RETROFITTING AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING FIBER REINFORCED POLYMERS

FINAL YEAR PROJECT UG 2013

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2017

This is to certify that the

Final Year Project titled

REPAIR AND RETROFITTING USING FIBER REINFORCED POLYMERS

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for the undergraduate degree

in

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ACKNOWLEDGEMENT

We would like to thank Dr. Syed Hasan Farooq our research advisor. His guidance and support helped us produce this research. During the course of this research project, he was a constant source of troubleshooting and support. He encouraged us to make this project our own work, while steering it in the right direction whenever possible. Also, we would like to thank our parents for providing us with unfailing love and support. It was the result of their encouragement and inspiration that this project was completed at all.

ABSTRACT

The possibility of natural deterioration exists in reinforced concrete structures which has created the need to investigate the extent of damage and instigate the reliable repairing and retrofitting techniques. Many reasons exist for this deterioration and the probable causes are ageing of the structure, inadequate maintenance, corrosion resulting from harsh weather conditions, outdated design practices or substandard construction and natural circumstances like earthquakes. Therefore, solutions need not only be effective, but also be economically and environmentally practical. Therefore, repairing of existing structures is an important issue to be addressed. FRPs (Fiber Reinforced Polymers) are emerging as a viable composite material in this regard. FRP is an elastic material, used mainly as wraps and strips in retrofitting of existing reinforced concrete structures. The research aims at the selection of viable FRP systems, their design and proper application techniques to retrofit reinforced concrete beams and to increase the flexural strength, achieved by retrofitting with FRP wraps as well as strips. The parameters of the study are:

- Comparison of changes in flexure behavior due application of FRP
- Comparison in flexure strengthening of both methods i.e. Wrap and Strips.
- The performance comparison between the retrofitting techniques.

Three beams are tested in flexure with a unique method of application of FRP. Results will be compared with each other as well as with a reference beam having the same design, casting and curing conditions. It is expected that retrofitting of beams will enhance their performance in flexure.

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Chapter 1

Introduction

1.1 Background

Since the invention of Reinforced Concrete in 1849 by Joseph Monier, due to its versatility, speed of construction, sustainability, availability of raw materials and its easiness to cast, it quickly became the first choice of building materials by the civil engineers of 19th century. Many reinforced concrete structures were built in the Era and many more in the following centuries up to the current date. The whole world, as well as our country Pakistan, has many ancient reinforced concrete structures. Reinforced concrete structures deteriorate due to a lot of factors. Ageing of the structure is the prime cause of a lot problems as with time and under the influence of environmental factors along with accidental forces the shortcomings in the structure during the design and construction phase start to appear gradually. As a result, cracks appear in the structure in the weak areas. These cracks are very dangerous as they propagate during the service life due to the application of repetitive loads on the structure. Thus, to improve their life cycle, retrofitting and repairing techniques are studied. Here specifically two methods (strips and wraps) are under focus, their retrofitting methods on beams and their mutual comparison along with other different types of retrofitting techniques to achieve improved structural behavior are studied.

1.2 Fiber Reinforced Polymer

FRPs are a polymer and fiber composite that is being used world-wide as

a) a substitute for steel reinforcement
b) a retrofitting material.

Traditionally steel reinforcement is used to resist the tensile forces in concrete structures as concrete in incapable of resisting tensile forces. However, FRPs are also used in contrast with other materials such as bolted steel jackets, as supplemental externally bonded reinforcement. These are most commonly available in the market as strips or sheets of the following two types:

- Sika Carbodur (S-812) strips
- Sika Wrap (230-C) sheets or fabrics

Fiber reinforced polymer systems are used to reinforce the deteriorated or damaged structural members by application of externally bonded FRP wraps and strips. This external reinforcement strengthens the structural member and increases its load bearing capacity for increased loads because of the changed purpose of the building and addressing the design/construction faults (ACI 440.2R-08). The success in the application of FRP composites has been linked to its higher ratio of strength to weight, ratio of stiffness to weight, weathering resistance, higher durability also its simpler field correction in case of installation defects of FRP with concrete substrate.

The main disadvantages of using fiber reinforced polymers are related to their epoxy resin as they are heat absorbents and have less resistance to fire. They are to be kept at a cool place away from direct sunlight. There is difficulty in application of epoxy at lower temperatures and on humid surfaces (D'Ambrisi and Focacci 2011). Another disadvantage of using epoxy resins as a bonding agent is that upon application of load on the structure epoxy behaves in a linearly elastic manner thus failing at large strains (brittle failure i.e. cracking of epoxy with no yielding point) (Nezamian, A., Setunge, S., & Lokuge, W. 2002).

Figure 1-1: FRP retrofitting of different structures

1.3 Applications and Use

There are numerous applications of FRP systems for retrofitting of reinforced concrete members. 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. Following paragraphs provide information on the applications and uses of both fiber reinforced polymer systems:

1.3.1 Strips

FRP strips are the most popular elements for FRP flexure strengthening in reinforced concrete elements. Strips are of specific width and are used in parallel with the reinforced concrete element, that is in the direction of the principle tensile stresses. Manual application method of FRP strips is commonly used using a wet lay process with cold cured adhesive bonding. FRP strips are mainly used on flat surfaces like the tension regions of a beam or that of a slab but the epoxy adhesive allows for a certain unevenness. The surfaces should be thoroughly cleaned before application to remove any loose particles or dust which prevent effective contact of epoxy with the concrete. An epoxy based, cold cured bonding agent attaches the FRP strips with the concrete portion of the reinforced concrete member.

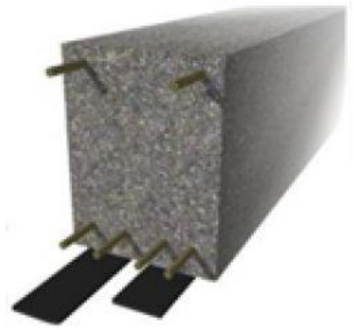

Figure 1-2: FRP strips on a beam

1.3.2 Wraps

FRP wraps are woven fibers in longitudinal as well as transverse direction and are also used for strengthening of reinforced concrete members. These are very flexible in use and are generally used where application of strips is impossible. Wraps or sheets are bonded and impregnated with low viscosity resin. Sheets are shaped and cured in-situ. A putty is applied on uneven surface to achieve evenness for effective application of FRP wrap and to avoid de-bonding of the wrap from the concrete surface.

Figure 1-3: FRP wrap on a column

1.4 Methodology

After studying similar research articles our project methodology was devised. We wanted to test the beams purely in flexure so we designed our specimens in such a way to induce flexural failure. D'Ambrisi and Focacci (2011) experimented on reinforced concrete beams that were retrofitted with FRP materials using four-point bending configuration. Our specimens were casted and cured in the same condition to ensure same geometrical and mechanical characteristics. These specimens were then retrofitted with different configuration of fiber reinforced polymer strips and wraps to conduct a comparative study among the different failure modes and FRP retrofitting techniques. The experimental results obtained were evaluated in terms of failure modes of the reference and retrofitted specimens, load-carrying capacity and difference of flexural capacity among the specimens.

1.5 Objectives

- Study the changes in flexure behavior of RC beams after strengthening by FRP.
- Comparison in flexure strengthening of both methods i.e. Wrap and Strips.
- The performance comparison between the retrofitting techniques.

Chapter 2

Literature Review

2.1 Introduction

Figure 2-1: Strengthening using steel plates

External reinforcement methods like bonded steel plates and concrete or steel jacketing have traditionally been used in the construction industry. Reinforced concrete members (i.e. beams etc.) that have been bonded with steel plates in the tension regions have exhibited an increase in load bearing capacity ultimately increasing the flexural capacity of reinforced concrete members. All over the world these traditional methods under discussion have been used to retrofit buildings, bridges and other weakened structures. However, these retrofitting methods are reported to have certain drawbacks including corrosion of steel plates, corrosion or weakening of the steel plate and concrete bond and other problems in application of these plates. Hence engineers have been searching for alternate methods of external reinforcement and found fiber reinforced polymers as a suitable material for this purpose.

Fiber reinforced polymers have widely been used across the world for improving the performance of structural elements. The behavior and characteristics of fiber reinforced polymers have extensively been investigated and catalogued. This resulted in the creation of different design codes for different countries like ACI 440.2R-08 and Canadian Code (CSA S806:2012) etc. Fiber reinforced polymers are lightweight, easily applicable and resistant to corrosion. However, some drawbacks concerning to its use are moderate heat and fire resistance of the epoxy resin used as a bonding agent, difficulty in use when applied over humid surfaces and lower rates of vapor transferability (D’Ambrisi and Focacci 2011).

2.2 Background of research in topic

Investigation into the usage of fiber reinforced polymers for externally reinforcing structures started as early as 1980. Under the initiative of National Science Foundation (NSF) and the Federal Highway Administration (FHWA) research was conducted on FRPs to check its feasibility as a retrofitting material. Earlier in 1978 the application of FRPs for reinforcement of concrete structures has been reported (Wolf and Miessler 1989). In the early 1980s, retrofitting concrete structures was in the same way investigated in Japan and many parts of Europe. In Switzerland, researchers successfully strengthened a reinforced concrete bridge using external application of FRPs to increase the flexural capacity of the bridge (Meier 1987, Rostasy 1987). In Japan, fiber reinforced polymers were for the first time used for wrapping a reinforced concrete member for achieving better confinement (Fardis and Khalili 1981, Katsumata et al. 1987).

2.3 Flexural Retrofitting of Beams

Additional studies on the behavior of FRPs in flexure is required and changes in the beam behavior due to retrofitting must be studied. Some which has been done by Triantafillou in 2006, who experimented on carbon-FRP retrofitted beams using four-point loading tests (Triantafillou and Papanicolau 2008). Triantafillou concluded that FRP strengthened beams had the ability to resist more flexural load. The productivity of FRPs in altering the response of RC beams in bending was also studied by D’Ambrisi and Focacci in 2011. They used carbon-FRP laminates on reinforced concrete beams which were then experimented using a four-point loading configuration.

Flexural strengthening can only be achieved in reinforced concrete beams if the FRPs are applied/ glued with the tension region of the beams such that the fibers of the polymers are in the direction of the principle tensile stresses generated upon the application of loads. FRPs have proved to provide additional stiffness to the beam and increase in load capacity with decreasing amount of cracking (Lacasse et al. 2001). This added stiffness in the beam leads to the reduction of the deflection in the retrofitted beam in comparison with the non-retrofitted beam (David et al. 1998). The stiffness of the beam further increases upon the application of numerous layers of FRPs. Ultimate load and load carrying capacity increases with adding additional layers of FRPs. This increased strength behavior was depicted upon the application of up to six layers by Shehata et al. 2001, Shahaway et al. 1996 and Toutanji et al. 2006.

2.4 Failure Modes in Retrofitted Beams

In the literature, we can categorize the failures in retrofitted beams in three main categories observed upon experimentation (Smith at al. 2002, Ashour et al. 2004, Esfahani et al. 2007, Garden at al. 1998). These include:

- FRP rupture
- Concrete failure
- Loss of bonding action (de-bonding of FRP)

Detailed discussion of all these failure modes is done in Obaidat Yasmeen's book "Structural Retrofitting of Concrete Beams using FRP - Debonding Issues" published in 2011. However here we will briefly discuss all these failure modes.
In the first and second failure type, the bonding action between the concrete and FRP is uncompromised. Mostly in the first type of failure, steel reinforcement yielding occurs after which the rupture of FRP takes place as shown in figure 2-2. This type of failure is more common FRP wraps as compared to strips. The reason of this behavior is the increased contact area between the fiber reinforced polymer and concrete of the member in the use of wrap-FRP.

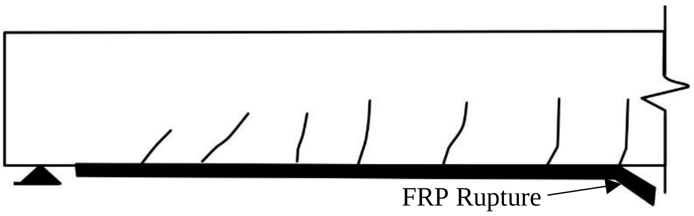

Figure 2-2: Rupture of FRP

In the second type, concrete failure occurs. This can be the crushing of concrete with or without yielding of steel but de-bonding of FRP from the member doesn't occur as shown in figure 2-3 or due to the generation of shear cracks from the ends of the FRP strip inclined to longitudinal axis of the beam as shown in figure 2-4.

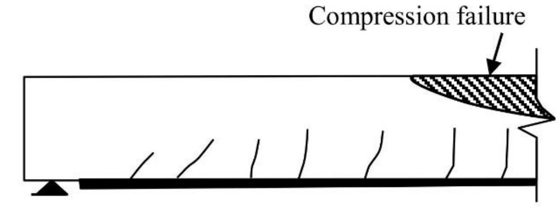

Figure 2-3: Compression failure

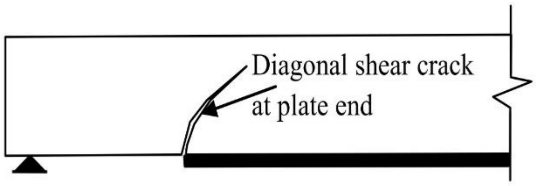

Figure 2-4: Shear failure mode

In the third type, de-bonding of FRP occurs which is the most common failure type. De-bonding failures can occur is several ways. Removal of the whole FRP strip can occur when the FRP no longer contributes to the strength of the member, due to stresses generated in the zone between the FRP and the member as shown in figure 2-5 or by de-bonding of FRP along with the cover as shown in figure 2-6. Also, by the generation of flexure or flexural-shear cracks and its propagation towards the end of the member de-bonding failure occurs. These cracks become horizontal at the bottom of the beam and remove the strip from the bottom as shown in figure 2-7 and 2-8.

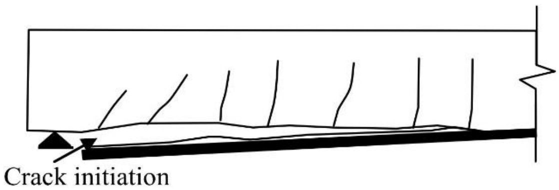

Figure 2-5: FRP strip de-bonding

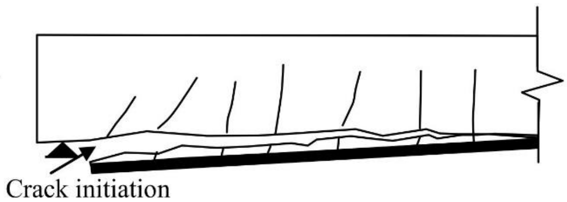

Figure 2-6: Concrete cover removal

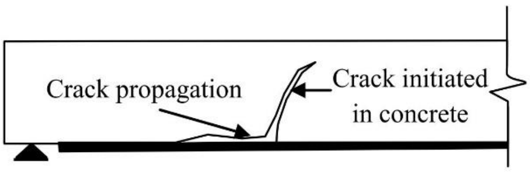

Figure 2-7: De-bonding due to flexural shear crack

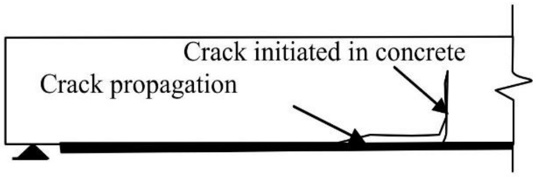

Figure 2-8: De-bonding due to flexural crack

2.5 Scope and Limitations

The scope of this study is based on the utilization of fiber reinforced polymers in retrofitting reinforced concrete beams and selecting the appropriate FRP system after comparison among them on different parameters. Before using fiber reinforced polymers, they should be first tested experimentally on reinforced concrete members and the difference between strength, ductility and other parameters must be investigated. According to ACI 440.2R-08 the condition of a structure must first be analyzed and then best FRP retrofitting system based on its application technique is selected according to the previously conducted assessment.

There are certain limitations concerning these composite materials being used for retrofitting the structures. Upon application of load in tension they act in a linear elastic manner. They don’t show much ductility and rupture on bigger values of strain while no yielding in the fibers of the composite material in experienced. This reduced ductile behavior of composite materials differ completely from the behavior of conventionally used steel reinforcement in the structures with exhibit elastic as well as plastic behavior. Furthermore, the cost of composites per unit weight or length is several times higher than that of steel. Nevertheless, upon the comparison of strength we find composite materials taking the lead over our conventionally used steel reinforcement.

Chapter 3

Material Properties

3.1 General

In this chapter, we will discuss the materials required for our project. We focused on using the most common materials easily available in the construction industry of Pakistan. There are two main highlights of this chapter one is the procurement of materials and the other is testing of those procured materials to determine their properties. The difference of our project from other researches done on this topic before is that we have performed this study for the construction industry of Pakistan by using conventional materials, whether they conform with the international standards or not. The main advantage of doing this is to investigate the retrofitting techniques that are most suitable to the construction in Pakistan.

3.2 Project Methodology

Our project methodology consisted of the following steps:

- Selection of materials
- Procurement of materials
- Testing of materials
- Casting of RC beams
- Strengthening of beams using FRPs
- Testing of beams
- Compilation of results

3.3 Procurement of Materials

Two types of materials were used in the project as mentioned:

1. Materials for beam casting
2. Materials for retrofitting

We selected locally available materials for casting of our beams as we wanted to conduct this study for the construction industry of Pakistan. We used Margalla crush, Lawrencepur sand and Bestway cement for casting our beams. Grade 40 steel being conventionally used in Pakistan was used as reinforcement.

For retrofitting, Sika products were used that are being already used in Pakistan. SikaWrap was used for wrap-FRP and Sika Carbodur was used as strip-FRP. Individual properties of the materials would be discussed below.

3.4 Aggregates

3.4.1 Aggregate Testing

Following tests were conducted to determine the properties of aggregates:

- Specific Gravity of Coarse and Fine Aggregate
- Absorption Capacity of Coarse and Fine Aggregate
- Crushing Value of Coarse Aggregate
- Fineness Modulus of Fine Aggregate
- Gradation Curves of Coarse and Fine Aggregate

3.4.2 Aggregate Properties

#	Properties of Aggregate	Standard	Coarse Aggregate	Fine Aggregate
1	Fineness Modulus	ASTM C136	-	2.2
2	Bulk specific gravity (oven dried)	ASTM C127	2.53	2.54
3	Bulk specific gravity (SSD)	ASTM C127	2.56	2.58
4	Absorption Capacity	ASTM C127	1.02%	1.6%
5	Crushing Value	BS 882/ 812	19.4 (%)	-

Table 3-1: Properties of Aggregates

3.5 Concrete

3.5.1 Mix Design

Concrete Mix Design was selected according to the most conventionally used concrete in Pakistan. The following properties of concrete were predetermined. Additional tests were then conducted on this concrete to find its additional properties.

#	Material	Value
1	Concrete Mix Design	1:2:4
2	Water Cement Ratio (w/c)	0.5

Table 3-2: Concrete Properties

The mix design and water cement ratio was the same for each sample beam to achieve similar properties in each sample. As this is a comparative study so homogeneity in the samples in very important to conduct a fair assessment of the strength differences among the retrofitted and un retrofitted samples.

3.5.2 Concrete Testing

Following tests were conducted to determine the properties of concrete:

- Compressive Strength Test – ASTM C39
- Slump Test – ASTM C143

3.5.3 Concrete Properties

The compressive strength of concrete at 7, 14 and 28 days is mentioned below.

#	Days	Compressive Strength
1	7	2094 psi
2	14	2900 psi
3	28	3190 psi

Table 3-3: Compressive Strength values for concrete

Slump test was conducted and the results are shown below.

#	Properties of Mix	Value
1	Slump	3-4”
2	w/c	0.5
3	Mix Design	1:2:4

Table 3-4: Concrete Mix Design

3.6 Steel

3.6.1 Steel Testing

Steel bars were tested for tensile strength using Universal Testing Machine according to the ASTM E8.

3.6.1 Steel Properties

Deformed bars were used which were procured from a local supplier in Islamabad.

#	Material	Value
1	Steel	Grade 40

Table 3-5: Properties of Steel

3.7 Fiber Reinforced Polymers

Two types of FRP materials were used in our project as discussed above i.e. Wraps and Strips along with their prescribed epoxies procured from Sika Pakistan. The properties mentioned below were provided from the supplier/ manufacturer.

3.7.1 FRP Wrap Properties

Figure 3-1: SikaWrap - fabric based FRP

SikaWrap - 230C was used as the wrap material. It is a carbon-FRP with carbon fibers woven unidirectionally like a fabric. Dry application process was used for application of SikaWrap with the concrete beams which used an epoxy SikaDur 330 as an impregnating resin/ adhesive. The mechanical properties of SikaWrap provided by the manufacturer are shown below.

Characteristics	Unit	Dry fiber properties
Tensile Strength	MPa(N/mm^2)	4300
Modulus of Elasticity	GPa	238
Fiber Density	g/cm^3	1.76
Weight per Area	g/m^2	230

Table 3-6: Mechanical properties of SikaWrap – 230C

In SikaWrap, fibers are woven in both directions and their individual fiber materials are discussed below

Direction of Fabric	Material
Warp (Longitudinal)	Black Carbon Fibers
Weft (Transverse)	White thermoplastic heat set fiber

Table 3-7: Fabric classification of SikaWrap – 230C

Properties of the epoxy SikaDur – 330 are mentioned below (manufacturer provided).

Characteristic	Units	Property
Chemical Base	-	Epoxy resin
Tensile Strength	N/mm^2	30
Bond Strength	N/mm^2	>4
Elastic Modulus	N/mm^2	Flexure 3800

Table 3-8: Properties of SikaDur – 330

3.7.2 FRP Strip Properties

SikaCarbodur – S812 was used as the strip material. It is also a C-FRP system for intensive strengthening of reinforced concrete structures. Dry application process was used for application of SikaCarbodur with the concrete beams which used an epoxy SikaDur - 30. The mechanical properties of SikaCarbodur provided by the manufacturer are shown in the table below.

Figure 3-2: SikaCarbodur - strip based FRP

Characteristics	Unit	Dry Properties
Tensile Strength	MPa(N/mm^2)	2800
Tensile Modulus of Elasticity	GPa	165
Fiber Density	g/cm^3	1.76
Weight per Area	g/m^2	230

Table 3-9: Mechanical properties of SikaCarbodur – S812

Sikadur – 30 is a two-component bonding agent conforming to the specifications of ASTM C881 and AASHTO M235 as indicated by the manufacturer. Properties of Sikadur – 30 are discussed below.

Characteristics	Unit	Dry Properties
Tensile Strength	MPA(N/mm^2)	24.8
Tensile Modulus of Elasticity	GPa	4.482
Bond Strength	MPa	22 (2 days dry cure)
Consistency	-	Non-sag paste

Table 3-10: Properties of Sikadur – 30

Chapter 4

Project Methodology

4.1 General

In this chapter, we will discuss comprehensively the project experimentation methodology we adopted along with the testing done and generation of final results. Our project was carried out in three main steps that are procurement of materials and testing, casting of specimen for retrofitting and testing of the control and retrofitted specimens. We used beams as our primary area of focus and conducted flexural testing on it. Our study was based on the optimization of these beams for higher loads and increased flexural capacity. This chapter takes us through all the steps involved in achieving our previously discussed objectives to strengthen and retrofit RC beams by the application of fiber reinforced polymers.

4.2 Quantity of Materials

4.2.1 Material Calculation

Number of sample beams: 4

Height of sample beams: 10 in.
Width of sample beam: 8 in.
Length of sample beam: 8 ft.

Volume of sample beam: 4.44 feet cube
Total volume: 18 feet cube (0.509 cubic meter)

W/C ratio = 0.5
Concrete mix = 1:2:4

4.2.2 Material Quantities

Material	Type	Required amount	Wastage	Total amount
Cement (Kg)	Bestway OPC	192	5%	202 kg
Fine Aggregate (Kg)	Lawrencepur sand	384	10%	422.4 kg
Coarse Aggregate (Kg)	Margalla Crush <0.5” (well graded)	768	20%	921.6 kg
Strips (ft.)	SikaCarbodur S812	15	-	15 ft
Wrap (ft.)	SikaWrap 230C	8	-	8 ft
Steel #4 bars (Kg)	40 ksi	45	5%	47.25 kg
Steel #3 bars (Kg)	40 ksi	26	5%	27.3kg

Table 4-1: Quantities of Materials

4.3 Sample Beams

4.3.1 Molds

Four large scale beam molds were available in NICE structure lab. The cross-sectional dimensions of molds were 8”x10” with 8 ft. length. Molds were cleaned and oiled before the preparation of RC beams in them.

4.3.2 Sample Preparation

Four large scale beams with same geometry and rebar placement were prepared for testing. There were two #4 bars as flexural reinforcement and two #4 bars as compression reinforcement. All bars were extended to the full length of beam. To ensure failure in flexure, shear reinforcement was provided as #3 bars at 7” center-to-center. A batching unit was set up in the lab and molds were then casted. Materials for each beam were separated and mixed in a controlled environment. All beams were cast in the same conditions to ensure maximum similarity for comparative study of the samples. The cross-section and longitudinal-section of beams are shown below.

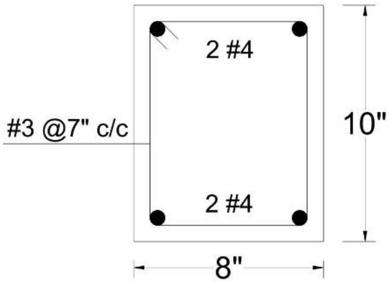

Figure 4-1: Cross-section of the beam

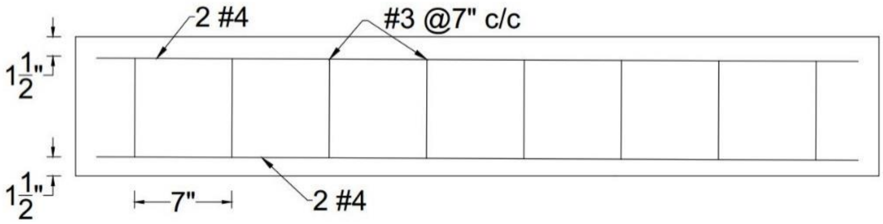

Figure 4-2: Longitudinal-section of the beam

Similar concrete batching, casting and curing condition were ensured. Type-B concrete was prepared having a strength of 3000 psi after 28 days with an acceptable slump of 4-5 in slump. After casting, all the beams were identical in their dimensions. Beams were cured using moist jute bags even after removal from the molds in 7-10 days of casting. After sufficient curing, the beams were left to dry to get them ready for retrofitting. Out of a total of four beams, one was used as a reference sample and the other three were strengthened using different FRP combination.

Figure 4-3: Casting of sample beams

Figure 4-4: Curing of sample beams

4.3.3 Beam Nomenclature

A description of each beam is given below.

Beam no.	Nomenclature	Description
1	VS-I	Reinforced concrete beam with no FRP reinforcement
2	STRIP-I	Control beam with 1 FRP strip reinforcement in the bottom
3	STRIP-II	Control beam with 2 FRP strips reinforcement in the bottom
4	WRAP	Control beam with FRP sheet as reinforcement at the bottom

Table 4-2: Beam nomenclature and description

All the beams (reference and retrofitted) are shown the figure below.

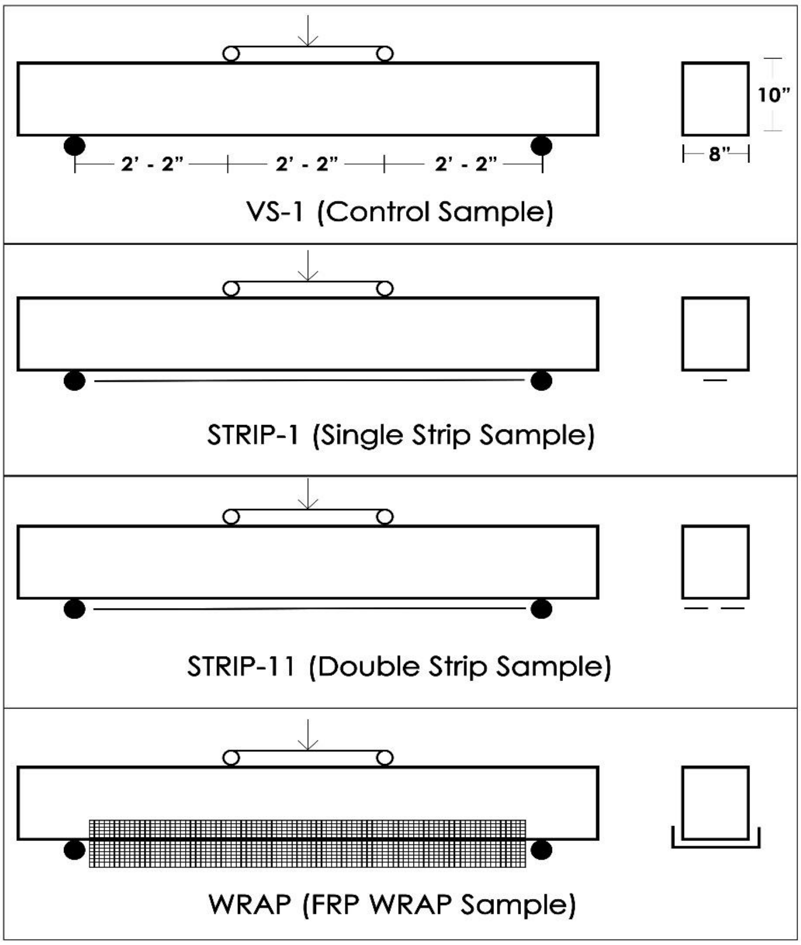

Figure 4-5: Beam sections after retrofitting

4.4 FRP Application Process

FRP application process is very simple. First, the FRP sheet or strip is cut according to the beams retrofit design specification. Avoid any folding or creasing of FRP while applying it. If FRP is to be overlapped at some location make sure the overlapping direction is parallel to the direction of the fibers. Don’t pull or apply excessive force on the fibers while application. Keep in mind while overlapping the FRP sheets, overlapping length must not be less than 10 cm instead if any other overlapping length is provided in the design. 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 FRP strip of sheet and on the application region of the beam. Make sure to remove all dust particles from the FRP and the beam before application of epoxy. After that apply the 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.

Figure 4-6: FRP double strip application

Figure 4-7: FRP wrap application

4.4.1 Dry application process

Dry application method of FRP is more common is woven fabric type FRPs. Its name “dry”, represents the dry state of FRP during its application. In this process, the epoxy is used both as a primary layer over the applied region of the member and the impregnating resin for the FRP sheet. SikaDur – 330 is the best example for this type of application process. There is a weight restriction for the dry application technique that is it’s more appropriate for woven fabrics with a weight of up to 430 g per a unit m^2 of area as stated by the manufacturer (Sika). We used dry application process for our project.

4.4.2 Wet Application process

Another type of FRP application process which requires the epoxy to be fully saturated in the FRP sheet as well as over the concrete member. Epoxy is applied over the concrete area after cleaning it and then left for absorption. Fabric is also saturated thoroughly with epoxy using a roller and the amount of saturation is determined by taking its weight before and after application. This wet FRP sheet is then attached over the concrete member is the specified direction and rolled over with a plastic roller to remove any air pockets entrapped between the attached surfaces.

4.5 Experimental Setup

Beams were loaded in a similar fashion which is according to the ASTM C78 (third point loading test). Beams are loaded along the direction of gravity on two points equally spaced from each support as well as each other. To depict a simply supported condition our supports were not restrained against moment about any direction as well as no fixity was present in the supports. The only force contributing to the fixity of the beams were the frictional force generated by the normal forces on the beams. Therefore, our beams loading setup could be assumed as simply supported.

All the beams were spanned at 6.5ft (1.98 m) with loading points at L/3 from each support as shown in the figure below.

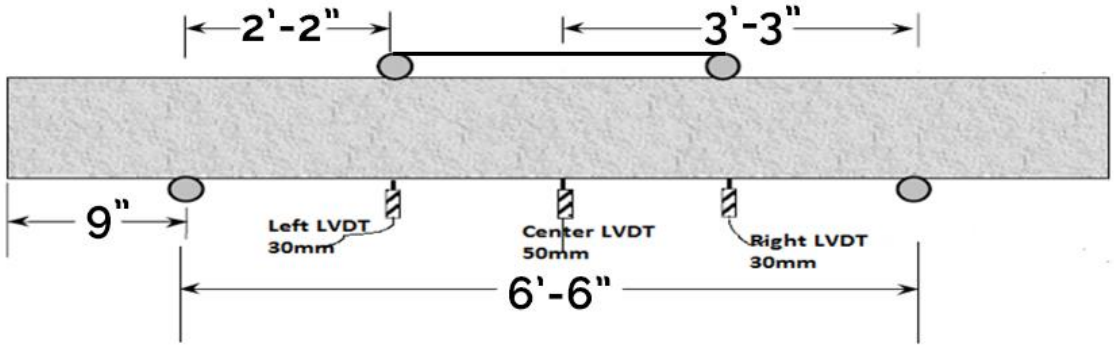

Figure 4-8: Testing configuration of the beams

Rollers were placed as supports and as well as loading points to ensure single point loading over the beams. Hydraulic press with a capacity of 100 tones was used for loading of beams. Loading was applied manually under prespecified increments to have better control over the results. Data collection was done automatically from the software linked to the loading apparatus. The actual loading configuration is shown in the figure 4-10.

Figure 4.9: 100-ton hydraulic press

Figure 4-10: Loading configuration of the beams

4.6 Data Collection

The data collected from our experiments was mainly the deflections at three points. One point was at mid-span and the other two were below the loading points as indicated by ASTM C78. These deflections were determined using Linear Variable Displacement Transducers (LVDTs) installed below the beams at the mentioned locations. The data acquisition software LAB-VIEW as connected with the load cells as well as the LVDT's which provided the deflection values against each load on the computer. As mentioned before we used manual loading for our project so the data collection was done manually at different load increments and this data was then organized and used to derive all results.

Chapter 5

Results

5.1 General

In this chapter, results of our experiment are discussed comprehensively along with the supporting graphs and tables. The data presented in this chapter is divided into three types:

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

All the retrofitted specimens were then compared with the reference specimen to conclude if retrofitting is beneficial and up to what extent. The most feasible retrofitting technique was then selected considering all the altered properties of the beams after retrofitting.

5.2 Load vs. Failure

Beams were loaded up to their ultimate load carrying condition as then till failure in the beams occurred. Cracks were highlighted as they started to occur and propagated on the beams. Now the load and failure condition of each beam will be discussed separately.

5.2.1 Reference Specimen

The ultimate load for reference specimen VS-1 was 62 kN, the failure occurred in a typical flexure fashion as the beam failed at mid-span with multiple cracks. The complete behavior of the beam till its failure along with pictures are shown below.

Load (kN)	Deflection (mm)	Remarks
45	8.9	First Crack
50	14.5	Multiple Cracks
58	25.7	Crack elongated
62	35.1	Failure

Table 5-1: Reference specimen load response summary

Figure 5-1: Reference specimen failure

5.2.2 FRP Wrap Specimen

Wrap sample failed at an ultimate load of 85 kN. The reason for failure was rupture of CRFP sheet along with yielding of the steel reinforcement combined. This beam showed somewhat similar behavior as compared to VS-1. The complete behavior of the beam before failure along with its pictures are shown below.

Load (kN)	Deflection (mm)	Remarks
45	5.79	Crack in epoxy
60	7.74	First Crack
75	14.2	Flexure Cracks
85	23	Rupture of FRP

Table 5-2: FRP wrap specimen load response summary

Figure 5-2: FRP wrap specimen failure

5.2.3 FRP Single Strip Specimen

For Single strip sample epoxy failure occurred as the CFRP strip de-bonded at an ultimate load of 73kN. The complete behavior of the beam before failure along with its pictures are shown below.

Load (kN)	Deflection (mm)	Remarks
60	6.5	First Crack
76	10.6	Epoxy De-bonded

Table 5-3: FRP single strip specimen load response summary

Figure 5-3: FRP single strip specimen failure

5.2.4 FRP Double Strip Specimen

The Double strip sample failed in shear as the beam was sufficiently reinforced in flexure with shear cracks appearing at the end of CFRP strips and propagating at almost 45-degree angle. This type of failure is known as shear delamination of the concrete cover.

Load (kN)	**Deflection (mm)**	**Remarks**
75	4.38	First Crack
90	5.87	Shear delamination
93	7.93	Crack Widens

Table 5-4: FRP double strip specimen load response

Figure 5-4: FRP double strip specimen failure

5.3 Strength and Deflection Comparison

Beams were loaded up to their ultimate load and further till their failures. A comparison is made on the strength and deflection exhibited by the specimens shown in table 17. Keeping VS-1 as reference all the strength and deflection changes obtained are shown in percentages.

Sample	Ultimate Load (kN)	% Strength Increase	% Deflection Decreased	Failure Type
Reference	62	-	-	Beam, Flexure
Wrap	85	37	35	Fibre, Rupture
Single Strip	73	18	70	Epoxy, De-bonding
Double Strip	93	50	79	Beam, Shear

Table 5-5: Strength and deflection comparison

As shown by the results, application of FRP significantly increases the strength of RC beams. This is mainly due to the difference in material of the FRP and the beam. As the stronger FRP stiffens the beam against external loading, the epoxy interface of the FRP needs to be properly applied so that transfer of forces is manageable. The load and ductility comparisons are shown in the graphs in figures 5-5 and 5-6 respectively.

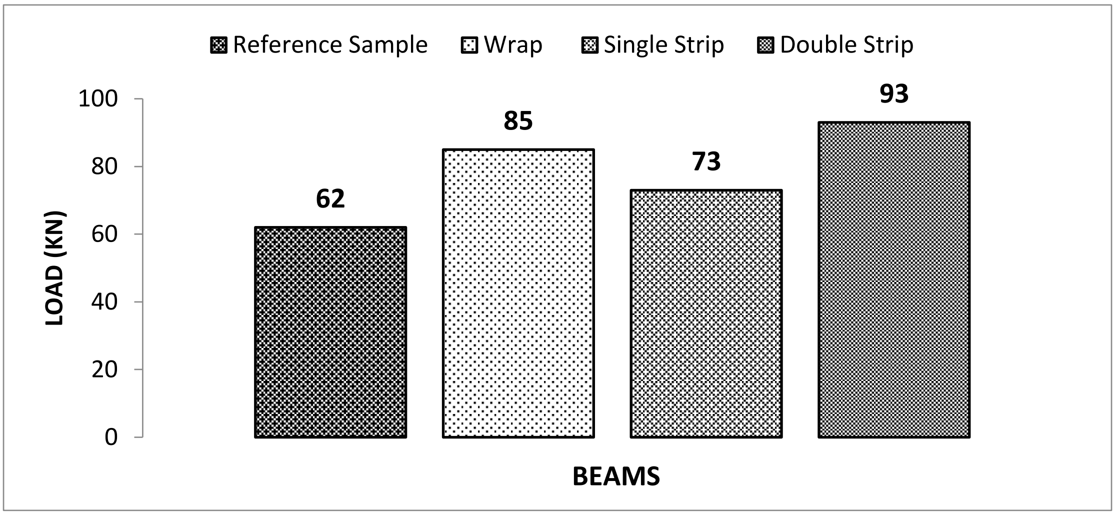

Figure 5-5: Ultimate load comparison of the specimens

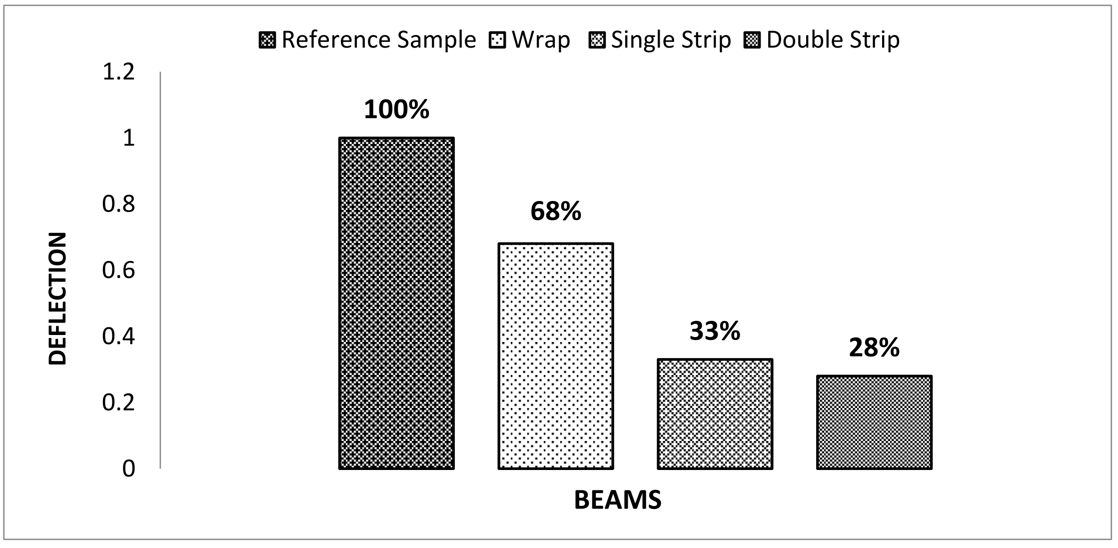

Figure 5-6: Ductility comparison of the specimens

5.4 Load vs. Deflection

5.4.1 Reference Specimen

The reference sample showed a typical load vs deflection graph of a reinforced beam with a yielding point at 45 kN and ultimate point at 62 kN.

5.4.2 FRP Wrap Specimen

The wrap specimen showed a similar behavior to the reference sample but the failure was slightly brittle than the reference sample. Yield point was observed at 60 kN and ultimate point was at 85 kN.

5.4.3 FRP Single Strip Specimen

The single strip specimen showed a visible brittle behavior as compared to reference and wrap sample. The yielding point was at 55 kN and ultimate point was at 73 kN.

5.4.4 FRP Double Strip Specimen

The double strip showed the most brittle behavior among all the samples. Before failure there was very little warning as yielding and failure points were at 90 kN and 93 kN respectively.

The deflections shown by the retrofitted beams are significantly less than the reference beam. At the point of failure, the reduction in deflection is of the range of 30% to 75%. Load vs. Deflection data tables and graphs of all specimen at center, left and right LVDTs are shown below

Sample	Right LVDT (mm)	Center LVDT (mm)	Left LVDT (mm)
Reference	26.3	35.1	43.6
Single Strip	5.89	10.6	5.92
Double Strip	7.71	7.53	7.02
Wrap	21	23	27.2

Table 5-6: Deflection at each LVDT

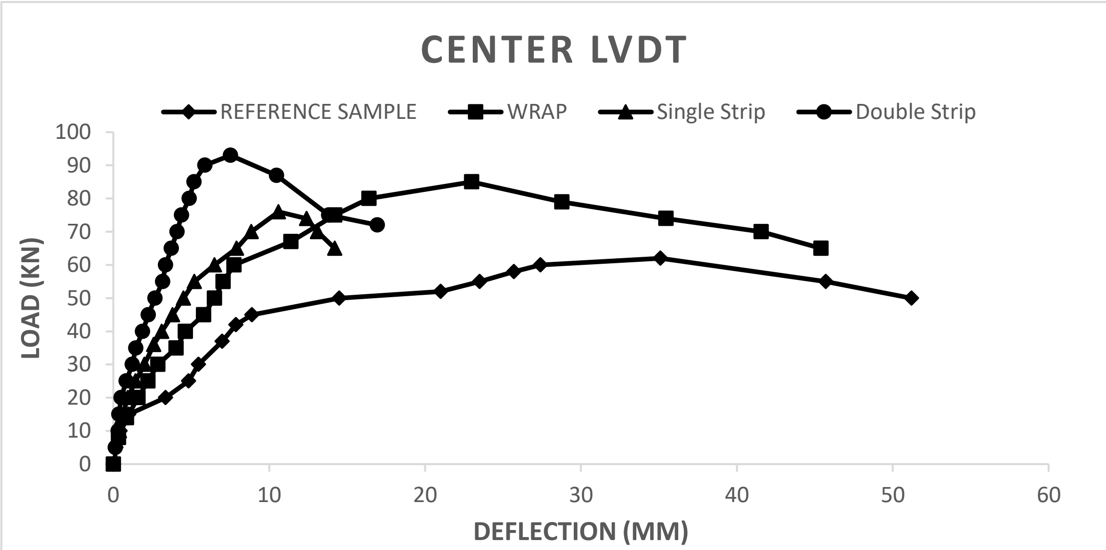

Figure 5-7: Load vs. Deflection graph at center LVDT

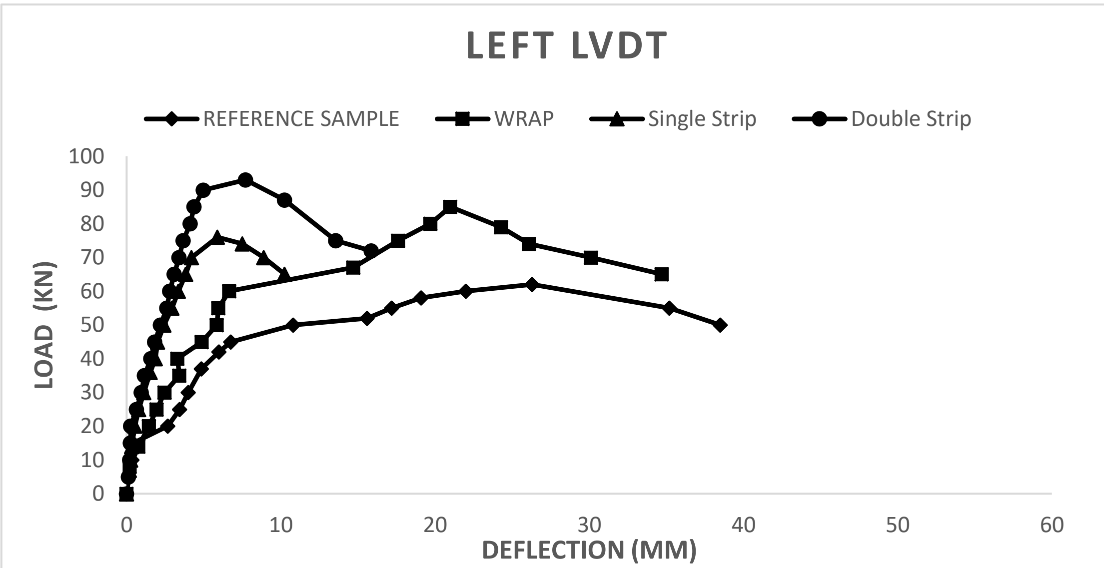

Figure 5-8: Load vs. Deflection graph at left LVDT

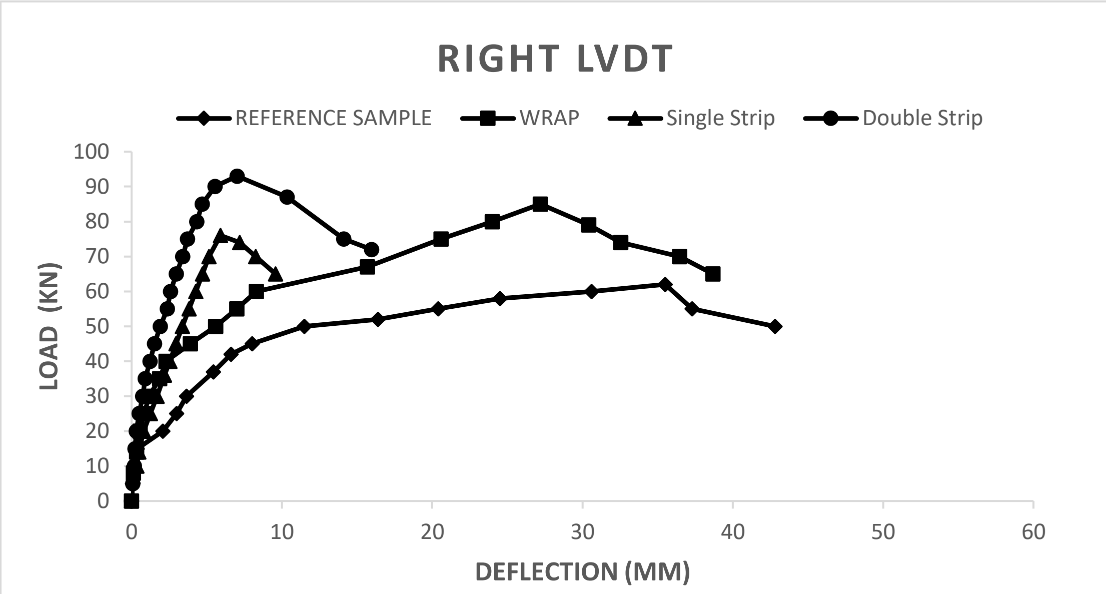

Figure 5-9: Load vs. Deflection graph at right LVDT

5.4 Location vs. Deflection

The elastic curves of all the beams at different load values are shown in the graphs below. There are two types of deflections in the graph, the elastic curves with black colored lines are before failure and the rest with red colored lines are those after failure of the beam. The load values on the y-axis have same limits for all the specimens, this is done to make a clear comparison between the deformed shapes of the beams.

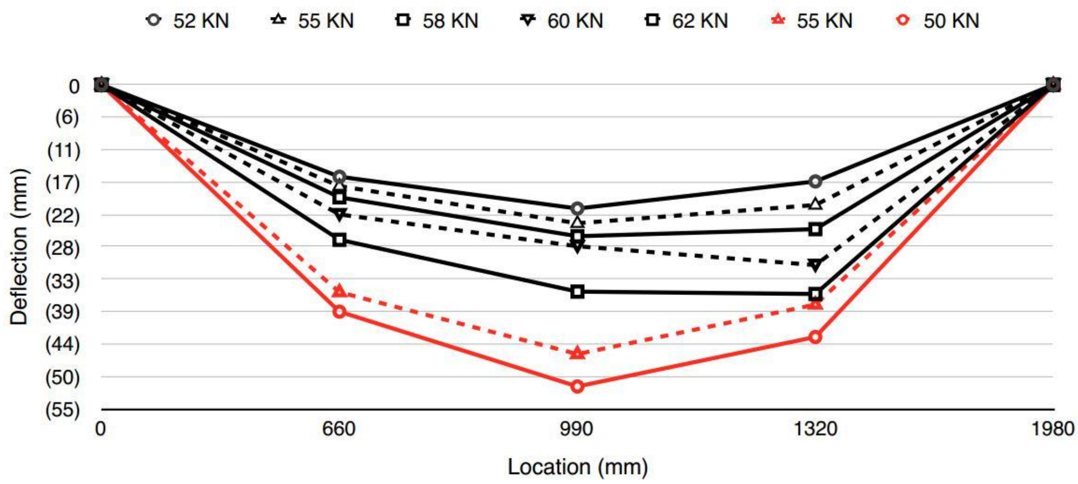

Figure 5-10: Location vs. Deflection graph for reference specimen

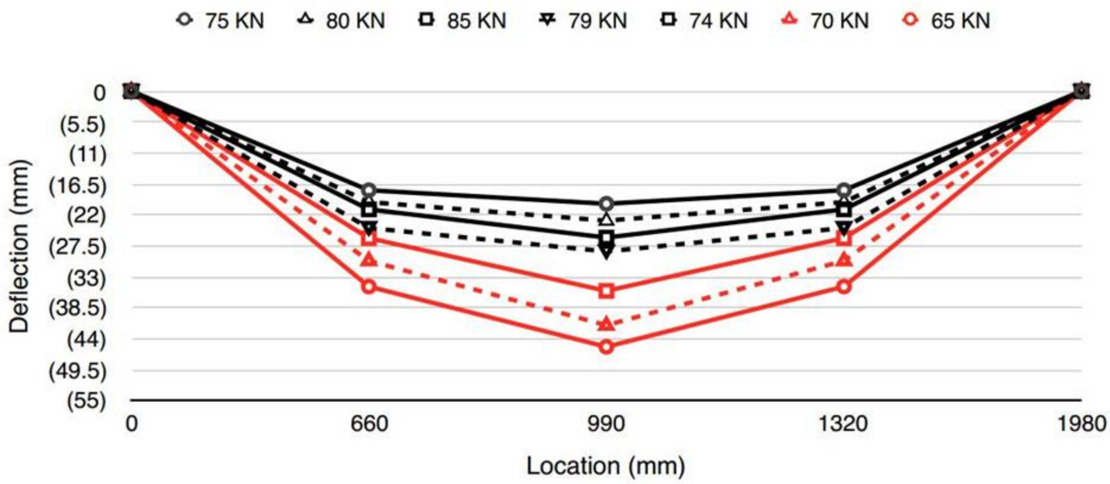

Figure 5-11: Moment curvature graph for FRP wrap specimen

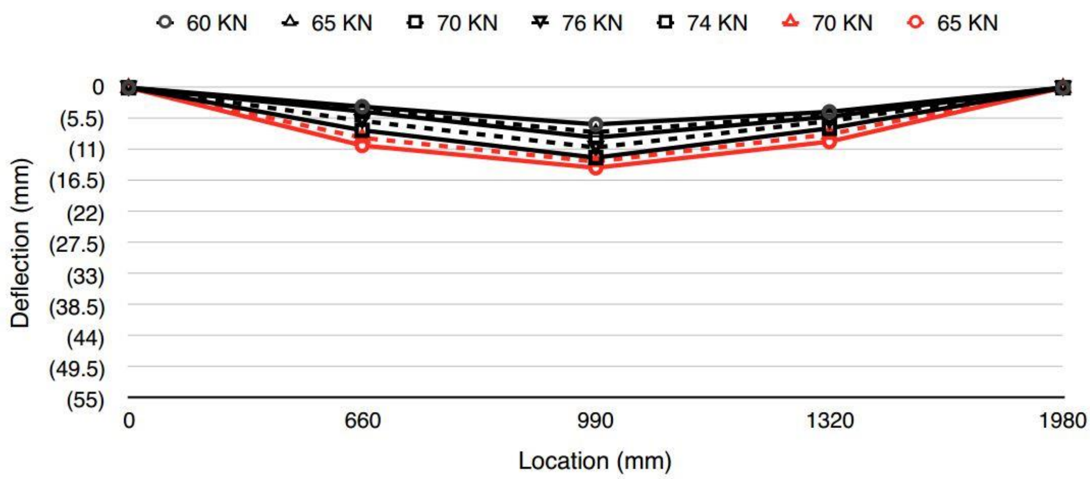

Figure 5-12: Location vs. Deflection graph for single strip specimen

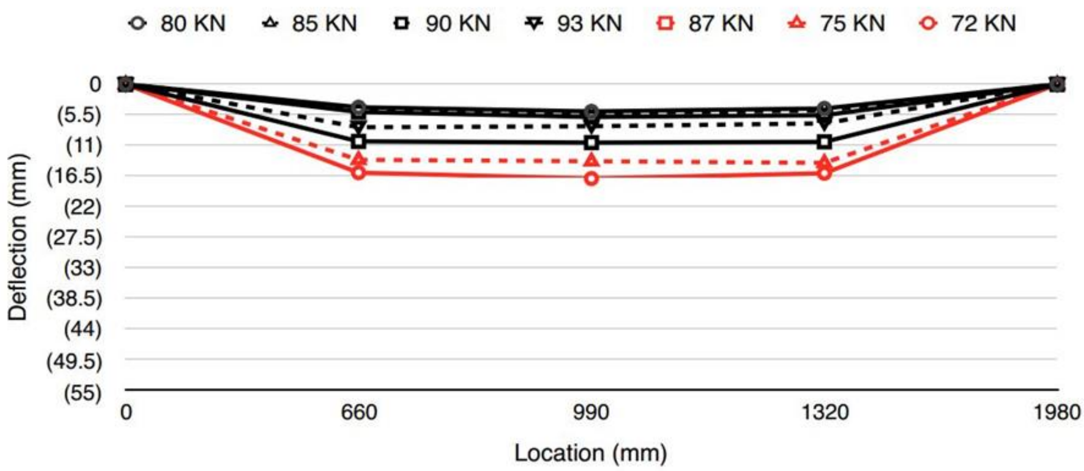

Figure 5-13: Location vs. Deflection graph for double strip specimen

The above shown Tables clearly state that retrofitting of the beam with FRP strips decreased the ductility while adding to the stiffness of the beam and for FRP wrap retrofitting, decrease in strength is not that significant while stiffness on the other hand has also increased.

5.5 Moment vs. Curvature

Moment curvature graphs were prepared for all the specimens as shown below.

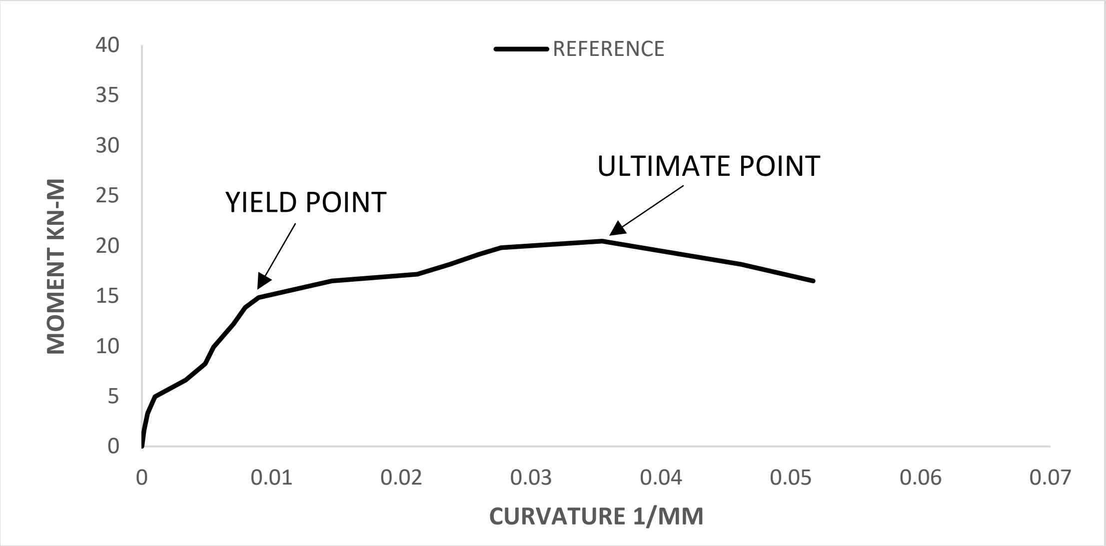

Figure 5-14: Moment curvature graph for reference specimen

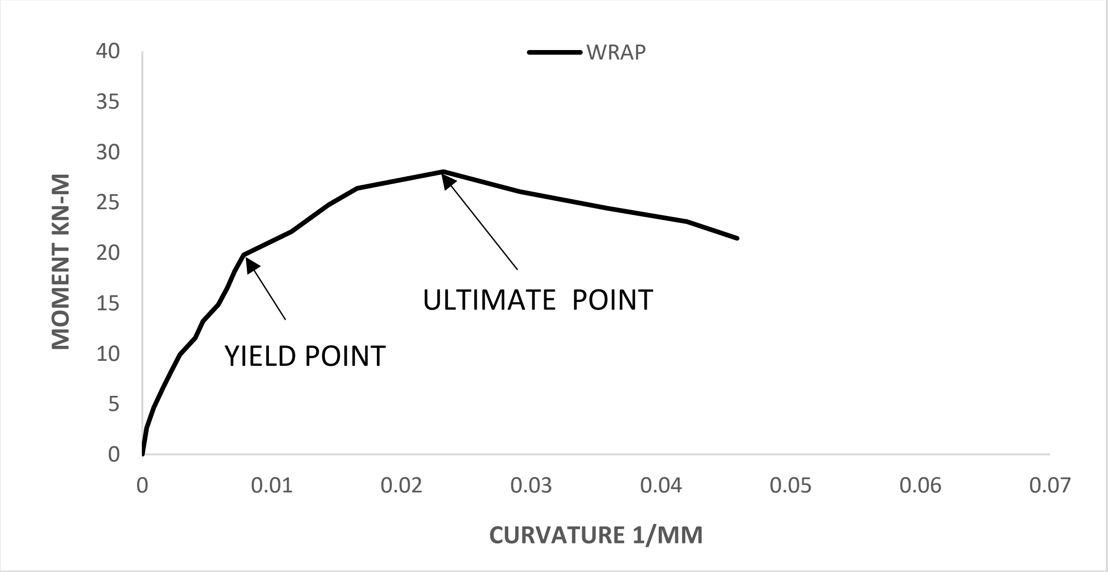

Figure 5-15: Moment curvature graph for FRP wrap specimen

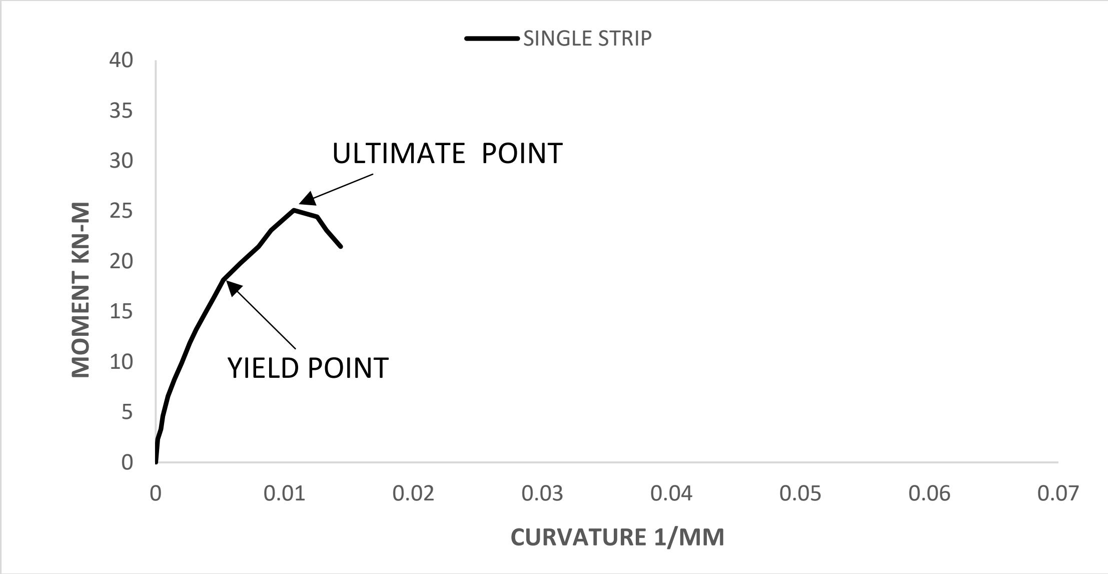

Figure 5-16: Moment curvature graph for FRP single strip specimen

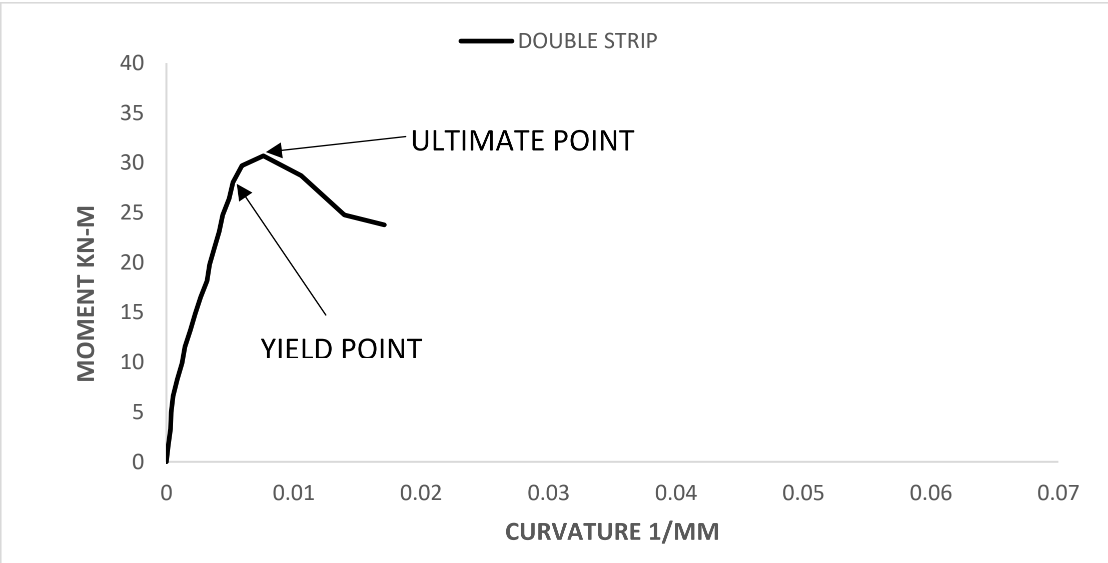

Figure 5-17: Moment curvature graph for FRP double strip specimen

These moment curvature graphs show the flexural rigidity of the beams. After analyzing the graphs flexural rigidity of wrap sample has not increased significantly which explains its better ductile behavior than single and double FRP strip samples. As the slope of the graphs in single and double strip sample have increased showing greater flexural rigidity of the beams similarly the ductility of these specimens has decreased as we have previously seen in the load vs. deflection graphs.

5.5 Conclusions

The conclusions drawn based on the previously shared results are briefly described below:

1. After application of FRP the load carrying capacity of the beams increased by 37-50%.
2. Decrease in deflection in the beams is caused by the increase in flexural rigidity and stiffness.
3. Compared to strips the wrapped specimen showed greater ductility.
4. For FRP strips, greater the contact area with the beam greater is the strength gain.

REFERENCES

- American Concrete Institute (ACI). (2008). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures." ACI 440.2R-08, Farmington Hills, MI.

- Ashour, A. F., El-Refaie, S. A., & Garrity, S. W. (2004). Flexural strengthening of RC continuous beams using CFRP laminates. *Cement and concrete composites*, *26*(7), 765-775.

- ASTM, C. (1996). 39, Standard test method for compressive strength of cylindrical concrete specimens. *Annual book of ASTM standards*, *4*.

- ASTM, C. (1999). Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). *Philadelphia, PA: American Society for Testing and Materials*.

- ASTM, C. (2003). 143:"Standard Test Method for Slump of Hydraulic-Cement Concrete,". *American Society for Testing and Materials, Annual Book of ASTM Standards*, *4*.

- ASTM, E. (1991). 8M: Standard test method for tension testing of metallic materials (Metric). *Annual Book of ASTM Standards, Philadelphia*.

- David, E., Djelal, C., & Buyle-Bodin, F. (1998). Repair and strengthening of reinforced concrete beams using composite materials. In *2nd international PhD symposium in civil engineering, Budapest*.

- D'Ambrisi, A., & Focacci, F. (2011). Flexural strengthening of RC beams with cement-based composites. *Journal of Composites for Construction*, *15*(5), 707-720.

- Esfahani, M. R., Kianoush, M. R., & Tajari, A. R. (2007). Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. *Engineering structures*, *29*(10), 2428-2444.

- Fardis, M. N., & Khalili, H. (1981, November). Concrete encased in fiberglass-reinforced plastic. In *Journal Proceedings* (Vol. 78, No. 6, pp. 440-446). Fardis, M. N., & Khalili, H. (1981, November). Concrete encased in fiberglass-reinforced plastic. In *Journal Proceedings* (Vol. 78, No. 6, pp. 440-446).

- Garden, H. N., & Hollaway, L. C. (1998). An experimental study of the influence of plate end anchorage of carbon fibre composite plates used to strengthen reinforced concrete beams. *Composite Structures*, *42*(2), 175-188.

- Kachlakev, D. I., & McCurry Jr, D. D. (2000). *Testing of full-size reinforced concrete beams strengthened with FRP composites: Experimental results and design methods verification* (No. FHWA-OR-RD-00-19,).

- Katsumata, H., Kobatake, Y., & Takeda, T. (1987). A Study of Strengthening with Earthquake-Resistant Capacity of Existing Reinforced Concrete Columns, (Part 2)-Tests on Strengthening Square-Sectioned Columns. *Report of Research Institute, Obayashi Construction*, (34), 114-118.

- Lacasse, C., Labossiere, P., & Neale, K. W. (2001, December). FRPs for the rehabilitation of concrete beams exhibiting alkali-aggregate reactions. In *Proceedings of 5th International Symposium on Fibre-Reinforced (FRP) Polymer Reinforcement for Concrete Structures* (Vol. 1, pp. 35-43).

- Meier, U. (1987). Bridge repair with high performance composite materials. *Material und Technik*, *4*, 125-128.

- Nezamian, A., & Setunge, S. (2004). Comparison between ACI 440 and FIB 14 design guidelines in using CFRP for strengthening of a concrete bridge headstock.

- Nezamian, A., Setunge, S., & Lokuge, W. (2002). Review of Strengthening Techniques Using Externally Bonded Fibre Reinforced Polymer Composites: Report 2002-005-C-01. *CRC Construction Innovation*, 1-48.

- Obaidat, Y. (2011). *Structural retrofitting of concrete beams using FRP-debonding issues*. Department of Construction Sciences, Lund University.

- Papanicolaou, C. G., Triantafillou, T. C., Papathanasiou, M., & Karlos, K. (2008). Textile reinforced mortar (TRM) versus FRP as strengthening material of URM walls: out-of-plane cyclic loading. *Materials and Structures*, *41*(1), 143-157.

- Pareek, S., Suzuki, Y., & Kobayashi, A. (2007). Flexural and shear strengthening of RC beams using newly developed CFRP and polymer-cement pastes as bonding agents. *Proceedings of Fiber-Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-8, Patras, Greece*.

- Pellegrino, C., & Sena-Cruz, J. (2016). Design procedures for the use of composites in strengthening of reinforced concrete structures. *State-of-the-Art Report of the RILEM Technical Committee*, 392.

- Rostasy, F. S. (1987). *Bonding of steel and GFRP plates in the area of coupling joints* (No. 3126/1429). Talbrucke Kattenbusch. Research report.

- Shahawy, M. A., Arockiasamy, M., Beitelman, T., & Sowrirajan, R. (1996). Reinforced concrete rectangular beams strengthened with CFRP laminates. *Composites Part B: Engineering*, *27*(3-4), 225-233.

- Shehata, I. A. E. M., Cerqueira, E. C., Pinto, C. T. M., & Shehata, L. C. D. (2001). Strengthening of RC beams in flexure and shear using CFRP laminate. In *FRPRCS-5: Fibre-reinforced plastics for reinforced concrete structures Volume 1: Proceedings of the fifth international conference on fibre-reinforced plastics for reinforced concrete structures, Cambridge, UK, 16–18 July 2001* (pp. 97-106). Thomas Telford Publishing.

- Toutanji, H., Zhao, L., & Zhang, Y. (2006). Flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix. *Engineering Structures*, *28*(4), 557-566.

- Wolff, R., & Miessler, H. J. (1989). New materials for prestressing and monitoring heavy structures. *Concrete International*, *11*(9), 86-89.

- Ye, L., Feng, P., & Yue, Q. (2011). Advances in FRP composites in civil engineering.