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Abstract

In recent years, strengthening of beams using carbon fiber reinforced polymer (CFRP) sheets has attracted considerable attentions around the world. The use of carbon fiber-reinforced polymers (CFRPs) for the strengthening and repair of existing beams is a field with tremendous potential. CFRPs are very durable and are ideally suited for use as external reinforcement.

An experimental study was carried out on flexural strengthening of beams as a part of undergraduate research project. In literature number of reports is available indicating the effectiveness of CFRPs in strengthening of the beams. Current study was performed to verify these reports. This experimental attempt was made to enhance the flexural strength of beams by using Carbon Fibers Reinforced Polymers (CFRP) Sheets. CFRP sheets are applied at the soffit of the beam with an adhesive epoxy for flexural strengthening of beams. In our testing program, six beams were tested. Two were simply reinforced, two were pre-cracked reinforced beams retrofitted with CFRP and two beams were un-cracked reinforced beams retrofitted with CFRP sheets. After performing the tests, the strength of beams retrofitted with CFRP sheets showed 95 percent more strength than simple RC beams. In addition to that, beams retrofitted with CFRP sheets decrease the deflections to 40-60 percent at same loading condition. Also there was significant decrease in crack widths of beams retrofitted with CFRP sheets. Results showed that pre-cracked and un-cracked beams represent nearly similar characteristics and strength. In literature, use of CFRP for other structural elements was also explained. So CFRPs are the best solution for the strength enhancement of weak members. The intent of conducting this research work is that instead of collapsing weak structures, and constructing new ones, we can enhance the strength by CFRPs. Using this technique the strength of weak structural members is enhanced to a great level and it is also very time saving technique. Another purpose is to encourage the use of this technique in Pakistan, because mostly people are hesitant to apply this technique due to cost without considering its effectiveness.

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Chapter 1

Introduction to Carbon Fiber Reinforced Polymers (CFRP)

1.1. General:

In recent years repair and retrofitting of existing structures like structural elements of buildings and bridges, etc., have been amongst the most important challenges in Civil Engineering. The main reasons for the strengthening of structures include upgrading the strength of structural members to withstand underestimated loads and to increase the load carrying capacity of weak members. Also to make structures safe against seismic loads. If the existing structures load carrying capacity of structures decrease due to corrosion or other types of degradation by aging, it will be necessary to strengthen these structures. If there are excessive deflections, cracks may be induced, so structures will may good from strength point of view but will not meet serviceability criteria. So it is also a challenge to avoid excessive deflections and cracks. The use of carbon fiber reinforced polymers (CFRP) in strengthening reinforced concrete (RC) structures has become an increasingly popular retrofit technique. The technique of strengthening reinforced concrete structures by externally bonded CFRP fabric was started in 1980s and has since attracted researchers around the world [1].

Strengthening with externally bonded CFRP fabric has shown to be applicable to many kinds of structures. Currently, this method has been applied to strengthen such structures as column, beams, walls, slabs, etc. The use of external CFRP reinforcement may be classified as flexural strengthening, improving the ductility of compression members, and shear strengthening. It is well known that reinforced concrete beams strengthened with externally bonded fiber-reinforced polymer (FRP) or CFRP to the tension face can exhibit ultimate flexural strength greater than their original flexural strength. However, these FRP and CFRP strengthened beams could lose some of their ductility due to the brittleness of FRP and CFRP plates. Reinforced concrete beams were strengthened with CFRP plates [2, 3].

The high strength-to-weight ratio, resistance to electrochemical corrosion, larger creep strain, good fatigue strength, potential for decreased installation costs and repairs due to lower weight in comparison with steel, and nonmagnetic and non-metallic properties of fiber reinforced polymer (FRP) composites offer a viable alternative to bonding of steel plates. The emergence of high strength epoxies has also enhanced the feasibility of using CFRP sheets and carbon fiber fabric for repair and rehabilitation.

1.1. Carbon Fibers Reinforced Polymers (CFRP):

Fiber reinforced polymers (FRP) is a composite material made of a polymer matrix reinforced with fibers. Normally Carbon, Aramid, Steel and Glass fibers are used for strengthening of beams. Carbon Fibers Reinforced Polymer (CFRP) is polymer matrix reinforced with carbon fibers. Carbon Fiber Reinforced Polymers Carbon fiber reinforced polymer is becoming popular day by day in strengthening and retrofitting of structures due to its special properties like it is very lightweight and show high tensile strength .Carbon fiber is a polymer derived from element carbon. Some people called it graphite fiber. The color of CFRP is black due to carbon. Carbon fiber is produced by combining thousands of very small strings of carbon to produce a filament. Using textile techniques these strings of filament are woven together to create cloth or sheet like materials that are used in composite structure. Carbon Fiber reinforced polymer is either mixed with concrete to strength the concrete structures, or they can be applied on exterior surface of concrete members for additional strength. Epoxy resins are used to apply CFRP on the exterior surfaces of concrete structures. The invention of high strength epoxies has also increased the efficiency of CFRP and resists cracking of concrete elements. Due to brittleness nature of CFRP it decreases the ductility of the structure, but it increases the strength of structures to great extent. CFRP is also less affected by environmental conditions, so it provides longer life and requires less maintenance.

1.3. Why CFRP:

Table 1.1: FRPs Strength Comparison

Tendon type	Units	AFRP	CFRP	GFRP	Prestressing Steel
Fiber		Aramid	Carbon	Glass	Steel
Density	(g/cm^3)	1.28	1.53	2.1	7.85
Tensile Strength	(MPa)	1.25-1.4	2.25-2.55	1.08	1.86
E-Modulus	(GPa)	65-70	142-150	39	210
Bond Strength	(MPa)	10-13	4-20	-	6.6-7.1
Longitudnal Strain	(%)	2.0-3.7	1.3-1.5	2.8	4.0

The above table shows a comparison of some of the characteristics of the different materials available in the market. All of the FRPs give brittle modes of failure in contrast to the pre-stressing steel. The tensile strength of all the materials is comparable, whereas giving high variations in E-modulus to density ratio. The ratio being the highest for CFRP while depicting least longitudinal strain. The bond characteristics are also highest for CFRP as compared to other materials. Also CFRPs provides a much higher strength than other FRPs. All these properties make CFRP a better option over the rest.

1.4. Properties of Carbon fiber:

- Very high strength. (Emean = 210’000 N/mm2)
- Very High modulus elasticity-to-weight ratio.
- Outstanding fatigue resistance.
- Good corrosion resistance.
- High temprature resistance (>150’C)
- High strength-to-weight ratio.
- Excellent durability.
- Increases the ductility of compression members.
- Less effected by heat and environmental effects.
- Lightweight. (Density = 1.60 gm/cm3)
- Low overall thickness, can be coated. (in mm)
- Easy transportation in form of rolls.
- Very easy to install.

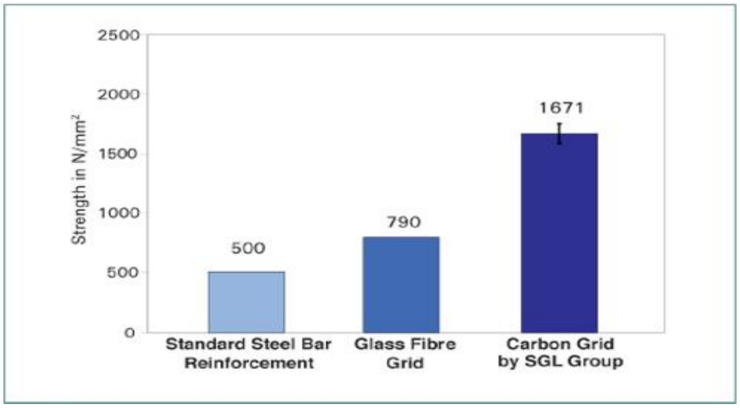


Figure 1-1: Tensie Strength Comparison [12]

1.5. Applications of Carbon fiber:

Carbon fiber has a wide range of applications as it can be formed in many forms and sizes. Some applications of carbon fiber reinforced polymers are:

- Strengthening the shear wall in case of new opening
- Increasing the load carrying capacity and ductility of columns.
- Increasing the load carrying capacity of slabs.
- Increasing the shear and flexure capacity of beams.
- Increasing the strength of columns and girders of bridges.
- Increasing the strength of bracings.
- Increase the strength of high chimneys.
- Increasing the strength of small hydrostatic structures and structures under water.

1.6. CFRP for strengthening of beams

For strengthening beams, two techniques are adopted.

- In order to increase the flexural strength of beams, we have to paste the carbon reinforced polymer sheets at the soffit of the beam. In this way it will provide flexural resistance against the loading.
- FRP strips can be pasted in 'U' shape around the sides and soffit of a beam, or wrapped completely around the beam resulting in higher shear resistance.

1.7. Objectives:

This project explores the flexural behavior of Carbon fiber reinforced polymer (CFRP) sheets for strengthening of beams. Main objectives of this project are:

- ★ To increase the flexural strength of reinforced concrete beams by using Carbon Fiber Reinforced Polymers (CFRP).
- ★ To decrease the deflections and crack widths of RC beams.
- ★ To compare the strength results of simple reinforced concrete beams, pre-cracked beams strengthened with CFRP sheets, and un-cracked beams retrofitted with CFRP sheets.
- ★ Repair of severely damaged structures or strengthening of overloaded structures can be done easily, economically and most important is timely, without collapsing existing structures and building new ones.

Chapter 2

Literature Review

2.1. Beams:

A beam is a rigid Horizontal or inclined structural member spanning a distance between one or more supports, and carrying vertical loads across (transverse to) its longitudinal axis , but can also be used to carry horizontal loads(i.e., loads due to an earthquake or wind, subject to bending stresses from a direction perpendicular to its length.

The loads carried by a beam are transferred to columns, walls, or girders, which then transfer the force to adjacent structural compression members.

2.2. CFRP and its properties:

Carbon Fiber Reinforced Polymer (CFRP) is a Polymer Matrix Composite material reinforced by carbon fibers.

Until the mid-1980s the high cost of carbon fibers limited their use in Portland cement composites. More recently, low cost carbon fibers have been manufactured with petroleum and coal pitch. Even though their cost is still higher then polymeric fibers, carbon fibers have potential for special applications that require high tensile and flexural strength.

Carbon fibers are typically produced in strands (tows) that can contain up to 12,000 individual filaments. These strands are normally spread before incorporation into cement matrices.

Carbon fibers have elastic moduli as high as steel, and are two to three times stronger than steel, yet they are very light, with a specific gravity of about 1.9. They are inert to most chemicals.

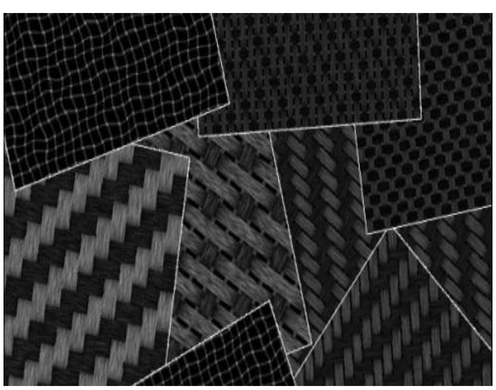


Figure 2-1: Carbon Fibers

Figure 2-2: Sika CarboDur S212

2.3. Effect of thickness and length of CFRP on beam's Strength:

2.3.1. Stiffness of strengthened beams

Deflections of all the CFRP strengthened beams are reduced under the same load as compared with the simple steel beam, which indicates that CFRP can significantly improve stiffness of strengthened RC beams. Variations of the stiffness of beams are not evident prior to tensile cracks appearing on the strengthened beam. The stiffness of the beam then increases with the increase of thickness and length of CFRP after cracking has happened. Longer CFRP can efficiently restrain the crack development than shorter ones and bi-layer strengthening CFRP can efficiently restrain the crack development than uni-layer strengthening ones.

2.3.2. Ductility

Moment versus curvature curves give the macro mechanical properties of members and are reflection of the member ductility. Curvatures increase slowly with the increase of moment and retain the linear relationship prior to cracking of the tensile concrete, but increase rapidly after the concrete cracked. The speed of curvature increase of the simple steel beam is far faster than that of the strengthened beams. There is not much difference among curvature curves when two layers of CFRP are used to strengthen beams. The length of the second strengthening CFRP layer has little influence on curvature.

2.3.3. Stresses of fiber

Loads are carried mainly by concrete prior to the beam cracking. At this time, the slopes of curves of load versus stress are steep. When cracks expand and reinforcing steel yields, more cracks occur in the tensile region, stresses in concrete release and loads are carried by fibers more than by concrete. There is thence, high strength contribution from the fibers. It can be seen from Fig. 6 that bigger stresses exist in the longer fiber under the same load. The stresses in fibers with two-layer strengthening are much smaller than in the case of single layer strengthening. Ultimate stresses of fibers are related with failure mode of strengthened beams. If properly anchored, the fibers will be snapped and strengthening level is low, whilst concrete will crush or have shear fracture when the level of strengthening is relatively higher, depending on the reinforcement ratio and the length of the fiber reinforcement.

2.3.4. Initial cracking load and ultimate load

At the beginning of loading, load is carried more by concrete than by fiber, and with the increase of load, load is carried more by fiber than by concrete. The ultimate load capacity of a concrete beam is improved by fiber strengthening. Initial cracking loads and ultimate loads both increase with the increasing of length of strengthening fiber, but the degree of increase is lower for the former. The increase is not proportional and will approach constant value when the length of fiber reaches some limit. There are some difference between test and numerical results; because non-slip modes is used and shear debonding failure is not considered in calculation, whilst debonding failure happens in testing.

2.4. Strength of Beams

2.4.1. Strength of simple RC beam before cracking:

Normally micro cracks appear in every beam, but in short-span beams supporting only their weight may not crack. These beams are typically analyzed using the gross section properties of the beam (much like a wood or a steel beam). The steel reinforcement is ignored in this case because load comes on steel only when tension concrete fails and cracks appear. So no load will come on steel in this case.

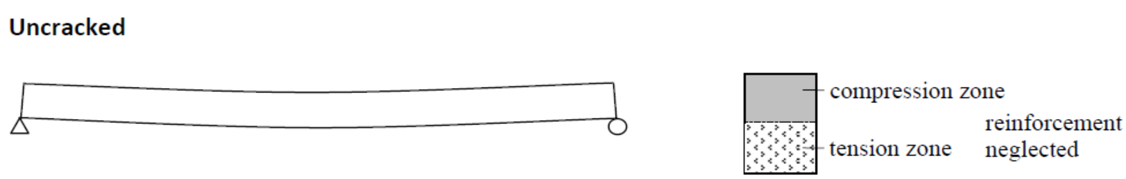


Figure 2-3: Uncracked RC beam

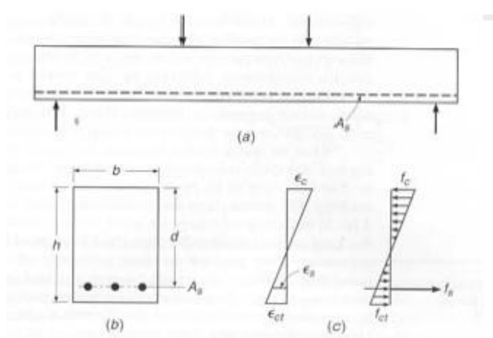


Figure 2-4 Stress, Strain of uncracked RC beam

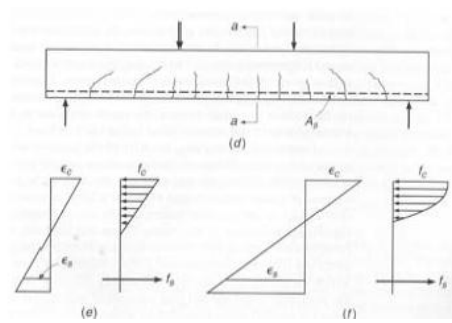


Figure 2-5: Stress, Strain of cracked RC beam

2.4.2. Strength of simple RC beam after cracking

Reinforced concrete consists of two materials, steel and concrete; the tension concrete normally cracked immediately at small loads and load will resisted by steel on tension side. The load-deformation behavior of both the steel and the concrete are non-linear at failure. The figure above shows characteristics of the response of a simply-supported reinforced concrete beam under increasing loads. Our project beams were designed for a load of 80kN, and the factored moment was 16.25kN-m. After testing, one beam failed at a load of 74kN and other at a load of 71kN.

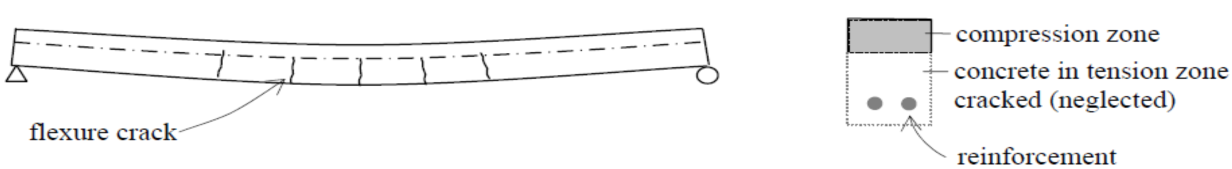
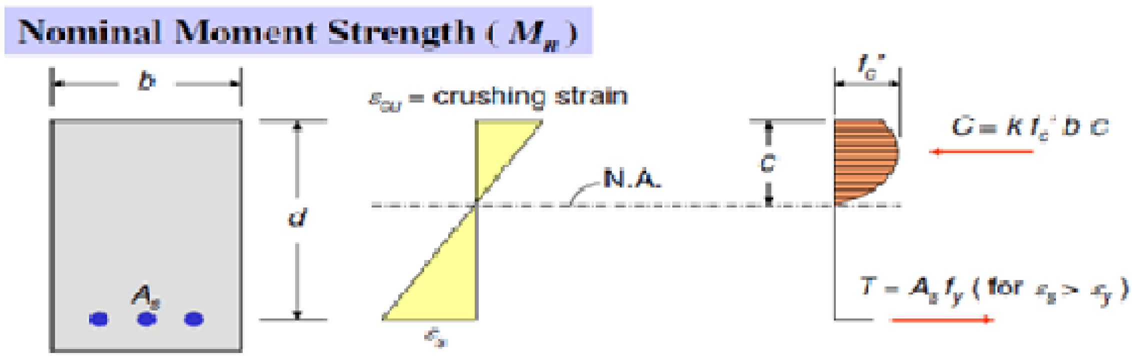
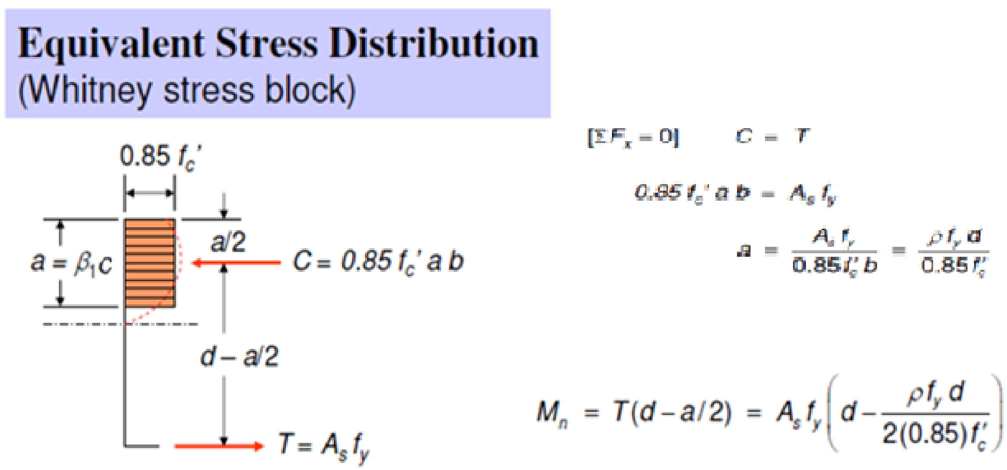


Figure 2-6: Cracked RC beam





2.4.3. Strength of un-cracked Beams with CFRP reinforcement:

This situation corresponds to beams strengthened with CFRP sheets before loading or before the attainment of the first cracking bending moment. In this case load is first resisted by carbon fiber reinforced polymer sheet and later by steel when cracks appear. As CFRP sheet is less ductile so it resists load and allow very small deflections. When cracks start appearing, load will come on steel also. Steel is much ductile, so steel and CFRP together will start resisting the load but deflection will increase rapidly as compare to before cracking. Our project beams were having a moment capacity of 36.79kN-m. After testing, both of the beams failed at a load of 142kN but there were slight differences in strain values.

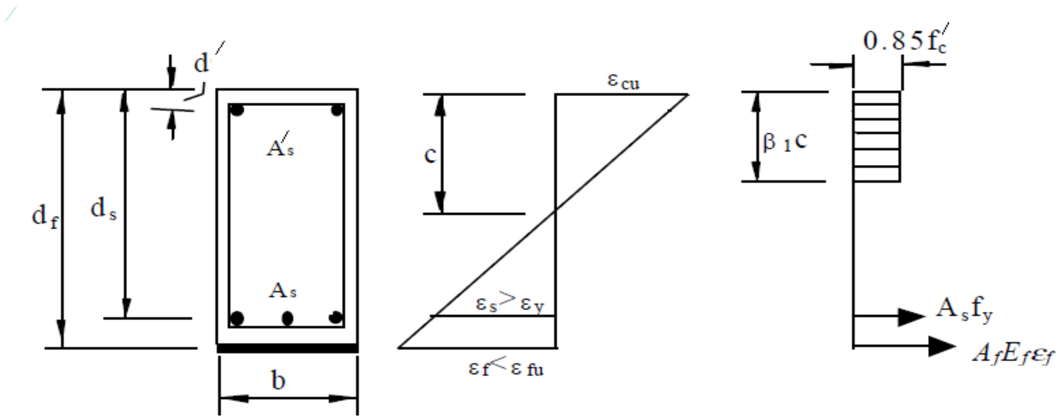


Figure 2-7: RC beam retrofitted with CFRP sheet

So in compression side, concrete resists the compressive force at top of the beam. While on tension side tensile force is resisted by both the tension steel and CFRP sheet. We have to select a specific cross sectional area of the CFRP sheet. If it is too large, the beam will fail from compression side i.e compression concrete crushes. If it is too small, the CFRP rupture may occur. But we need yielding of steel, so we select a suitable area of CFRP sheet, so that beam will not fail in compression, neither CFRP rupture occurs. So at ultimate state, the tension failure will be the yielding of the steel in tension followed by concrete crushing. The ultimate moment of resistance after strengthening is:

$$M_n = 0.85 f'_c b \beta_1 c (d_f - \frac{\beta_1 c}{2}) - A_s f_y (d_f - d_s)$$

2.4.4. Strength of cracked beams with and without CFRP reinforcement:

Cracked beams are of two types, depending on the condition of loading. Under service loads they can crack only from tension side i.e. flexural cracking. Under ultimate stress, along with tension side, they also get cracked from compression side. But we have to deal only with tension side i.e. for flexural cracking only.

When we paste CFRP on a pre cracked beam, in that beam already some cracks appear and steel some load came on steel. So after retrofitting of pre cracked RC beam with CFRP, when load is applied, Load will come on both steel and CFRP. As a result initially the defections increase rapidly. But later on when CFRP will be main resistance against loading, deflections will start increasing slowly. Our project beams were having a moment capacity of 36.79kN-m. After testing, both of the beams failed at a load of 136kN. An interesting thing was that they failed nearly at the same load at which un-cracked beams failed.

2.5. Crack Width, Cracks Spacing, Curvature, and Deflections

2.5.1. Deflections

We want to be able to predict the deflection of beams in bending, because many applications have limitations on the amount of deflection that can be tolerated. Another common need for deflection analysis arises from materials testing, in which the transverse deflection induced by a bending load is measured. If we know the relation expected between the load and the deflection, we can "back out" the material properties (specially the modulus) from the measurement. [11]

The amount of beam deflection depends on the cross-sectional shape of the beam, the materials used and its stiffness, and the weight and position of any object placed on it as well as the more obvious applied loads and supports. Deflections are of interest at service load levels, generally speaking there are two limit states of strength and serviceability. If a structure approaches a limit state, it ceases to be deficient in that regard. With availability of high strength material (steel and concrete) and by using strength design methods usually slender member dimensions are obtained. Though such members are good enough with respect to strength limit state, they show excessive deflections even at service loads.

Structural beams can be exposed to different types of stress. Tension is a force that pulls the beam apart, which steel can resist well, but concrete cannot. Rebar is placed inside reinforced concrete structures to resist tension forces. The amount of beam deflection depends on the size of the beam, the materials used, and the weight and position of any object placed on it. A concrete floor poured on a RC beam structure may have little deflection, because the weight of the floor is distributed, or spread out evenly over the entire beam surface. A beam can deflect more if a large weight is placed at a point furthest away from where the beam is supported or attached to the building. This type of load is very important for beam deflection calculations, and can require additional beams or supporting walls below the maximum deflection point.

At service loads, the flexural member behaves as a cracked section and therefore the accurate value of I are needed to be calculated. There are two approaches to a realistic value of I.

- Sketch a transformed section and find I after locating neutral axis location.
- Follow the ACI code guidelines. For beam: I = 0.35 Ig.

2.5.1.1 Importance of Deflections calculations

Deflections of horizontal sub-systems are of considerable significance. High deflections may create cracking of masonry, difficulty in the openings of doors and windows, pounding of water during cleaning process in addition to being looking unpleasant. If the actual deflections exceed the maximum allowable deflections, the structural sub-systems may be declared unserviceable.

Immediate deflection of simply supported RC beam subjected to two point loading is:[10]

$$\delta = Fa^2(3L - 4a)/6EI$$

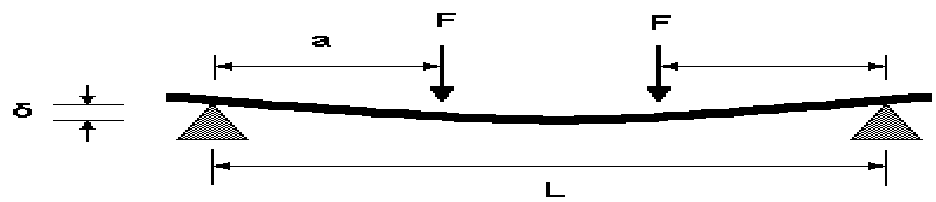


Figure 2-8: Deflection under Third point loading

Furthermore, the deflections of the beams can also be evaluated by means of the principle of virtual work as,

$$\Delta = \int_0^L xMdz$$

Where, L=clear span of the beam

And M=bending moment corresponding to a unit load applied at the section where the deflection are needed to be evaluated.

The above integral is numerically solved using Simpson's rule by dividing the span of the beam into a number of small sections along its length L; keeping the length of the sections sufficiently small so as to keep the bending moment constant in each of the divisions.[5]

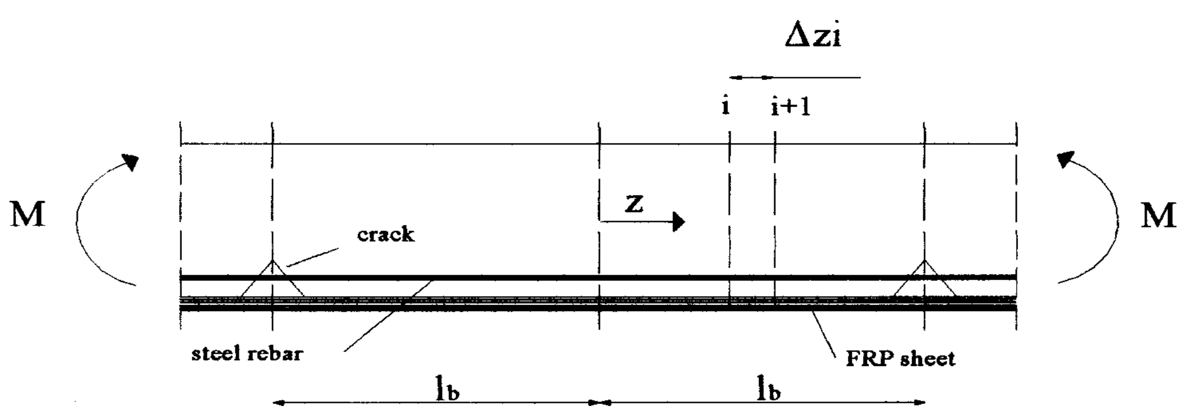


Figure 2-9 Evaluation of Development length

2.5.2. Crack Width:

The cracks width of beams at the CFRP sheet level is two times the slip value at the cracked section.[6]

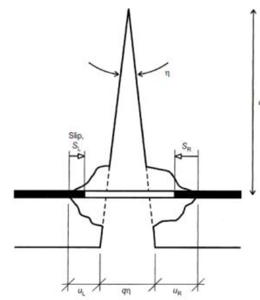
Crack Width=2u

Where, u=slip value

2.5.3 Crack Curvature:

The mean curvature of the cracked element is evaluated as, [6]

$$X = \frac{1}{lb\ i=1,n} \Sigma \frac{\varepsilon ci \varepsilon si}{h}$$



Where, εci = strain of the concrete at the compression side of beam,

εsi= strain of the steel reinforcement

and h=effective height of the beam.

Here, the development length (lb) can be calculated using the equation, lb=$\Sigma i=1,n\ \Delta zi$.

Where, n= number of discrete subintervals considered in the numerical procedure.

2.5.4 Crack-based analysis of a single, flexural crack

The crack-based analysis can be explained using a single flexural crack, as shown in Fig. 1. The assembly consists of a crack of height q and opening η, contained within a beam of total height d and effective depth dE, splitting the beam into two rigid blocks which can rotate relative to each other due to the opening η, under the actions of the external axial forces N and moments M.

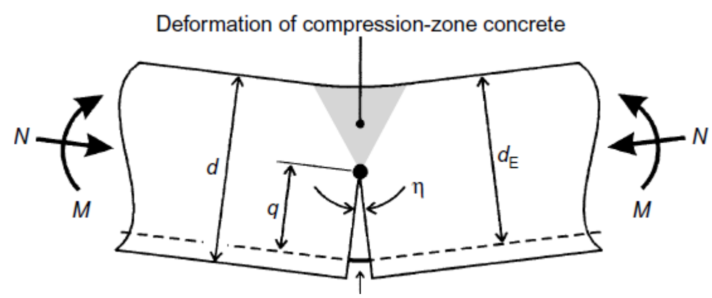


Figure 2-10: Compression zone model

The magnitude of the external actions (M, N) for each crack configuration (q, η) is governed by the compatibility in the region of the crack. In particular, two components of the beam require consideration

(a) Compatibility of the compression-zone concrete

(b) Compatibility of the reinforcement with the concrete to either side of the crack (or axial compatibility of the flexural reinforcement).

2.6. Failure Modes:

There are different possible modes of failure of a simply reinforced concrete beam as well as beam strengthened with carbon fiber reinforced polymers (CFRP). When we are designing a simple reinforced beam, we have to design it such that it will be under reinforced. In case of under reinforced beam a tension failure is indicated, while in case of over reinforced beam compression failure is indicated. As steel is strong in tension so, steel is provided in tension (bottom) side, while concrete is strong in compression. Also steel is ductile and concrete is brittle material. We prefer ***under reinforced*** beam because in this way steel will yield first and the beam failure will be of ***ductile*** nature. If we design it ***over reinforced*** beam the compression concrete will fail first and the failure mode will be ***brittle*** and sudden. So to avoid this sudden failure we design under reinforced beam, so that yielding of steel first induces much deflection and then later on it will fail.

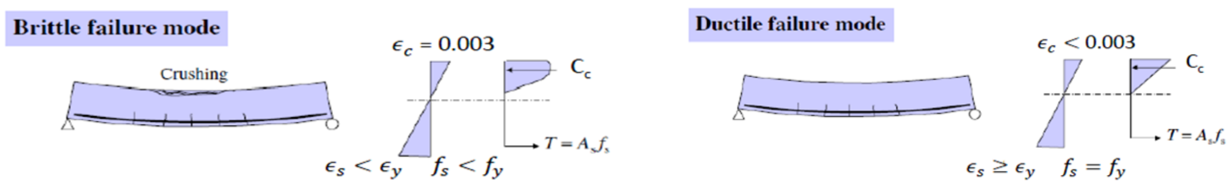


Figure 2-11: Brittle and Ductile Failure Mode

When the simply reinforced beam is designed it should be checked for both shear and flexure. Flexure design of the beam depends on the moment induced due to loading. To avoid ***flexural failure*** the moment capacity of the beam should be more than the induced moment due to loading. Longitudinal steel is used to enhance the flexural capacity of beam. More the longitudinal steel more will be the flexural strength. Sometimes, due to very thin sections, we have to provide steel also in the compression zone.

Figure 2-12: Flexure Failure

Other type of failure is shear failure. In ***shear failure*** the beam fails due to high shear strength at the ends of the simply supported beam. If the shear stress exceeds the shear capacity of the beam, it will fail in shear. We can provide shear stirrups (hooks) in the beams to avoid shear failure of the beam. According to ACI code, to avoid shear failure in beam, the clear span of the beam should be atleast more than 4 times the effective depth of the beam.

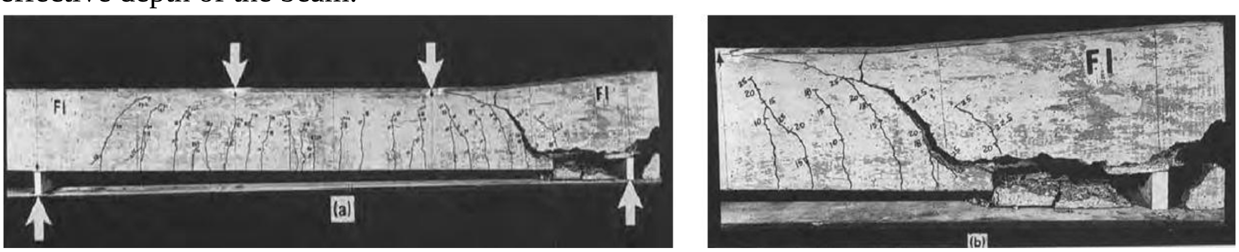


Figure 2-13: Shear Failure

Normally shear failure is not preferred. Whenever we design a beam, we design it in such a way that if it fails, I will fail in flexure. Our testing program also includes flexural testing. We have to test the beams such that they will fail in flexure. That's why we provide sufficient shear reinforcement to avoid shear failure.

Now coming over to beam strengthened with carbon reinforced fiber polymers (CFRP). After strengthening the beam with CFRP there are four possible modes of faiure.

- Peeling Failure
- Debonding failure
- CFRP Rupture
- Concrete Crushing

2.6.1 Peeling Failure:

Peeling failure normally occurs when the CFRP sheets are not provided throughout the clear span. This type of failure always starts from the end of the CFRP sheets, because the dowel action of the stirrups causes the weakest plane forms right under the longitudinal steel reinforcement. [7]

Figure 2-14: Peeling Failure of Concrete Cover

When CFRP fabrics are applied to the soffit of the concrete beam, they introduce shear transfer to the concrete/epoxy interface. The point (position) where CFRP fabric terminates (ends), a high stress is concentrated in the concrete due to change in stiffness and discontinuity of beam curvature that initiates cracks as a result the CFRP fabrics are separated from the beam. The mechanism of the peeling failure for third point loading is described below in a sequence.

- When the loads are applied, for properly under reinforced designed beam, uniformly spaced cracks developed in the constant bending moment zone and some small cracks in the shear span (Fig. 2a).

- as a result of shear stress in shear span (at ends of beam) and normal stress concentrations at the CFRP fabric end, the concrete rupture strength at the tension face exceeded at this point and a crack formed near the CFRP fabric end. This crack at the end of CFRP fabric widened with increasing magnitude of load and propagated to the level of the internal steel reinforcement of the beam (Fig. 2b).

- In this way separate concrete cover blocks were formed between two adjacent cracks, after further increasing the loads, the end concrete cover block peeled away (Fig. 2c).

- The same process is continued sequentially for the rest of the concrete cover blocks, and along with CFRP fabric the concrete cover below the tension reinforcement is also separated from the beam. (Fig. 4d).

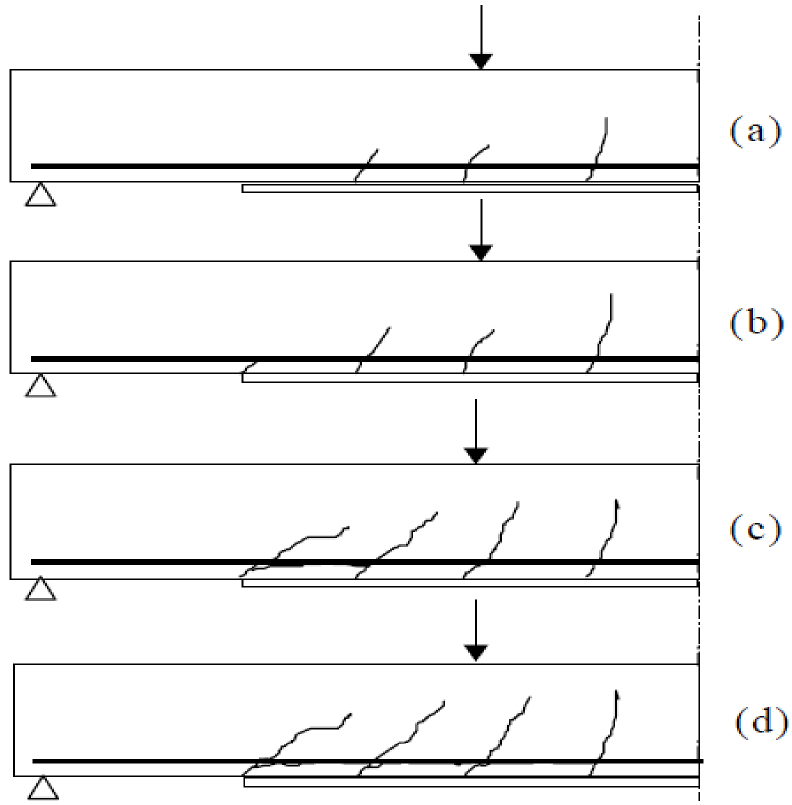


Figure 2-15: Procedure of Peeling Failure Propagation

2.6.2 De-bonding Failure:

De-bonding failure normally occurs between concrete and CFRP fabric when CFRP sheets are provided throughout the length of the beam (clear span). So the stress concentration will be less at the end of the CFRP fabrics. Under the point of loading, some cracks appear that propagates at an inclined angle. When these cracks reach the soffit of the beam, de-bonding of the CFRP sheets start that will propagate up to the end of the CFRP sheet.[7]

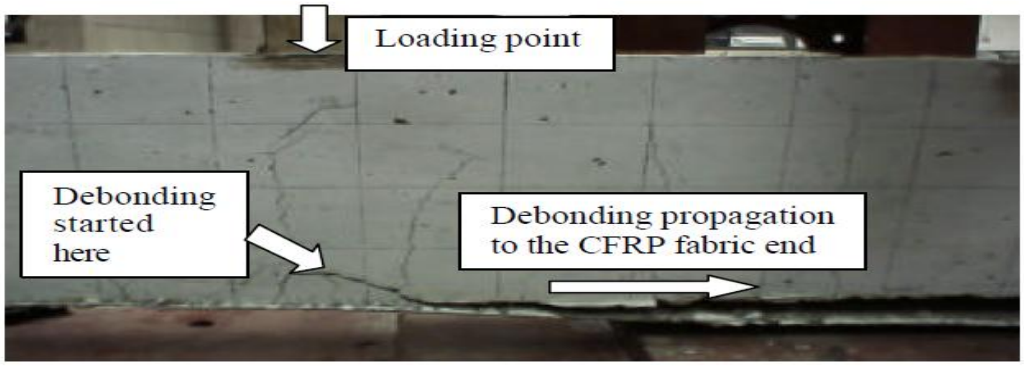


Figure 2-16: Debonding Failure between FRP Fabric and Concrete

Debonding failure occurred due to susceptibility of the interface relative to vertical displacements of shear cracks in the concrete beam. If the CFRP fabrics are extended throughout the clear span of the beam the stress concentrations will be less at the CFRP cutoff points and shear crack may not developed at these points. But within the shear span, the shear stress concentration around the flexural or shear crack mouth displacements will cause the local debonding of the CFRP fabric along concrete-fabric interface (Fig. 2.7).

The flexural cracks developed in regions of the beam in which there is large moment that starts the interfacial fracture which propagates between the concrete and CFRP fabric interface (Fig. 2.7b). Crack mouths located in regions of the beam with mixed shear and moments can subject an interfacial crack to mixed mode loading (Fig. 2.7c).

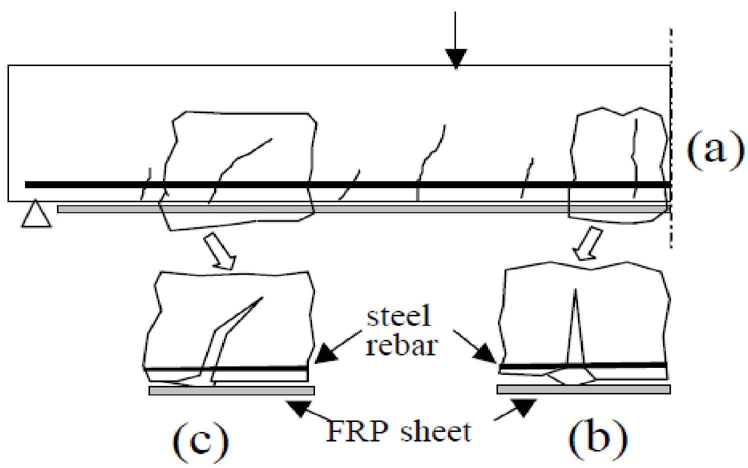


Figure 2-17: Debonding Failure between FRP Fabric and Concrete

2.6.3 CFRP Rupture Failure:

CFRP sheet rupture failure occurs when the area of CFRP fabric is very less. For under reinforced members there is a tension type failure. In case of simply reinforced concrete beam the load is carried mainly by tension steel, while in CFRP strengthened beam the CFRP sheet carries the most load. As it is less ductile so it will resist any deformation in it and hence the bending in the beam so, less load will come on steel and more on CFRP sheet. So there should be enough cross section of the CFRP sheets that can carry the load and avoid CFRP rupture failure.[5]

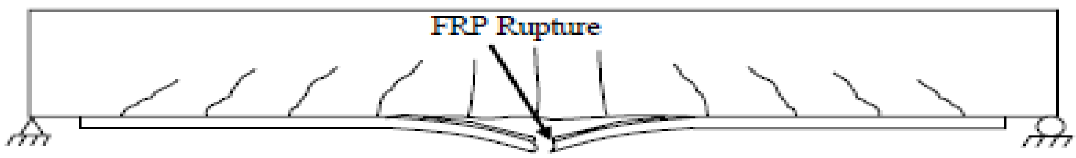


Figure 2-18: CFRP Rupture Failure

In order to avoid CFRP rupture failure, the centroid of the CFRP coated beam is located by this formula:

$$cf = d_f \frac{\varepsilon cu}{\varepsilon cu + \varepsilon fu}$$

and the minimum cross-sectional area of CFRP required is:

$$Af_{,min} = \frac{0.85 f c' b \beta cf - Asfy}{f fu}$$

So, we have to provide at least this or more area, otherwise the CFRP sheet provided at the bottom of bottom of the beam will break.

2.6.4 Concrete Crushing:

Crushing occurs in the compression concrete, if the cross section area of CFRP sheet is too large. More the area of CFRP sheet, more it will resist the loads and deflections. So when the load is applied on the beam, due to large cross sectional area of the CFRP sheet there is no or very small deflections in the beam the punching effect of the load increases on the top compression side of the beam and if the concrete is of low strength then crushing of concrete will start.[5]

Figure 2-19: Crushing of compressive concrete

In order to avoid concrete crushing failure, the centroid of the CFRP coated beam is located by this formula:

$$cb = d_s \frac{\varepsilon cu}{\varepsilon cu + \varepsilon y}$$

and the minimum cross-sectional area of CFRP required is:

$$Af_{,max} = \frac{0.75\ (0.85 f c' b \beta cb - Asfy}{f fb}$$

So, we have to provide at most this or less area than the above, otherwise crushing will start in the compression side of the concrete and static equilibrium of the beam may get disturbed.

In order to avoid all these type of failures we should use the proper epoxy that can hold the bond between CFRP and beam and avoid debonding failure when loading is applied. We should also have to provide CFRP sheet throughout the beam length to avoid peeling off failure. Finally the cross sectional area of CFRP should be adequate, neither it will be too less that CFRP rupture occurs, nor it will be too large that compression concrete crushes.

2.7. Flexure Testing:

The basic purpose of flexural testing is to find out, how the material will react when it is subjected to some kind of bending, flexural strength of the material or modulus of rupture of the material. Generally it is also called transverse testing or modulus of rupture testing. In this type of testing load is applied perpendicular to the longitudinal axis of the element. The strength determined can vary depending upon specimen size, preparation, moisture condition and curing differences or where the beam has been molded or sawed to size.

Due to relatively simple methodology for testing and equipment needed this type of testing is commonly and frequently used for testing resins and fiber composites for their mechanical properties. by using relatively shorter beams ,flexure tests can give us an idea about the inter laminar shear strength of the laminate. Inter laminar fracture toughness of the laminate can also be determined through flexure testing which ultimately can be helpful in assessing the complex structures for their fatigue, strength and stiffness response.

Components and materials like PVC pipes, polymer bars or rods, automotive and aeronautical structural beams, composites, concrete beams etc. Depending upon the type of material being tested there are variety of industry standards. Bending tests generally measure the ductility of the materials. Bending tests can also be used to determine the load at specific limit and then comparing to the load specifications. This helps in determining whether a material is pass or fail. This test may also include loading the material to its breaking limit and then measuring the load and deflection for that breaking point.

2.7.1 Benefits of flexural testing:

The benefits of flexural testing are:

- It helps in ensuring the integrity and safety of the components and products.
- It can give us an idea about the fitness of different materials, products and components for their use.
- It reduces material costs and helps in achieving lean manufacturing goals.
- It ensures compliance with industry standards.

2.7.2 Standards:

Organizations such as ISO, BS, and ASTM etc have developed certain standards for flexural strength testing. Some of them are:

- ASTM C67 – 08: It discusses the methods for Sampling and Testing Brick and Structural Clay Tile.
- ASTM C674 - 88(2006): These are basically standard test methods for flexural properties of ceramic white ware materials.
- BS EN 2746:1998: It includes three point bending test methods for glass fiber reinforced plastics.
- C31/C31M: It describes the practice for making and curing concrete test specimens in the field.
- C192/C192M: It includes practice for making and curing concrete test specimens in the laboratory.
- E4: It includes practices for force verification of testing machines.
- C617: It includes practice for capping cylindrical concrete specimens.

2.7.3 Need of flexural test:

The force required to bend a beam is generally measured through flexure testing under centre point or third point loading. The data of these tests is often used to check the suitability of materials for different parts and elements which have to support loads without bending.

2.7.4 Types of flexural testing:

Depending upon the loading pattern they are classified into two categories:

- Third point flexural testing
- Three point flexural testing

2.7.5 Third point flexural testing:

In this type of testing two parallel supports support the specimen with rectangular or flat cross section. Two point loads are applied at a distance of 1/3 of the span length each from the face of the beam. The beams are generally cast and cured in the field in order to cater field conditions and then the beams are taken to labs for testing.

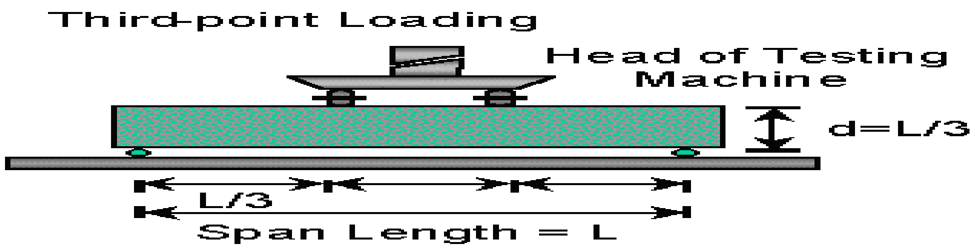


Figure 2-20:Third Point Loading

In four point loading the stress is concentrated at the points of loading. However there is constant or uniform bending moment between the inner two loading points. A diagram showing the shear stress and bending moment in case of four point loading is as under:

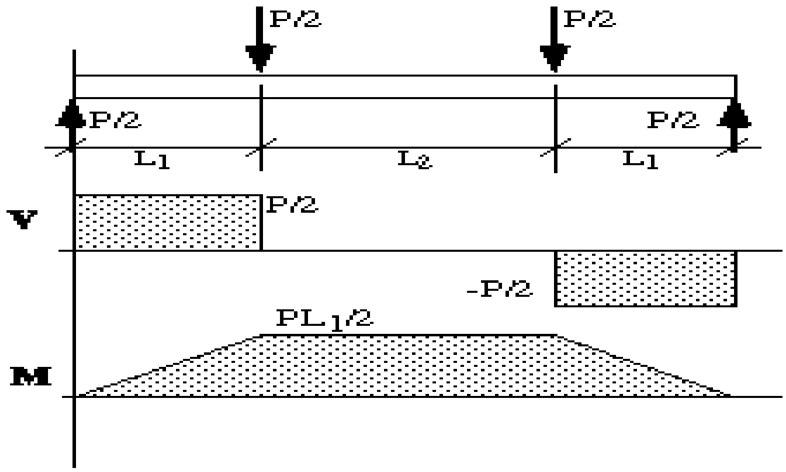


Figure 2-21: SFD and BMD under Third point loading

In four point flexural testing we consider that the properties of the material along the thickness of the beam are constant and similar. In this kind of situation the normal stress changes linearly. The normal stress is maximum at top and bottom ends of the cross section i.e. compression and tension. The Value of normal stress becomes zero at midpoint which is generally called the neutral axis. An idea about the change in shear and normal stress can be made by viewing the following diagram:

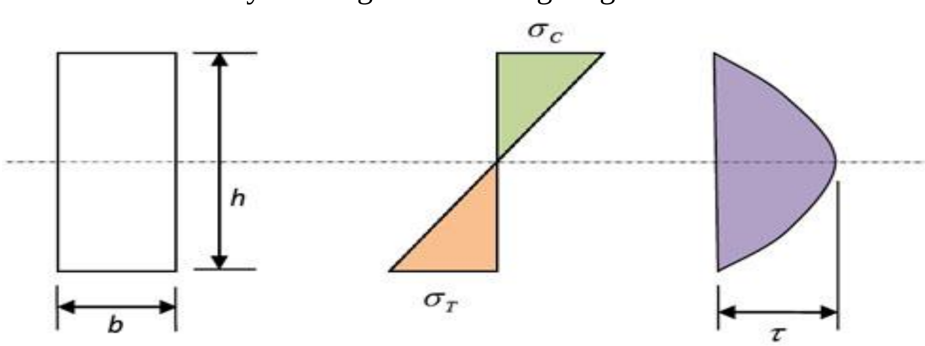


Figure 2-22: Shear and Normal Stress

The maximum value of tensile or compressive stress can be obtained by the following equation:

$$|\sigma_C| = |\sigma_T| = \frac{6M}{bh^2}$$

Where M= Bending Moment, b= specimen width, h= specimen thickness, σ_T= Tensile normal stress and σ_C= Compressive normal stress

2.7.6 Three point flexural test:

In this type of flexural test the specimen is placed over two parallel supports and load is applied vertically on the mid span. The advantage of this method is that the sample can be prepared comfortably and test can be conducted easily. However the disadvantage of this test includes the sensitivity of the results concerning the loading and specimen geometry. The other disadvantage is that the result is also sensitive to the amount of strain produced.

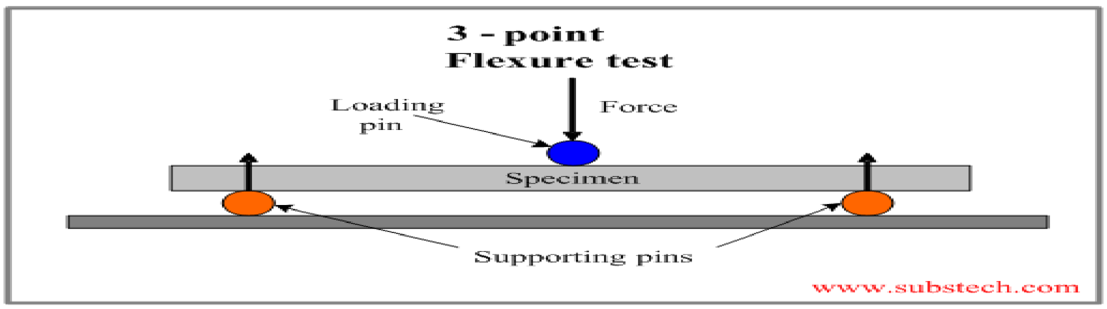


Figure 2-23: Single point loading

The shear force and bending moment diagram in case of three point loading can be idealizes as under:

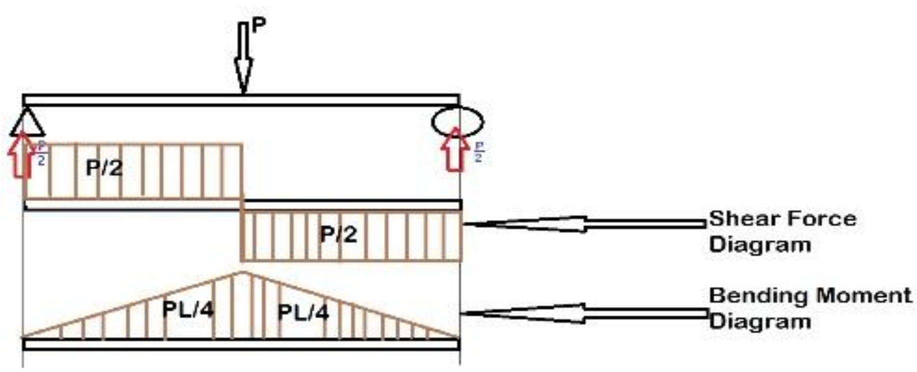


Figure 2-24: Shear force and Bending Moment Diagram

This test results in concentration of stress at the mid span i.e. the maximum value of stress is at the middle point of the span and at other points the value is smaller than the maximum value.

2.7.7 Note:

Flexure test generally creates tensile stress at the lower side while compressive stress at the upper side of the specimen. Due to this reason a shear stress area is created along the midline. The shear stress must be minimized in order to ensure that the primary failure comes from compressive or tensile stress. Shear stress can be minimized by controlling the span to depth ratio that is the length of the outer span divided by the depth (height) of the specimen. Acceptable value for most of the materials is S/d =16 however for some materials the values required may be 32 to 64 in order to keep the shear low enough.

2.7.8 Best loading pattern for flexure testing:

Four point Flexural test results in pure bending loading and this is due to the fact that there is no shear force between the loading points and inter laminar shear stress. The bending moment is constant between the loading points. These conditions give rise to pure bending loading which is generally desired.

2.7.9 Flexure testing apparatus:

Description of different types of flexural testing machines is as under:

2.7.9.1 Flexural testing machine (150kN):

This type of flexural testing machine has a capacity of 150kN and it is used for the flexural testing of beams. The maximum size of the beam which can be tested through this machine is 150x150x600mm.

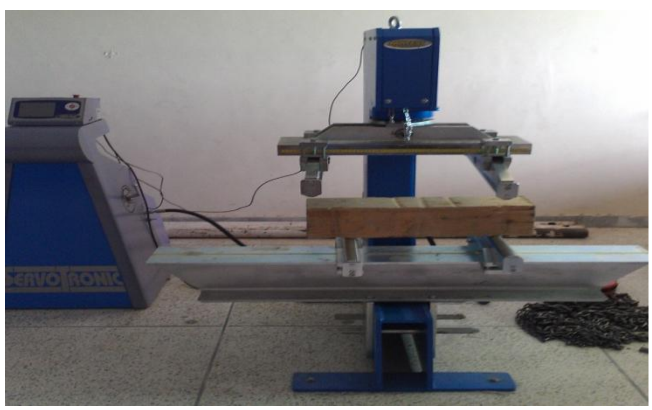


Figure 2-25: Flexural testing machine (150kN)

2.7.9.2 Flexural testing machine (200kN):

This machine has the capacity of 200kN and is used for the flexural testing of concrete beams. Maximum size of the concrete beam which can be tested from this machine is 150x150x600/750 mm. This machine can also be used for the testing of other components like masonry units, slabs, tiles etc.

Figure 2-26: Flexural testing machine (200kN)

2.7.9.3 Universal flexural frame (100-150kn):

This machine has two versions i.e. one with pressure transducer and the other with load cell. The pressure transducer has a capacity of 150kN. On the other hand the load cell has a capacity of 100kN. High accuracy of testing can be achieved through load cell for the components possessing low strength. The multipurpose flexural frame can be used in a variety of ways either in concrete beams meeting the standards and specifications or other components of concrete structures since it has quite large space for testing.

Figure 2-27: Universal flexural frame (100-150kn)

2.7.9.4 Deflection measuring devices:

There are different devices which can be manually installed on the beam if required to measure the deflections during the flexural testing procedure. Some of them are as under:

2.7.9.5 Mechanical Dial Gauge:

The strains in of concrete beams can be measured through this device. Strain gauges neither records data digitally not electronically. Strain gauges are mechanical analog devices, from which readings are taken manually. The strain gauge we use have a least count of 0.01mm.

Figure 2-28: Mechanical Dial Gauge

2.7.9.6 Vibrating wire embedment strain gauge:

Strain in the structures of concrete can also be measured through this device. This device is generally fixed in the component during the casting or in other words direct burial. Different types of concrete structure components where this device can be used include concrete beams subjected to loads, columns, piles etc.

Figure 2-29: Vibrating wire embedment strain gauge

2.7.9.7 LVDT:

LVDT stands for Linear Variable Displacement Transducer. It is a displacement based device not strain based. Transducers are basically devices which convert one form of energy into another. So LVDT's convert displacement into voltage. This device can be used during the testing of beams for displacement measurements.

Figure 2-30: LVDT

2.7.9.8. Crack measuring microscope:

Crack measuring microscope is used to measure crack widths in concrete. There is an adjustable light source attached with it which provides a well-illuminated image of cracks. The focus of the image is adjusted by turning the knob. This crack measuring microscope is very easy and convenient to use.

Figure 2-31: Crack Microscope

2.8. ACI code requirements:

There are different ACI code requirements which must be taken into account while designing beam for flexure testing. Those requirements are discussed below:

2.8.1 Strength:

According to ACI code the strength requirements can be depicted as under

$$\varphi \text{ (Nominal Strength)} \geq U$$

Here U is the strength required and φ is the reduction factor.

ACI 318 9.1.1 suggests that the design of a member should be such that it should have strength designed at least equal to the strength which is obtained from the calculations made on the basis of factored forces and factored loads.

2.8.2 Design strength (ACI 318 9.3):

The design strength is basically the nominal strength. It is calculated keeping in view all the requirements and clauses discussed in the code. After calculating the nominal strength it is multiplied by a factor less than one and is called strength reduction factor. The values of strength reduction factor vary with the situation. Some values for different situations are discussed below:

For sections which are compression controlled there are generally two conditions

For members which have spiral reinforcement the value of the factor φ is 0.70(ACI 318 9.3.3.2a)

For other members the value of φ is 0.65(ACI 318 9.3.3.2b).

For sections which are under tension controlled situation the value for the factor φ is 0.9(ACI 318 9.3.2.1). This is the situation in which the steel strain is equal to or greater than the concrete yield strain.

2.8.3 Required strength (ACI 318 9.2):

This strength generally expresses the effect of factored forces or loads. Loads which are mentioned in the codes for building design are called factored loads and are multiplied with the factors which are suitable in the particular situation. This strength is generally given in relation with internal forces and moments, or factored loads.

2.8.4 Length and width (ACI 318 10.4):

The maximum distance limitation is 50 b for lateral supports, where b is compression flange minimum width. Beams are often loaded eccentrically which can create deformations and stresses which are destructive for deep or narrow beams .So in this type of situation the limitation for lateral support distance comes into play and it should be less than 50 times compression flange minimum width.

2.8.5 Minimum reinforcement (ACI 318 10.5):

This minimum reinforcement is required for the members for architectural requirements or for any other reason where the cross section required is shorter than the cross section of the beam designed for strength. When very small tensile reinforcement is provided, the moment strength calculated for the section which is not reinforced ,depending upon rupture modulus is greater than the value calculated for the section which which is reinforced depending upon analysis of cracked section. Sudden failure happens due to this situation. A minimum amount of reinforcement is provided in negative moment and positive moment locations in order to prevent this kind of failure.

2.8.6 Maximum reinforcement (ACI 318 10.3.5):

In the situation when the concrete strain reaches to its ultimate value i.e. 0.003 the code requires steel to have sufficient strain at that point. The reason behind this check is to have suitable ductility in the beams. Steel strain is usually taken greater than 0.005 for practical reasons otherwise φ would have to be decreased.
After calculating neutral axis, the strain in the tensile reinforcement can be obtained by using strain diagram. The strain in the steel generally reduces by increasing the amount of steel reinforcement for a particular section of beam. For the case of pure flexure the code provides restriction over the amount of steel used by providing limitation for the allowable strain in steel.

2.8.7 Limitation for spacing of reinforcement (ACI 318 7.6):

This clause of the ACI code gives us spacing requirements for different situations of reinforcement. The purpose of this limitation is to provide comfort for concrete flow. This limitation will help concrete to move with comfort between the bars.

2.8.8 Maximum crack width (ACI 318 r10.6.4):

There is no specific value for crack width. However before 1999 a maximum value of 0.016in was used in order to calculate the distribution of reinforcement. Now-a-days the code provisions are meant to limit the width of the surface cracks to an acceptable level.

2.9. Major Projects supervised for repair & restoration with CFRP in PAKISTAN

- Park tower,F-10, Islamabad
- Mustafa Tower,G-8 markaz, Islamabad
- Jamia mosque ,naval headquarters, Islamabad
- Sailors Barracks,naval headquarters, Islamabad
- College of safari villas, Rawalpindi
- PAF Jinnah camp college, Rawalpindi
- AWT plaza , mall road ,Rawalpindi
- Frobels intel school, H-8, Islamabad
- Head start school,F-7 , Islamabad
- Kohinoor textile mills,Gujjar khan
- BTS cell tower at chakwal and talla Gang
- Telenor switch building at fazale haq road, Islamabad
- Pakistan military academy kakul,Abbottabad

- ✪ Nandipur hyderal power project
- ✪ Mangla dam hyderal power project
- ✪ Mari gas head office, Mauve area Islamabad
- ✪ Permanent art gallery ,Lahore
- ✪ Issa cement factory, Hyderabad
- ✪ Karachi port trust Wharf
- ✪ Telenor building ,Faisalabad
- ✪ Allama iqbal airport ,Lahore
- ✪ Tariq heights , Islamabad
- ✪ Fauji fertilizer factory , sadiqabad
- ✪ GHQ gymnasium ,Islamabad
- ✪ Taunsa barrage, Multan
- ✪ Pakistan railways bridge , Tando Adam
- ✪ Pakistan railways bridge, Muridke
- ✪ Pak-American fertilizer ,Mianwali

Chapter 3

Methodology, Testing and Design

We have to test the flexural strength of beams, so first of all we have to design the beam in flexure and also provide adequate shear reinforcement to avoid shear failure of the beams.

3.1. Testing Program:

Our testing program includes flexural testing of six beams. The location of testing the beams was NIT transportation lab, where we performed the testing on universal testing machine by attaching specific assembly of beam testing with it. The beams classification was that two beams are taken as controlled beams that are simply reinforced concrete beams. Two beams are initially cracked by applying loads more than service loads then they are retrofitted with Carbon Fiber Reinforced Polymers (CFRP) sheets. On two beams, CFRP sheets are initially applied without applying any loading and cracking of these beams. All beams are of same sizes and same reinforcement details.

The beam's sizes and reinforcement details are summarized in table.

Table3.1: Beams size and reinforcement details

Size of Beams (mm)	No. of specimens	Bottom Reinforcement	Top Reinforcement	Stirrups Detail
200*250*1200	6	2 - #4 φ	-	#2 – 90mm c/c

3.1.1 Samples Detail:

As mentioned in the above table all the six specimens are of same sizes i.e. width 200mm, height 250mm and length 1200mm. As they are singly reinforced beams so no compression reinforcement is provided at the top side. While at tension side 2 - #4 bars are provided at the bottom side. The stirrups provided are of #2 provided at 90mm c/c spacing in the side spans. In mid span there was no need to provide stirrups because shear force is zero in that span, but for safety we provide #2 at 110mm c/c. The details of specimens and their labeling are displayed in table.

Table3.2: Beams Labeling and Experimental Parameters

Beam Label	Beam Size	Longitudinal Reinforcement	Stirrups Detail	Arrangement	Remarks
CB1	200*250*1200	2#4	#2 – 90mm c/c	Third point loading	(Control) Simple RC Beam
CB2	200*250*1200	2#4	#2 – 90mm c/c	Third point loading	(Control) Simple RC Beam
RFB1	200*250*1200	2#4 & 2#s212	#2 – 90mm c/c	Third point loading	Cracked beam retrofitted with CFRP
RFB2	200*250*1200	2#4 & 2#s212	#2 – 90mm c/c	Third point loading	Cracked beam retrofitted with CFRP
CFB1	200*250*1200	2#4 & 2#s212	#2 – 90mm c/c	Third point loading	Uncracked beam retrofitted with CFRP
CFB2	200*250*1200	2#4 & 2#s212	#2 – 90mm c/c	Third point loading	Uncracked beam retrofitted with CFRP

The dimensions and reinforcement details of the beam are shown in the figure.

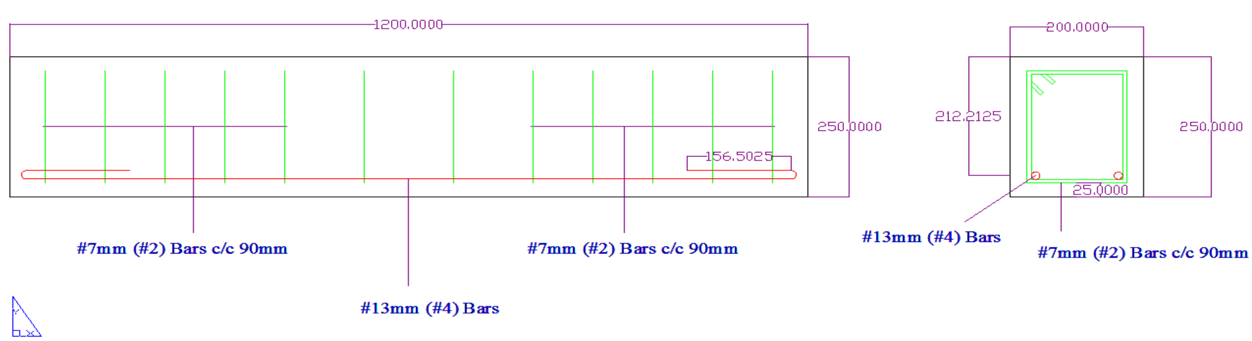


Figure 3-1: Beam size and reinforcement details

3.1.2 Beam Material Properties:

Ordinary Portland cement was used in all the mixtures. The mix proportion of constituents by weight was 1:3:4, which corresponded to cement, sand and gravel. The water to cement ratio was taken as 45%. The average 28-day concrete compressive strength obtained from standard cylinders of same mixture was 21MPa. The longitudinal steel reinforcement consisted of 13mm diameter Grade 60 standard rebars. The transverse reinforcement consisted of 7mm diameter Grade 40 smooth bars. The effective depth of the beam becomes 212.5mm from the top surface of the beam.

3.1.3 CFRP and Epoxy Properties:

The carbon fiber reinforced polymer (CFRP) sheets used in this experimental work was manufactured by Sika Corporation (Sika Carbodur S212). This fabric, with a width of 20 mm and a thickness of 1.2 mm, is a high strength, unidirectional carbon fiber. Two such fabrics were used on bottom sides of all beams. As per manufacturer's data, the tensile strength and modulus of elasticity of the fabric were 3,100MPa and 165,000MPa, respectively, with an elongation of 1.70 percent.

Figure 3-2: Sika CarboDur S212

Figure 3-3: Epoxy Sikadur 30 lp

The epoxy sheets used in this experimental work was manufactured by Imporient Chemicals. The fabric was bonded with beam by ChemDur 30 epoxy to form a carbon fiber reinforced polymer (CFRP) system.

3.1.3.1 How we applied CFRP:

Externally bonded reinforcement system requires high standard of skill for it application. Excellent workout and surface preparation is a key to the optimized performance of the fiber system. The application procedure is discussed briefly in following.

- First of all mark the portion of beam on which you have to apply the Carbon fiber reinforced polymer sheets.
- The surface is made rough so that bond between reinforced concrete beam and epoxy and CFRP will be strong.

Figure 3-4: Preparing Beam and CFRP for epoxy

- Any weak spot, honey combed area must be removed until sound surface is achieved.
- Surface will be wire brushed and dust will be removed with blower.
- Epoxy Chemdur 30lp (Adhesive for Bonding Carbon-Fibre Strips) will be applied on the surface as thin base layer to ensure a good bond on the concrete surface.

Figure 3-5: Applying Epoxy Resin

- The cleaned laminate will be applied Chemdur 30 adhesive with roof shaper spatula fixed in special wooden box for even required thickness of adhesive on the laminate.
- Within the open time of adhesive depending on the temperature the coated laminate will be fixed on to the already primed surface with Chemdur 30 on already prepared surface.
- Using rubber roller press the plate into epoxy adhesive until the material is forced out on both sides of laminate. The squeezed out epoxy will be removed with help of scrapper.

Figure 3-6: Binding CFRP to Beam using Epoxy

After this exercise laminate will be left to get cured. No supports for laminate during curing time are required.

Cleaning:

Clean tools immediately. Wash hands and skin thoroughly in warm soap water. Cured material can only be removed mechanically.

Safety Instructions:

Wear protective clothing (gloves, glasses).In contact with eyes, rinse thoroughly with clean, warm water and seek medical attention.

In our project we used two strips of Sika Carbodur s212 on four beams (two pre-cracked beams and two un-cracked beams). The epoxy we used was Chemdup lp30. Their properties are also explained below.

3.1.4 Testing Setup:

All beams were tested under four point bending. Our proper beam testing machine at NICE was out of order, so we made some special arrangement with our UTM machine to test the beam. The clear span of the beams was 1100mm and the distance between the center point loads was 305mm. Deflections at mid-span were measured by two LVDTs (linear variable differential transducer) on the two sides of the beam. Dial gauges were installed at the support points to measure their vertical displacements. The readings from LVDTs and dial gages were used to calculate the actual deflection at the mid-span. The arrangement of four point bending is shown in figure.

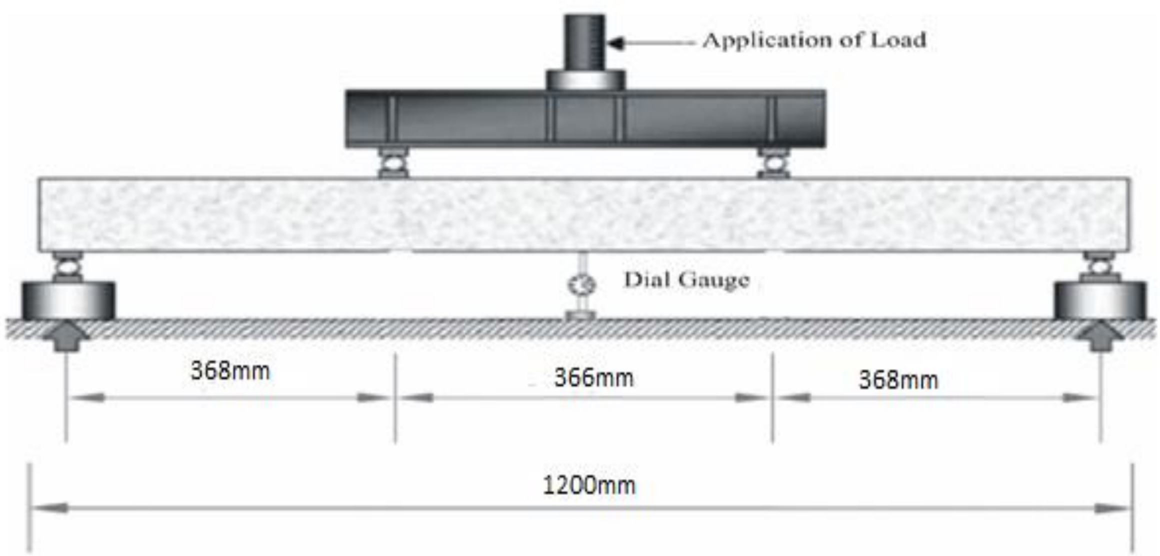


Figure 3-7:Four point bending arrangement

3.2. Flexural Testing at Laboratory:

Figure 3-8: Flexural Testing at Laboratory

3.3. Design of Beam:

We design the beam for a load of service load of 50kN and factored load of 80kN. This value of load was taken after studying many research papers. Most of the researchers designed the beam for ultimate load of 50kN to 120kN.

The properties of the beams are:

Total length of beam = L = 1200mm.

Clear Span = Ln = 1100mm.

Width = b = 200mm.

Height = h = 250mm.

Effective depth = d = 215.5mm.

Φstirrup = 6.35mm.

Area of Stirrup = 32mm2.

28-days Concrete Compressive Strength = fc' = 21MPa

Strength of longitudinal steel = fy = 420MPa.

Flexural Design of beam:

Live Load = P = 50kN

Self Weight = w = 0.20*0.25*23.6 = 1.18kN/m.

Unfactored Moment = M(uf) = $\frac{wL^2}{8} + \frac{PL}{6}$ = 10.21kN-m.

Factored Live Load = P_f = 80kN

Factored Dead Load = w_f = 1.416kN/m.

Factored Moment = Muf = $\frac{w_f L2}{8} + \frac{P_f L}{6}$ = 16.25kN-m.

Minimum Reinforcement Ratio = $\rho_{min} = \frac{0.25\sqrt{fc'}}{fy}$ = 0.00329

Balanced Reinforcement Ratio = $\rho_b = 0.85*\beta_1*\frac{fc'}{fy}*\frac{600}{600+fy}$ = 0.02095

Maximum Reinforcement Ratio = $\rho_{max} = 0.75*\rho_b$ = 0.01571

Rn = $\frac{Mu}{\varphi b d^2}$ = 2.00644kN/m^2.

Reinforcement ratio = $\rho = \frac{0.85*fc'}{fy}*(1-\sqrt{1-(\frac{2.353Rn}{fc'})})$ = 0.00509

Area of steel = As = ρ*b*d = 215.803mm^2

Select Reinforcement

2 – 13mm φ bars.

So Area of Steel = As = 258mm^2

Reinforcement ratio = ρ = $\frac{A_s}{bd}$ = 0.00608

Bar spacing = b – 2*cover – 2*$\varphi_{stirrup}$ – No. of bars*Bar spacing = 111.5

Checking adequacy of beams in shear:

Consider left span of the beam i.e. from left support to load on left side.

x = 50mm.

Vu at distance x = $\frac{w_f * L}{2}$ + $\frac{P_f}{2}$ - $\frac{w_f * x}{2}$ = 40.8142kN.

Mu at distance x = Vu*x = 2.04071kN-m.

Shear Capacity of beam = φVc = φ*(0.158*√fc' + 17.2* ρ*$\frac{Vu * d}{Mu}$)*b*d = 16.03035kN.

As φVc < Vu, so we have to provide appropriate shear stirrups to make it safe in shear.

Check whether by providing steel, it will be safe in shear.

Vs = Vu – φVc = 24.78385kN.

$\frac{2}{3}$*√fc'*b*d = 128.6966kN.

As Vs < $\frac{2}{3}$*√fc'*b*d, so we can provide steel that will make it safe in shear.

Shear Design of Beams:

$S_{max} = \frac{\varphi_v A_v f_y d}{V_u - \varphi V_c}$ = 195.58mm.

$S_{max} = \frac{3 A_v f_y}{b}$ = 403.2mm.

S_{max} = d/2 = 106.075mm.

S_{max} = 600mm.

Selecting the minimum value, so

S_{max} = 106.075mm.

Left side of clear span of beam = Ln/3 = 367mm

No. of spacings = Ln/(3* S_{max}) = 3.456.

No. of stirrups = 5.

Moment Capacity of Strengthened beams:

To avoid rupture failure of CFRP, the minimum cross sectional area of CFRP needed is:

$c_f = d_f \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{fu}}$ = 37.59mm.

$A_{f,min} = \frac{0.85 f_c' b \beta c_f - A_s f_y}{f_{fu}}$ = 7.716mm^2

To avoid crushing of compression concrete, the maximum cross sectional area of CFRP needed is:

$c_b = d_s \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_y}$ = 124.79mm

$A_{f,max} = \frac{0.75\ (0.85 f c' b \beta c_b - A s f y)}{f_{fb}}$ = 55.35mm

Select the area of CFRP according to the sizes available in market.

A_f = 48mm^2 (width 20mm and thickness 1.2mm).

Now,

A = 0.85fc'bβ_1 = 2991.15

B = - $A_s f_y$ + ($A_s' E_s$ + $A_f E_f$)ε_{cu} = -84600

C = - ($A_s' E_s d'$ + $A_f E_f d_f$)ε_{cu} = -5954256

c can be solved by following equation

$c = \frac{-B + \sqrt{B^2 + 4AC}}{2A}$ = 60.9457mm.

Finally Mn of the strenthened beam is calculated by this equation

$Mn = 0.85 f_c' b \beta_1 c(d_f - \frac{\beta_1 c}{2}) + A_{s'} E_s \varepsilon_s'(d_f - d') - A_s f_y(d_f - d_s)$ = 36.795kN-m

3.3.1 Note:

These are the theoretical values of the moment capacities of simply reinforced beams and beams strengthened with CFRP sheets. The actual results may vary from them due to uncertainties.

Chapter 4

Results and Conclusions

4.1. Results

After the beams were tested, the results we obtained are:

For control beams, the ultimate load for **CB1** was 73 kN and that for **CB2** was 70.2 kN, and both of them failed due to yielding of the steel reinforcement, because they were designed under-reinforced for ductile mode of failure. They showed more deflections and less cracks of large crack widths.

For the cracked beams, the ultimate load for both of **RFB1** and **RFB2** was 136 kN, and the failure was due to the de-bonding of the CFRP sheets along with the yielding of the steel reinforcement. They showed less deflection and more cracks of with crack widths.

For the un-cracked beams, the ultimate load for both of **CFB1** and **CFB2** was 142 kN, and again the failure was due to the de-bonding of the CFRP sheets and yielding of the steel reinforcement combined. They showed less deflection and more cracks of with crack widths.

The deflections and the load at various stages are summed up in the following table:

Table 2.1: Load, Deflection and Crack widths Comparison

Beam Code	Service load of CB		Yield load of CB		Ultimate stage		Crack Width at Service Load of CB (mm)	Crack Width at failure of beams (cm)
	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)		
CB1	50	3.96	66	8.26	73.5	38	0.13	1.30
CB2	50	4.42	66	8.80	70.2	35	0.13	1.20
RFB1	50	2.90	66	4.30	136	21.8	0.09	0.88
RFB2	50	3.40	66	4.40	136	24.0	0.09	0.92
CFB1	50	2.24	66	2.90	142	22	0.07	0.74
CFB2	50	1.55	66	2.25	142	23	0.07	0.70

4.2. Flexural Cracks in the beams after testing

Figure 4-1: Cracking Pattern of RC Beam

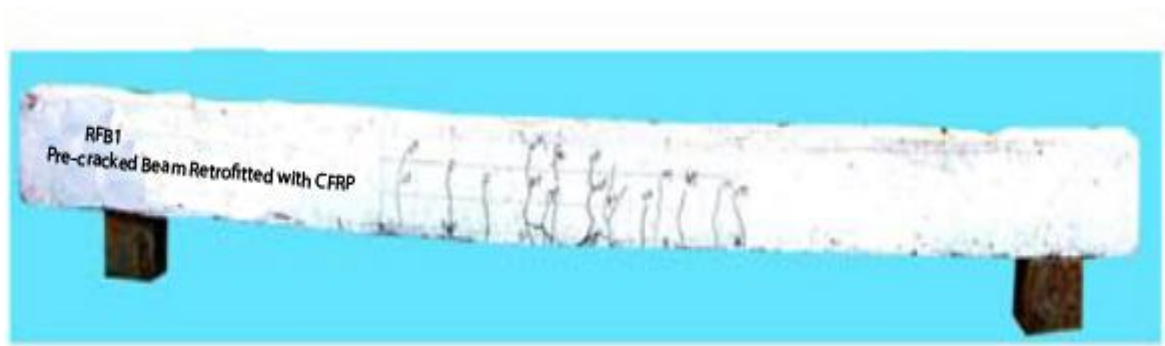


Figure 4-2: Cracking Pattern of Pre-Cracked Beam.

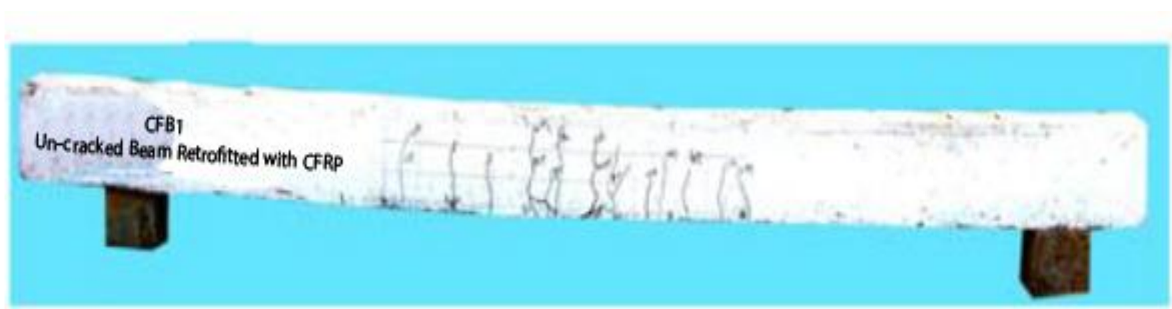
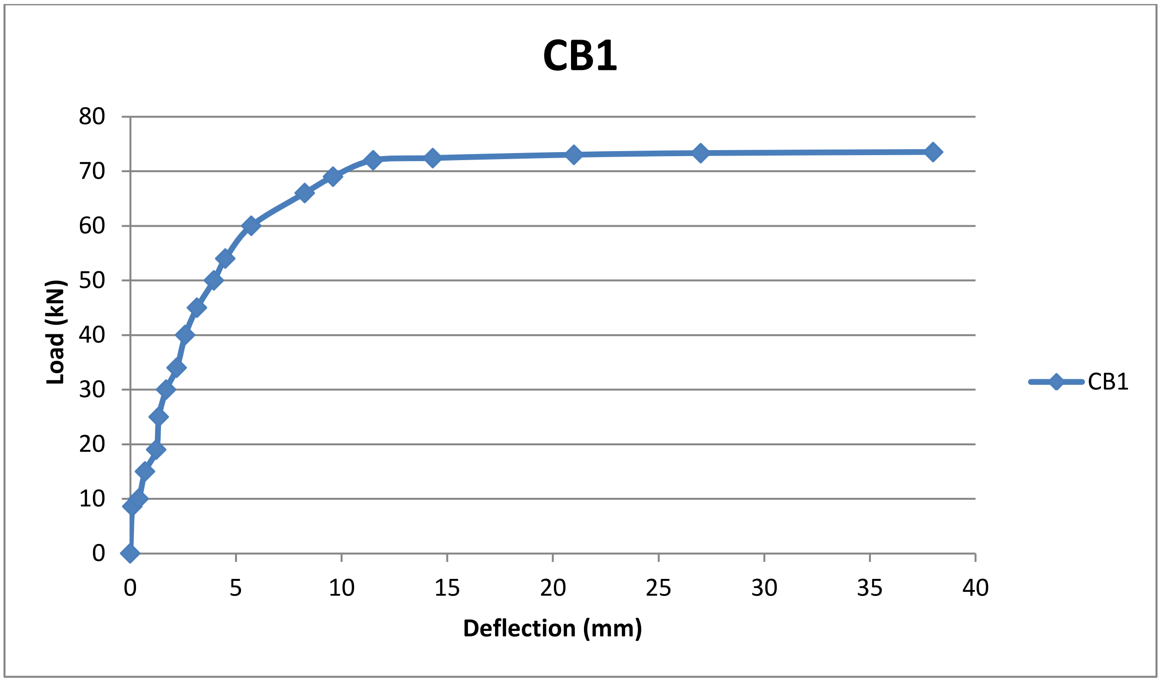


Figure 4-3: Cracking Pattern of Uncracked Beam

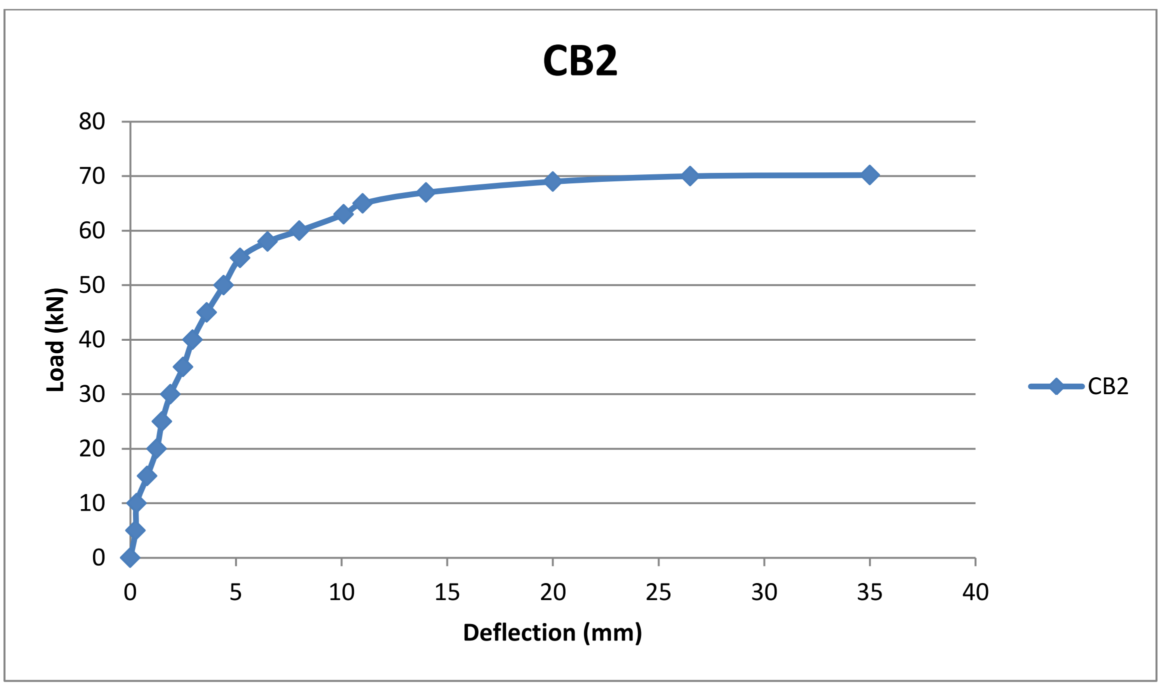
4.3. Load vs Deflections Graphs

<u>Load vs Deflection of curve of beam CB1 (Simply RC beam)</u>



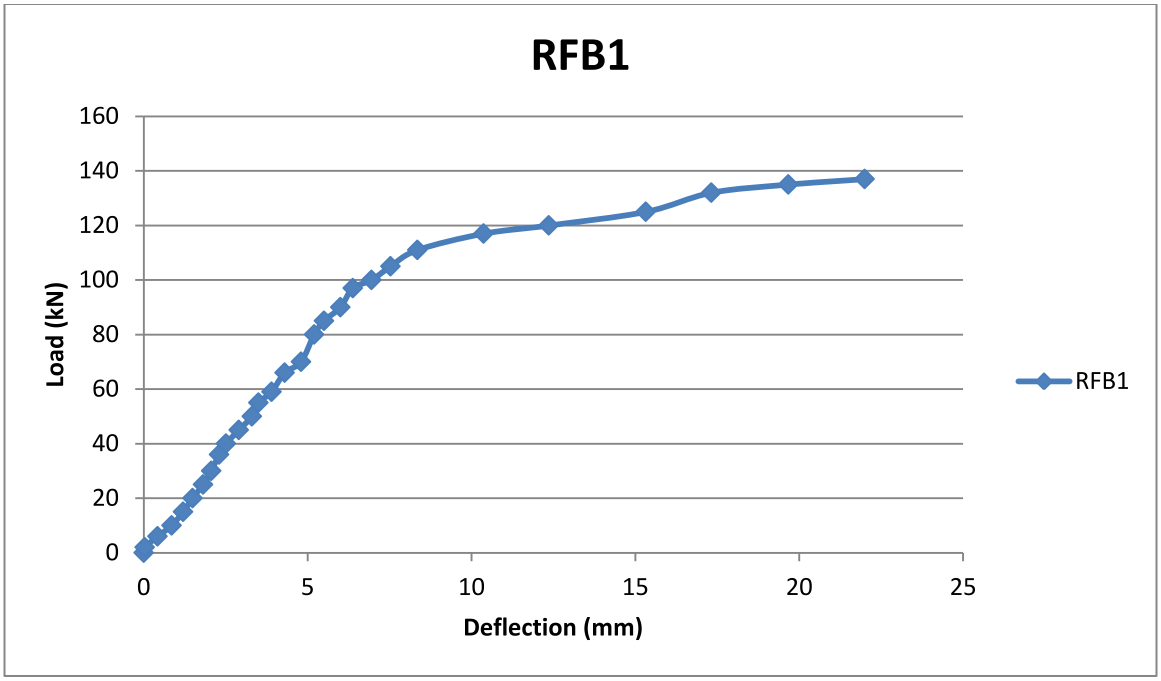
Graph 1: Load vs Deflection of curve of beam CB1 (Simply RC beam)

<u>Load vs Deflection of curve of beam CB2 (Simply RC beam)</u>



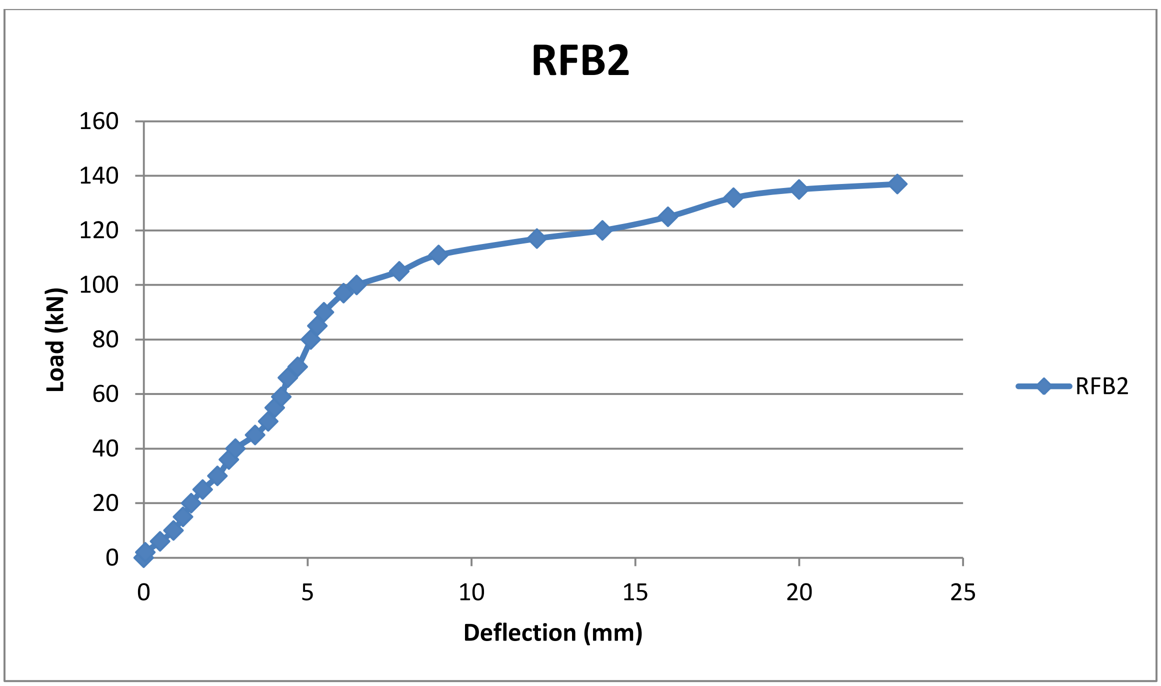
Graph 2: Load vs Deflection of curve of beam CB2 (Simply RC beam)

Load vs Deflection of curve of beam RFB1 (Cracked beam retrofitted with CFRP)



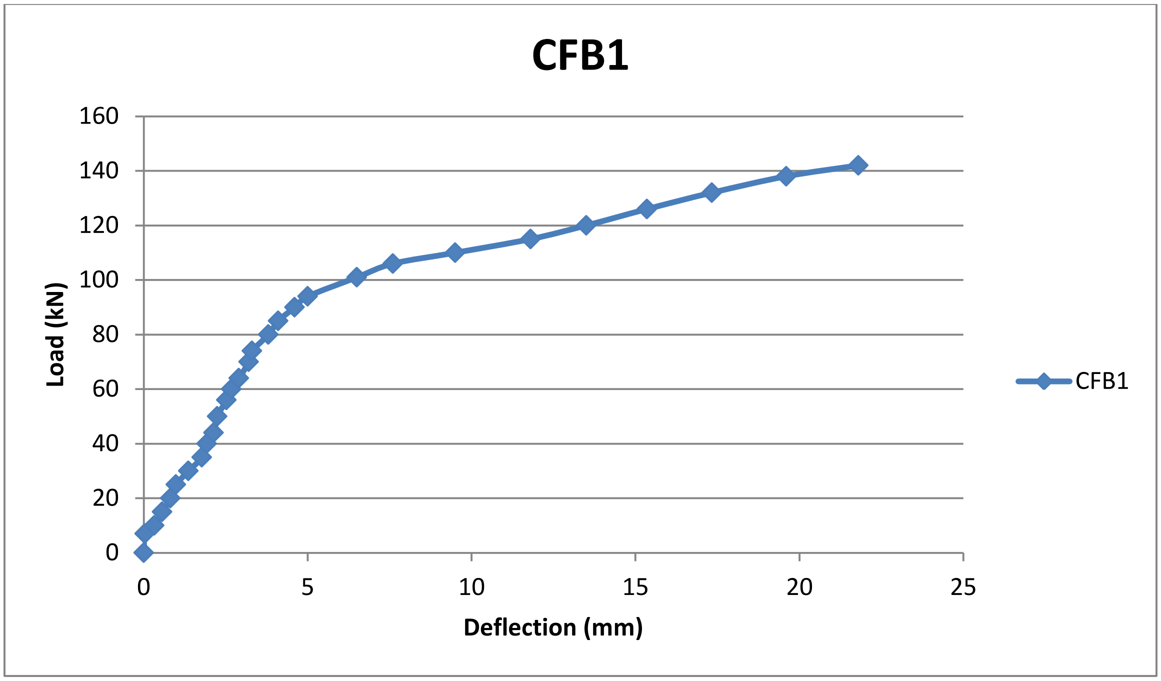
Graph 3: Load vs Deflection of curve of beam RFB1 (Cracked beam retrofitted with CFRP)

Load vs Deflection of curve of beam RFB2 (Cracked beam retrofitted with CFRP)



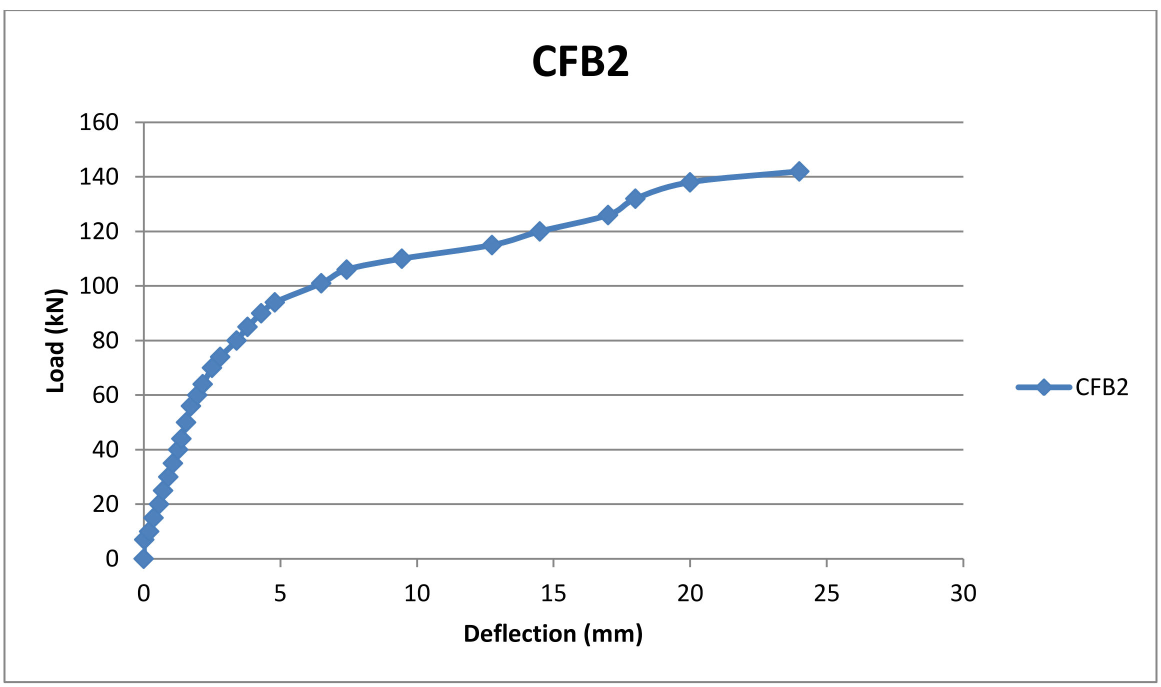
Graph 4:Load vs Deflection of curve of beam RFB2 (Cracked beam retrofitted with CFRP)

Load vs Deflection of curve of beam CFB1 (Beam initially retrofitted with CFRP)



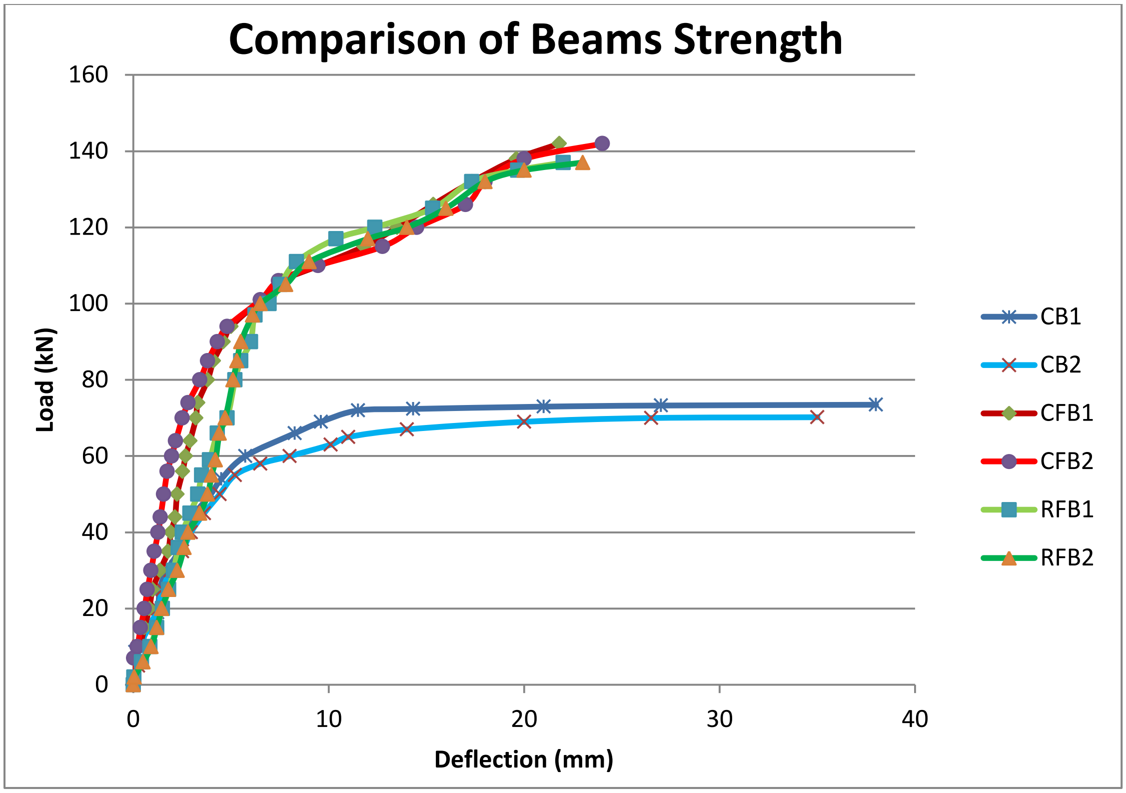
Graph 5:Load vs Deflection of curve of beam CFB1 (Beam initially retrofitted with CFRP)

Load vs Deflection of curve of beam CFB2 (Beam initially retrofitted with CFRP)



Graph 6:Load vs Deflection of curve of beam CFB2 (Beam initially retrofitted with CFRP)

Comparing the Results of Load vs Defection of all beams.



Graph 7:Comparing the Results of Load vs Defection of all beams

4.4. Discussions

These graphs show the load vs deflection curves of all beams. We can observe that simple RC beams fail at a load of about 70-75 kN. While the beams strengthened with Carbon Fiber Reinforced Polymer Sheets have higher stiffness than simple RC beams due to failure load having twice the value i.e 135-145 KN. The deflections of beams strengthened with CFRP are very much less than the deflections of simple reinforced concrete beams. Pre-cracked beam shows more deflection at the start of load with respect to un-cracked, but they failed at approximately same loading value, and the final deflection values are also same.

The main purpose of this project is to check the efficacy of CFRP in strengthening the flexural member (beam) of existing structures. If the structures is weak or to carry more than design loading than we can use CFRP which is cost efficient and less time consuming way to strengthen these structures. Areas of applications may be as under:

- If we have an existing structure and we have to build a new block or portion above it. The beams were designed for lower loads and will not be able to carry the load of new block or portion. In this way one option is to demolish them and built new, but it will be much costly as well as time taking process. So CFRP sheets are applied at the soffit of beams. It is a very effective and time saving technique for strengthening of beams, because it can increase the load carrying capacity of beams to a great extent.

- With the passage of time, the concrete strength of beams is reduced due to creep and shrinkage. So the deflections in beams may increase. Higher deflections may create cracking of masonry, difficulty in the openings of doors and windows, pounding of water during cleaning process in addition to being looking unpleasant thus rendering it unserviceable. So CFRP sheets are applied at the soffit of the beams, because CFRP sheet can reduce the deflections to great extent.
- If in a building, the loading increases with the passage of time i.e initially building was made for residential purpose but later it will be converted into a commercial building, than the loading increases. If the loading increases than beams of the building designed for residential purpose will become unsafe for commercial use of same building. So we can apply CFRP at soffit of beams to strengthen them.
- Cracks are also big problems for serviceability. ACI-318 does not allow crack width more than 0.016" for interior and 0.013" exterior exposure. After the epoxy grout injected with pressure in to the cracks, CFRP sheets once applied at soffit of beam control both cracking and deflections in the beams.

So we can say that Carbon Fiber Reinforced Polymer Sheets are very effective and time saving technique for strengthening of beams, and to control the deflections of beams and also reduce the crack widths. CFRP sheets are useful for making structure safe both with respect to strength and serviceability.

4.5. Conclusions:

The following results were obtained from the experimental study carried on,

- CFRP sheets increased the strength and stiffness of the beams to a great extent with eventual de-bonding failure at the ultimate load. The ultimate load-carrying capacity of the strengthened beams was increased 95 percent as compared to the control beams.
- Beams strengthened with CFRP sheets showed about 40 to 60 percent deflection as compared to Simple RC beams.
- The cracks were much narrower in the strengthened beams as compared to those in the control beams at service load of simple RC beam due to the presence of the CFRP fabric at the concrete surface.
- The pre-cracked and un-cracked strengthened beams exhibited similar deflection characteristics. But pre-cracked beam showed about 60% more deflection than un-cracked beams at service load of simple RC beam, but later on both showed similar behavior.

- Initially un-cracked beams showed very less deflections, because both steel and CFRP were resisting stresses but after steel yields, deflections increased because only CFRP started resisting stresses.
- The load at which the steel yielded was higher for the strengthened beams, because the tensile forces were shared between the steel and the CFRP reinforcement.
- The control beams were designed as under reinforced, so they failed due to the yielding of the internal steel reinforcement in a ductile mode.
- The CFRP strengthened beams failed by the de-bonding of the fabric along with yielding of the steel reinforcement at the location of the flexural cracks, with the de-bonding starting at one of the flexural cracks.
- The beams were deformed considerably, even though the CFRP's capacity was not fully utilized.

4.6. Recommendation

- In those areas where seismic risk levels are high, seismic design of reinforced concrete buildings are performed. For these buildings beam-column joints are the critical sections because of the formation of plastic hinges at beam ends. This induces high shear stresses in beam-column joints. That's why beam-column joints along with special steel reinforcement, are also retrofitted with CFRP to properly resist the earthquake forces. So use and effectiveness of CFRP in seismic retrofitting of concrete frame beam-column joints should be analyzed.

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