REHABILITATION OF EXISTING STRUCTURES USING CARBON FIBER-REINFORCED POLYMER (CFRP) JACKETING

FINAL YEAR PROJECT UG 2014

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It is certified that the

Final Year Project titled

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has been accepted towards the requirements

for the undergraduate degree

in

CIVIL ENGINEERING

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ABSTRACT

While new reinforced concrete (RC) structures are being constructed at an incredible pace around the globe, existing structures seek periodic maintenance and damaged ones need necessary rehabilitation. The deterioration of existing structures might occur due to ageing of materials, environmental corrosion of embedded steel, inadequate quality of concrete, poor operations and maintenance, design deficiency, changes in use or imposed loading, fire damage, malpractices during construction, and natural calamities.

The damaged structural members may be strengthened in flexure with the use of Carbon Fiber-Reinforced Polymer (CFRP) bonded to their tension zone using suitable epoxy as a common adhesive. In comparison to traditional rehabilitation techniques, for instance externally bonded steel plates, steel jackets, concrete jackets or external post-tensioning, CFRP wrapping has proved to be far more advantageous.

The increasing popularity of CFRP can be ascribed to its light weight, corrosion resistance, high tensile strength, easy installation and aesthetically pleasing outlook. Despite its unprecedented structural viability, its high initial cost and lack of conversance of contractors and consultants of construction industry of Pakistan with this technique has put it behind other rehabilitation techniques.

With the intent to troubleshoot the aforementioned obstacles toward its choice as a rehabilitation technique particularly in the construction industry of Pakistan, an experimental study is carried out to economize the quantitative use of CFRP for rehabilitation of RC beams. The experimental program involves testing of three full-scale beams, having 7.5”x10.5” cross-section and 7.5’ clear span, under four-point bending. A comparative analysis between beams fully and selectively jacketed with CFRP in U-shape configuration has been drawn. To simulate degradation of structural members in real-time, two beams are first loaded to 65% of ultimate strength, unloaded, and then

wrapped before testing. In addition, a technical survey is carried out to determine how conversant, and confident are the contractors and consultants of construction industry of Pakistan with CFRP jacketing as a potential technique for rehabilitation of existing structures. The experimental results indicate that CFRP jacketing increases the strength of degraded structural member significantly. Furthermore, the ultimate load recorded for fully jacketed beam is almost same as that for selectively jacketed beam. The technical survey shows that the contractors and consultants in Pakistan are not confident in adopting this technique as an alternate solution.

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Chapter 1

INTRODUCTION

1.1 Background

Rehabilitation of existing deteriorated reinforced cement concrete (RCC) structures has been a serious concern for civil engineers across the globe. The deterioration might occur due to ageing of materials, environmental corrosion of embedded steel, inadequate quality of concrete, poor operations and maintenance, design deficiency, changes in use or imposed loading, fire damage, malpractices during construction and natural calamities (Kumar, 2016). The need to repair the damaged RCC structures increases with frequently changing requirements. Therefore, there is a need to address the issue of rehabilitation of existing RCC structures.

1.2 Fiber-Reinforced Composites

Fiber-reinforced composite materials comprise of fibers possessing high strength and modulus bonded to a matrix. Fibers carry the load and matrix transfer the load between them. Matrix also keeps the fibers in intended place and orientation. The matrix material may be a polymer, a metal, or a ceramic. Laminate is one of the form in which fiber-reinforced composites are used in structural applications. A laminate is a stalk of a larger number of thin films of fibers and matrix, bonded together into intended thickness. (Mallick, 2008).

The orientation of fiber in a layer and the way layers are stalked dictate the physical and mechanical properties of composite laminate. For instance, tensile strength and modulus of a unidirectionally oriented fiber-reinforced polymers (FRP) are maximum when these properties are measured in the longitudinal direction of fibers and minimum when measured in transverse direction of fibers. This non-isotropic nature of fiber-reinforced composites permit customization in its properties according to design requirements. They may be used to selectively reinforce a structure in the directions of major stresses, increase its stiffness in desired direction and even construct structures with zero coefficients of thermal expansion (Mallick, 2008).

1.3 Applications and Use

1.3.1 General

Fiber reinforced polymers are used to strengthen structural members that are deteriorated due to ageing of materials, environmental corrosion of embedded steel, inadequate quality of concrete, poor operations and maintenance, design deficiency, changes in use or imposed loading, fire damage, malpractices during construction and natural calamities (Kumar, 2016).

1.3.2 Site Inspection Consideration

Prior to implementation of an FRP system for a certain application, comprehensive site investigation, a review of existing design, and a structural analysis in accordance with (ACI Committee 364, 2007) needs to be carried out. As a minimum, the field investigation should determine the following:

a. Existing dimensions of the structural members
b. Location, size, and cause of cracks and spalls
c. Location and extent of corrosion of reinforcing steel
d. Presence of active corrosion
e. Quantity and location of existing reinforcing steel
f. In-place compressive strength of concrete
g. Soundness of the concrete, especially the concrete cover, in all areas where the FRP system is to be bonded to the concrete

1.3.3 Field Tests on Existing Structure

The tensile strength of concrete surfaces to be jacketed should be determined by conducting a pull-off adhesion test in accordance with ACI 503R (ACI Committee 503, 2002). The compressive strength of concrete should be determined using cores in accordance with ACI 318-05 (ACI Committee 318, 2005) requirements. The load-carrying capacity of existing structure should be based on the data and information collected in site inspection, review of structural drawings and calculations, and analytical techniques.

1.3.4 Strengthening Limits

The key consideration in strengthening of a structural member with FRP systems is that the member must be able to resist the sustained service load in case the FRP system is damaged to avoid abrupt failure of member. (ACI Committee 440, 2017) recommended that the existing strength of surface should be sufficient to resist a level of load as described by Equation 1-1 below.

$$(\phi R_n)_{existing} \geq (1.2 S_{DL} + 0.85 S_{LL})_{new} \qquad \text{(Equation 1-1)}$$

where,

ϕR_n = Ultimate Strength

S_{DL} = Super imposed dead load

S_{LL} = Super imposed live load

1.3.5 Commercial Forms of CFRP

Carbon, glass and Kevlar are main types of commercially available fiber. Carbon fibers are available in a variety of tensile modulus ranging from 30 x 10^6 psi to 150x10^6 psi. Low modulus fibers have lower density, lower cost, higher tensile and compressive strengths, and higher tensile strains-to-failure as compared to high-modulus fibers (Mallick, 2008). FRP wraps are used in tension regions of beams and wrapped on columns for providing better confinement while FRP strips are used in tension regions of beams and slabs.

1.3.6 FRP Wraps

FRP wraps are woven fibers in longitudinal as well as transverse direction and are also used for strengthening of reinforced concrete members. FRP wraps can also be used where the cross-section of reinforced concrete members is irregular or non-uniform as they are very flexible.

Figure 1-1: FRP wrapped on columns (after Sika (Pvt.) Ltd.)

1.3.7 FRP Strips

Strips are most widely used forms of FRP, in strengthening of reinforced concrete members. They are bonded in the direction of principal tensile stresses. They are preferred for members with flat, regular or uniform cross-section, for instance RCC beams and slabs.

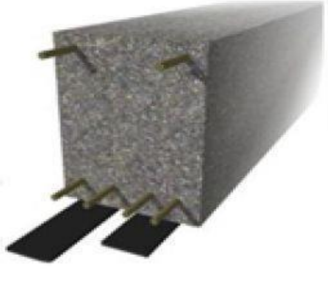

Figure 1-2: FRP strips on a beam (after Sika (Pvt.) Ltd.)

1.4 Objectives

The aim of this study is to investigate the effect of selective CFRP jacketing on flexural strength on RCC beams. The specific objectives are:

a. To analyze the use of CFRP jacketing for rehabilitation of existing RCC structures.

b. To examine the flexural response of a structural member strengthened with CFRP.

c. To find out how conversant, confident and aware are the contractors and consultants of construction industry of Pakistan with CFRP jacketing as a potential technique for rehabilitation of the existing RCC structures.

d. Depending upon the results of this investigation, a seminar/workshop might be held at MCE Risalpur tentatively in June 2018, to give confidence to engineers, contractors, and consultants about the rehabilitation of existing reinforced structural members.

1.5. Scope

This study is limited to experimental investigation of flexural response of reinforced concrete beams strengthened fully and selectively with CFRP jacketing in U-shape configuration, in accordance with (ACI Committee 440, 2017)-Guide for Externally Bonded FRP Systems for Strengthening Concrete Structures.

1.6. Methodology

Based on the literature review, three reinforced concrete beams are tested. The beams are designed such that flexure controls the failure. The first specimen, B-1, is loaded to failure. The second specimen, B-2, is loaded to about 65% of the ultimate load for B-1 followed by wrapping with CFRP in U-shape configuration over its full span of length and finally loaded to failure. The third specimen, B-3 is first loaded to about 65% of the ultimate load for B-1 followed by selective wrapping with CFRP in U-shape configuration over its middle and finally loaded to failure. The load deflection and moment-curvature curves of the tested beams are plotted and compared to derive conclusions.

Chapter 2

LITERATURE REVIEW

2.1 Review of Rehabilitation Techniques

RCC structures require ample acquisition of resources to be constructed. Therefore, substantial attention must be paid in ensuring that they keep meeting their intended function, at least up to their design life. Although gradual deterioration of RCC structures is inevitable, yet detailed planning and adoption of adequate methodology for repair and rehabilitation can be considerably effective in coping up with this problem. (Atea, 2017). The rehabilitation of existing reinforced concrete structures to resist higher design loads, correct strength loss due to deterioration, rectify design errors or construction malpractices, or enhance ductility has traditionally been carried out using conventional materials and construction techniques. These include externally bonded steel plates, steel or concrete jackets, and external post-tensioning (ACI Committee 440, 2017).

RCC elements rehabilitated with steel plates in the tension regions have manifested an increase in load carrying capacity and in turn increasing the flexural capacity of members. However, corrosion of steel plates, debonding of the steel plate and concrete and related problems in installation of these plates have led engineers to adopt alternative means of rehabilitation. FRP have turned out as an alternate to conventional materials for rehabilitation of existing concrete structures (ACI Committee 440, 2017). Externally bonded, FRP sheets are currently being studied and applied around the world for the overhaul and establishment of structural concrete members because of their superior properties such as high stiffness and strength as well as ease of installation when compared to other materials (Atea, 2017). As a result, FRP are sufficiently capable of replacing other composites in strengthening of deteriorated structures.

FRP can increase the serviceability life of a structure and can reduce the maintenance and repair costs. Other environmental factors such as high-temperatures, corrosive fluids and ultraviolet rays adversely affect the mechanical properties of composites (Mallick, 2008). In addition, FRP materials are light weight and possess exceptionally high tensile strength. However, a few bottlenecks to its use are moderate heat and fire resistance of the epoxy resin, resulting in difficulty in use when applied over wet surfaces and lower rates of vapor transferability (D'Ambrisi, 2011). They are available in form of factory-made laminates and fiber sheets that may be wrapped around the structural members prior to addition of epoxy. Thin sheets of cured FRPs are also in use where aesthetics is of prime consideration (ACI Committee 440, 2017).

The epoxies, polymers or other remedies being employed for repair purposes must be compatible with the existing structure in order that the repair may be conclusive. The final decision of carrying out repair or replacement of existing structure or its members depend on the service design life of structure, technical assessment and economic concerns. In any way, the decision taken must be in compliance with structural integrity and safety, attractiveness of structure and lack of use of distress-inducing agent (Kumar, 2016).

2.2 Failure Modes in Retrofitted RCC beams

There are seven different types of failures that have been observed with retrofitted reinforced concrete members. These include:

a. Flexural failure by FRP rupture
b. Flexural failure by crushing of compressive concrete
c. Shear failure
d. Concrete cover separation
e. Plate-end interfacial de-bonding
f. Intermediate flexural crack-induced interfacial de-bonding

g. Intermediate shear cracked-induced interfacial de-bonding.

All these failure modes can be divided into three broader categories.

a. Rupture of FRP
b. Concrete crushing
c. De-bonding of FRP

In first mode of failure, the steel yields followed by rupture of FRP. This kind of failure mode is more prevalent in wraps than in strips owing to greater in-contact surface area between FRP and concrete.

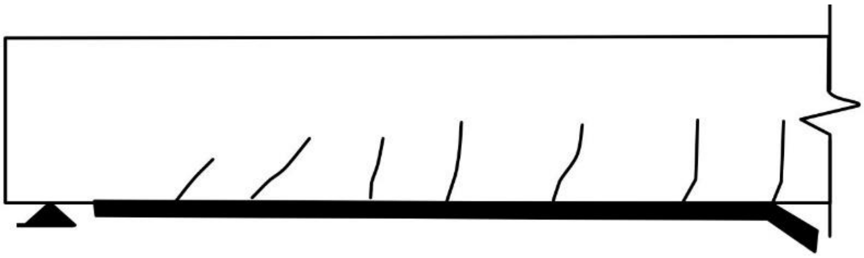

Figure 2-1: Rupture of FRP (after Obaidat, 2011)

In the second type of failure, concrete reaches crushing in compression with or without yielding of steel reinforcement, as shown in Figure 2-2. Alternatively, shear cracks may also form, originating from ends of FRP as shown in Figure 2-3. However, the composite action of concrete and FRP is maintained until either concrete fails in compression or FRP fails in tension.

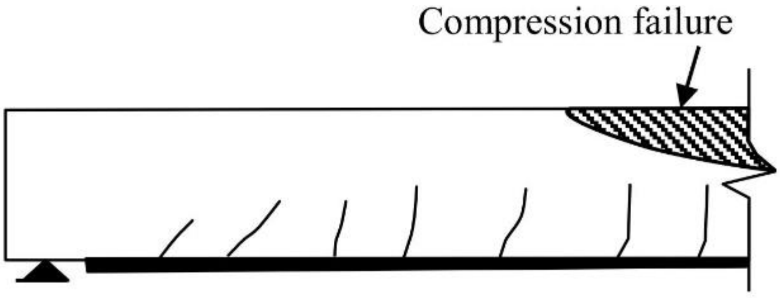

Figure 2-2: Rupture of FRP due to concrete crushing (after Obaidat, 2011)

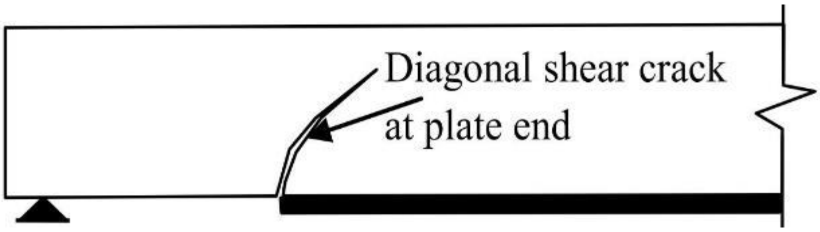

Figure 2-3: Shear Failure Mode (after Obaidat, 2011)

The third type of failure is referred to as de-bonding of FRP. It can occur in many different ways. One of the debonding modes initiates at or near the plate end is the separation of the FRP strip/plate from the beam. This kind of debonding failure takes place when high interfacial shear and normal stresses near the end of the plate exceeds the strength of concrete. If the strength of adhesive is less as compared to that of concrete, this kind of failure may initiate through adhesive. So, this kind of de-bonding failure is seen when either at high temperatures or when the strength of concrete is high.

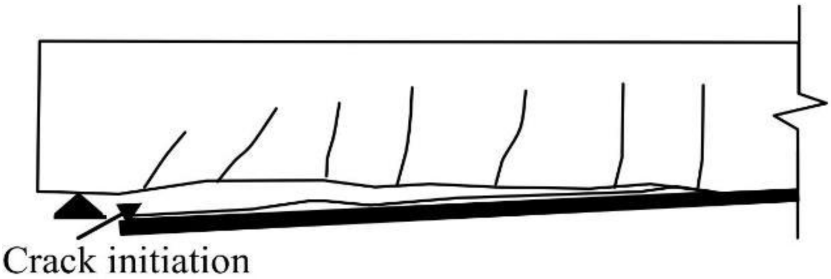

Figure 2-4: Separation of FRP plate (after Obaidat, 2011)

Another common kind of de-bonding failure involves loss of concrete cover at or near one of the two ends of FRP plate. It occurs due to stress concentration near the ends of bonded plate and is initiated by appearance of a crack at or near the plate end, owing to high interfacial shear and normal stresses caused by sudden separation of plate.

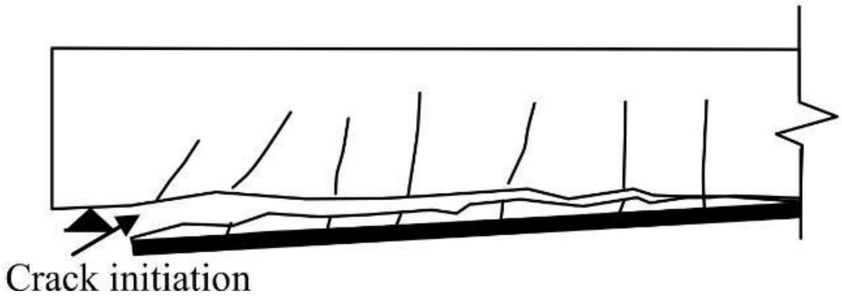

Figure 2-5: Separation of concrete cover (after Obaidat, 2011)

Other modes of de-bonding failure initiate by formation of flexure or flexural-shear cracks as shown in figure below. These cracks become horizontal near the bottom of Reinforced Concrete beam and result in separation of plate.

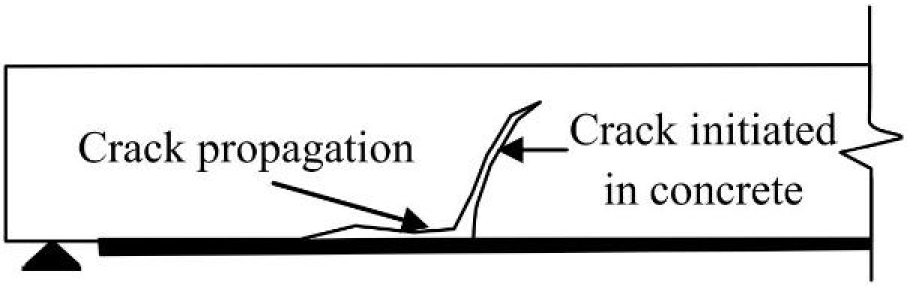

Figure 2-6: Debonding due to flexural shear cracks (after (Obaidat, 2011)

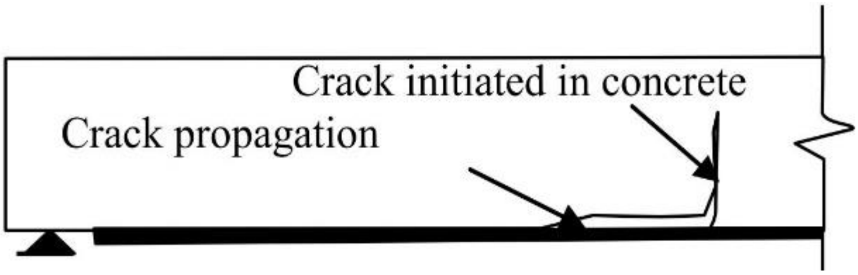

Figure 2-7: Debonding due to flexural cracks (Obaidat, 2011)

2.3 Manufacturing of CFRP

There are three methods of preparing FRP composites namely fiber impregnation (hand lay-up) technique, vacuum bagging and pultrusion. These methods are briefly discussed below.

2.3.1 Fiber Impregnation

Also referred to as hand lay-up, this process involves placing successive layers of resin-impregnated reinforcement in position manually. Brushes and grooved rollers are used to force the resin into the fabric and to remove much of entrapped air. However, if air voids remain within the product, they can form cracks which may spread throughout the structure (Hollaway & Leeming, 1998).

2.3.2 Vacuum Bagging

In this method, the successive layers of resin impregnated fiber reinforcement are applied to a mould and rolled. A rubber or nylon sheet or a bag is placed over the lay-up and the air is removed by means of a vacuum pump. The mould is then placed either in an oven and heated to 176-392° Fahrenheit, or into an autoclave and is subjected to both temperature and pressure.

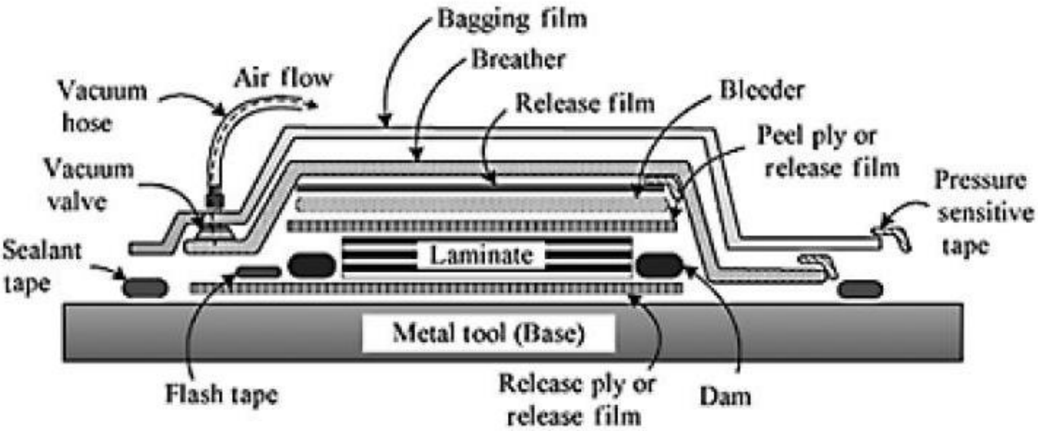

Figure 2-8: Vacuum bagging setup for laminate composites (after Hollaway & Leeming, 1998)

2.3.3 Pultrusion

Pultrusion is an automated, continuous process for manufacturing shapes with regular cross-section. In this technique, dry reinforcing fibers are pulled first through a resin and then through a heated steel die. The die is heated to about 302° Fahrenheit, causing resin to undergo polymerization and curing. As the profile exits from the die, it has attained considerable degree of cure. It is pulled by either reciprocating pullers or a caterpillar haul-off and is automatically sawn to length. In pultrusion, the incoming fibers are normally unidirectional and must be pulled through the pultrusion die since the uncured material lacks the rigidity to be pushed through the die. The process is illustrated in the figure below (Hollaway & Leeming, 1998).

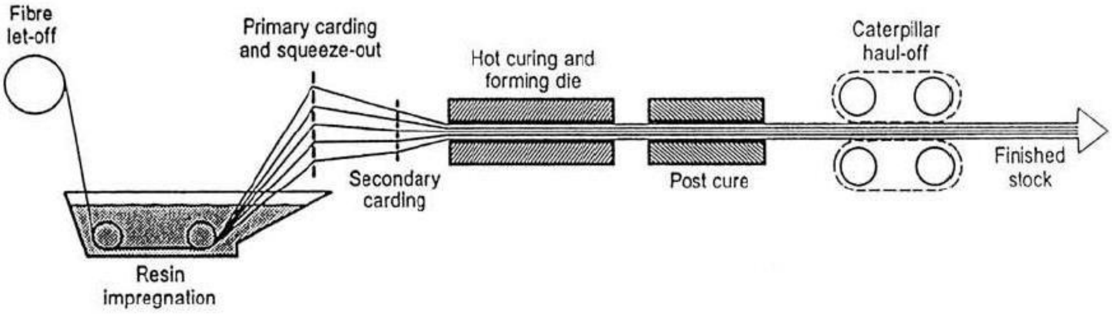

Figure 2-9: Pultrusion process (after Hollaway & Leeming, 1998)

2.4 Review of Experimental Investigations

Ladner et. al (1990) experimetally investigated flexural response of approximately 23' long beams strengthened with CFRP under 4-point loading. The beams were strengthened with 0.04" thick CFRP laminate. The authors concluded that CFRP increased the load carrying capacity of beams by 22% and the ultimate deflection was significantly reduced.

Meier & Kaiser (1992) experimentally investigated flexural response of approximately 7' long beams strengthened with CFRP under 4-point loading. The experiments involved testing the control specimen the beams strengthened with pultruded carbon fiber/epoxy laminates up to 0.04” thick. The beams were designed with low proportion of internal reinforcement and hence, the strength of control specimen was low. The authors concluded that beams strengthened with CFRP failed at ultimate load twice as much as for control specimen. The ultimate deflection for the beams strengthened with CFRP was considerably reduced. The authors recommended that in strengthening applications, the external CFRP should fail in tension after yielding the internal steel but before the concrete crushing in the compression zone as this would ensure a more ductile failure.

Hutchinson & Rahimi (1993) experimentally investigated the response of approximately 7’ 6” long beams with strengthened with CFRP. The experiments involved loading the specimens to 80% of their ultimate moment capacity and then wrapping them with unidirectional CFRP. The authors concluded that as much as 230% increase in load carrying capacity of the beams was observed. They added that the increase also depended on degree of internal reinforcement in the beam before wrapping.

Malvar et. al (1995) experimentally investigated the response of approximately 5’ 6” long beams containing no shear reinforcement and strengthened with unidirectional CFRP sheets. The authors reported that longitudinally strengthening the beams increased the flexural strength but resulted in shear failure of the beams. Upon additional CFRP-wrapping onto the sides and soffit over the entire span of length of the beams, considerable shear strength was imparted to revert a flexural failure in which steel yielded, then concrete crushed before CFRP material ruptured. The authors also concluded that the ductility of the wrapped specimens was less as compared to control specimen.

Hyder et. al (2017) experimentally investigated the efficacy of CFRP wraps and strips on the normal strength RC beams. The experiments involved testing 8’ long beams under 4-point loading. The authors concluded that beams strengthened with CFRP wraps, applied only onto the soffit, manifested 35% increase in flexural strength.

2.5 Summary and Conclusions of Literature Review

The increasing level of interest in the technique manifests its potential advantages and also current emphasis on economical rehabilitation and upgrading methods. Although the field applications of the technique are widespread, there remain many material and structural implications that need to be addressed. For instance, long term performance of CFRP under loads needs to be investigated.

Chapter 3

PROPERTIES OF MATERIALS

3.1 General

This chapter defines the properties of materials procured for the mix design and casting of beam specimens. To simulate general construction practices in Pakistan, most widely available construction materials were procured, and concrete mix was designed for moderate 28 days compressive strength. The primary aim was to investigate the efficacy of CFRP jacketing when applied on RCC beams made with locally available construction materials and prepared under routine construction practices. Properties of the material tested are shown in this chapter.

3.2 Selection and Procurement of Material

For mix design and casting of beams, Margalla crush, Lawrencepur sand and Bestway cement were selected and procured. Grade 60 steel being widely used in Pakistan was used as reinforcement. Rehabilitation of beams was carried out with Sika products, SikaWrap-230C and Sikadur-330. Properties of these materials are given below.

3.2.1 Coarse Aggregates

A series of tests were carried out to determine the properties of aggregates shown in Table 3-1. These tests include:

a. Sieve Analysis of Coarse and Fine Aggregates
b. Specific Gravity of Coarse and Fine Aggregate
c. Absorption Capacity of Coarse and Fine Aggregate
d. Crushing Value of Coarse Aggregate

e. Fineness Modulus of Fine Aggregate

Table 3-1: Properties of Coarse Aggregates

Ser.	**Properties of Aggregate**	**Standard**	**Coarse Aggregate**	**Fine Aggregate**
1	Maximum Aggregate size	-	1”	-
2	Fineness Modulus	ASTM C136	-	2.85
3	Bulk specific gravity	ASTM C127	2.70	2.64
4	Absorption Capacity	ASTM C127	1.07%	1.66%

3.3 Concrete

Taking into consideration the concreting practices in Pakistan, five 6” x 12” cylinders were cast for 1:2:4 trial mix with target compressive strength of 2500 psi. The results of the test are given in Table 3-2 and Table 3-3 respectively.

Following tests were carried out to determine the properties of concrete

a. Compressive Strength Test (in accordance with ASTM C39)

b. Slump Test (in accordance with ASTM C143)

Table 3-2: Properties of Mix

Ser.	**Properties of Mix**	**Value**
1	Slump	3-4”
2	Water cement ratio	0.6
3	Mix design trial	1:2:4

Five 6” x 12” cylinders were cast for 1:2:4 trial mix. Cylinders were then put in curing pond for 28 days. The compressive strength of concrete at 28 days for the mix is given below.

Table 3-3: 28-Days compressive strength values for concrete

Mix	**Compressive strength (psi)**	**Average compressive strength (psi)**	**Standard Deviation**	**Coefficient of variance (%)**
Mix design (1:2:4)	2785	2680	217.6	8%
	2610			
	2930			
	2350			
	2725			

The mix of 1:2:4 was chosen owing to its widespread prevalence in the construction industry of Pakistan. To draw a fair comparison in strengths between jacketed and unjacketed beams, all three specimens were cast with same mix design and water-to-cement ratio.

3.4 Steel

For casting of reinforced concrete beams, deformed bars with acclaimed tensile strength of 60 ksi were procured from Ittehad Steel, Agha Shahi Avenue, Islamabad.

3.5 Carbon Fiber-reinforced Polymer (CFRP)

CFRP, in form of wraps, and suitable epoxy were used in this project for external strengthening and bonding respectively. The material was procured from Sika Pakistan (Pvt.) Ltd.

3.5.1 CFRP Wrap Properties

SikaWrap-230C was used for jacketing of beam specimens. A unidirectional woven carbon fiber fabric with mid-range strength, designed for installation using the dry or wet application process.

Table 3-4: Mechanical properties of SikaWrap-230C

Ser.	Characteristics	Unit	Dry fiber properties
1	Tensile Strength	psi	580×10^3
2	Modulus of Elasticity	psi	333×10^5
3	Fiber Density	lb/ft^3	114
4	Area Density	lb/ft^3	14700±620
5	Elongation at break	%	1.7
6	Thickness	inch	5×10^{-3}

3.5.2 Properties of Epoxy

Sikadur-330 is used as impregnation resin for SikaWrap fabric reinforcement for the dry application method, comprises of two-component, thixotropic epoxy based impregnating resin and adhesive. As per general guideline, provided by Sika Pakistan, 0.15-0.3 lbs of epoxy is required per square feet of wrapping. The properties of epoxy, provided by manufacturer, are given in the Table 3-5.

Table 3-5: Properties of Sikadur-330

Ser.	Characteristics	Unit	Dry Properties
1	Tensile Strength	psi	4350 (7 days at + 73.4°F)
2	Tensile Modulus of Elasticity	psi	650×10^3
3	Bond Strength	psi	3200 (2 days dry cure)
4	Consistency	-	Non-sag paste
5	Elongation at Break	%	0.9

Chapter 4

EXPERIMENTAL PROGRAM

4.1 General

This chapter provides details of experimental methodology, material quantities and instruments used for testing. Finalization of tests scheme of beam specimens was the first step of this project followed by estimation of material required for the preparation of specimens. The experimental program focused on determining a wrapping configuration that could optimize the quantity of CFRP material whilst increasing, or otherwise without compromising, the flexural strength of reinforced concrete beams.

4.2 Testing Methodology

To draw a comparison between selective and complete U-shape fiber wrapping, three beam specimens were cast at Structures Lab, National Universities of Sciences & Technology, Islamabad. The summarized procedure of testing is shown in Table 4-1.

Table 4-1: Testing strategy of the specimen

Specimen	**Testing Strategy**
B-1	• Loaded to ultimate moment capacity
B-2	• Loaded to 65% of the ultimate load for B-1 • Fully wrapped with CFRP in U-shape configuration • Loaded to ultimate moment capacity
B-3	• Loaded to 65% of the ultimate load for B-1 • Selectively wrapped with CFRP in U-shape configuration • Loaded to ultimate moment capacity

4.3 Design of Beam Specimens

Based on the dimensions of available molds in Structures Lab, NICE, NUST, beam width is taken equals to 7.5" and depth equals to 10.5" for the design.

General specifications:

- Depth of beam, $h = 10.5"$
- Width of beam, $b = 7.5"$
- Length of beam, L$= 8.5'$
- $f_c' = 2500psi$
- $f_y = 60{,}000psi$

Effective depth;

$$d = h - c_c - half\ bar\ dia - stirrup\ dia$$

$$d = 10.5\text{"-1"} - \frac{4}{2 \times 8} - \frac{3}{8} = 8.8"$$

Tension Reinforcement ratio

$$A_s = 3\ \#4 = 3 \times 0.2 = 0.6$$

$$\rho_s = \frac{A_s}{bd} = \frac{0.6}{7.5 \times 8.8} = 0.0091$$

Minimum reinforcement for tension zone;

$$A_{s,min} = \frac{3\sqrt{f_c'}b_w d}{f_y} = \frac{3\sqrt{2500} \times 7.5 \times 8.8}{60000} = 0.165$$

$$A_{s,min} = \frac{200 b_w d}{f_y} = \frac{200 \times 7.5 \times 8.8}{60000} = 0.22$$

$A_{s,min} = 0.22$ (Use greater)

$$\rho_{min} = \frac{0.22}{7.5 \times 8.8} = 0.003$$

$$\rho_s > \rho_{min}$$

Tension reinforcement ratio for balanced section

$$\rho_b = \left(\frac{0.85\beta_1 f_c'}{f_y}(\frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_y})\right)$$

$$\rho_b = \left(\frac{0.85 \times 0.85 \times 2500}{60000}(\frac{0.003}{0.003 + 0.00207})\right) = 0.0178$$

Maximum Tension reinforcement;

$$\rho_{max} = 0.75 \times 0.0178 = 0.0133$$

$$\rho_{max} > \rho_s$$

Use $2\#4$ $(A_s' = 0.4)$ bar for compression zone and $3\#4$ $(A_s = 0.6)$ bar for tension zone

Section reinforcement;

$$5\#4\ (A_s + A_s' = 0.6 + 0.4 = 1.0\ in^2)$$

Neutral axis of beam cross section;

$$c = \frac{d}{4} = 2.2"$$

Compression stress block depth;

$a = \beta_1 c = 0.85 \times 2.2 = 1.87"$

Distance from top extreme fiber to center of compression reinforcement, d'

$$d' = 1" + \frac{4}{2 \times 8} + \frac{3}{8} = 1.67"$$

Compression steel strain;

$$\varepsilon_s' = \varepsilon_{cu}\left(\frac{c - d'}{c}\right) = 0.003"\left(\frac{2.2" - 1.67"}{2.2"}\right) = 0.0007$$

$f_s' = 29000ksi \times 0.0007 = 21ksi\ < 60ksi$ Compression steel is not yielding

Force in compression reinforcement;

$$C_s = A_s'(f_s' - 0.85 f_c')$$

$$C_s = 0.4in^2\ (21ksi - 0.85 \times 2.5ksi) = 7.55kips$$

Compressive force in concrete;

$$C_c = 0.85 f_c' b \beta_1 c$$

$$C_c = 0.85 \times 2.5ksi \times 7.5" \times 0.85 \times 2.2" = 29.8kips$$

Force in tension reinforcement;

$$T = A_s f_y$$

$$T = 0.6in^2 \times 60ksi = 36kips$$

Section equilibrium check;

$$C_s + C_c = \ 7.55 + 29.8 \ = 37.5 \ kips$$

$$T = 36kips$$

Nominal moment strength of beam section will be

$$M_n = C_C\left(d - \frac{a}{2}\right) + C_s(d - d')$$

$$M_n = 29.8\left(8.8 - \frac{1.87}{2}\right) + 7.55(8.8 - 1.67) = 288.21kip.in$$

$$M_n = 24kip.ft$$

For four points loading configuration shown in figure maximum moment will be

$$M_{max} = Pa$$

$$P = \frac{M_{max}}{2.5} = 9.6kips$$

$$2P = 19.2kips$$

Self-weight of beam;

$$w = \frac{7.5" \times 10.5" \times 8.5' \times 144}{144} = 669 \ lb$$

Maximum failure load

$$19.2 - 0.669 = 18.5 \ kips$$

The cross-section and longitudinal section of the designed beam are given below.

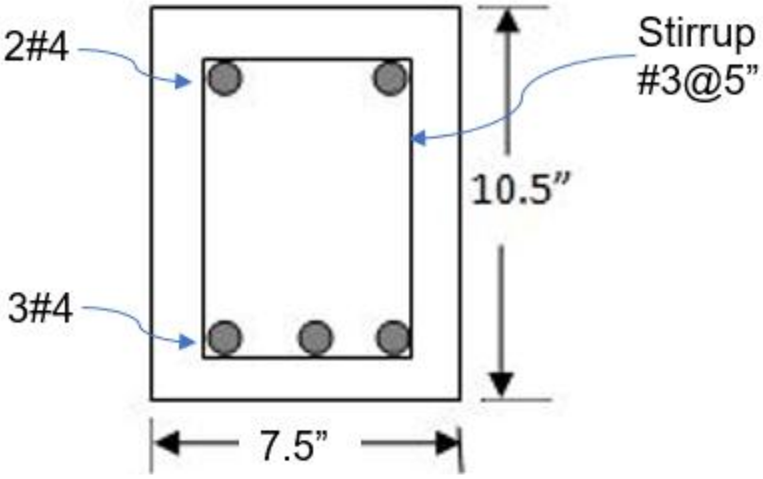

Figure 4-1: Cross section of beam

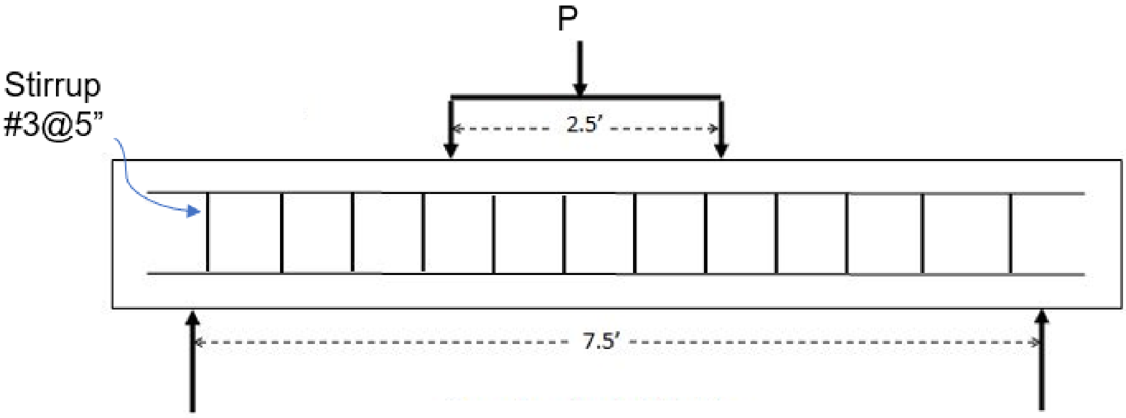

Figure 4-2: Longitudinal section of the beam

4.4 Material Quantity Estimation

Total volume of concrete (1:2:4)

Number of beam specimens= 3

Length of beam specimen= 8 ft.

Cross-section of beam specimen= 7.5 in x 10.5 in

Volume of beam specimen = $\frac{7.5}{12} \text{ x } \frac{10.5}{12} \text{ x } 8 = 4.375 \text{ ft}^3$

Dry weight of concrete = 1.54 x Volume of sample beam

= 1.54 x 4.375 ft^3

= 6.74 ft^3

Adding 5% wastage, volume required for 1 specimen = 1.05 x Dry weight of concrete

= 1.05 x 6.74 ft^3

= 7.10 ft^3

Volume of concrete required for 3 specimens = 3 x 7.10 ft^3

= 21.30 ft^3

For casting of five 6 x 12 in cylinders at the time of preparation of beam specimens,

Volume of concrete required= $\pi r^2 h$

= 3.142 x 6^2 x 12

= 1357.34 in^3

= 0.785 ft^3

Total volume of concrete= 21.30 + 0.785 = 22.1 ft^3

Number of bags of cement

Quantity of cement = $\frac{1}{7}$ x 22.1 = 3.16 ft^3

Volume of cement in 1 bag = 1.236 ft

Number of cement bags = $\frac{3.16}{1.236}$

= 2.6 bags

Quantity of sand

Volume of sand = $\frac{2}{7}$ x 22.1

= 6.31 ft^3

Quantity of coarse aggregate

Volume of aggregate = $\frac{4}{7}$ x 22.1

= 12.63 ft^3

Quantity of steel (G-60)

For a single beam specimen,

Number of longitudinal bars in beam specimen = 5 (#4)

Cut length = 8 ft.

Total length = 40 ft.

Number of stirrups = 16 (#3 @ 6” c/c)

Perimeter of 1 stirrup = 2 (10.5 + 7.5) in

= 36 in. (3 ft.)

Total length of stirrups = 3 x 18

= 54 ft.

Weight of longitudinal bars= $N^2/53$ x total length (N refers to bar number)

= $4^2/53$ x 40 ft

= 12.10 kg

Weight of stirrups = $N^2/24$ x total length of stirrups

= $3^2/53$ x 54 ft

= 9.17 kg

For all 3 beam specimens,

Total weight of steel (# 4 deformed bars) = 12.10 x 3

= 36.30 kg

Total weight of steel (#3 deformed bars) = 9.17 x 3

= 27.50 kg

Total weight of steel = 36.30 + 27.50

= 63.80 kg

Adding 5% wastage in cutting, bending or other operations

= 5/100 x 63.80

= 3.20 kg

Total weight of steel = 63.80 + 3.20

= 67 kg

The results of estimations are summarized in Table 4-2

Table 4-2: Quantity of materials

Ser	Item	Type	Arithmetic Unit	Quantity
1	Portland Cement	Bestway Cement	Bags	3
2	Sand	Lawrencepur Sand	ft^3	7
3	Crush	Margalla Crush	ft^3	13
4	Structural Steel	Ittehad Steel Grade-60	Kg	67
7	CFRP Wraps	SikaWrap-230C	m^2	4
8	Epoxy	Sikadur-330	Kg	5

4.5 Casting of Beam Specimens

4.5.1 Molds

Concrete beam molds were available in Structures Lab, NICE, NUST, Islamabad. The molds were 7.5” X 10.5” cross-section and 8’ in length. The molds were cleaned and oiled before the casting of beams.

4.5.2 Preparation of Specimen

Three beam specimens with same geometry and rebar placement were cast. 3#4 deformed bars of Grade-60 were provided as longitudinal reinforcement in tension while 2#4 bars were provided in compression. The stirrups were made of #3 deformed bars and provided at 6 in. center-to-center. A small batching unit with bucket capacity of 154 lb was used to prepare concrete batches. All beams were cast in same working conditions to achieve similarity in their ready-to-test state for an effective comparative study.

Figure 4-3: Mixing in the batching unit

Figure 4-4: Placement of reinforcement into the molds

4.5.3 Curing of Beams

A day after casting, beams were removed from the molds and their curing was started with moist jute bags. The beams were cured for about four weeks. After satisfactory curing, beams were left to dry to get them ready for wrapping with CFRP.

Figure 4-5: Curing of beams

4.6 CFRP Jacketing of Beam Specimens

Firstly, care should be exercised in ensuring that fiber wrap do not get folded while cutting it to a desired size or while applying it to a beam specimen. In case CFRP is to be overlapped at some section, the overlapping should be done in a direction parallel to the orientation of carbon fibers and the lap length should be kept at least 4 inches. In addition, the concrete bond surface should be properly rubbed prior to application of epoxy. Ideally, concrete bond surface should be blasted with copper slag and then cleaned by a vacuum process. However, sand dust may also be used for rubbing the concrete surface. This process tends the concrete surface good for adhesion with CFRP. Secondly, fiber wrap should be laminated to concrete surface with a suitable epoxy using a roller to ensure its uniform application and in a direction that is parallel to the orientation of fibers. The rolling with a plastic roller helps to remove any air pocketed entrapped between the concrete surface and the CFRP Wrap.

After cutting FRP to the required size laminate it with the prescribed epoxy evenly with a roller along the direction of the fibers. Make sure to spread the epoxy evenly on the CFRP strip of sheet and on the application region of the beam. Make. All dust particles from the FRP and the beam should be removed before application of epoxy followed by application of FRP strip or sheet on the beam in the direction of the axis of the beam. Protect the finished FRP from dust, rain, sand or any other particles that may hinder the bonding process of FRP. Two types of FRP application processes exist which are described below.

4.6.1 Dry application process

In this method, epoxy serves both as a primary layer over the applied surface of structural member and impregnation resin for the CFRP Wrap. For instance, SikaDur-330 is most suitable for dry processes. However, this method is applicable as long as the weight of woven fabrics does not exceed 10.2 lb/ft^2 of area. For this experimental research, dry process was employed.

4.6.2 Wet application process

In this method, epoxy has to applied separately over the concrete surface as well on the CFRP Wrap. The wet CFRP Wrap is then applied over the RC member in a specific direction and rolled over with a plastic roller to remove any air pockets entrapped between the in-contact surfaces.

Figure 4-6: Wrapping of a beam specimen with CFRP using Dry Process

4.7 Analysis of Flexural Strength of CFRP-jacketed Beams

Nominal flexural strength enhancement M_f provided by the composite is a function of area of the fiber wrap, the design stress, and the moment arm as follows:

Flexural strength enhancement by CFRP wrap

$$M_f = A_f f_{fe}(jd)$$

where,

A_f = Area of FRP flexural reinforcement

$A_f = nt_f w_f$

n = Number of layers = 1

t_f = Thickness of one layer = 0.00437”

w_f = Width of FRP flexural reinforcement

$$A_f = 1 \times 0.00437 \times 7.5 = 0.0328 \text{ inch}^2$$

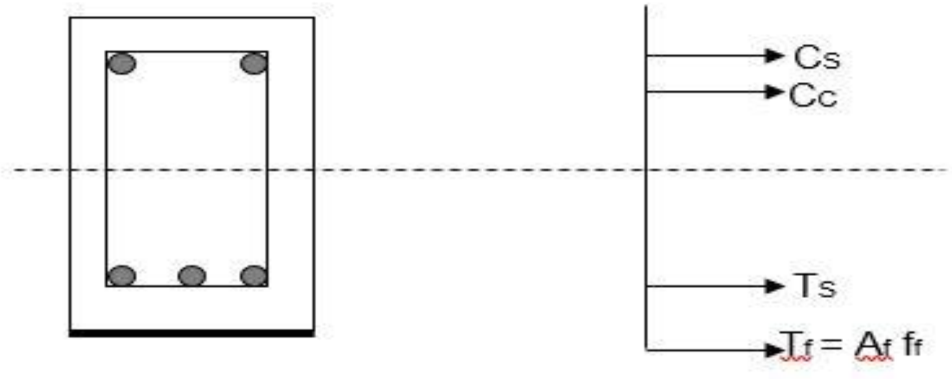

Figure 4-7: Beam X-Section & the distribution of forces

$f_{fe} = \varepsilon_{fe} E_f$ = Effective stress in CFRP

E_f = Modulus of elasticity of CFRP wrap= 230000 N/mm^2

$$E_f = 230000 \text{ N/mm}^2 = 33277.366 \; ksi$$

ε_{fe} = Design strain in wrap

4.7.1 Strain values for different failure modes

4.7.1.1 De-bonding of FRP

$$\varepsilon_{fd} = \varepsilon_{fe}$$

ε_{fd} = De-bonding strain in FRP wrap

$$\varepsilon_{fd} \leq 0.083 \sqrt{\frac{f_c}{nE_f t_f}} \leq 0.9\varepsilon_{fu} \quad \text{(Inch-lb units)}$$

$$\varepsilon_{fd} \leq 0.083 \sqrt{\frac{2500}{1 \times 33277366 \times 0.00437}} \leq 0.9 \times 0.015$$

$$\varepsilon_{fd} \leq 0.0108 \leq 0.0135$$

$$\varepsilon_{fd} = 0.0108$$

$\varepsilon_{fu} = 0.015$ = FRP ultimate strain

ε_{fd} is debonding strain in the FRP. In case of FRP U-wraps along the length of beam, 30% increase in debonding strain has been observed

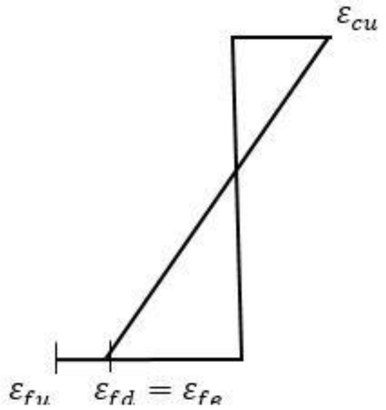

Figure 4-8: Strain distribution for FRP de-bonding

4.7.1.2 Rupture of FRP

$$\varepsilon_{fu} = \varepsilon_{fe} = 0.015$$

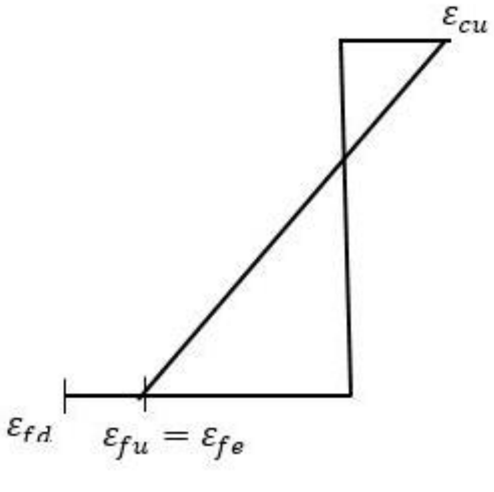

Figure 4-9: Strain distribution for FRP Rupture

4.7.1.3 Concrete Crushing

$$\varepsilon_{fe} < \varepsilon_{fd} \,\&\, \varepsilon_{fu}$$

In case if surface strength of concrete is very less, this case is mostly occurring when compressive strength of concrete is less than 2500psi.

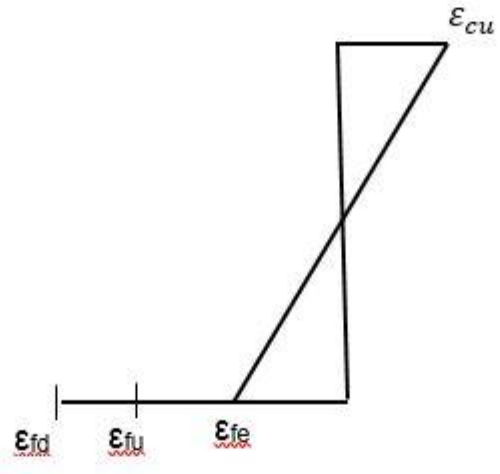

Figure 4-10: Strain distribution for concrete crushing

For debonding of FRP based design take $\varepsilon_{fu} = \varepsilon_{fe} = 0.0108$

$$f_{fe} = \varepsilon_{fe} E_f$$

$$f_{fe} = 0.0108 \times 33277366 = 359.395\, ksi$$

The moment arm for the fiber wrap is represented by the term jd, which is the distance from centroid of FRP to centroid of compression zone. jd is calculated using an iterative process. A value for the neutral axis of the strengthened section is assumed, the strain level is calculated in each material (concrete, steel, and FRP) using strain compatibility, and the internal force equilibrium is checked. If the forces do not equilibrate, this process is repeated.

Compression steel strain

Assume $c = \frac{d}{4} = 2.2''$

$$\varepsilon_s' = \varepsilon_{cu}\left(\frac{c-d'}{c}\right) = 0.003"\left(\frac{2.2"-1.67"}{2.2"}\right) = 0.0007$$

$f_s' = 29000ksi \times 0.0007 = 21ksi\ < 60ksi$ Compression steel is not yielding

Force in compression reinforcement;

$$C_s = A_s'(f_s' - 0.85f_c')$$

$$C_s = 0.4in^2\ (21ksi - 0.85 \times 2.5ksi) = 7.55kips$$

Compressive force in concrete;

$$C_c = 0.85f_c'b\beta_1 c$$

$$C_c = 0.85 \times 2.5ksi \times 7.5" \times 0.85 \times 2.2" = 29.8kips$$

Force in tension reinforcement;

$$T = A_s f_y$$

$$T = 0.6in^2 \times 60ksi = 36kips$$

Tension force in FRP wrap

$$T_f = A_f f_f$$

$$T_f = 0.0328 \times 359.395 = 11.788\ kips$$

Section equilibrium check;

$$C_s + C_c = 7.55 + 29.8 = 37.5\ kips$$

$$T_s + T_f = 36 + 11.788 = 47.788\ kips$$

Increase c value to equilibrate the section forces, use $c = 2.6$

$$C_s + C_c = 11.59 + 35.22 = 46.8\ kips \qquad ok$$

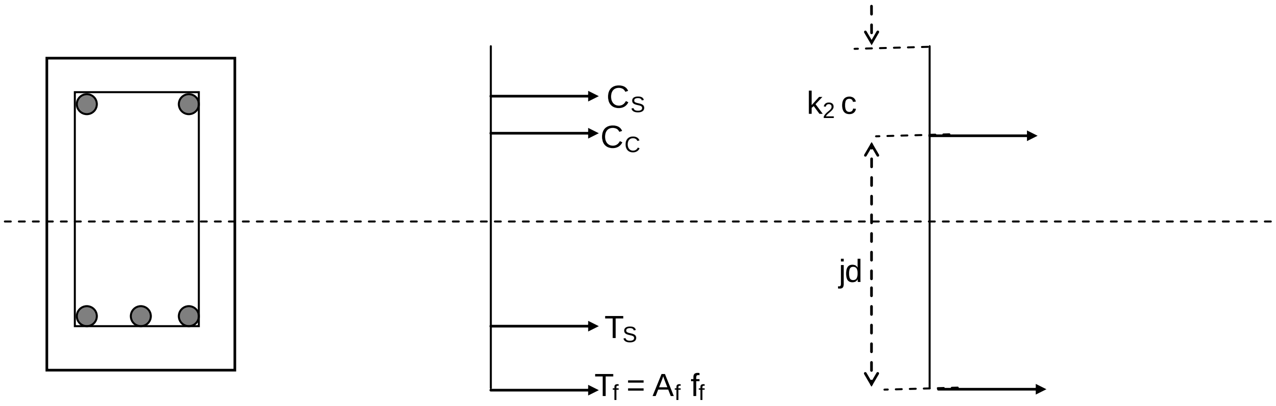

Figure 4-11: Section Forces

$$jd = 10.5'' - 0.375 \times 2.6 = 9.525''$$

$$M_f = A_f f_{fe}(jd)$$

$$M_f = 0.0328 \times 359.395 \times 9.525$$

$$M_f = 112.28\ kip - in = 9.35\ kip - ft$$

Total moment strength

$$M = 9.35 + 24 = 33.35\ kip - ft$$

For two points loading configuration given in figure maximum moment will be

$$M_{max} = Pa$$

$$P = \frac{M_{max}}{2.5'} = 13.34\ kips$$

$$2P = 26.68\ kips$$

Self weight of beam;

$$w = \frac{7.5'' \times 10.5'' \times 8.5' \times 144}{144} = 669\ lb$$

Maximum failure load

$$26.68 - 0.669 = 26.01\ kips$$

Therefore, increase in strength is 40.5 % by use of CFRP Jacketing

4.8 Experimental Setup

The aim of our project was to enhance the flexural capacity of beams and in order to know their flexural strength, specimens were tested under 4-point loading in accordance with ASTM C78-12, where the beam is simply supported at one third of clear span as depicted in figure 4-12. This configuration provides pure bending in the middle third of clear span with no shear force acting in the specified region.

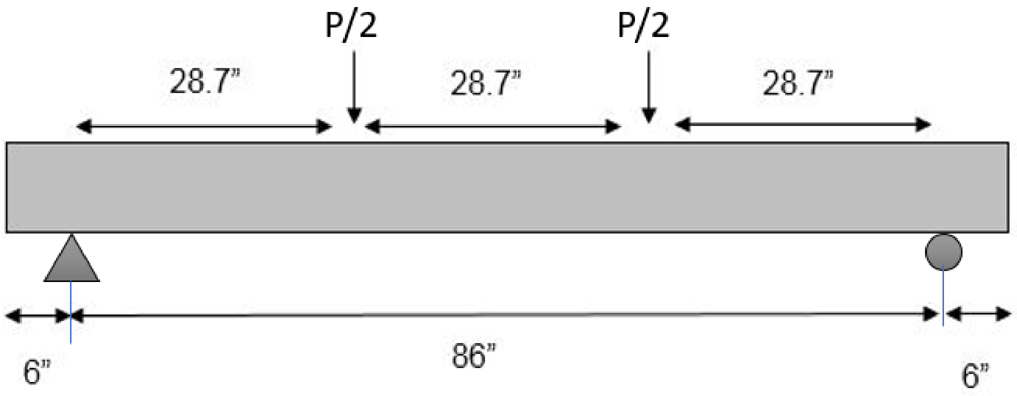

Figure 4-12: 4-Point loading configuration

Figure 4-13: Loading Configuration of Beams

4.9 Data Collection

Linear Variable Deflection Transducers (LVDT) were used to note the deflection at center and on the points of loading. LVDT's were connected to the load cell which provided deflection against the applied load at an interval of 0.5 sec.

Chapter 5

RESULTS AND CONCLUSIONS

5.1 General

This chapter reports the results from the experimental investigations including the relevant graphs. The results are divided into two types:

1. Load vs. Deflections
2. Moment vs. Curvature

Three beams with same geometric and material properties were tested. The control specimen, B-1, was loaded to failure. The development of cracks and their propagation on the beam were observed. To replicate the deterioration of structural members in the field loading conditions, the second and third specimens were loaded to about 65% of the ultimate capacity of B-1.

5.2 Load vs. Deflections

The first beam specimen, B-1, was loaded to failure. Cracks were marked as soon as appeared and propagated on the beam. The beam failed in flexure at its ultimate capacity. The behavior of beam at its failure is shown in the picture below.

Figure 5-1:Failure of B-1

The first beam specimen, B-1, showed a typical load vs deflection graph of a reinforced beam with a point of major reduction in stiffness at around 15 kips and ultimate point at 16.18 kips. The load vs. deflection graph for B-1 is given below.

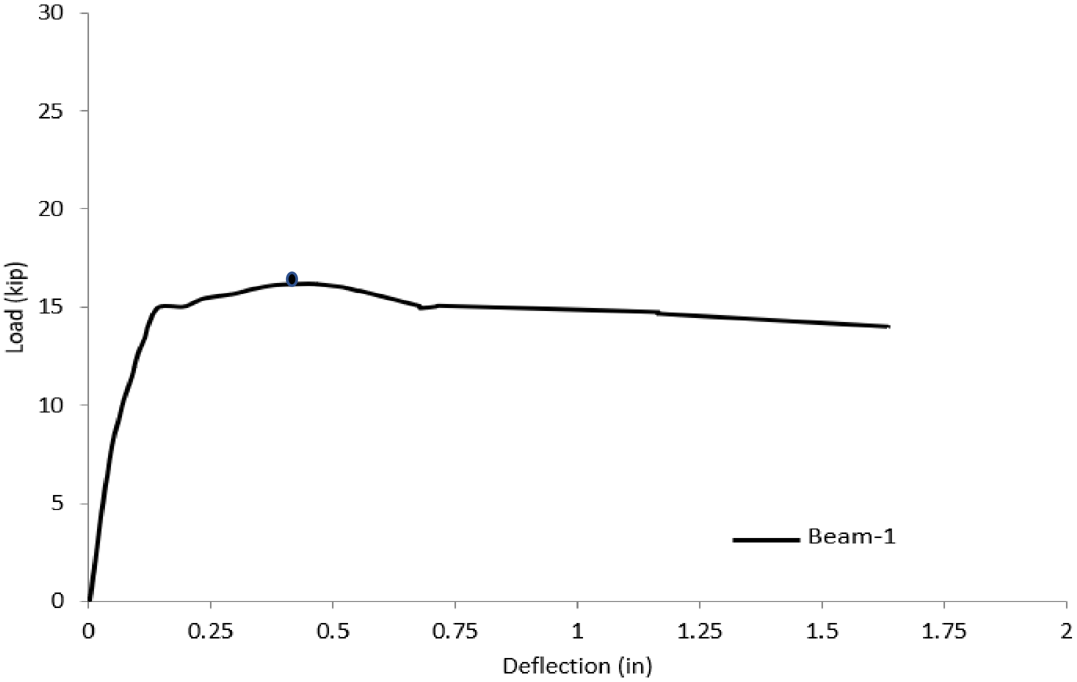

Figure 5-2: Load-deflection curve of B-1

B-2 was first loaded to about 65% of the ultimate load for B-1. The specimen was then unloaded, wrapped with CFRP over its full span of length in U-shape configuration and cured (for epoxy to dry) for 48 hours before testing.

The failure of beam occurred with delamination of CFRP Wraps from the side faces of the beam. The picture below shows the B-2 at its failure.

Figure 5-3: Failure of Fully jacketed beam specimen, B2

For B-2, yield point was observed at 21.16 kips and ultimate point at 27 kips.

The load vs. deflection curve for the B-2 is given below. The solid line labelled “Beam 2A” indicates behavior of specimen when loaded to about 65% of the ultimate moment capacity of B-1. The dashed line labelled “Beam 2B” refers to behavior of fully jacketed beam specimen when loaded to its ultimate capacity. The yield point was observed at 21.16 kips and ultimate point at 27 kips.

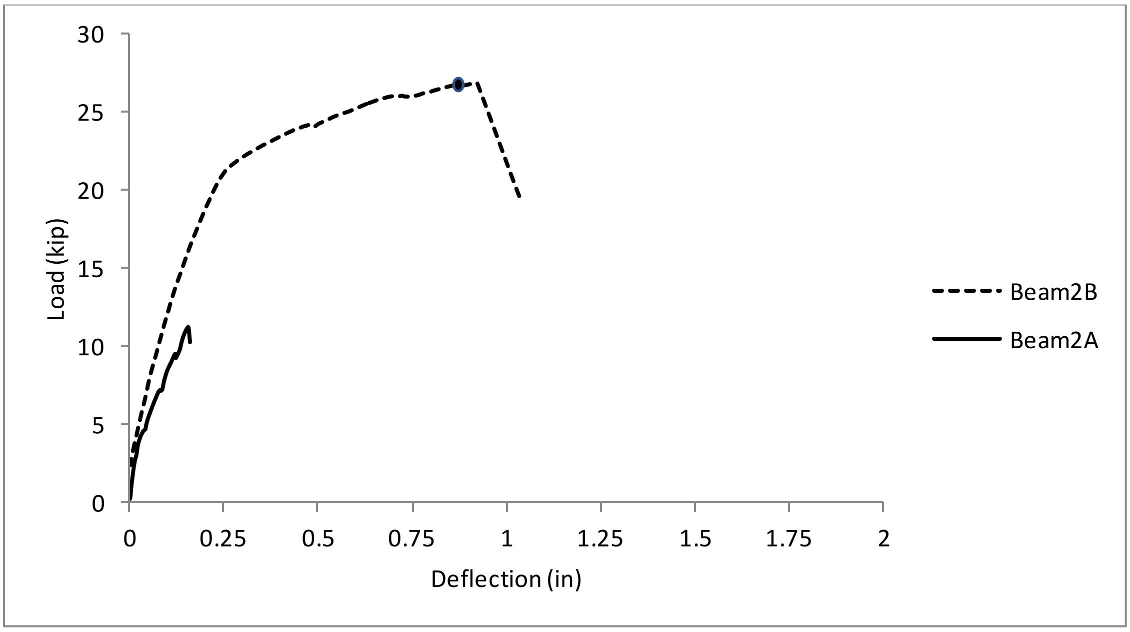

Figure 5-4: Load-deflection graph of B-2

B-3 was first loaded to about 65% of the ultimate load for B-1. The specimen was then unloaded, wrapped with CFRP in the middle third in U-shape configuration and cured for 48 hours before testing.

Failure of the tested specimen occurred with yielding of steel followed by delamination of CFRP wrap from the side faces. The picture below shows the condition of B-3 at its failure.

Figure 5-5: Failure of selectively jacketed specimen

The load vs. deflection curve for the B-3 is given below. The solid line labelled “Beam 3A” indicates behavior of specimen when preloaded to about 65% of the ultimate moment capacity of B-1. The broken solid line labelled “Beam 3B” refers to behavior of selectively jacketed beam specimen when loaded to its ultimate capacity. The yield point was observed at 22.5 kips and ultimate point at 25 kips.

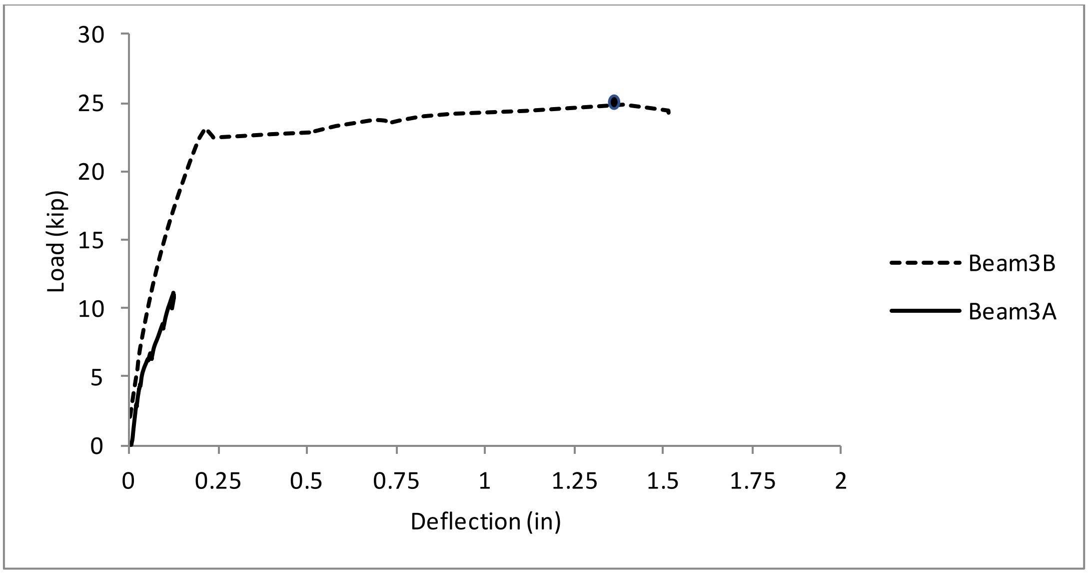

Figure 5-6: Load-deflection graph of B-3

5.3 Moment vs. Curvature

This section details the procedure for calculation moment–curvature curve. Each point is usually determined by selecting a specific value for the maximum compression strain at the extreme compression fiber of the section, "ε_c". From the assumption that plane sections before bending remain plane, the strain distribution through the depth of the section is linear.

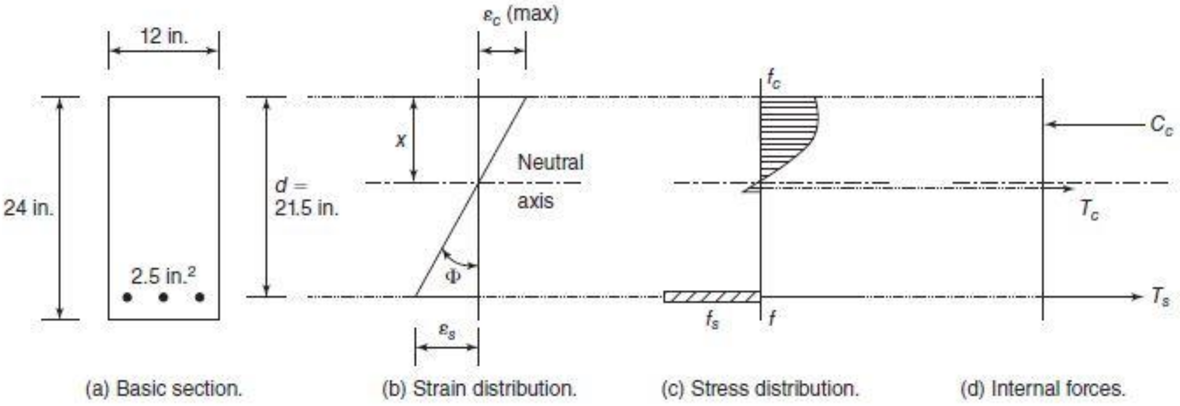

Figure 5-7: Strain & stress distribution on cross section

From the strain diagram and the assumed material stress–strain relationships, the distribution of stresses from distributed strain values in section can be determined by following formulas.

$$f = f_c' \left[1 - 0.15\left(\frac{\varepsilon - \varepsilon_o}{\varepsilon_o}\right)\right] \; for\,\varepsilon > \varepsilon_o$$

$$f = f_c' \left[2\left(\frac{\varepsilon}{\varepsilon_o}\right) - \left(\frac{\varepsilon}{\varepsilon_c}\right)^2\right] \; for\,\varepsilon \leq \varepsilon_o$$

The strain that corresponds to the peak compressive stress, “ε_o" , is often assumed to be 0.002 and "ε " represent the different values in beam section at top it will be equals to “ε_c" and reduce to zero to neutral axis.

Once the distribution of stresses is determined in beam section, which will be maximum at top and zero at neutral axis. Then by integration, the volume under the stress distributions represented in shaded region in figure, will give compressive force expression in x terms. Tension force expression in x terms in beam section can be determined by following formulas.

$$T = \varepsilon_s \times E_s \times A_s$$

$$T = \varepsilon_s \times 29000 \times 0.6$$

$$\frac{\varepsilon_c}{x} = \frac{\varepsilon_c + \varepsilon_s}{d}$$

$$\varepsilon_s = \frac{\varepsilon_c \times d}{x} - \varepsilon_c$$

Once these expressions are developed by equation them we can find out position of neutral axis (x-value). Then curvature can be determined by

$$\emptyset = \frac{\varepsilon_c}{x}$$

After the section forces are determined, the corresponding moment is determined by summing the moments of the internal forces about a convenient point—often selected to be the centroid of the tension reinforcement for singly reinforced beam sections. This process can be repeated for several values of maximum compression strain (Wight, 2016).

The moment-curvature graphs show the flexural rigidity of the beams. The moment-curvature graphs of all tested beam specimens are given below.

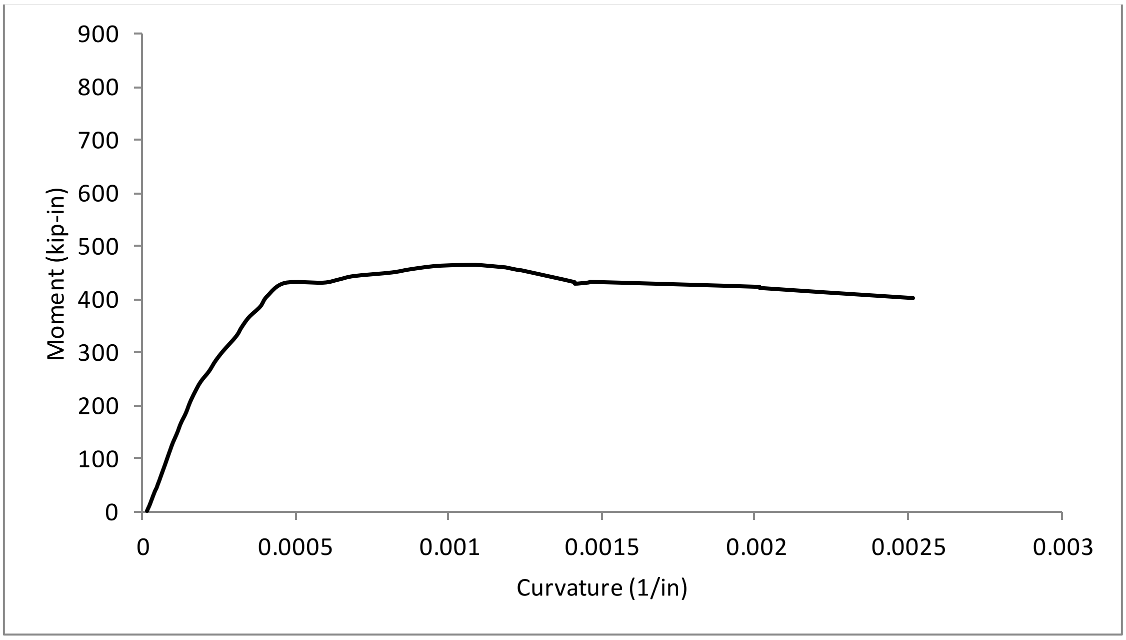

Figure 5-8: Moment-curvature graph of B-1

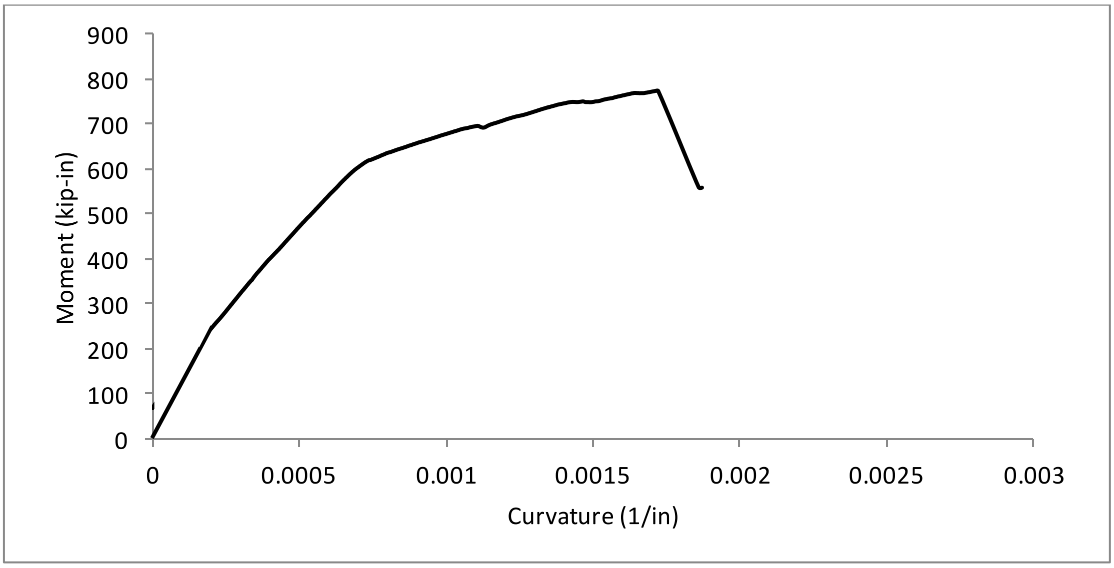

Figure 5-9: Moment-curvature graph of B-2

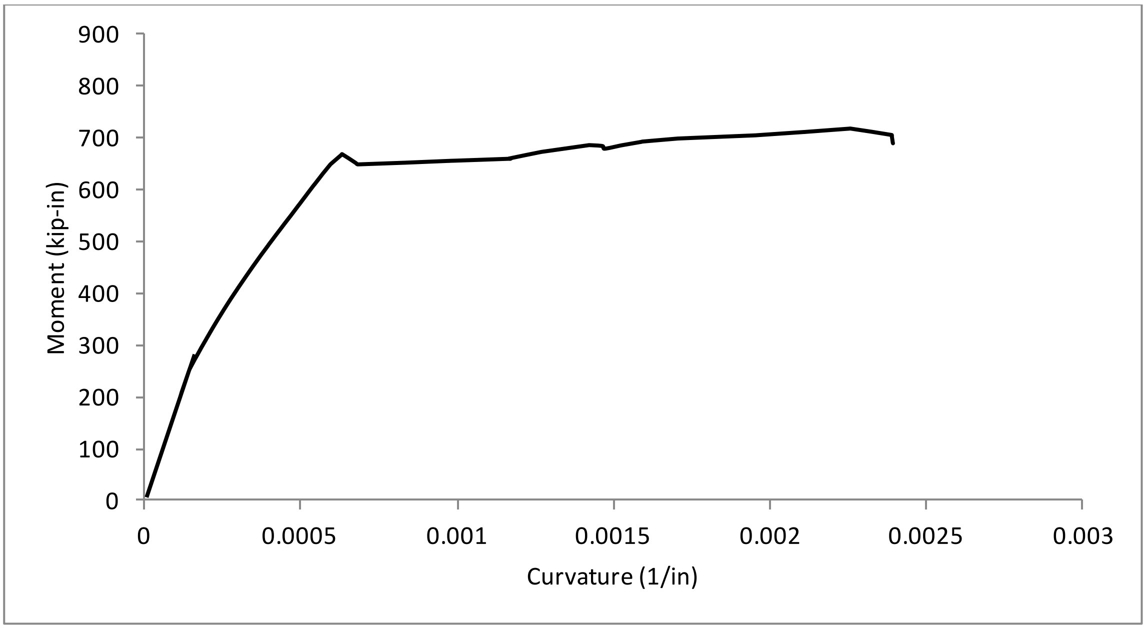

Figure 5-10: Moment-curvature graph of B-3

5.4 Analysis and Discussion

The graphs for tested specimens show that the CFRP-jacketing enhanced the strength and ductility of the beams. The CFRP-jacketing also increased the stiffness of the beams. The graphs dictate that selectively jacketed beam exhibited more ductility than fully wrapped. Apparently the reasons that can be attributed to this response are redistribution of stresses and yielding of reinforcement before concrete crushing in compression zone. However more tests are suggested to be conducted before this conclusion can be drawn. The strength of the selectively jacketed beam was comparable to fully jacketed beam.

A recent experimental investigation conducted in 2017 at NUST, Islamabad, reported 35% increase in load carrying capacity of a beam strengthened with CFRP wraps in its soffit. The control specimen failed at 14-kip load, whereas CFRP-jacketed specimen failed at 19-kip load (Hyder, 2017). In comparison, this study reports approximately 69% increase in load carrying capacity of the beam strengthened in the bottom and U-shape, and 56% increase in load carrying capacity of beam strengthened selectively with CFRP in the middle-third.

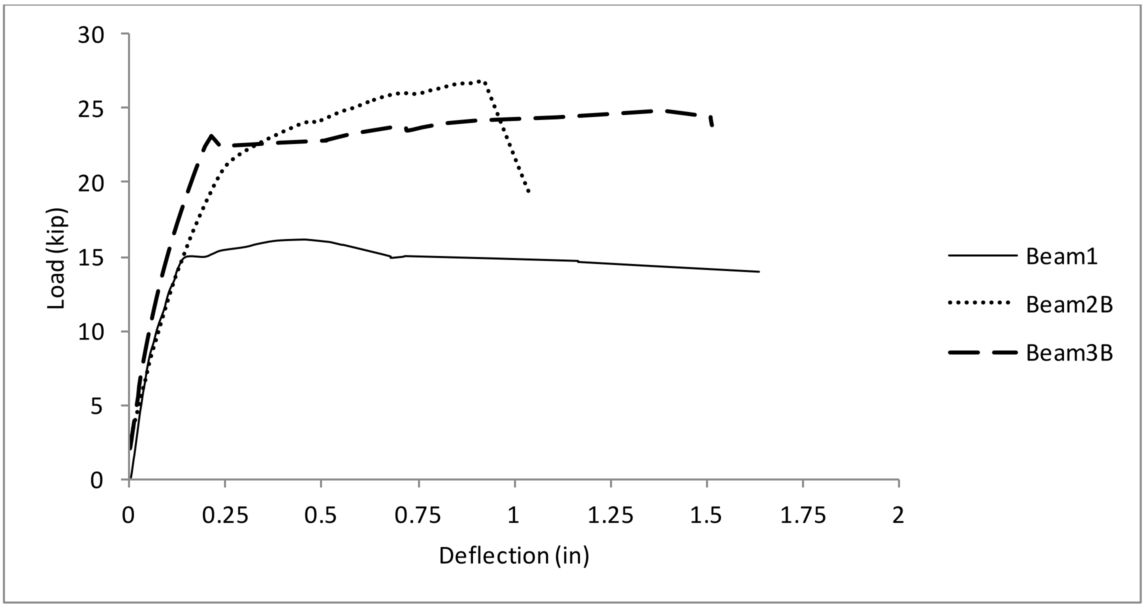

Figure 5-11: Load vs Deflection curve of all beams

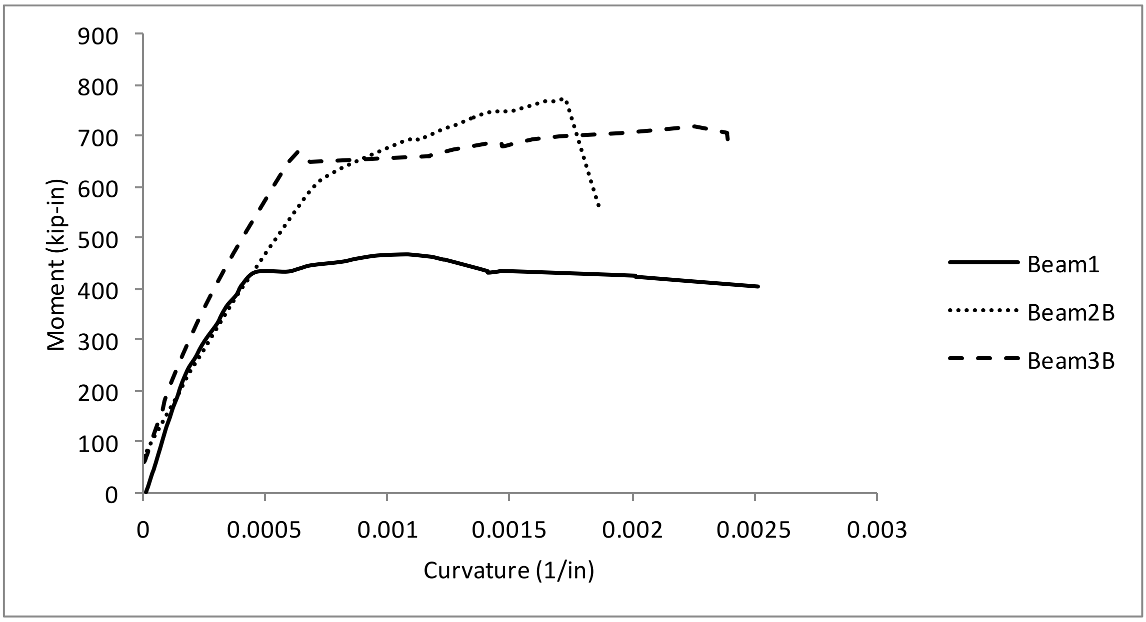

Figure 5-12: Moment vs curvature curve of all beams

5.5 Conclusions

The following conclusions are drawn after comparative analysis and discussion of the results of tested beam specimens.

a. CFRP-jacketing increased the load carrying capacity of the fully jacketed beam (already subjected to service load behavior), by approximately 69%.
b. CFRP-jacketing increased the load carrying capacity of the selectively jacketed beam (already subjected to service load behavior), by approximately 56%.
c. Selective jacketing of the beam with CFRP yielded almost same strength and stiffness as full jacketing.
d. CFRP-jacketing is not prevalent as a rehabilitation technique in the construction industry of Pakistan.

5.6 Recommendations

CFRP-Jacketing is structurally advisable technique for rehabilitation of existing structures. However, high initial cost of CFRP wraps and epoxy mitigate the long-term structural benefits of this rehabilitation technique. In addition, local contractors in the construction industry of Pakistan are not well-conversant with field implementation of CFRP-jacketing.

The conclusions of this study provide a way forward to bringing down the cost of CFRP-jacketing through its optimal usage. Furthermore, the conclusions necessitate an initiative of imparting confidence into engineers, consultants and contractor of construction industry of Pakistan on potential long-term structural benefits of CFRP-jacketing and available methods of installation.

5.7 Future Research Suggestions

This study focused on flexural response of normal strength RC beams and rehabilitation using CFRP jacketing. The future research may include following aspects.

a. Response of beams strengthened with CFRP under three-point load.
b. Shear strengthening of beams by CFRP.
c. Investigation of increase in axial load capacity of columns strengthened with CFRP.

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