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Flexural retrofit of RC beams using CFRP laminates

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Abstract. RC structural members have to be retrofitted to comply with the revised codal provisions and changes in functionality of structures. This study aims to investigate the behaviour of prototype RC beams having high shear span ratio externally bonded with CFRP laminates. Four-point bending tests were conducted up to failure of the specimens. The applied load, deflection, strain in concrete, steel reinforcements and CFRP laminate were measured during the testing. The retrofitted specimens showed an increase in ultimate load carrying capacity and stiffness up to 53% and 61% respectively. The retrofitted specimens failed by interfacial crack induced debonding failure mode at a strain of 25% of CFRP laminate's rupture strain. This study concludes that CFRP laminates are to be anchored on RC beams along with bonding using adhesives.

1. Introduction
RC beams were retrofitted by bonding steel plates to the soffit of the beam to increase flexural strength. Corrosion, handling difficulties, and premature failures are the disadvantages of this technique. Fibre Reinforced Polymer (FRP) composite materials have been introduced for strengthening in Civil Engineering and the addition of steel plates is replaced. High strength, cast-to-any shape, ease of handling, and non-corrosive nature make FRP composites a suitable material for retrofitting. Alagusundaramoorthy et al. [2] conducted experiments to study the flexural behaviour of RC beams externally bonded with different CFRP laminates and carbon fibre fabric. Brena et al. [6] conducted experiments on a series of RC beams and observed that externally bonded beams experiences debonding mode of failure regardless of the contact area of the FRP laminates. Fanning and Kelly [9], Ceroni [7], Brena and Macri [5] tested small scale externally bonded specimens and observed the debonding mode of failure. Garden and Hollaway [11] reported that ultimate load and failure mode is dependent on shear span ratio. Teng et al. [18] demonstrated through experiments that load distribution on the beam has a beneficial effect on debonding load. Debonding failure mode is widely reported in literature, which is not desired due to under-utilization of FRP composite. Debonding failure modes are classified into plate end debonding and intermediate crack induced debonding (IC-debonding) and are influenced by the shear span ratio [8] and extension length of FRP composite on the shear span [16] [18]. It was observed that studies on full scale RC beams with shear span ratio greater than 5 externally bonded with CFRP pultruded laminates are not available. The main objective is to study the flexural behaviour and failure mode of prototype RC beams of high shear span ratio externally bonded with CFRP laminates. The scope of the work includes (i) testing of prototype RC beams with shear span ratio greater than 5 externally bonded with CFRP laminates (ii) study on stiffness, strength, and failure mode of externally bonded beams and (iii) measuring the failure strains at critical locations of failure.

2. Test specimens
The experimental program consists of tests on two control beams and two retrofitted beams under four-point bending. The beams were retrofitted by bonding 50 mm wide and 1.4 mm thick CFRP

laminate on the tension zone. The total length (*l*), span (l_{eff}), breadth (*b*), and depth (*d*) of the beams are 5000 mm, 4700 mm, 230 mm, and 400 mm respectively. The beams were reinforced identically with two 12 mm diameter bars in tension zone and two 10 mm diameter bars in compression zone. 100 mm long 90-degree bends were provided to anchor the reinforcements at the two ends of the beam. 8 mm diameter shear reinforcements were provided at 100 mm c/c spacing. A clear cover of 30 mm was provided to shear reinforcements. The control specimens were designated as RCB1 and RCB2 and the retrofitted specimens were designated as RCBEB3 and RCBEB4. 'RCB' stands for reinforced concrete beam and 'EB' stands for external bonding. The details of test specimens are given in Table 1. Cross sectional dimensions of specimens with reinforcements are shown in figure 1.

Table 1. Test specimens

Specimen	Beam dimensions			Effective Span	CFRP laminate			
	l (mm)	b (mm)	d (mm)	l_{eff} (mm)	Length l_f (mm)	Width b_f (mm)	Thickness d_f (mm)	Layers n
RCB1	5000	230	400	4700	...	...	...	...
RCB2	5000	230	400	4700	...	...	...	...
RCBEB3	5000	230	400	4700	4500	50	1.4	1
RCBEB4	5000	230	400	4700	4500	50	1.4	1

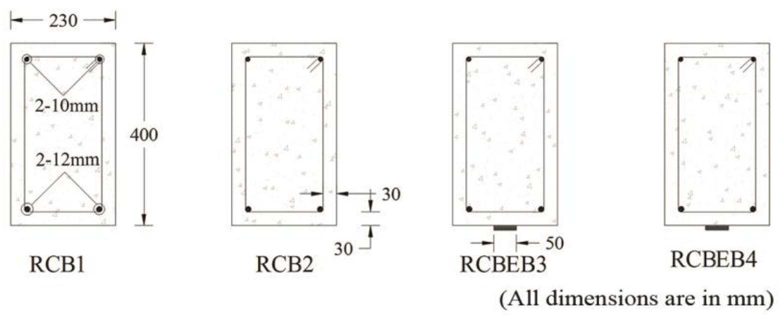

Figure 1. Cross-sectional view of specimens

3. Material properties

M 25 grade concrete was used for casting the beams. Cement, fine aggregate, and coarse aggregate in the ratio 1:3.3:4.8 was arrived by trial mixes and water-cement ratio was kept as 0.65. Standard cubes of 150 mm size were casted and tested in accordance to IS 516-1959 in the 1000 kN compression testing machine on the day of testing to find the compressive strength of concrete in the corresponding specimen. The average compressive strengths of concrete in specimens RCB1, RCB2, RCBEB3, and RCBEB4 were 27.7 MPa, 25.5 MPa, 26.3 MPa, and 33.1 MPa respectively. Fe 500D grade steel was used for reinforcements. The mechanical properties of steel reinforcements were found from tension tests conducted as per IS 1608-2005 (Table 2). The yield strengths of 8 mm diameter, 10 mm diameter, and 12 mm diameter bars were found to be 588 MPa, 545 MPa, and 532 MPa respectively. Tensile strength and tensile modulus of CFRP laminate were found from tension tests done as per ASTM D3039-07 and given in Table 3. The ultimate tensile strength and modulus of CFRP laminate were found to be 2599 MPa and 168 GPa respectively. Properties of epoxy resin were found by casting and testing plates in accordance to ASTM D638-14. The ultimate tensile strength and modulus of epoxy resin were found to be 28 MPa and 11 GPa respectively.

Table 2. Properties of steel reinforcements

Bar diameter (mm)	Number of specimens	Elastic Modulus E_s (MPa)	Yield stress f_y (MPa)	Yield strain ε_y (μm/m)	Ultimate stress f_u (MPa)	Ultimate strain ε_u (μm/m)	% elongation (%)
8	3	204	588	4882	709	70975	28
10	3	203	545	4723	652	78714	24
12	3	201	532	4644	625	67460	21

Table 3. Properties of epoxy resin and CFRP laminate

Material	Number of specimens	Density ρ (g/cc)	Elastic Modulus E (GPa)	Ultimate Strength f_u (MPa)	Ultimate Strain ε_u (μm/m)	Poisson's Ratio μ
Epoxy Resin	5	1.85	11	28	3025	0.27
CFRP laminate	5	1.60	168	2599	18267	0.29

4. Bonding of CFRP laminate

The bonding surface (tension zone) was made rough using an angle grinder and cleaned with acetone to remove any dust and loose particles. The bonding surface was made dry before bonding. A two component epoxy primer with resin and hardener in the ratio 1:0.5 was mixed thoroughly and applied to the prepared surface. After tack free time of primer a layer of adhesive resin (1:0.75) was applied over the primer coat. The protective cover of the CFRP laminate was removed and adhesive resin was applied. Air bubbles were removed using rollers. Slotted weights were placed on the laminate to apply a constant pressure. The bonded specimen was left undisturbed for 72 hours for the curing of resin.

5. Test setup and instrumentation

The tests were conducted in Structural Engineering Laboratory IIT Madras. The test setup is shown in figure 2. Displacement controlled loading was applied at the rate of 1 mm/min using a 500 kN capacity actuator. A 1000 kN load cell was placed directly below the ram of the actuator to measure the load. The load from actuator was transferred to the specimen at two points using a stiffened steel girder. The test specimens had a constant moment span of 1000 mm and shear span of 1850mm with shear span ratio of 5.2. Simply supported end condition was established by resting the beam on a welded immovable roller on one end and a movable roller on the other end. 10 mm thick plates cushioned with cement mortar were kept between roller and the beam to prevent local crushing. Electrical resistant strain gauges of 5 mm gauge length and 120 ohm resistance (SG S1 to SG S6 and SG F1 to SG F9) were bonded to measure strain on steel reinforcements and CFRP laminate. Strain gauges of 60 mm gauge length and 120 ohm resistance (SG C1 to SG C3) were bonded on concrete surfaces. Displacements were measured using 100 mm linear variable differential transducers (LVDT1 to LVDT5). The strain gauges, LVDTs, and load cell were connected to a data acquisition system and continuous data was recorded at 0.05 s interval. The photograph of the test setup is shown in figure 3.

6. Test results

The load vs. deflection and load vs. strain curves of RCB1, RCB2, RCBEB3, and RCBEB4 specimens are shown in figure 5 to figure 8. The retrofitted specimens show a stiff behaviour than the control specimens. At an allowable deflection of 18.8 mm (IS 456:2000) the average corresponding load of RCB1 and RCB2 was 33 kN and RCBEB3 and RCBEB4 was 51 kN and 53 kN. The stiffness of RCBEB3 was increased up to 55% and RCBEB4 was increased up to 61% respectively compared to the control specimens. This shows the effectiveness of external bonding in increasing the stiffness of beams.

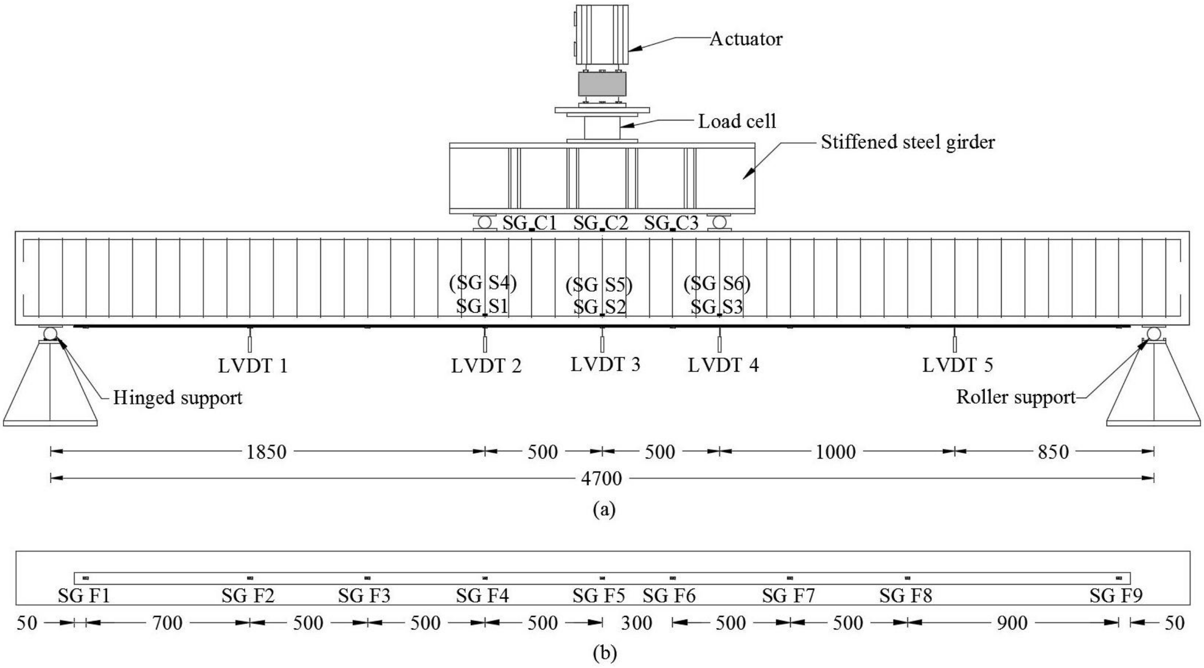

Figure 2. Test setup and instrumentation: (a) LVDT positions and strain gauge positions on the beam; (b) Strain gauge positions on CFRP laminate

Figure 3. Test setup

The loads at first crack, yield, and ultimate and the corresponding deflections are given in Table 4. The load when a steel strain gauge reaches yield strain of 4644 µm/m is taken as load at yield. The average load at yield of control specimens was 34 kN. The load at yield of RCBEB3 and RCBEB4 was 49 kN and 50 kN respectively. The increase in load at yield is 44% and 47% respectively. Maximum recorded load is taken as ultimate load. The average ultimate load of control specimen was 41 kN and the ultimate loads of RCBEB3 and RCBEB4 was 55 kN and 62 kN respectively. The increase in ultimate load is 36% and 53% respectively. The displacement ductility of RCB1 and RCB2 was 7.3 and 8.6 and RCBEB3 and RCBEB4 was 1.3 and 2.0.

The strain gauges SG S1 and SG S6 on tension steel reinforcement of RCB1 and RCB2 reached the yield strain of 4644 µm/m and the average strain in concrete was 561 µm/m and 471 µm/m and the failure mode was by yielding of tension steel followed by crushing of concrete. The strain gauges

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SG S2 and SG S6 on tension steel of RCBEB3 and RCBEB4 reached the yield strain of 4644 µm/m and the strain in concrete was 666 µm/m and 460 µm/m and the failure mode is yielding of steel followed by debonding of CFRP laminate. The debonding of CFRP laminate was initiated from the flexural crack below loading point. A visible debonding was observed at the flexural crack and the debonding continued to the end with a tearing sound and the other portion was intact. The strain on CFRP laminate at debonding failure of RCBEB3 and RCBEB4 was 4486 µm/m and 5823 µm/m respectively. Specimen RCBEB4 had higher strain in CFRP laminate due to its higher concrete strength. The average ultimate strain of CFRP from uniaxial tensile tests was found to be 18267 µm/m. Due to debonding mode of failure, the material utilisation efficiency was only 25% and 32%.

Table 4. Load and deflection values of the tested specimens

Specimen	Cracking Load		Yield Load		Ultimate Load		Ductility	Mode of Failure
	P_{cr} (kN)	δ_{cr} (mm)	P_y (kN)	δ_y (mm)	P_u (kN)	δ_u (mm)	δ_u/δ_y	
RCB1	9.9	0.92	35	14.53	42	106.35	7.34	SY-CC
RCB2	9.9	1.01	33	16.01	39	137.21	8.57	SY-CC
RCBEB3	11.7	1.01	49	18.00	55	22.67	1.26	SY-FD
RCBEB4	10.5	1.11	50	15.73	62	31.44	2.00	SY-FD

SY - Steel Yielding; CC - Concrete Crushing; FD - FRP Debonding

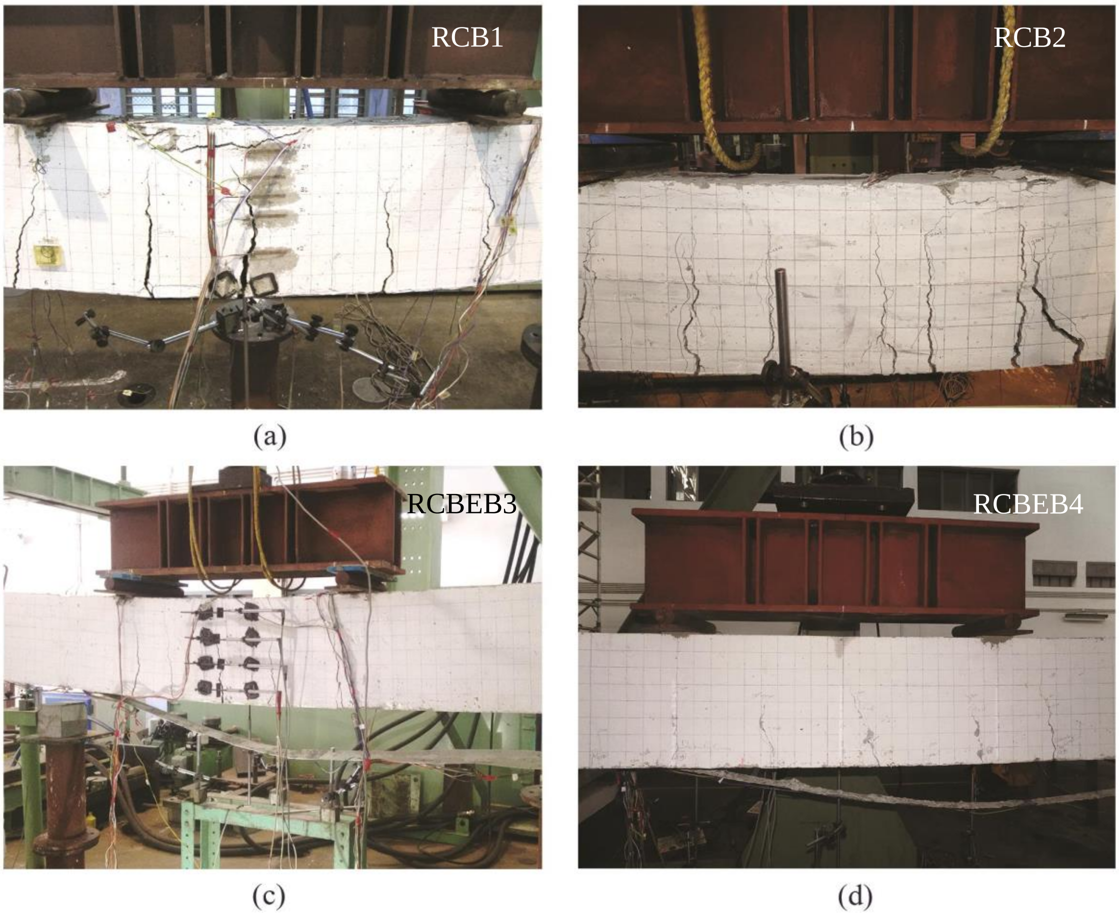

Figure 4. Failure of specimens (a) RCB1 (b) RCB2 (c) RCBEB3 (d) RCBEB4

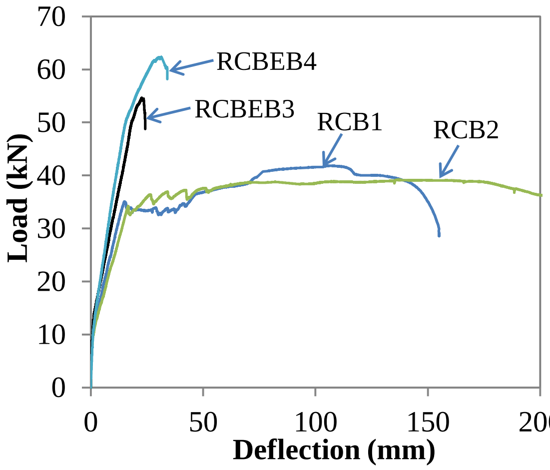

Figure 5. Load vs. deflection curves of all specimens

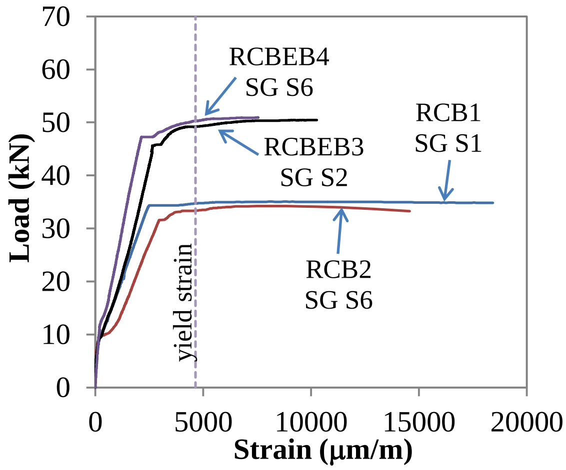

Figure 6. Load vs strain curves of steel reinforcements of all specimens

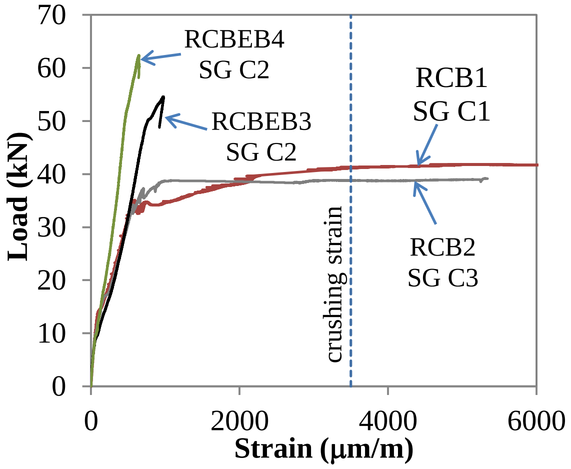

Figure 7. Load vs strain curves of compression concrete of all specimens

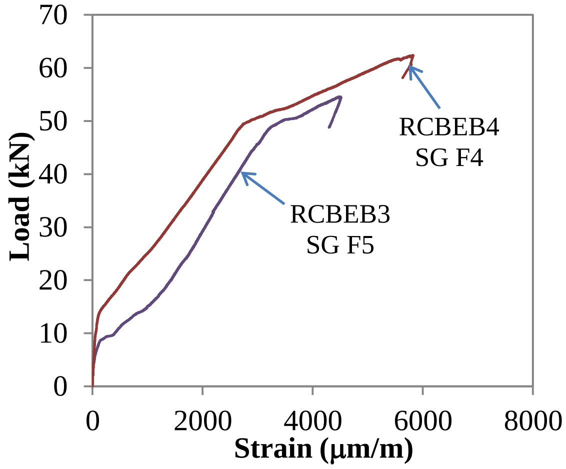

Figure 8. Load vs strain curves of CFRP laminate of retrofitted specimens

7. Conclusions

Four-point bending tests were conducted on four prototype RC beams having shear span ratio 5.2 with two as control specimens and the remaining two as retrofitted specimens. CFRP laminate was used for retrofitting RC beams. All the specimens were tested up to failure. The strain on concrete, steel and CFRP laminate and the deflection at specific points were measured during the testing. The following conclusions were drawn from this experimental study:

- The debonding of CFRP laminate starts from a flexural crack below loading point and propagates towards the support of RC beam.
- The maximum strain in CFRP laminate is 25% of its ultimate tensile strain at debonding.
- The capacity if the CFRP laminate is underutilized in externally bonded RC beams.
- The Stiffness, yield load, and ultimate load were increased upto 61%, 47%, and 53% respectively on RC beams retrofitted with CFRP laminate compared to the corresponding control beams.

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