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Flexural behaviour of pre-damaged RC beams retrofitted using CFRP laminates

Karuppiah Palaniappan[1], Philip Saratha Joanna[1], Murali Rajasekaran[1], Angeline Prabhavathy[2], Daniel Cruze[1] and Samuel James[1]

[1] *Hindustan Institute of Technology and Science, Department of Civil Engineering, 603103, Padur, Chennai, India*

[2] *Annai Vailankanni College of Engineering, Department of Civil Engineering, 629401, Pottalkulam, Kanyakumari, India*

Corresponding author:
Daniel Cruze
danielckarunya@gmail.com

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Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
This study entailed an investigation on retrofitting methods, aimed at enhancing the strength of reinforced concrete (RC) beams by applying carbon fibre-reinforced polymer (CFRP) laminates and CFRP fabrics in the flexural and shear zones of damaged RC beams. The experimental examination involved the casting and subsequent strengthening of six rectangular RC beams, via external bonding techniques utilizing both CFRP laminates and fabrics. The research design included five distinct systems of strengthening of pre-damaged RC beams up to the ultimate load level and 90 % of the ultimate load level. All RC beams were cast using M20-grade concrete and uniform reinforcement detailing. The results revealed a significant enhancement in the load-bearing capacity of the RC beams externally strengthened u CFRP laminates. Particularly, the beams retrofitted with U-shaped wrapping exhibited a substantial improvement in both crack and ultimate loads. These findings underscore the efficacy of the CFRP retrofitting approach, demonstrating a positive impact on the overall structural performance of pre-damaged RC beams. This study indicates that incorporating CFRP laminates and fabrics in the shear and flexural zones of pre-damaged beams up to the ultimate load level can enhance the ultimate load-carrying capacity by up to 13 %. The proposed approach offers a cost-effective strategy to enhance strength and maintain ductility without compromising the overall structural integrity.

Keywords:
CFRP; Flexure; RC beam; retrofitting

1 Introduction

Fibre-reinforced polymers (FRPs) have been extensively utilised in the construction industry for various applications owing to their excellent mechanical properties, for instance, their remarkable capability to strengthen reinforced concrete (RC) structures. FRPs possess several beneficial characteristics such as easy on-site handling, high strength-to-weight ratios, and resistance to corrosion. FRPs exhibit good tensile stress, which renders them effective in strengthening RC members subjected to flexure.

Strengthening of RC structures is a relatively quick and cost-effective strategy for rehabilitating structures or repairing structural members such as beams, columns, and slabs. In the conventional externally bonded FRP (EB-FRP) method, FRP strips are adhesively attached or bonded to flexural RC members in the tension zone [1]. However, the failure modes in the flexure tests for the strengthened beams involved premature debonding of the FRP laminates. Further, the tensile stresses at failure are approximately 10-15 % of the ultimate tensile strength [2, 3]. Recently, various novel technologies have been developed to enhance the bonding between FRP laminates and concrete.

Externally bonded carbon fibre-reinforced polymer (CFRP) reinforcement is the most preferred method for strengthening RC structures, largely because it does not require either concrete removal or section drilling, thus minimizing the risk of damaging the existing reinforcement. Lima and Barros [4] examined the strengthening of RC beams using EB-FRP models by analysing 250 retrofitted beams on the basis of data available in the literature; they concluded that further research is required to optimise retrofit designs [5-6]. Bousselham and Chaallal reported that increasing the thickness of the CFRP laminates in EB-FRP systems may not result in increased shear strength [7]. Further, Deniaud and Cheng reported that strengthened beams may fail at lower shear loads as compared to unstrengthened control beams [8]. Anchoring CFRP laminates in the compression zone of the beam would form an effective external shear-strengthening system [9-11].

FRP laminates can be bonded onto beams via the following three methods: side bonding, U-wrapped bonding, and complete wrapping. In side bonding, the laminates are attached to the vertical sides of the beam. U-wrapped bonding involves attaching the laminates to the sides and tension zone of the beam in a U-shaped configuration. Complete wrapping entails bonding the laminates around the entire beam. Completely wrapped beams tend to exhibit better performance by increasing the shear capacity and ductility owing to the strain along the vertical direction of the fibre, as compared to those with side-bonded and U-wrapped beams. However, in practical applications, complete wrapping may not be feasible because beams are often connected to slabs [12, 13]. Flexural behaviours of pre-damaged RC beams repaired and strengthened using CFRP laminates have been studied. Two reinforcement techniques have been used: externally bonded reinforcement (EBR) and near-surface-mounted (NSM) reinforcement. Prior studies have indicated that reducing the extent of damage leads to increased ultimate strength. The preloaded beams repaired using CFRP laminates exhibit higher ultimate loads and lower midspan deflections at the maximum load, as compared with beams without CFRP reinforcement. The beams preloaded with 30 % of the ultimate load and repaired using CFRP laminates exhibited higher ultimate loads and lower midspan deflection at maximum load compared to beams without CFRP reinforcement [14]. RC beams damaged up to 20 %, 40 %, 60 %, and 80 % of the ultimate load and then repaired using CFRP laminates have demonstrated that reducing the initial damage percentage increases the ultimate strength by 3,6-17,2 % [15].

Extensive research has been conducted on retrofitting damaged RC beams. However, studies focusing specifically on retrofitting of RC beams damaged up to the ultimate load level and 90 % of the ultimate load level are limited. In this study, six RC beams strengthened using different techniques were tested. Of these six RC beams, five underwent retrofitting-one was pre-damaged to the ultimate load level and strengthened using the grouting technique, whereas two were damaged up to 90 % of the ultimate load and retrofitted using CFRP laminates and fabrics. The remaining two beams were damaged to the ultimate load and then retrofitted. A control beam was also tested to serve as a reference for comparing the results of the retrofitted specimens.

2 Experimental Investigation

The experimental program entailed six different systems for strengthening RC beams. M20-grade concrete was used in this study and was prepared using 53-grade ordinary Portland cement (OPC), satisfying the Indian Standard specifications, with a specific gravity of 3.12 and initial and final setting times of 32 and 320 min, respectively [14]. Nine cube specimens, each with dimensions of 150 × 150 × 150 mm, were cast, cured in water, and then tested at 7, 14, and 28 days to assess the compressive strength. The average compressive strengths of M20-grade concrete are shown in Figure 1. In accordance with the Indian Standard specifications, naturally available river sand with a specific gravity of 2,60 was used as a fine aggregate, and locally available coarse aggregate with a specific gravity of 2,74 were used [15].

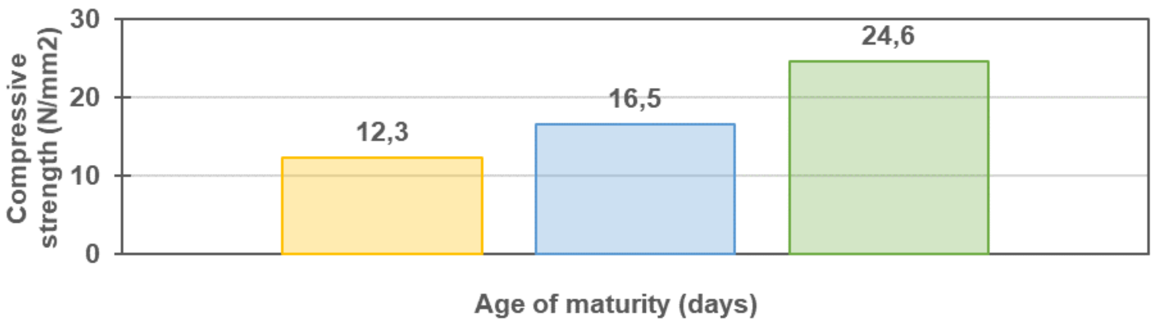

Figure 1. Compressive strength of M20 grade concrete

Six beams with cross-sectional dimensions of 150 × 200 mm and a length of 1800 mm were cast and tested under two-point loading. Each beam incorporated four steel bars (with 10 mm diameter) as bottom reinforcement; two 8-mm diameter bars as top reinforcement; and 6 mm diameter stirrups at a spacing of 150 mm centre-to-centre (c/c), as depicted in Figure 2
The RC beams were tested by using a loading frame with a capacity of 400 kN. The beams were subjected to two-point loads with simply supported end conditions, as shown in Figure 2. The deflection at midspan was measured using a linear variable displacement transducer (LVDT). Both the load cell and LVDT were connected to a data logger, which recorded the readings in real-time on a computer at each load interval until the beam failed.

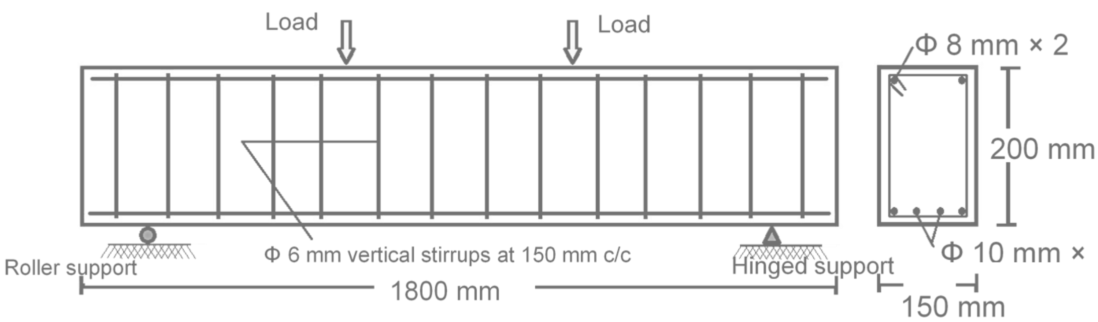

Figure 2. Reinforcement details of the control beam

Among the six RC beams tested, four beams were subjected to failure, while two beams were subjected to 90 % of the ultimate load in the loading frame. All five pre-damaged beams were cleaned, and grouting was performed on the cracked regions. PVC pipes were inserted into drilled holes-20 mm in diameter, up to a depth of 50 mm to inject the chemicals, which included Cera Poly Clay mortar (a microfibre-enriched cementitious repair mortar) and Cera Poly Crack

Filler (a non-shrink, polymer-modified cementitious material reinforced with micro fibers), which were combined with water to form a paste and applied over the cracked regions. Thereafter, styrene-butadiene rubber latex, mixed with cement and water, was applied onto the surface of the pre-damaged beams. Figure 3. illustrates the grouting process of pre-damaged beams. Subsequently, a thixotropic adhesive base (Nitowrap 40) and its hardener were mixed and applied to the prepared and cleaned surfaces. This ensured effective pasting or bonding of the CFRP laminate (Figure 4). Nitowrap 30 epoxy primer and Nitowrap 410 saturant were used for bonding the CFRP fabrics onto the laminates.

Figure 3. Grouting process for the pre-damaged beams

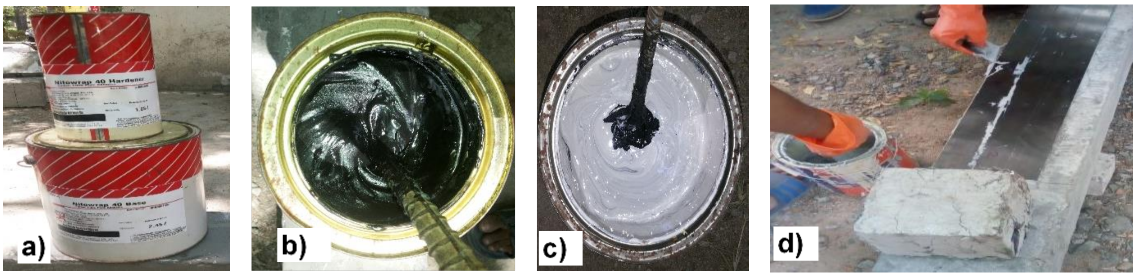

Figure 4. CFRP laminates bonding: a) Nitrowrap 40; b) Nitrowrap 40 hardner; c) Nitrowrap 40 base; d) Pasting of CFRP on the surface epoxy

Figure 5 shows a schematic of the loading setup for the testing beams. Table 1 lists the details of reinforced concrete beams. A schematic of the retrofitting system is presented in Figure 6.

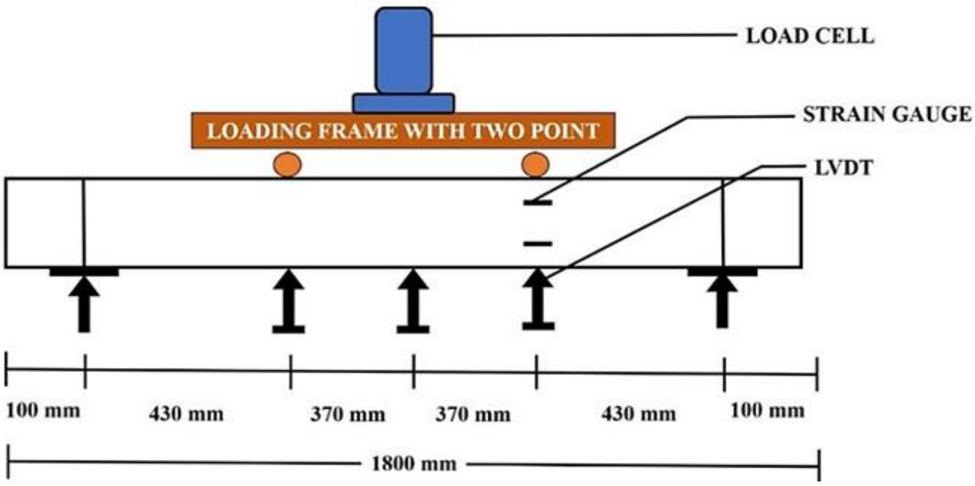

Figure 5. Typical schematic of loading set-up

Table 1. Beam designations and strengthening systems employed

S. No	Beam	Retrofitting system					
		Details	**Pre-damage load level**	**Grouting details**	**Zones strengthened With CFRP laminates**	**Size of CFRP laminates**	**Size of CFRP fabric**
1	CB	Control Beam	None	None	None	None	None
2	RB	Beams pre-damaged up to ultimate load level and then strengthened via grouting only.	Ultimate load level	At 3 locations on pre-damaged beams	Only by grouting over the entire area	None	None
3	A1	Beams pre-damaged up to 90% of the ultimate load level and retrofitted with CRFP laminate placed at the bottom of mid span (500 mm) and U-wrapped with CRFP fabric at the ends of CFRP laminate.	90% of the Ultimate load level	At 3 locations on pre-damaged beams	Flexural zone	500 mm × 100 mm (bottom of the beam)	550 mm × 250 mm (U-wrapped at the ends of the CFRP laminate)
4	A2	Beams pre-damaged up to ultimate load level and retrofitted with CRFP laminate placed at bottom (1400 mm) and U-wrapped with CRFP fabric over the ends of CFRP laminate (250 mm from support).	Ultimate load level	At locations on pre-damaged beams	Both shear and flexural zones	1400 mm × 100 mm (bottom of the beam)	550 mm × 250 mm (U-wrapped at the ends of the CFRP laminate)
5	A3	Beams pre-damaged up to 90% of the ultimate load level and retrofitted with CRFP laminate U-wrapped at mid span and U-wrapped with CRFP fabric at the ends of CFRP laminate.	90% of the Ultimate load level	At 3 locations on pre-damaged beams	Flexural zones	500 mm × 250 mm (bottom of the beam)	550 mm × 250 mm (U-wrapped over the ends of the CFRP laminate)
6	A4	Beams pre-damaged up to ultimate load level and retrofitted with CRFP laminate placed at the bottom of mid span (1400 mm) and U-wrapped with CRFP fabric at the ends of CFRP laminate.	Ultimate load level	At 3 locations on pre-damaged beams	Both shear and flexural zones	1400 mm × 100 mm (bottom of the beam)	550 × 250 mm (U-wrapped at the ends of the CFRP laminate)

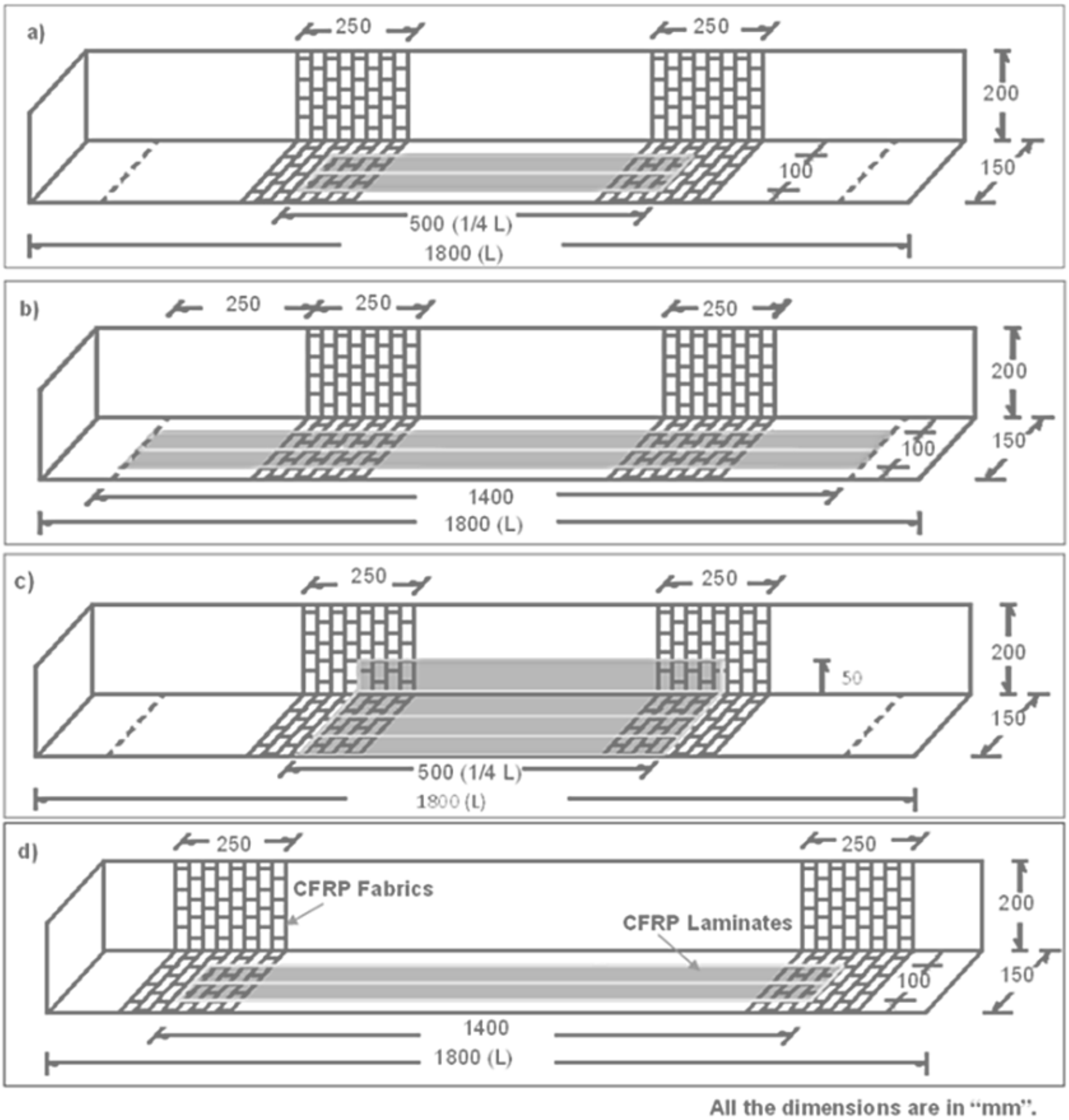

Figure 6. Details of specimens: beams a) A1, b) A2, c) A3, and d) A4

3 Results and Discussion

3.1 Failure pattern of the beams

Figure 7 shows the crack pattern of the control beam, which was designed to fail in flexure. Flexural failure occurred owing to the yielding of steel, followed by the crushing of concrete in the compression zone, with cracks evenly distributed in the flexural zone. In addition, cracks propagate faster after cracking [16,17]. In the control beam, the initial crack was observed at a load of 28,2 kN, and failure occurred at the ultimate load of 97,5 kN. The maximum deflection (28 mm) occurred at the centre of the beam. Figure 8 shows the crack pattern of the pre-damaged RC beam, which was strengthened using only cement grouting. The retrofitted beams were pre-damaged to the ultimate load level, and the cracks were grouted and tested again. The initial crack in the strengthened beam occurred at 17,6 kN, with an ultimate load of 62,6 kN. The maximum deflection was found to be 10,3 mm.

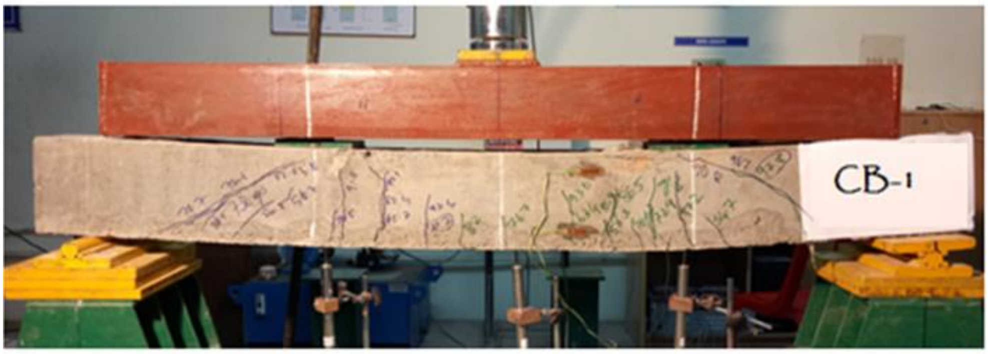

Figure 7. Crack pattern of the control beam

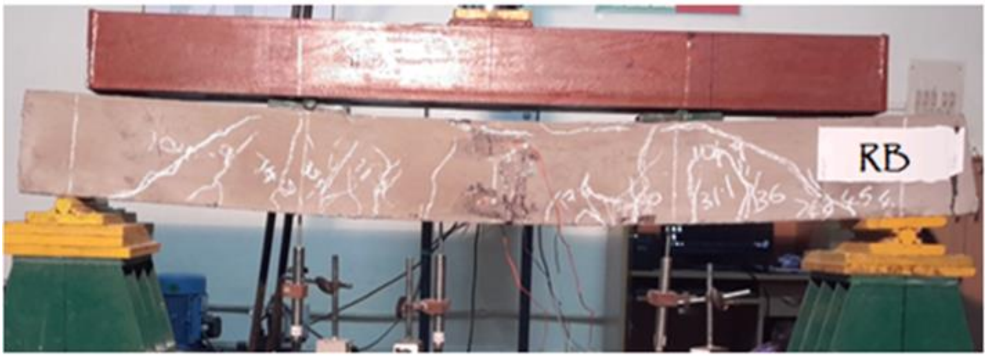

Figure 8. Crack pattern of the grouted pre-damaged beam

As shown in Figure 9, beam A1 was pre-damaged up to 90 % of the ultimate load level, strengthened with CFRP laminates at the midspan of the beam, and U-wrapped with CFRP fabrics on both ends of the CFRP laminates. Evidently, the beam failed in flexure by the rupture of the laminates with an initial crack load of 40,7 kN and an ultimate load of 86,8 kN. The maximum deflection was 37,6 mm. Moreover, the cracks occurred evenly along the edges of the CFRP laminates.

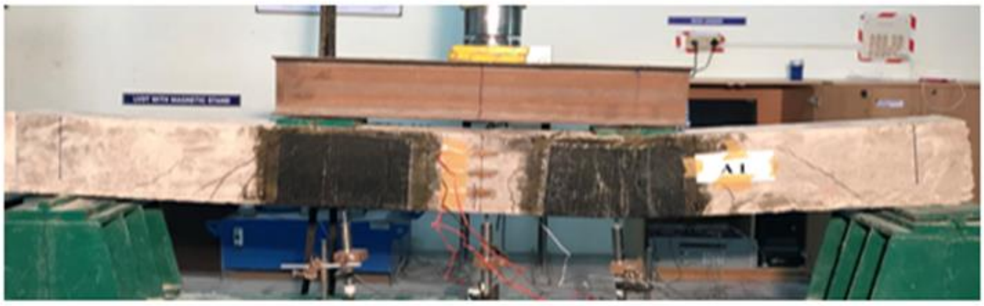

Figure 9. Crack pattern of the retrofitted beam (A1)

Beam A2 was pre-damaged up to the ultimate load and strengthened using CFRP laminates with horizontal strips at the midspan of the beam on both faces of the beam (Figure 10). The beam failed in flexure owing to the rupture of the laminates, with an initial crack occurring at 32,4 kN and an ultimate load of 96,3 kN. The maximum deflections observed for the beam were 22,4 mm.

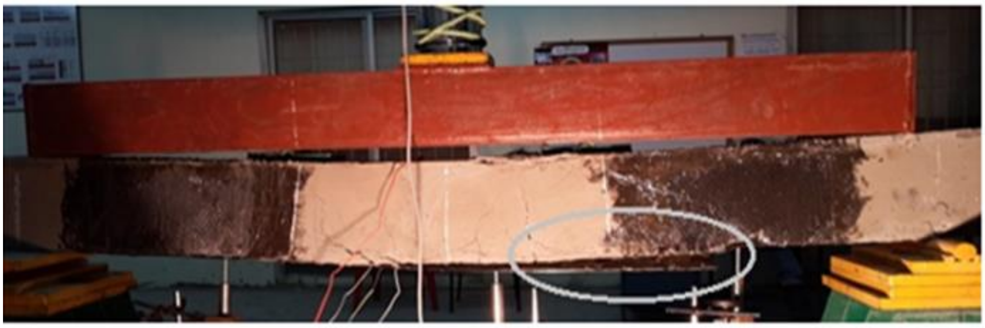

Figure 10. Crack pattern of the retrofitted beam (A2)

Figure 11 shows beam A3 pre-damaged at 90 % of the ultimate load level and strengthened by side wrapping of CFRP laminates on both side faces of the beam. The initial crack developed at 27 kN, and the ultimate load was 95 kN, with a maximum deflection of 10.7 mm. Figure 10 shows the crack pattern of beam A3 at the loading point where delamination occurred.

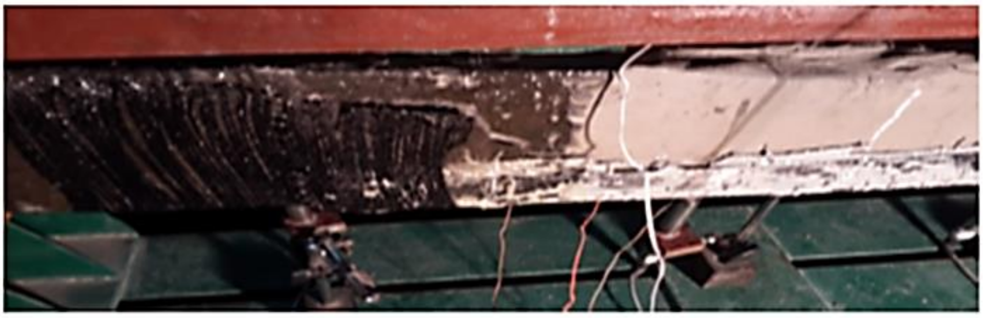

Figure 11. Crack pattern of the retrofitted beam A3

Figure 12 shows the crack pattern of beam A4 pre-damaged up to the ultimate load, strengthened with CFRP laminates at the mid-span of the beam, and U-wrapped with CFRP fabrics on both ends of the CFRP laminates. The initial crack occurred at 32,7 kN, with the ultimate load at 109,8 kN. The maximum deflection was 17 mm. In beam A4, debonding occurred at the end of the CFRP laminate, along with peeling of the concrete.

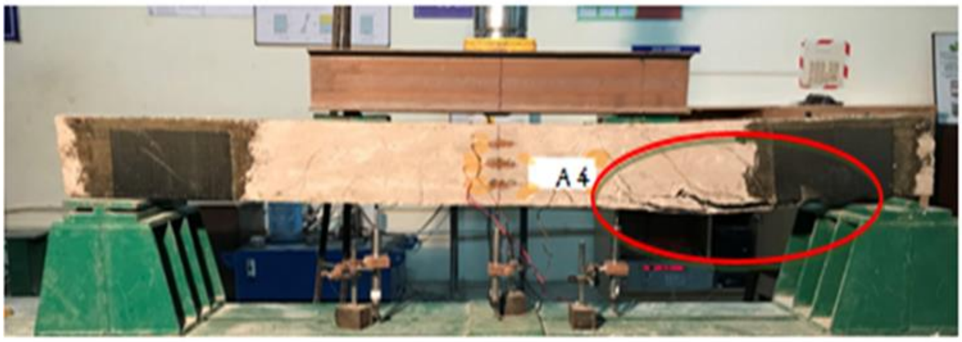

Figure 12. Crack pattern of the retrofitted beam A4

Table 2 presents the load and corresponding deflection values, along with the statistical analysis results of the RC beams with and without retrofitting. Figure 13 shows the load–deflection curves obtained experimentally.

Table 2. Load and deflection values obtained from the experimental results

S. No	Beam	First crack load (kN)	Ultimate load (kN)	Deflection (mm)
1	CB	28,20	97,50	16,10
2	RB	17,60	62,60	8,50
3	A1	40,70	86,80	28,50
4	A2	32,40	96,30	48,60
5	A3	27,00	95,00	10,70
6	A4	32,70	109,80	8,10
Mean		32,20	97,08	22,40
Range		13,70	23,00	40,50
Standard deviation		4,81	6,14	14,86

The first crack of the control beam occurred at a load of 28,2 kN. The first crack load decreased by 38 % for beam RB, with only cement grouting, compared to the control beam. The first crack loads of beams A1, A2, and A4 increased by 44 %, 15 %, and 15 %, respectively compared to that of the control beam.

3.2 Load–deflection behaviour of the beams

The ultimate loads of the specimens RB, A1, A2, and A3 decreased by 36,0 %, 11,0 %, 1,2 %, and 2,5 %, respectively, compared to that of the control beam. In contrast, it increased by 12,62 % in the case of beam A4. Thus, retrofitting the beam with grouting significantly reduced the load-carrying capacity of the fully damaged beam. Adding CFRP laminate solely to the flexural zone at the bottom of the 90 % pre-damaged beam resulted in 11 % reduction in the ultimate load carrying capacity, whereas incorporating U-wrapped CFRP laminate at the bottom led to only a 2,5 % reduction. Therefore, implementing the U-wrapping of CFRP laminates at the bottom is a superior solution for retrofitting damaged beams [18, 19]. Therefore, implementing the U-wrapping of CFRP laminates at the bottom is a superior solution for retrofitting damaged beams. Incorporating CFRP laminate in both the flexural and shear zones, with the ends of the beam enveloped by CFRP fabrics, resulted in a 13 % increase in the ultimate load-carrying capacity.

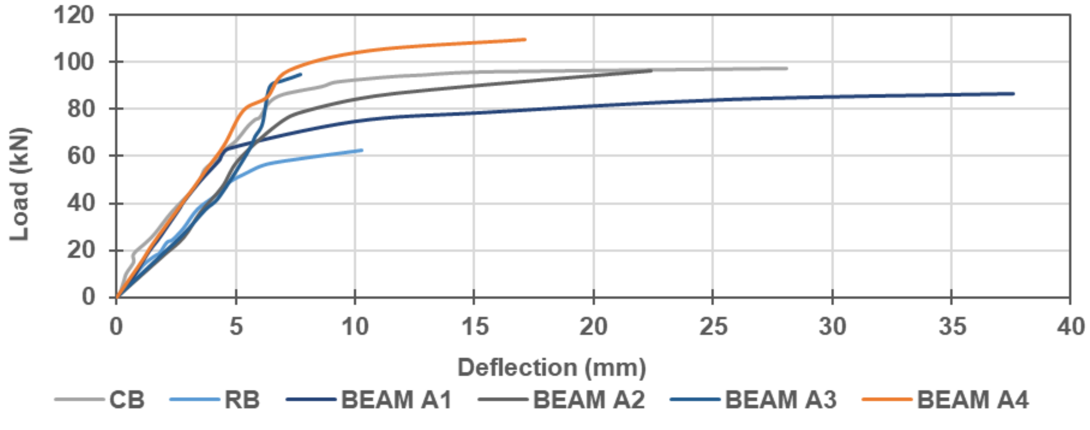

Figure 13. Load–deflection curves of RC beam specimens

3.3 Ductility index

The ductility of a beam is a critical parameter as it indicates its ability to undergo plastic deformation before failure, thereby offering insights into its overall toughness and energy absorption capacity. Displacement ductility index is the ratio of the deflection at the ultimate load to that at yield load and is calculated as follows:

$$ductilitiy\ index = \frac{\Delta_u}{\Delta_y} \quad (1)$$

The displacement ductility indices of the strengthened RC beams were calculated, as illustrated in Figure 14.

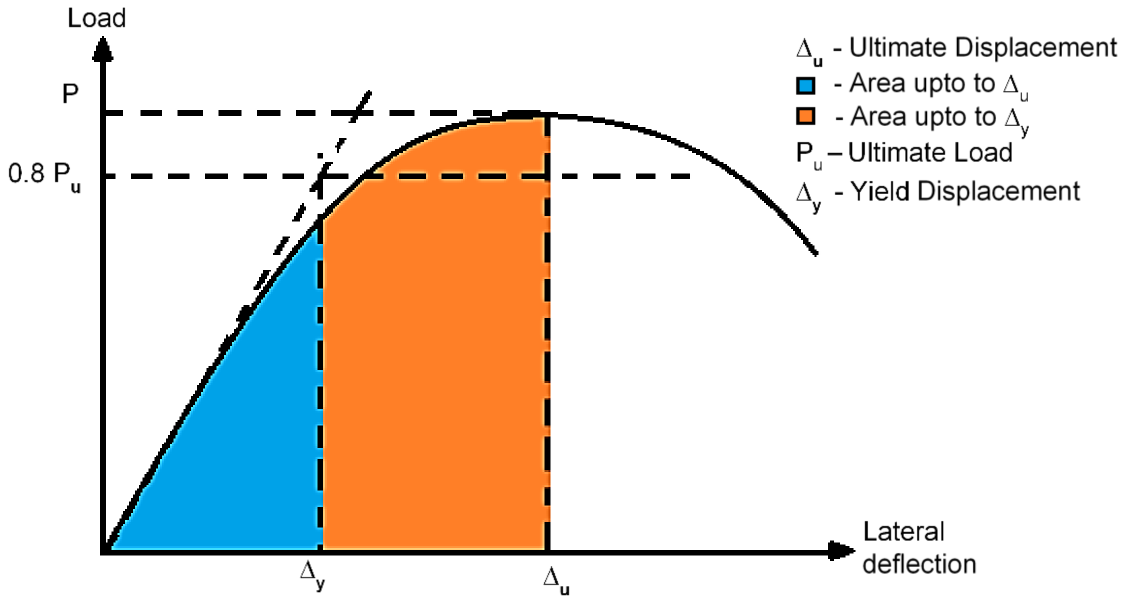

Figure 14. Illustration of displacement ductility index [20]

The ductility indices of the CB, RB, A1, A2, A3, and A4 beams were 3,92; 1,56; 7,48; 1,47; 2,64; and 4,34 respectively. Figure 15 shows a comparison of the ductility indices of the pre-damaged RC beams. The ductility index of beam A1 was 3,6 % higher and that of beam A4 was 0,4 % higher than that of the control beam.

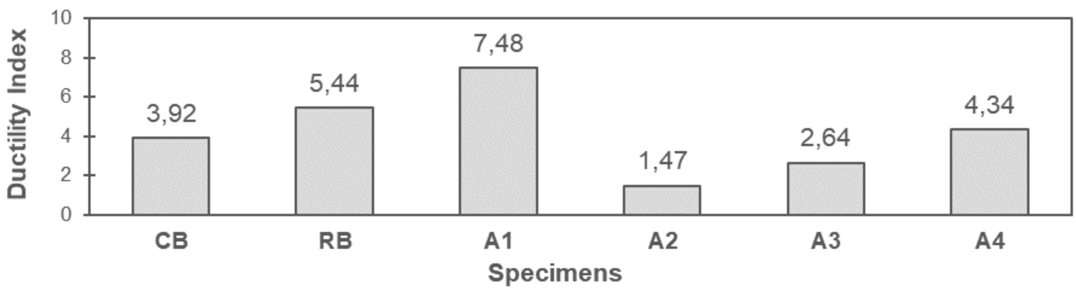

Figure 15. Comparison of the ductility indices of strengthened pre-damaged RC beams

Thus, incorporating the CFRP laminate in both the flexural and shear zones, with its ends enveloped by CFRP, led to only a slight increase in ductility; notably, it did not result in any reduction relative to the control beam. This can be attributed to the properties of the CFRP fabrics, which are intended to inhibit crack propagation, particularly when compared with the control beam. In contrast, the ductility indices of beams RB, A2, and A3 were 2,4 %, 2,5 %, and 1,3 % lower, respectively, than that of the control beam.

4 Conclusions

This study experimentally investigated six RC beams with and without external bonding using CFRP laminates and CFRP fabrics. The following conclusions were drawn:

- Grouting alone is not an efficient technique for improving the strength of damaged beams.
- U-wrapping of CFRP laminates and CFRP fabrics in the flexural zone of the RC beam pre-damaged up to 90% of the ultimate load level (A3) enabled the retrofitted beam achieve an ultimate strength almost equal to that of the control beam.
- Application of CFRP laminates and fabrics in the shear and flexural zones of the beam pre-damaged up to the ultimate load level (A4) increased the ultimate load carrying capacity of the retrofitted beam by 13% computed to control beam.
- Incorporating the CFRP laminates in both the flexural and shear zones of the beam, with its ends enveloped by CFRP, led to only a slight enhancement in ductility; however, it did not result in any reduction in ductility relative to the control beam.

Thus, the retrofitting of damaged beams by using CFRP laminates and fabrics is a cost-effective technique for strengthening and maintaining their ductility, obviating the need for demolishing the structure. In the future, large-scale beams and other structural elements will be examined using numerical models, validated against experimental results.

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