

Full Length Research Paper

Flexural performance of CFRP strengthened RC beams with different degrees of strengthening schemes

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Externally bonded carbon fiber reinforced polymer (CFRP) composite laminates have been successfully applied to reinforced concrete (RC) beams and other structural elements for the purpose of increase load carrying capacity of such elements. This paper presents the experimental results on the flexural strengthening of reinforced concrete beams by CFRP laminates attached to the tensile soffit of the beams by epoxy adhesive. A total of six reinforced concrete beams having different degrees of strengthening scheme were tested to failure under transverse bending over an effective span length of 1900 mm. The increase of ultimate strength provided by the bonded carbon fiber was assessed by varying the layers of composite laminates. The results indicate that the flexural strength of beams was significantly improved as the layers of laminate increased. No de-lamination of the superimposed CFRP plates was observed from the test. However, de-bonding of CFRP laminates from concrete surface was observed for the case of multi-layer strengthening of beam. It is concluded that the attachment of CFRP laminates with edge strip plates has substantially influenced the performance of CFRP strengthened beams. The paper also highlighted the beams failure modes due to the different level of strengthening scheme.

Key words: Carbon fiber reinforced polymer, strengthening, ultimate strength, deflection and flexural performance.

INTRODUCTION

Over the last decade there has been significant growth in the use of carbon fiber reinforced polymer (CFRP) as construction materials in the field of civil engineering. 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 or prestressing tendons in concrete structures. 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. These factors may cause the infrastructure structurally inefficient and sometimes responsible for making the structures functionally obsolete. Before the introduction 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., 1987; Hamoush and Ahmed, 1990). However, this method suffers from the following drawbacks:

- (i) The possible deterioration of the bond at the steel-concrete interface caused by the corrosion of the steel.
- (ii) Difficulties in manipulating heavy steel plates at the construction site.
- (iii) The need for adequate scaffolding.
- (iv) Possible difficulties related to limits in the delivery lengths of the steel plates (in the case of the upgrading of long elements).

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Table 1. Test program.

Beam designation	Strengthening scheme					
	Control (Not bonded)	1-layer bonded	2-layer bonded	3-layer bonded	1-layer U-strip bonded	1-layer W-strip bonded
	CB	FB-1L	FB-2L	FB-3L	FB-1LU	FB-1LW

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 (Rahimi and Hutchinson, 2001; Ross et al., 1999; 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). Early studies (Saadatmanesh and Ehsani, 1991; Meir and Kaiser, 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 researches have been carried out in recent years, to evaluate the flexural performance of either steel plate or FRP sheet strengthened structure (Sobuz and Ahmed, 2011; Jumaat and Alam, 2010; Jumaat et al., 2010; Barris et al., 2009; Esfahani et al., 2007; Dash, 2009; David et al., 1998). The use of CFRP laminates has shown considerable improvement in flexural performance, although de-bonding of plates was a concern in some of these studies (Jumaat et al., 2011; Jumaat and Alam, 2011; Aram et al., 2008; Alam, 2009; Yao and Teng, 2007).

De-bonding problems in FRP bonded RC members are a priority mechanics and design issue due to their premature and brittle nature. In the last few decades, there has been a concentration of research efforts into characterization and modeling of de-bonding failures that lead to a significant progress in understanding the modes and mechanisms of premature de-bonding failures of FRP. End anchorage can prevent the premature failure of CFRP laminates from the concrete tension side. In fact, proper anchoring systems may help CFRP pre-cured laminate to develop higher stresses throughout its length decreasing stress concentrations and increasing bond strength. Alam and Jumaat (2009) tested a full-scale reinforced concrete beams strengthened with single layer CFRP laminates with U-shaped end anchorage. It was observed that end anchorage eliminated premature end peeling and it has significant effects on the failure mode, ultimate strength, deflections and strain characteristics of the strengthened beams. Siddiqui (2009) carried out an

experimental test program on U-shaped CFRP end anchorage strengthened reinforced concrete beams for the flexural strengthening. It was concluded that tension side bonding of CFRP laminates with U-shaped end anchorages is very efficient in flexural strengthening.

In this paper, the effect of the number of CFRP layers on the flexural performance of strengthened beams is investigated. The effectiveness of transverse edge strips in preventing the de-bonding of FRP laminates is also discussed based on the experimental study. The failure modes and crack patterns are noted to get better understanding on the performance of beams strengthened with multi-layer CFRP laminates.

EXPERIMENTAL INVESTIGATION

Test program

Table 1 shows the test program that was initiated to investigate the effect of CFRP laminates on the flexural performance of RC beams. A total of six beams having different level of strengthening scheme were fabricated in the laboratory. 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) and the rest two beams (designated as FB-1LU and FB-1LW) were bonded with one layer CFRP laminates and having one U-shaped and two W-shaped edge strips respectively. These transverse CFRP laminates provide anchorage for the longitudinal plate, and considered effective in preventing de-bonding failure of laminates from the concrete surface.

Material properties

Concrete

To achieve a 28-day concrete cube compressive strength of 36 MPa, the mix proportions were set at 1:1.65:2.45:0.45 by weight of ordinary Portland cement, locally available natural sand, and crushed granite aggregate of 10 mm nominal size and water. Standard size specimens were tested in the laboratory to determine the compressive strength, modulus of elasticity, splitting tensile strength and modulus of rupture of the concrete at 28 days. These characteristics as obtained from laboratory tests are shown in Table 2.

Steel reinforcement

High yield deformed bars of 6 and 10 mm (T6 and T10) were used as compression and tension reinforcement for the beam specimens

Table 2. Concrete properties.

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

Table 3. Steel properties.

Reinforcement type	Yield strength (MPa)	Modulus of elasticity (GPa)
Tension (T10)	482	195
Compression (T6)	470	186
Shear (R6)	215	200

Table 4. CFRP laminates and epoxy adhesive properties.

Materials	Property	Values
	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)
Elongation at ultimate (%)		2.6
Tensile strength (MPa)		55

and plain round mild steel bar of 6 mm diameter (R6) was used as transverse shear reinforcement. Tests were conducted in the laboratory to obtain the modulus of elasticity and yield strength values of the steel reinforcing bars and the results are shown in Table 3.

CFRP laminates and epoxy adhesive

Unidirectional roving CFRP laminates of 1.2 mm thickness per layer was used for the strengthening purposes of the beams and they were cut from the Sika Carbodur S1012/160 (2008) rolled laminate. 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 at failure. The other properties of the carbon fibers and epoxy adhesive as supplied by the manufacturer are shown in Table 4.

Specimen details

The specimen configuration is shown in Figure 1. All the beam specimens are 150 × 200 mm in cross section and 1900 mm in span length on a simply supported span. They were reinforced longitudinally with two T10 bars (10 mm in diameter) as tensile

reinforcement and two T6 bars (6 mm in diameter) as compressive reinforcement. R6 stirrups were placed at a constant spacing of 125 mm throughout the entire length of the beams so as to prevent the beams from failing in shear. The tensile reinforcements were placed at a depth of 168 mm while the compressive reinforcement depth was 30 mm. The control beam was designed to fail in flexure following the British code of practice BS 8110-1(1997). Figure 2(a), (b) and (c) shows the schematic diagram of single, double and triple layer strengthening schemes of the reinforced concrete beams. The detail of the specimens FB-1LU and FB-1LW are shown in Figure 2(d) and (e) respectively. In these cases, at the CFRP cut-off points near the end of the span, carbon fiber of U and W shaped sheets were attached transversely to prevent any type of premature de-bonding of the CFRP laminates from the beam soffit.

Preparation and bonding of CFRP laminates

In the fabrication of beams, it was needed to prepare the substrate before the composite sheets were bonded to the tensile face of the concrete beams. The surfaces were prepared as suggested by the manufacture instruction for proper bonding of the CFRP laminates onto the concrete. Prior to the bonding of the CFRP laminates to the beams, the concrete substrate was mechanically abraded by using a grinding wheel, creating somewhat a rough surface to

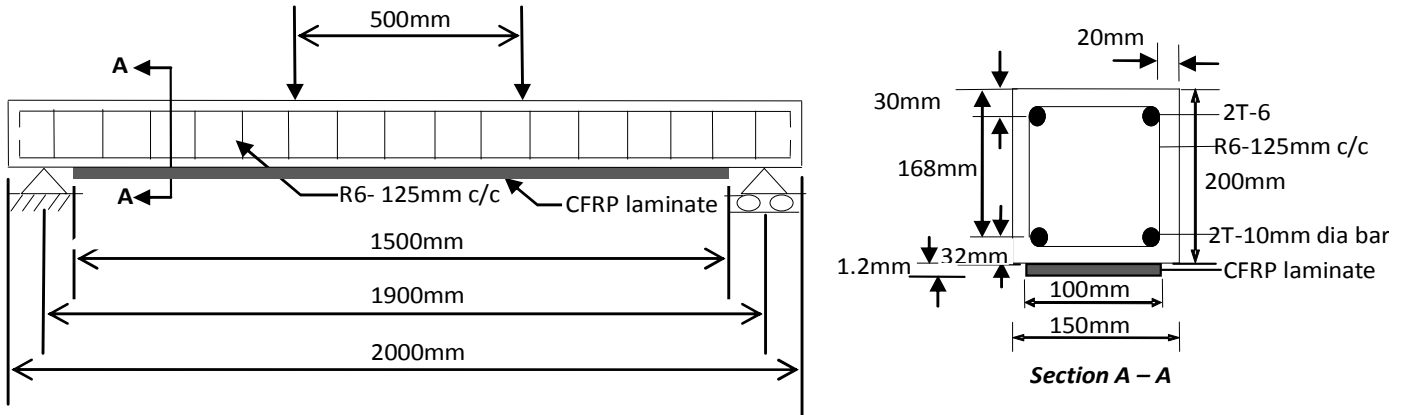


Figure 1. Longitudinal and cross section detail of the experimental beams.

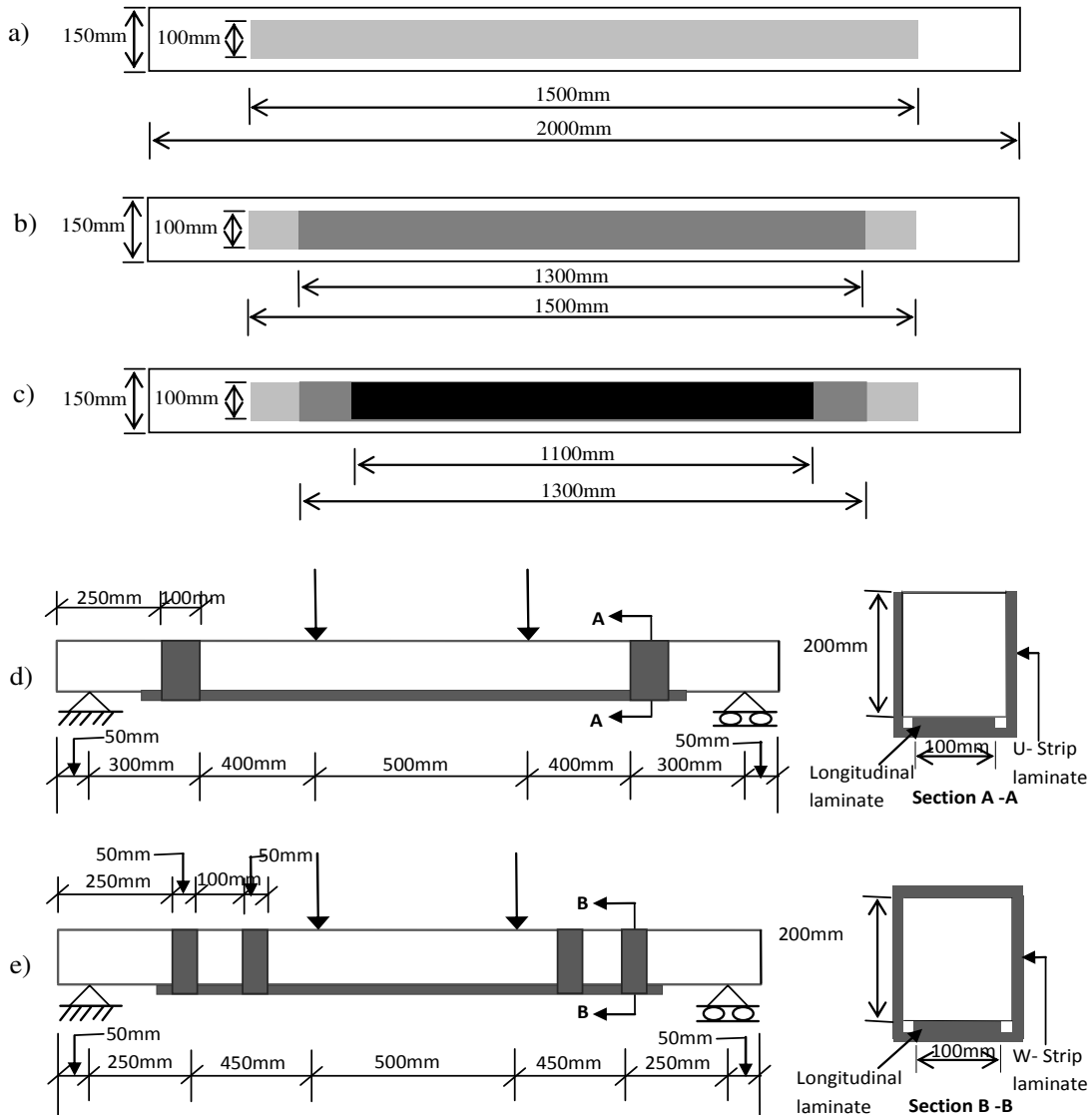


Figure 2. Strengthening schemes of RC beams: CFRP laminates of (a) single, (b) double and (c) triple layers (d) strengthened beam with one U-shaped strip (e) with two W-shaped edge strips.

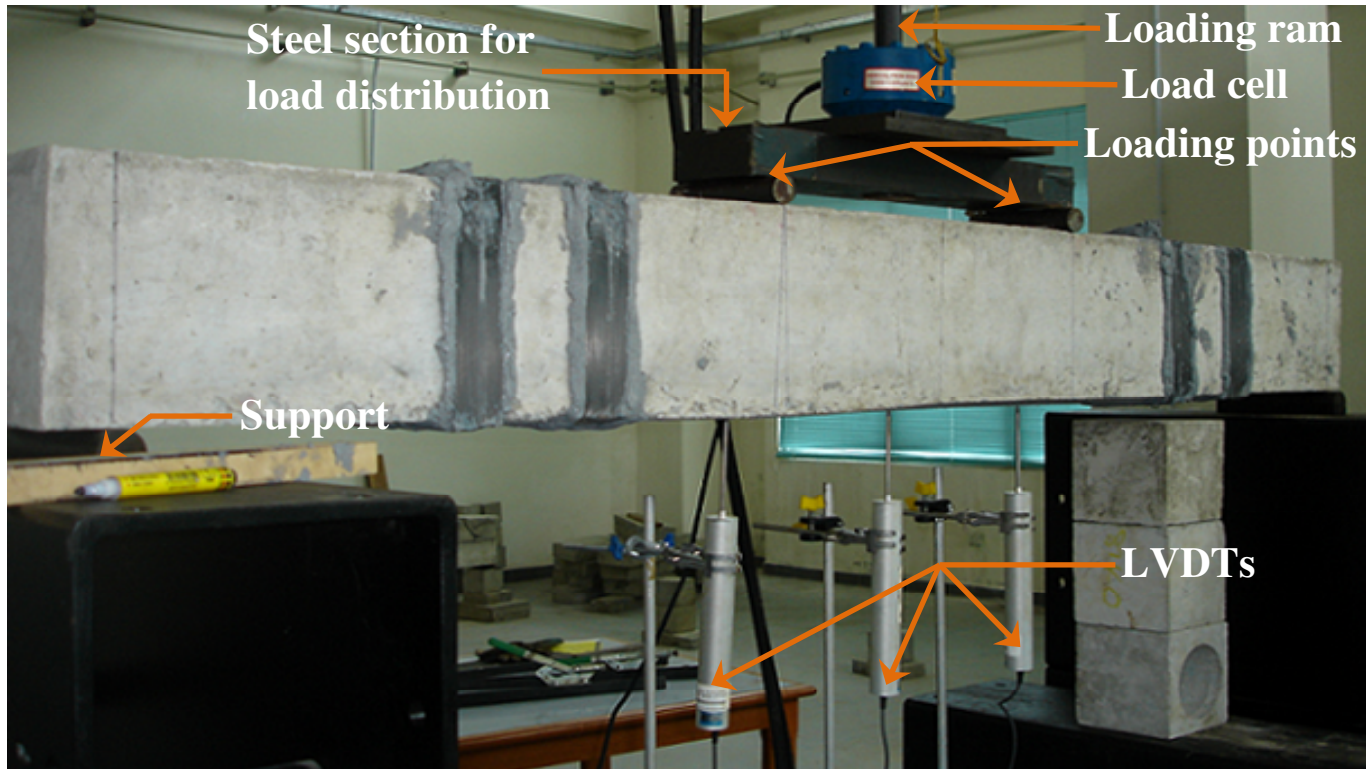


Figure 3. Set-up for four-point bending test in laboratory.

remove laitance, grease, loosely adhering particle and other dirt. Also, it was observed that no moisture was visible on the roughened surface. 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 of 1:3 and then 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. A nominal thickness of the epoxy adhesive has been controlled for the CFRP surface. Sikadur-30 adhesive was applied on cleaned and prepared substrate components and 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 rubber roller to press out any excess epoxy from the sides of the laminates. All the excess epoxy was removed from the sides of the laminates. To ensure a proper bonding, a minimum of 3 days curing of the externally applied adhesive was maintained for all the specimens.

Instrumentation and test procedure

In the test, the load was applied monotonically in a four-point bending test set-up as shown in Figure 3. All the beams were tested over a simple span of 1900 mm and instrumented for the measurement of quarter and mid-span deflections. Linear variable displacement transducers (LVDTs) were used to measure the deflection of the beams. Portable electronic data logger was used to record the reading of deflections. Load was applied by two hydraulic jacks, which are attached to a pressure gauge. 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. The quarter span LVDTs were used mainly to check the symmetrical nature of the loaded beams. Cracks were visually detected using a magnifying glass and its propagation was traced and the corresponding loads were recorded on the surface of the beam.

TEST RESULTS AND DISCUSSION

Load-deflection characteristics

The load-deflection behavior of the control beam and beam strengthened with different layers of CFRP laminates are shown in Figure 4. Figure 5 displays the load-deflection response of beams strengthened with single layer of CFRP laminate but having different degrees of restrain at the edges against premature debonding. It is observed from Figure 4, that 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

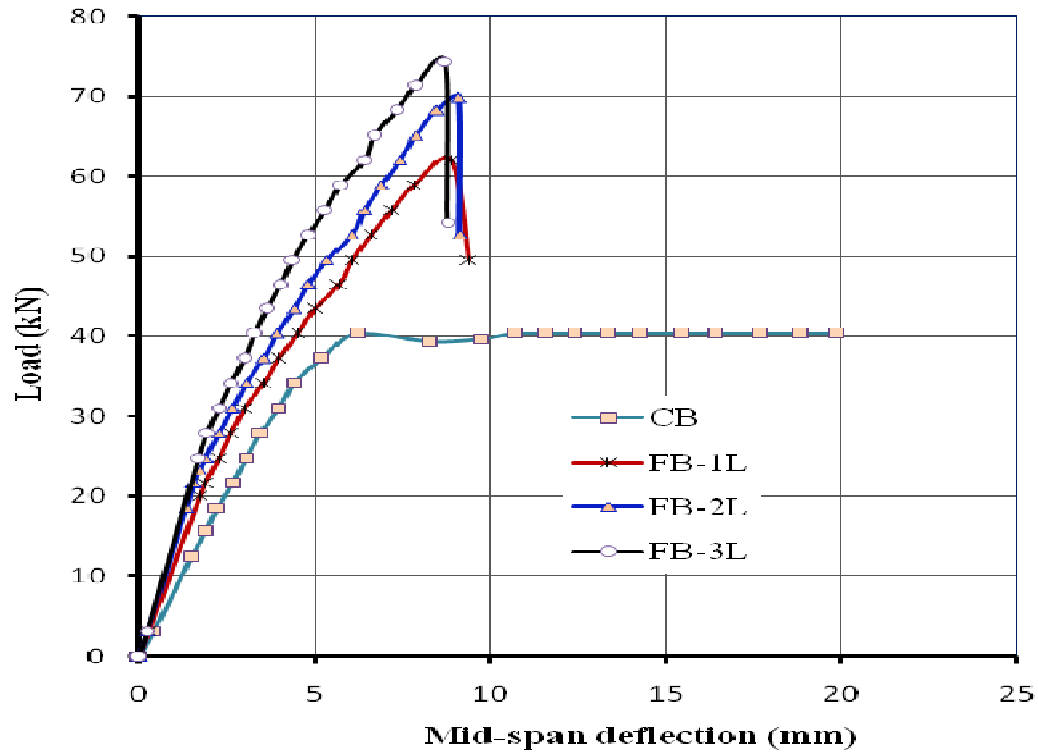


Figure 4. Load-deflection responses of control beam and multi-layer CFRP strengthened beams.

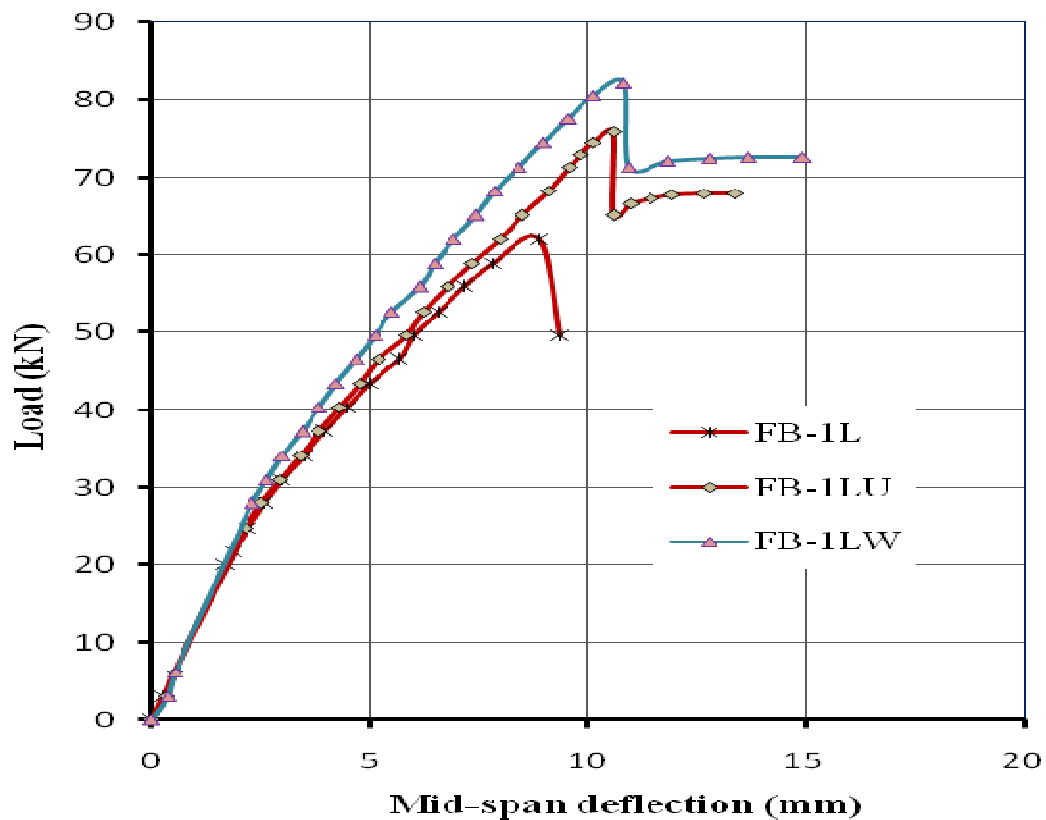


Figure 5. Load-deflection response of 1-layer strengthened beam with different edge restraint beams.

Table 5. Experimental and theoretical results.

Beam designation	Experimental load (kN)		Theoretical load (kN)		$\frac{P_{ult(The.)}}{P_{ult(exp)}}$	Failure mode	Ductility Index
	P_{cr}	P_{ut}	P_{cr}	P_{ult}			
CB	12.4	40.3	11.3	31.5	0.78	Concrete crushing	3.81
FB-1L	15.5	62.0	12.3	82.6	1.33	Debonding	1.65
FB-2L	18.6	69.75	13.4	98.8	1.41	Debonding	1.48
FB-3L	21.7	74.4	14.4	106.8	1.43	Debonding	1.29
FB-1LU	23.25	75.95	12.3	82.6	1.09	Debonding and concrete crushing	2.28
FB-1LW	27.9	82.15	12.3	82.6	1.00	Debonding and concrete crushing	2.42

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. The displacement ductility index (displacement at failure divided by displacement at yield) can give an estimation of the lack of ductility of these beams (Table 5). The use of second and third layer of CFRP plates can lead to significant increase in the ultimate load and stiffness of the beam. During the test, no de-lamination was observed between the superimposed CFRP plates in the case of multi-layered strengthened beams. The load deflection plots of strengthened beams with U and W-shaped edge strips show similar response to that of strengthened beam without transverse edge strips. However, a significant increase in the ultimate strength was noted in these two beams, although it still showed sign of de-bonding just before ultimate failure.

First cracking and ultimate loads

Table 5 shows the experimental results of the control and strengthened beams in terms of the first cracking load and ultimate load. It also includes the theoretical prediction of first cracking loads and ultimate loading capacity of the tested beams. Theoretical predictions of the first cracking load was calculated from the equivalent transformed section analysis of the beam cross-section and ultimate load carrying capacity was predicted using equivalent stress block of the cracked cross section in accordance to the provision mentioned in British Standard BS 8110-1(1997).

Table 5 also tabulates the failure modes of the test beams. It was observed from the test result that the control beam failed by yielding of tensile steel reinforcement followed by crushing of the concrete directly under the 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

12.4 kN. At load of about 37.2 kN, the tensile reinforcing steel yielded. Finally, the beam failed in flexure due to the crushing of extreme compression zone of concrete at a load 40.3 kN.

The last column of Table 5 shows the ductility index calculated for the beams. The lower value of ductility index for the CFRP strengthened beams (FB-1L, FB-2L and FB-3L) indicates the lacking of ductility of such strengthened beams. It was also observed that end anchored strengthened beams showed more displacement or ductility as compared to those of without anchored one. However, the observed improvement of ductility index from U-shaped edge strip beam to two W-edge strips was not that significant. It is seen in Table 5 that the percentage improvement of ductility of carbon fiber strengthened U and W-wrapped edge anchored beams are 40 and 36% respectively as compared to that of un-wrapped (single layer CFRP) beam.

In general, different levels of CFRP strengthened reinforced concrete beams (FB-1L, FB-2L, FB-3L, FB-1LU and FB-1LW) showed significant increases in flexural stiffness and ultimate capacity as compared to that of control beam. From the experimental investigation, it is identified that the percentage improvement of cracking load of 1, 2 and 3-layers CFRP strengthened beams are 25, 50 and 75% respectively whereas the percentage improvement of ultimate load are 54, 73 and 85% respectively as compared to the control beam. The improvement in first crack load of strengthened beams can be attributed to the increase of stiffness due to the laminates restraining effects. The use of transverse U and W shaped wrap strips gives an improvement of 88 and 103% flexural capacity respectively as compared to that of control beam and 23 and 33% increase respectively to that of one layer non end anchored beam. In this study, flexural capacity of U-shaped end anchored RC beams was nearly similar to that reported for CFRP composite laminate strengthened beams with U-shaped end anchored beams (Alam and Jumaat, 2009). They found that the failure loads of the non end anchored and

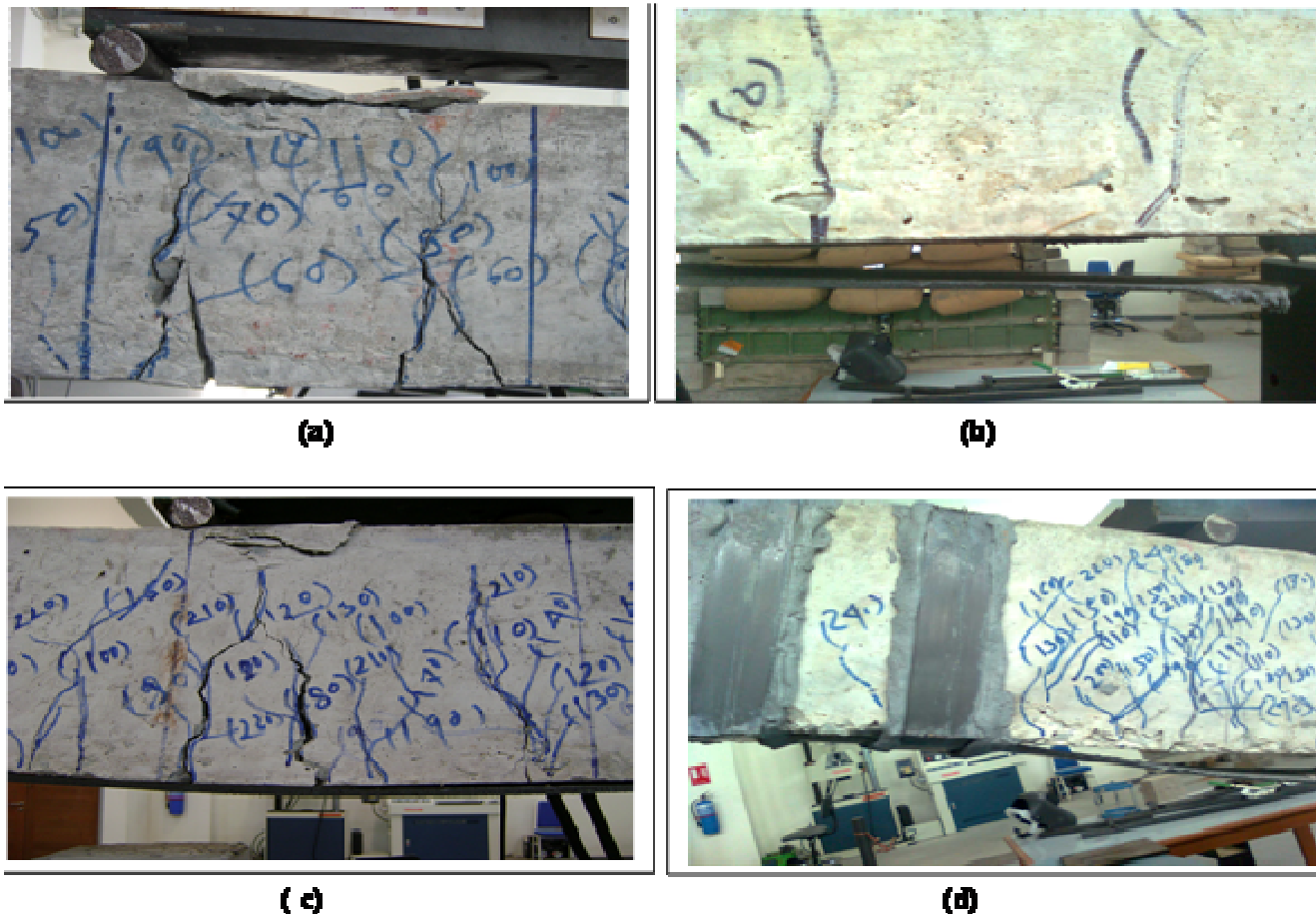


Figure 6. Mode of failure. (a) Control beam, (b) typical CFRP laminate strengthened beam, (c) strengthened beam with U-shaped edge strip, (d) strengthened beam with W-shaped edge strips.

end anchored CFRP laminate strengthened beams were 54 and 89%, respectively higher than the control beam. Also, the failure load of end anchored CFRP laminate strengthened beam was 23% higher to that of the one layer non end anchored strengthened beam. Small variation is sometimes attributed to the variability of materials, mix proportions, loading conditions, age of concrete, curing and strengthening procedure. However, it is concluded that the laminate thickness and transverse edge strips significantly influence the structural performance of the strengthened beams.

A comparison between experimental and theoretical result shows that the theoretical calculation give conservative estimate 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.

Crack pattern and failures modes

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 de-bonding was prevented using U and W-wrap strips at the ends, failure was due to crushing of concrete in the compression zone near the mid span region. This is also clearly indicates that, the use of end anchorage in the beam FB-1LU and FB-1LW changed the failure mechanisms than that of without end anchored and control beam. In beams FB-1LU and FB-1LW, CFRP rupture and failure due to concrete crushing were prominent when strengthening was done using both the wrapping schemes. The crack patterns and modes of failure of the control beam, typical CFRP strengthened beams, and CFRP strengthened beams with U and W-shaped transverse strips are shown in Figures 6(a), (b), (c) and (d) respectively.

During the testing, the un-strengthened (control) beam exhibited widely spaced and greater number of cracks compared to the strengthened beams. It can be realized

that, compared with the control beam, the strengthened beams has a smaller cracking amplitude and the cracking bandwidth. The use of CFRP sheets had resulted in delaying the growth of crack formation. This behavior shows the enhanced concrete confinement due to the influence of 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.

Conclusions

This paper has 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 results, observations and theoretical investigations, the following conclusions can be stated:

- 1) The result of the experimental study indicates that externally bonded CFRP laminates is an effective method to strengthen the reinforced concrete beams and improve the structural load carrying capacity.
- 2) Regarding the effect of number of layers, an increase in flexural stiffness, yield load, and ultimate load is achieved with the increase of carbon fiber laminate layers. It seems that the beam behaves as if the plate was thicker and no inter-layer de-lamination is observed in all cases. Nevertheless, the possible brittle failure of the strengthened beams still needs to be considered.
- 3) Regarding the effect of transverse edge strip, significant improvement in flexural strength was noted and the de-bonding of laminates occurred just before or at the final failure. The use of transverse edge strips increased the flexural capacity of strengthened beams by as much as 33% when compared to strengthened beams without edge strips. The W-wrapped CFRP edge strips arrest the propagating cracks more effectively than the U-shaped CFRP edge strips.
- 4) Beams strengthened with different CFRP layered have not reached their ultimate flexural capacity due to the effect of peeling and premature de-bonding failure of the laminates. When the beams were strengthened with transverse CFRP edge strips, the mode of failure changed from flexural failure (yielding of steel reinforcement) to sudden rupture of the CFRP laminates. The use of the CFRP edge strips is more prominent since the full flexural capacity for the strengthened beams can be achieved in terms of end anchoring scheme.
- 5) It was also observed that the ultimate load carrying capacity cannot be increased uniformly by simply adding the number of CFRP laminates layers. This suggests that the gain in the ultimate flexural strength was more significant in beams with lower FRP reinforcement ratios with end anchoring scheme. From the experimental

results it is clear that minimum one layer of CFRP sheets with end anchorage can give the desired results.

- 6) In general, theoretical flexural strength based on strain compatibility in the concrete, steel and CFRP reinforcement gave a reasonable prediction of the experimental results. A closer agreement for the ultimate load achieved provided the premature de-bonding of CFRP laminates can be prevented by using the transverse edge strips in the beam.

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