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Flexural Performance of RC Beams Strengthened with Different Reinforcement Ratios of CFRP Laminates

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Abstract. In this paper, experimental study is carried out to evaluate the flexural performance of reinforced concrete beams strengthened with different ratios of carbon fibre reinforced polymer (CFRP) laminates. Four rectangular reinforced concrete beams strengthened with different reinforcement ratios of CFRP laminates are tested to failure under transverse bending on a simply supported span of 1.9 m. The increase of ultimate strength provided by the bonded carbon fiber is assessed and failure mode is identified. The results indicated that the flexural capacity of beam was significantly improved as the layers of laminates increased. It is concluded that the attachment of CFRP laminates has substantial influence on the performance of CFRP strengthened beams. However, de-bonding of CFRP laminates from the concrete surface is still a concern for the case of multi-layer strengthening of beam. Based on the observed results, recommendations are made to prevent the premature de-bonding failure of strengthened beams.

Introduction

Researches and field application [1-2] of reinforced concrete beams bonded with steel plates have been conducted in the past. Even though this technique has been recognized to be an effective in increasing flexural capacity and enhancing flexural stiffness thereby reducing deflection as well as controlling cracking it is difficult to implement and in practice it requires complicated manipulation. In the past two decades FRPs, which were originally developed for the aerospace and defense industries, have shown great potential for use in civil engineering structures [3]. Recently, one popular strengthening method has been developed, consists of using FRPs material as external bonded reinforcement strips [4]. In practice, FRP can be incorporated into concrete structures in different forms, like embedded bars, meshes, gratings and external plates [5]. Among them, external use of FRPs sheet appears to be the most convenient, fast, cost-effective and promising way of rehabilitation and strengthening over the steel plates [6].

In this paper, the effect of the number of CFRP layers on the flexural performance of strengthened beams is investigated. The effectiveness of using CFRP laminates to improve the stiffness and the structural capacity of RC beams 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.

Methodology

Experimental Program. Table 1. shows the experimental program that was initiated to investigate the effect of CFRP laminates on the flexural performance of RC beams. A total of four beams having different level of strengthening scheme were fabricated in the laboratory. First beam (designated as CB) was not bonded with CFRP laminates and considered as control beam, the rest three beams namely, FB-1L, FB-2L and FB-3L were bonded with different layers of CFRP laminates (1, 2 and 3–layers respectively).

Table 1. Experimental Program

Beam designation	FRP ratio, ρ_{FRP} (%)	Type of strengthening
CB	0	Un-strengthened (control) beam
FB-1L	0.4	One layer of CFRP sheets strengthened beam
FB-2L	0.8	Two layers of CFRP sheets strengthened beam
FB-3L	1.2	Three layers of CFRP sheets strengthened beam

Specimen Details. The specimen configuration is shown in Fig. 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 (10mm in diameter) as tensile reinforcement and two T6 bars (6mm 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 [7].

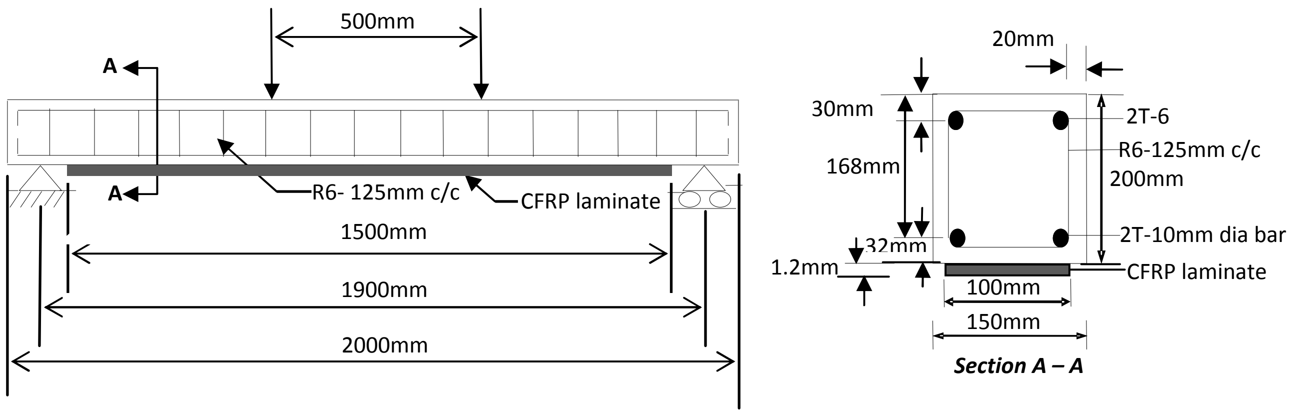

Fig.1 Longitudinal and Cross section detail of the experimental beams

Material Properties. The concrete mix proportion was set at 1:1.65:2.45:0.45 by weight of ordinary Portland cement, locally available natural sand, and crushed granite aggregate of 10mm nominal size and water. The concrete has a compressive strength of 36.0MPa, modulus of elasticity of 28.6GPa, and a modulus of rupture of 3.7MPa. High yield deformed steel reinforcement bars of 6mm and 10mm (T6 and T10) were used as compression and tension reinforcement for the beam specimens and plain round mild steel bar of 6 mm diameter (R6) is used as transverse shear reinforcement. The average modulus of elasticity of steel reinforcing bars was 195GPa, 186GPa and 200GPa and yield strength was 482MPa, 470MPa and 215MPa for T10, T6 and R6 bars respectively. Unidirectional CFRP laminates of 1.2mm thickness per layer was used for the strengthening purposes of the beams and are cut from the Sika Carbodur S1012/160 [8] 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 until the failure. The other properties of the carbon fibers and epoxy adhesive as supplied by the manufacturer are shown in Table 2.

Table 2. 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
	Tensile strength (MPa)	1685
	Density (g/cm^3)	1600
Epoxy adhesive	Modulus of Elasticity (GPa)	3
	Elongation at ultimate (%)	2.6
	Tensile strength (MPa)	55

Strengthening System. The surfaces were prepared as suggested by the manufacture instruction for proper bonding of the CFRP laminates into 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 remove laitance, grease, loosely adhering particle and other dirt. 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. The CFRP laminates were cleaned properly using sika colma cleaner. 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 is maintained for all the specimens. Fig. 2 shows the schematic diagram of single, double and triple layer strengthening scheme of reinforced concrete beams.

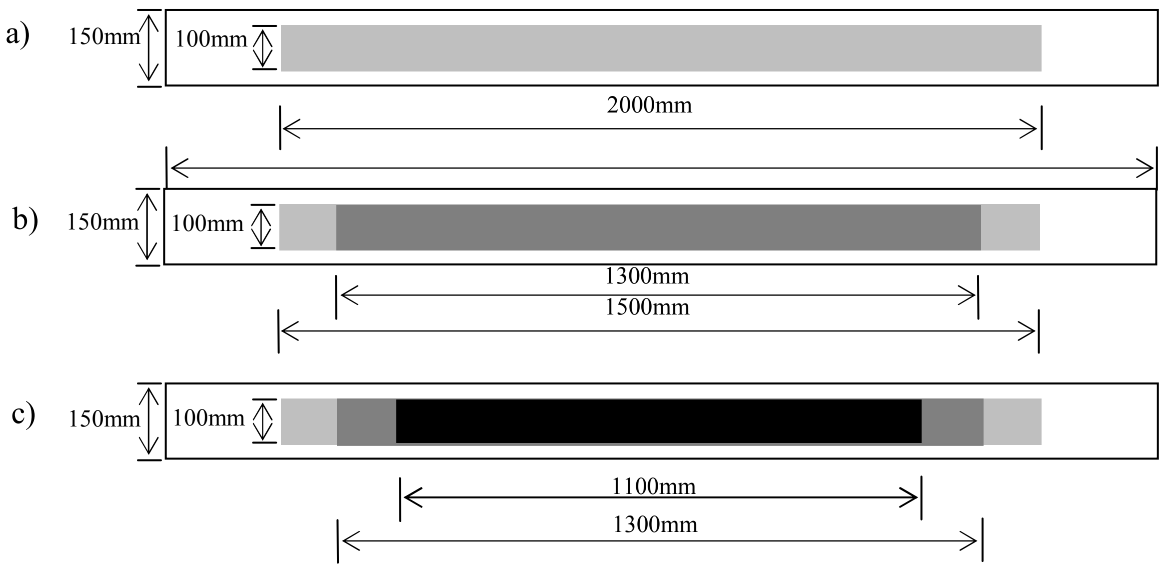

Fig. 2 Strengthening schemes of RC beams: CFRP laminates of (a) single, (b) double and (c) triple layers

Test Setup and Procedure. In the test, the load is applied monotonically and the bending test set-up is a four-point one. All the beams were tested over a simple span of 1900mm and instrumented for the measurement of quarter and mid-span deflections. Linear displacement transducers were used to measure the deflection of the beams. Portable electronic data logger was used to record the reading of deflections. Loads were applied by two hydraulic jacks, which are attached to the 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 transducers 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.

Results and Discussion

Load-deflection Relationship. The load-deflection behavior of control beam and beam strengthened with different layers of CFRP laminates are shown in Fig.4. It is observed from Fig. 3, 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. 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 is observed between the superimposed CFRP plates in the case of multi-layered strengthened beams.

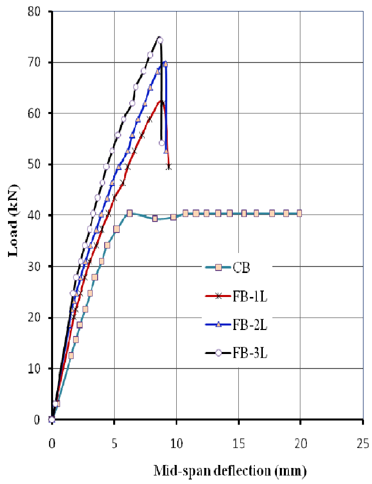

Fig. 3 Load-deflection response of control beam and multi-layer CFRP strengthened beams

Ductility Characteristics. When applied to RC members, the term ductility implies the ability to sustain significant inelastic deformation prior to collapse. In this study, the displacement ductility was investigated. 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 3 shows the displacement ductility of the tested RC beams using different CFRP laminates configurations. It was also observed that un-strengthened beam showed more displacement or ductility as compared to that of different CFRP configurations concrete beam. The maximum deflection prior to the final failure of the CFRP strengthened beams was found about 12.8mm and it indicate that the strengthened beams are less ductile compared to the un-strengthened beams. The lower value of ductility index for the CFRP strengthened beams (FB-1L, FB-2L and FB-3L) indicate the lacking of ductility of such strengthened beams.

First Cracking and Ultimate Loads. Table 3 shows the experimental results of 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 test beams. Theoretical predictions of the first cracking load is calculated from the equivalent transformed section analysis of the beam cross-section and ultimate load carrying capacity is predicted using equivalent stress block of the cracked cross section in accordance to the provision mentioned in British Standard [7].

Table 3. Experimental and Theoretical results

Beam designation	Experimental load (kN)		Theoretical load (kN)					
	P_{cr}	P_{ut}	P_{cr}	P_{ult}	$\frac{P_{ult(The.)}}{P_{ult(\exp)}}$	Crack spacing(mm)	*Ductility Index*	Failure mode
CB	12.4	40.3	11.3	31.5	0.78	105	3.81	Concrete
FB-1L	15.5	62.0	12.3	82.6	1.33	126	1.65	De-bonding
FB-2L	18.6	69.75	13.4	98.8	1.41	138	1.48	De-bonding
FB-3L	21.7	74.4	14.4	106.8	1.43	149	1.29	De-bonding

Table 3 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 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 12.4kN. At load around 37.2kN, the tensile reinforcing steel yielded. Finally, 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. From the experimental investigation, it is identified 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 the increase of stiffness due to the laminates restraining effects. Thus, it is concluded that the laminate thickness significantly influence the structural performance of the strengthened beams. 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.

Failures Modes and Crack Patterns. 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 3. During the testing, the un-strengthened (control) beam exhibited widely spaced and greater number of cracks compared to the strengthened beams (refer to Table 3). The cracks have appeared on the surface of the strengthened beams at relatively closer spacing. 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. It was observed from the experimental investigation that all beams strengthened with CFRP laminates have failed in the same manner. The crack patterns and modes of failure of control beam, typical CFRP strengthened beams are shown in Figs. 4 (a) and 4 (b) respectively.

(a) (b)

Fig. 4 Mode of failure (a) Control beam (b) typical CFRP laminate strengthened beam

The peeling of CFRP laminates starts from the end of the beam in the region of high shear stress. Research shows that the de-bonding of FRP sheets can be prevented by introducing edge transverse strips at the location of critical shear stress. Hence, to get the full benefit of the strengthening effect, it is suggested to use U or W shaped edge CFRP strips to prevent the premature failure of de-bonding.

Summary

The result of the experimental study indicates that externally bonded CFRP laminates can be used effectively to strengthen the reinforced concrete beams. 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 de-lamination is observed in any cases. Nevertheless, the possible brittle failure of the strengthened beams still needs to be considered. Failure mode of beam strengthened with CFRP sheets was by de-bonding of the strips and concrete crushing in compression zone. To get the full benefit of strengthening effect, it is suggested to prevent the de-bonding failure by using edge strips. In general, the experimental results are in very good agreement with the theoretical predictions. A closer agreement for the ultimate load can be achieved provided the premature de-bonding of CFRP laminates can be prevented.

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