Comparative study of Flexural behavior of CFRP strengthened beams using different techniques.

By

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<u>THESIS ACCEPTANCE CERTIFICATE</u>

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ABSTRACT

This research studies the flexural behavior of Carbon fiber reinforced polymer (CFRP) strengthened beams. Two different strengthening methods are used in this work and mainly deal with how the strip is applied. All the beams in this study were designed for under-reinforced section. For testing, six beams were used consisting of two control beams. Remaining four beams were classified into two groups having two beams each. One set was strengthened by applying carbon fiber-reinforced polymers strip on the external tension soffit of the beam using adhesive and the second set was strengthened by applying carbon fiber-reinforced polymers strip inside an already made 10mm slit in the tension soffit of beam and filling the remaining portion by epoxy. This study was mainly focused on the improvement of flexural strength of beams and ultimate load carrying capacity. The experimental testing of beams was based on Four-Point loading condition. The experimental results show a considerable improvement in the flexural behavior of beams and ultimate load carrying capacity of the strengthened beams with reference to control beams. The beams strengthened by using carbon fiber-reinforced polymer inside the slit technique show maximum improvement in flexural behavior and in ultimate load, i.e., 128.7% as compared to control beams.

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CHAPTER 1: INTRODUCTION

1.1 General

Civil engineering structures are mainly reinforced concrete structures which are subjected to different loading conditions and environmental constraints. For an effective design of civil engineering structures, the basic requirement is the understanding of response of structure under different loading conditions. There are a no of methods to study the response of structures i.e. numerical, analytical and experimental. The most accurate approach to study and understand the behavior of structure is by testing it experimentally. For small structures, experimental results show actual response. However, experimental testing of large and complex structures is costly, time consuming and difficult. It becomes very difficult to create real loading conditions and the scenario that matches the real environment to which the structure is subjected. Moreover, usage of proper material, combinations and availability of material is often challenging. Alternate approach, to understand the response of civil structures is the Numerical one. Numerical approaches are generally easier to conduct, user friendly and have flexibility for any alteration to design and conditions etc. The numerical approach used most extensively for analysis of civil engineering structures is Finite Element Analysis. The software used for such analysis are ANSYS, STRAND7, ABAQUS and SEISMOSTRUCT. Earlier approaches to test structures numerically were time consuming and infeasible. However, the use of FEA Software for numerical analysis of structures is increasing vastly due to technological shift, advancement in workstation and computers and the increasing trend towards use of software for analysis and design of structures. The proper use of FEA Package and understanding of pros and cons and limitations of each software is necessary for an effective design and analysis. This numerical approach is immensely cost effective as well as time saving.

In this study, the flexural behavior of Carbon fiber reinforced polymer (CFRP) strengthened beams is studied. Two different strengthening methods are used in this work and mainly deal with how the strip is applied. All the beams in this study were designed for under-reinforced section. For testing, six beams were used consisting of two control beams. Remaining four beams were classified into two groups having two beams each. One set was strengthened by applying carbon fiber-reinforced polymers strip on the external tension face of the beam using adhesive and the second set was strengthened by applying carbon fiber-reinforced polymers strip inside an already made 10mm slit in the tension soffit of beam and filling the remaining portion by epoxy.

1.2 Research Problem

Nowadays, carbon Fiber Reinforced Polymer CFRP is extensively used for flexural strengthening of structural components such as columns and beams. In order to provide extra flexural strength and repairing of damaged beams the use of CFRP strips is quite efficient due to ease in application and local availability. But till now, a very little study has been carried out on locally available CFRP Strips and their strengthening ability. The use of locally available material can be encouraged by providing some study on its effects and advantages.

1.3 Relevance to the national needs

The use of CFRP strips to strengthen beams is increasing in many advanced countries. However, in Pakistan, their use is limited due to little or no research on locally available material. It can aid to our national needs, by constructing stronger structures and repairing of damaged structure. CFRP strengthened beams show excellent response in flexural capacity due to much higher value of ultimate tensile strength of CFRP Strip as compared to control beam's tensile strength. Their deflection values are much lower than conventional beams and can be used where excessive deflections are not acceptable. These can also be used to repair the damaged beams and restore damaged structures by saving time and money.

1.4 Research Methodology

Research methodology comprises of below mentioned steps.

a. Preparation of control beams with M-20 concrete.
b. Preparation of beams with 10mm slit at the bottom for incorporation of CFRP strips.
c. Curing of specimens for 28 days to achieve designed compressive strength.
d. After 28 days, preparation of specimens and application of CFRP strip in two different ways.
e. One technique was called internally bonded laminate technique (IBL) in which CFRP strip was applied in the 10 mm slit prepared during casting of beams.
f. The second technique was to apply CFRP strip externally on the bottom of beam called externally bonded laminate (EBL)
g. After 7 days when the strengthened beams achieved their strength, specimen were moved to reaction floor.
h. Specimen were raised with crane. First 2 Control beams were tested and then the strengthened specimens.

1.5 Research Objectives

Foremost objective of study is to study the effect on the flexural behavior of beams strengthened with CFRP as compared to control specimens. The factors studied under monotonic loadings are

a. The effect of CFRP strengthening on ultimate load carrying capacity of beam.

b. The effect of CFRP strengthening on maximum deflection of beam.

c. The effect of CFRP strengthening on energy dissipation of beam.

d. The effect of CFRP strengthening on ductility of beam.

e. The effect of debonding in various techniques of CFRP Strengthening.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The use of CFRP strips with epoxy resin to repair and strengthen reinforced concrete beams is an effective practice. It strengthens the beam under flexural loading and increases the flexural capacity. Generally, two types of FRPs are used for improvement in flexural properties of beams: CFRP (Carbon fiber-reinforced polymers) and GFRP (Glass fiber-reinforced polymers). CFRPs are more extensively used as compared to GFRPs due to their local availability and ease in application. From literature, it can be seen that FRP strengthening of beams increase the flexure capacity of beams but decreases the ductility. Existing structures often need strengthening due to application of excessive loads, change in usage of the structure and deterioration of structure over time. Strengthening of existing structures using FRP Strips is increasingly replacing the conventional methods of strengthening of existing structures i.e. external post tensioning, jacketing by steel plates and external reinforcement etc.

2.1.1 Flexural strengthening of beams

Flexural strength is defined as the maximum stress that a material exhibits at failure due to a three or four-points flexural load (Saikia and de Brito 2012). Flexural strength is an indirect measure of the tensile strength of concrete. Flexural strengthening is the process of upgrading the Flexural properties of structure to improve the building's performance under existing loads or to increase the strength of the existing structure to carry additional loads.

2.1.2 Methods of flexural strengthening

CFRP Strips: Beams are strengthened using CFRP strips with epoxy adhesive applied directly to the bottom of beam or by using various techniques.

GFRP Strips: Beams are strengthened using GFRP strips with epoxy adhesive applied directly to the bottom of beam or by using various techniques.

Jacketing: Jacketing of RC beams is done by enlarging the existing cross section with a new layer of concrete that is reinforced with both longitudinal and transverse reinforcement. (Raval and Dave 2013)

2.1.3 CFRP vs GFRP

CFRP: Carbon fiber is a material consisting of extremely thin fibers about 0.005-0.010 mm in diameter consists of carbon atoms. Carbon fiber has many different weave patterns and can be combined with a plastic resin and wood or molded to form composite materials such as carbon fiber reinforced polymer. Light weight with low density, Greater tensile strength and Greater impact strength.

GFRP: GFRP is a type of fiber reinforced polymer where the reinforcement fiber is specifically glass fiber. The material is typically far less brittle, and the raw materials are much less expensive.

Medium weight with medium density, Greater percentage elongation and more ductile.

2.2.4 Advantages of using CFRP strips

High stiffness and strength.

Lightweight.

Corrosion resistance.

Low CTE (Coefficient of Thermal Expansion)

Chemical resistivity.

Application flexibility.

2.2 Previous studies conducted

Considerable amount of research has been done globally on reinforced concrete beams flexural strengthening using CFRPs which is discussed here in detail. A significant no of research papers were studied that contributed towards the flexural strengthening of reinforced concrete beams. Two main issues that the researchers faced were Debonding and the separation of Laminate end-cover. Because of these issues only 50-60% of the design strength of laminate was incorporated during the tests. Most of the research was carried out to find an effective method of application of CFRP laminate that minimizes the Debonding and end-cover separation of the laminate.

(Ashour and Morley 1993) Used the nonlinear elastic isotropic model of concrete to study the behavior of concrete before cracking or crushing. When the state of stress hits experiment-based failure, concrete behavior changes from isotropic to orthotropic. The interaction between concrete and steel is modeled using a new linkage element. The validity of model was checked with a comparative study of two example RC (reinforced concrete) beams.

(Büyükkaragöz 2010) Studied the flexural strengthening of beam by applying prefabricated plate of 80 mm thickness on the lower side of beam. Center point loading condition was used to test the specimens in the laboratory. Modeling of beam in ANSYS finite element program was used to validate the experimental results. The strengthening of beam using prefabricated plate with epoxy improved the ultimate load carrying capacity by 32%. The same results were compared with the modeled specimen which were in good agreement with the experimental results.

(Ugale and Raut 2014) studied the GFRP retrofitted external beam-column joint of a five storey two bay frame building. Ground round floor beam column joint was studied in this work. For analytical study of beam-column joint, ANSYS and STAAD Pro were used. Glass fiber mat class

E grade 300 (chopped Fiber) was used to wrap the specimens. Specimens were divided into two groups, one having Two Single Layer thickness and other specimen had double Layer Thickness. Results showed that ultimate load carrying capacity was increased by 60% as compared to the control specimen. The energy absorption of the system increased about 30-40% as compared to control sample. Under seismic conditions, the most important member of the system is column. In this study, in control sample the failure was in column while in the retrofitted sample the beam failed and column was still intact. This type of failure was the most desirable specimen failure subjected to seismic loading conditions.

(Akbarzadeh and Maghsoudi 2010) Studied the improvements of flexural properties and redistribution of moment in reinforced high strength concrete (RHSC) continuous beams. Beams were strengthened with CFRP (Carbon fiber-reinforced polymers) and GFRP (Glass fiber-reinforced polymers) sheets. The ultimate strength increased with increasing the CFRP and GFRP sheets while this resulted in the decrease in the ductility, CFRP sheet ultimate strain and redistribution in moment. By increasing the number of CFRP sheet layers, moment redistribution significantly decreased from 16.06% in the control beams to 1.51% in strengthened beams. An analytical model was prepared and used for the tested continuous beams. Good agreement between analytical and experimental values is achieved.

(Jeevan, Reddy, and Prabhakara 2018) Carried out a detailed study to examine the flexural strengthening of Reinforced concrete (RC) beams using CFRP applied using different techniques. Total Eight specimens were prepared out of which two were control beams; two were strengthened by applying CFRP Sheets externally which was also called as EBL i.e. externally bonded laminate. Two beams were strengthened by applying anchor bolts to the externally bonded laminate also known as EBLA i.e. externally bonded laminate anchored. The remaining two beams were strengthened by using prestressed laminate and then these were anchored using bolts they called this EBPLA i.e. externally bonded prestressed laminate anchored. Concrete used was M-40 and for shear and flexure reinforcement, deformed bars of high yield strength were selected. CFRPs were casted and cured for 7 days. For bonding, the adhesive epoxy used was Nitobond PC. Different tests were conducted to evaluate various properties and parameters in their study. For experimental testing of samples, Two-point loading condition was used. After the testing of samples, a detailed study was carried out to compare various parameters of strengthened beams in response to control beams. The ultimate load carrying capacity increased by 23.91% in EBL technique. The EBLA technique showed 43.47% increase in ultimate load carrying capacity and the EBPLA technique showed an increase of about 73.91% in ultimate load carrying capacity as compared to the control beams. The crack width and deflection values of all the cases were within the specified values and satisfy all the strengthening codes. A comprehensive study was also made on the Debonding strain. The EBPLA technique delayed the debonding more efficiently as compared to EBL and EBLA Technique. A comparison was made between experimental ultimate moments and the theoretical ultimate moments. The percentage increase in ultimate moment capacity for all the cases is 8.63% for EBL technique, 23.88% for EBLA technique and 50.13% for EBPLA technique. section is also difficult to understand as compared to the section with square cross section.

The CFRP strips used in this study were Sika CarboDur strips with Sikadur Resin. The FRP strips were applied using two different techniques, i.e. bonded externally to the bottom of beam called EBL (Externally bonded Laminate) and applied internally in an already made 10mm deep slit and covering the remaining portion of the slit with epoxy called IBL (Internally bonded Laminate). The experimental testing of beams was based on Four-Point loading condition.

CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 Materials & Mechanical properties

3.1.1 Steel reinforcement and Concrete

For concrete, M20 grade was selected and mix design was prepared in accordance with ACI C211 (211 1991) Standard. Aggregate size, gradation, water cement ratio etc. were selected as per guidelines given in ACI C211 to give a compressive strength of 3000-3500 psi at 28 days. The steel reinforcement used was 60 grade steel (i.e. characteristic tensile strength of 60000 psi) conforming to ASTM A283 (Specification n.d.).

3.1.2 Fine aggregate, coarse aggregate and Cement

Fine aggregate used in this study was coarse sand from Nizampur with maximum size 2mm. Coarse aggregate used was brought from Margallah Crush Plant with maximum size of 12 mm. Ordinary Portland Cement of grade 53 conforming to Pakistan standard PS-232-2008 was used which was manufactured by Bestway Cement Pvt. Limited.

3.1.3 Carbon Fiber-Reinforced Polymer (CFRP)

The CFRP strips used in this study are Sika CarboDur with the properties given below and as per specification data sheet provided by manufacturer (Del 2006).

Table 1 Properties of CFRP Strip

S.No.	Properties	Values
1	Strip width	80 mm
2	Strip thickness	1.2 mm
3	Density	0.0016 g/mm^3
4	Young's Modulus/ Modulus of elasticity	165,000 MPa
5	Ultimate tensile strength	3,100 MPa
6	Design area	96 mm^2

The length of CFRP Strip used in experimental work was 1219.2 mm.

3.1.4 Epoxy Adhesive

To bond CFRP Strips to concrete surface, Sikadur 30 epoxy adhesive was used which is a structural 2-component adhesive based on a blend of different epoxy resins and filler. The normal temperature recommended for its use is between +8 °C and +35 °C. It contains 2 components A & B mixed in the ratio 3:1 respectively. Mixing, application and curing etc. were done as per guidelines mentioned in the product data sheet (Sikadur®-30 LP 2017).

3.2 Preparation of Specimens

3.2.1 Test Specimen description

Total 6 beams were prepared in which two were control samples, two were strengthened by applying Sika CarboDur on the exterior surface with epoxy (EBL) and the remaining two were strengthened by applying Sika Carbador in the 10 mm slit made in the tension side of beam and the remaining portion of slit was covered with epoxy (IBL). During each casting, cylinders were also casted to calculate the compressive strength of the concrete being used for casting of beams.

3.2.2 Detailing of beam and preparation of test samples

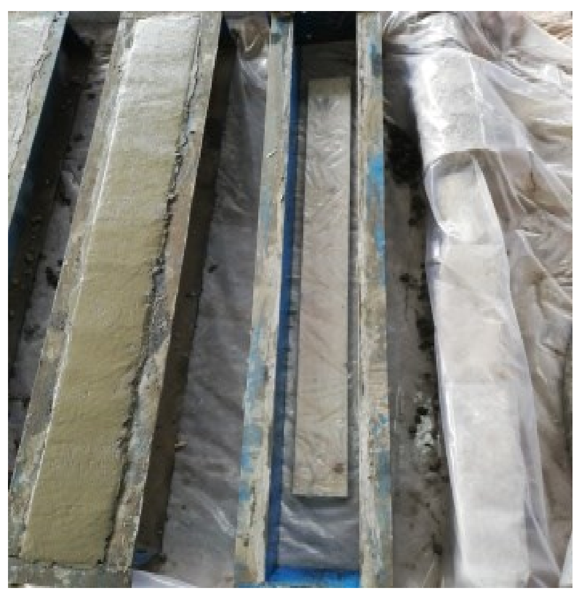
The dimensions of beams were 152.4 mm x 152.4 mm cross section with 1524 mm length. The beams were designed for minimum reinforcement as per guidelines of ACI-318 (Assignment 2013). The preparation procedure is described as; initially steel reinforcement was cut into required length and then was fabricated and detailed. Concrete components were mixed as per mix design by using machine mixer. Concrete was poured in the molds and 25mm vibrator was used for suitable compaction of the mix and to ensure that there are no voids left. Along with each casting, three cylinders were casted for determining the compressive strength of concrete. After 24 hrs.

beams and cylinders were de-molded. Cylinders were kept in curing tank while beams were covered with gunny bags. The beams were sprinkled with water for curing purposes for about 28 days. Fig 1. a-e show the complete procedure of preparation of samples in lab.

a

b

c



d

e

Figure 1 Preparation of samples in lab

a Reinforcement preparation; **b** Mixing of ingredients; **c** concrete preparation.

d preparation of 10 mm slit in beams; **e** curing of beams.

After preparation of specimen, moist curing was done and after 28 days specimens were prepared for application of CFRP strips.

3.2.3 Application of CFRP on concrete beams

The stepwise procedure of application of CFRP strips on reinforced concrete beams is indicated in the below images. Two different techniques were used for application of CFRP strips namely internally bonded Laminate technique also called IBL and externally bonded Laminate technique also called EBL. The stepwise procedure is explained below.

3.2.3.1 Marking of Specimen

The specimens were marked with ink marker for correct application of CFRP strips. The marking area was 1219.2 mm long and 80 mm wide.

3.2.3.2 Cutting of CFRP strips

CFRP strip was a single coil having length 6096 mm, width 80 mm and thickness 1.2 mm. CFRP strip was cut into small strips having length 1219.2 mm, width 80 mm and thickness 1.2 mm.

3.2.3.3 Preparation of epoxy

Sikadur 30 epoxy adhesive was used which is a structural 2-component adhesive based on a blend of different epoxy resins and filler. The normal temperature recommended for its use is between +8 °C and +35 °C. It contains 2 components A & B mixed in the ratio 3:1 respectively.

3.2.3.4 Preparation of beam surface and CFRP application in EBL technique

The beam surface was made rough only in the marked area by using grinder for a better bond of epoxy with concrete. After making the beam surface rough, epoxy was applied over which the CFRP sheet was laid. The corners were strengthened by applying epoxy to cover the corner voids. CFRP sheet was pressed so that a better bond is achieved. The specimens were kept for 7 days so that the epoxy can gain its full strength before testing.

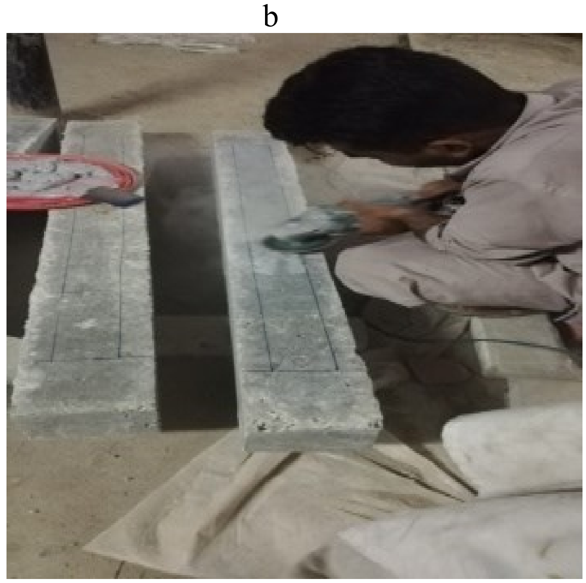
3.2.3.5 Preparation of beam surface and CFRP application in IBL technique

For IBL technique, a 10 mm slit was made in the bottom of beam during the casting by placing a 10 mm thick, 1219.2 mm long and 101.6 mm wide wooden plank. The wooden plank was covered with plastic sheet for easy removal after the concrete is hardened. After 28 days when the concrete had gained its strength, wooden plank was removed leaving behind a 10 mm deep slit in the bottom of beam. This slit was made rough with grinder for better bond between epoxy and concrete. Epoxy coat was applied and over it CFRP strip was laid. The remaining portion of slit was covered with epoxy and leveled with the bottom of beam. The specimens were kept for 7 days so that the epoxy can gain its full strength before testing.

a

b

c



d

e

f

g

h

Figure 2 Application of CFRP

a marking of beams; **b** cutting of CFRP sheets for required length/size; **c** mixing of Sikadur resin; **d** preparation of beam surface; **e** application of CFRP sheet on beam; **f** placement of CFRP sheet in 10 mm slit; **g** filling of slit with epoxy; **h** finished beam after applying CFRP inside the slit.

3.3 Testing of specimens in Lab

Four Point loading test was used to test the samples. The key difference between four and three-point bending tests is the distribution of the bending moments. Four-point technique is used for relatively high modulus composites. The stress distribution is uniform between points in four-point technique as shown in the Figure 3. The three-point loading test introduces stress distribution under the central point where the load is acting. In order to distribute the load in two equidistant points, a steel girder was used. To note the displacement at mid-point, Two LVDTs were applied.

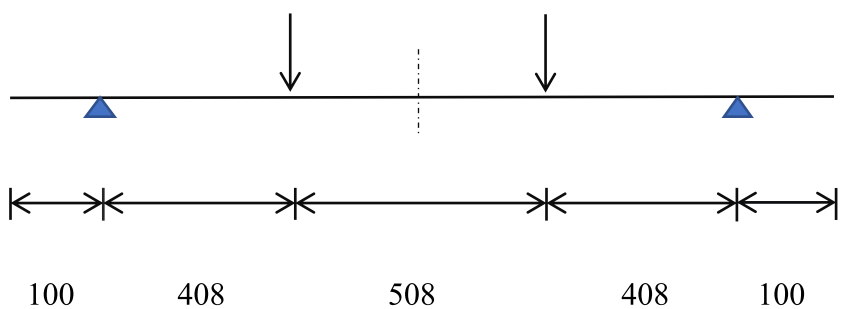


Figure 3 Test Setup sketch

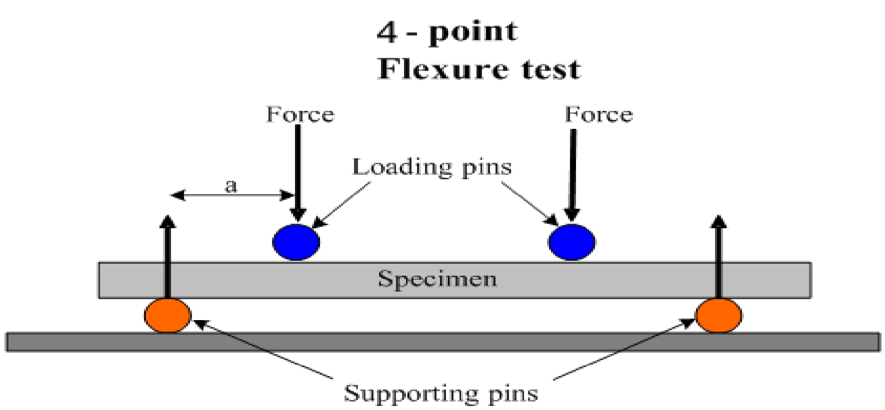


Figure 4 Schematic of 4-point Flexural Test

Figure 5 Experimental Arrangement of 4-point Flexural Test

3.4 Loading Protocols for Monotonic Test

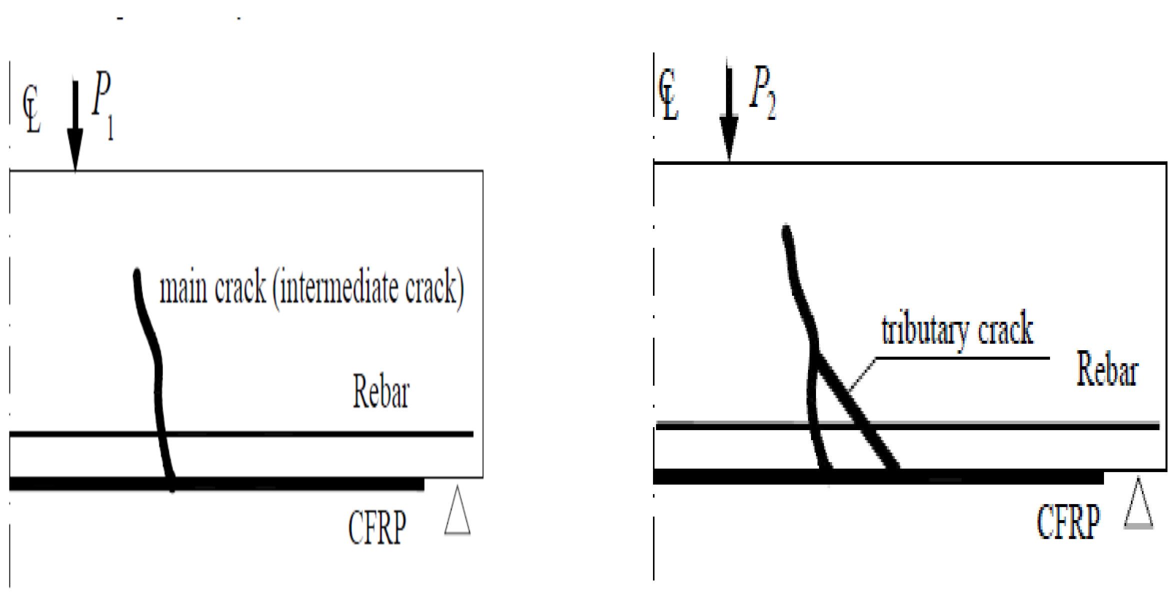
Two kinds of loading can be used to test the specimen i.e. cyclic or monotonic. In this study, Monotonic loading is used to test the specimens. The cases of monotonic tests are compression and tension tests. In this study load is applied to the specimen at a constant and steady rate which increases constantly to obtain various properties such as ultimate strength and yield strength etc. the loading rate used in test was 29.42 KN/min.

3.5 Investigation of Failure mode of Strengthened Samples:

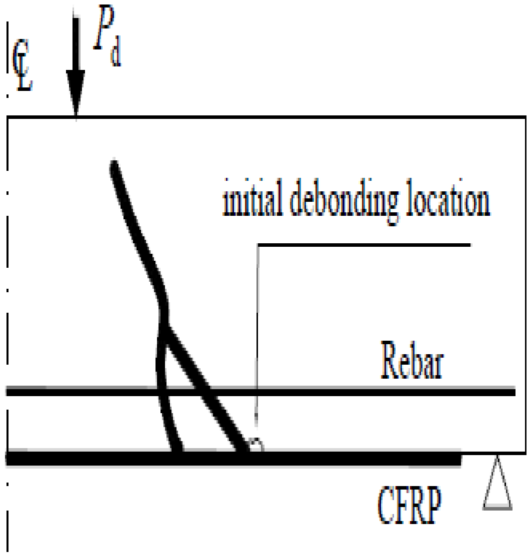
After carrying out the flexure test on all the specimens, they were inspected for the failure mode. The different failure modes are discussed as under,

3.5.1 Failure mode of EBL (Externally bonded laminate) technique strengthened beam

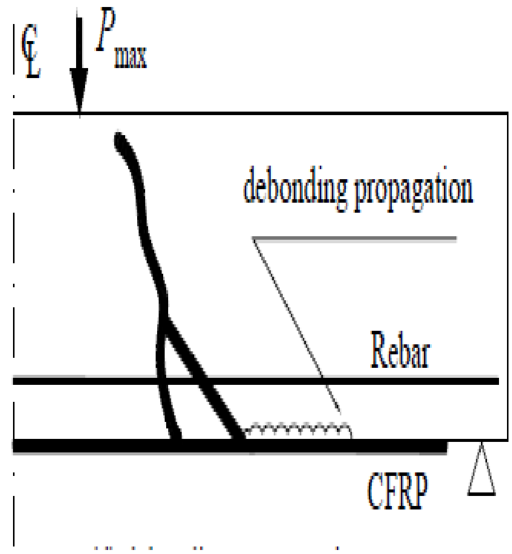
The EBL strengthened beams failed due to cover separation. Flexure-Shear cracks that initiated at one end of the beam forced this cover separation. As per the study carried out by (Li, Zhang, and Guo 2013) the failure mode of EBL technique.is as under;



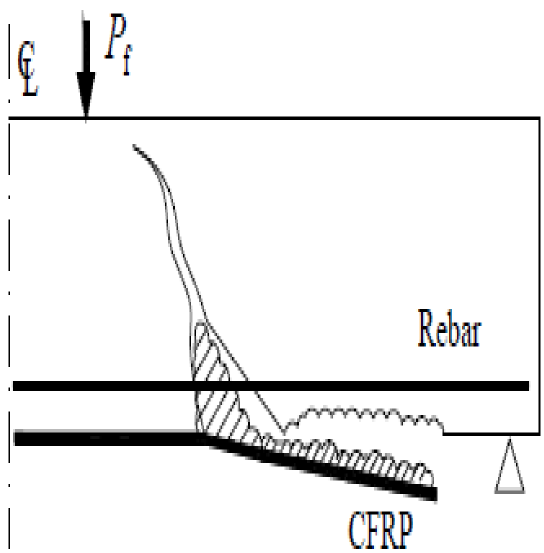
(a) Formation of main crack (b) Formation of tributary crack



(c) Initial debonding



(d) Debonding propagation



(e) collapse of beam

Figure 6 Schematic Failure mode of EBL (Externally bonded Laminate) strengthened beam

Figure 7 Experimental Failure mode of EBL (Externally bonded Laminate) strengthened beam

3.5.2 Failure mode of IBL (Internally bonded laminate) technique strengthened beam

The IBL strengthened beams failed due to ripping off epoxy cover with CFRP laminate. The Debonding was delayed as compared to EBL technique but still it occurred when the epoxy failed to hold on for long. It showed similar failure mode as of EBL technique but managed to delay the debonding.

Figure 8 Experimental Failure mode of EBL (Externally bonded Laminate) strengthened beam

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Load-Deflection Relationship

Load deflection curves were obtained from LVDT placed at mid-span. The various parameters studied and observed from these load deflection curves are as under.

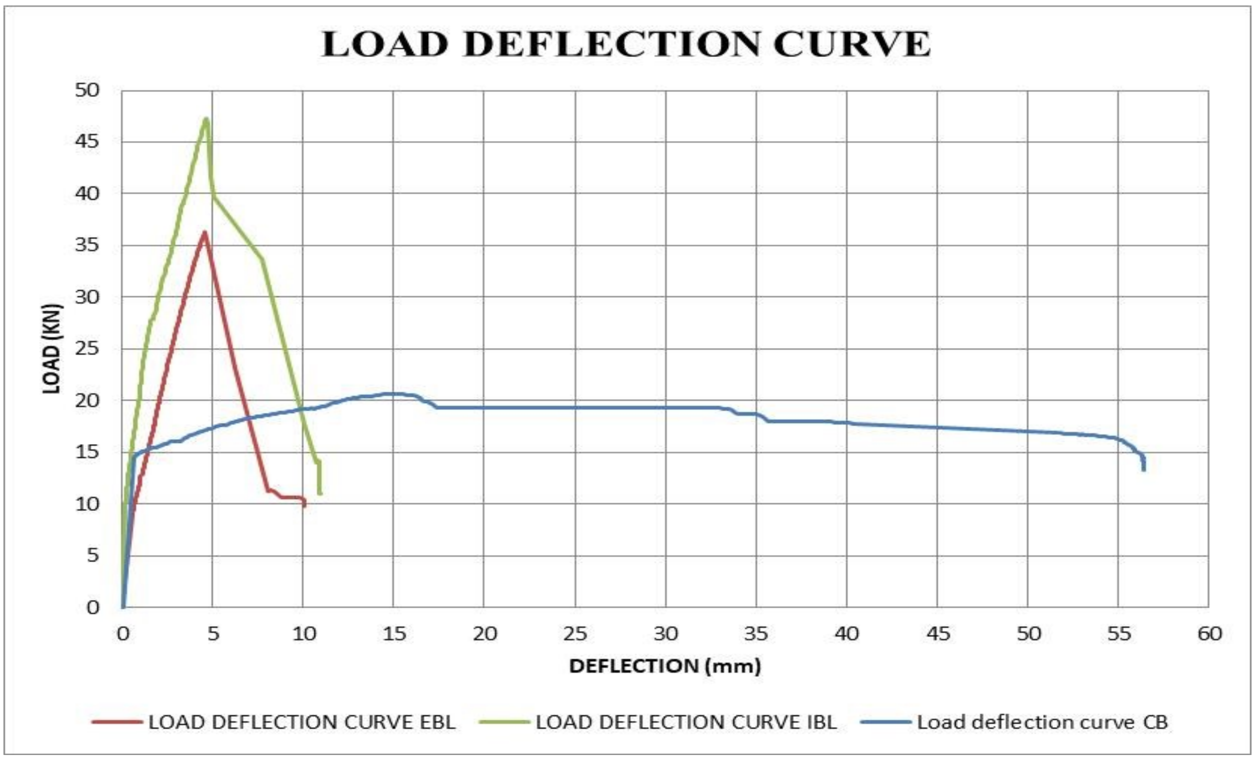


Figure 9 Combined Load Deflection Curve

The different parameters studied from these load deflection curves are highlighted below.

4.1.1 Ultimate load carrying capacity

The ultimate load carrying capacity was increased with the strengthening of beams. The average ultimate load for control beam was 20.68 KN. The average values for ultimate load for EBL and IBL strengthened beams are 36.25 KN and 47.3 KN respectively. With reference to control beam, EBL and IBL techniques have shown 75.33% and 128.7% increase in ultimate load carrying capacity respectively.

Table 2 Percentage (%) increase in ultimate load carrying capacity.

Beam Description	Ultimate load (KN)	Average Ultimate load (KN)	Percentage (%) increase in Ultimate load carrying capacity with reference to control beam
CB-1	20.68	21.45	
CB-2	22.15		
EBL-1	36.25	37.58	75.33
EBL-2	38.92		
IBL-1	47.30	49.05	128.7
IBL-2	50.81		

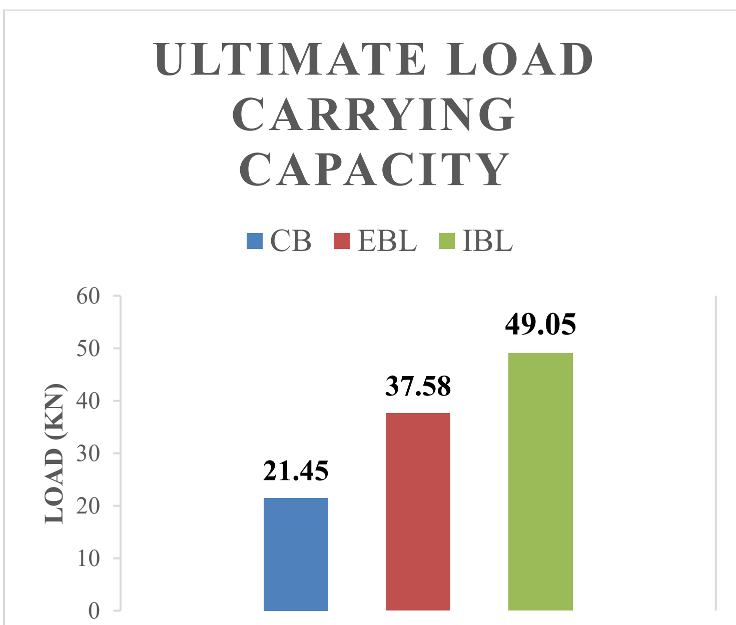


Figure 10 Ultimate load carrying capacity of CB, EBL and IBL strengthened beams

This increase in ultimate load carrying capacity of CFRP strengthened beams is due to much higher value of ultimate tensile strength of CFRP Strip as compared to control beam's tensile strength. The failure of EBL strengthened beams was due to cover separation. IBL technique managed to provide the highest value of ultimate load carrying capacity by delaying the debonding process.

4.1.2 Maximum deflection:

The maximum deflection in strengthened beams decreased with reference to control beams. The maximum deflection for each beam is as under.

Table 3 Average Maximum deflection of specimens

Beam Designation	Maximum deflection (mm)	Average Maximum deflection (mm)
CB-1	54.12	56.40
CB-2	58.68	
EBL-1	9.97	10.07
EBL-2	10.18	
IBL-1	9.96	10.98
IBL-2	12.00	

Strengthened beams showed brittle failure with minimal values of deflection. This is due to higher value of Modulus of elasticity of CFRP Strip as compared to concrete. Higher values of modulus of elasticity mean greater flexural rigidity and lesser deflection.

4.1.3 Displacement ductility or ductility index:

It is defined as "The ratio of maximum deflection at which compression concrete crushes to the deflection at which tensile steel yields." Mathematically,

$$\mu_D = \Delta_u/\Delta_y$$

Where,

μ_D = Ductility index or displacement ductility factor.

Δ_u = Maximum deflection of bilinear idealized curve.

Δ_y = Deflection at yield load of bilinear idealized curve.

4.1.3.1 Ductility index of control beam

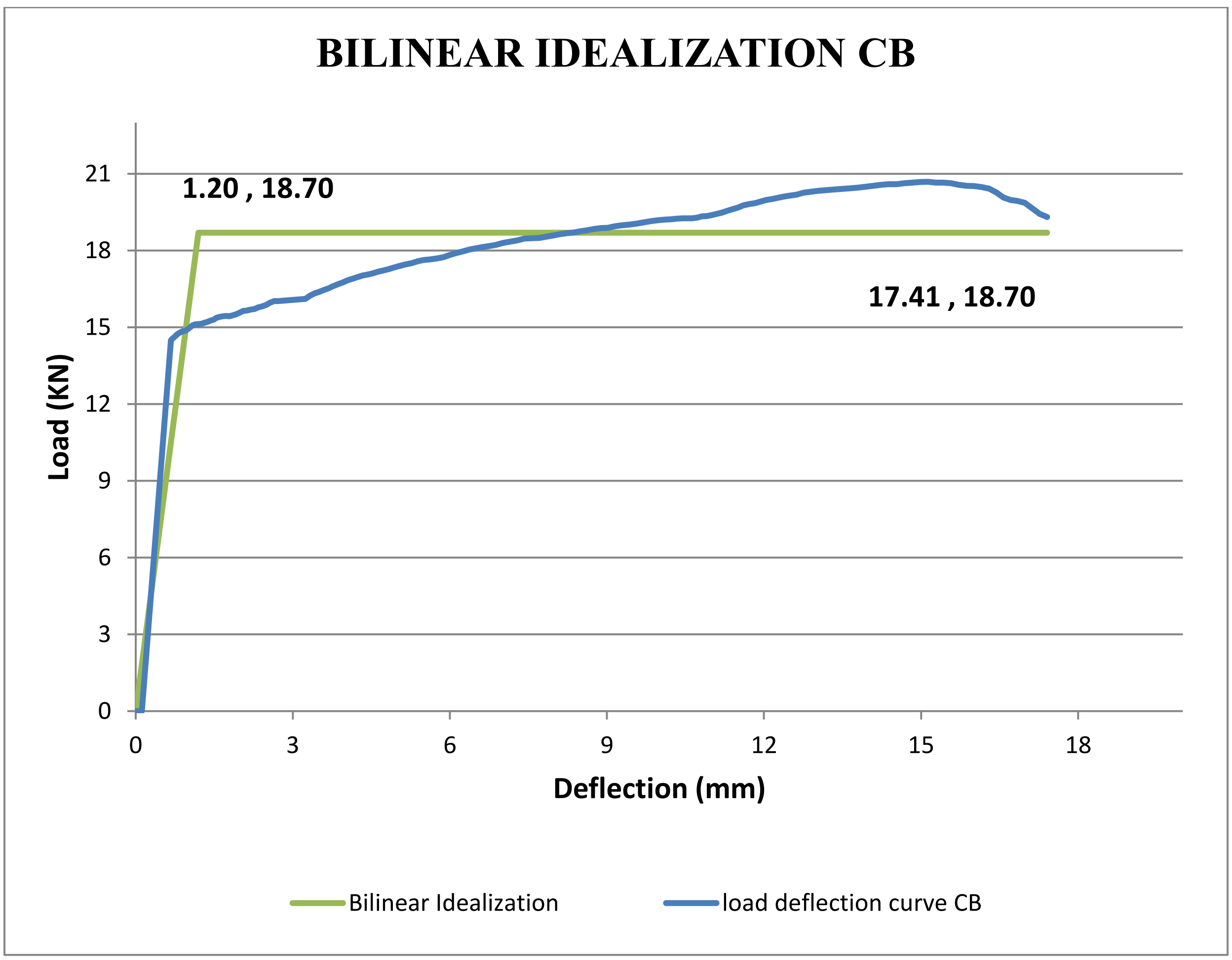


Figure 11 Bilinear idealization curve Control beam

In control beam, Maximum deflection = 54.04 mm, Yield point deflection = 1.05 mm

So, Ductility index = 54.04/1.05 = 51.46

4.1.3.2 Ductility index of EBL beam

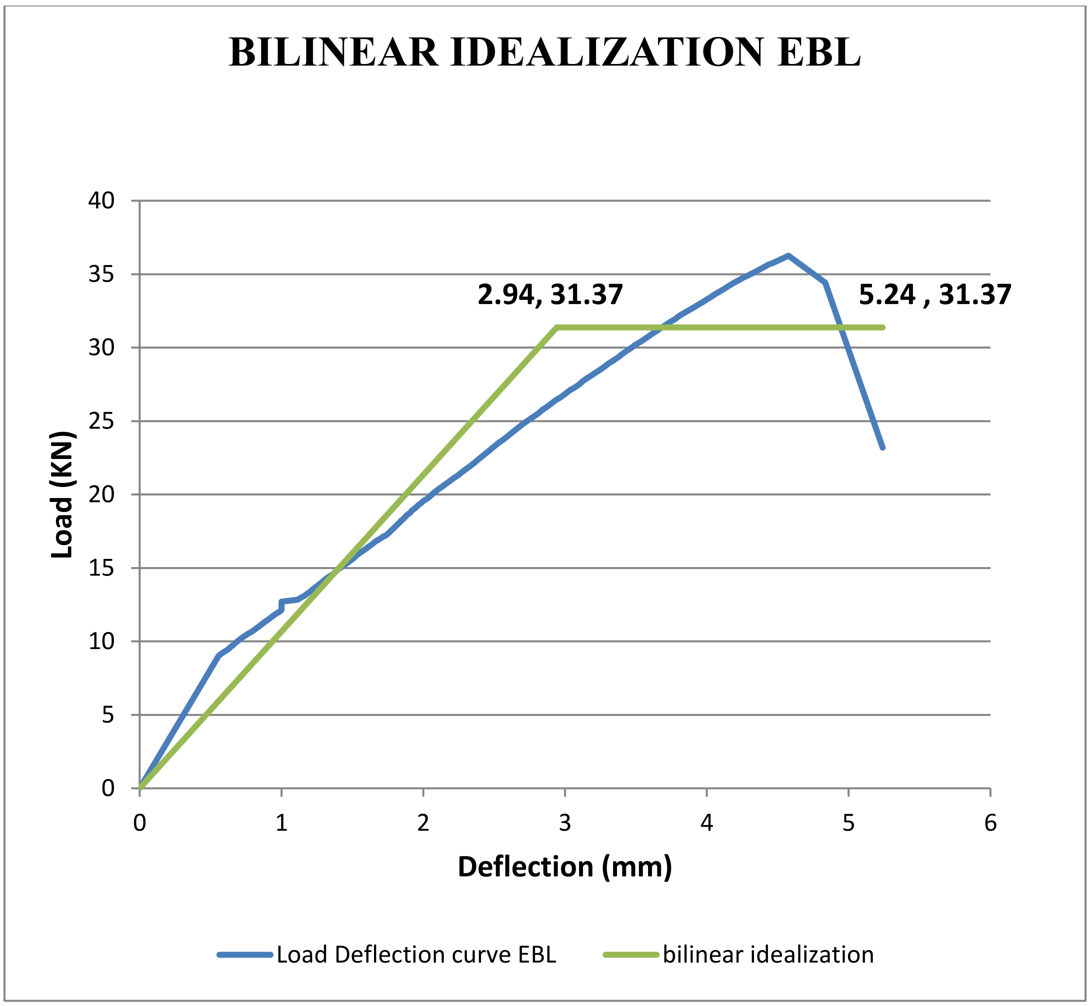


Figure 12 Bilinear idealization curve EBL

In EBL beam, Maximum deflection = 5.24 mm, Yield point deflection = 2.94 mm

So, Ductility index = 5.24/2.94 = 1.78

4.1.3.3 Ductility index of IBL beam

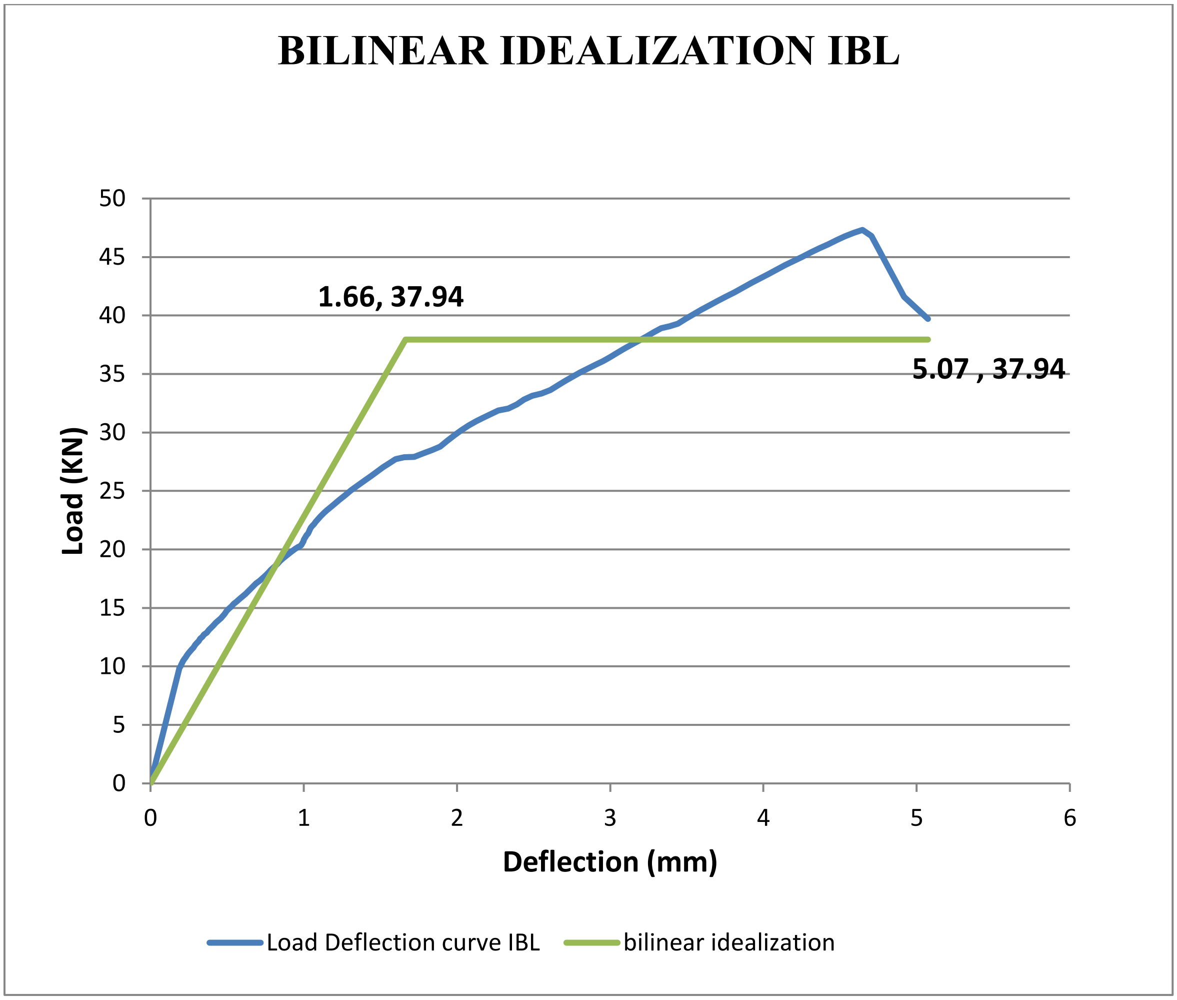


Figure 13 Bilinear idealization curve IBL

In IBL beam, Maximum deflection = 5.07 mm, Yield point deflection = 1.66 mm

So, Ductility index = 5.07/1.66 = 3.05

The ductility values of CB, EBL and IBL Strengthened beams are summarized in the below table.

Table 4 Average ductility of specimens

Specimen	**Deflection at yield point Δ_y (mm)**	**Deflection at ultimate point Δ_u (mm)**	**Ductility μ**	**Average Ductility**
CB-1	1.05	54.04	51.46	50.90
CB-2	1.11	55.89	50.35	
EBL-1	2.94	5.24	1.78	1.84
EBL-2	2.78	5.13	1.89	
IBL-1	1.66	5.07	3.05	3.09
IBL-2	1.58	4.96	3.13	

The decrease in ductility of EBL and IBL strengthened beams is mainly due to the additional tension stiffening of Laminate. As compared to EBL technique, IBL strengthened beams showed greater value of ductility due to resistance in debonding. The value of ductility index of control beam is greater due to greater deflection at ultimate load.

4.1.4 Energy Dissipation:

Area under load deflection curve in monotonic loading is called Energy dissipation (Ahmad et al. 2018).

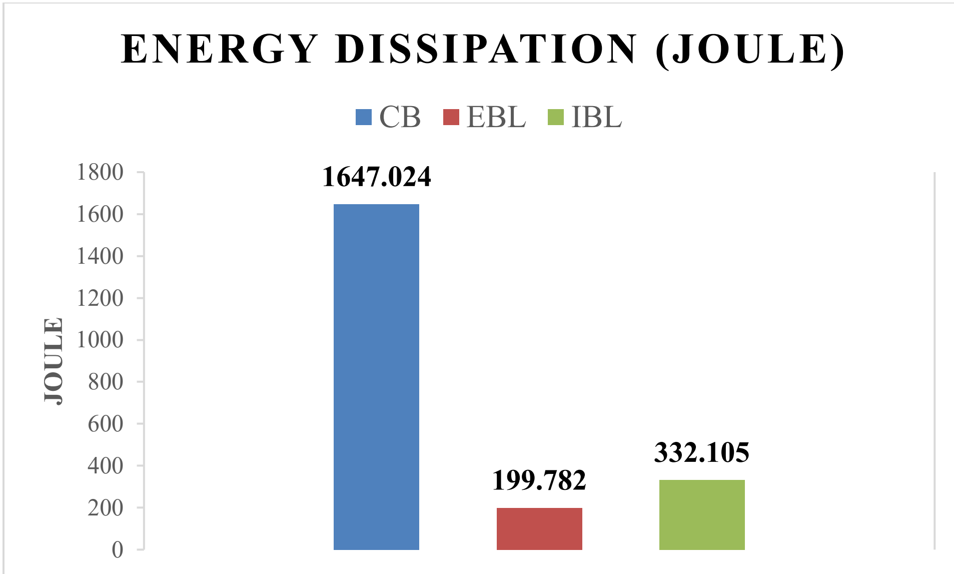


Figure 14 Energy dissipation in CB, EBL and IBL strengthened beams

Due to lesser deflection, the area enclosed under load deflection curve of CFRP Strengthened beams is less as compare to control beams resulting in lower values of energy dissipation. IBL and EBL techniques have almost the same values of deflection; however, the greater energy dissipation in IBL strengthened beams is due to higher ultimate load carrying capacity.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The ultimate load carrying capacity increased with the strengthening of beams. The average ultimate load for control beam was 20.68 KN. The average ultimate load for EBL and IBL technique is 36.25 KN and 47.3 KN respectively. In reference to control beam, EBL and IBL techniques have shown 75.33% and 128.7% increase in ultimate load carrying capacity, respectively.
- The maximum deflection in the strengthened beams decreased with reference to control beams. The average maximum deflection for control beam was 56.40 mm. The average maximum deflection for EBL and IBL technique was 10.07 mm and 10.98 mm respectively.
- The experimental results have shown that IBL technique provides the maximum strength by delaying the de-bonding failure to maximum extent as compared to EBL technique.
- The Ductility index values show that strengthening of beams decreases ductility index and a more brittle failure is induced. The ductility index values of control beam, EBL strengthened beams and IBL strengthened beams are 50.90, 1.84 and 3.09 respectively.
- Energy Dissipation also decreased with strengthening of beams. The values of energy dissipation (Joule) of Control beam, EBL Strengthened beam and IBL Strengthened beam are 1647.02 J, 199.78 J and 332.10 J respectively.

5.2 Recommendations

CFRP strengthening is gaining massive importance in recent times for rehabilitation of damaged structures and providing additional flexural strength to members. Hence, investigation of behavior of CFRP strengthened members is important. Additional work is needed to study the properties of CFRP strengthened beams so that their use for a certain purpose can be more fruitful and safe. These strips can be used at places where deflection is least acceptable but keeping in mind its brittle behavior. Further research is needed to formulate a general expression for easy and swift calculation of upgraded results. Furthermore, analytical model can also be used to verify the experimental results and suggest a base model for calculation of desired parameters. This FEA model shall be flexible so that the various parameters and properties can be changed and the effect of these properties on actual behavior of member can be investigated.

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