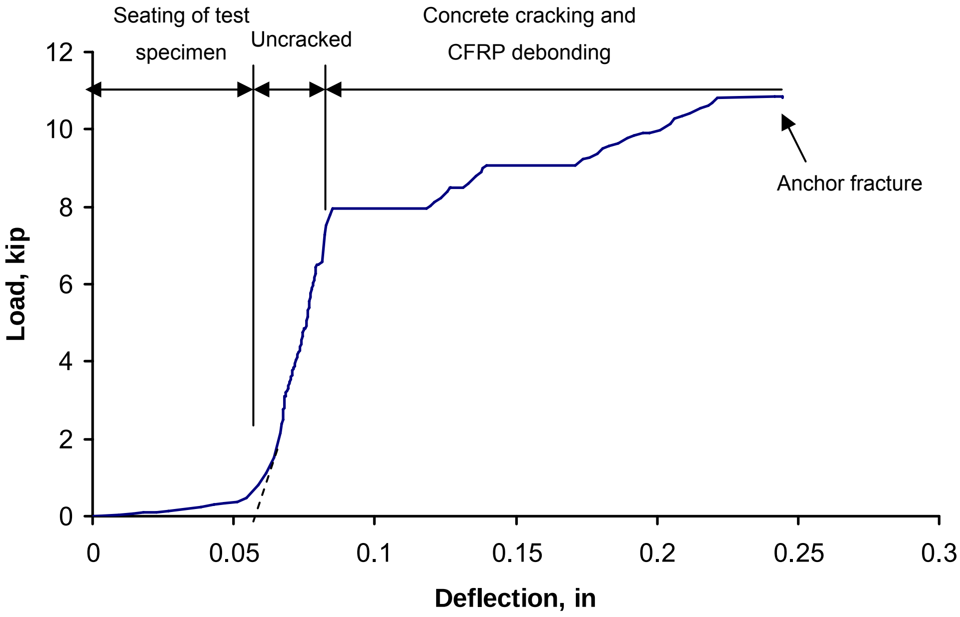


Figure 3.14 Load - Deflection relation of specimen BM-i-1

The load-deflection curves of the six specimens were similar with three characteristic segments. The first segment shows initial displacements of the test machine. The second segment characterizes an uncracked specimen. The remaining of the curve features the specimen with cracking and CFRP debonding. The curve for specimen BM-i-1 is presented in Figure 3.14.

First, it should be noted that the potentiometer was attached to the moving bottom part of the testing machine. Thus, the potentiometer actually measured the displacement of the machine, not the deflection of the specimen. This is the reason for the initial displacement of about 0.05 in as shown in the figure. Although the displacement of the machine and the deflection of the beam were different at the beginning of the test, they coincided after the beam was seated. In this test, when the load was over 1-2 kips, the measured displacement reflected the deflection of the beam at its mid-span.

The specimens behaved linearly until the concrete cracked. In the above figure, the cracking load was about 8 kips. The flat line right after cracking can be attributed to the debonding of the CFRP sheet, triggered by the crack. After that, inclined and flat lines occurred alternatively until failure, indicating an extension of concrete cracks and debonding of the CFRP sheet.

3.4.5 Discussion

Fracture of the CFRP sheets occurred in specimens BM-i-2 and BM-i-5. This type of failure, as mentioned above, can be used as a qualification criterion for the CFRP anchor system. This result indicates that it is possible to develop a standard quality control test with the selected specimens and test setup.

The fracture of CFRP anchors occurred when there was not enough material in the anchors or the anchors were not properly installed or both. The first five specimens had the same amount of material in the anchors but only two of them, BM-i-1 and BM-i-4, failed due to the fracture of the anchors. It was noted that in those two specimens, the edges of anchor holes were rather sharp due to inadequate grinding. This probably caused excessive stress concentration at the anchor bend and decreased anchor capacity in those two specimens.

The concrete failures of specimens BM-i-3 and BM-i-6 need to be avoided since they provide no information regarding the strength of the anchor system. Some of the concrete failures appeared to be caused by uneven loading and reaction surfaces.

3.5 EFFECTS OF BEND RADIUS ON CFRP ANCHORS - BEAM SPECIMENS

3.5.1 Objectives

In the previous tests, the widths of CFRP strips used to make anchors were selected based on previous research by Kim (2008). The studies by Kim show that the amount of material in CFRP anchors equal to 133% of that in the anchored CFRP sheet is adequate to cause the fracture of the anchored sheet. He recommended that 150% be used. However, two specimens designed according to the recommendation above failed due to fracture of the anchors, instead of the sheets (see Section 3.4). One possible cause was a stress concentration at the anchor bend, possibly caused by insufficient grinding of the edge of the anchor holes. (Figure 3.15)

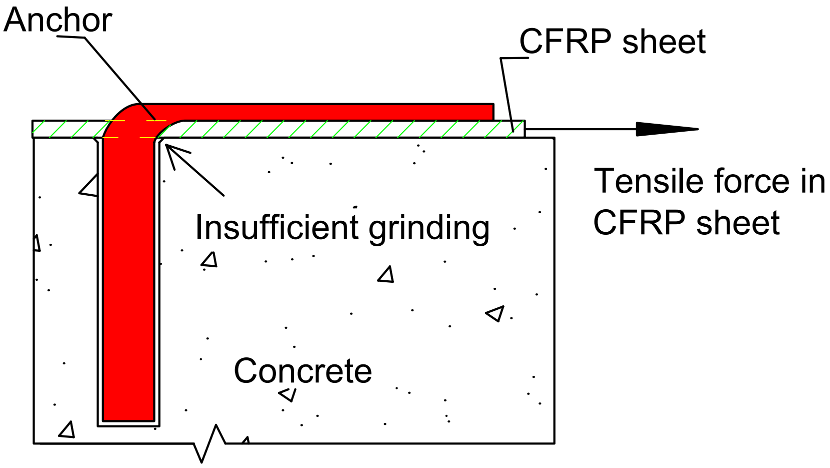


Figure 3.15 Insufficient grinding led to excessive stress concentration in the CFRP anchor

In order to verify this argument, a series of six specimens were tested to investigate the effects of bend radius on the anchor capacity. The specimens were divided into three groups; each of them had two beams with anchor hole edges rounded to achieve a specified radius of zero, 0.25 or 0.50 in. (Figure 3.16). The radius of edges of the holes was measured with a radius gage (Figure 3.17). It was assumed that the bend radius of the anchor is equivalent to the radius of the edge of the hole. Other parameters including the widths of CFRP sheets, anchors, embedment depth, and hole diameter were the same for all the specimens as shown in Table 3.7. For the purpose of investigating the anchor capacity, the width of the anchor was chosen smaller than that of the CFRP longitudinal sheet so that the specimens would fail by fracture of the anchor, instead of the CFRP sheet.

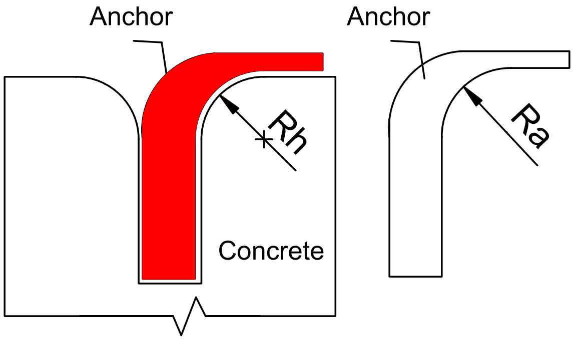


Figure 3.16 Bend radius achieved by grinding edges of the holes

Figure 3.17 Radius gage

3.5.2 Specimens, Test Setup and Test Procedure

The specimen geometry was kept the same as in the initial tests. In order to reduce the likelihood of concrete failure, steel bearing plates were added at the loading and support points. The plates were aligned and grouted to the concrete surface (Figure 3.18). A linear potentiometer was installed to record the deflection at mid-span. The test procedure was the same as in the first test series.

Figure 3.18 Test setup with bearing plates

3.5.3 Summary of Results

3.5.3.1 Ultimate loads and failure modes:

In this test series, two failure modes were observed: fracture of CFRP anchors (Figure 3.19 and Figure 3.20) and concrete failure (Figure 3.21). The use of bearing plates and grouting the plates to the beam improved the consistency of test results. Unfortunately, some concrete failures still occurred. A summary of the results is given in Table 3.7.

Figure 3.19 Failure caused by anchor fracture

Figure 3.20 Detail of anchor fracture

Figure 3.21 Concrete failure

Table 3.7 Result summary of bend radius tests

Specimen	Width of CFRP sheets	Width of CFRP anchors	Diameter of anchor holes (d)	Embedment depth (h)	Bending radius (r)	Failure load	Failure mode
	in	in	in	in	in	kip	
BM-b-1	2.66	2.22	0.5	4	0.00	8.96	Anchor fracture
BM-b-2	2.66	2.22	0.5	4	0.00	8.97	Anchor fracture
BM-b-3	2.66	2.22	0.5	4	0.25	10.46	Concrete failure
BM-b-4	2.66	2.22	0.5	4	0.25	10.71	Anchor fracture
BM-b-5	2.66	2.22	0.5	4	0.50	10.82	Concrete failure
BM-b-6	2.66	2.22	0.5	4	0.50	11.23	Concrete failure

3.5.3.2 *Effect of bend radius on CFRP anchors' capacity:*

Although undesirable failures of concrete occurred, the results show a significant increase in load capacity of the beams when the bend radius of the anchor increased. Compared to the specimens with zero radiuses, those with 0.25-in radius carried 18% more load and those with 0.5-in radius carried at least 23% more load.

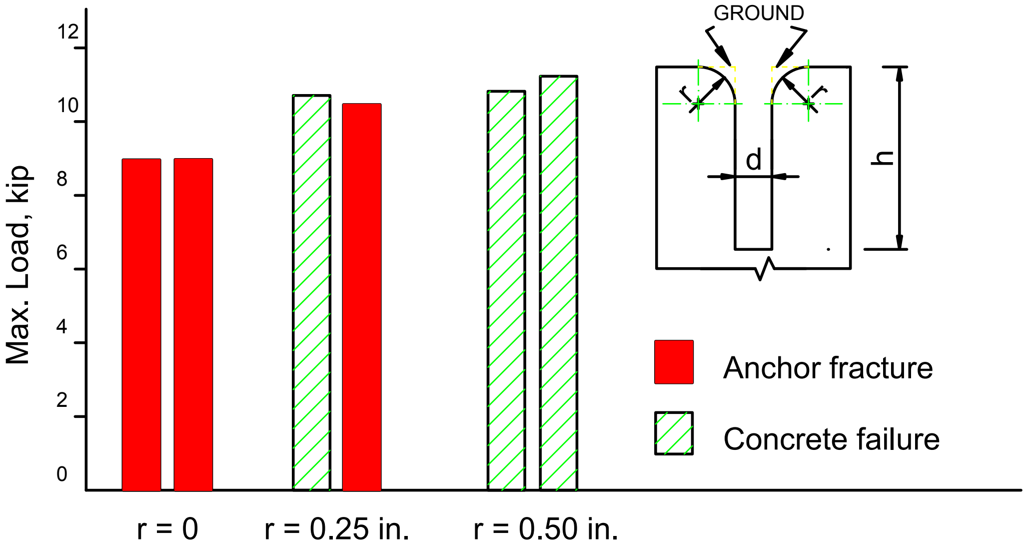


Figure 3.22 Effects of anchors' bend radius on maximum loads

3.5.3.3 *Load – Deflection relation:*

The load-deflection behavior of the specimens was basically the same as in the first series. There were initial displacements of the test machine at the beginning. The behavior was linear until cracking occurred at mid-span region. After cracking, debonding followed until failure of the beam (Figure 3.23).

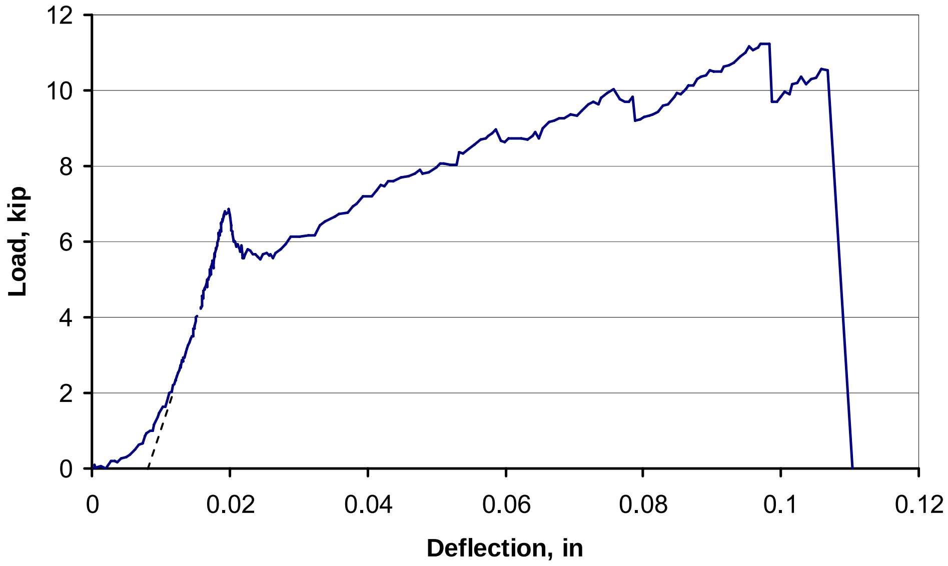


Figure 3.23 Load – Deflection relation

3.6 TESTS OF BEAM SPECIMENS WITH HIGH-STRENGTH CONCRETE

3.6.1 Objectives, Specimens, Test Setup and Test Procedure

In previous tests, some specimens still failed due to concrete tensile strength, instead of fracture of CFRP sheets or anchors, giving no usable information on the CFRP anchor system. In an effort to prevent this type of failure, high-strength concrete was used to make the beam specimens. Strength of the concrete at 28 days was 11,500 psi.

The same test setup as in the previous series was used (Figure 3.24). In addition, strain gages were attached to the CFRP sheets to measure strain in the primary direction of the fibers. For 2-in and 3-in sheets, one gage was used for each sheet (Figure 3.25). For each 4-in sheet, 2 gages were used across the width of the sheet (Figure 3.26). The data acquisition included load, deflection at mid-span and strains in CFRP sheet.

Figure 3.24 Test setup and deflection transducer

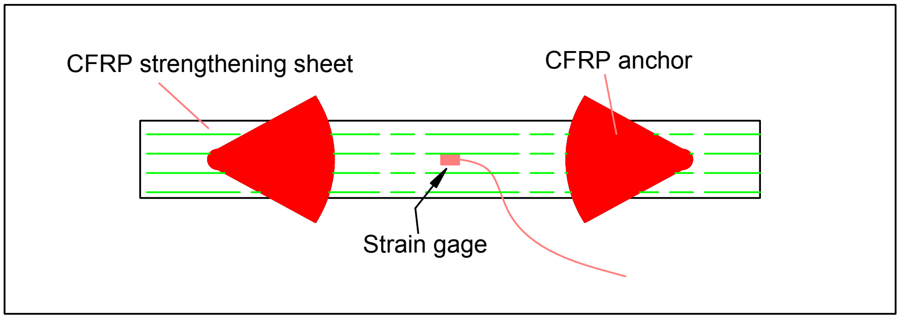


Figure 3.25 Strain gages for 2-in and 3-in CFRP sheets

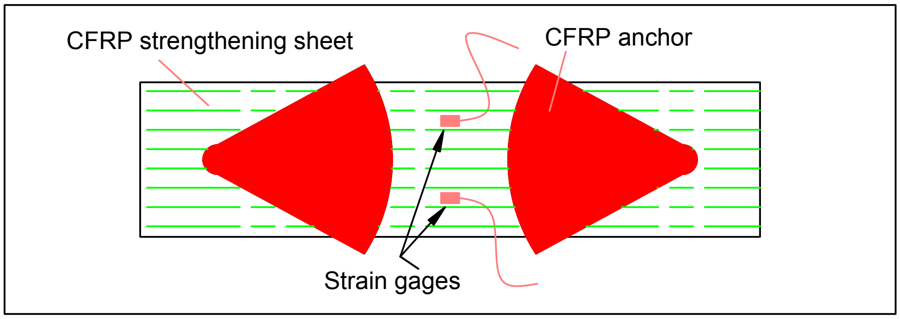


Figure 3.26 Strain gages for 4-in CFRP sheet

3.6.2 Results

3.6.2.1 Ultimate loads and failure modes

In this series, unexpected concrete failure still occurred in two of the specimens, BM-h-2 and BM-h-3 (Figure 3.27). A new failure mode, debondign between the CFRP sheet and the anchor fan, occurred in specimen BM-h-1 as shown in Figure 3.28 and Figure 3.29. No fracture of the CFRP sheet or anchor was observed. The maximum loads and strains in CFRP sheets are presented in Table 3.8.

Figure 3.27 Concrete failure

Figure 3.28 Failure caused by anchor debonding

Figure 3.29 Debonding between CFRP sheet and anchor

Table 3.8 Test results for beam specimens with high-strength concrete

Specimen	Width of CFRP sheet	Width of strip used to make anchor	Max load	Strain in CFRP	Failure mode
	in	in	kip	in/in	
BM-h-1	2	4	11.8	0.0063	Anchor debonding
BM-h-2	3	6	14.24	0.0055	Concrete failure
BM-h-3	4	8	13.43	0.0043	Concrete failure

3.6.2.2 Load – Deflection relation

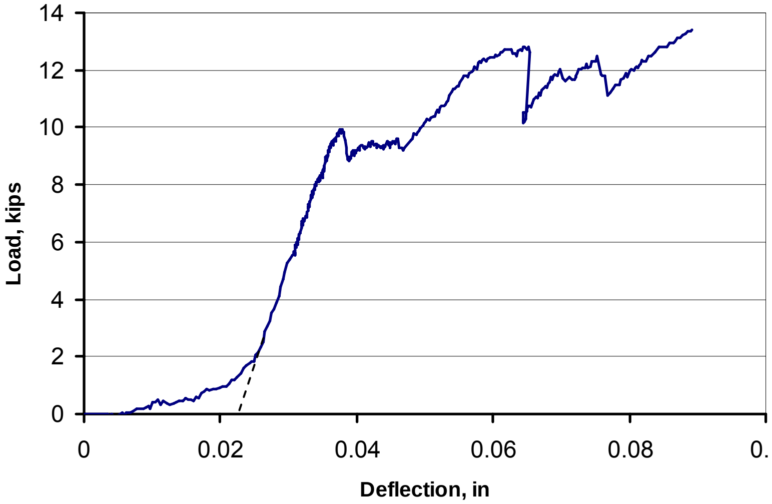


Figure 3.30 Load – Deflection relation for specimen BM-h-3

The load-deflection behavior of the specimens was basically the same as in the first series. There were initial displacements of the test machine at the beginning. The behavior was linear until cracking occurred at mid-span region. After cracking, debonding followed until failure of the beam (Figure 3.30).

3.6.2.3 Load – CFRP strain relation

Load-strain relation of the specimen with 4-in CFRP sheet, BM-h-3, is presented in Figure 3.31. The two strain values matched well indicating that the tensile stresses were distributed evenly across the CFRP sheet at the measured section. It is interesting that there seems to be a plastic plateau in the load-strain relation. Given the linear elastic tensile behavior of CFRP laminate, the plateau is due to debonding of CFRP from the concrete surface after cracking occurs. Load-strain relations in specimens with 2-in and 3-in CFRP sheets show similar behavior.

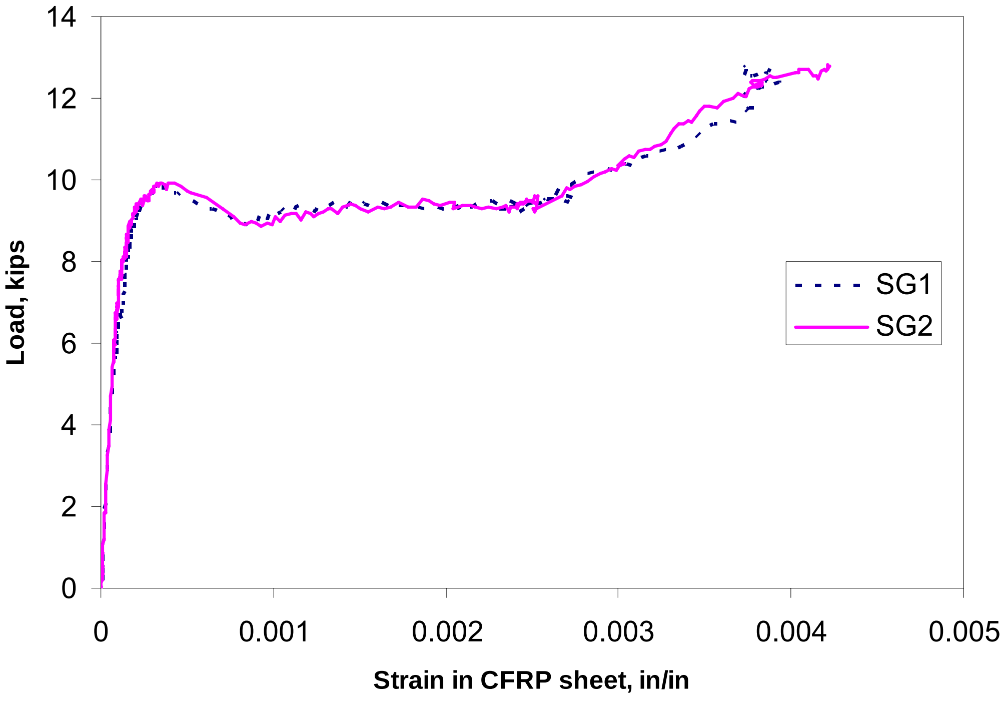


Figure 3.31 Load – CFRP strain relation of specimen BM-h-3

3.6.3 Discussion

The specimens with 3-in and 4-in CFRP sheets failed due to concrete at load levels much lower than the values calculated following the ACI 318 code provisions for shear and flexural strength. At failure, the strains in CFRP sheets were 0.55% in the 3-in sheet and 0.43% in the 4-in sheet, which are 65% and 50% of the design ultimate elongation respectively. This result indicates that the use of high-strength concrete did not prevent concrete failure before CFRP sheets fractured.

In the specimen with a 2-in sheet, loss of bond between the anchor and the sheet caused the failure. Given that all parameters of the anchors were similar to those in previous tests, it is suspected that the loss of bond was due to the quality of the epoxy used in this series. The container was not tightly covered after its first use, possibly contaminating the epoxy.

3.7 TESTS OF TWO-BLOCK SPECIMENS

3.7.1 Objectives and Test Specimens

In the previous tests of beam specimens, concrete failures occurred even when high-strength concrete was used (Section 3.6). In order to produce a test unaffected by concrete failure, three new specimens were tested. Each specimen consists of two concrete blocks sized 6 in by 8 in by 12 in, which is half the size of the beam specimens used in the previous test series. The two blocks were connected to each other by two CFRP sheets on opposite sides (Figure 3.32). The sheets were anchored into the concrete blocks. A hydraulic jack was placed between the blocks to push them apart. The jack created tensile forces in the CFRP sheets and was expected to fracture the sheets. A CFRP anchor system that results in such a failure of the sheet would be considered "qualified".

Strain gages were attached to CFRP sheets on both sides. For 2-in and 3-in CFRP sheets, one gage was used for each sheet (Figure 3.33) while two gages were used for each 4-in sheet (Figure 3.34).

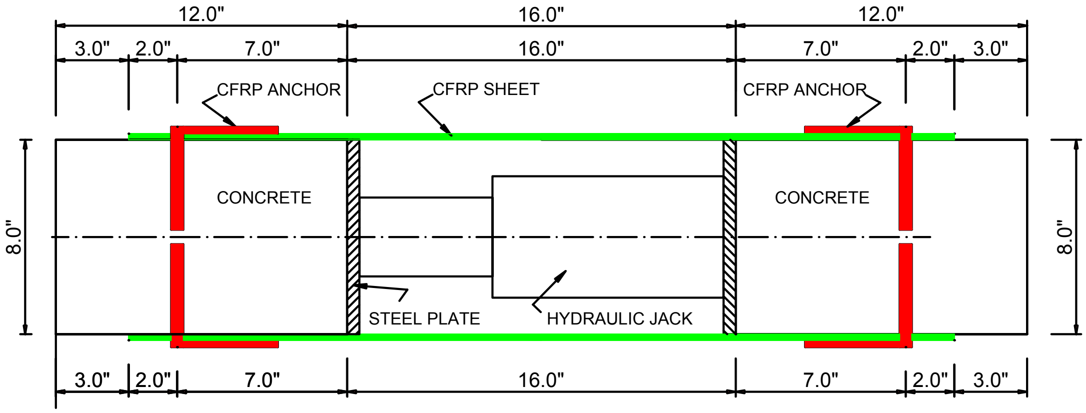


Figure 3.32 Two-block specimen

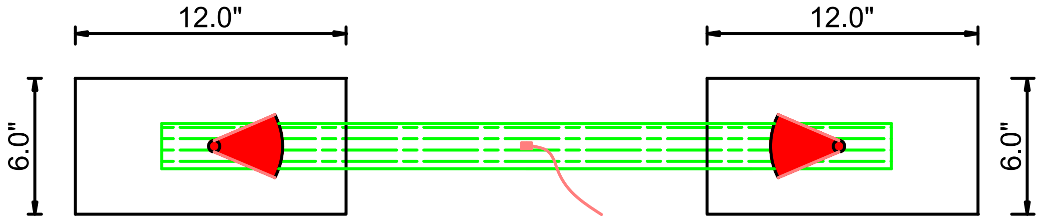


Figure 3.33 Strain gages for 2-in and 3-in CFRP sheets

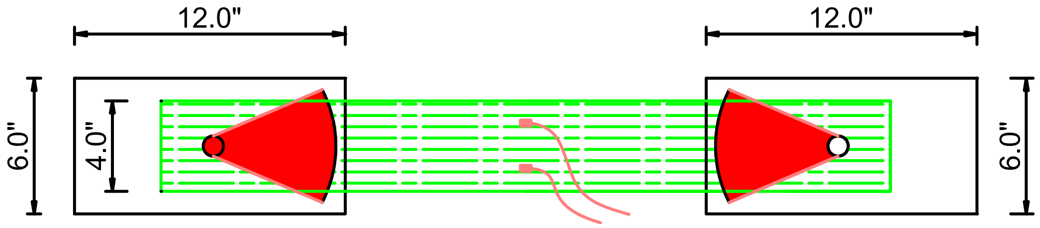


Figure 3.34 Strain gages for 4-in sheets

3.7.2 Parameters of the CFRP anchor system

The width of longitudinal CFRP sheets ranged from 2 in. to 4 in. The length of CFRP sheets allowed a 16-inch space between the two blocks for placing the hydraulic jack, load cell, spherical head and loading plates.

Width of CFRP anchors was two times greater than that of longitudinal CFRP sheet to account for stress concentration at anchor bend. Fan length, fan angle and length of anchors were determined the same way as in the first test series (see 3.4.2.2).

Depth of anchor holes was 3.5 inches due to limited width of the concrete blocks. Diameter of the holes was selected as described in 3.4.2.4.

3.7.3 Preparation of the specimens

In addition to the general steps presented in chapter 2, preparation of the two-block specimens required careful alignment of the concrete blocks so that the tensile force was distributed equally between the two CFRP sheets. Two wood planks were fixed to the base to frame the two concrete blocks. Two plywood panels covered with plastic sheets were placed between the blocks to serve as bases for applying CFRP sheets (Figure 3.35).

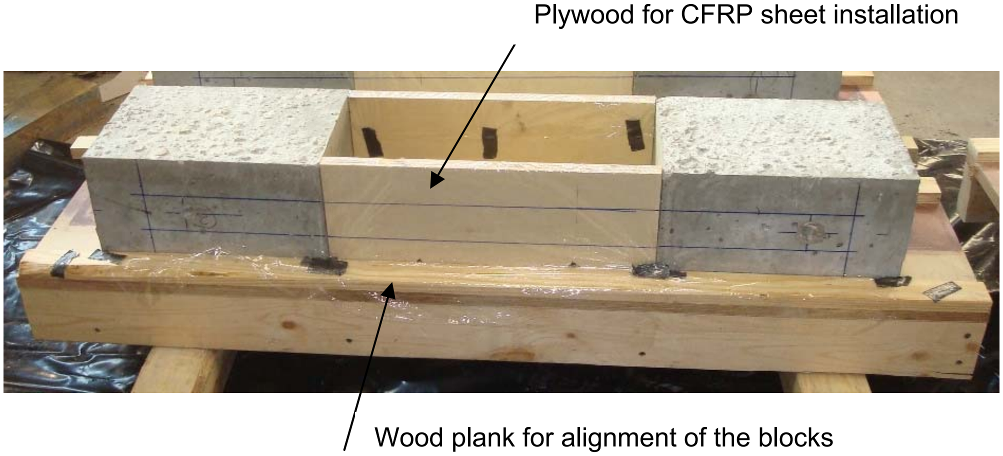


Figure 3.35 Alignment of two-block specimen

Installation of CFRP sheets and anchors followed the general instructions in Chapter 2. The only difference is that CFRP sheets and anchors were applied on the sides instead of the top of concrete blocks. This requires an injection of epoxy into the anchor holes. Special attention was given to avoiding sagging and bending of the sheet.

3.7.4 Test Setup

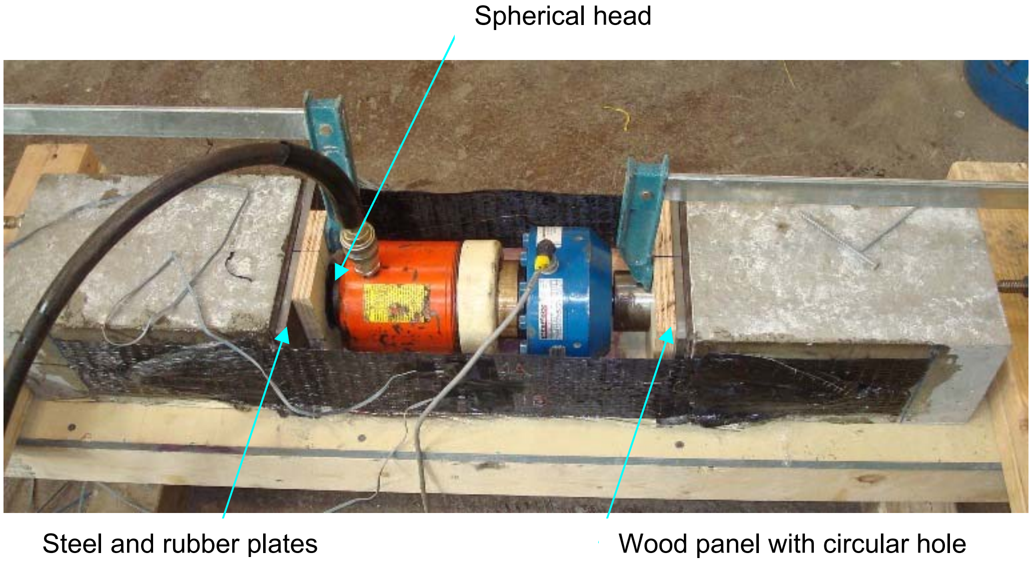


Figure 3.36 Test setup for 2-block specimen

The test setup for the two-block specimens consisted of a hydraulic jack, a load cell, a spherical head and steel and neoprene plates (Figure 3.36). The loading points at both ends were guided through circular holes in wood panels. The steel and neoprene plates were placed between the loading points and concrete surfaces to help distribute forces evenly.

Figure 3.37 Hand pump

3.7.5 Test Procedure

After loading was started by operating a hand pump (Figure 3.37), the test setup was checked for any visible eccentricity. If a significant eccentricity existed, the specimen was unloaded for the test set up to be adjusted. After the eccentricity is corrected, loading was restarted and steadily increased until failure occurred. The loading rate was selected according to ASTM FRP coupon test (ASTM D3039) in order to obtain a strain rate of approximately 0.01 min^{-1}.

3.7.6 Results

3.7.6.1 Ultimate loads and failure modes

Two failure modes were observed: anchor debonding and anchor fracture. No concrete failure occurred. In the specimen with 2-inch CFRP sheets, one sheet was debonded and separated from the anchor (Figure 3.38). The sheet was split into several parts but did not fracture. In the specimens with 3-in and 4-in CFRP sheets, fracture of one of the anchors caused failure (Figure 3.39). Loads and strains at failure are presented in Table 3.9.

Figure 3.38 Anchor debonding

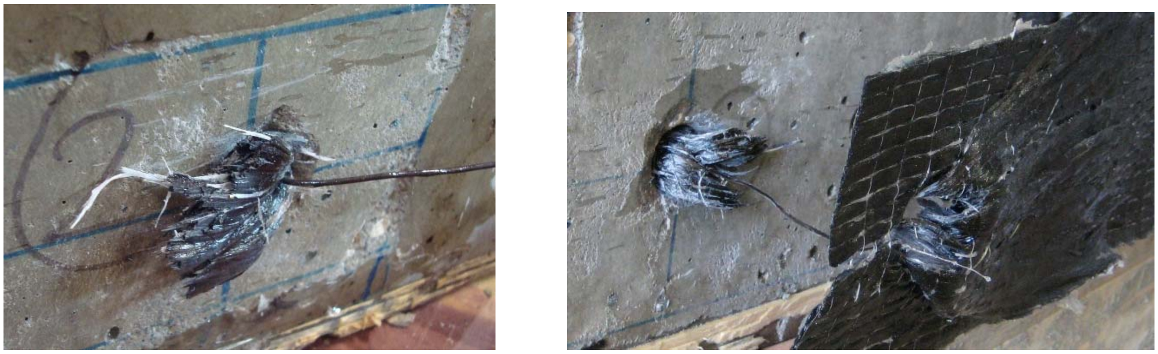


Figure 3.39 Anchor fractures, specimens BL-2 and BL-3

Table 3.9 Test results for 2-block specimens

Specimen	Width of CFRP sheet	Width of anchor	Max load	Strain in CFRP 1	Strain in CFRP 2	Failure mode
	in	in	kip	in/in	in/in	
BL-1	2	4	15.65	0.0030	0.0042	Anchor debonding
BL-2	3	6	21.79	0.0066	0.0075	Anchor fracture
BL-3	4	8	14.52	0.0037	0.0035	Anchor fracture

3.7.6.2 Load – CFRP strain relation

The relation between load and strain in CFRP sheet was linear as shown in Figure 3.40. There are differences between the strains on two sides, indicating an uneven distribution of forces in the two CFRP sheets. The difference was larger in specimens with smaller CFRP sheets.

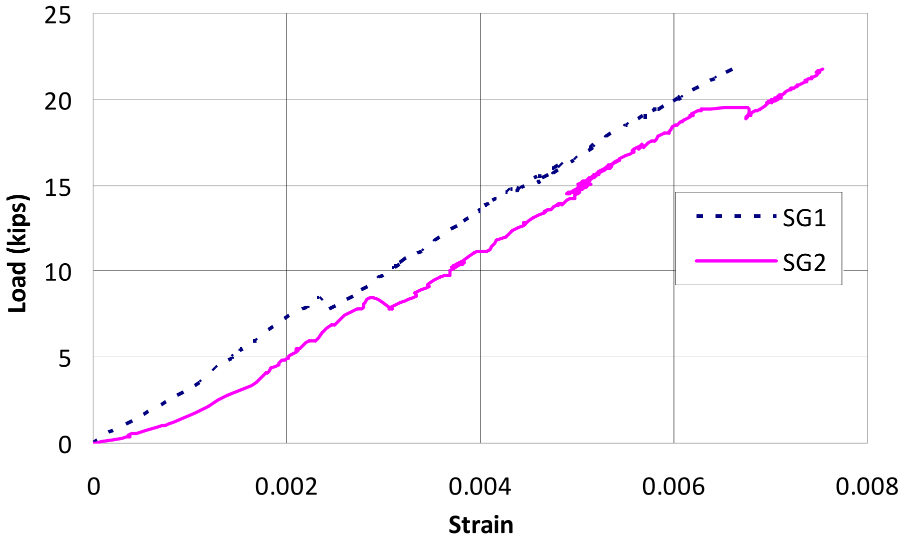


Figure 3.40 Load – CFRP strain relation of specimen BL-2

3.7.7 Discussion

In this test series, concrete failure was avoided. However, the expected fracture of CFRP sheets did not occur. The maximum strain in the CFRP sheets at failure was 0.75% in specimen BL-2, equivalent to 88% of the design ultimate strain. Debonding of an anchor in specimen BL-1 was likely because of the quality of the epoxy as mentioned in Section 3.6.3. The same epoxy was used for tests of the high-strength beam specimens discussed in Section 3.6 and the two-block specimens in this section.

It is remarkable that the capacity of large anchors in specimens with 3-in and 4-in sheets was very low. The cross-sectional area of these anchors is twice that of the longitudinal sheets but the full strength of the sheets was not developed. Specimen BL-3 with 4-in CFRP sheets and 8-in anchors carried a smaller load than specimen BL-1 with 2-in CFRP sheets and 4-in anchors. Possible reasons for this result are the low quality of epoxy, insufficient impregnation of the anchors and uneven distribution of force in the large anchors. These problems were more likely with horizontal installation of the anchors. The fibers in the anchors may have fractured one after another instead of at the same time, causing a reduction in the anchor capacity. It was observed that during the test of specimen BL-1, one concrete block was rotated and lifted off the base due to eccentricities of the load in vertical direction (Figure 3.41). These eccentricities likely caused non-uniform stresses across the width of CFRP sheet and reduced the anchor capacity. The test was restarted after wood frames were built to hold down the blocks.

Figure 3.41 One block lifted during testing

Figure 3.42 Blocks held down by wood frames

CHAPTER 4

Discussion of the Experimental Program

4.1 FAILURE MODES OF CFRP ANCHOR SYSTEMS

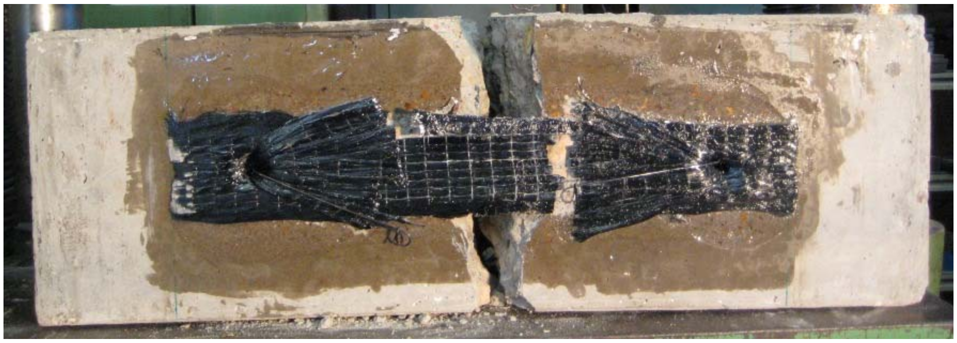
Understanding failure modes of CFRP anchor systems is critical to the quality control process. It is important to know what each failure indicates and what failure modes should be avoided. In the experimental program, four failure modes were observed as shown in Figure 4.1, including:

- Fracture of anchored CFRP strengthening sheet
- Fracture of CFRP anchors
- Debonding between CFRP anchors and strengthening sheet
- Failure of concrete behind the anchors

4.1.1 Fracture of anchored CFRP strengthening sheet

Except for some cases mentioned later in this section, fracture of the anchored sheet indicates that the CFRP sheet has developed its full strength in combination with the use of CFRP anchors. Therefore, this failure mode is the most desireable and can be used as a criterion to qualify the design and installation of the CFRP anchor system.

In some cases, the fracture of the CFRP strengthening sheet does not mean that its full strength is developed. For large CFRP sheets with a few large CFRP anchors, tensile stresses may not distribute uniformly across the width of the sheet. As a result, regions of higher stress may fracture first and will be followed by the fracture of the remaining sheet. If this type of failure occurs, the load capacity of the sheet is likely to be lower than the capacity when the entire sheet fractures simultaneously. For this reason, it may be advisable to monitor strains across the width of the CFRP sheet to verify the uniformity of stress distribution.



a) Fracture of CFRP strengthening sheet

b) Fracture of CFRP anchor c) Debonding of CFRP anchor

d) Failure of concrete behind the anchor

Figure 4.1 Failure modes of CFRP anchor systems

4.1.2 Fracture of CFRP anchors

This failure indicates that the anchorage does not have adequate capacity to develop the full strength of the CFRP sheet. Therefore, this type of failure is generally undesirable. In some applications where the anchors are designed to develop a lower stress level in the CFRP strengthening sheet than that at fracture, this failure may be accepted.

The results in this experimental program show that fracture of CFRP anchors depends not only on the amount of fibers used to make the anchors but also on bend radius, force transfer mechanism between the sheet and the anchor, and CFRP installation procedure. Test results of the two-block specimens presented in Section 3.7 show that a cross-sectional area of the anchor equal to twice of that of the strengthening sheet was not adequate to develop full strength of the sheet.

4.1.3 Debonding of CFRP anchors

This failure indicates a lack of bond between the anchor and the sheet. The reasons for this failure may be lack of bond area, low-quality of epoxy, improper installation or a combination of the factors. Debonding of the anchors is not an acceptable condition.

4.1.4 Failure of concrete behind the anchor

This failure indicates a lack of shear or flexural capacity of the concrete members. This is evidence that strengthening concrete structures with CFRP materials may change the structure failure modes. For example, when CFRP sheet and anchors are used to strengthen the flexural capacity in flexural-critical regions, failures may occur due to shear or flexure in other regions. This failure mode is generally undesirable.

4.2 SELECTION OF THE QUALITY CONTROL TEST

In order to find a simple quality control test, two types of specimens were tested: beam specimens and two-block specimens. The ultimate goal was to seek a test so that at failure of the specimens, anchored CFRP strengthening sheets fractured instead of debonding from the concrete surface. Although the two types of specimens have the potential to be used as a qualification test, the test results are not reliable due to failure of concrete. An evaluation of the two types of specimen is provided as follows.

4.2.1 Beam tests

4.2.1.1 Applicability

Nine beam specimens were tested in order to investigate their applicability as a qualification test. Only two of them caused fracture of the CFRP strengthening sheets. The other specimens failed due to lack of concrete capacity and fracture or debonding of the anchors.

Failures of the anchors could be prevented by increasing the amount of CFRP material used in the anchors and/or optimizing anchor details. The most critical details are the bend radius and the fan part of the anchors. Test results in Section 3.3 demonstrate that increasing the bend radius can significantly improve the anchor capacity. Debonding of the anchors could be prevented by increasing the area of the fan and maintaining the quality of the adhesive.

Failures of the concrete behind the anchors, either in shear, flexure or both, are not easy to prevent without a considerable increase in the sizes of the specimens. The 6x8 in beam specimen may be used for quality control tests of CFRP anchors with CFRP strengthening sheets less than 2 in wide. If CFRP sheets are larger, concrete failure may occur, unless larger beams are used. This size increase would make the specimens too heavy for one person to carry. Steel reinforcement may also be needed to prevent cracking under the beam’s self weight.

4.2.1.2 Complexity of the tests

Beam specimens were simple to make and test. The CFRP sheets and anchors were installed on the top concrete surface, instead of the bottom or sides. In addition, the test is similar to the ASTM standard test for concrete modulus of rupture. The workmanship, therefore, is rather easy to control.

The average time to prepare one specimen, including drilling holes, cleaning surfaces and preparing CFRP sheets and anchors, was 90 minutes. The time to prepare the test setup including hydro-stone grouting was 75 minutes. Each test was completed in about 15 minutes. In total, each specimen required approximately 180 minutes to prepare and test.

4.2.2 Two-block tests

4.2.2.1 Applicability

Three two-block specimens were tested. None of them resulted in fracture of the CFRP strengthening sheets. Two specimens failed due to fracture of the anchors and the other caused anchor debonding. The maximum strain in the longitudinal CFRP sheet was 0.0075, equivalent to 88% of the design ultimate elongation (0.0085). It appeared that the tests were not affected by concrete failures as in the beam specimens. However, the results and numer of the tests were not sufficient to determine whether this type of specimen could be improved to be considered for a quality control test.

4.2.2.2 Complexity of the tests

Compared to the beam specimens, the two-block specimens were more complicated to prepare and test. CFRP sheets and anchors were installed from the sides, instead of the top of concrete surfaces. Alignment of the two blocks had to be done very carefully in order to avoid eccentricities. Finally, each two-block specimen required two CFRP strengthening sheets and four anchors, doubling the number required in the beam specimen.

Regarding time consumption, each two-block specimen required about 200 minutes to prepare compared to 90 minutes in the beam specimen. The time for preparing test setup and testing was about 30 minutes. The total required time for one specimen was approximately 230 minutes.

4.3 FACTORS THAT AFFECT THE PERFORMANCE OF CFRP ANCHORS

In the experimental program, the following factors were shown to influence the capacity of CFRP anchors.

4.3.1 Bend radius of CFRP anchors

Test results in Section 3.5 showed that bend radius had a significant effect on CFRP anchor capacity. The larger the radius, the higher was the anchor capacity. The anchor with ½-in bend radius had 20-30% higher capacity than the one with zero radius. This means 20-30% of the materials used in the anchors can be saved if the edge of the anchor hole is rounded off. However, more labor is required to achieve higher bend radius. This result demonstrates the need for controlling the bend radius of CFRP anchors. Until more experimental data can be obtained, a bend radius of at least ¼-in. is recommended.

4.3.2 Quality of CFRP constituent materials and installation procedure

Several specimens with similar anchor designs failed due to anchor debonding at much lower load levels. Potential causes for this result are the quality of epoxy resin and improper installation of CFRP anchors, factors that are very important in the quality control of CFRP anchor systems.

4.4 RECOMMENDED QUALITY CONTROL PROCESS OF CFRP ANCHOR SYSTEMS

4.4.1 Quality of materials

The first step in controlling the quality of CFRP anchors is to control the quality of the materials. The storage and usage of the materials should strictly follow manufacturer’s instructions. To verify the quality of CFRP laminates, the Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials (ASTM D 3039/D 3039M – 07) can be used.

4.4.2 Preparation of CFRP anchors

Sizes of the anchors including width, length and diameter should be designed by an engineer and in the field, checked before installation.

4.4.3 Details of anchor holes:

The most important parameters are depth, diameter and corner radius. The holes should be free of dust and oil in order to obtain a good bond between the anchor and concrete element.

4.4.4 Installation procedure

In addition to ACI instruction for FRP wet-layup systems, attention should be paid to the following procedures when the installation procedure presented in Chapter 2 is applied:

- Insertion of CFRP anchors: there should be some measure to ensure that the anchors are fully inserted into the hole. In this experimental program, a steel wire tied at the middle of the anchor was used to push the anchor to its entire depth. In addition, the anchor insertion should not affect the alignment of CFRP sheet. Experience shows that problems frequently occurred during the insertion of anchors.
- Splaying CFRP anchors: special attention should be paid to fanning out the protruding end of the anchor over the strengthening sheet, particularly with large anchors. Care is needed to ensure proper bond between the anchor and the sheet.

4.4.5 Curing of CFRP anchor systems

Curing of CFRP systems should follow instructions of the CFRP manufacturers and ACI 440.

CHAPTER 5

Conclusions and Recommendations

5.1 CONCLUSIONS

In the experimental program, a total of 18 specimens were tested. Nine beam specimens and three two-block specimens were proposed for a qualification test of CFRP anchors. The other six beam specimens were tested to investigate the effect of bend radius on CFRP anchor capacity. A summary of the findings is presented as follows.

5.1.1 The need for the quality control of CFRP anchors

The experimental program demonstrated the need for quality control of CFRP anchors. Test results showed that CFRP anchor systems can fail in different ways including fracture of CFRP strengthening sheet, fracture of CFRP anchors, debonding between the sheet and the anchors and failure of concrete behind the anchors. Of these four failure modes, only the first one is acceptable, the others three generally should be avoided unless the designer does not want to utilize the strength of the CFRP material. Quality control of CFRP anchors is critical to ensure that the desired failure and capacity are developed.

The research program also showed that capacity of a CFRP anchor can vary considerably. With regard to the required amount of material in CFRP anchors to account for stress concentration due to anchor bend, Orton (2008) suggested that twice of the cross-sectional area of the strengthening sheet be used for the anchors. Kim (2008) recommended that the cross-sectional area of the anchors be 50% more than that in the base sheet. Test results in Section 3.4 of this report show that anchors with area equal to 150% that of strengthening sheet may not account for the stress concentration at anchor bend. These differences highlight the need for quality control processes to maintain reliable performance of CFRP anchor systems.

5.1.2 Factors of the quality control process of CFRP anchor systems

Based on test results and experience from the experimental program, the following factors are considered having critical effects on performance of CFRP anchor systems and should be included in the quality control process:

- Quality of CFRP materials, including resins and adhesives.
- Sizes of CFRP anchors
- Details of anchor holes
- Installation procedure of CFRP sheets and anchors
- Curing of the CFRP system

5.1.3 Selection of qualification test for CFRP anchors

Two types of specimens were proposed for the qualification test. The beam specimen is simple and easy to conduct. However, concrete failures due to shear and/or flexure occurred, providing no information regarding performance of the CFRP anchor system. There was no easy way to improve the specimen's concrete capacity without a significant increase in its sizes. The two-block specimen appears not to be affected by concrete failures. However, it requires a great deal of labor to prepare the specimen, including alignment of the blocks, drilling holes and installation of CFRP sheets and anchors. It is also not easy to prevent eccentricities which may cause undesirable forces such as twisting and bending in the sheets and anchors. Due to these issues with the proposed specimens, other types of specimens and test setup should be considered for a CFRP anchor qualification test.

5.1.4 Effects of bend radius on CFRP anchor capacity

Six specimens were tested to quantify the effects of bend radius on CFRP anchor capacity. A comparison of specimens having zero, ¼-in and ½-in bend radii shows significant increase in load-carrying capacity when the edges of anchor holes are rounded. Based on these results, it is recommended that the edges of anchor holes be rounded to a radius of at least ¼ in.

5.2 RECOMMENDATIONS FOR FUTURE STUDY

1) With regard to selection of a qualification test, other types of specimen should be considered. It is important that the test not be affected by concrete failures. The test should also require as small amount of CFRP sheets and as few anchors as possible so that it can be repeated without too much labor. An option would be a direct shear test of the anchors, but such a test would require development of grips to load the CFRP sheet.

2) More studies are needed to quantify the effects of bend radius on the anchor capacity. Tests to compare the capacity of a straight anchor and bent anchors with different radiuses are recommended. The results from such tests can provide a more reliable basis for calculating the required amount of material in CFRP anchors in order to account for stress concentration.

3) Tests of other types of FRP materials and anchor configurations should be performed.

APPENDIX A

Coupon Test Results

A.1 PICTURES OF COUPON FAILURES

Figure A.1 Failure of coupon C-1

Figure A.2 Failure of coupon C-2

Figure A.3 Failure of coupon C-3

Figure A.4 Failure of coupon C-4

Figure A.5 Failure of coupon C-5

Figure A.6 Failure of coupon C-6

Figure A.7 Failure of coupon C-7

A.2 COUPON TEST RESULTS

Table A.1 Coupon test results

Coupon	Width	Thickness	Ultimate load	Ultimate stress	Ultimate strain	Average tensile modulus
	in	in	kip	ksi	in/in	ksi
C-1	2	0.04	8.4	105	N.A	N.A
C-2	2	0.04	8.94	111.75	0.0091	12280
C-3	2	0.04	8.05	100.625	0.0091	11058
C-4	2	0.04	6.26	78.25	0.0072	10868
C-5	2	0.04	9.6	120	0.0076	15789
C-6	2	0.04	8.85	110.625	N.A	N.A
C-7	2	0.04	9.19	114.875	N.A	N.A
Average				105.875	0.00825	11402

(N.A: results not available)

APPENDIX B

Installation of Strain Gages to CFRP Laminates

B.1 STRAIN GAGES AND ADHESIVES

B.1.1 Strain gages

Table B.1 Strain gage properties

Property	Value
Type	BFLA – 5 – 8 – 3LT
Gauge length	5 mm
Gauge factor	2.1
Gauge resistance	120 Ω
Transverse sensitivity	0.1
Wire length	3 – 5m

B.1.2 Adhesives

Two types of adhesives were used to install strain gages to CFRP laminates (Figure B.1):

1. PS adhesive:

PS is a two-component room-temperature-curing polyester adhesive and consisted of Drug A (main agent) and Drug B (hardener). PS adhesive was used as surface precoating agent for bonding strain gages.

2. CN-Y adhesive

CN-Y is a single component room-temperature-curing adhesive for strain gages. CN-Y adhesive was used to bond strain gages to the PS precoated surface. Curing time of CN-Y adhesive was 60-120 seconds. The time required for starting measurements was 60 minutes.

Figure B.1 Adhesives for installation of strain gages to CFRP

B.2 INSTALLATION PROCEDURE

B.2.1 Installation of PS adhesive to CFRP laminates

1. Put Drug A of the PS adhesive into a mixing vessel (Figure B.2)
2. Drop the right amount of Drug B into the Drug A and mix them (Figure B.3)
3. Apply the mixed adhesive to the CFRP surface (Figure B.4)
4. Place a piece of gage binder over the adhesive, smooth it out and tape its ends (Figure B.5)
5. Let the adhesive cure for at least 5 hours

Figure B.2 Put Drug A of PS adhesive into a mixing vessel

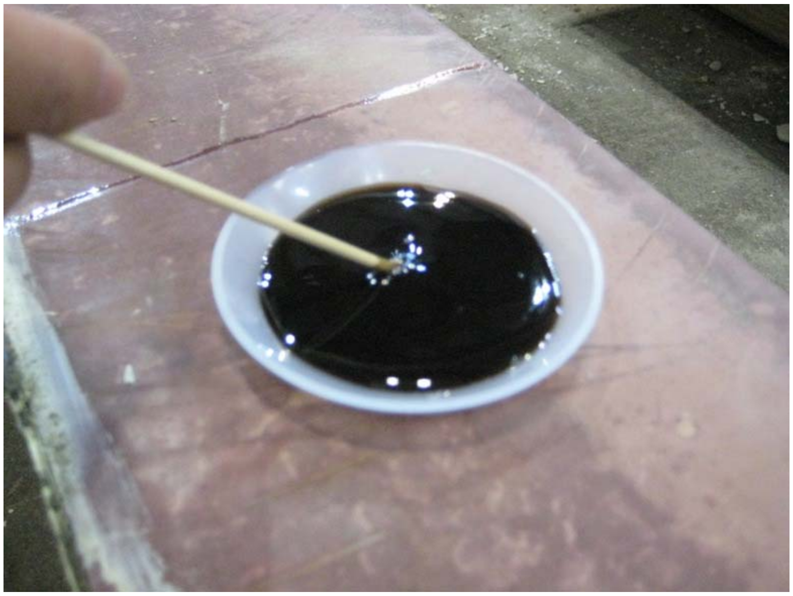


Figure B.3 Drop Drug B of PS adhesive into the Drug A and mix

Figure B.4 Apply the mixed PS adhesive to CFRP laminate

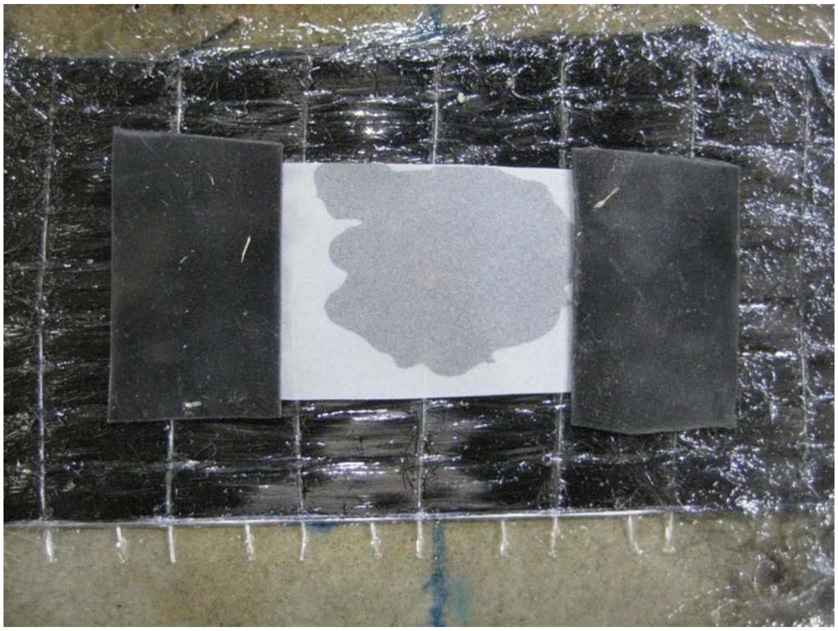


Figure B.5 Cover the adhesive with a piece of gage binder

B.2.2 Installation of strain gages to the PS surface

1. Remove the paper covering the PS adhesive (Figure B.6)
2. Clean and smooth the surface with sand paper if necessary
3. Use plastic tape to stick the strain gage to the PS adhesive. The circuit side of strain gage sticks to the tape (Figure B.7)
4. Peel off the plastic tape (Figure B.8)
5. Apply the CN-Y adhesive to the gage or to the PS surface
6. Press on the plastic tape to stick the gage to the PS surface (Figure B.9)
7. Keep pressing for 1-2 minutes
8. Remove the plastic tape (Figure B.10)
9. Check if the gage completely sticks to the surface. If there is void under the gage as shown in Figure B.11, it should be removed and replaced with a new one.
10. Apply water-proof coating if necessary
11. Cover the gage with a neoprene sheet for protection (Figure B.12)
12. Let the adhesive cure for at least 1 hour before testing

Figure B.6 PS precoated surface

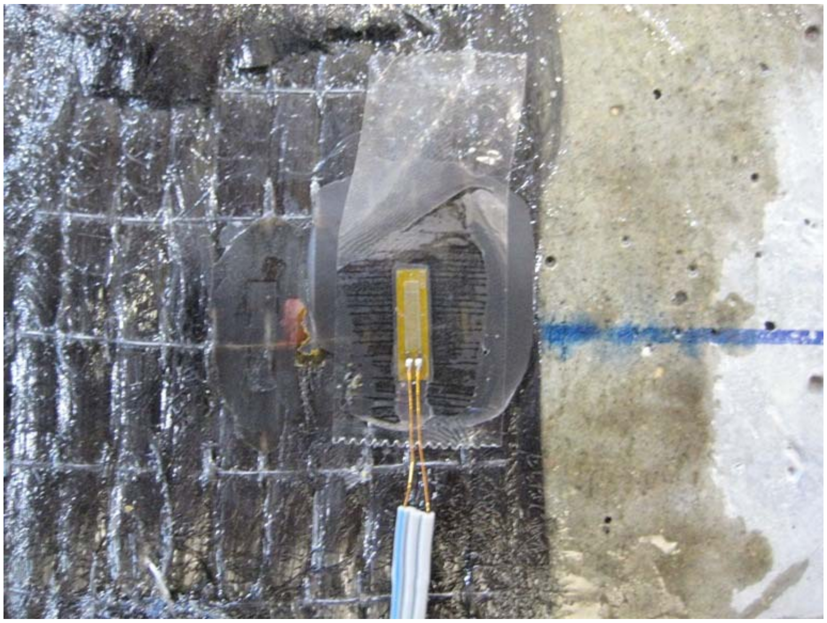


Figure B.7 Stick the strain gage to PS surface with plastic tape

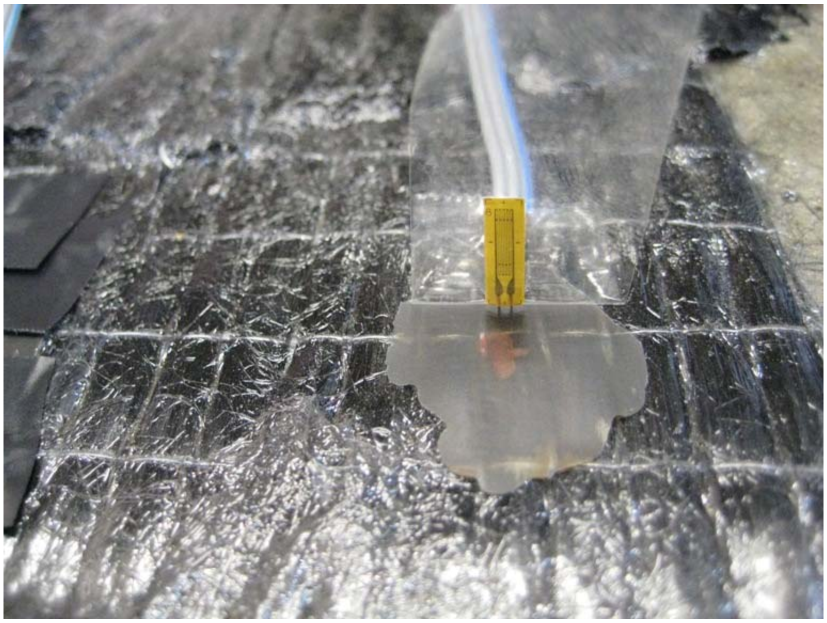


Figure B.8 Peel off the plastic tape

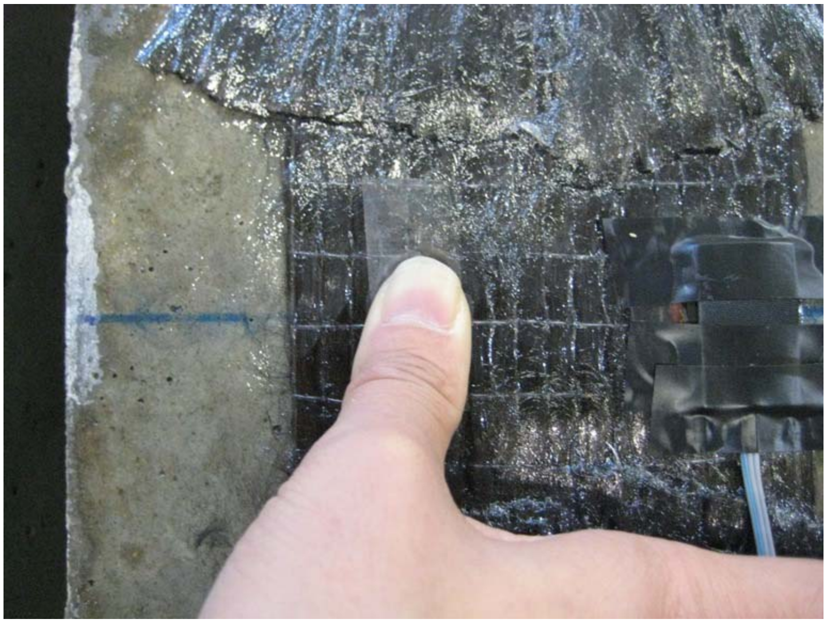


Figure B.9 Press on the plastic tape

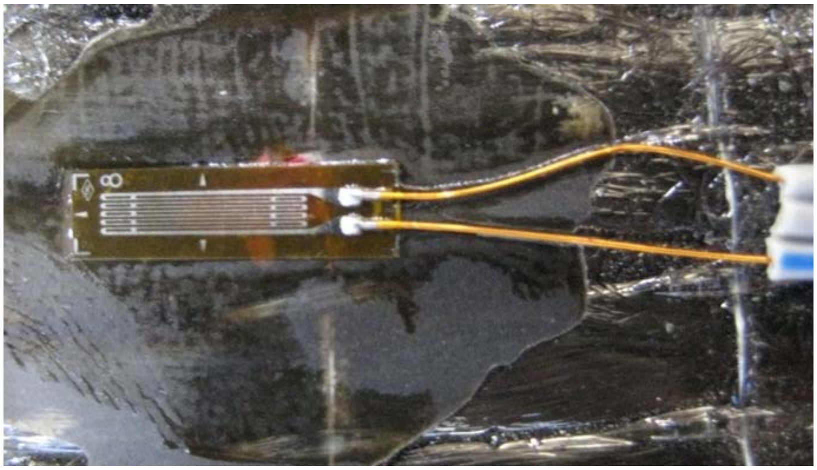


Figure B.10 Remove the plastic tape

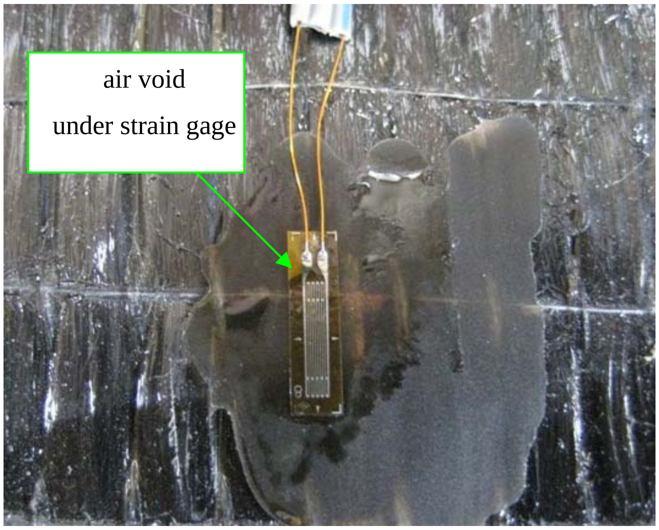


Figure B.11 Unusable gage due to void

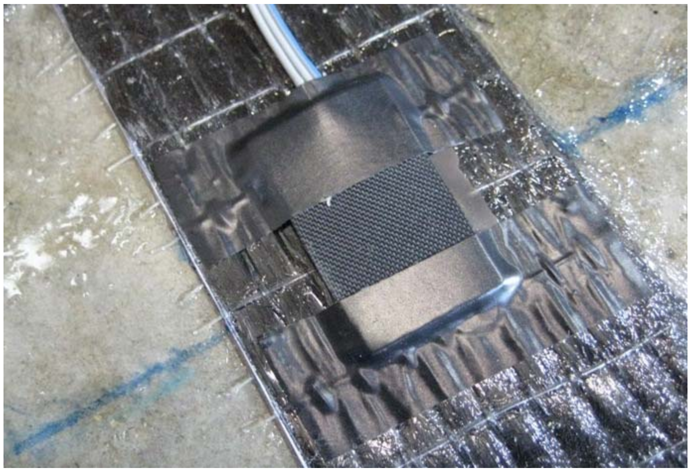


Figure B.12 Cover the gage for protection

APPENDIX C

Load–Deflection Relationship of Beam Specimens

C.1 BEAM SPECIMENS IN THE FIRST SERIES – SECTION 3.4

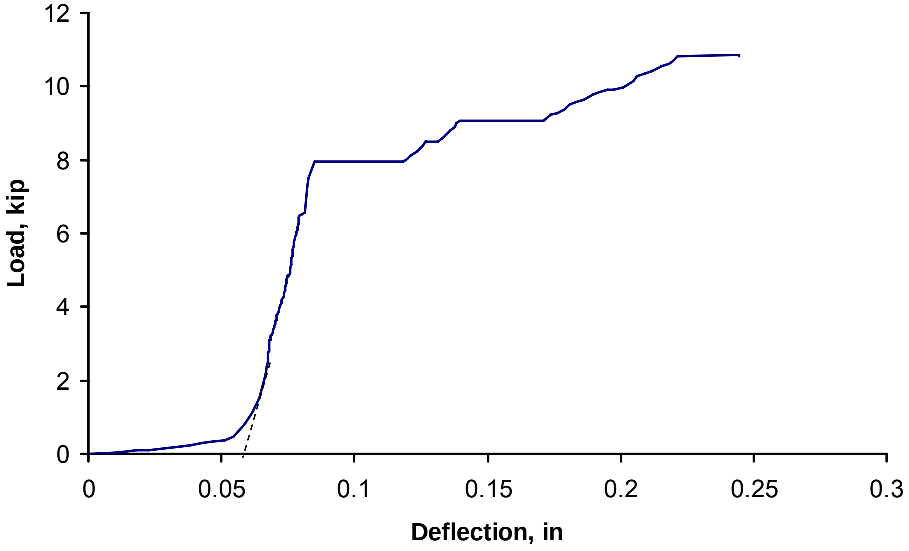


Figure C.1 Load – Deflection relation, BM-i-1

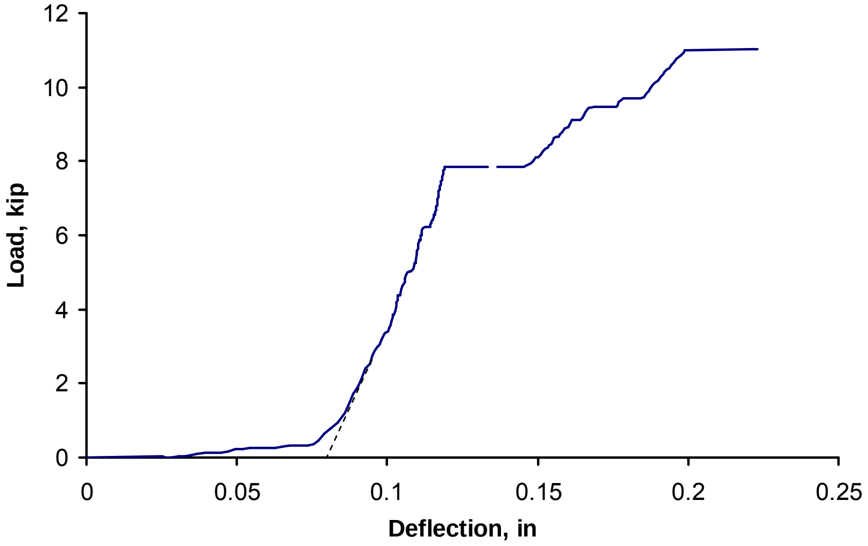


Figure C.2 Load – Deflection relation, BM-i-2

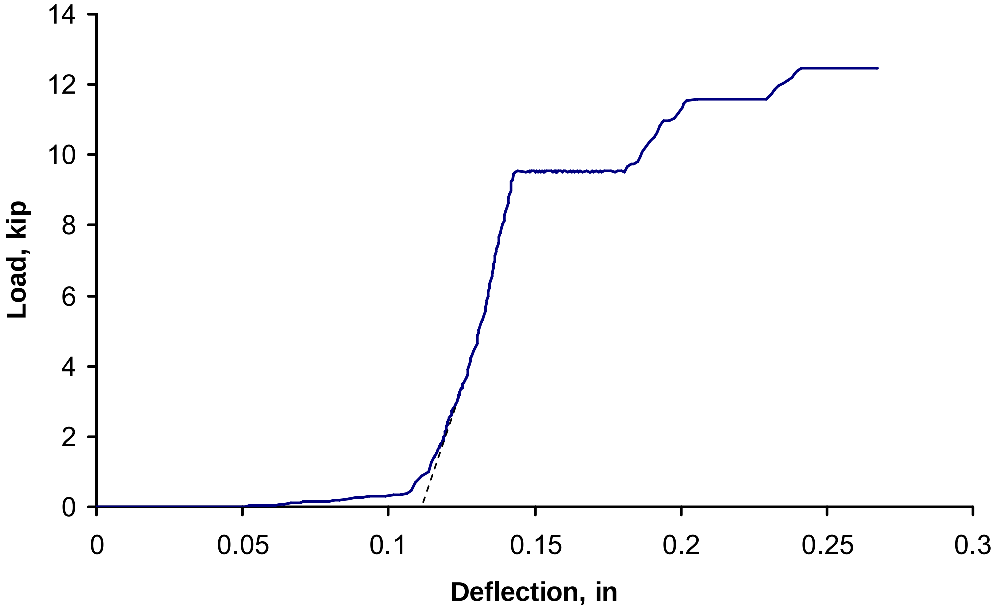


Figure C.3 Load – Deflection relation, BM-i-3

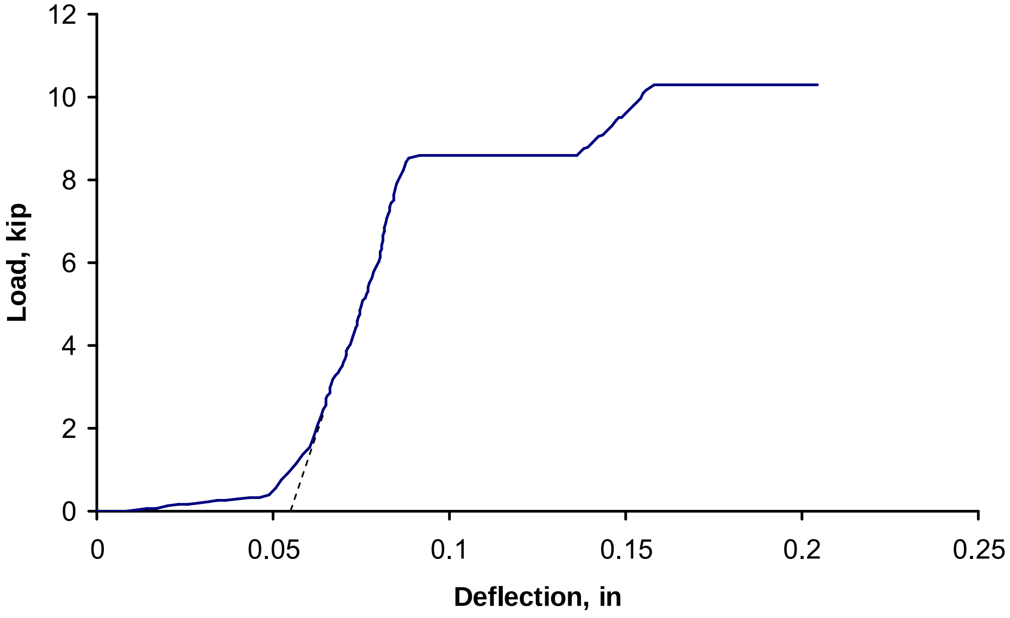


Figure C.4 Load – Deflection relation, BM-i-4

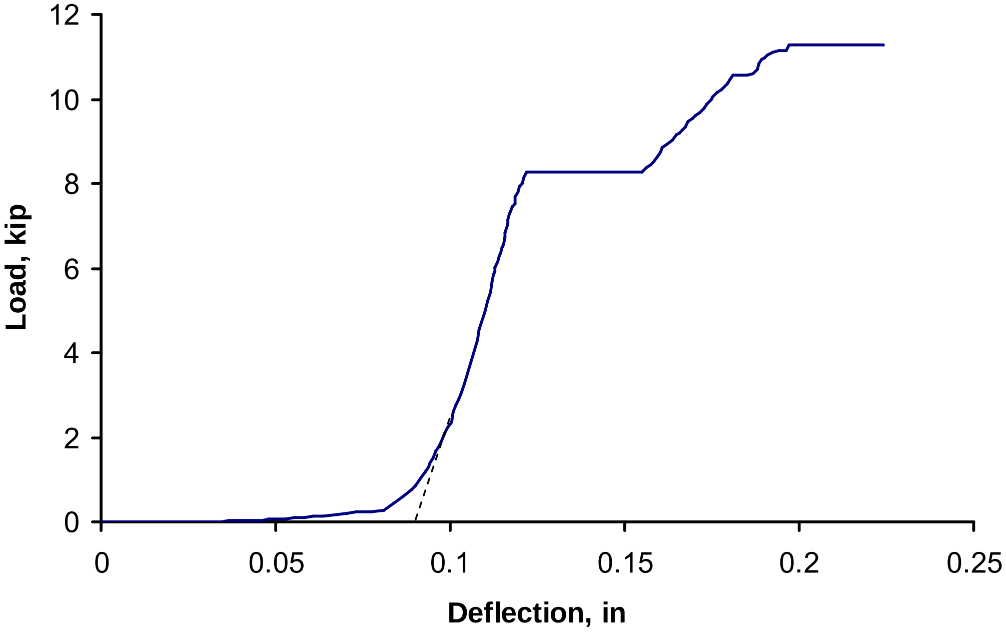


Figure C.5 Load – Deflection relation, BM-i-5

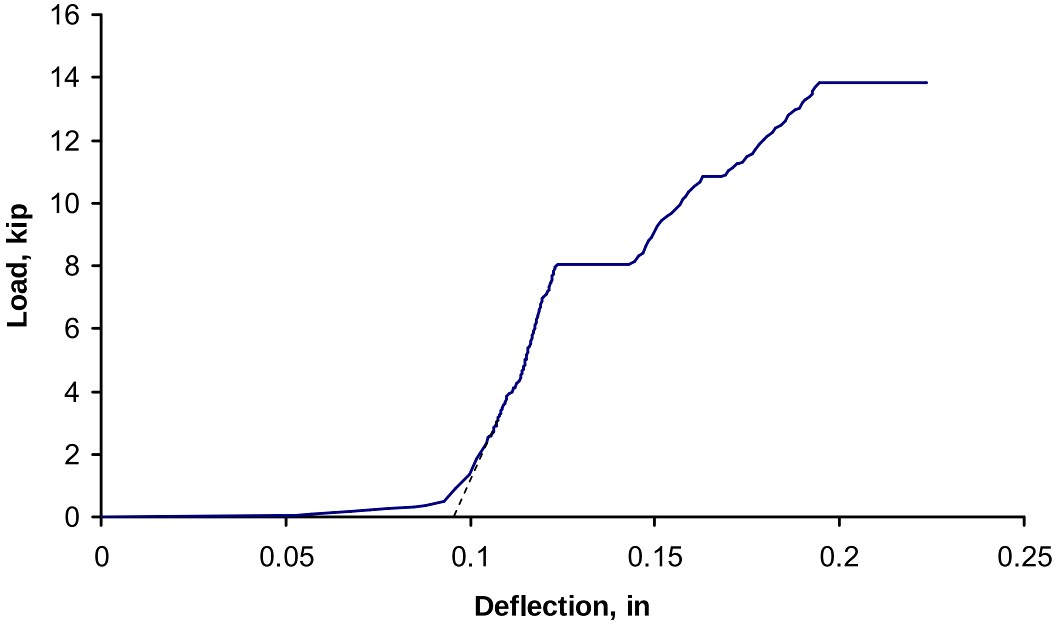


Figure C.6 Load – Deflection relation, BM-i-6

C.2 BEAM SPECIMENS IN THE SECOND SERIES – SECTION 3.5

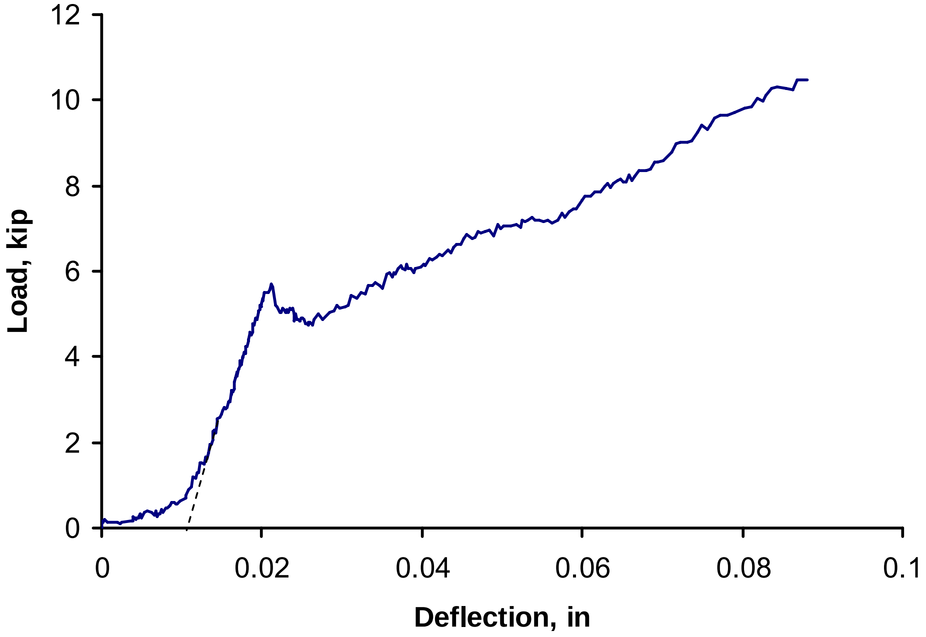


Figure C.7 Load – Deflection relation, BM-b-3

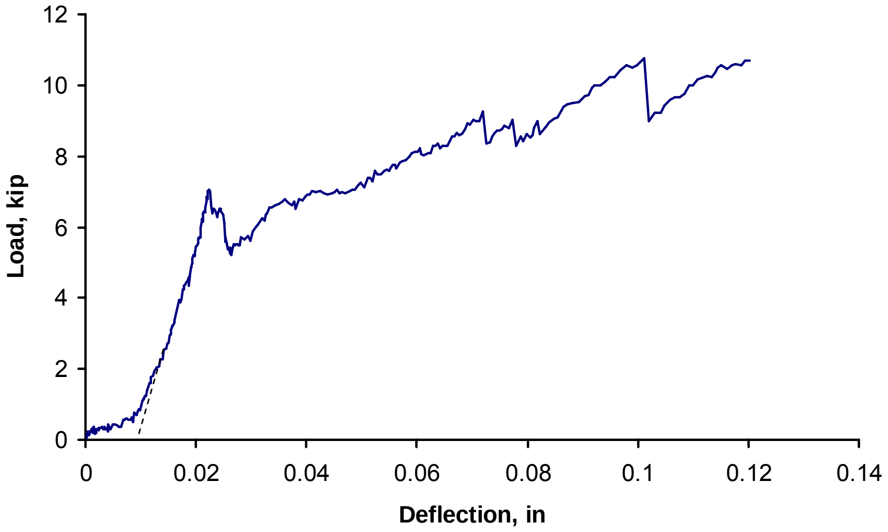


Figure C.8 Load – Deflection relation, BM-b-4

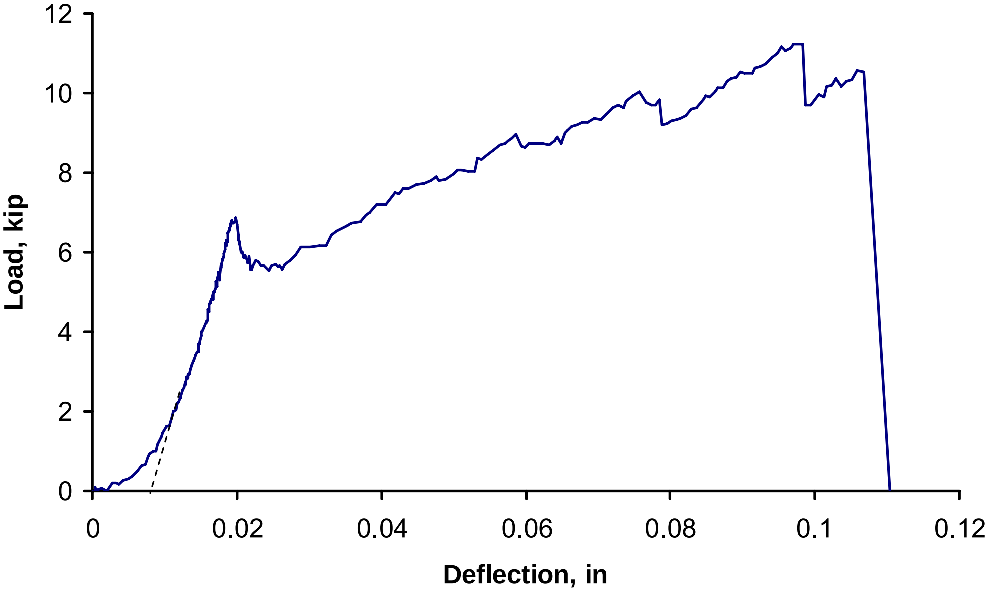


Figure C.9 Load – Deflection relation, BM-b-5

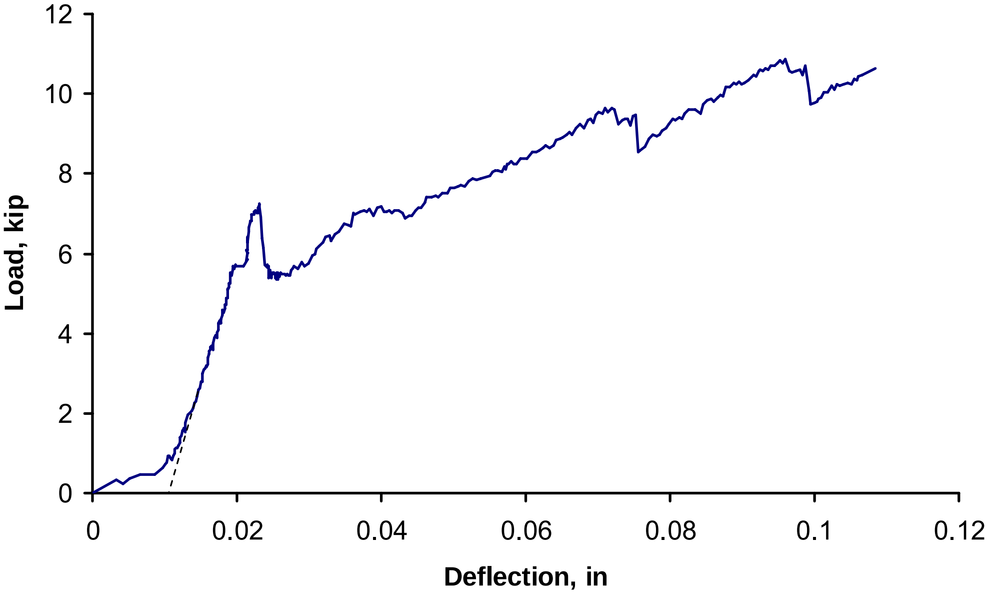


Figure C.10 Load – Deflection relation, BM-b-6

APPENDIX D

Formwork

Figure D.1 Formwork for beam specimens

Figure D.2 Formwork

Figure D.3 Pre-formed holes using backer rods

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