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BEHAVIOR OF RC BEAMS STRENGTHENED IN FLEXURE WITH CFRP COMPOSITES LAMINATES

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ABSTRACT

Strengthening of reinforced concrete (RC) beams with externally bonded Carbon Fiber Reinforced Polymer (CFRP) composites is one of the attracting techniques developed over the last few years for the purpose of increase load carrying capacity of such elements. The paper presents the results of an experimental study designed to investigate the flexural behavior of reinforced concrete beams strengthened with CFRP laminates attached to the tensile soffit of the beams by epoxy adhesive. A total of four reinforced concrete beams are tested to failure in four-point bending over an effective span length 1900mm. Three beams are strengthened by changing the layers of CFRP composites laminates whereas the last one is not strengthened with FRP and considered as a control beam. Test results indicate that with increasing the number of laminate layers, the flexural strength of beams was significantly improved. However, debonding of CFRP laminates is still a major concern for the case of multi-layer strengthening of beam. This study showed that strengthening of RC beams with CFRP laminates has substantially influence the better performance and increased the flexural strength. The paper also highlighted the beams failure modes due to the different layers of strengthening scheme.

Keywords: *Carbon Fiber Reinforced Polymer, Beams, Ultimate strength, Debonding, Flexural behavior.*

1. INTRODUCTION

The use of Fiber Reinforced Polymer (FRP) is becoming an increasingly popular method of repairing and strengthening ageing in the field of civil engineering around the world. Due to its high stiffness-to-weight ratio and flexibility in its use over steel plates, CFRP has attracted researchers' interests worldwide to investigate the feasibility and effectiveness of using CFRP as reinforcements. Moreover, these materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance. The need for rehabilitation or strengthening of bridges, building and other structural elements may arise due to one or a combination of several factors including construction or design defects, increased load carrying demands, change in use of structure, structural elements damage, seismic upgrade, or meeting new code requirements. This implies that these factors are contributed to infrastructure becoming either structurally inefficient or functionally obsolete. Before the introduce of fibre reinforced polymer (FRP) strengthening technologies, one popular technique for upgrading reinforced concrete beams was the use of external epoxy-bonded steel plates (Swamy *et al.,* 2003; Hamoush *et al.,* 1990). Fiber reinforced plastic material do not suffer from corrosion problem, and most of their mechanical and physical properties are better than the steel. Swiss researchers pioneered work on the use of FRP as a replacement for steel in plate bonding applications (Meier *et al.,* 1991) and numerous researchers have shown that the concrete rehabilitation using FRP is very successful application at retrofit or increasing the strength of reinforced concrete members (El-Badry *et al.,* 1996; Tamuzs *et al.,* 2004). There is currently a wide range of techniques available to repair or strengthen structurally deficient and functionally obsolete structures. Interest in these techniques is widespread, and continues to grow; one such technique is adding fiber reinforced polymer (FRP) as external bonded reinforcement. Strengthening techniques using external bonding of FRPs have been successfully used to retrofit reinforced concrete structures like beams, wrapping of concrete columns, slabs, girders in bridge structures, building and parking decks (Ramana *et al.,* 2000; Katsumata *et al.,* 1988). The basic concepts in the use of FRPs for strengthening of concrete structures are covered in a review article (Triantafillou, 1998). Studies (Saadatmanesh, *et al.,* 1991; Meier *et al.,* 1991) have shown that Fiber Reinforced Polymer (FRP) composites in strengthening RC members, in the form of sheets, have emerged as a viable, cost-effective alternative to steel plates.

Many research studies have been investigated on flexural performance of RC beams externally bonded with CFRP laminates (Barris *et al.,* 2009; Esfahani *et al.,* 2007; David *et al.,* 1998). From these studies, it was identified that the flexural capacity of RC beam increased due to the different level of CFRP strengthening, although debonding of laminates was a concern in some of these studies (Aram *et al.,* 2008; Alam *et al.,* 2009; Yao *et al.,* 1998; Siddiqui *et al.,* 2009).

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In the present study, through an experimental program, efforts have been made to study the efficiency and effectiveness of the number of CFRP layers on the flexural performance of strengthened beams. The flexural behavior is studied in terms of cracking load, ultimate strength and crack pattern along with different failure modes to get better understanding on the performance of beams strengthened with multi-layer CFRP laminates.

2. FLEXURAL STRENGTHENING

Analytical approaches to evaluate the flexural behavior of FRP laminates to concrete structures are described in this code. CEB-FIP (1993) uses a rectangular stress block similar to that used in normal reinforced concrete beams. This code also considers a linear strain variation over the depth of sections, and uses the value of 0.0035 for the maximum concrete compressive strain. In this codes adopt the traditional sectional analysis called "plane sections remain plane" for strain compatibility, and the stress strain relationships of concrete, steel and FRP laminates are used for equilibrium equations (refer to Figure1).

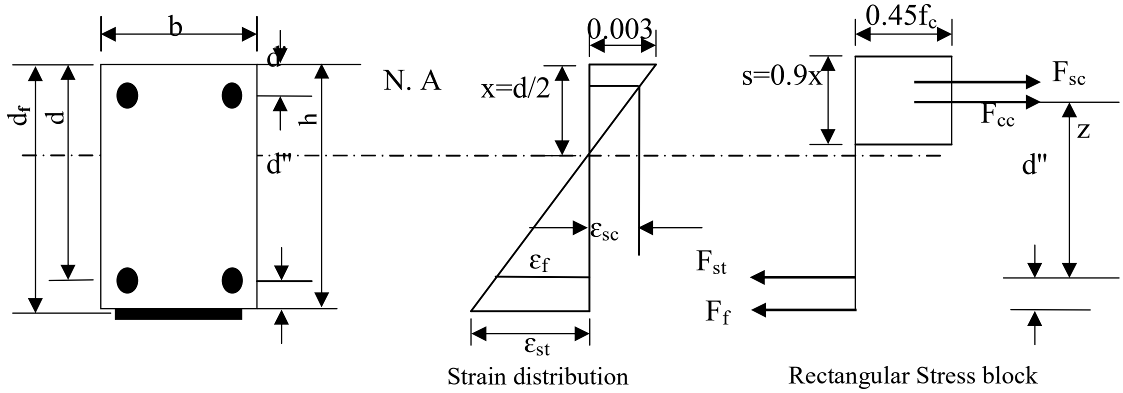


Figure 1: Linear Strain Variation over the Depth of the Section and CEB-FIP Rectangular Stress Block

The cracking moment M_{cr} of the strengthened beams may be computed as follows

$$M_{cr} = \frac{f_r I_g}{y_t}$$

where y_t is the distance from the neutral axis to the tension face of the beam, f_r is the modulus of rupture of the concrete and I is the second moment of inertia of the cross section about neutral axis. The first cracking load P_{cr} is then calculated from the cracking moment.

According to the provision of the CEB-FIP (1993), the ultimate moment capacity of the strengthened beams is calculated using equivalent rectangular stress block of the beam cross section and then calculated the failure load. The ultimate bending moment is expressed by the following equation:

and taking moment at the centroid of the tension steel, A_s (refer to Figure 1)

$$M_u = F_{sc}(d - d') + F_{cc}(d - 0.45x) + F_f * d''$$

3. EXPERIMENTAL INVESTIGATION

3.1 Test Matrix

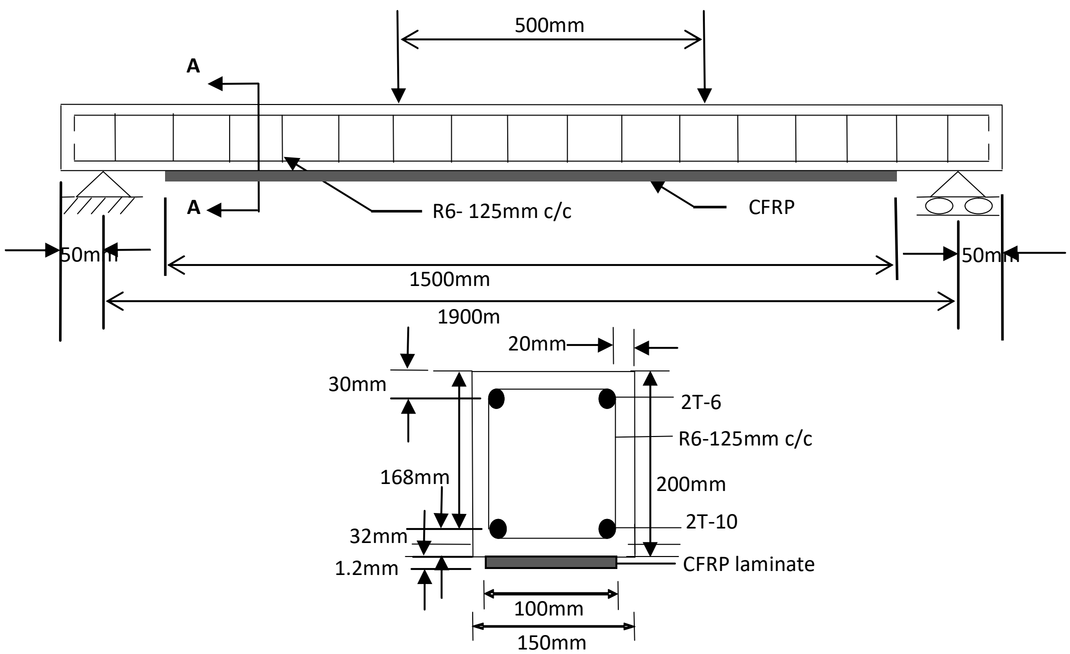
Table 1 summarizes the general experimental test program to evaluate the effect of externally bonded CFRP laminates on the flexural behavior of RC beams. This program consisted of testing four rectangular beams having different level of strengthening scheme. First beam (designated as CB) was not bonded with CFRP laminates, three beams (FB-1L, FB-2L and FB-3L) were bonded with different layers of CFRP laminates (1, 2 and 3–layers respectively). It was observed that soffit of the reinforced concrete beam bonding of CFRP laminates is very efficient in flexural strengthening.

3.2 Specimen Reinforcing Details

All the beam specimens were 2000 mm long with a 150 × 200 mm rectangular cross section and reinforced with two T10 (10mm in diameter) bars bottom longitudinal deformed reinforcing bars at an effective depth of 168mm and two T6 (6mm in diameter) top longitudinal plain reinforcing bars. R6 stirrups were placed at a constant spacing of 75 mm throughout the entire length of the beams. The stirrups are designed to ensure that none of the beams would fail in shear. The longitudinal reinforcement ratio is about 0.62% of the beam cross-section. Keeping in mind that usual longitudinal reinforcement ratio are ranges between 0.1% (minimum reinforcement) and 2.5 %, this value may be considered as mean design ration for average flexural members. Fig. 2 shows the reinforcement details of the experimental test beams. All beams were designed to fail in flexure according to the specification of the code of practice BS 8110-1(1997).

Table 1: Test Program

	Strengthening scheme			
	Control (Unstrengthened)	1-layer strengthened	2-layer strengthened	3-layer strengthened
Beam designation	CB	FB-1L	FB-2L	FB-3L



Section A – A

Figure 2: Longitudinal and Cross-section details of the test beams

3.3 Material Properties

3.3.1 Concrete

The 28-day concrete having average compressive strength of 36MPa is specified for all beam specimens. The concrete is prepared with the mix proportion of 1:1.65:2.45 by the weight of ordinary Portland cement, locally available natural sand, and crushed granite aggregate. The water-cement ratio was maintained 0.45.The nominal size of coarse aggregate was used 10mm to cast all the beams. The beams are cast from the same batch. After demoulding, they are cured in fresh water for 28 days. Standard size specimens were tested in the laboratory to determine the cube's strength, modulus of elasticity, splitting tensile strength and modulus of rupture at 28 days. The characteristics concrete strengths are shown in Table 2 as based on the laboratory test results.

Table 2: Concrete Properties

Properties	Values found in the laboratory
Concrete cube strength (MPa)	36.0
Modulus of elasticity (GPa)	28.6
Modulus of rupture (MPa)	3.7
Splitting tensile strength (MPa)	2.95

3.3.2 Steel

Two types of high yield steel deformed bars, 6 and 10mm in diameters (T6 and T10) and plain round mild steel bars, 6mm in diameter (R6 as stirrups) were used for all beams fabrication. The tests were conducted in the laboratory using a Universal Testing Machine to obtain the modulus of elasticity and yield strength values of steel reinforcing bars. Table 3 shows the details of steel reinforcement properties.

Table 3: Steel Properties

Reinforcement type	Yield strength (MPa)	Modulus of elasticity (GPa)
Tension,T10	482	195
Compression,T10	470	186
Shear,R6	215	200

3.3.3 CFRP laminates and epoxy adhesive

Unidirectional CFRP laminates (each of 1.2mm thickness) used for the strengthening purposes of the beams are cut from the Sika Carbodur S1012/160 (2008) rolled laminate. They contain 68% volumetric fraction of high strength fibers and 32% of epoxy adhesive resin. The CFRP composite laminate was tested in the laboratory to get the tensile strength, yield strength, modulus of elasticity and the percentage of ultimate elongation until the failure. The other properties of the carbon fibers and epoxy adhesive, as supplied by the manufacture, are presented in Table 4.

Table 4: CFRP laminates and epoxy adhesive properties

Materials	Property	Values
CFRP laminate	Sheet form	Uni-directional roving
	Yield strength (MPa)	1315
	Modulus of Elasticity (GPa)	165
	Elongation at ultimate (%)	2.15
	Design thickness (mm/ply)	1.2
	Tensile strength (MPa)	1685
	Density (g/cm^3)	1600
Epoxy adhesive	Modulus of Elasticity (GPa)	3
	Elongation at ultimate (%)	2.6
	Flexural strength (MPa)	100
	Tensile strength (MPa)	55

3.4 Bonding of the CFRP laminates

For the strengthening purposes, the beam substrate should prepare before composites sheets bonded to the soffit of the beam. Hence, the concrete substrate was mechanically abraded by using a grinding wheel, creating somewhat a rough surface to remove laitance, grease and loosely adhering particle. The composites laminates were bonded to the tension face (bottom) of the concrete beams using a two-part cold curing epoxy resin Sikadur-30 (Part-A and Part-B) mixed at a proportion 1:3 and can be cured at room temperature. It was ensured that the surface was kept free from any contaminant, air entrapment and unevenness areas and was smooth. The CFRP laminates were cleaned properly using sika colma cleaner. Sikadur-30 adhesive was applied on both cleaned and prepared substrate components to ensure that to prevent the formation of air bubbles while spreading the adhesive from one surface to the other. Then the CFRP laminates were placed onto the prepared concrete surface. The composites laminates was attached starting at one end and applying enough pressure by sika carbodur rubber roller to press out any excess epoxy from the sides of the laminates. Excess epoxy was removed from the sides of the laminates. The prepared specimens were tested to failure using an Universal Testing Machine after a minimum of 3days after bonding to ensure the full curing of the epoxy adhesive. The beams bonded with one, two and triple layer of CFRP composite laminate are illustrated in Figure 3(a-c).

3.5 Instrumentation and test procedure

The test procedure consisted of loading monotonically until the failure of the beams. All the beams were tested in four-point static loading over a 1900 mm simply supported span to investigate the flexural behavior. The two point loads were positioned using hollow steel sections at one-third span length, and loading was under displacement control as shown in Figure 4. After a regular increase of loading, the loading values and the corresponding deflections were recorded. The load and the corresponding deflection taken from the test were then used to investigate the behavior of beams. During the testing, the deflections of all beams were measured at mid-span and at the location of the applied loads using three linear variable displacement transducers. Portable electronic data logger was used to record the reading of deflections. The quarter span transducers were used to check the symmetrical nature of the loaded beams. Load at first crack instance was noted down. Also subsequent crack pattern were marked on the beam surface as they develop during the application of load from first crack appear until the failure of the beam.

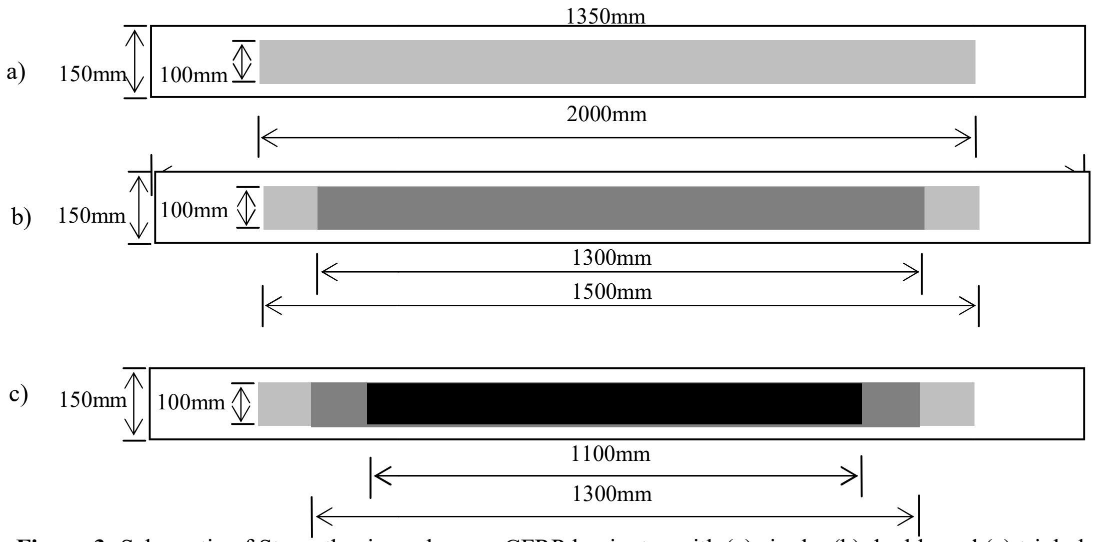


Figure 3: Schematic of Strengthening schemes: CFRP laminates with (a) single, (b) double and (c) triple layer

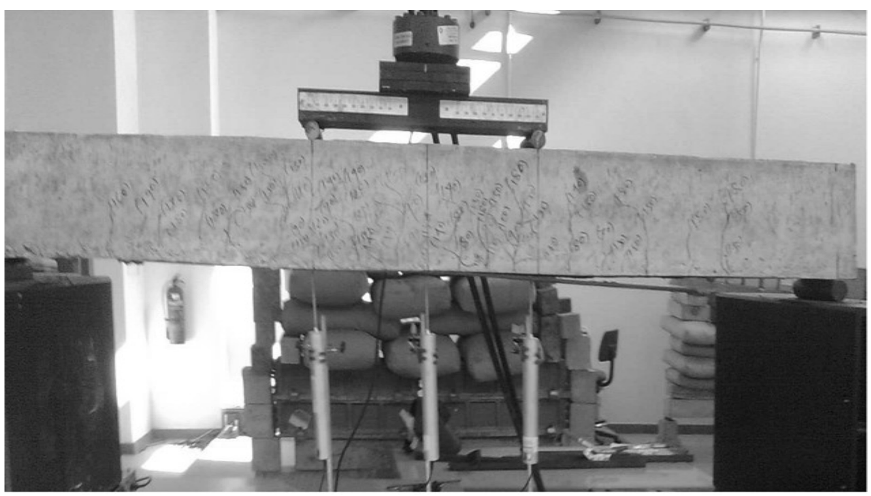


Figure 4: Typical four-points bending test set-up in the laboratory

4. TEST RESULTS AND DISCUSSION

4.1 First cracking and ultimate loads

From the experimental investigation, the first cracking load and the ultimate load carrying capacity of the strengthened and unstrengthened (control) tested beams are noted. Theoretical predictions based on transformed section analysis and using equivalent stress block are also used to determine the first cracking load and ultimate load for the four types of reinforced concrete beams strengthened with CFRP laminates. Table 5 presents the flexural performance of theoretical and experimental values of cracking and ultimate load for the tested beams.

The unstrengthened (control) beam failed by yielding of steel tension reinforcement followed by crushing of the concrete directly under four-point bending test. When loaded in the laboratory, the control beam (CB) developed flexural tensile cracks in the constant bending region at load of 11.3kN. The tensile steel has yielded at loads near 37.2kN. The beam failed in flexure due to the crushing of extreme compression zone concrete at load 40.3kN.

In general, different level of CFRP strengthened reinforced concrete beams (FB-1L, FB-2L and FB-3L) showed significant increases in flexural stiffness and ultimate capacity as compared to that of control beam (CB). From the experimental investigation, it was observed that the percentage increase of cracking load of 1, 2 and 3-layers CFRP strengthened beams are 25%, 50% and 75% respectively whereas the percentage increase of ultimate load are 54%, 73% and 85% respectively as compared to the control beam. The increase in first crack load of strengthened beams can be attributed to increase stiffness due to the laminates restraining effects. Mid span deflection and cracks width were also reduced and an increase of the flexural stiffness of the beams was noticed. The bonding of a third layer of CFRP laminates can lead better performance to delay the first crack and increase of the ultimate load as well as stiffness of the beams compared with single and double layers laminates strengthening. From the experimental tests, it can be conclude that the influence of CFRP laminates thickness on the flexural behavior of the beams is obvious.

A comparison between experimental and theoretical result shows that the theoretical calculation give conservative estimation of the first cracking load but underestimate the ultimate capacity of the strengthened beams. In general, the experimental results are in close agreement with the theoretical predictions.

Table 5: Theoretical and Experimental results

Beam designation	Experimental load (kN)		Theoretical load (kN)			Failure mode
	P_{cr}	P_{ut}	P_{cr}	P_{ult}	$\frac{P_{ult(The.)}}{P_{ult(\exp)}}$	
CB	12.4	40.3	11.3	31.5	0.78	Concrete crushing
FB-1L	15.5	62.0	12.3	82.6	1.33	Debonding
FB-2L	18.6	69.75	13.4	98.8	1.42	Debonding
FB-3L	21.7	74.4	14.4	106.8	1.43	Debonding

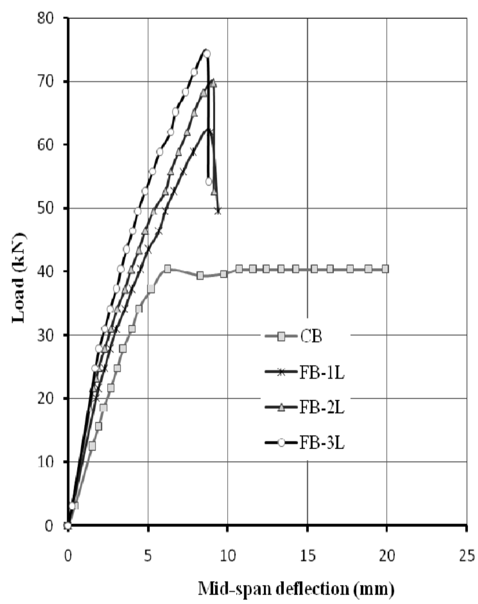


Figure 5: Load-deflection relationships for CFRP layers strengthened and Unstrengthened beams

4.2 Load-Deflection Characteristics

The typical load-deflection behavior of six different types of reinforced concrete beams to the different level of strengthening scheme with CFRP laminates (CB, FB-1L, FB-2L and FB-3L) is shown in Fig. 5. It is observed from Fig. 4, initially all the strengthened beams behave like the control beam with the internal steel reinforcing bars carrying the majority of the tensile force in the section. When the internal steel yields, the additional tensile force is carried by the FRP system and an increase of the load capacity of the member is obtained. Eventually, the FRP strengthened beams fail. The failure modes which are observed on the CFRP strengthened beams are different from that of the classical reinforced concrete control beam. CFRP reinforced beams behaves in a linear elastic fashion nearly up-to the failure. This brittle mode of failure is considered as a drawback for this way of reinforcement.

4.3 Failure Modes and Crack Patterns

The final crack patterns and modes of failure of control beam, typical CFRP strengthened beams are shown in Figs. 6(a-b) respectively. The failure modes which are observed on the CFRP strengthened beams are different from those of the classical control beam. The failure modes of the experimental beams have been tabulated in Table 5. It was observed from the experimental investigation that all beams strengthened with CFRP laminates have failed in the same manner. When having a look at the load-versus-deflection diagram for beam FB-1L, FB-2L and FB-3L, the failure of a brittle-type is more obvious as the strengthened beams seem to behave plasticity.

During the testing, the unstrengthened (control) beam exhibited widely spaced and greater number of cracks compared to the strengthened beams. The cracks have also appeared on the surface of the strengthened beams at relatively close spacing. This behavior shows the enhanced concrete confinement due to the highly influenced by the CFRP laminates. Also the composite action has resulted in shifting of failure mode from flexural failure (steel yielding) in case of control beam to peeling of CFRP laminates for the strengthened beams. Failure of the beams started at mid-span within the vicinity of the point of application of loading. The debonding started at the laminates end and then spread over the whole length of the beam. A crack normally initiates in the vertical direction and as the load increases it moves in inclined direction due to the combine effect of shear and flexure. With further increase in loading, the crack pattern propagated further from the tension face to the neutral axis of the beams. The flexural crack after reaching the neutral axis, started to incline and continue until the final failure.

(a) (b)

Figure 6: Mode of failure: (a) Unstrengthened (control) beam (b) beam strengthened with layered CFRP laminate

5. CONCLUSION

This paper presented the results of an experimental program investigating the flexural performance of reinforced concrete beams strengthened with CFRP composites laminates subjected to different degrees of strengthening scheme. Based on the experimental test results, following conclusion can be made:

i. From the experimental investigation, it was observed that 1, 2 and 3-layers CFRP strengthened RC beams significantly enhanced the performance with the load carrying capacity of 54%, 73% and 85% over the unstrengthened (control) beams.

ii. Regarding the effect of number of layers, an increase in stiffness and flexural strength is achieved with the increase of CFRP layers. It seems that the beam behaves as if the plate was thicker and no inter-layer delamination is observed in any cases.

iii. All the beams in the experimental programme failed in a brittle or quasi-brittle mode due to concrete crushing, a high degree of deformability was attained before failure.

iv. Failure mode for a beam strengthened with CFRP laminates was by debonding of the sheets and the time to delaminate was shortened.

v. The experimental results are in very good agreement with the theoretical predictions; especially for the different layers CFRP strengthened reinforced concrete beams.

vi. In estimating the beams strength with external carbon fibre reinforcement, due to displacement of external reinforcement in respect to concrete, it is essential to evaluate the stiffness of the joint between carbon fibre and concrete.

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