Rehabilitation of Poorly Detailed RC Structures Using CFRP Materials

by

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Rehabilitation of Poorly Detailed RC Structures Using CFRP Materials

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Abstract

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In many reinforced concrete structures built in the 1970's and earlier, bottom beam reinforcement is not continuous and if a column support is lost due to terrorist attack or other unexpected action, the structure could be vulnerable to progressive collapse. The use of CFRP material may provide a solution for rehabilitating such structures. CFRP materials can not develop full tensile capacity unless they are properly anchored to the reinforced concrete structure. The intent of this study is to find an effective method of anchoring CFRP material to a reinforced concrete beam so that the ultimate tensile strength of the CFRP is realized. In this study, ten reinforced concrete beams rehabilitated using different configurations of anchors were tested to assess the effectiveness of the anchors. Both CFRP anchors and CFRP U-wraps were investigated. The rehabilitated beams were loaded until failure of the CFRP material or anchor occurred. Different failure modes, strengths and deformation capacities of the rehabilitated beams were observed depending on the configurations of anchors. The maximum capacity was obtained using a combination of CFRP anchors and U-wraps.

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CHAPTER 1
INTRODUCTION

1.1 MOTIVATION

In many reinforced concrete structures built in the 1970's and earlier, bottom beam reinforcement is not continuous and if a column support is lost due to terrorist attack or other unexpected action, the structure could be vulnerable to progressive collapse. The beams may not develop catenary action if the reinforcement is not continuous. The use of Carbon Fiber Reinforced Polymer (CFRP) materials may provide a solution for rehabilitating such structures.

1.2 OBJECTIVE

CFRP materials can not develop full tensile capacity unless they are properly anchored to the reinforced concrete structure. The intent of this study is to find an effective method of anchoring CFRP material to a reinforced concrete beam so that the ultimate tensile strength of the CFRP is realized.

The basic rehabilitation technique for this program was installation of CFRP materials on the sides of the beam to provide continuity to bottom reinforcements and is shown in Figure 1.1 and 1.2. A CFRP sheet was attached to the concrete surface by epoxy resin and additional anchorage using CFRP materials in order to develop full tensile capacity of CFRP sheet after delamination of CFRP sheet occurs.

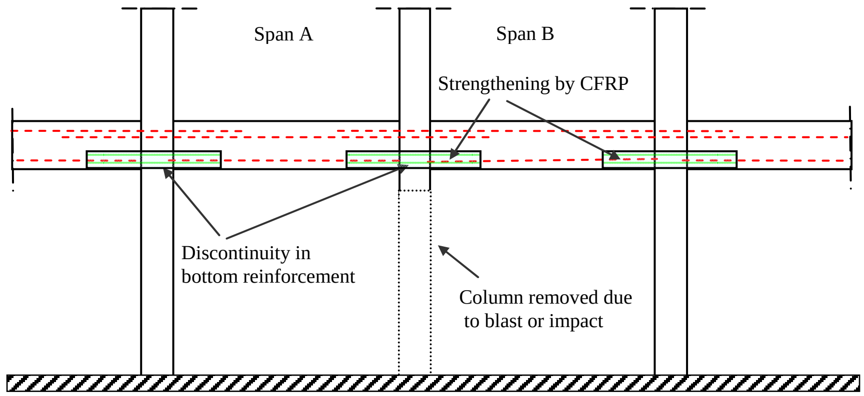


Figure 1.1 Rehabilitation Technique

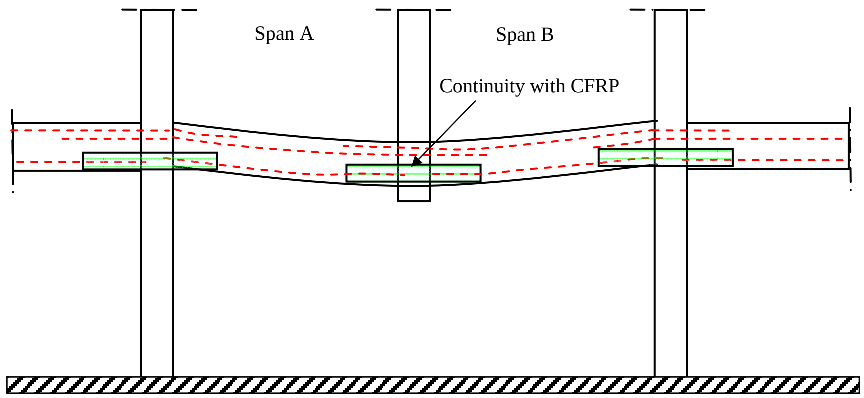


Figure 1.2 Behavior of Rehabilitated Structure after Removal of the Column

CHAPTER 2
BACKGROUND

2.1 LITERATURE REVIEW

2.1.1 Continuity in Members of Structures

Continuity in members of structures is discussed in *ASCE 7-02, Section 1.4, General Structural Integrity.* According to the section, local damage in the structure shall not extend disproportionately to the remaining portion of the structure. Damage is limited by providing sufficient continuity and redundancy, or energy-dissipating capacity (ductility), or a combination thereof, in the member of structure. It clearly expresses the requirement of continuity in the structural members although it does not discuss specific methods to achieve structural integrity.

Continuity in members of structures is also discussed in *Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects, (2003, US General Service Administration).* One of the recommended structural characteristics in the document (Section 4 Reinforced Concrete Building Analysis and Design) to provide a robust structure and to increase the probability of achieving a low potential for progressive collapse is 'the use of detailing to provide structural continuity and ductility' in reinforced concrete structures. It also expresses correct detailing of connections to provide *beam-to-beam continuity across a column.* The existing structures considered in this research do not have such continuity. The document also recommends that existing structures undergoing modernization should be upgraded to new construction requirements. This means that an existing structure rehabilitated to limit progressive collapse should have the same level of the continuity in the members as a new structure designed to limit progressive collapse.

2.1.2 Flexural Strengthening Using CFRP Materials

Design guidelines for rehabilitation of reinforced concrete structures using CFRP materials are provided by *ACI 440.2R-02, Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures.* Chapter 9, Flexural Strengthening, of the document includes design procedure for flexural strengthening of reinforced concrete structures that is topic of this report.

The main flexural design procedure of ACI 440.2 R-02 follows ACI318-99 and is based on strain compatibility and internal force equilibrium. ACI 440.2 R-02 recommends the use of the strength reduction factors ϕ required by ACI-318-99 (Eq.2-1) with an additional strength reduction factor ψ_f of 0.85 applied to the flexural contribution of FRP reinforcement alone. Equation (2-2) is an application of ψ_f factor to a reinforced rectangular section with tension reinforcement only.

$$\phi M_n \geq M_u \qquad \textbf{\textit{(2-1)}}$$

$$M_n = A_s f_s (d - \frac{\beta_1 c}{2}) + \psi_f A_f f_{fe} (h - \frac{\beta_1 c}{2}) \qquad \textbf{\textit{(2-2)}}$$

M_n is the nominal moment strength, M_u is the factored moment at the section, *d* and *c* are the depth to the steel reinforcement and neutral axis, *h* is the overall thickness, A_s and f_s are area and stress in steel reinforcement, A_f and f_{fe} are area and effective stress in FRP external reinforcement, and β_1 ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis (Figure2.1).

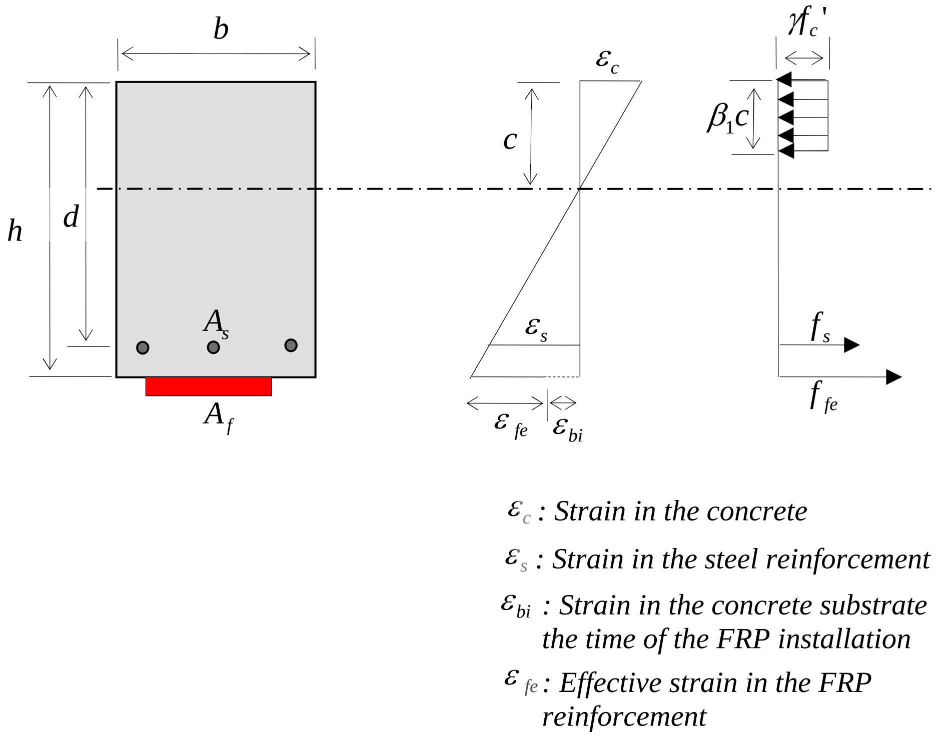


Figure 2.1 Internal Strain and Stress Distribution for a Rectangular Section under flexure at ultimate stage.

FRP delamination can occur if the force in the FRP cannot be sustained by the substrate. ACI 440.2 R-02 assumes that FRP delamination precedes fracture of FRP materials. In order to prevent the delamination, a limitation is placed on the strain level developed in the CFRP through the specification of an effective stress in the FRP external reinforcement f_{fe} that is reduced from an ultimate tensile strength of FRP f_{fu}. ACI 440.2 R-02 recommends not using this design procedure in expected plastic hinge regions.

However, in this research, CFRP materials were applied at expected hinge region and the designed failure mode of the member is not the delamination of CFRP but fracture of the CFRP sheet. Therefore, the target flexural strength was selected corresponding to an ultimate tensile strength of CFRP f_{fu}, and no reduction factor (i.e. ψ_f) was used in the calculation of M_n.

2.1.3 CFRP Anchor

A CFRP anchor is shown in Figure and consists of a roll of CFRP sheet inserted into the concrete and splayed out over the CFRP sheet. Pictures of the CFRP anchor are shown in Figure 2.2 and Figure 2.3.

Figure 2.2 CFRP Anchor before Installation

Figure 2.3 CFRP Anchor after Installation

Early use of CFRP anchors is reported by Kobayashi et. al. (2001). Kobayashi investigated application of CFRP anchors to a CFRP wrapped column with wing walls (Figure 2.4). 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.

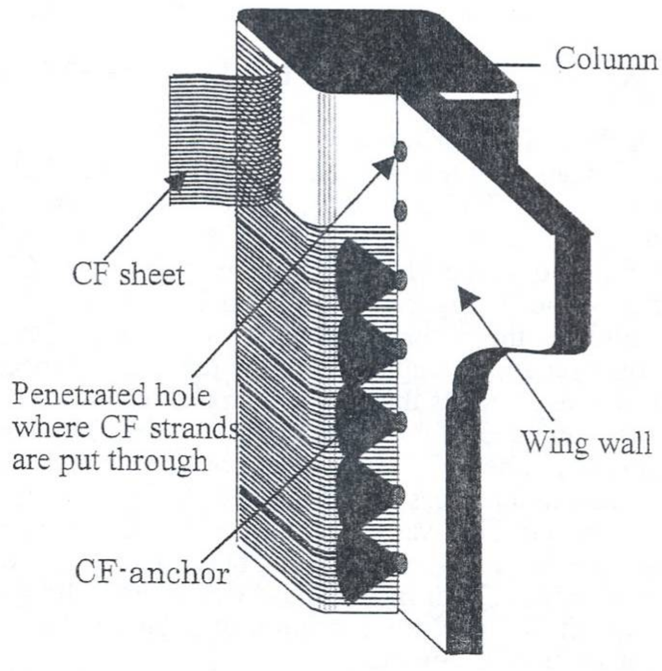


Figure 2.4 CFRP Anchors for CFRP Wrapping the Column with Wing Walls (Kobayashi et. al.2001)

Further research on the capacity of the CFRP anchor was conducted by Ozdemir and Akyuz (2005). They investigated the effects of concrete compressive strength, anchorage depth, anchorage diameter, and number of fibers on the tensile strength capacity of CFRP anchor, and found 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, as embedment depth increased, the effect of concrete compressive strength became more significant.
- As embedment depth increased, tensile capacity of the CFRP anchor also increased linearly until the depth reached an effective bond length of 100mm. Beyond this length the tensile capacity did not increase.

- The diameter of the anchor hole did not have a significant effect on the tensile capacity of the CFRP anchor.
- The tensile capacity of the CFRP anchor increased with an increase in the amount of CFRP materials, but the capacity increase was not proportional to the increase in the material.

2.2 MATERIAL PROPERTIES

2.2.1 Concrete

Five specimens were cast from a single batch of concrete. Concrete cylinders (6 in. diameter by 12 in. height) were as specified in ASTM C - 40 for tensile and compressive strength. ASTM C 39 - 04a and ASTM C 496 - 96 were used for measuring the compressive and tensile strength of the concrete. The design value of the compressive strength was 3,500 psi for all the specimens. Test results are shown in Table 2.1.

Cast	Compressive Strength		Tensile Strength	
	Cylinder No.	f_c', psi	Cylinder No.	f_t, psi
Cast 1 (Sp.1~5)	1	2,772	1	321
	2	3,162	2	220
	3	3,041	3	254
			4	355
			5	292
			6	254
	Mean	**2,992**	Mean	**283**
Cast 2 (Sp.6~10)	1	3,641	1	355
	2	3,364	2	420
	3	3,475	3	406
	4	3,318	4	424
	5	3,594	5	446
	6	3,172	6	368
	Mean	**3,427**	Mean	**403**

Table 2.1 Compressive and Tensile Strength of Concrete

2.2.2 Steel

Grade 60 steel bars were used in the specimens, and the bars were from two different heats. The bars in specimen No.1 ~ No.7 were from one heat (1) and the bars in specimen No.8~No.10 were from another heat (2). The bar coupons for the tensile strength tests were loaded only to the yield strength as measured by 0.2% offset method. No bars yielded during the tests of the specimens. The yield strength f_y of the bars from heat 1 was 70 ksi and 65 ksi for heat 2.

2.2.3 CFRP

The CFRP material used in this study was Tyfo® SCH -35 composites with Tyfo® S Epoxy from FYFE Co. LLC.

The tensile strength of the CFRP materials was measured using ASTM D 3039 procedures. Two in. wide by 12 in. long CFRP coupons were tested (Figure 2.5). The test results showed that the material properties of the CFRP materials were consistent with the specified properties from the manufacturer and are shown in Table 2.2. The CFRP material was one directional material and had no tensile capacity in the transverse direction of the fabrics.

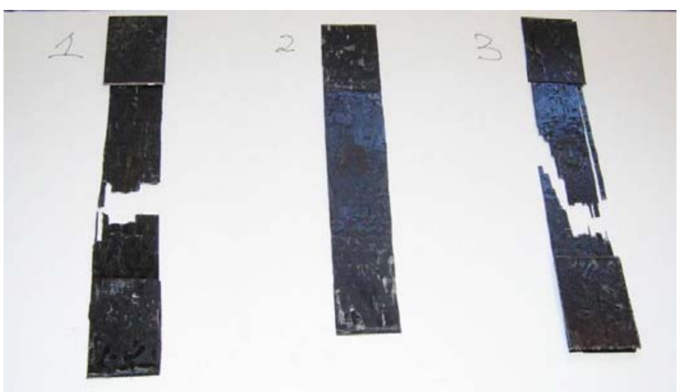


Figure 2.5 CFRP Coupons for Tensile Strength Test

Property	Typical Test Value
Ultimate tensile strength in primary fiber direction, psi	143,000 psi
Elongation at fracture	1.26 %
Tensile Modulus, psi	11.4×10^6 psi
Ultimate tensile strength 90 degree to primary fiber, psi	0
Laminate thickness, in	0.035 in.

Table2.2 Specified Material Properties of CFRP

The stress-strain curves of the CFRP materials and the steel bars are shown in Figure 2.6. Although the CFRP materials had higher strength than the steel bar, the CFRP materials were less stiff than the steel bars. The CFRP material had a linear stress-strain relationship up to fracture.

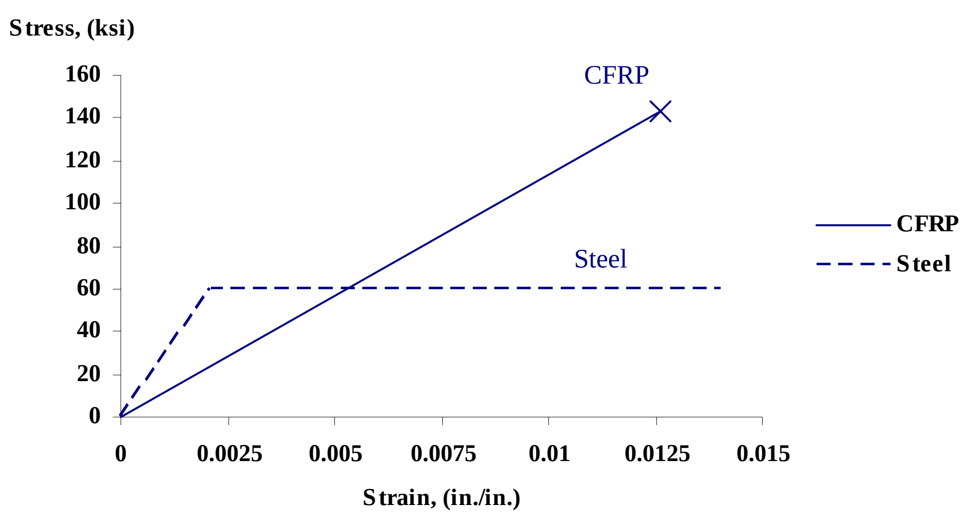


Figure 2.6 Stress - Strain Curves of the CFRP Material and the Steel bar

CHAPTER 3
EXPERIMENTAL METHOD

3.1 SPECIMEN CONFIGURATION

All the specimens had the same configuration before the CFRP materials were placed. The scale of the specimen was 3/4 of the prototype structure. The length of the specimens was determined so that it would correspond to the distance between the inflection points of the beams. The represented portion of the structure by the specimens is shown in Figure 3.1.

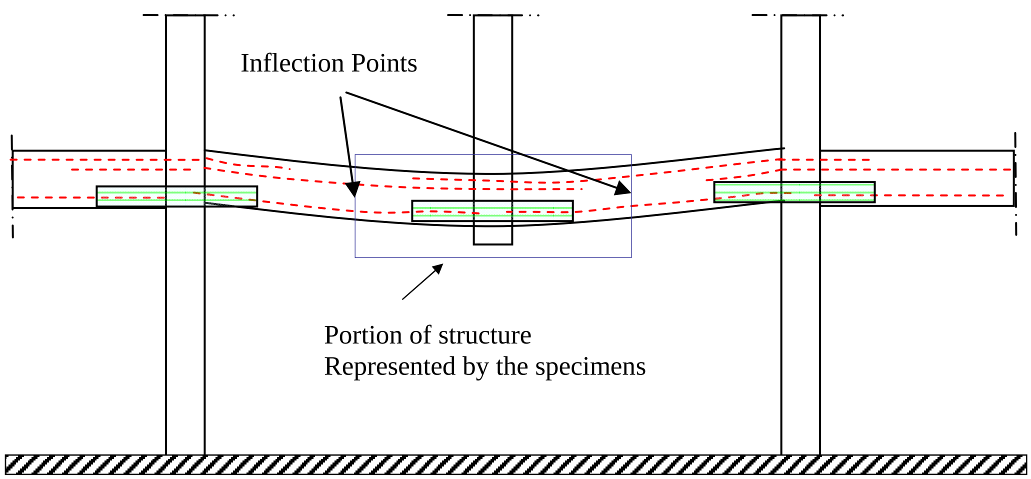


Figure 3.1 Portion of Structure Represented by the Test Specimens

The 12 in. long deepened section at mid span represented a portion of the supporting column. Bottom beam reinforcement extended 4.5 in. from column face leaving a 3 in. discontinuity at the middle of the column (Figure 3.2).

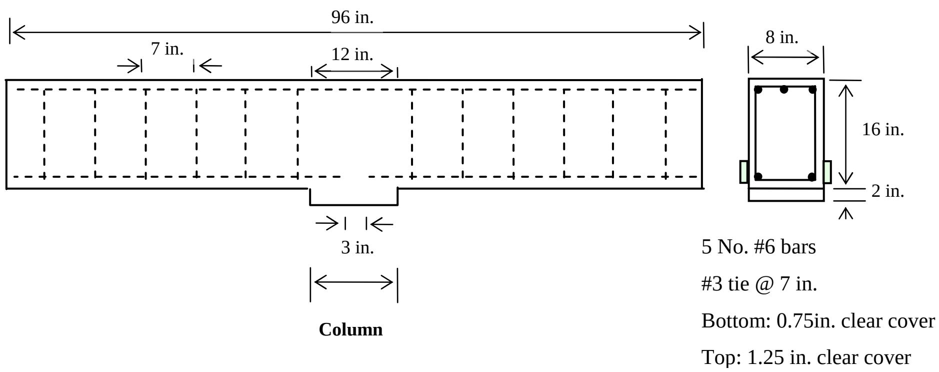


Figure 3.2 Specimen Configuration

Strain gages were installed on the bottom bars. Specimens No.1 ~ No.5 had strain gages at the column faces only (4 gages per specimen), but specimen No.6- No.10 had 3 additional strain gages at 6 in. spacing in each direction from the mid span to observe the strain distribution on the bottom bars. (16 gages per specimen) The distribution of strain gages are shown in Figure 3.3.

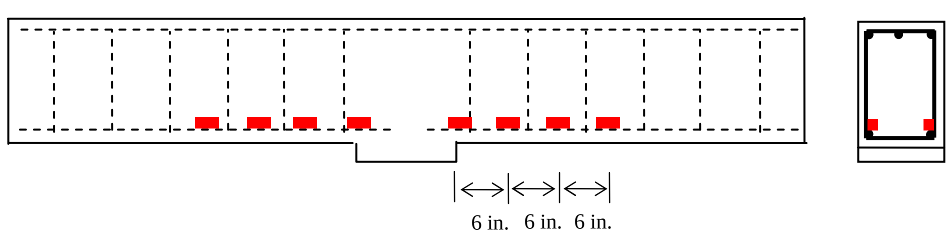


Figure 3.3 Strain gages on the Bars

3.2 CONFIGURATION OF CFRP IN SPECIMENS

The CFRP materials were used for 2 different purposes. First, they were used as a tensile element to provide continuity to the bottom reinforcement. *CFRP sheet* indicates use for flexural continuity. Second, the CFRP materials were used as anchors to transfer forces from the CFRP sheet to the concrete substrate. Three types of the anchors were used, and they are 1)*CFRP anchor, 2)CFRP U-wrap* and *3) insertion of ends of CFRP sheet into holes.*

. . In this research, The *CFRP sheet* was attached using two different sheet arrangements. In one case, a CFRP sheet 5.5 in. wide x 66 in. long was attached on the both sides of the beam (Figure 3.4). In the other case, two CFRP sheets 2.75 x 66 in. were placed on top of one another (Figure 3.5). The area of the CFRP materials in both cases was the same. The area and strength of the CFRP sheet were selected to provide an ultimate tensile force the same as that for two #6 bottom bars at yield. The length of the CFRP sheet was determined considering the development length of the steel bar. The development length of a #6 bar was 30.4 in. for the geometry of test specimen. The distance from the end of bar in the column to the end of CFRP sheet was 31.5 in..

Figure 3.4 One Layer of CFRP sheet, 5.5 in. wide

Figure 3.5 Double Layers of CFRP sheets, 2.75 in. wide

Three types of anchorage methods were investigated in this research, 1)CFRP anchor, 2)CFRP U-wrap and 3) insertion of ends of CFRP sheet into holes. One or more of these types of anchorage methods were used in all the specimens except specimen No.1 which had a CFRP sheet attached only with epoxy resin and no additional anchorage.

CFRP anchors were used in specimen No.2, 4, 6, 7, 8, 9. A CFRP anchor was made using the same width of CFRP, 5.5 in., sheet as that of the attached to the beam. The length of the anchor was 9.5 in. with 4 in. of the anchor inserted into a 5/8 in. hole drilled into the concrete. The rest of the anchor was splayed out in a fan shape on the CFRP sheet. Pictures of CFRP anchor before and after installation are shown in Figure 3.6 and 3.7. The angle of fan shape portion depended on the width of the CFRP sheet. It was 60 degree for the 5.5 in. wide CFRP sheet and 30 degree for the 2.75 in. wide CFRP sheet. Kobayashi (2001) recommended that the use of CFRP anchors with less than 90 degree angle of spreading. The number of CFRP anchors installed in a specimen varied.

The diameter of anchor holes was 5/8 in. for all the specimens. The anchor hole was always installed right under the longitudinal bar where the core of a concrete section was located in order to decrease the possibility of concrete cover failure.

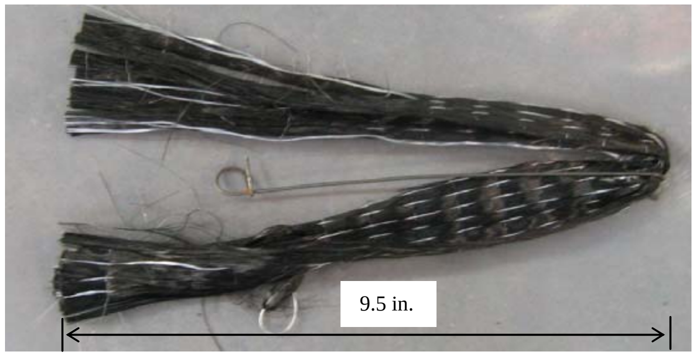


Figure 3.6 CFRP Anchor before Installation

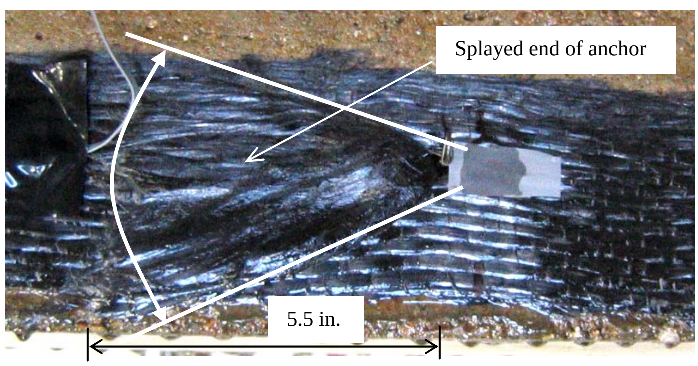


Figure 3.7 CFRP Anchor on 2.75 in. wide CFRP sheet after Installation

CFRP U-wraps were used in specimens No.5, 8, 9 and 10. A CFRP U-wrap was also made of the same 5.5 in. width of CFRP sheet with a total length of 26 in.. The CFRP U-wrap was attached on each side of the beam over the CFRP sheet, and extended 9 in. from the bottom face of the beam. Pictures of CFRP anchor before and after installation are shown in Figure 3.8 and 3.9.   The number of CFRP U-wraps installed in a specimen varied, and both CFRP U-wraps and CFRP anchors were installed in specimens No.8 and 9.

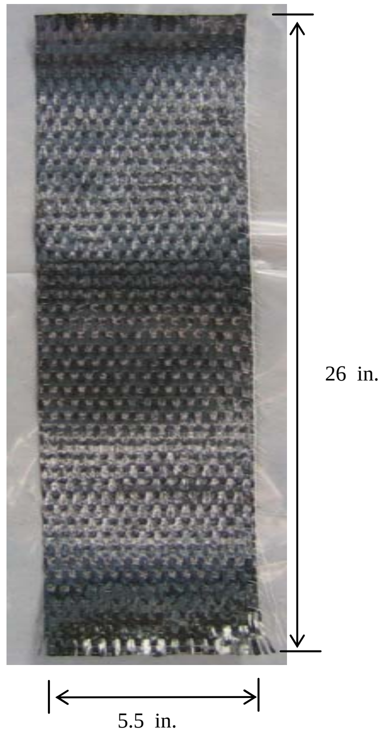


Figure 3.8 CFRP U-wrap before Installation

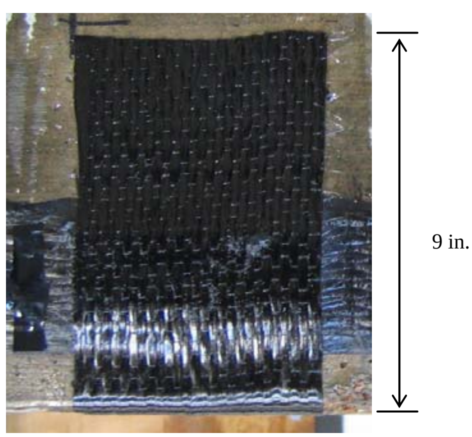


Figure 3.9 CFRP U-wrap after Installation

The third anchorage method was the *insertion of the end of the CFRP sheets into holes* in the specimen without any additional anchor (Figure 3.10). The inserted depth was 4 in. long as the same as CFRP anchor. This anchorage method was used only in specimen No.3. It was quite difficult to place the end of sheet into the hole and provide a smooth transition from the sheet width to the hole dimension as can be seen in Figure 3.10.

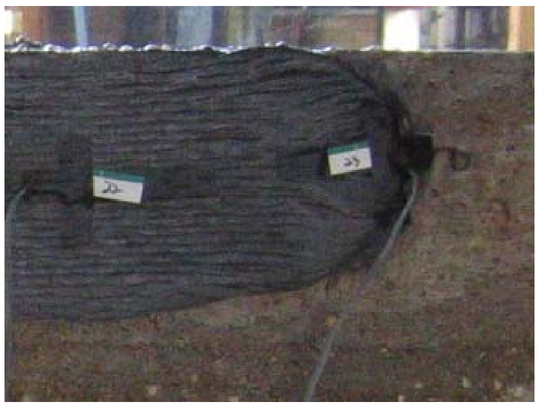


Figure 3.10 Insertion of end of CFRP Sheet into Hole

All the configurations of the CFRP materials in the specimens are shown in Table 3.1. Both sides of the specimens had a symmetric configuration.

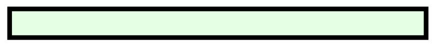
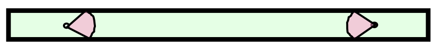
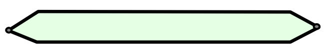
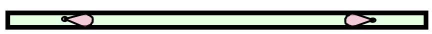
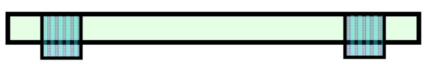
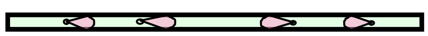
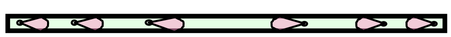
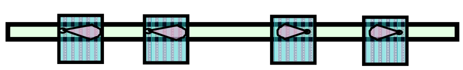
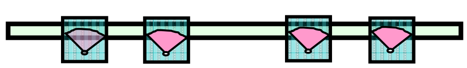
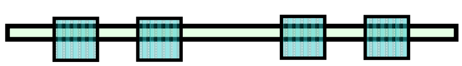
Specimen No.	specimen	CFRP sheet & Anchorage Method
1		1 layer & No anchor
2		1 layer & 1 CFRP anchor each side
3		1 layer & Insertion end of CFRP sheet into holes
4		2 layers & 1 CFRP anchor each side
5		1 layer & 1 CFRP U-wrap each side
6		2 layers & 2 CFRP anchors each side
7		2 layers & 3 CFRP anchors each side
8		2 layers & 2 CFRP anchors each side with CFRP U-wrap
9		2 layers & 2 CFRP U-wraps each side anchored by CFRP anchor
10		2 layers & 2 CFRP U-wraps each side

Table 3.1 Configuration of CFRP materials on Test Specimens

3.3 INSTALLATION PROCEDURE OF CFRP MATERIALS

The installation procedure of the CFRP materials was based on procedure ACI 440.2R Chapter 5. The installation procedure is as follows.

1) Sand-blast to roughen the concrete surface
2) Drill holes if required for anchorage
3) Prepare the epoxy resin
4) Saturate the concrete surface and holes with epoxy resin
5) Saturate carbon fiber with epoxy and remove excess epoxy
6) Place the CFRP material on a specimen
7) Cure

The concrete surface of a specimen where CFRP material would be applied was sand – blasted. The concrete surface before and after sand-blasting are shown in Figure3.11 and 3.12.

The concrete surface was prepared to meet the requirement for a minimum concrete surface profile (CSP) 3 as defined in the International Concrete Research Institute (ICRI)-surface-profile-chips. However, it was not possible to maintain the same surface condition for all the specimens because the concrete quality was different in the specimen. Some specimens were over blasted because of the poor quality of the concrete. The surface preparation conditions are shown in the Figure 3.13 and 3.14.

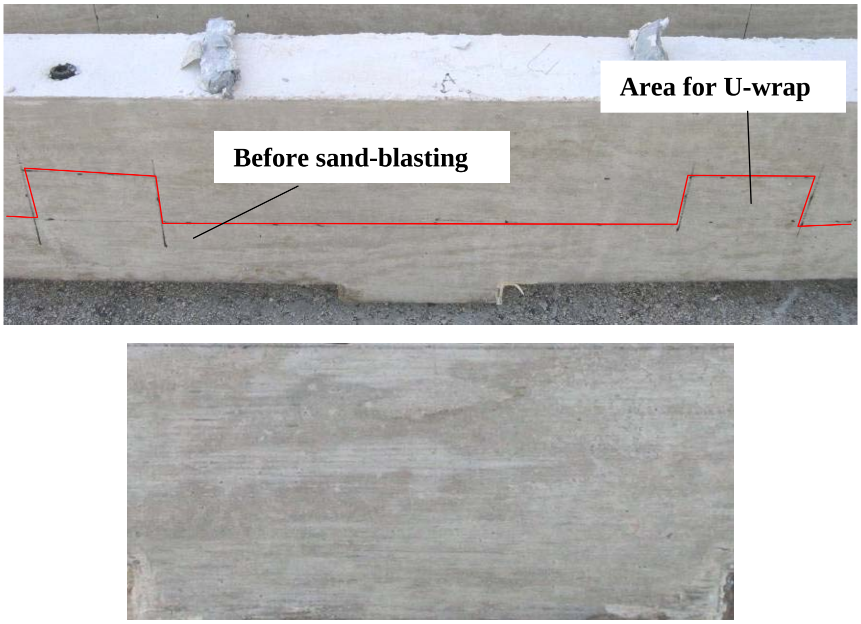


Figure 3.11 Concrete Surface before Sand - Blasting

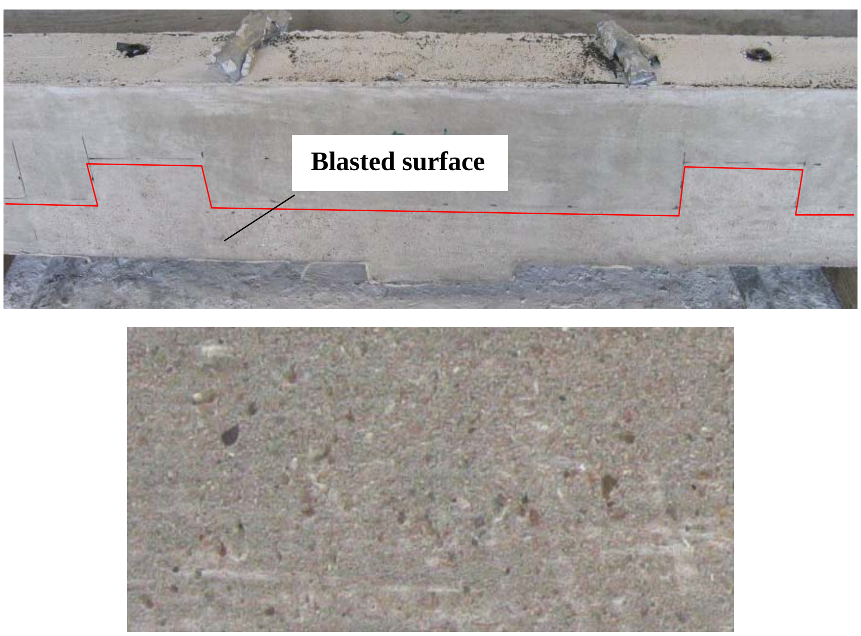


Figure 3.12 Concrete Surface after Sand – Blasting

Figure 3.13 Regularly Blasted Surface

Figure 3.14 Over Blasted Surface

A CFRP anchor requires a hole in the concrete for installation. The holes were drilled with 5/8 in. diameter masonry drill bit, and they were cleaned with air compressed. The edge of hole was ground to smooth perimeter transition of the CFRP materials from the hole to the sheet. An anchor hole prior to installation of the CFRP materials is shown in Figure 3.15.

Figure 3.15 Hole for CFRP Anchor

Epoxy resin was used for bonding the carbon fabric to the concrete surface. The epoxy resin used in this study was Tyfo® S Epoxy and it was a two component epoxy matrix material. The specified mix ratio between two components was 100 parts of the component A to 42 parts of the component B by volume. They were mixed for five minutes at 400 ~ 600 RPM until uniformly blended (Figure 3.16).

Figure 3.16 Preparation of Epoxy Resin

The concrete surface and holes were saturated with epoxy before the CFRP materials were applied. The concrete surface and holes were saturated with the epoxy resin by a small paint roller (Figure 3.17) and an injector.

Figure 3.17 Saturation of Concrete Surface with Epoxy

Pieces of carbon fabric for the CFRP sheet and additional anchorage were saturated with epoxy resin and squeezed with a roller. Then the CFRP fabric saturated with epoxy resin was placed on the specimen and smoothed by hand to remove air pockets (Figure 3.18).

The specimen was cured for at least 72 hours at ambient temperature before test.

Figure 3.18 Placement of CFRP Materials

3.4. TEST SETUP

Specimens were tested in an upside -down position for convenience of testing. The specimen was supported 4 in. from both ends, and all the specimens were loaded at “mid span” to represent the loading when the column below is removed (Figure 3.19).

Deflection of specimen was measured by two linear transducers on the top of specimen at mid span.

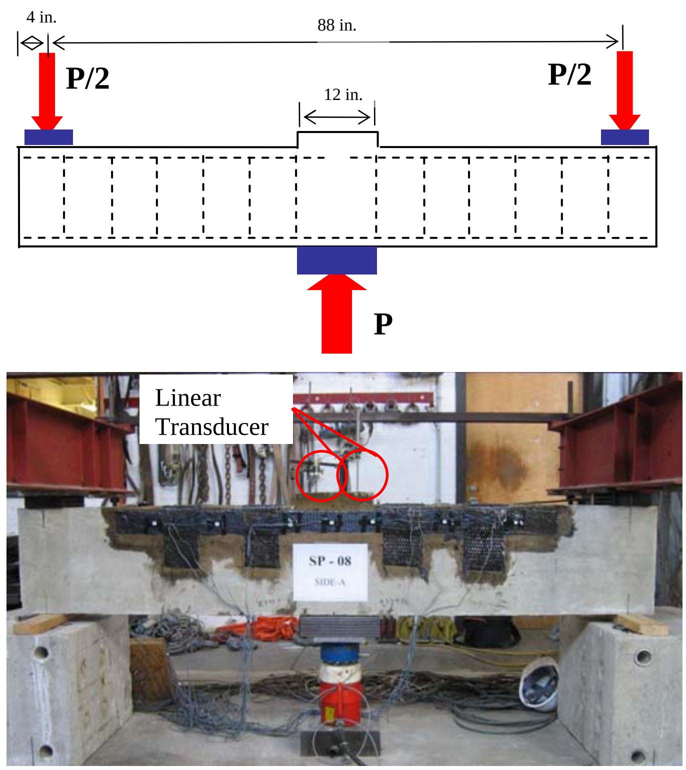


Figure 3.19 Test Setup

3.5 TARGET STRENGTH OF SPECIMEN

The target strength was P=32 kip which corresponded to nominal strength of the beam with two #6 continuous bottom bars. The nominal moment capacity M_n of specimen was 707 kip-in. and the required mid span point load was 32 kip ($\frac{P_n l}{4} = M_n$). If full tensile capacity of the CFRP sheet can be developed, the target strength will be achieved. The area of the CFRP sheet was determined through the procedure in ACI 440.2 R-02, and no strength reduction factor was used. The procedure was introduced in Chapter 2.1.2.

CHAPTER 4
EXPERIMENTAL RESULT

4.1 GENERAL

In Chapter 4, data from each test result and an interpretation of that data are presented as follows:

1) Configuration of Specimen
2) Failure Mode
3) Load - Deflection Relationship
4) Strain in CFRP Sheet
5) Strain in Steel Bar
6) Summary

Geometry of CFRP materials in a specimen will be presented under *Configuration of Specimen*.

Failure mode of each specimen will be discussed in the subsection entitled *Failure Mode*. Two main failure modes existed in the tests except specimen No.1 whose failure mode was delamination of CFRP sheet. One main failure mode was *failure of anchorage* and the other failure mode was *failure of the CFRP sheet.* These failure modes were observed after delamination of the CFRP sheet occurred. The failure of anchorage involved failure of CFRP anchors, CFRP U-wraps or the end of a CFRP sheet inserted into a hole. Such failures occurred in the CFRP materials used for anchorage or by concrete crushing around the anchorage. The second main failure mode involved failure of the CFRP sheet in tension. Two different failure patterns of the CFRP sheet were observed through the tests. One failure pattern of the CFRP sheet was splitting of the CFRP sheet and fracturing progressively. The other failure pattern was fracture of the whole CFRP sheet simultaneously.

The desirable failure mode was not the failure of the anchorage but the failure of the CFRP sheet, and fracture of the whole CFRP sheet was more desirable than split-and-fracture pattern because fracture of the whole CFRP sheet led to develop the full strength of the CFRP sheet.

The peak load and deflection at the peak load are presented under *Load - Deflection Relationship*. In addition, the failure load and deflection at the failure are also presented in this section. The peak load indicated the strength of a specimen and was compared with the target strength 32 kip. The failure load was compared with the peak load of the specimen to investigate the load carrying capacity of a specimen before failure. The deflection at the failure load was compared with that of specimen No.1 which had no additional anchorage. The deflection at the failure indicated peak deformation of a specimen.

In the subsection, *Strain in CFRP Sheet*, the location of strain gages in the CFRP sheet, maximum strain measured and strain distribution along the CFRP sheet are presented. The value and location of the maximum strain in the CFRP sheet were an important parameter to determine whether full strength of CFRP sheet was developed. The strains in the CFRP materials in the additional anchorage were also measured but did not provide data that could be easily interpreted.

The maximum strain measured in steel bar is indicated in the subsection, *Strain in Steel Bar* and was compared with the yield strain of bar. Strain gages were installed only at the location of the column face in specimens No.1 ~ No.5 but the strain gages in specimens No.6 ~No.10 were installed at the column face and along the bar. The maximum value of bar strain and distribution of strain on the bar gave an indication of load transfer from the CFRP sheets to the bars. In other words, they provided measure of the continuity and efficiency of the alternative load path created by the CFRP materials.

4.2 SPECIMEN NO.1

4.2.1 Configuration

Specimen No.1 had 1 layer of the CFRP sheet and no additional anchorage. The width of CFRP sheet was 5.5 in. when it was cut, but it extended about 0.5 in. after it was attached to the specimen (6 in. total) because the CFRP materials were one directional material and there was no restraint in the transverse direction. The CFRP sheets were placed on the both sides of the specimen. Configuration of specimen No.1 is shown in Figure 4.1.

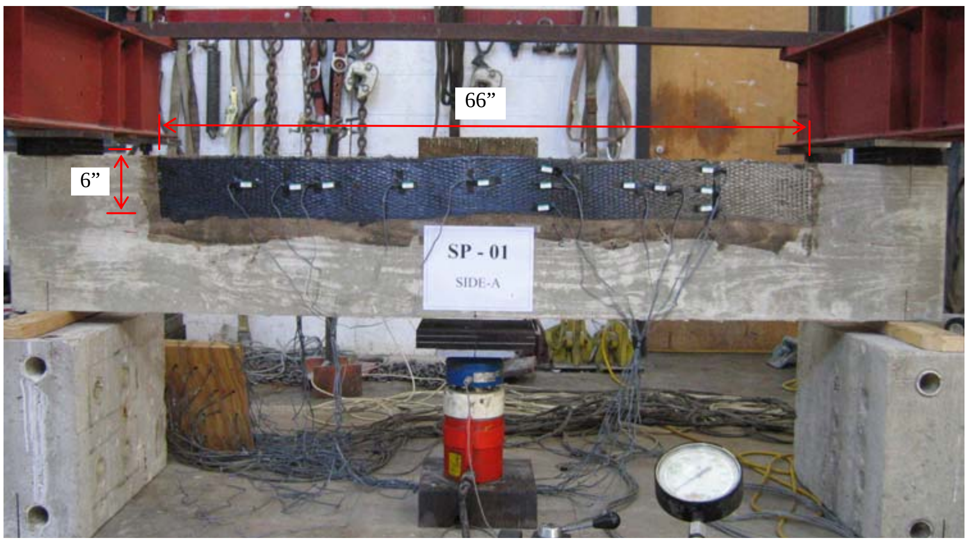


Figure 4.1 Configuration of Specimen No.1

4.2.2 Failure Mode

The failure mode of specimen was delamination of the CFRP sheet from the concrete surface because no additional anchorage existed in specimen No.1. Both sides showed the same failure mode, and one side failed right after the other (Figure 4.2).

Figure 4.2 Failure mode of Specimen No.1, Delamination of CFRP Sheet

4.2.3 Load - Deflection Relationship

The peak load was 14.6 kip for specimen No.1, and the strength of specimen No.1 was 46% of the target strength, 32 kip. The deflection at this point was 0.21 in.

The failure load (13.9 kip) was 95 % of the peak load, 14.6 kip, and the deflection at the failure (0.35 in.) was compared with the deflection of the other specimens in order to find relative deformation capacities of the specimens.

Three key points were noted in the load - deflection curve for specimen No.1 (Figure 4.3). The first key point corresponded with the occurrence of the first concrete crack at the mid span. Delamination of the CFRP sheets on the both sides started from this crack. Applied load increased until total debonding of the CFRP sheet on one side of the specimen occurred. After the peak point, the load was carried by the CFRP sheet on the other side. The specimen maintained nearly the same load carrying capacity for a short duration until the total debonding occurred the other side. Debonding of the CFRP sheet in the other side proceeded rapidly when the third key point in the curve was reached. Comparing load-strain relationships of the CFRP sheets in from strain gages placed in symmetric positions, almost the same load - strain relationship was found.

The curve begins above the origin because reactions had some play in them before they seated.

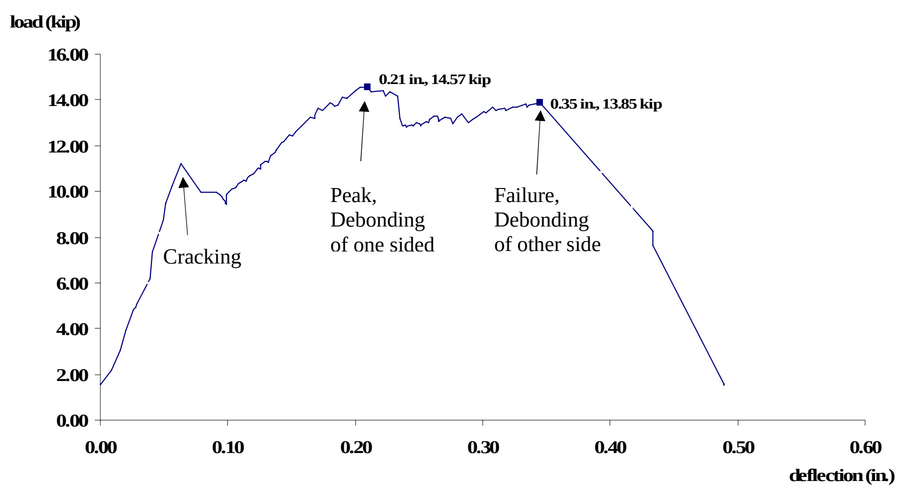


Figure 4.3Load - Deflection Relationship of Specimen No.1

4.2.4 Strain in CFRP Sheet

The location of the strain gages installed on both sides of specimen No.1 and the maximum measured strain in each gage are shown in Figure 4.4 and 4.5.

The maximum strain measured in specimen No.1 was 0.0053 at strain gage No.14 in side-A, and was 42% of the specified maximum fracture strain, 0.0126. The maximum measured strain was not as the same as the true maximum strain of the CFRP sheet because it was possible that the true maximum strain occurred at other points away from the strain gage locations.

From the data of the horizontal distribution of strains on the CFRP sheet, the part of the CFRP sheet developed the highest strain was where debonding failure occurred, and the same pattern was observed on the both sides of the specimen (Figure 4.4 and 4.5).

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (12kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.4 and 4.5.

Vertical distribution of strains in the CFRP sheet was observed by strain gages No.10, 11 and 12 (Figure4.4). As indicated in the figure, the strain was 0.0049 closest to the extreme fiber of the beam and reduced to 0.0039 and 0.0033 as the distance from the extreme fiber increased. The highest strain was observed in the strain gage closest to the extreme tension fiber, strain gage No.10, and it was smaller at strain gages below that point. Vertical distribution of strains in the CFRP sheet was also observed using gages No.15, 16 and 17 but rapid delamination of the CFRP sheet occurred at that location, so the strain data did not properly indicate the vertical distribution of strains.

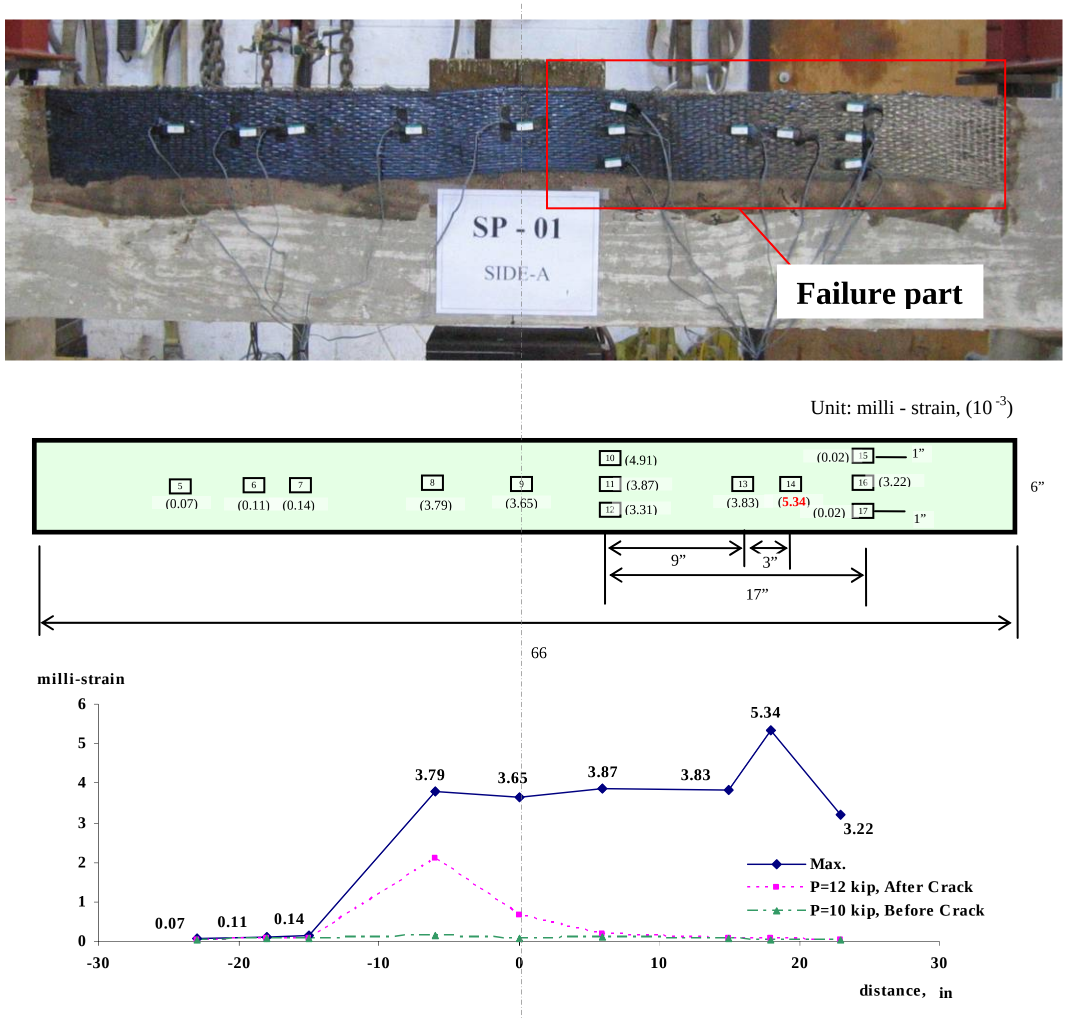


Figure 4.4 Strain in CFRP Sheet in Specimen No.1, Side-A

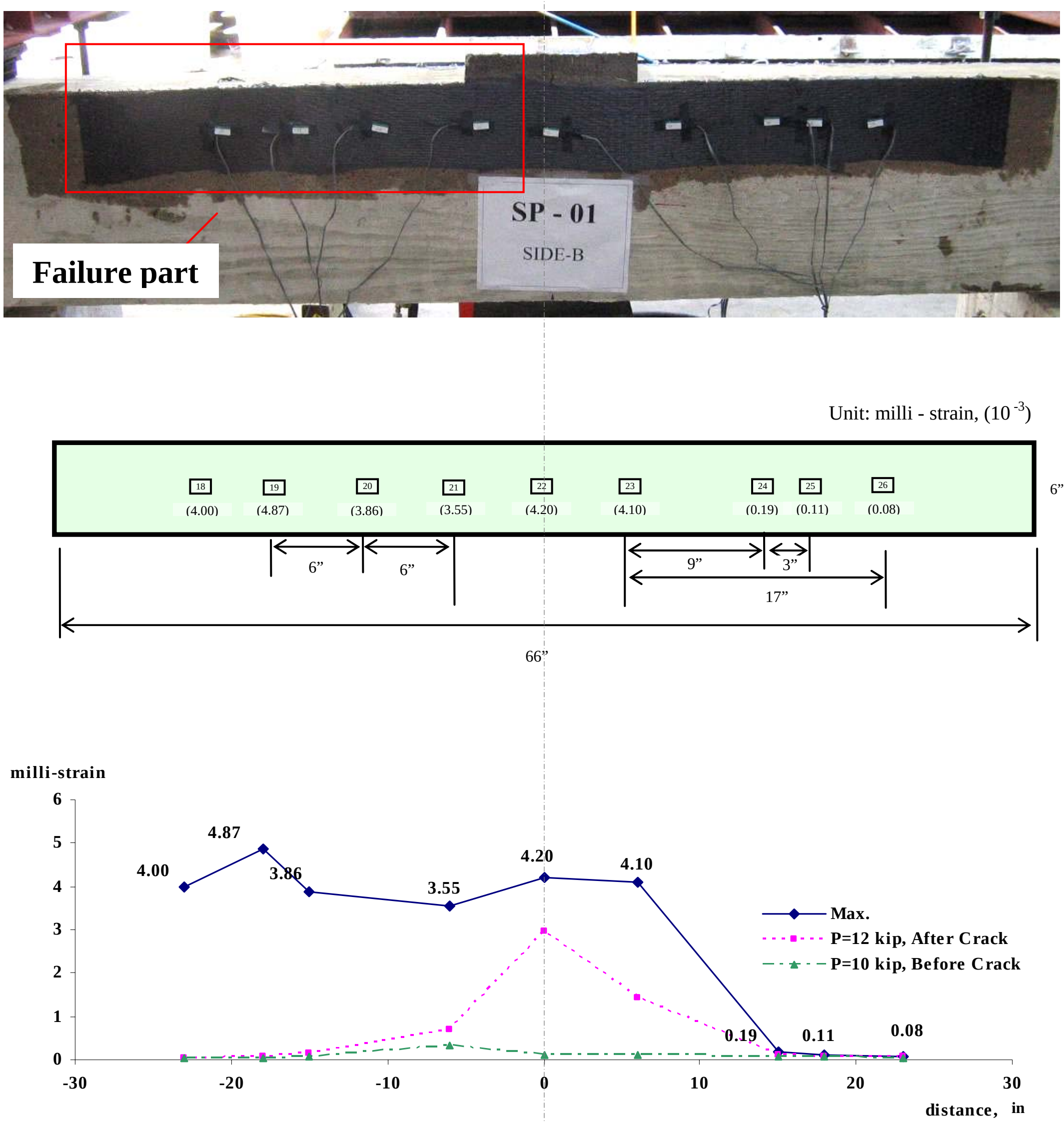


Figure 4.5 Strain in CFRP Sheet in Specimen No.1, Side-B

Load-strain relationship in a pair of strain gages placed in symmetric positions showed similar load - strain relationship. It meant that the CFRP sheets on the both sides developed their capacity at the same time (Figure 4.6).

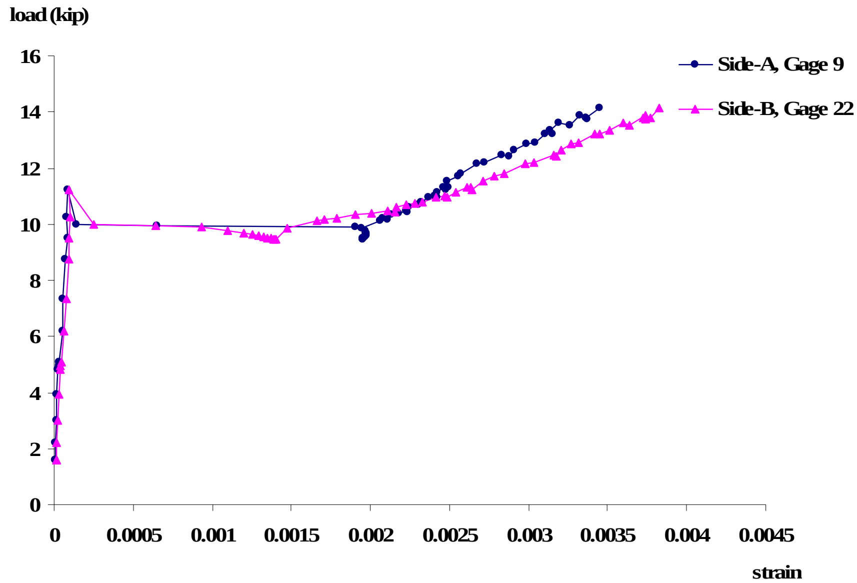


Figure 4.6 Load - Strain Relationship Measured in the Strain Gages at Symmetric Position

4.2.5 Strain in Steel Bar

The strains in the bar were measured only at the column face with 4 strain gages in specimen No.1 (Figure 4.7), so it was not possible to observe the distribution of strains in the bar. Therefore, load transfer from the CFRP sheet to the bar was estimated only by the strain at the location of the column face. The maximum measured bar strain in specimen No.1 was 0.0005 which was 24% of the yield strain. It showed that the load did not transfer effectively from the CFRP sheets to the bars over that short distance (4.5 in).

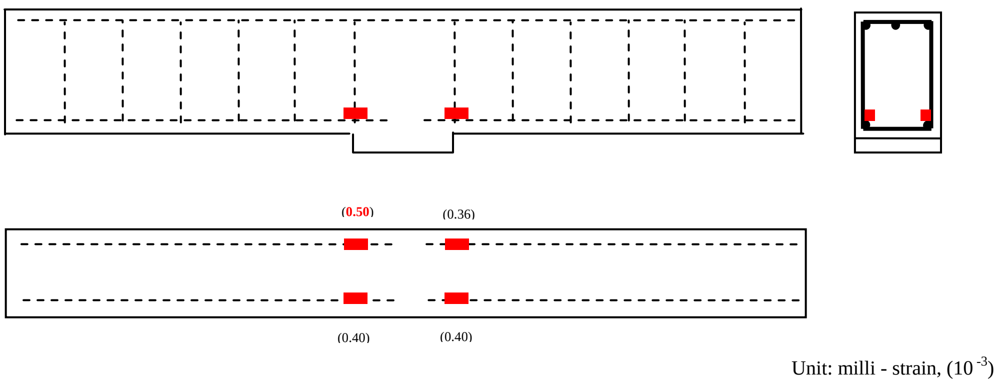


Figure 4.7 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before cracking of the specimen as shown by comparing measured strains in the bar and the CFRP sheet at the same distance from the mid span (Figure 4.8).

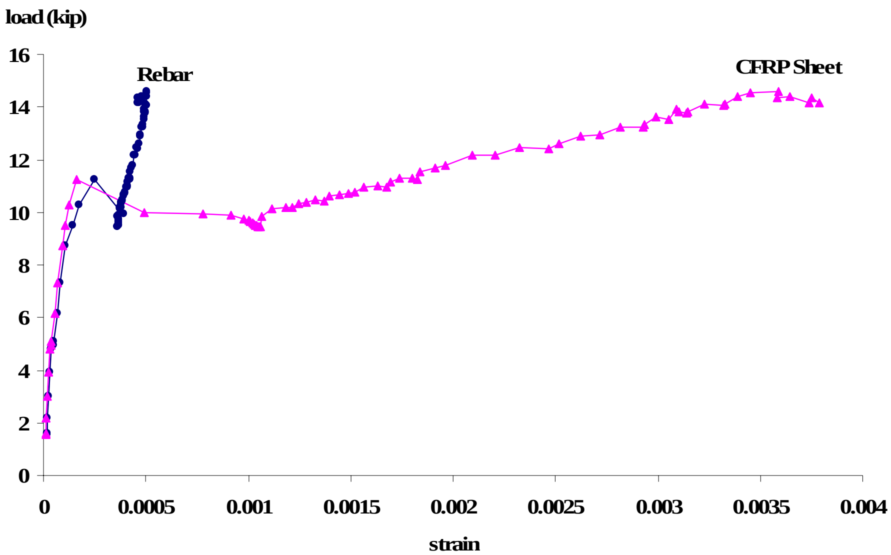


Figure 4.8 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.2.6 Summary

Specimen No.1 was a pilot test specimen which has no additional anchorage. Summary of the test results is shown in Table4.1.

Failure Mode	Delamination CFRP sheet
Peak Load Displacement at the peak	14.6 kip, 46% of target strength 0.21 in.
Failure load Displacement at the failure	13.9 kip, 95% of peak load 0.35 in.
Measured maximum **CFRP** strain	0.0053, 42% of specified fracture strain
Measured maximum **bar** strain	0.0005, 24% of yield strain

Table 4.1 Summary of Test Results of Specimen No.1

4.3 SPECIMEN NO.2

4.3.1 Configuration

Specimen No.2 had 1 layer of the CFRP sheet and 1 CFRP anchor at each end of the CFRP sheet. The dimension of the CFRP sheet was the same as specimen No.1 except the CFRP anchors. Location of the anchor holes for the CFRP anchors was selected as 2/3 of the development length of the bar, and it was 18 in. from the column face. Configuration of specimen No.2 is shown in Figure 4.9.

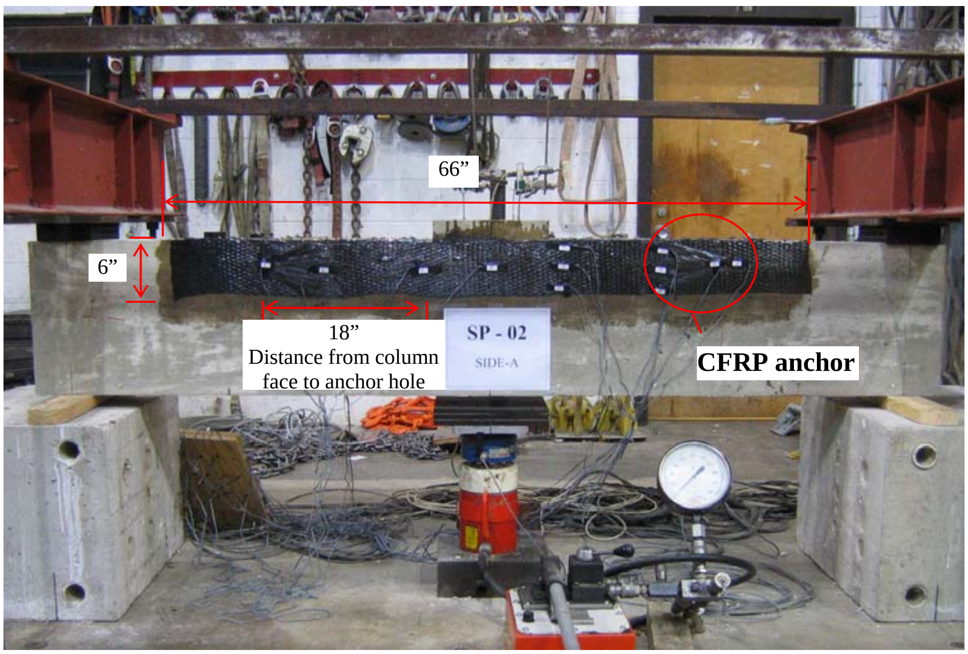


Figure 4.9 Configuration of Specimen No.2

4.3.2 Failure Mode

The failure mode of specimen No.2 involved split-and-fracture of the CFRP sheet. Both sides showed the same failure mode (Figure 4.10 and 4.11).

Figure 4.10 Failure mode of Specimen No.2, Side-A

Figure 4.11 Failure mode of Specimen No.2, Side-B

4.3.3 Load - Deflection Relationship

The load-deflection curve of specimen No.2 is shown in Figure 4.12. The peak load was17.1 kip for specimen No.2, and the strength of specimen No.2 was 53% of the target strength, 32 kip. The deflection at this point was 0.59 in.. The increase in strength of specimen No.2 with respect to that of specimen No.1 was only 2.5 kip because a split-and-fracture failure occurred. It was impossible to develop the full strength of the CFRP sheet failing in this manner.

The failure load (16.3 kip) was 95 % of the peak load, 17.1 kip, and the deflection at the failure (0.69 in.) was about twice as that of specimen No.1. Deformation capacity of the specimen increased significantly after installation of the CFRP anchors although the strength of the specimen was not improved much.

The load-deflection curve showed many peak points rather than showed only 3 peak points which are represent crack of specimen, failure of one side, and failure of the other side. The 'jagged' shape of the load-deflection curve is the result of splitting and fracturing of the CFRP sheets. When one piece of the CFRP sheet split and fractured, the load decreased, and then increased again until another piece split and fractured. Repeat of that process on the both sides of the specimen resulted in multiple peaks in the load - deflection curve.

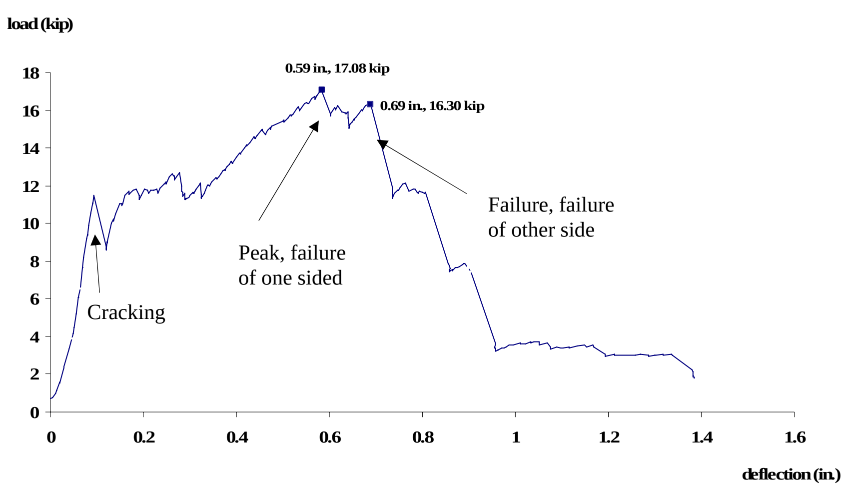


Figure 4.12 Load - Deflection Relationship of Specimen No.2

4.3.4 Strain in CFRP Sheet

The location of the strain gages installed on the both sides of specimen No.2 and the maximum measured strain in each strain gage are shown in Figure 4.13 and 4.14.

The maximum strain measured in specimen No.2 was 0.0136 at strain gage No.6 in side-A in front of the CFRP anchor, and reached 108% of the specified fracture strain of 0.0126.

From horizontal distribution of strain in the CFRP sheet, the highest strains indicate where failure occurred on both sides of specimen (Figure 4.13 and 4.14)

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (14 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.13 and 4.14.

The vertical distribution of strains in the CFRP sheet was observed by strain gages No.9, 10, 11and 12, 13 and 14 (Figure4.13). The highest strain was observed in the strain gages closest to the extreme tension fiber, strain gage No.9 and 12, and reduced near the neutral axis of the beam.

Strain gages were also installed on the CFRP anchors but the data were not available.

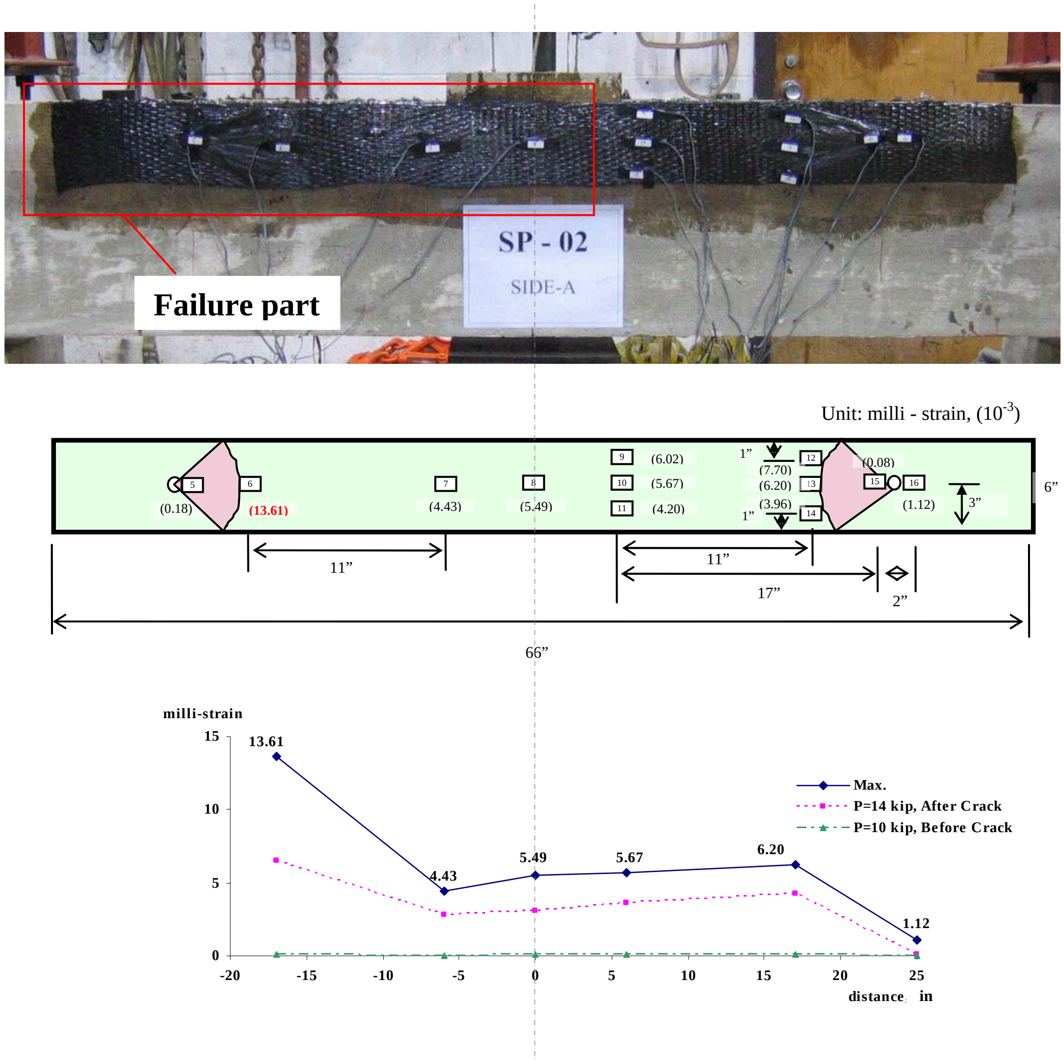


Figure 4.13 Strain in CFRP Sheet in Specimen No.2, Side-A

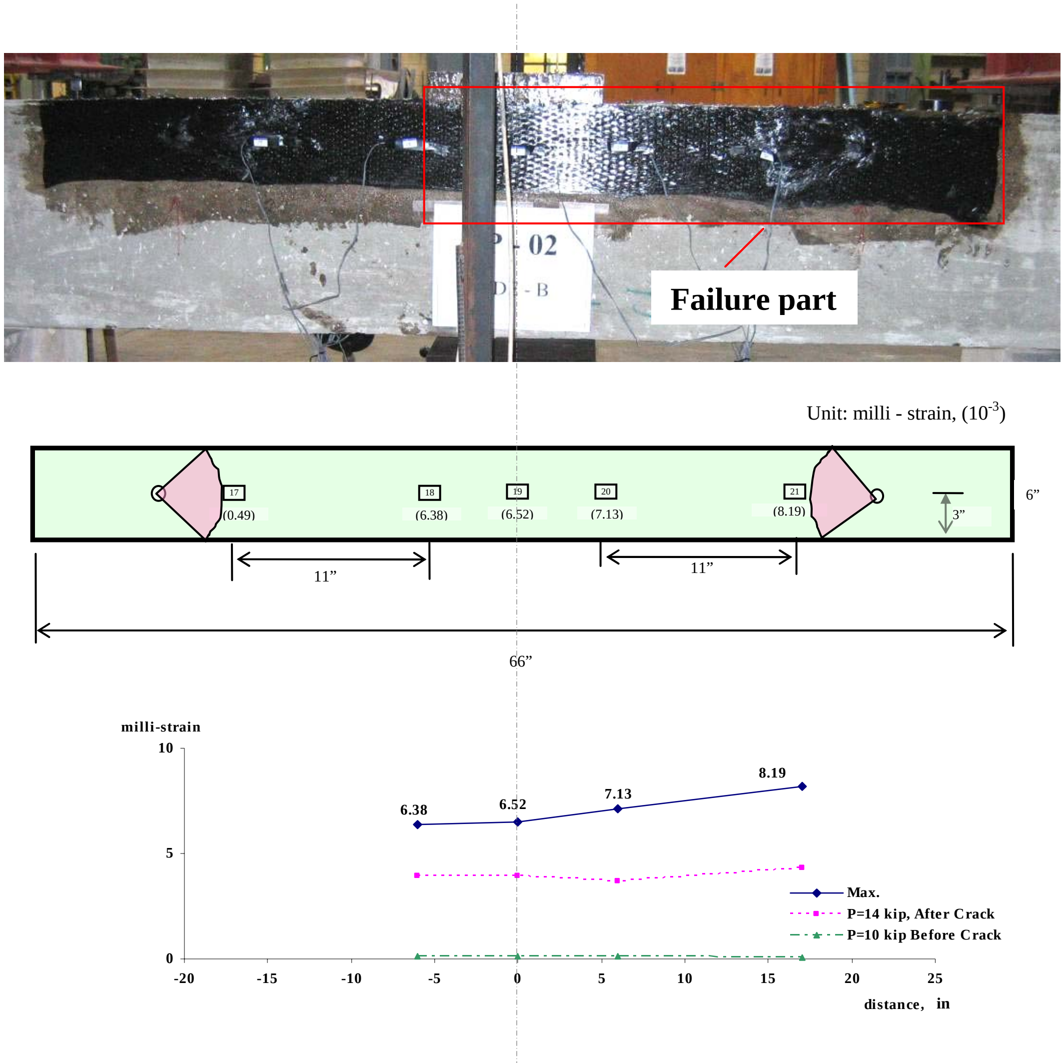


Figure 4.14 Strain in CFRP Sheet in Specimen No.2, Side-B

Load - strain relationship in a pair of strain gages placed in symmetric position showed similar load - strain relationship and indicated the CFRP sheets on the both sides reached capacity at the same time (Figure 4.15). Strain gages at other symmetric position showed similar strains.

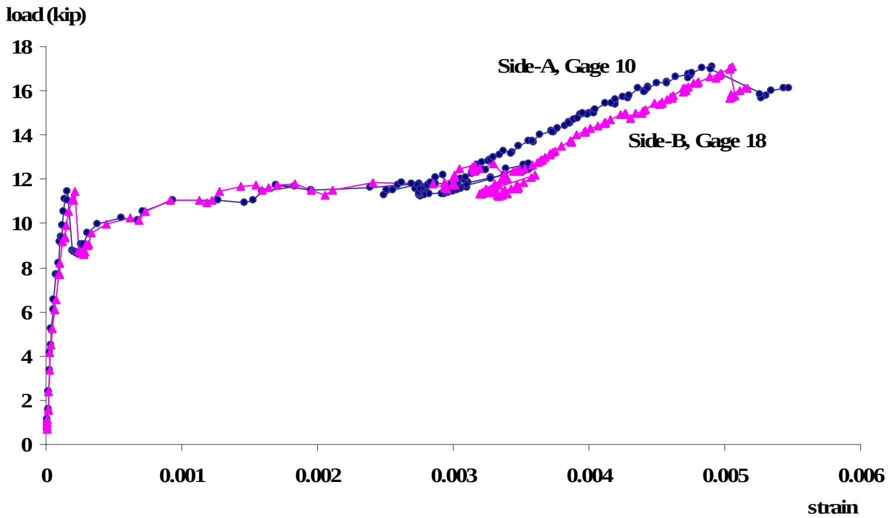


Figure 4.15 Load - Strain relationship measured in strain gages at symmetric position (At the Mid Span)

4.3.5 Strain in Steel Bar

The strains in the bar were measured only at the column face with 4 strain gages in specimen No.2 (Figure 4.16), so it was not possible to observe the distribution of the strains in the bar. Therefore, load transfer from the CFRP sheet to the bar was estimated only by the strain at the location of the column face. The maximum measured bar strain in specimen No.2 was 0.0004 which was 19% of the yield strain of bar. It showed that the load did not transfer effectively from the CFRP sheets to the bars in the short 4.5 in. distance with in the column.

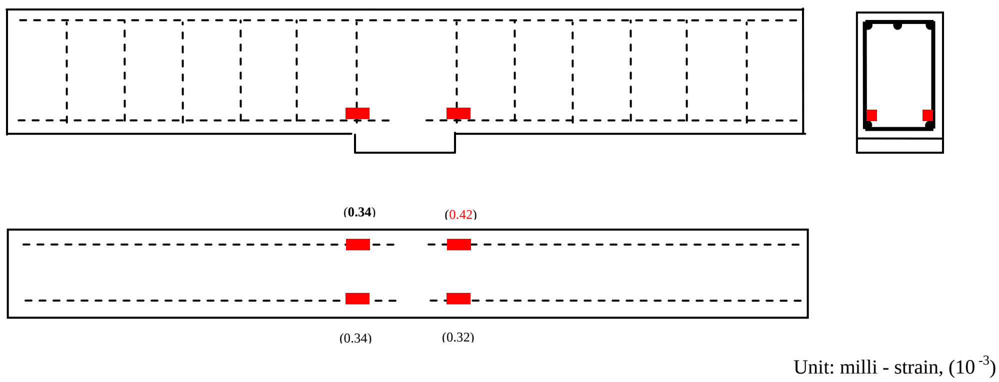


Figure 4.16 Location of bar strain gages and maximum measured strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.17.

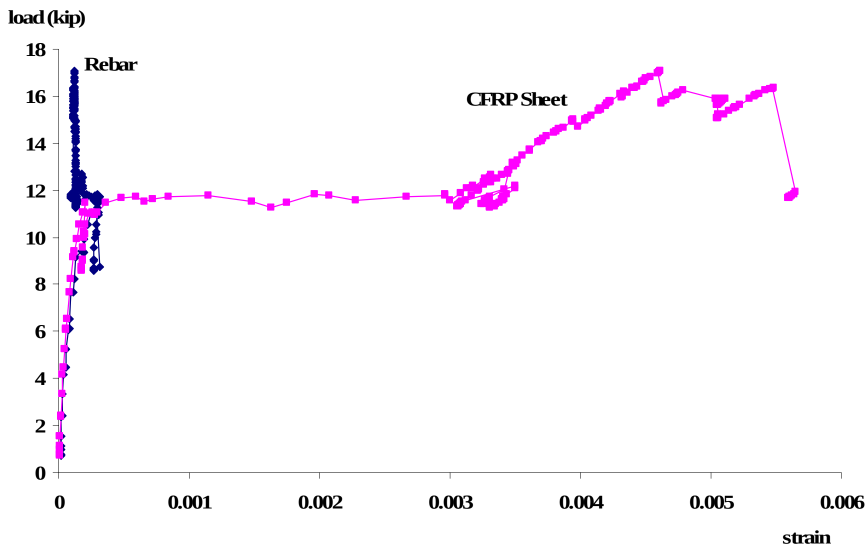


Figure 4.17 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.3.6 Summary

Summary of the test results is shown in Table 4.2.

Failure Mode	CFRP sheet failure, split-and-fracture pattern
Peak Load Displacement at the peak	17.1 kip, 53 % of target strength 0.59 in
Failure load Displacement at the failure	16.3 kip, 95% of peak load 0.69 in
Measured maximum **CFRP** strain	0.0136, 108 % of specified fracture strain
Measured maximum **bar** strain	0.0004, 19% of yield strain

Table 4.2 Summary of test results for specimen No.2

The specimen with the CFRP anchors showed better behavior than the specimen without them but its performance was not improved significantly. The reason for the poor behavior was a split-and-fracture type of failure.

One wide layer of CFRP tended to fail in the split and fracture and indicated that it was not an efficient way of using the repair materials because the centroid of the CFRP sheet was not close to the extreme tension fiber or to the reinforcement. Therefore, the use of double layers of CFRP sheet with half width but the same amount of materials became a more attractive alternative although it had less bond strength between the CFRP sheet and the concrete because bonded area was smaller. Such a drawback was overcome with proper additional anchorage of the sheet.

4.4 SPECIMEN NO.3

4.4.1 Configuration

Specimen No.3 had 1 layer of the CFRP sheet and inserted ends of the CFRP sheet into holes. Location of the holes for the inserted portion of the CFRP sheets was selected as 2/3 of the development length of the bar, and it was 18 in. from the column face which was the same location as specimen No.2. Configuration of specimen No.3 is shown in Figure 4.18.

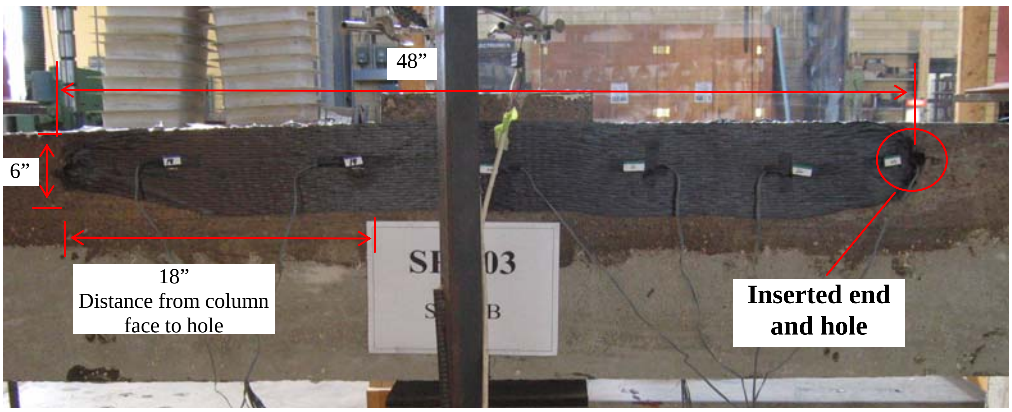


Figure 4.18 Configuration of Specimen No.3

4.4.2 Failure Mode

The failure mode of specimen No.3 was failure of the inserted part of the CFRP sheet near the hole. Both sides showed the same failure mode. The failure mode of specimen No.3 is shown in Figure 4.19 and 4.20

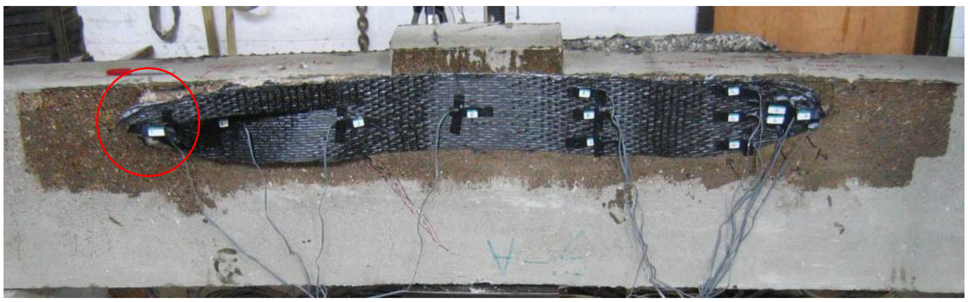


Figure 4.19 Failure Mode of Specimen No.3

Figure 4.20 Failure Mode of Specimen No.3

4.4.3 Load - Deflection Relationship

Load-deflection curve of specimen No.3 is shown in Figure 4.21. The peak load was 14.2 kip for specimen No.3, and the strength of specimen No.3 was 44 % of the target strength, 32 kip. The deflection at this point was 0.25 in. The peak point was the same as the failure point. There was no increase of the strength with respect to specimen No.1, and the deformation capacity of specimen No.3 was less than that of specimen No.1.

It was more difficult to insert the ends of the CFRP sheet into the holes than to install CFRP anchors. As a result, the performance of specimen No.3 was not as good as that of specimen No.2, and moreover, the strength and deformation capacities were near those of specimen No.1 which had no additional anchorage. It indicates that this procedure was ineffective.

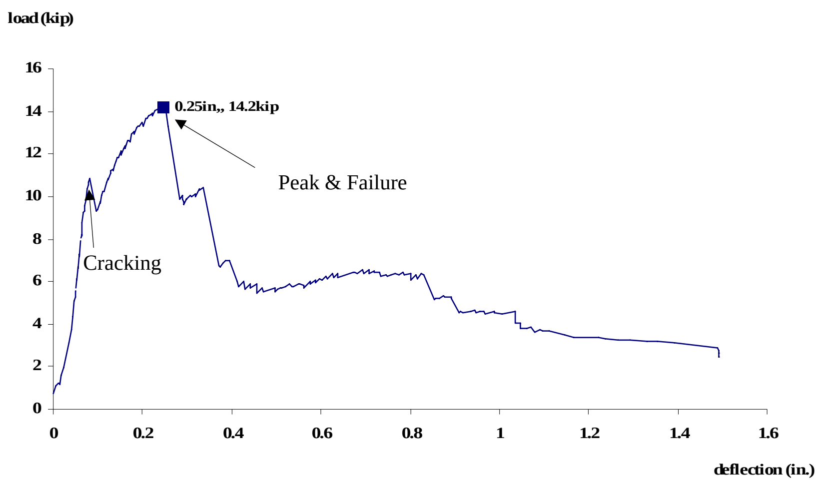


Figure 4.21 Load - Deflection Relationship for Specimen No.3

4.4.4 Strain in CFRP Sheet

The location of the strain gages installed on the both sides of specimen No.3 and the maximum measured strain in each gage are shown in Figure 4.22 and 4.23. The maximum strain measured in specimen No.3 was 0.0054 at strain gage No.6 in side-A where the transition of CFRP sheet to the hole started. At that location, strain was 43% of the specified fracture strain. In side-B, the highest strain was observed at mid span.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (12 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.22 and 4.23.

The vertical distribution of strains in the CFRP sheet was determined using strain gages No.9, 10, 11and 12, 13, 14 (Figure 4.22). The highest strain was observed in the strain gages closest to the extreme tension fiber, strain gage No.9 and12, and was less at gages nearer the neutral axis.

Strain gages were also installed near by the holes, but the strains were very low even though the failure occurred around the holes.

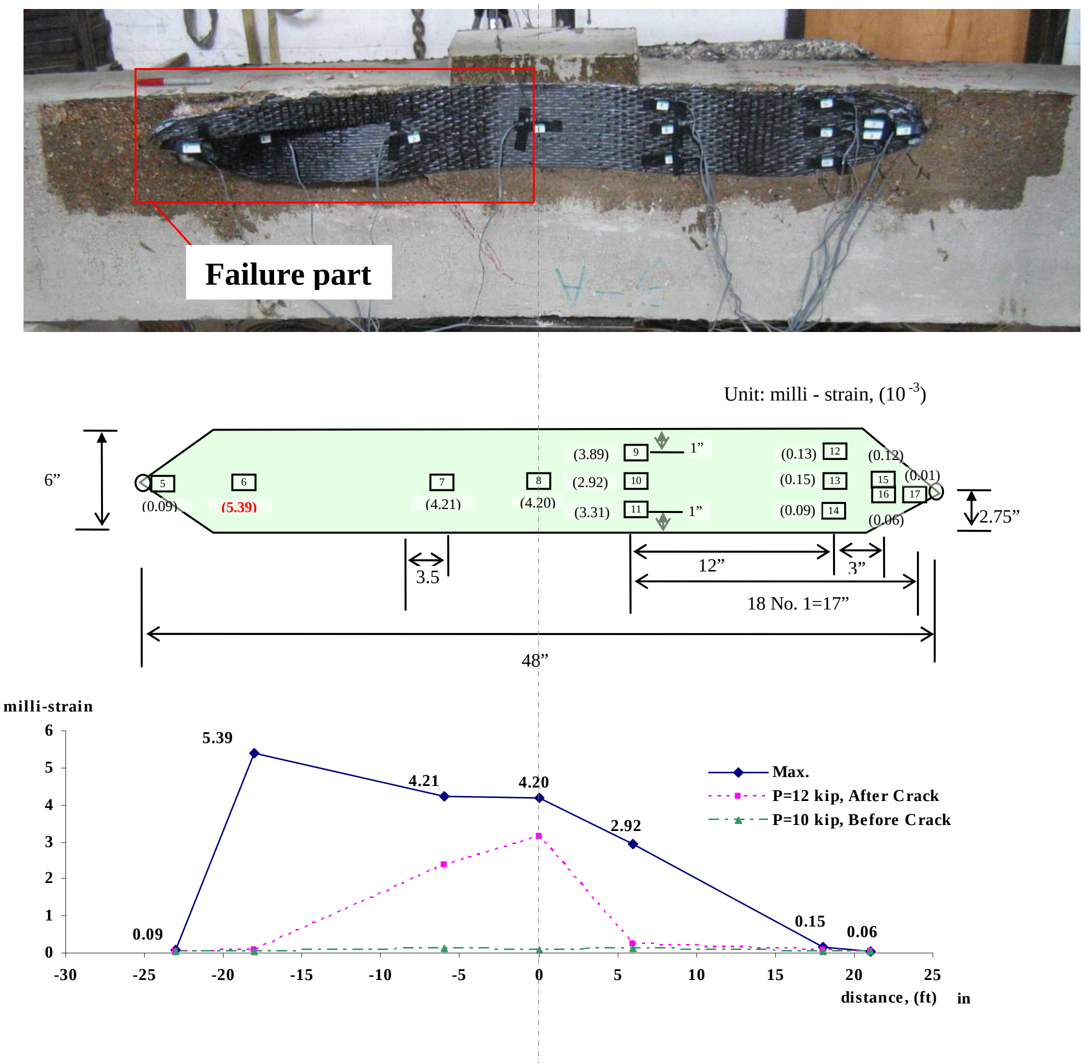


Figure 4.22 Strain in CFRP Sheet in Specimen No.3, Side -A

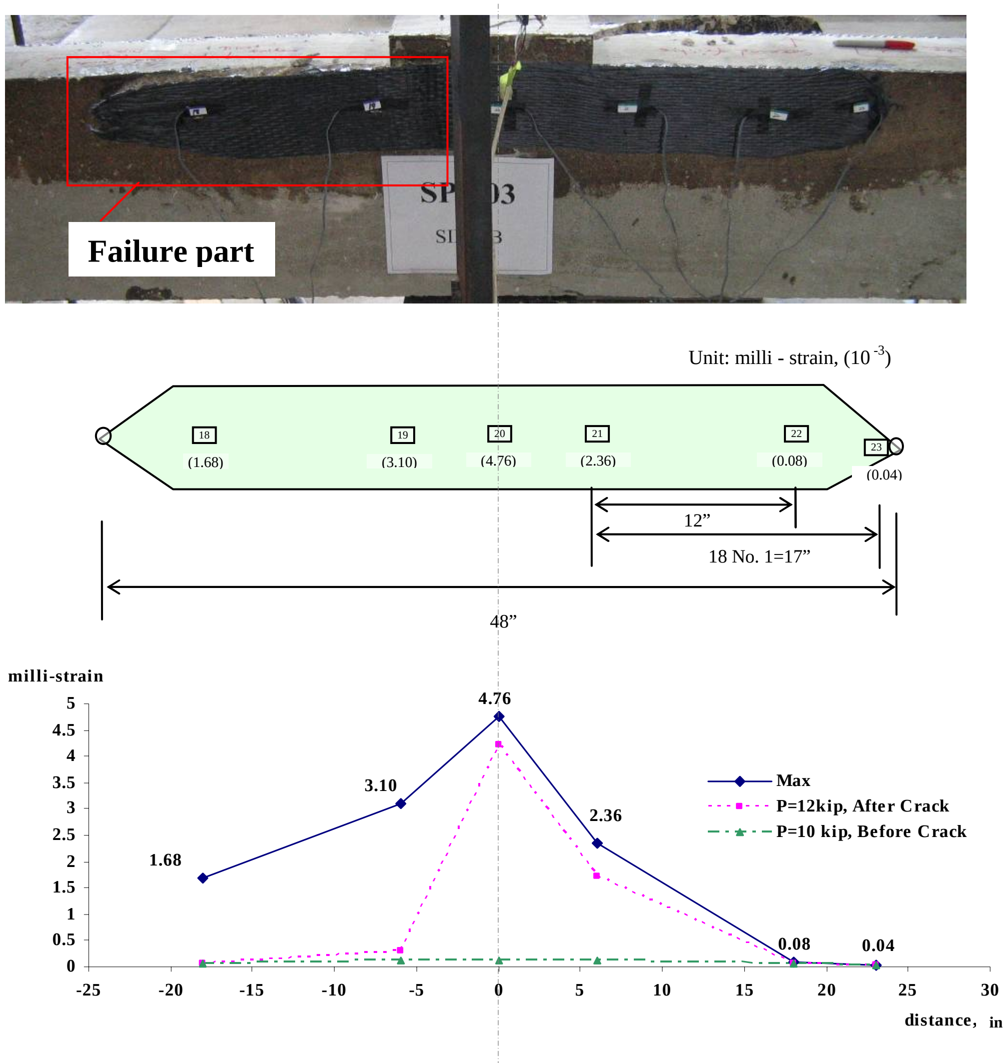


Figure 4.23 Strain in CFRP Sheet in Specimen No.3, Side-B

Load - strain relationships in a pair of strain gages in symmetric position showed similar load - strain relationship but they were not as similar as the other specimens (Figure 4.24). It was because the installation conditions of the CFRP sheets on the both sides were different. The CFRP sheets in specimen No.3 were not installed as good quality as specimen No.1 or No.2 because of the inserted part. It was a reason for the poor performance of specimen No.3.

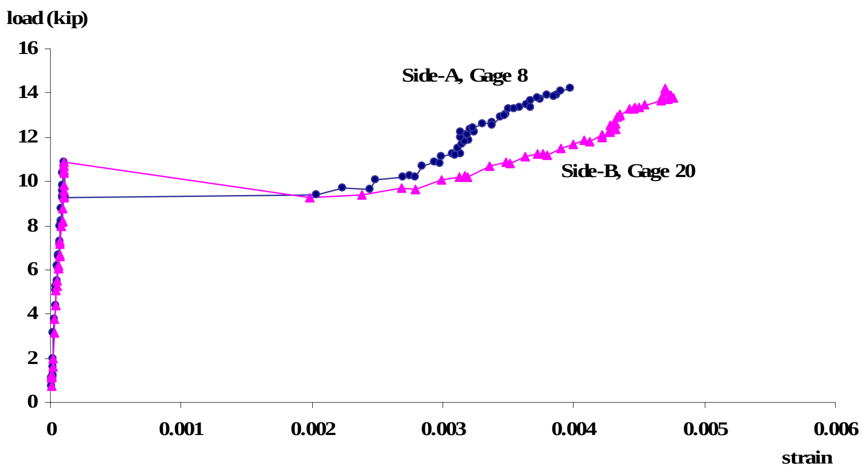


Figure 4.24 Load - Strain Relationship Measured on Strain Gages at Symmetric Position (At the Mid Span)

4.4.5 Strain in Steel Bar

The strains in the bar was measured only at the column face with 4 strain gages in specimen No.3 (Figure 4.25) so it was not possible to observe the distribution of strains in the bar. Therefore, load transfer from the CFRP sheet to the bar was estimated only by the strain at the location of the column face. The maximum measured bar strain in specimen No.3 was 0.0005 which was 24% of the yield strain of the bar. It showed that the load did not transfer effectively from the CFRP sheets to the bars over that short distance (4.5 in).

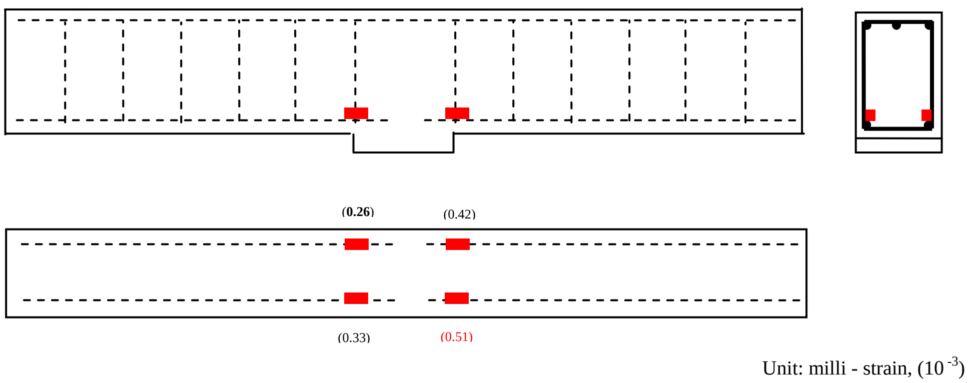


Figure 4.25 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.26.

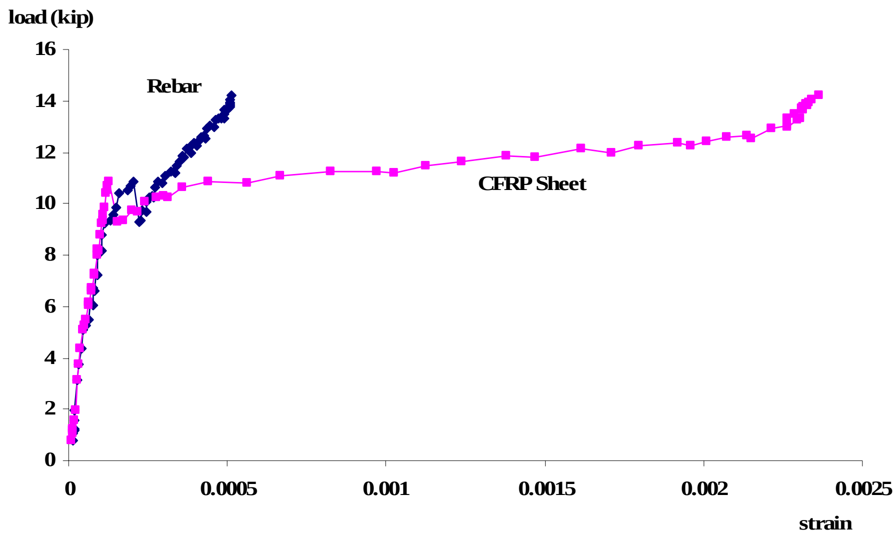


Figure 4.26 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.4.6 Summary

Summary of the test results is shown in Table 4.3.

Failure Mode	Failure of inserted CFRP sheet near the hole
Peak Load Displacement at the peak	14.2 kip, 44 % of target strength 0.25 in
Failure load Displacement at the failure	14.2 kip, 100 % of peak load 0.25 in
Measured maximum **CFRP** strain	0.0054, 43 % of specified fracture strain
Measured maximum **bar** strain	0.0005, 24% of yield strain

Table 4.3 Summary of Test Results for Specimen No.3

Specimen No.3 showed poor performance comparing with specimen No.1 and specimen No.2. The reasons were the CFRP sheet became weak near the hole because of stress concentration and poor quality in installation of the CFRP sheet due to the inserted part. Additional anchorage with CFRP anchors provided higher performance and easier quality control in installation than additional anchorage with the inserted part of the CFRP sheet.

4.5 SPECIMEN NO.4

4.5.1 Configuration

Specimen No.4 had 2 layers of the CFRP sheet and 1 CFRP anchor at each end of the CFRP sheet. Location of the holes for the CFRP anchors was selected as 2/3 of the development length of the bar, and it was 18 in. from the column face which was the same location as specimen No.2 and specimen No.3. Configuration of specimen No.4 is shown in Figure 4.27.

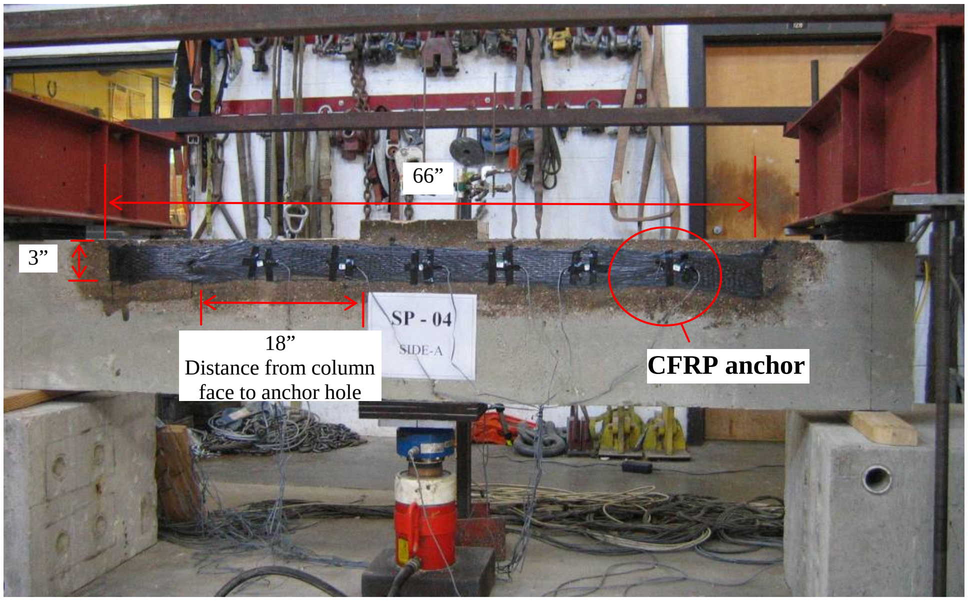


Figure 4.27 Configuration of Specimen No.4

4.5.2 Failure Mode

The failure mode of specimen No.4 involved of the additional anchorage, and it was not the failure of the CFRP materials but the failure of the concrete around the CFRP anchors. Both sides showed the same failure mode (Figure 4.28 and 4.29).

Figure 4.28 Failure mode of Specimen No.4

Figure 4.29 Failure mode of Specimen No.4

4.5.3 Load - Deflection Relationship

Load-deflection curve of specimen No.4 is shown in Figure 4.30. The peak load was 17.3 kip for specimen No.4, and the strength of specimen No.4 was 54 % of the target strength, 32 kip. The deflection at his point was 0.53 in. The increase of the strength of specimen No.4 with respect to that of specimen No.1 was only 2.7 kip because the additional anchorage failed before developing the full strength of the CFRP sheet.

The failure load (16.1 kip) was 93 % of the peak load, 17.3 kip, and the deflection at the failure (0.61 in.) 1.7 times as high as that of specimen No.1. Deformation capacity of the specimen increased significantly after installation of the CFRP anchors although the strength of the specimen was not improved much.

Although this specimen showed a similar load - deflection relationship as specimen No.2, the failure mode was different. A possibility of the strength increase was observed by the installation of 2 layers of the CFRP sheets with improved additional anchorage because the CFRP sheet did not fracture.

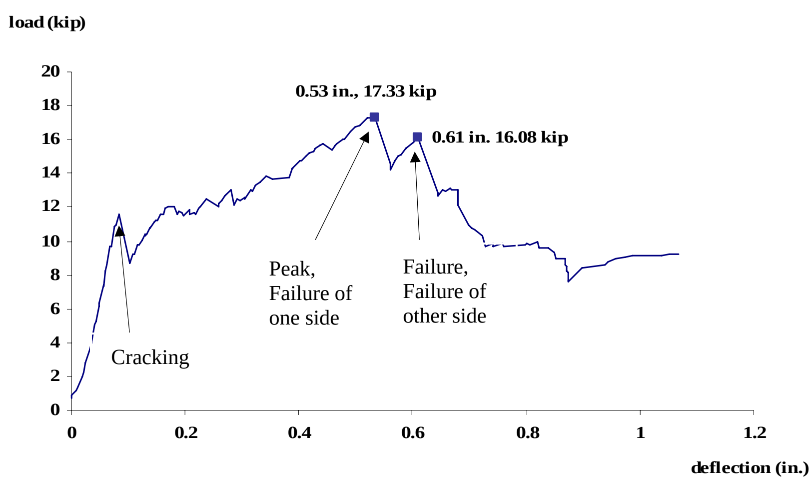


Figure 4.30 Load - Deflection Relationship of Specimen No.4

4.5.4 Strain in CFRP Sheet

The location of the strain gages installed on the both sides of specimen No.4 and the maximum measured strain in each strain gage are shown in Figure 4.31 and 4.32. Gage No.7 and gage No.15 did not work.

The maximum strain measured in specimen No.4 was 0.0086 at strain gage No.9 in side-A in front of the CFRP anchor, and reached 68% of the specified fracture strain of 0.0126.

From the horizontal distribution of strains in the CFRP sheet, the highest strains indicate where failure occurred on both sides of the specimen (Figure 4.31 and 4.32).

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (14 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.31 and 4.32

Strain in the CFRP sheet behind the CFRP anchor (gage No.10) was much less than that in the sheet in front of the anchor. It was evidence that the CFRP anchor effectively held the CFRP sheet.

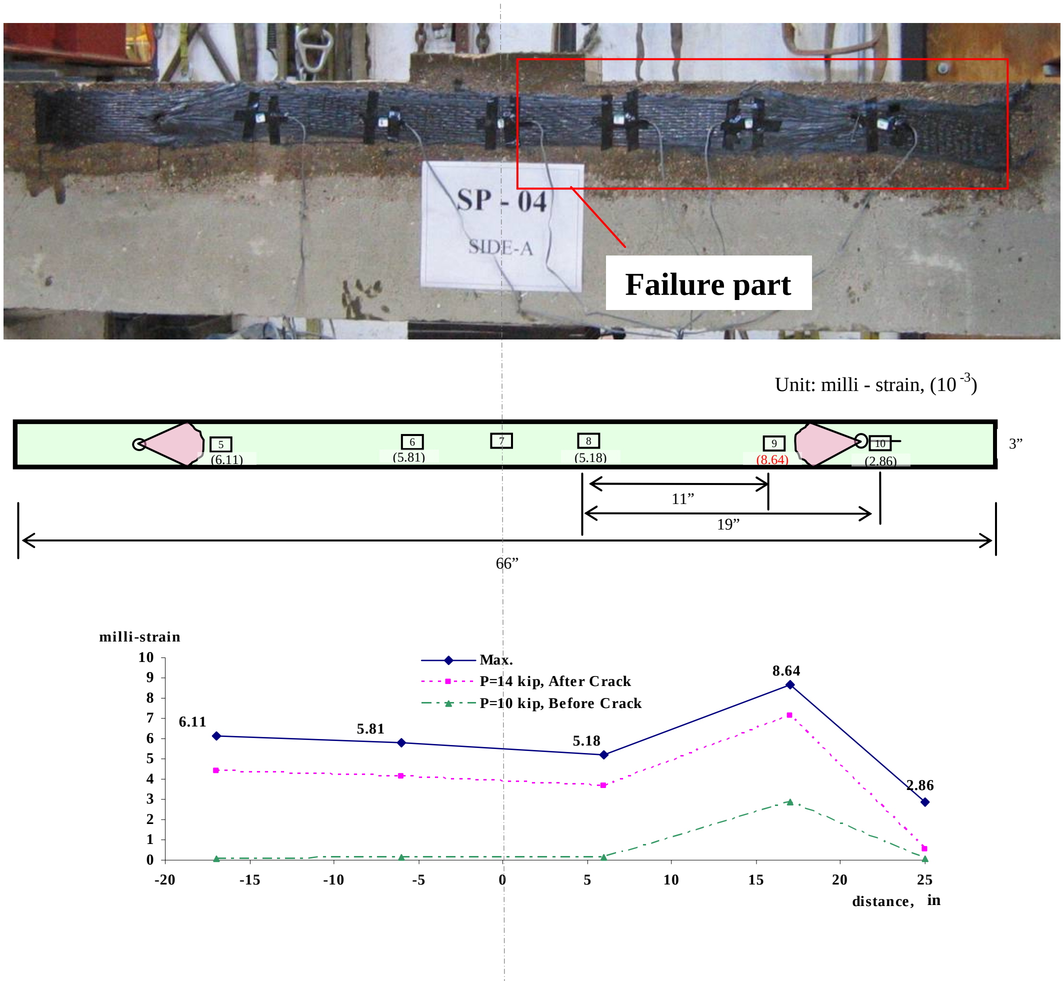


Figure 4.31 Strain in CFRP Sheet in Specimen No.4, Side-A

Figure 4.32 Strain in CFRP Sheet in Specimen No.4, Side-B

Load - strain relationship in a pair of strain gages placed in symmetric position showed similar load - strain relationship and indicated CFRP sheets on the both sides reached capacity at the same time (Figure 4.33). Strain gages at other symmetric position showed similar strains.

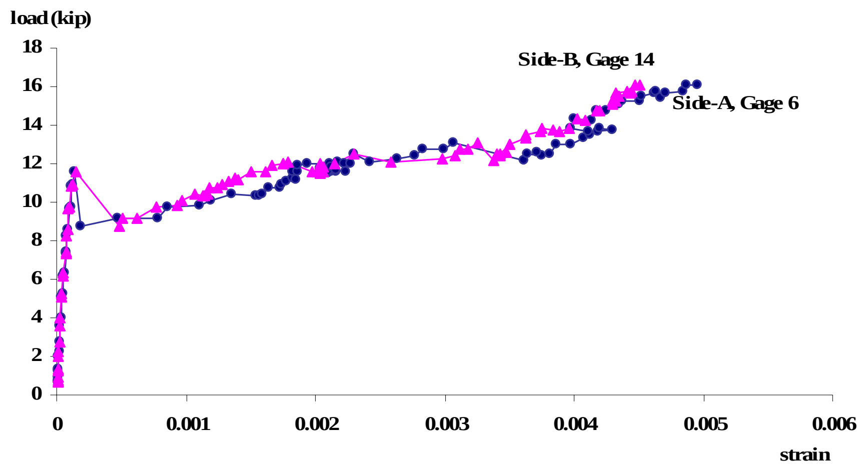


Figure 4.33 Load - Strain Relationship Measured on Strain Gages at Symmetric Position (At the Column Face)

4.5.5 Strain in Steel Bar

The strain in the bars were measured only at the column face with 4 strain gages in specimen No.4 (Figure 4.34) so it was not possible to observe the distribution of strains in the bar. Therefore, load transfer from the CFRP sheet to the bar was estimated only by the strain at the location of the column face. The maximum measured bar strain in specimen No.4 was 0.0005 which was 24% of the yield strain of the bar. It showed that the load did not transfer effectively form the CFRP sheet s to the bars in the short 4.5 in. distance within the column.

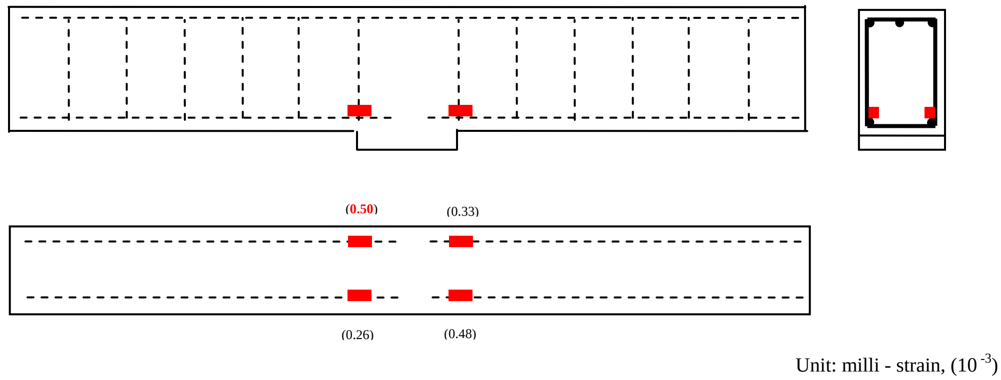


Figure 4.34 Location of Bar Strain Gage and Maximum Measured Strain

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.35.

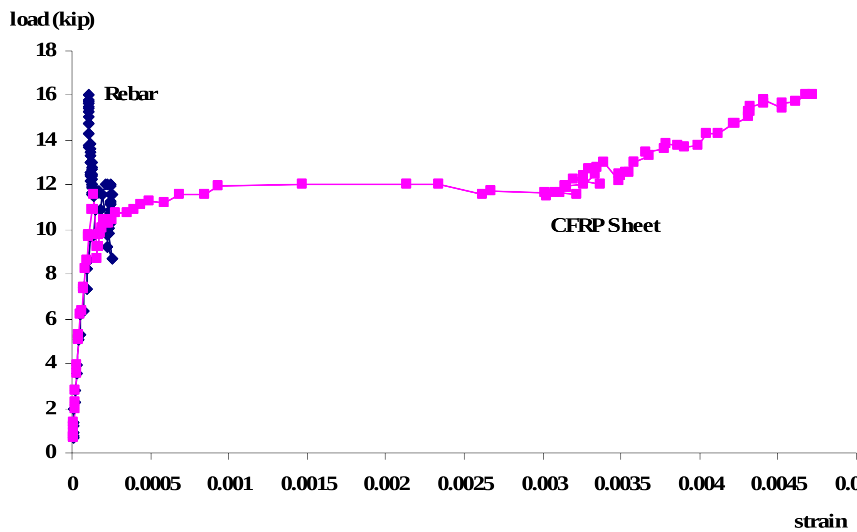


Figure 4.35 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.5.6 Summary

Summary of the test results is shown in Table 4.4.

Failure Mode	Concrete failure around CFRP anchor
Peak Load Displacement at the peak	17.3 kip, 54 % of target strength 0.53 in
Failure load Displacement at the failure	16.1 kip, 93 % of peak load 0.61 in
Measured maximum **CFRP** strain	0.0086, 68% of specified fracture strain
Measured maximum **bar** strain	0.0005, 24% of yield strain

Table 4.4 Summary of Test Results for Specimen No.4

The specimens with the CFRP anchors showed better behavior than the specimens without them but the strength and deformation capacity of the specimens with the anchors were not improved significantly. One CFRP anchors at the each end of the CFRP sheet was not enough to develop full strength of the CFRP sheet, and failure of anchorage occurred before failure of CFRP sheet.

A split-and-fracture pattern of the CFRP sheet failure did not occurred in specimen No.4 because of two layers of the CFRP sheets. Two layers of the CFRP sheets were more effective way of using CFRP materials because they provided larger moment arm than one layer of the CFRP sheet with the same tensile force capacity. However, since two layers of the CFRP sheets had small bonding area to the concrete comparing with one layer of the CFRP sheet, the bonding strength between the concrete and the CFRP sheet was relatively small. Therefore, the additional anchorage was critical to develop the full capacity of the two layers of the CFRP sheets. Alternative way to increase performance of specimens with two layers of the CFRP sheets were found by testing specimen No.4, installation of improved additional anchorage. The effectiveness of the various anchorages with the two layers of the CFRP sheets was estimated by specimens No.6, 7, 8, 9 and10.

4.6 SPECIMEN NO.5

4.6.1 Configuration

Specimen No.5 had 1 layer of the CFRP sheet and 1 CFRP U-wrap at each end of the CFRP sheet. Location of the CFRP U-wrap was selected as 2/3 of the development length of the bar, and it was 18 in. from column face which was the same location as the CFRP anchors in specimen No.2 and specimen No.4. Configuration of specimen No.4 is shown in Figure 4.36.

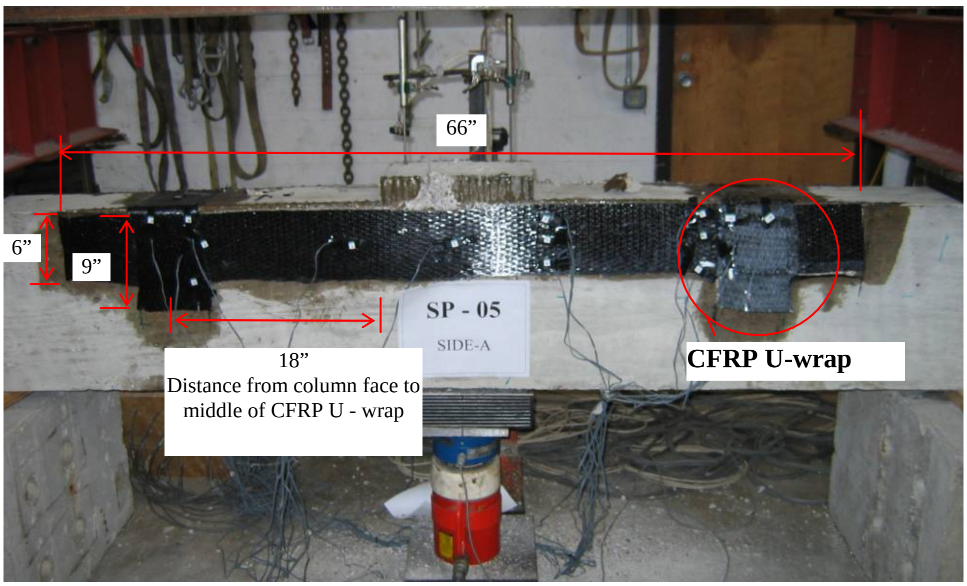


Figure 4.36 Configuration of Specimen No.5

4.6.2 Failure Mode

The failure mode of specimen No.5 involved of the additional anchorage which was delamination of CFRP U-wraps. Both sides showed the same failure mode (Figure 4.37 and 4.38).

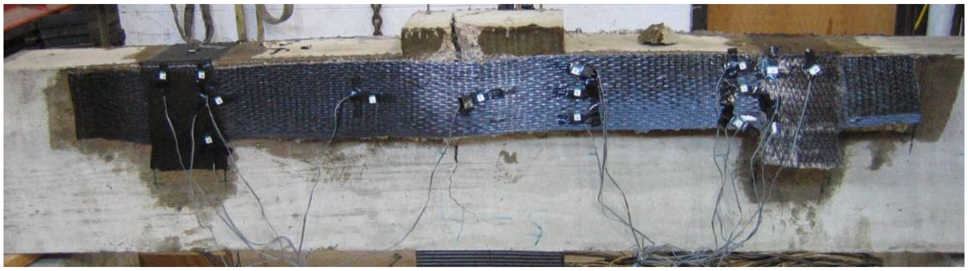


Figure 4.37 Failure Mode of Specimen No.5

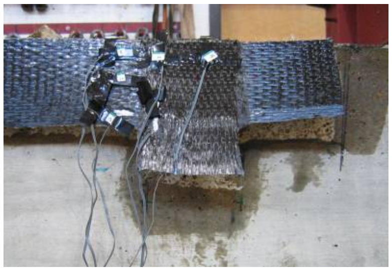


Figure 4.38 Failure Mode of Specimen No.5, Delamination of CFRP U-wrap

4.6.3 Load - Deflection Relationship

Load-deflection curve of specimen No.5 is shown in Figure 4.39. The peak load was 17.6 kip for specimen No.5, and the strength of specimen No.5 was 55% of the target strength, 32 kip. The deflection at his point was 0.66 in. The increase in strength of specimen No.5 with respect to that of specimen No.1 was only 3 kip because the anchorage failed before developing the full strength of the CFRP sheet. The peak point was the same as the failure point.

The deflection at the failure (0.66 in) was 1.9 times as high as that of specimen No.1. Deformation capacity of the specimen increased significantly after installation of the CFRP U-wraps although the strength of the specimen was not improved much. The strength decreased rapidly after the peak point because the CFRP U-wrap in one side delaminated from the concrete right after that in other side delaminated.

The load - displacement curve showed plateau when delamination of the CFRP sheet was propagating. The delamination of the CFRP sheet propagated from the cracking to the CFRP U-wrap until the U-wrap failed.

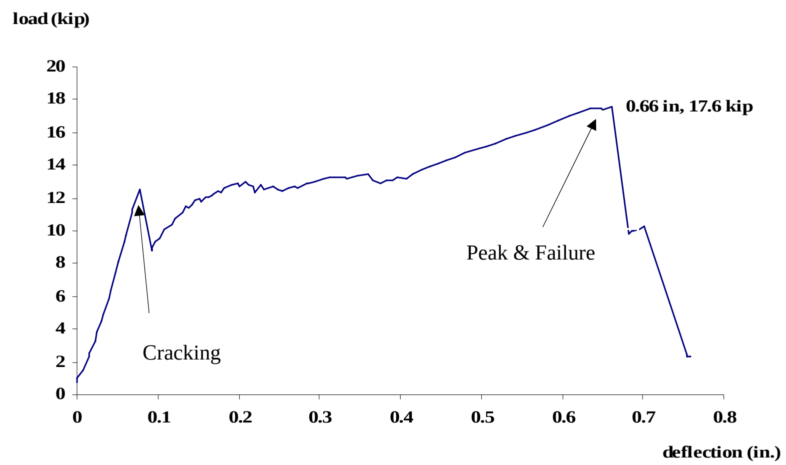


Figure 4.39 Load - Deflection Relationship of Specimen No.5

4.6.4 Strain in CFRP Sheet

The location of the strain gages installed on the both sides of specimen No.5 and the maximum measured strain in each strain gage are shown in Figure 4.40 and 4.41. Gage No.7 had a calibration strain error about 0.0005.

The maximum strain measured in specimen No.5 was 0.0065 at strain gage No.8 in side-A at the column face, and the strain was 52% of the specified fracture strain of 0.0126.

From the horizontal distribution of strains in the CFRP sheet, the highest strains indicate where failure occurred on the both sides of specimen.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (14 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.40 and 4.41

The vertical distribution of strains in the CFRP sheet was observed by strain gage No.8, 9,10 and strain gages No.11, 12, 13 (Figure 4.40). The highest strains were observed in the strain gages closest to the extreme tension fiber, strain gages No.8 and 11, and reduced nearer the neutral axis of the beam.

Strain gages were also placed in the CFRP U-wrap. The strain gages placed at the edge of the beam, gages No.17, 18, 21, 22 and 23 showed compressive strain because the CFRP U-wrap bended upward after delamination, and strain gages No.19 and 24 showed tensile strain. Strain gages were also placed in the CFRP U-wrap at the top face of the beam (the bottom face of the prototype beam) but no strain was observed.

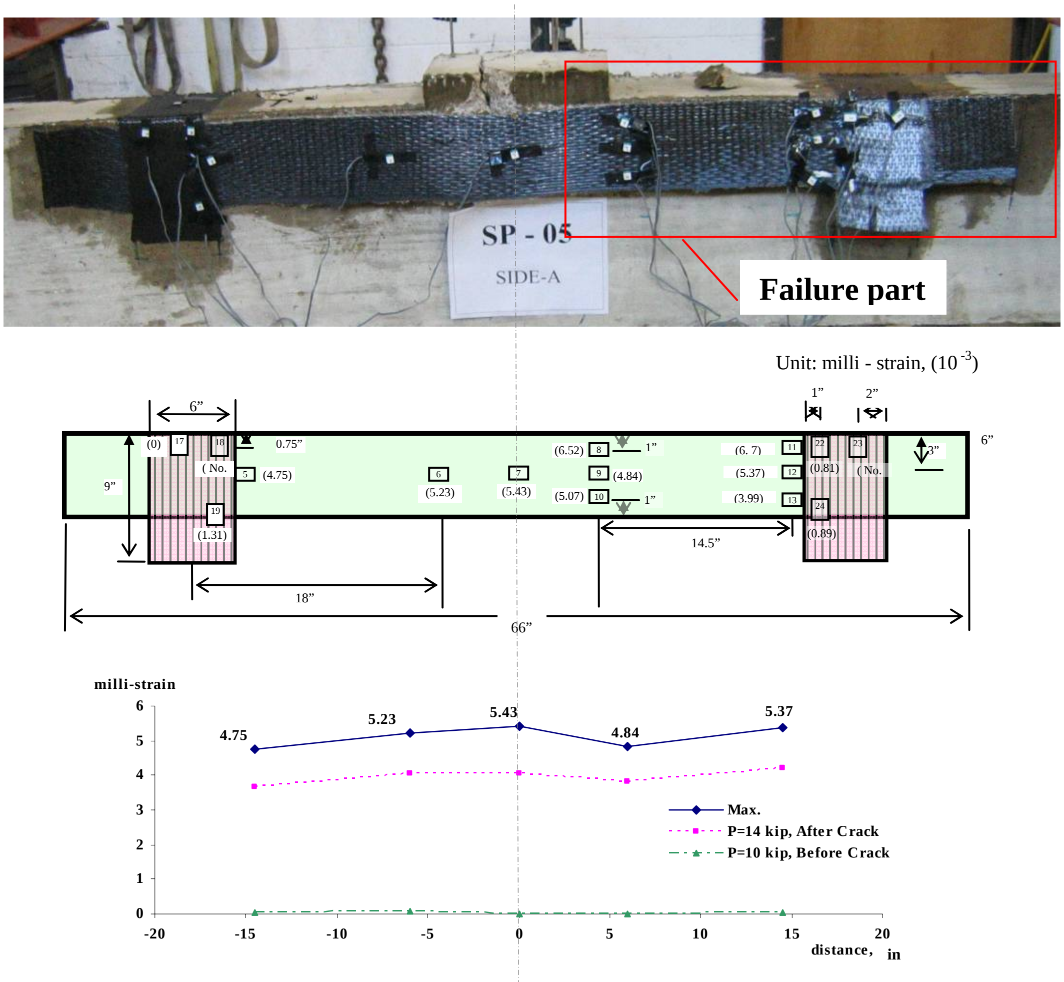


Figure 4.40 Strain in CFRP Sheet for Specimen No.5 Side-A

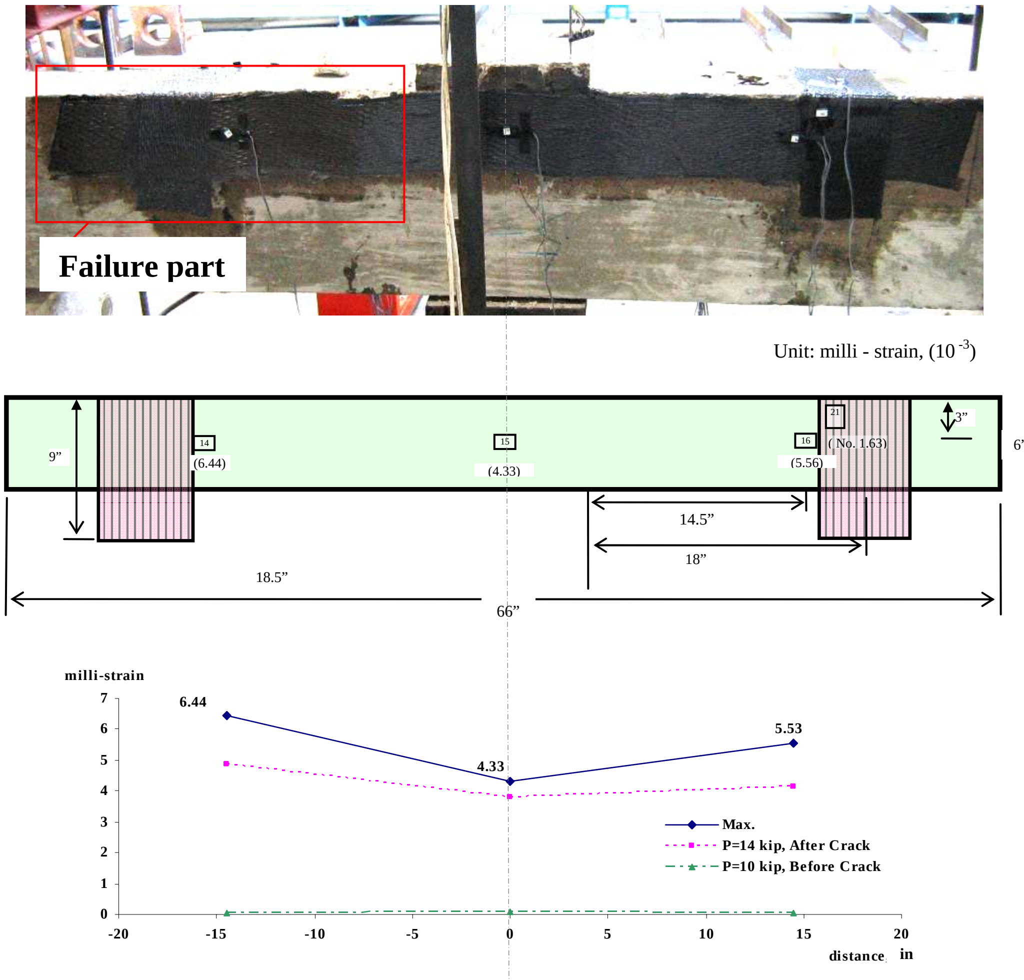


Figure 4.41 Strain in CFRP Sheet for Specimen No.5 Side-B

Load-strain relationships in a pair of strain gages in symmetric position showed similar load-strain relationship although the calibration error of gage No.7 and indicated the CFRP sheets on the both sides reached capacity at the same time (Figure 4.42).

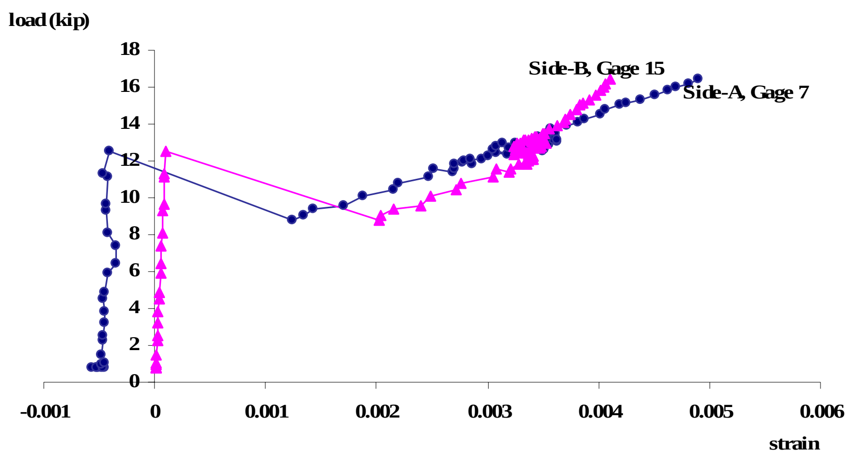


Figure 4.42 Load - Strain Relationship Measured in Strain Gages at Symmetric Position (At the Column Face)

4.6.5 Strain in Steel Bar

The strains in the bars were measured only at the column face with 4 strain gages in specimen No.5 (Figure 4.43) so it was not possible to observe the distribution of strains in the bar. Therefore, load transfer from the CFRP sheet to the bar was estimated only by the strain at the location of the column face. The maximum measured bar strain in specimen No.4 was 0.0004 which was 19% of the yield strain of the bar.

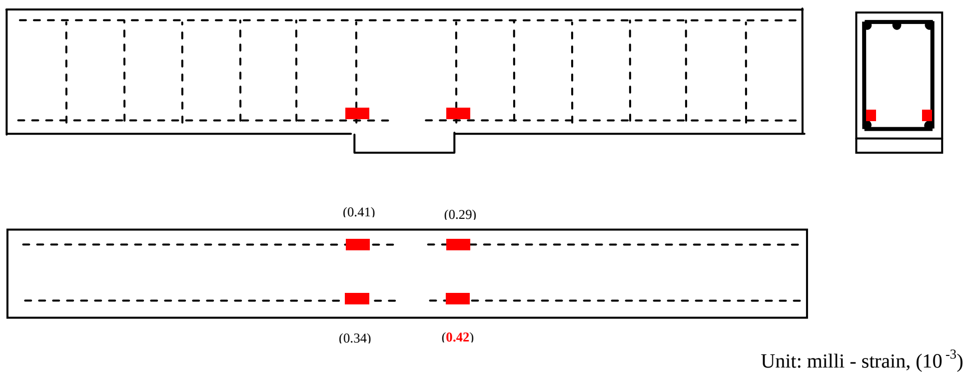


Figure 4.43 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.44.

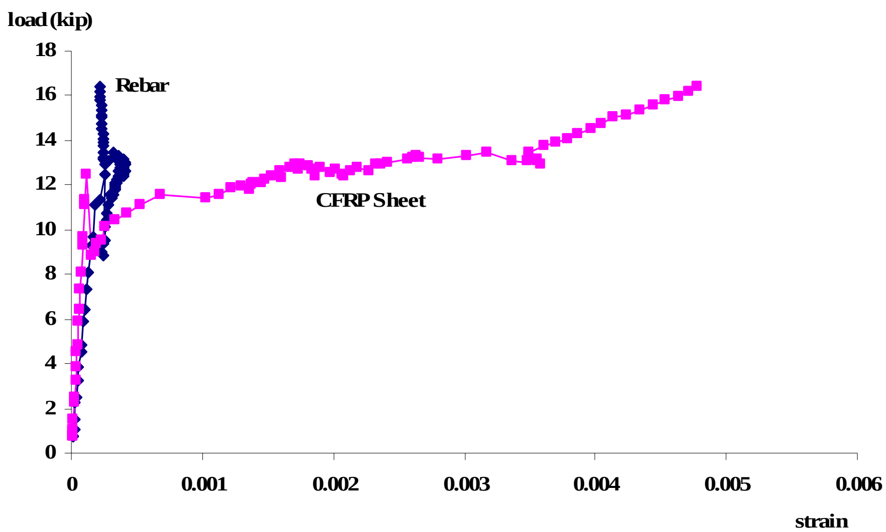


Figure 4.44 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.6.6 Summary

Summary of the test results is shown in Table 4.5

Failure Mode	Delamination of CFRP U-wrap
Peak Load Displacement at the peak	17.6 kip, 55% of target strength 0.66 in
Failure load Displacement at the failure	17.6 kip, 100% of target strength 0.66 in
Measured maximum **CFRP** strain	0.0065, 52% of specified fracture strain
Measured maximum **bar** strain	0.0004, 19% of yield strain

Table 4.5 Summary of Test Results for Specimen No.5

Although the strength and deformation capacity of specimen No.5 were similar to those of specimen No.2, the failure modes were different. While fracture of the CFRP sheet was the failure mode of specimen No.2, delamination of the CFRP U-wrap, anchorage failure, was the failure mode of specimen No.5. Therefore comparing the CFRP U-wrap with the CFRP anchor, the CFRP anchors were more efficient way to provide anchorage to the sheets to the concrete than the U-wraps.

4.7 SPECIMEN NO.6

4.7.1 Configuration

Specimen No.6 had 2 layers of the CFRP sheets and 2 CFRP anchors at each end of the CFRP sheet. Location of one group of the anchor holes for the CFRP anchor was selected as 2/3 of the development length of the bar, and it was 18 in. from the column face which is the same location as specimen No.2 and specimen No.3. Location of the other group of the anchor holes was selected as 6 in. from the column face to place the CFRP anchors as close as to the column face without over it. Configuration of specimen No.6 is shown in Figure 4.45.

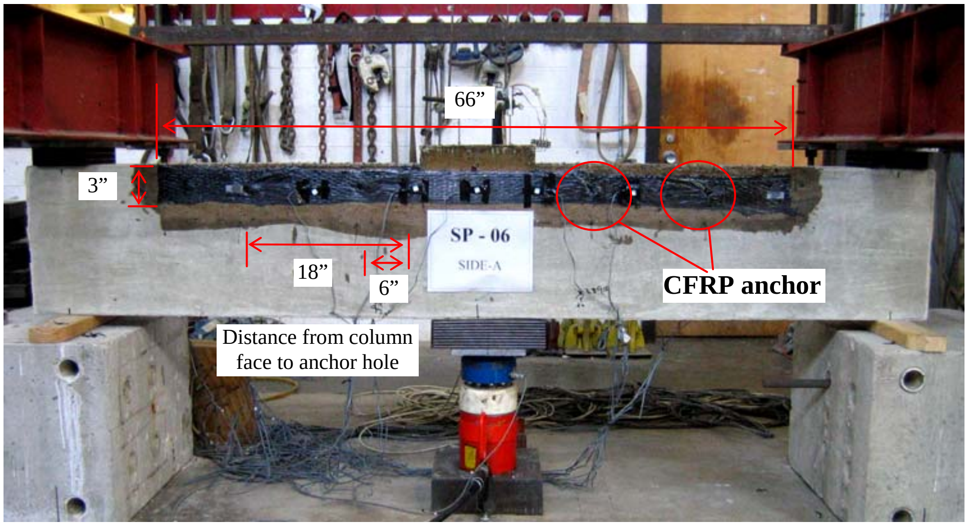


Figure 4.45 Configuration of Specimen No.6

4.7.2 Failure Mode

The failure mode of specimen No.6 involved of the additional anchorage and was not material failure of the CFRP anchors but the failure of the concrete around the CFRP anchor (Figure 4.46). Both sides showed the same failure mode. It was similar to the failure mode of specimen No.4. The CFRP sheet on the specimen was cut after the test in order to see the concrete crack and failure shape (Figure 4.47), and then the cover concrete was removed because the crack propagated along the longitudinal bar from the mid span to the anchor holes located at 6 in. from the column face (Figure4.48).

Figure 4.46 Failure Mode of Specimen No.6

Figure 4.47 Failure Mode of Specimen No.6, After Cutting CFRP Sheet

Figure 4.48 Failure Mode of Specimen No.6, After Removing Concrete Cover

Although the CFRP sheet did not fracture, the CFRP sheet slipped about 1.25 in. after delamination. It allowed more deflection to specimen No.6 with maintaining its strength (Figure 4.49 and 4.50)

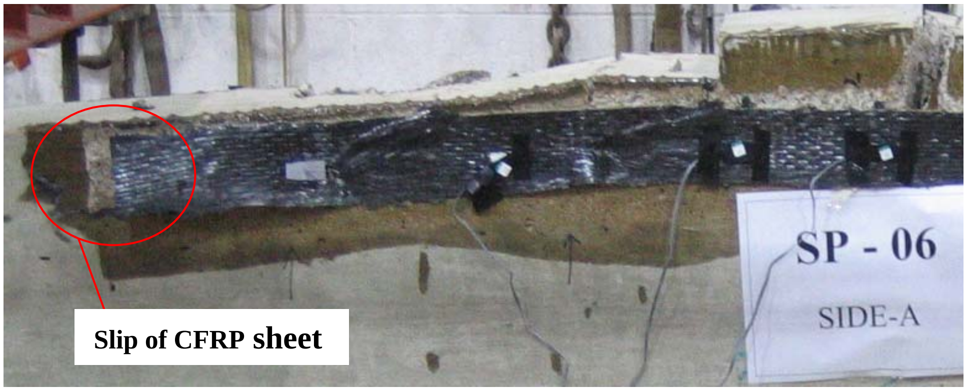


Figure 4.49 Slip of CFRP Sheet

Figure 4.50 Slip of CFRP Sheet

4.7.3 Load - Deflection Relationship

Load deflection curve of specimen No.6 is shown in Figure4.51. The peak load was 25.8 kip for specimen No.6, and the strength of specimen No.6 was 81% of the target strength, 32 kip. The deflection at his point was 0.65 in.. The increase of the strength of specimen No.6 was 11.2 kip with respect to that of specimen No.1.

The failure load (21.5 kip) was 83 % of the peak load, 25.8 kip, and the deflection at the failure (0.91 in.) was 2.6 times as high as that of specimen No.1. Both the strength and deformation capacity increased significantly after the use of two CFRP anchors at each end of the CFRP sheet.

However, although two CFRP anchors increased the performance of the specimen significantly, specimen No.6 did not develop the full tensile capacity of the CFRP sheet.

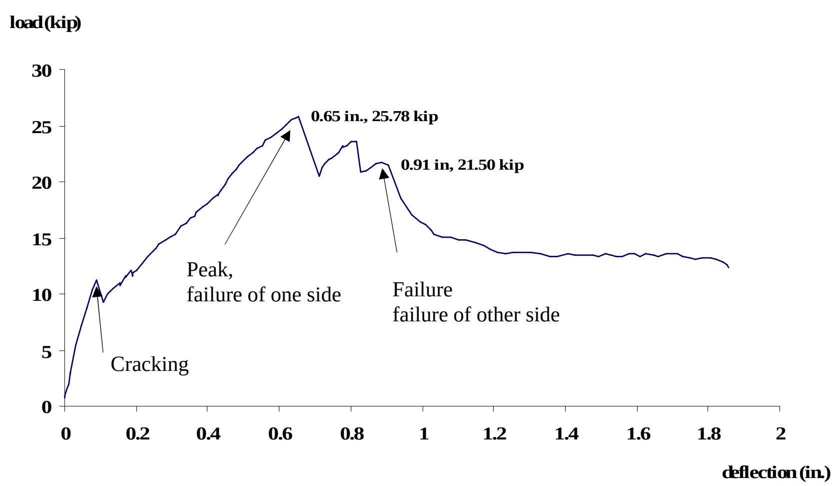


Figure 4.51 Load - Deflection Relationship of Specimen No.6

4.7.4 Strain in CFRP Sheet

The location of strain gages installed in both sides of specimen No.6 and the maximum measured strain in each strain gage are shown in Figure 4.52 and 4.53. Gages No.15 and No.17 did not work.

The maximum strain measured in specimen No.6 was 0.0097 at strain gage No.20 in side-B at the mid span, and the strain was 77 % of the specified fracture strain of 0.0126.

From the horizontal distribution of strains in the CFRP sheet, slightly high strain was observed in which the failure occurred, but more symmetric horizontal distribution of strains was observed in specimen No.6 than that of the previous specimens tested. The delamination propagated to the anchors located 18 in. from the column face. The CFRP anchors controlled the direction of delamination, and it occurred in more uniform way over the length of the CFRP sheet until the anchorage failure.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (18 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.52 and 4.53

The strain of the CFRP sheet behind the CFRP anchor (gages No.16 and 24) was much less than that of the sheet in front of the anchor.

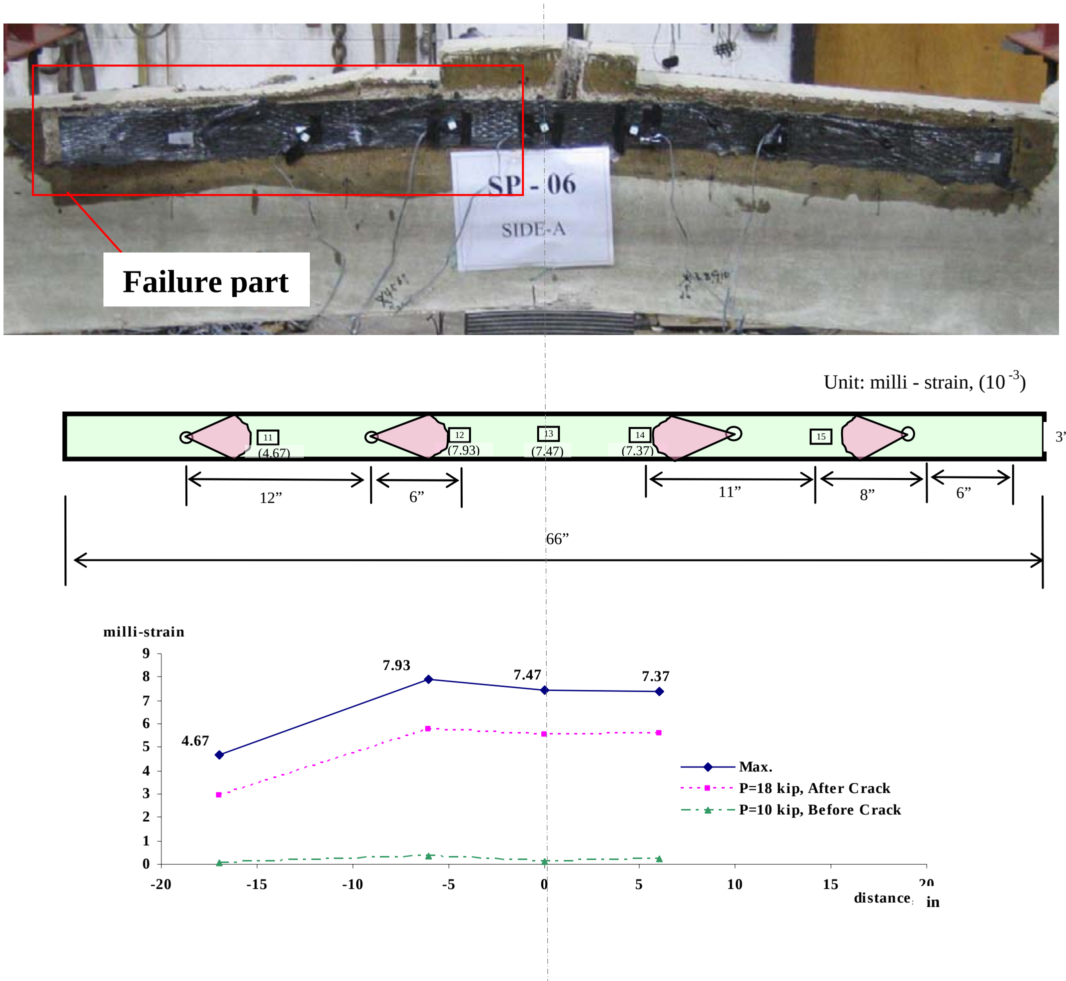


Figure 4.52 Strain in CFRP Sheet in Specimen No.6, Side-A

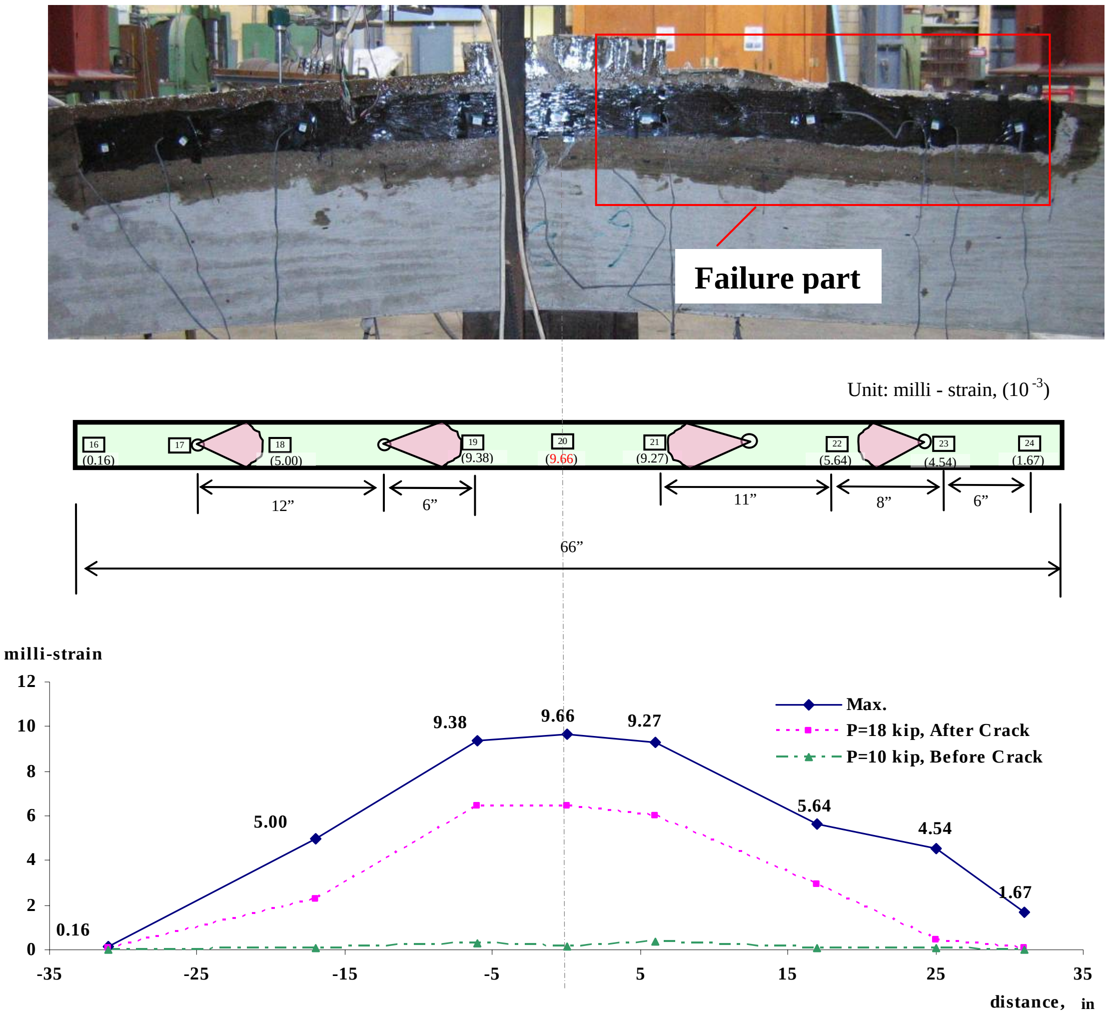


Figure 4.53 Strain in CFRP Sheet in Specimen No.6, Side-B

Load - strain relationships in a pair of strain gages placed in symmetric position showed similar load - strain relationship and indicated the CFRP sheets on the both sides reached capacity at the same time (Figure4.54).

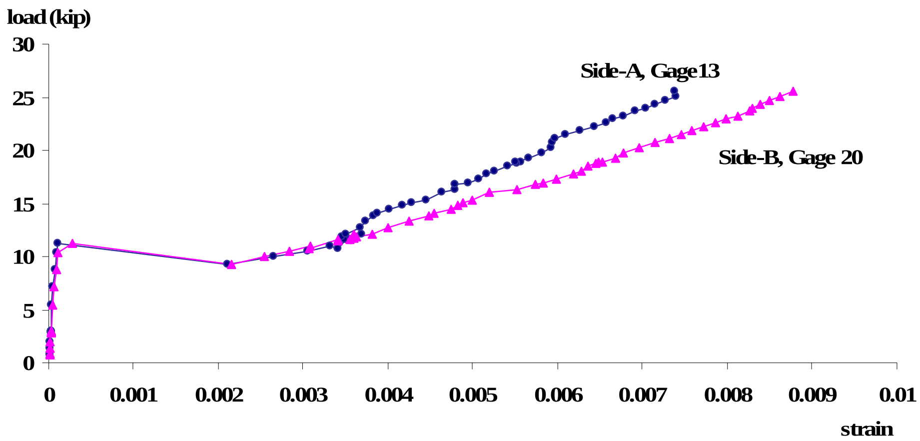


Figure 4.54 Load - Strain Relationship Measured on Strain Gages at Symmetric Position (At Mid span)

4.7.5 Strain in Steel Bar

The strains in the bars were measured with 10 strain gages for specimen No.6, but 3 strain gages did not work (Figure 4.55). The bar strain gages in specimens No.6, 7, 8, 9 and 10 were distributed horizontally as shown in Figure 4.55 to observe transfer of force from the CFRP sheets to the bar. The maximum measured bar strain in specimen No.6 was 0.0007 which was 33% of the yield strain of the bar.

The force did not effectively transfer from the CFRP sheet to the bar because the observed strains were low with respect to the yield strain and the strain in the gages decreased as they became more distance from mid span. It indicated that the bars did not contribute to the strength after the cracking.

From the horizontal distribution of strains in the bar, bar strain gages located at the failure part of specimen showed higher strain than those located where failure did not occur.

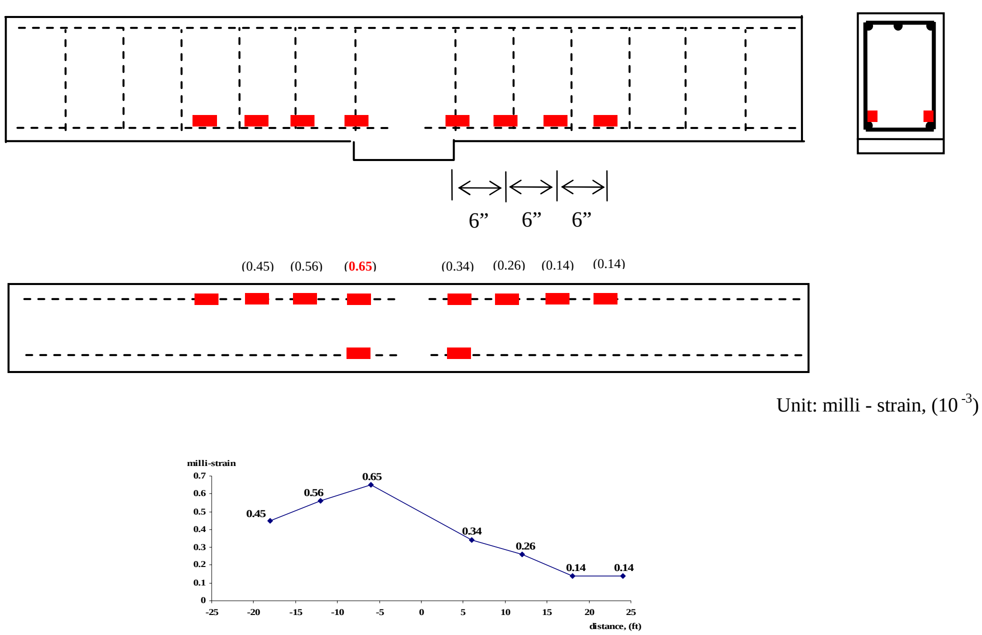


Figure 4.55 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure4.56.

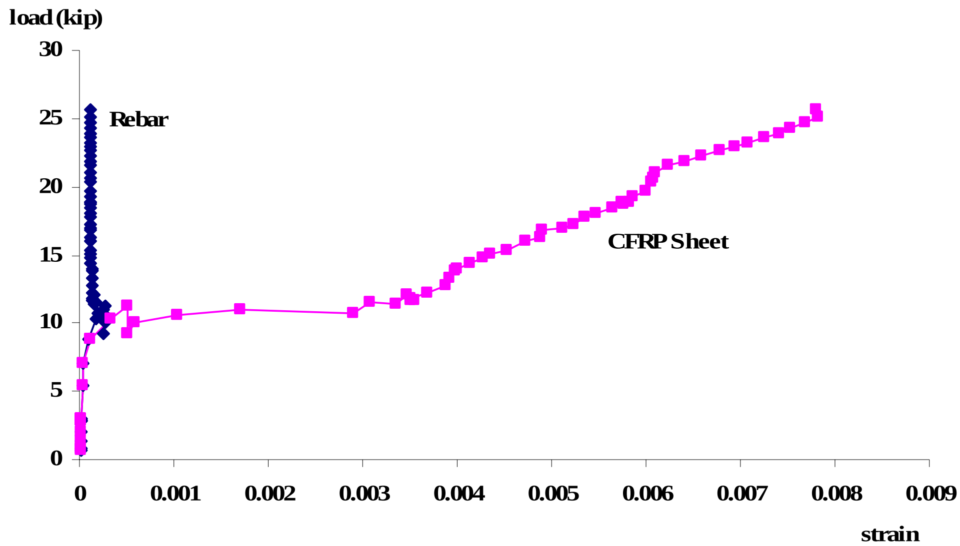


Figure 4.56 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.7.7 Summary

Summary of the test results is shown in Table 4.6.

Failure Mode	Concrete failure around CFRP anchor
Peak Load Displacement at the peak	25.8 kip, 81% of target strength 0.65 in.
Failure load Displacement at the failure	21.5 kip, 83% of peak load 0.91 in
Measured maximum **CFRP** strain	0.0097, 77% of specified fracture strain
Measured maximum **bar** strain	0.0007, 33% of yield strain

Table 4.6 Summary of Test Results of Specimen No.6

The strength and deformation capacity of the specimen increased significantly with two CFRP anchors at each end of the CFRP sheet. However, the failure mode of specimen No.6 was failure of anchorage, and the capacity of the CFRP sheet did not fully developed. Therefore, the possibility of increasing capacity of a specimen still existed by improving anchorage. The specimens with improved anchorage were tested with specimens No.7, 8 and 9, and these improved anchorages were built based on the anchorage of specimen No.6.

4.8 SPECIMEN NO.7

4.8.1 Configuration

Specimen No.7 had 2 layers of the CFRP sheets and 3 CFRP anchors at each end of the CFRP sheet. The locations of two groups of anchor holes were as the same as those of specimen No.6. One group of the anchor holes was located at 18 in. from the column face and the other group was located at 6 in. from the column face. The location of the additional group of anchor holes was located at 26 in. from the column face. The length of the CFRP sheet increased by 2 in., 1 in. for each end, to place the additional CFRP anchors at the far ends. Configuration of specimen No.7 is shown in Figure 4.57.

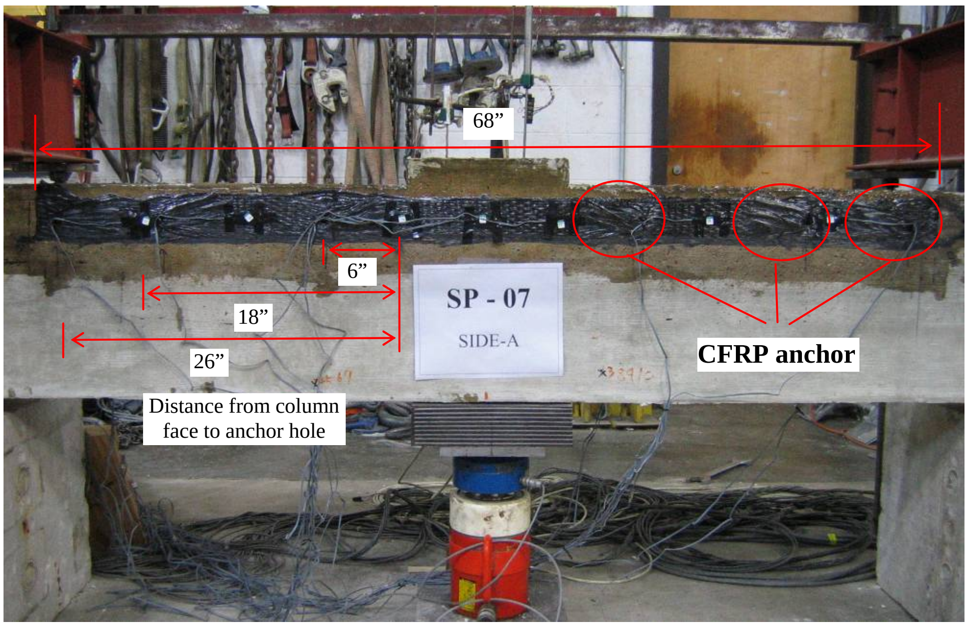


Figure 4.57 Configuration of Specimen No.7

4.8.2 Failure Mode

Various failure modes were observed in specimen No.7 as shown in Figures from 4.58 to 4.63.

The failure modes of specimen No.7 was a failure of both anchorage and CFRP sheet. The failure pattern of CFRP sheet was a whole-sheet-fracture. The location of the fracture was near the anchor hole closest to the column face on both sides (Figure 4.59 and 4.62). However, the failure mode of anchorage was different between side-A and side-B. The CFRP anchor in side-A fractured (Figure 4.60), and the concrete crushing occurred around the CFRP anchor in side B (Figure 4.63). Specimen No.7 was the first specimen showed a material failure of the CFRP anchor.

Figure 4.58 Failure Mode of Specimen No.7, Side-A

Figure 4.59 Failure Mode of Specimen No.7, Side-A, Fracture of CFRP Sheet

Figure 4.60 Failure Mode of Specimen No.7, Side-A, Fracture of CFRP Anchor

Figure 4.61 Failure Mode of Specimen No.7, Side-B

Figure 4.62 Failure Mode of Specimen No.7, Side-B, Fracture of CFRP Sheet

Figure 4.63 Failure Mode of Specimen No.7, Side-B, Concrete failure around CFRP Anchor

The CFRP sheet in specimen No.7 did not slip because the additional CFRP anchors held the far ends of the CFRP sheet (Figure 4.64). The deformation capacity of specimen No.7 was less than that of specimen No.6 because slip did not occur. The strength of specimen No.7 was also less than that of specimen No.6 although specimen No.7 had one more CFRP anchor at each end of the sheets than specimen No.6. A possible reason of the less strength was stress concentration due to this additional anchor.

Figure 4.64 Slip Condition of CFRP Sheet

4.8.3 Load - Deflection Relationship

Load-deflection curve of specimen No.7 is shown in Figure 4.65. The peak load was 23.8 kip for specimen No.7, and the strength of specimen No.7 was 74 % of the target strength, 32 kip which was less than the strength of specimen No.6. The deflection at this point was 0.74 in.. The peak point was the same as failure point. The increase in the strength of specimen No.6 was 11.2 kip with respect to that of specimen No.1.

The deflection at the failure (0.74 in.) was about twice as that of specimen No.1. Both strength and deformation capacity of specimen No.7 were less than those of specimen No.6 although more CFRP anchors were placed.

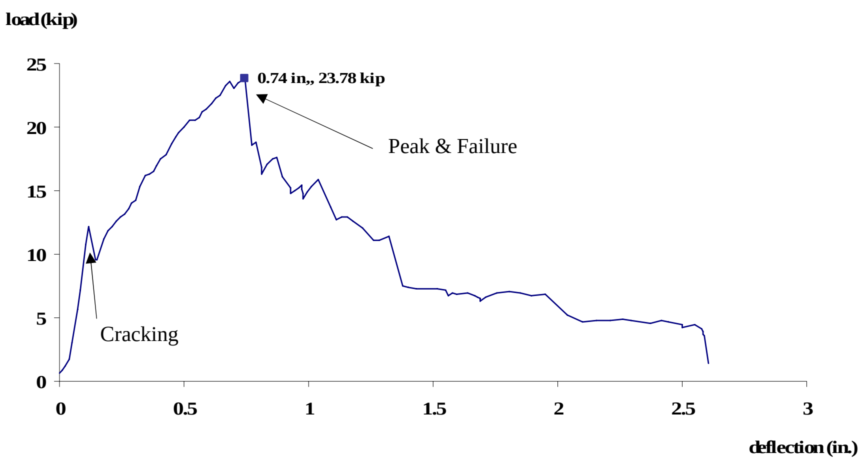


Figure 4.65 Load - Deflection Relationship in Specimen No.7

4.8.4 Strain in CFRP Sheet

The location of strain gages installed on the both sides of specimen No.7 and the maximum measured strain in each strain gage are shown in Figure 4.66 and 4.67. Gages No.14 and No.16 did not work.

The maximum strain measured in specimen No.7 was 0.0117 at strain gage No.23 in side-B at the column face, and the strain was 93% of the specified fracture strain of 0.0126.

From the data of the horizontal distribution of the strains in the CFRP sheet, a symmetric distribution of the strains was observed with respect to the mid span.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (17 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.66 and 4.67

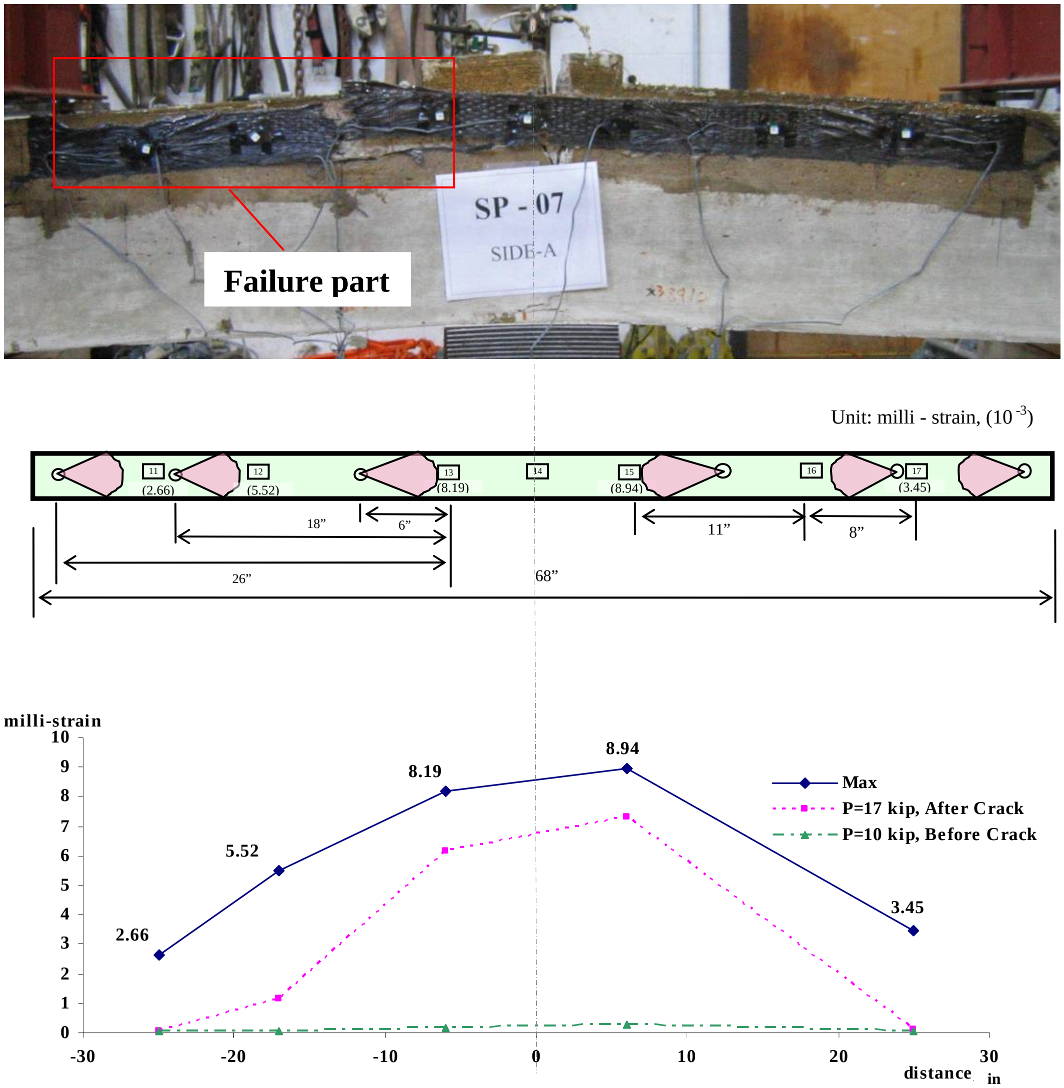


Figure 4.66 Strain in CFRP Sheet for Specimen No.7, Side-A

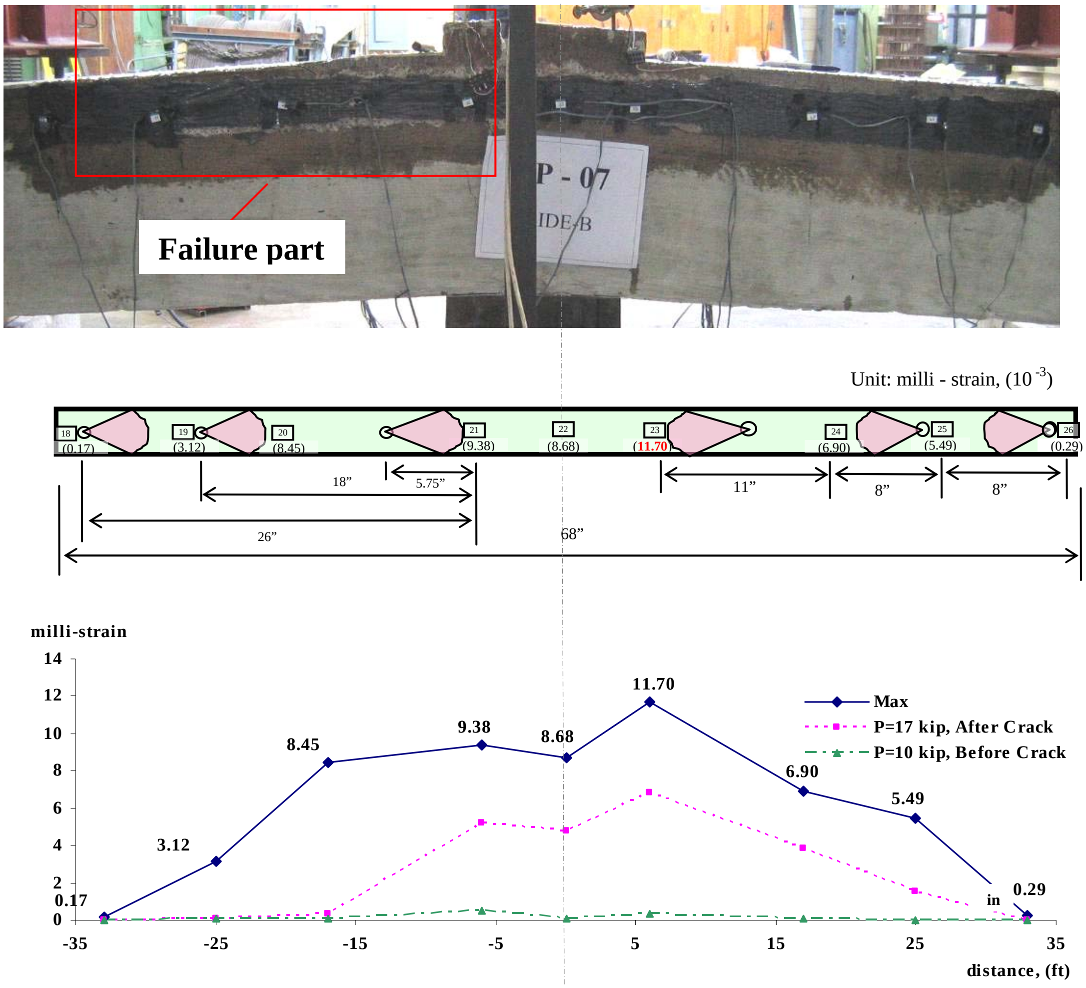


Figure 4.67 Strain in CFRP Sheet for Specimen No.7, Side-B

Load - strain relationships in a pair of strain gages placed in symmetric position showed similar load - strain relationship and indicated that the CFRP sheets on the both sides reached capacity at the same time (Figure 4.68).

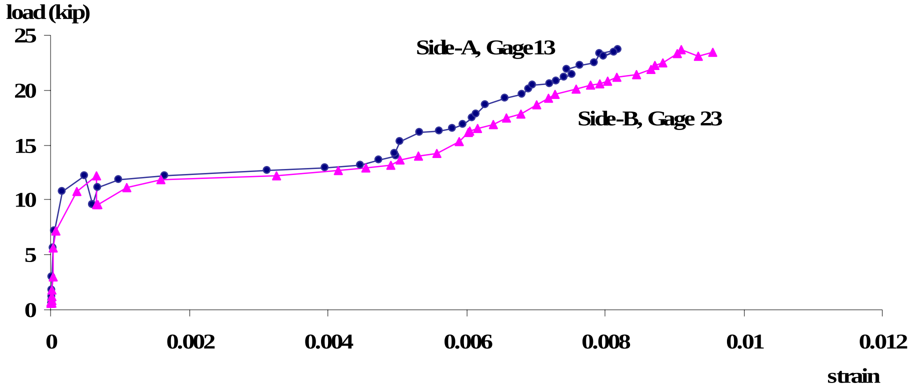


Figure 4.68 Load - Strain Relationship Measured in Strain Gages at Symmetric Position (At the Column Face)

4.8.5 Strain in Steel Bar

The strains in the bars were measured with 10 strain gages for specimen No.7, but 3 strain gages did not work (Figure 4.69). The maximum measured bar strain in specimen No.7 was 0.0007 which was 33% of the yield strain of the bar.

The force did not effectively transfer from the CFRP sheet to the bar because the observed strains were low with respect to the yield strain and the strain in the gages decreased as they became more distance from mid span. It indicated that the bars did not contribute to the strength after the cracking.

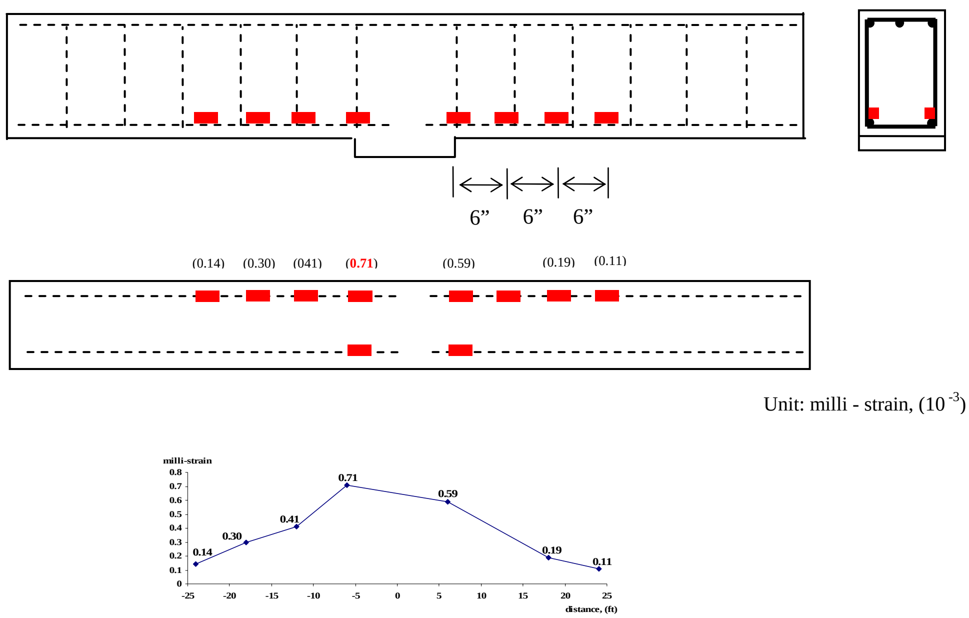


Figure 4.69 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.70.

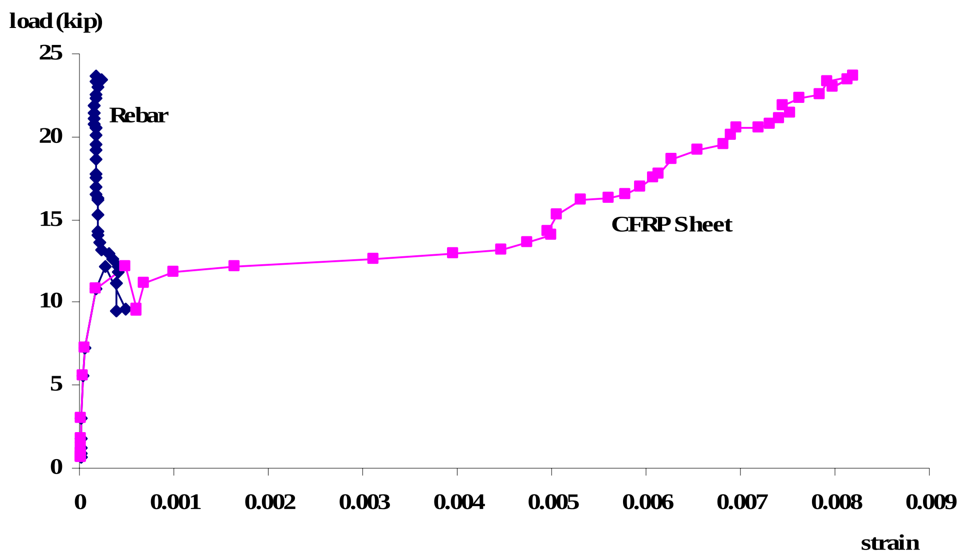


Figure 4.70 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.8.6 Summary

Summary of the test results is shown in Table 4.7.

Failure Mode	Whole-fracture of CFRP sheet , material failure of CFRP anchor and concrete failure around CFRP anchor
Peak Load Displacement at the peak	23.8 kip, 74 % of target strength 0.74 in
Failure load Displacement at the failure	23.8 kip, 100 % of peak strength 0.74 in
Measured maximum **CFRP** strain	0.0117, 93% of specified fracture strain
Measured maximum **bar** strain	0.0007, 33% of yield strain

Table 4.7 Summary of Test Results for Specimen No.7

One additional CFRP anchor at the each end of the CFRP sheet was installed in specimen No.7 in order to improve anchorage. However, both strength and deformation capacity of the specimen were less than those of specimen No.6. A possible reason of the result can be improper quantity and geometry of CFRP anchors.

If slip of the CFRP sheet is not allowed after delamination due to excessive quantity of CFRP anchors or improper geometry such as the anchors located at the far ends of the sheet, stress concentration can occur in the sheet near the anchor hole where discontinuity of materials exist. Information from this test was not sufficient to verify effect of the quantity and geometry of CFRP anchors.

Instead of increasing the number of CFRP anchors, CFRP U-wraps were used in specimen No.8 to prevent the concrete from crushing. The anchorage in specimen No.8 was a combination of CFRP anchors and CFRP U-wraps.

4.9 SPECIMEN NO.8

4.9.1 Configuration

Specimen No.8 had 2 layers of the CFRP sheets and 2 CFRP anchors and 2 CFRP U-wraps at each end of the CFRP sheet. Location of one group of the anchor holes for the CFRP anchor was selected as 2/3 of the development length of the bar, and it was 18 in. from the column face. Location of the other group of the anchor holes was selected as 6 in. from the column face to place the CFRP anchors as close as to the column face without over it. The location of the holes was the same as that of specimen No.6. The CFRP U-wrap was placed on the CFRP sheet, and then CFRP anchor was placed on the CFRP U-wrap. The anchor was inserted into the anchor hole through the U-wrap and the sheet. Purpose of using the CFRP U-wrap was to prevent the concrete from the failure around the anchor hole by confining it and collect tensile force from the CFRP sheet to the CFRP anchor effectively (Kobayashi, 2001). Configuration of specimen No.8 is shown in Figure 4.71.

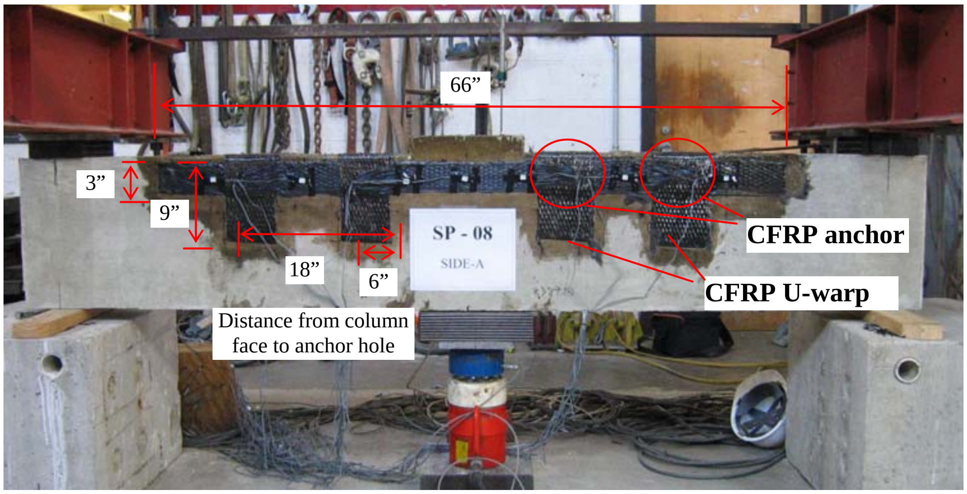


Figure 4.71 Configuration of Specimen No.8

4.9.2 Failure Mode

The failure mode of specimen No.8 was a whole-sheet-fracture (Figure 4.72 and 4.73). Both sides showed the same failure mode. Although delamination of the CFRP U-wrap occurred, the CFRP anchor held both CFRP sheet and U-wrap. The U-wrap prevented the concrete around the anchor hole from crushing (Figure 4.74).

The fracture of CFRP sheet did not occurred around the anchor hole but in front of the CFRP anchor closest to the column face. The U-wrap helped the anchor collect the tensile force efficiently and prevented the sheet from the stress concentration around the anchor hole.

Figure 4.72 Failure Mode of Specimen No.8

Figure 4.73 Failure Mode of Specimen No.8

Figure 4.74 Failure Mode of Specimen No.8

The CFRP sheet slipped after delamination occurred until it fractured. The slip increased the deflection capacity of specimen No.8 (Figure 4.75).

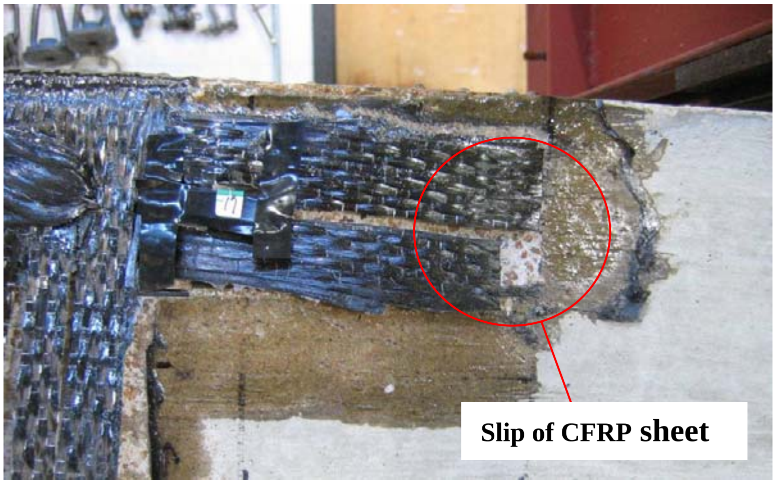


Figure 4.75 Slip Condition of CFRP Sheet

4.9.3 Load - Deflection Relationship

Load-deflection curve of specimen No.8 is shown in Figure 4.76. The peak load was 31.9 kip for specimen No.8, and the target strength was achieved. The deflection at this point was 0.88 in.. The increase of the strength of specimen No.8 with respect to that of specimen No.1 was 17.4 kip.

The failure load (27.7 kip) was 87 % of the peak load, 31.9 kip, and the deflection at the failure (1.12 in.) was 3.2 times as high as that of specimen No.1. Tensile capacity of the CFRP sheet was fully developed in specimen No.8 which showed the highest load carrying capacity among all the specimens tested.

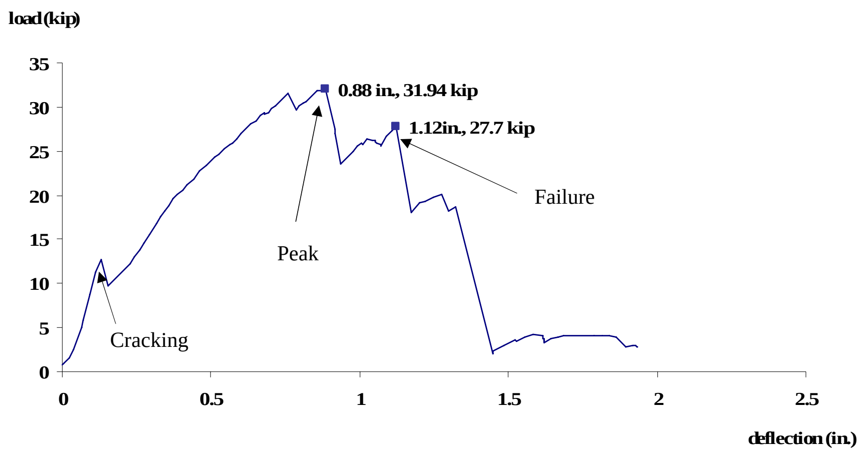


Figure 4.76 Load - Deflection Relationship of Specimen No.8

4.9.4 Strain in CFRP Sheet

The location of strain gages installed on the both sides of specimen No.8 and the maximum measured strain in each strain gage are shown in Figure 4.77 and 4.78. Gage No.15 did not work.

The maximum strain measured in specimen No.8 was 0.0118 at strain gage No.21 in side-B at the mid span, and the strain was 94 % of the specified fracture strain of 0.0126.

From the horizontal distribution of strains in the CFRP sheet, slightly high strain was observed where failure occurred, but symmetric horizontal distribution of strains was observed on both sides of specimen No.8.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (21 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.77 and 4.78

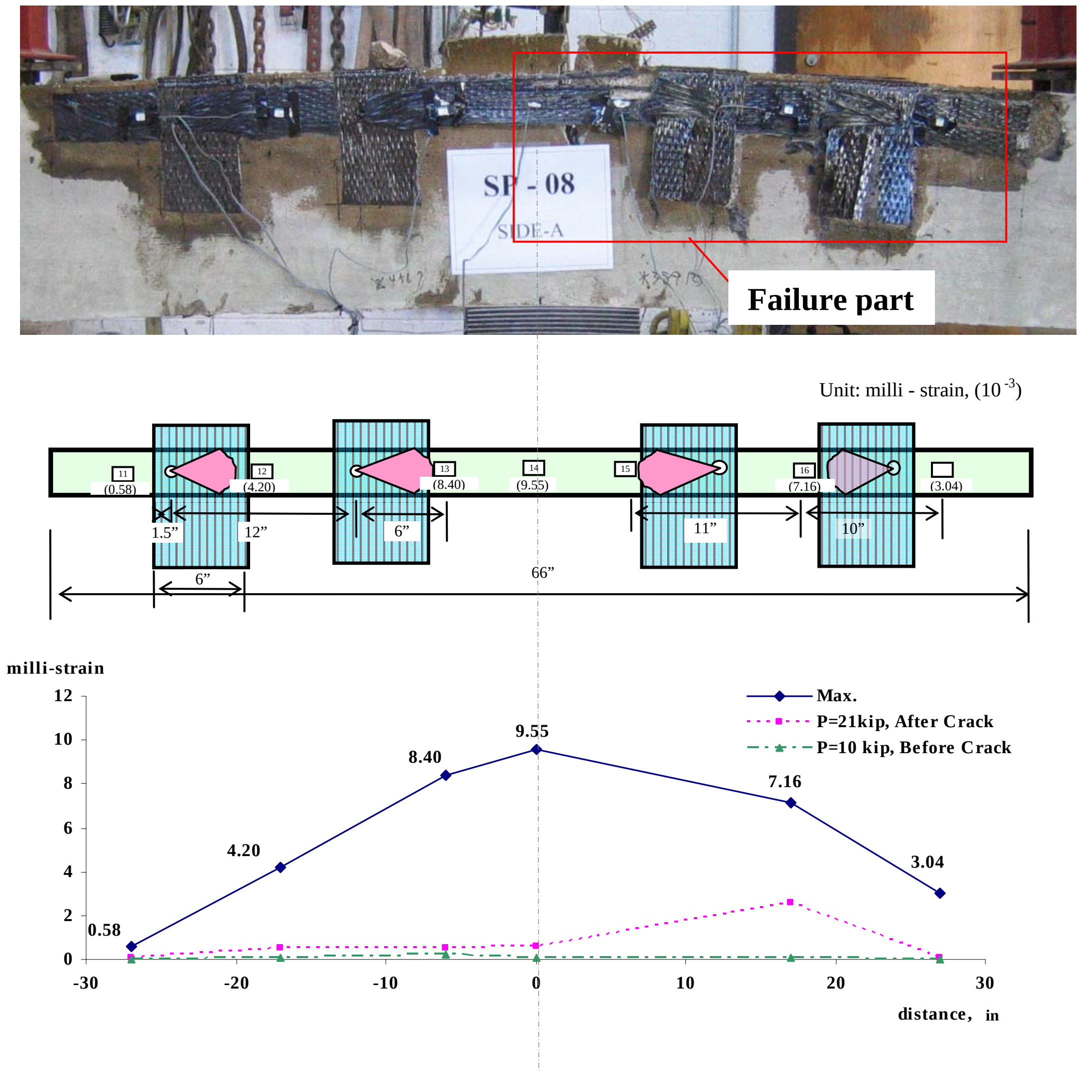


Figure 4.77 Strain in CFRP Sheet for Specimen No.8, Side –A

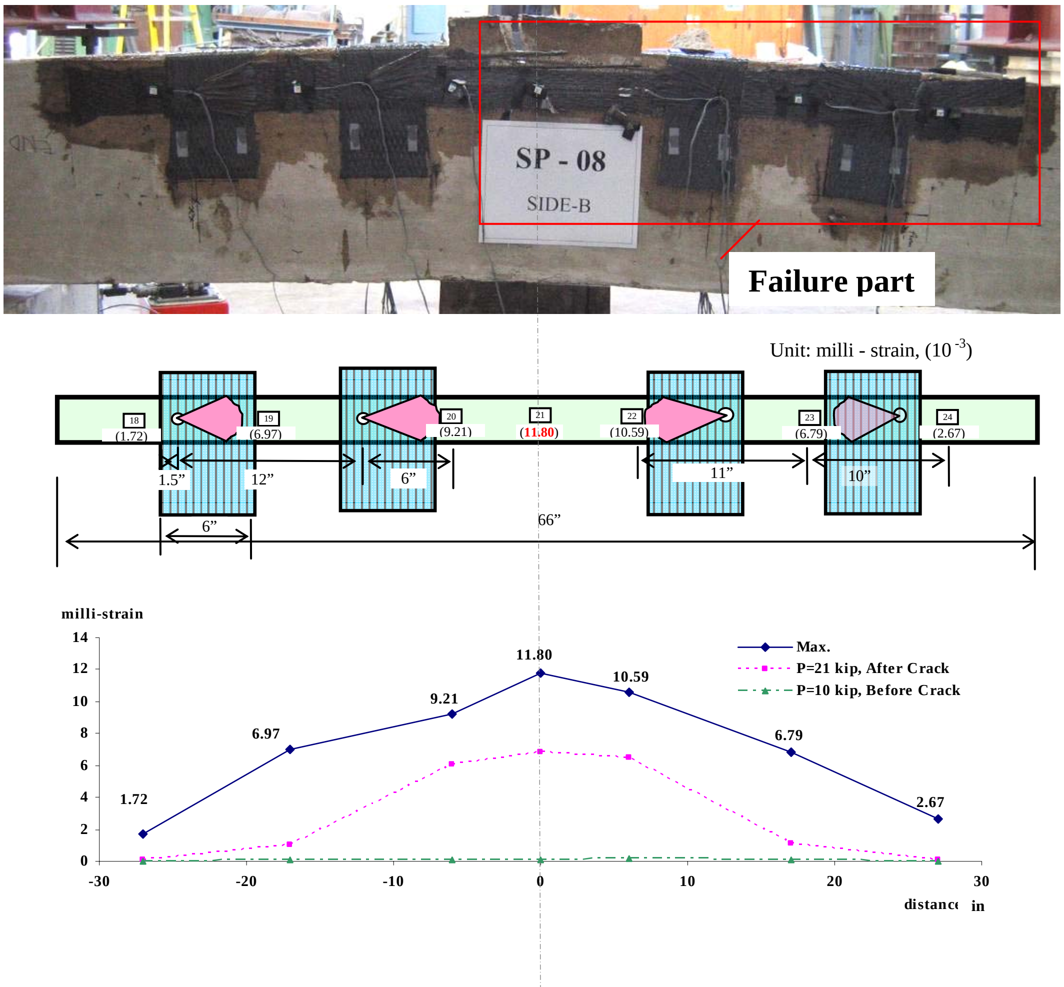


Figure 4.78 Strain in CFRP Sheet for Specimen No.8, Side-B

Load - strain relationships in a pair of strain gages placed in symmetric position showed similar load - strain relationship and incidicate the CFRP sheets on the both sides reached capacity at the same time (Figure 4.79).

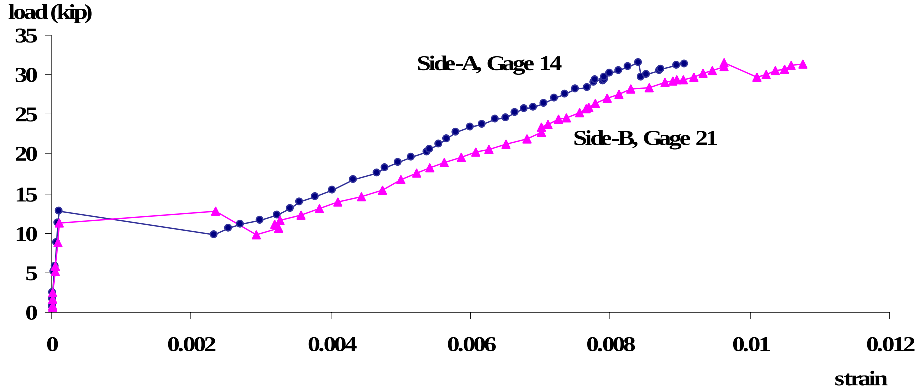


Figure 4.79 Load - Strain Relationship Measured in Strain Gages at Symmetric Position (At the Mid Span)

4.9.5 Strain in Steel Bar

The strains in the bars were measured with 10 strain gages for specimen No.8, but 2 strain gages did not work (Figure 4.80). The maximum measured bar strain in specimen No.8 was 0.0008 which was 38% of the yield strain of the bar.

The difference of the horizontal distribution of bar strains between specimen No.8 and other specimens was the location of the maximum strain. While the maximum strain occurred at the location closest to the mid span in other specimens, the maximum strain in specimen No.8 occurred at the location closest to the supports. The result indicated the force of the CFRP sheet was effectively transferred to the bar and the rebar contributed to the load carrying capacity after the cracking.

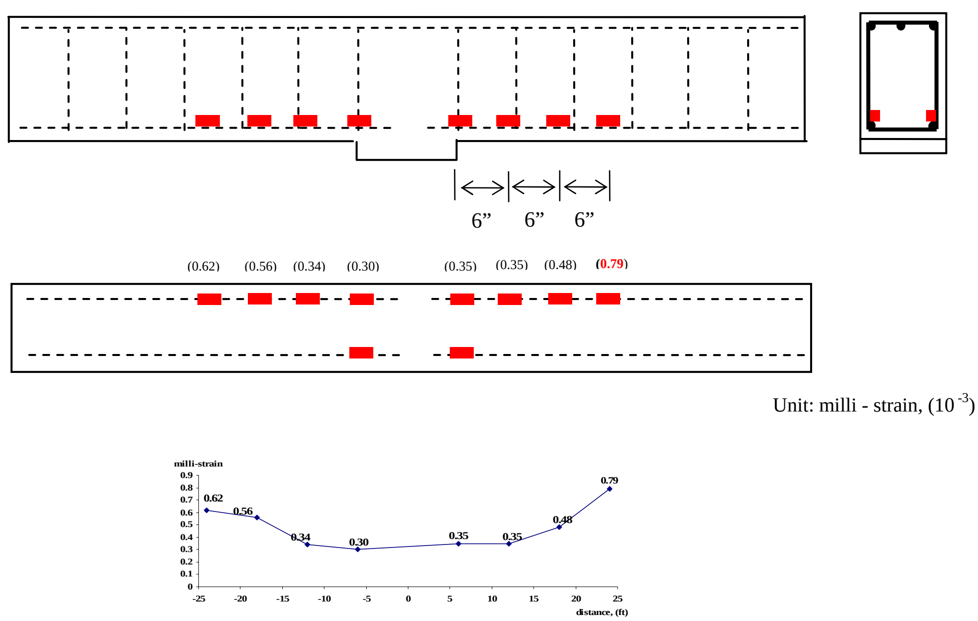


Figure 4.80 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.81.

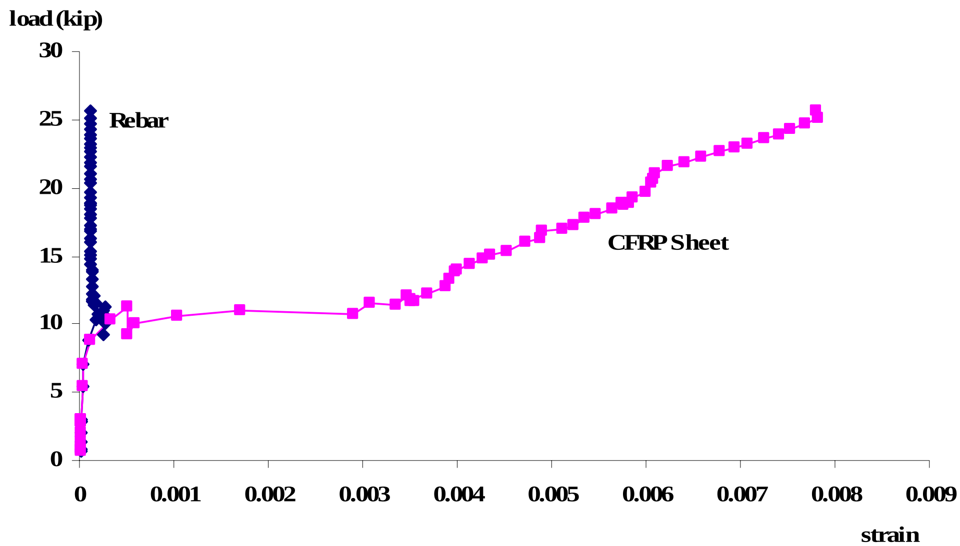


Figure 4.81 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.9.6 Summary

Summary of the test results is shown Table 4.8.

Failure Mode	Whole-sheet-fracture of CFRP sheet
Peak Load Displacement at the peak	31.9 kip, 100% of target strength 0.88 in.
Failure load Displacement at the failure	27.7 kip, 87% of peak load 1.12 in.
Measured maximum **CFRP** strain	0.0118, 94% of specified fracture strain
Measured maximum **bar** strain	0.0008, 38 % of yield strain

Table 4.8 Summary of Test Results for Specimen No.8

The tensile capacity of the CFRP sheet was fully developed with the anchorage with a combination of CFRP anchors and CFRP U-wraps. The failure mode of specimen was whole-sheet-fracture of the sheet which was the most desirable failure mode. In addition, Force was effectively transferred from the sheet to the bar. The result indicated that the CFRP materials were able to be used for providing continuity to the poorly detailed reinforced concrete structures.

4.10 SPECIMEN NO.9

4.10.1 Configuration

Specimen No.9 had 2 layers of the CFRP sheets, and 2 CFRP U-wraps with the CFRP anchors on the U-wrap at each end of the CFRP sheet. The location of the CFRP U-wrap in specimen No.9 was the same as that in specimen No.8. The CFRP U-wrap was placed on the CFRP sheet, and then the CFRP anchor was placed only on the U-wrap but not on the sheet. This geometry of the CFRP materials was selected because there was high possibility to hit the longitudinal bars during drilling the holes for the CFRP anchors because the CFRP sheets needed to be placed as close as to the extreme tension face in order to increase the moment arm. Therefore, if the anchor holes were placed near the neutral axis of the beam, they were not required to drill the holes around the bar. In addition, the possibility of the concrete crushing around the anchor hole reduced because of the sufficient confinement. Configuration of specimen No.9 is shown in Figure 4.82.

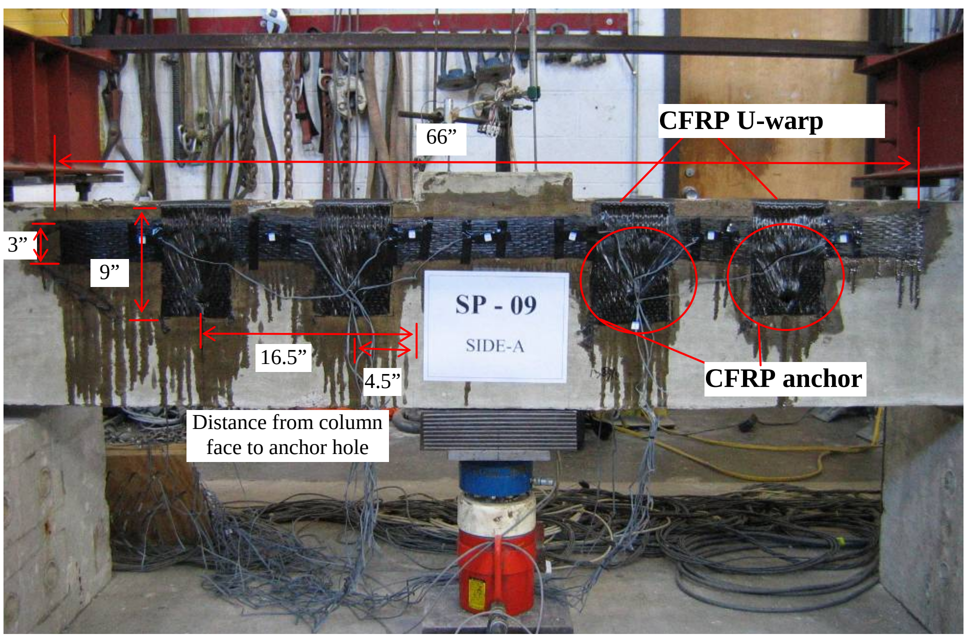


Figure 4.82 Configuration of Specimen No.9

4.10.2 Failure Mode

The failure mode of specimen No.9 was material failure of the CFRP U-wrap (Figure 4.83, 4.84). Both sides showed the same failure. Although the CFRP anchor held the U-wrap after delamination of both the U-wrap and sheet, the U-wrap failed by shear (Figure 4.84).

Figure 4.83 Failure Mode of Specimen No.9

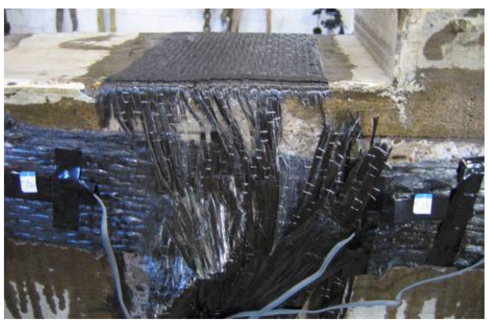


Figure 4.84 Failure Mode of Specimen No.9

CFRP sheet slipped after delamination until the U-wrap fractured. The slip provided large deformation capacity to specimen No.9 (Figure 4.85).

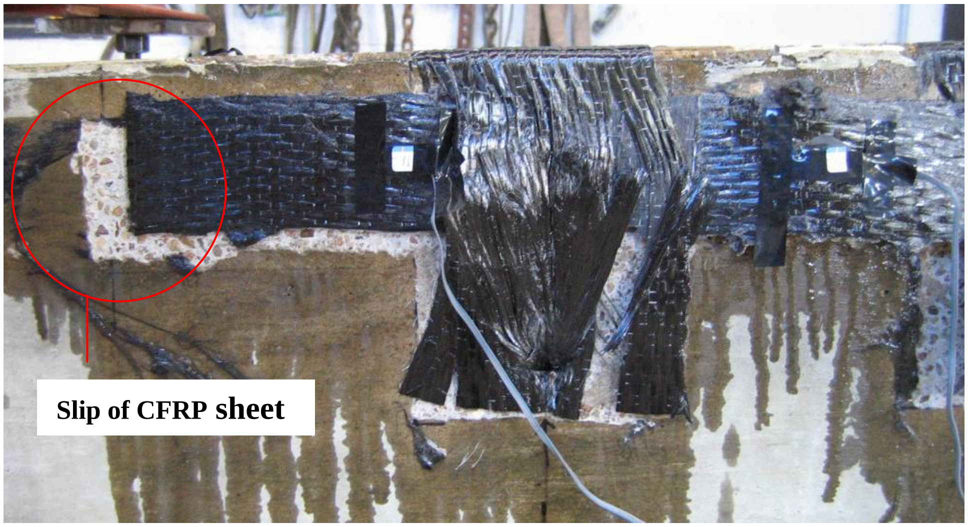


Figure 4.85 Slip of CFRP Sheet

4.10.3 Load - Deflection Relationship

Load-deflection curve of specimen No.9 is shown in Figure 4.86. The peak load was 16.2 kip for specimen No.9, and the strength was 51 % of the target strength, 32 kip. The deflection at this point was 0.48 in. The increase of the strength of specimen No.9 with respect to that of specimen No.1 was only 1.6 kip. The strength did not increased although the same amount of the CFRP materials as specimen No.8 was installed in specimen No.9. The strength was only as half as that of specimen No.8.

The failure load (14.9 kip) was 92 % of the peak load, 16.2 kip, and the deflection at the failure (1.33 in.) was 3.8 times as high as that of specimen No.1. The specimen No.9 showed the highest deformation capacity among all the specimens tested. The anchorage used in specimen No.9 is not effective for strength but effective for deformation capacity.

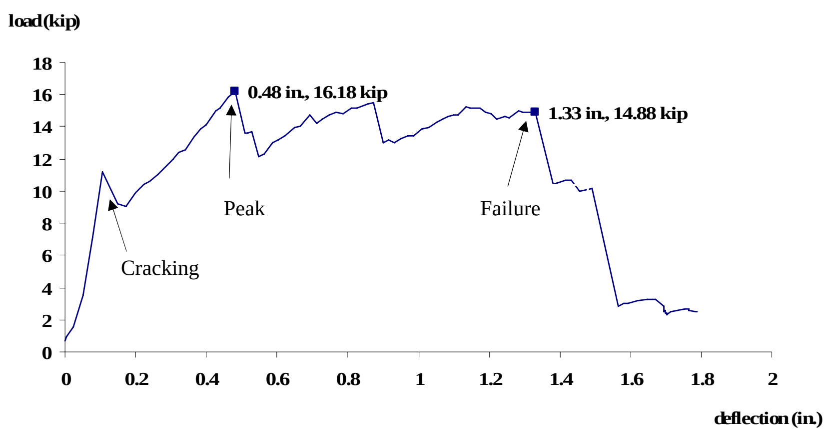


Figure 4.86 Load - Deflection Relationship of Specimen No.9

4.10.4 Strain in CFRP Sheet

The location of strain gages installed in both sides of specimen No.9 and the maximum measured strain in each strain gage are shown in Figure 4.87 and 4.88. Gage No.14 did not work.

The maximum strain measured in specimen No.9 was 0.0063 at strain gage No.22 in side-B at the location of the column face, and the strain was 50% of the specified fracture strain of 0.0126.

From the horizontal distribution of strains in the CFRP sheet the highest strains indicate where failure occurred on the highest strains were observed where failure occurred on the both sides.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (13 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.87 and 4.88

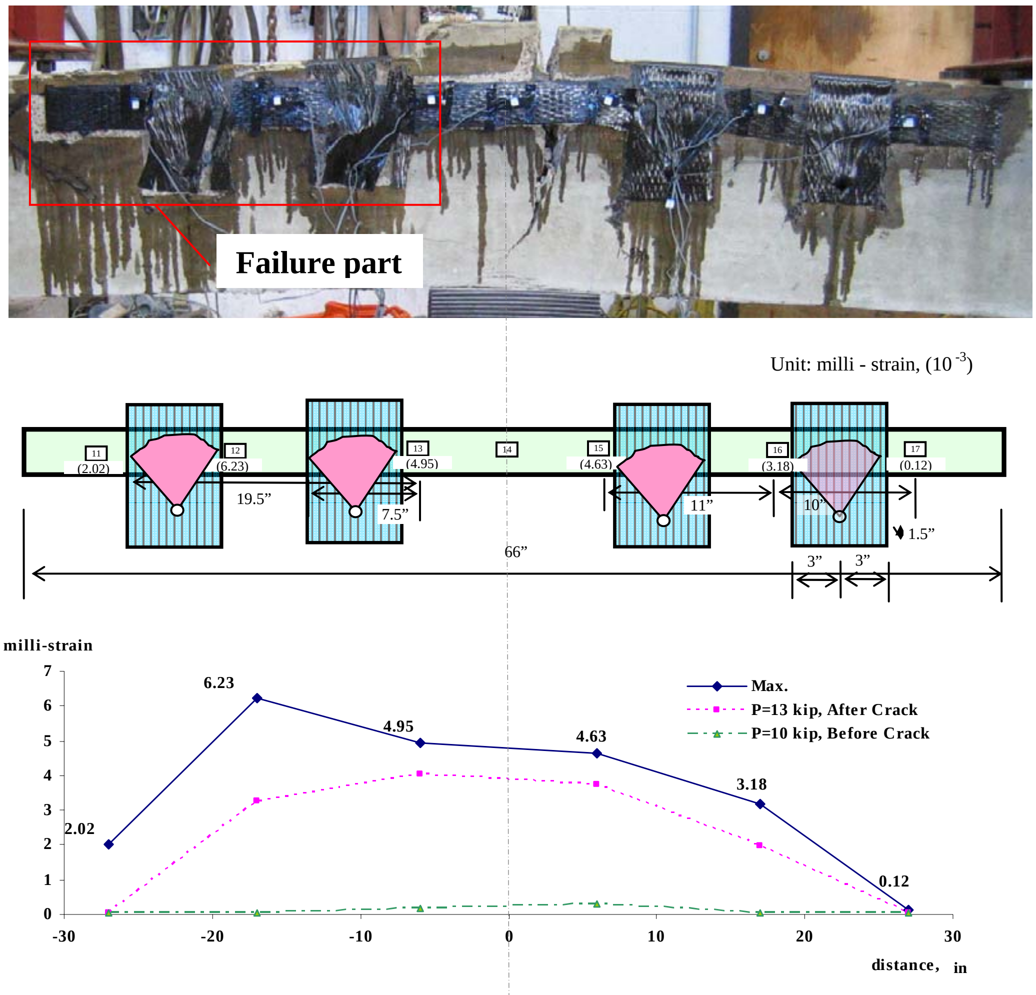


Figure 4.87 Strain in CFRP Sheet in Specimen No.9, Side-A

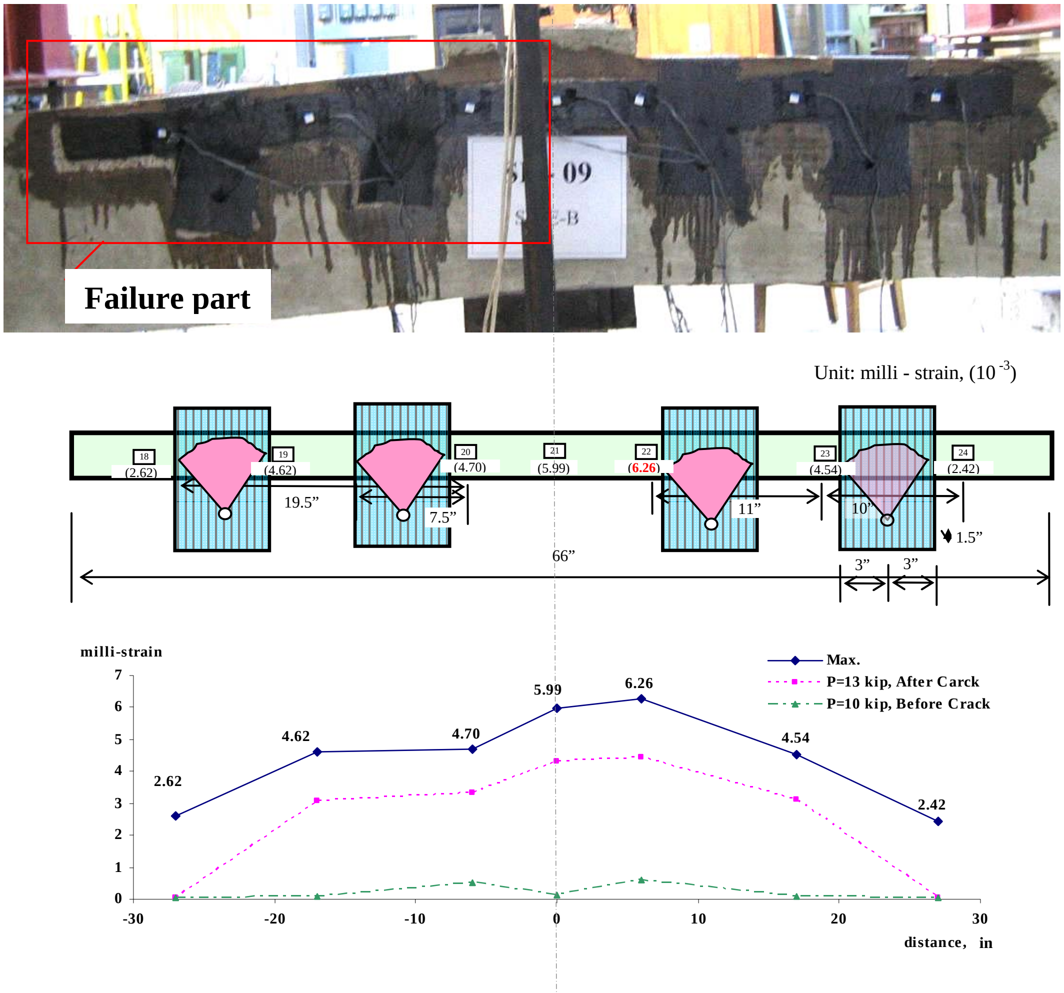


Figure 4.88 Strain in CFRP Sheet in Specimen No.9, Side-B

Load - strain relationships in a pair of strain gages placed in symmetric position showed similar load - strain relationship. It meant that the CFRP sheets on the both sides developed their capacity at the same time (Figure 4.89).

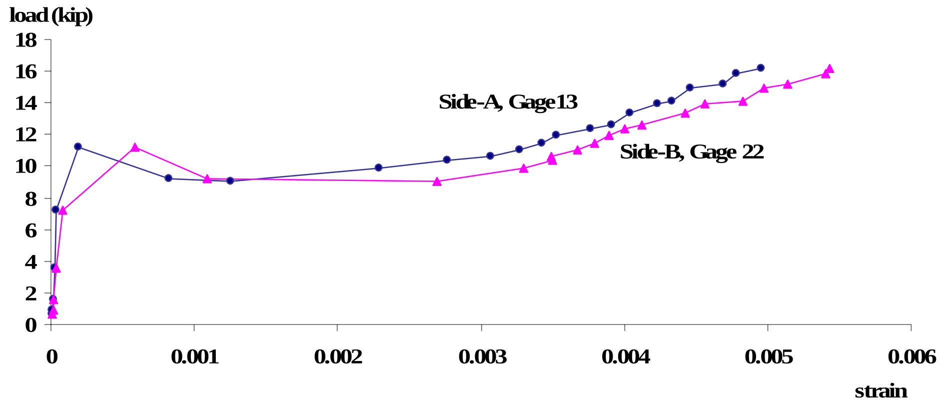


Figure 4.89 Load - Strain Relationship Measured in Strain Gages at Symmetric Position (At the Column Face)

4.10.5 Strain in Steel Bar

The strains in the bars were measured with 10 strain gages for specimen No.9, but 1 strain gage did not work (Figure 4.90). The maximum measured bar strain in specimen No.9 was 0.0005 which was 24% of the yield strain of the bar.

The force did not effectively transfer from the CFRP sheet to the bar because the measured strains were low comparing with the yield strain and the strain in the gages decreased as they became more distance from the mid span. It indicated that the bars did not contribute to the strength after cracking.

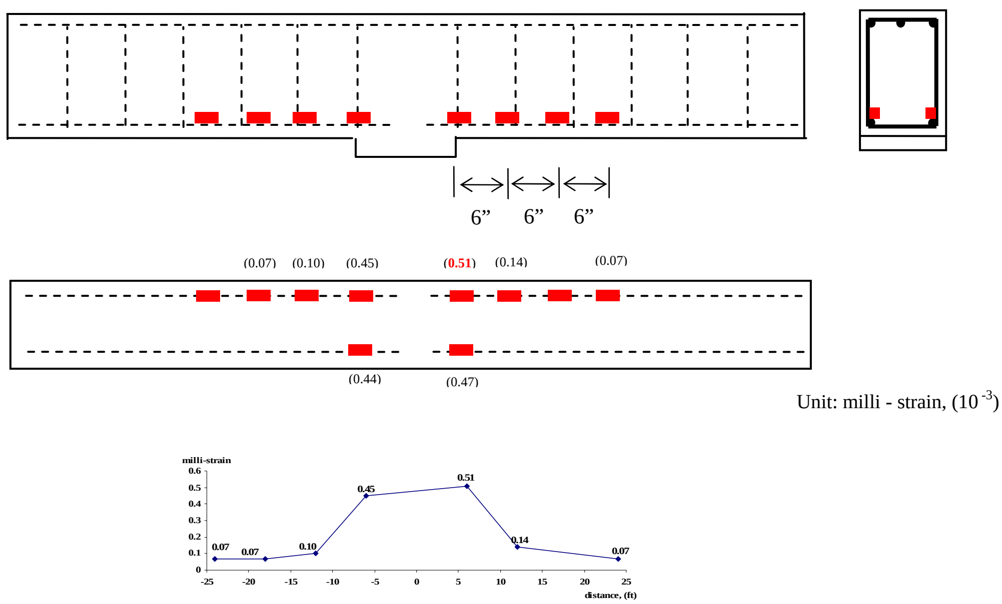


Figure 4.90 Location of Bar Strain Gages and Maximum Measured Strain

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.91.

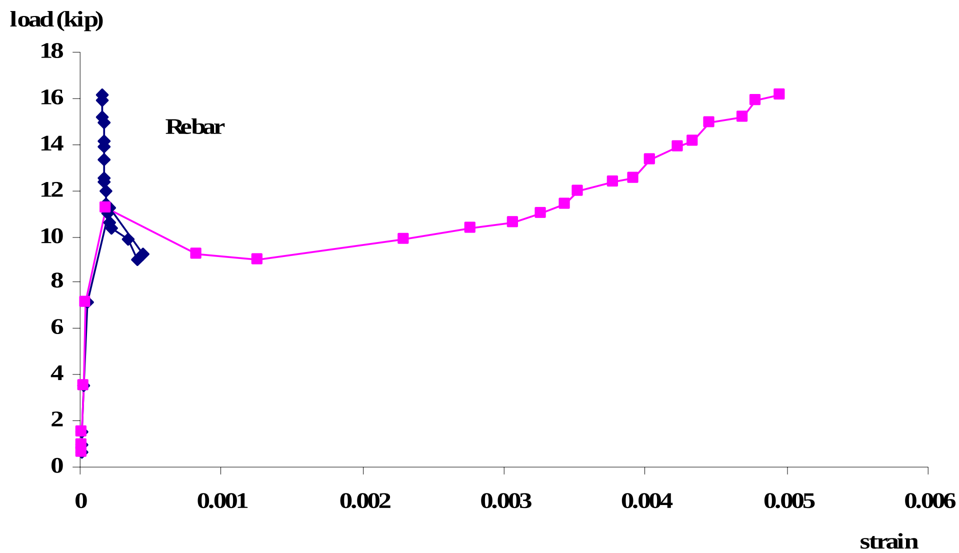


Figure 4.91 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.10.6 Summary

Summary of the test results is shown in Table 4.9

Failure Mode	Material Failure of CFRP U-wrap
Peak Load Displacement at the peak	16.9 kip, 51% of target strength 0.78 in
Failure load Displacement at the failure	14.9 kip, 92% of peak load 1.33 in
Measured maximum **CFRP** strain	0.0063, 50% of specified fracture strain
Measured maximum **bar** strain	0.0005, 24% of yield strain

Table 4.9 Summary of Test Results for Specimen No.9

While the strength of specimen No.9 did not improved, the deformation capacity increased significantly, and the highest deformation capacity was observed in it

The anchorage of specimen No.9 is possible to use structures whose deformation capacity is more critical than strength.

4.11 SPECIMEN NO.10

4.11.1 Configuration

Specimen No.10 had 2 layers of the CFRP sheets and 2 CFRP U-wraps at each end of the sheet. The location of CFRP U-wraps in specimen No10 was the same as those in specimens No.8 and No.9.

Specimen No.10 was tested for comparison with other specimens with 2 layers of the CFRP sheets although expected performance was very poor. Configuration of specimen No. 10 is shown in Figure 4.92.

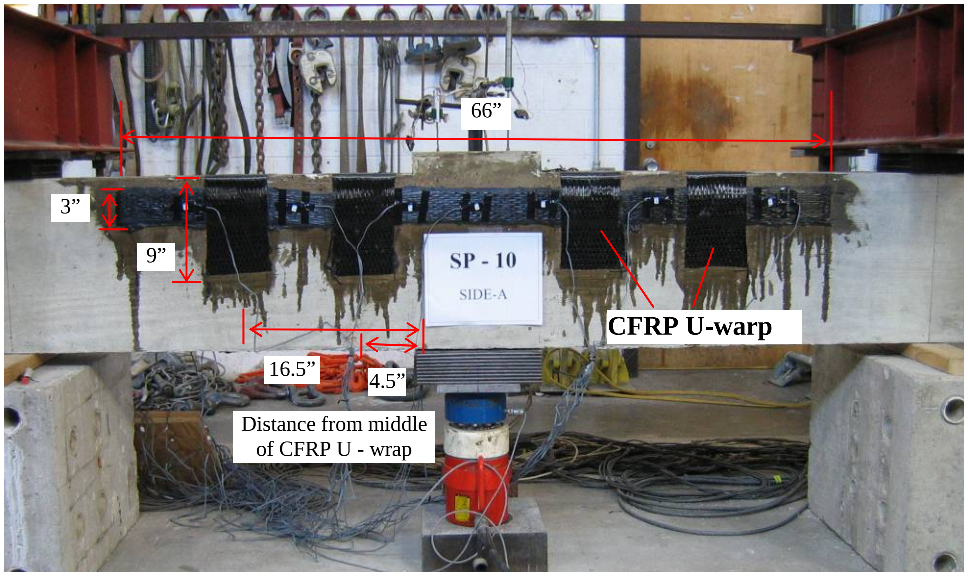


Figure 4.92 Configuration of Specimen No.10

4.11.2 Failure Mode

The failure mode of specimen No.10 was delamination the CFRP U-wrap which was the same as specimen No.5 (Figure 4.93 and 4.94). Both sides showed the same failure mode. When only the U-wrap is used for additional anchorage of the CFRP sheet, bonding strength of the sheet to the concrete is a critical factor to load carrying capacity. The U-wrap was not able to anchor the CFRP sheet once delamination of the sheet occurred. Therefore, specimen No.10 which had less bonding area than that of specimen No.5 showed less strength although specimen No.10 had two U-wraps at the each end of the sheet.

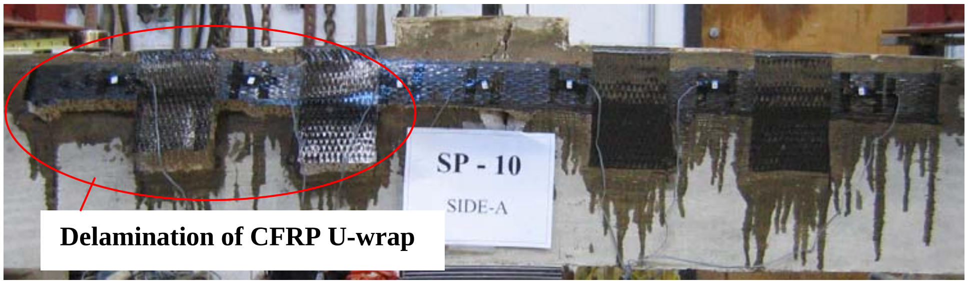


Figure 4.93 Failure Mode of Specimen No.10

Figure 4.94 Failure Mode of Specimen No.10, Delamination of CFRP U-wrap

4.11.3 Load - Deflection Relationship

Load-deflection curve of specimen No.10 is shown in Figure 4.95. The peak load was 15.4 kip for specimen No.10, and the strength was 48 % of the target strength, 32 kip. The deflection at this point was 0.43 in. The peak point was the same as the failure point. The increase of the strength of specimen No.10 with respect to that of specimen No.1 was only 0.8 kip.

The deflection at the failure (0.43 in.) was 1.2 times as high as that of specimen No.1.

The shape of load - deflection curve for specimen No.10 was similar to that of specimen No.5. The load - deflection curve showed only one peak after cracking because the U-wraps in one side failed right after those in other side failed.

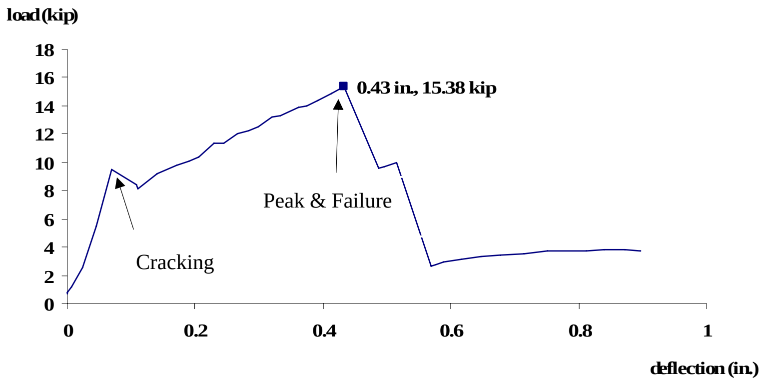


Figure 4.95 Load - Deflection Relationship of Specimen No.10

4.11.4 Strain in CFRP Sheet

The location of strain gages installed in both sides of specimen No.10 and the maximum strain measured in each strain gage are shown in Figure 4.96 and 4.97. Gage No.14 did not work.

The maximum strain measured in specimen No.10 was 0.0056 at strain gage No.15 in side-A at the column face, and the strain was 44 % of the specified fracture strain of 0.0126.

From the horizontal distribution of the strains in the CFRP sheet, a symmetric distribution of the strains was observed with respect to the mid span.

The horizontal strain distribution at 10 kip load (before the cracking) and middle load (13 kip) between 10 kip and the peak load (after the cracking but before reaching the peak load) are also shown in Figure 4.96 and 4.97

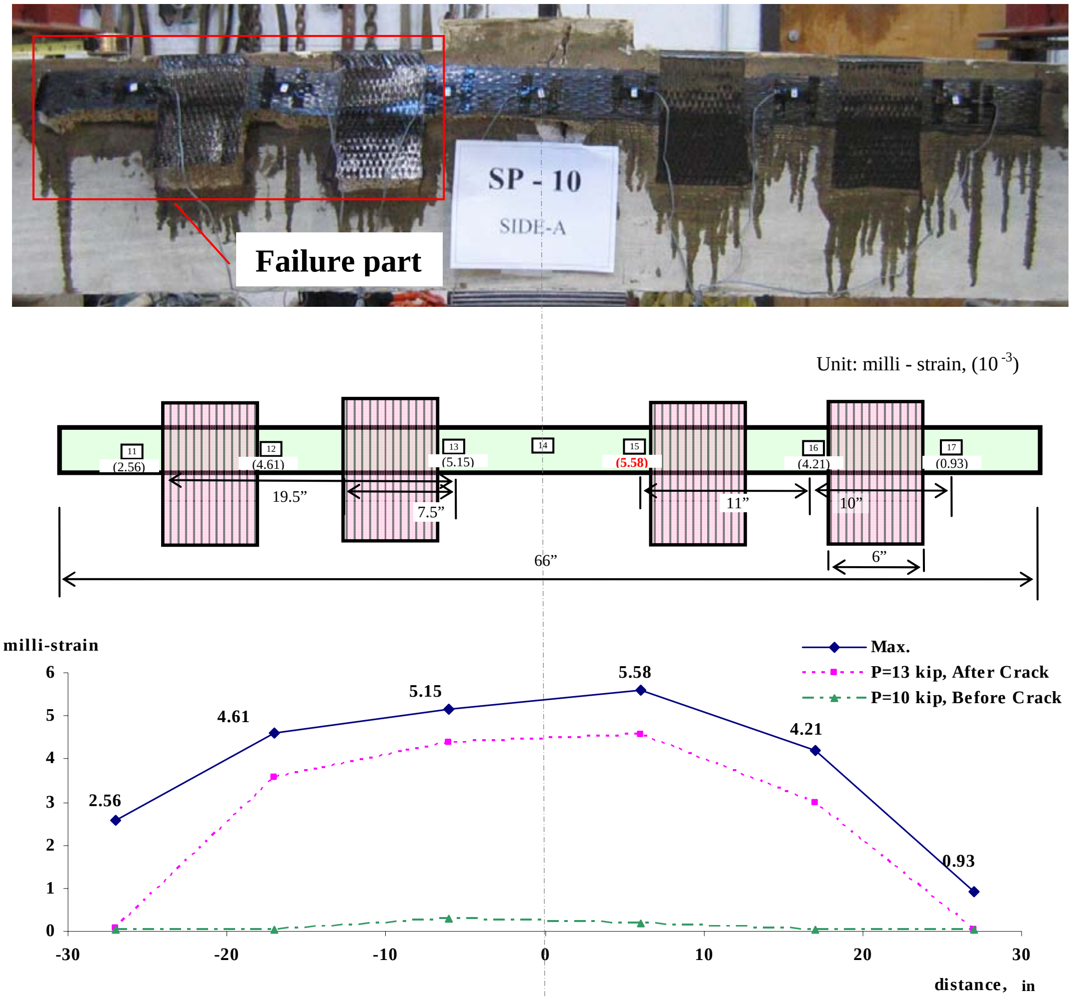


Figure 4.96 Strain in CFRP Sheet in Specimen No.10, Side-A

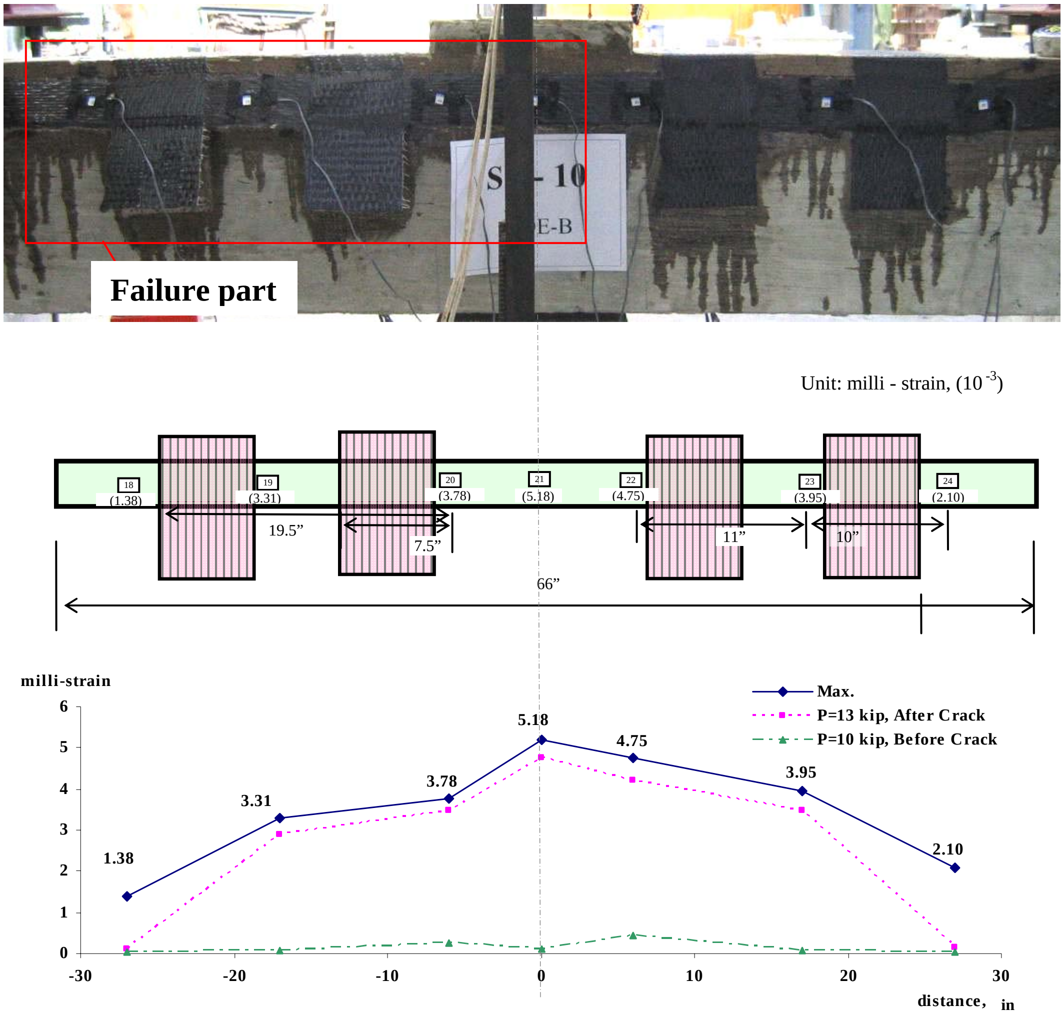


Figure 4.97 Strain in CFRP Sheet in Specimen No.10, Side –B

Load - strain relationships in a pair of strain gages placed in symmetric position showed similar load - strain relationship and idicated the CFRP sheets on the both sides developed their capacity at the same time (Figure 4.98).

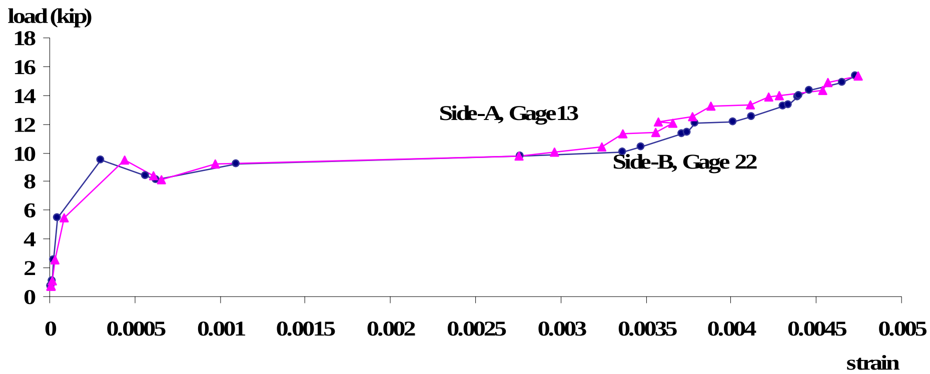


Figure 4.98 Load - Strain Relationship Measured in Strain Gages at Symmetric Position (At the Column Face)

4.11.5 Strain in Steel Bar

The strains in the bars were measured with 10 strain gages for specimen No.10, but 1 strain gage did not work (Figure 4.99). The maximum measured bar strain in specimen No.10 was 0.0004 which was 19% of the yield strain of the bar.

The force did not effectively transfer from the CFRP sheet to the bar because the measured strains were low comparing with the yield strain and the strain in the gages decreased as they became more distance from mid span. It indicated that the bars did not contribute to the strength after cracking.

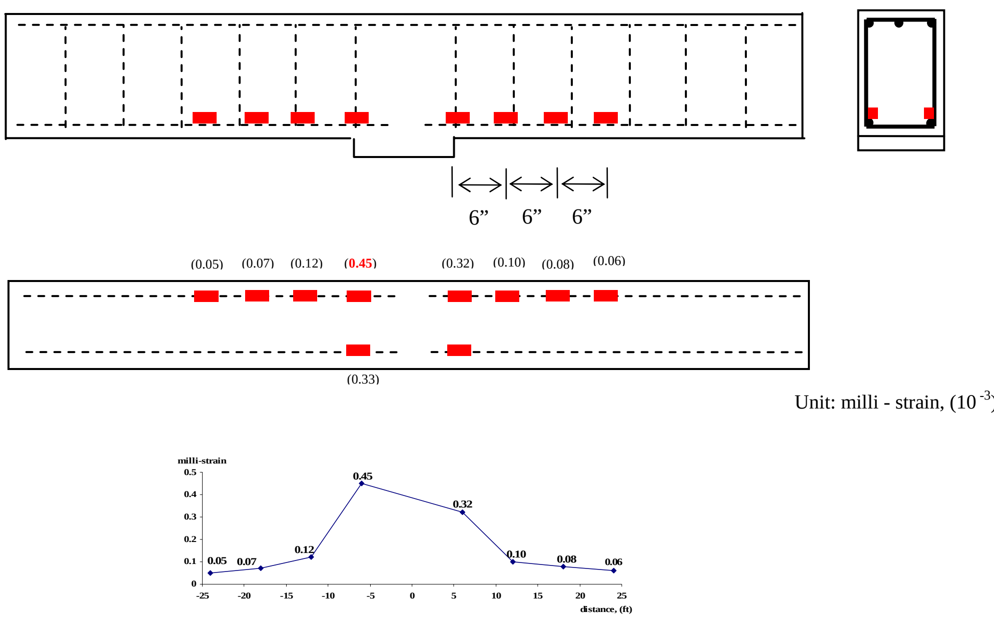


Figure 4.99 Location of Bar Strain Gages and Maximum Measured Strains

Load - strain relationships of the bar and the CFRP sheet were similar before crack of the specimen as shown in Figure 4.100.

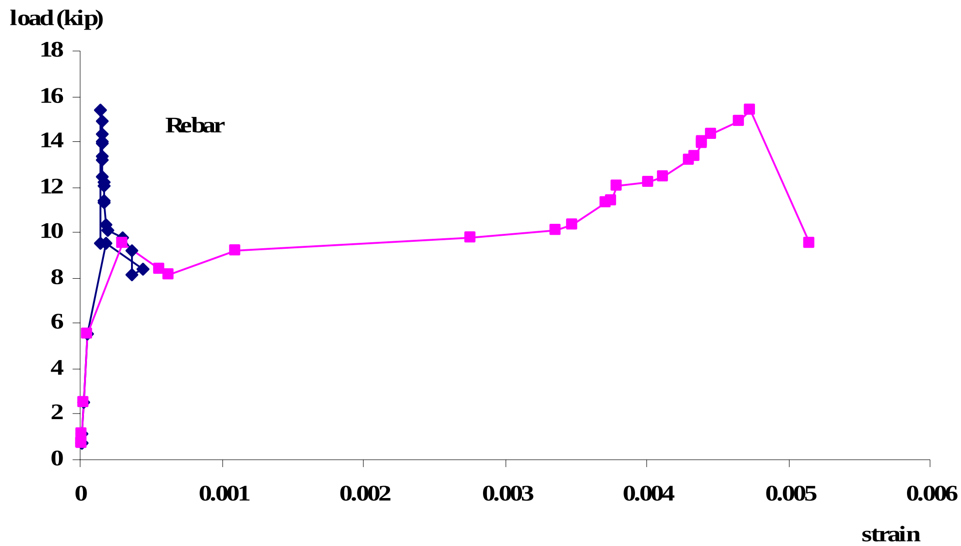


Figure 4.100 Load - Strain Relationship between Bar and CFRP Sheet, At the Column Face

4.11.6 Summary

Summary of the test results is shown in Table 10.

Failure Mode	Delamination of CFRP U-wrap
Peak Load Displacement at the peak	15.4 kip, 48% of target strength 0.43 in
Failure load Displacement at the failure	15.4 kip, 100% of peak load 0.43 in
Measured maximum **CFRP** strain	0.0056, 44% of specified fracture strain
Measured maximum **bar** strain	0.0004, 19% of yield strain

Table 4.10 Summary of Test Results for Specimen No.10

CFRP U-wraps were not an effective way of anchoring the CFRP sheets. However, the U-wrap was able to be used to prevent the concrete crushing around the CFRP anchor, and it increased the performance of the beam significantly. Therefore, The CFRP U-wraps were effective supplementary element for the CFRP anchors but did not provide efficient anchorage to the beam alone.

CHAPTER 5
DISCUSSION OF TEST RESULTS

5.1 FAILURE MODE

A summary of the failure modes of the specimens is given in Table5.1. If the CFRP sheets were attached to the concrete only by epoxy resin without any additional anchorage, the failure mode was delamination of the CFRP sheets (specimen No.1). Two main failure modes existed after delamination of the CFRP sheet if additional anchorage existed. They were *failure of CFRP sheets* and *failure of anchorage*. Failure of CFRP sheets after developing their full tensile capacity was the most desirable failure mode, but if the CFRP sheets split and fractured, they did not develop the full tensile capacity although they had sufficient anchorage (specimen No.2). Multiple layers of the narrow width CFRP sheets were required in order to prevent the split-and-fracture type of failure. In this case, additional anchorage was critical to the capacity of the specimens.

Failure patterns of anchorage were different depending on the types of the anchorage. However, they were generalized to three patterns *delamination, material failure,* and *concrete failure*. Delamination in anchorage occurred when CFRP U-wraps were used for the additional anchorage (specimen No.5, 10). Material failure anchorage was observed in specimen No.3, 7 and 9. The inserted part of the CFRP sheet fractured near the hole in specimen No.3, the inserted part of the CFRP anchor also fractured in specimen No.7, and shear failure of the CFRP U-wrap was observed in specimen No.9. Concrete failure around the anchor holes was observed in specimen No.4 and 6. Such failure was observed only when CFRP anchors were used for anchorage.

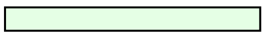
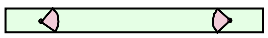
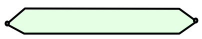
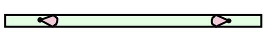
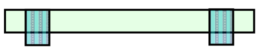
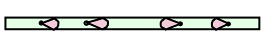
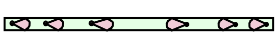
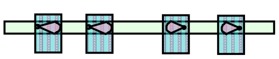
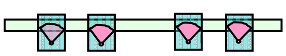
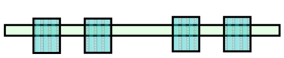
No.	Specimen	Layers of CFRP sheet	Type of anchorage	**Failure mode**
1		1 layer	No anchorage	**Delamination of CFRP sheet**
2		1 layer	1 CFRP anchor each side	**Split-and-fracture of CFRP Sheet (partial failure of CFRP anchor)**
3		1 layer	Insert end of CFRP sheet into holes	**Failure of inserted CFRP sheet near the hole**
4		2 layers	1 CFRP anchor each side	**Concrete Failure around CFRP anchors (Cover failure)**
5		1 layer	1 CFRP U-wrap each side	**Delamination of CFRP U-wrap**
6		2 layers	2 CFRP anchors each side	**Concrete Failure around CFRP anchors (Cover failure)**
7		2 layers	3 CFRP anchors each side	**Whole-sheet-fracture of CFRP sheet and failure of CFRP material in CFRP anchor**
8		2 layers	2 CFRP anchors each side with CFRP U-warp	**Whole-sheet-failure of CFRP sheet**
9		2 layers	2 CFRP U-wrap each side anchored by CFRP anchor	**Material failure of U-wrap**
10		2 layers	2 CFRP U-wrap each side	**Delamination of CFRP U-wrap**

Table 5.1 Test Results, Failure Mode

5.2 LOAD-DEFLECTION RELATIONSHIP

5.2.1 Strength

A summary of the strength (peak load) of the specimens is shown in Table5.2. The target strength (32 kip) was achieved in specimen No.8. The strength of a specimen was related to its failure mode. If split-and-fracture of the CFRP sheets and anchorage failure were prevented, target strength was achieved. Split-and-fracture of the sheet was prevented by using two layers of CFRP sheets (No.4, 6, 7, 8, 9 and 10).

5.2.2 Deformation Capacity

A Summary about deformation capacity (deflection at failure) of the specimens is also shown in Table 5.3. Deformation capacity is an important factor in developing catenary action. Large deflection capacity at the location of a removed column allows the structure to sustain loads without collapse. Typically, as load carrying capacity increased, deformation capacity also increased in the tests. As anchorage was improved, both strength and deformation capacity were increased. However, specimen No.9 showed increase of the deformation capacity without much increase in the load carrying capacity.

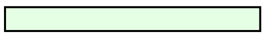
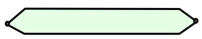
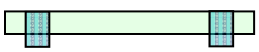
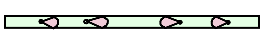
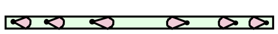
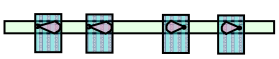
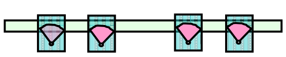
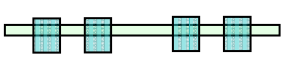
No.	Specimen	Layers of CFRP sheet	Type of anchorage	Peak		Failure	
				Load (kip)	Deflection (in)	Load (kip)	**Deflection (in)**
1		1 layer	No anchorage	**14.6**	0.21	13.9	**0.35**
2		1 layer	1 CFRP anchor each side	**17.1**	0.59	16.3	**0.69**
3		1 layer	Insert end of CFRP sheet into holes	**14.2**	0.25	14.2	**0.25**
4		2 layers	1 CFRP anchor each side	**17.3**	0.53	16.1	**0.61**
5		1 layer	1 CFRP U-wrap each side	**17.6**	0.66	17.6	**0.66**
6		2 layers	2 CFRP anchors each side	**25.8**	0.65	21.5	**0.91**
7		2 layers	3 CFRP anchors each side	**23.8**	0.74	23.8	**0.74**
8		2 layers	2 CFRP anchors each side with CFRP U- warp	**31.9**	0.88	27.7	**1.12**
9		2 layers	2 CFRP U-wrap each side anchored by CFRP anchor	**16.2**	0.78	14.9	**1.33**
10		2 layers	2 CFRP U-wrap each side	**15.4**	0.43	15.4	**0.43**

Table 5.2 Test Results, Strength and Deformation Capacity

5.2.3 Load - Deflection Relationship

5.2.3.1 Specimens of Single Layer of CFRP Sheet

Although the failure modes of the specimens with a single layer of CFRP were different (Table 5.1), strength and deformation capacity of the specimens were not improved much with respect to specimen No.1 which had no additional anchorage (Figure 5.1).

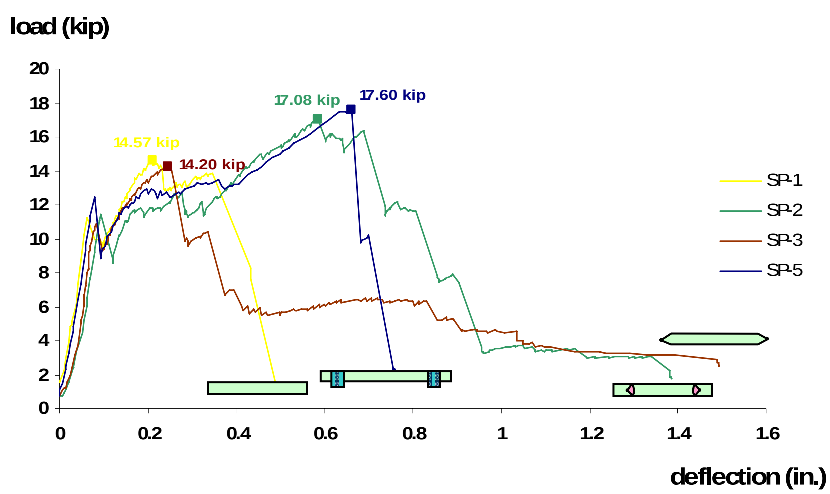


Figure 5.1 Load - Deflection Relationship, Specimens of Single layer of CFRP sheet

5.2.3.2 Specimens of Double Layers of CFRP Sheet with Two Additional Anchorages Each Side

As anchorage improved, the load carrying capacity and deformation capacity increased. The load carrying capacity of specimen No.10 which had only the CFRP U-wraps for its anchorage was not improved in comparison with specimen No.1. The CFRP U-wraps provided less effective anchorage than the CFRP anchors. A combination of the CFRP U-wraps and the CFRP anchors was the most effective anchorage tested.

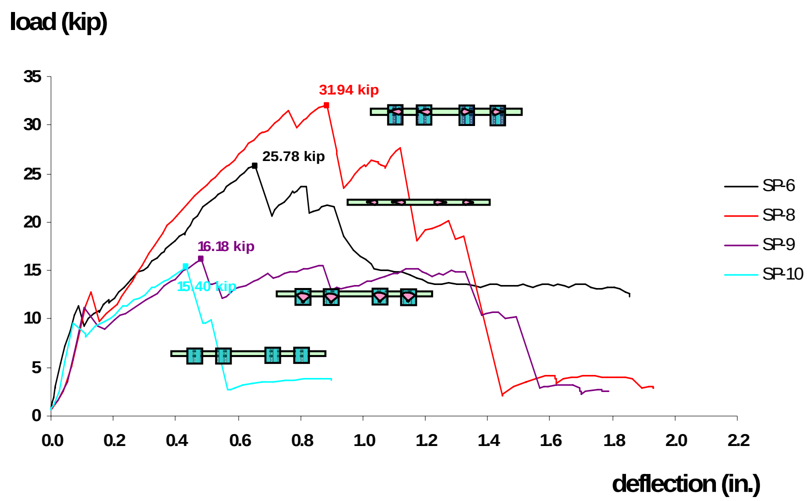


Figure 5.2 Load - Deflection Relationship, Specimens of Double layers of CFRP sheet with two additional anchorages each side

5.2.3.3 Specimens of Double Layers of CFRP Sheet with CFRP Anchor

An increase in the number of the anchors did not always lead to an increase of the strength and deformation capacity. The number of CFRP anchors in specimen No.7 was more than those in specimen No.6, but the strength of specimen No.7 was less than that of specimen No.6. A possible reason was stress concentrations at the anchors that did not permit other anchors to carry load before local failure of the sheet occurred. However, further research is required to understand this type of failure and to verify the proper quantity and location of anchors for the design.

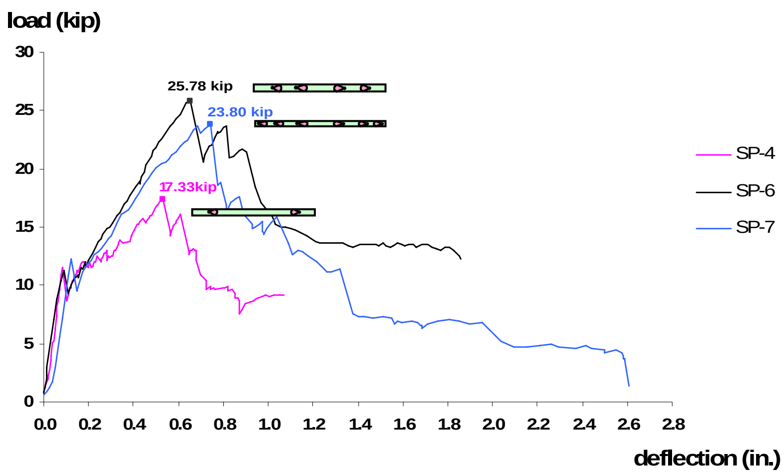


Figure 5.3 Load - Deflection Relationship, Specimens of Double layers of CFRP sheet with CFRP anchor

5.2.3.4 Specimen No.1 and Specimen No.8

The strength and deformation capacity increase from specimen No.1 to specimen was significant. If all the undesirable failure modes were prevented, the CFRP sheets developed full tensile capacity, and both strength and deformation capacity of structure were improved

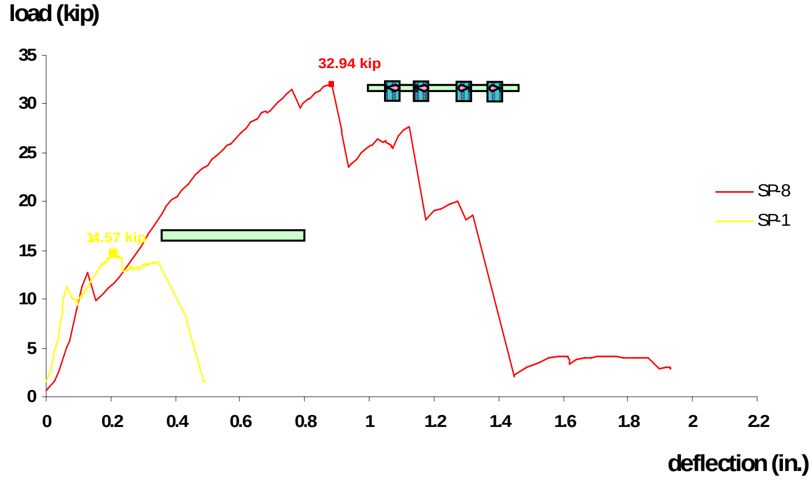


Figure 5.4 - Deflection Relationship, Specimen No.1 and specimen No.8

5.4 MATERIAL EFFICIENCY

A summary of the material efficiency of the test specimens is shown in Table 5.3. Value of material efficiency is ratio of the maximum load carried by a specimen to the area of the CFRP materials in the specimen including the CFRP sheets and additional anchorage. Specimen No.7 showed the highest value of material efficiency among all the specimens although it did not have highest load carrying or deformation capacity. With respect to the material efficiency, anchorage with only CFRP anchors was more efficient than combined anchorage of the CFRP anchors and U-wraps.

5.5 WORKABILITY

For best performance, CFRP sheets must be straight, and air voids must not exist between CFRP sheets and the concrete surface. A wide single layer CFRP sheet was easier to install than narrow double layer CFRP sheets.

In application of the additional anchorage with CFRP materials, CFRP U-wraps were easier to install than CFRP anchors. While CFRP U-wraps only required surface preparation of the concrete, drilling holes was needed for CFRP anchors. The holes had to be saturated with epoxy, and CFRP anchors had to be inserted into the holes through the CFRP sheets and splayed out on the sheets.

Inserting ends of CFRP sheets into the anchor holes (specimen No.3) was the most difficult way to provide additional anchorage because a portion of the CFRP sheet had to be anchored while the rest of the sheet was maintained in straight, well-bonded condition.

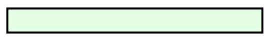
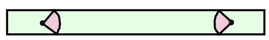
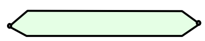
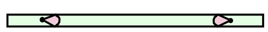
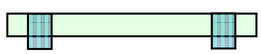
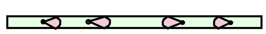
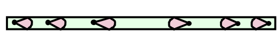
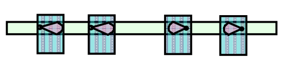
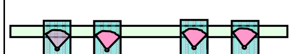
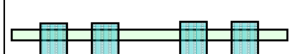
No.	Specimen	Layers of CFRP sheet	Type of anchorage	Peak load (kip)	Area of CFRP (ft^2)	**Material Efficiency, (kip/ft^2) (peak Load /CFRP Area)**
1		1 layer	No anchorage	14.6	5.04	**2.9**
2		1 layer	1 CFRP anchor each side	17.1	5.77	**3.0**
3		1 layer	Insert end of CFRP sheet into holes	14.2	5.04	**2.8**
4		2 layers	1 CFRP anchor each side	17.3	5.77	**3.0**
5		1 layer	1 CFRP U-wrap each side	17.6	7.03	**2.5**
6		2 layers	2 CFRP anchors each side	25.8	6.49	**4.0**
7		2 layers	3 CFRP anchors each side	23.8	7.22	**3.3**
8		2 layers	2 CFRP anchors each side with CFRP U- warp	31.9	10.47	**3.1**
9		2 layers	2 CFRP U-wrap each side anchored by CFRP anchor	16.2	10.47	**1.5**
10		2 layers	2 CFRP U-wrap each side	15.4	9.01	**1.7**

Table 5.3 Test Results, Material Efficiency

CHAPTER 6
CONCLUSION

The following major conclusions can be drawn from this study.

1. It was possible to use CFRP materials to create alternative load path in a beam -column connection.
2. Anchorage of the CFRP sheet was critical to develop full fracture strength of the CFRP sheet.
3. Both strength and deformation capacity increased by installation of additional anchorage for the CFRP sheet with CFRP material to the CFRP sheet.
4. A combination of the CFRP anchor and the CFRP U-wrap was a solution to provide proper anchorage to the CFRP sheet..

Rehabilitation using CFRP materials to correct poor details was successful only if proper anchorage was provided. It was necessary to use both CFRP anchors and CFRP U-wraps to achieve full strength of the CFRP sheet. If either CFRP anchors or CFRP U-wraps were used alone, delamination of the sheet led to failure of the anchor or U-wrap.

Further research into various geometries and quantities of CFRP anchors and U-wraps are required before design guidelines can be developed. Moreover, application may be limited because the method requires flat side surfaces and many beam-column connections consist of columns that are wider than the beams. However, it is possible to use the method in other applications in which CFRP sheets are used to provide continuity in the same plane.

Reference

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Vita

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