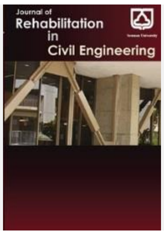

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Synergistic Enhancement of RCC Beam Performance Using Epoxy Grouting and CFRP Wrapping: A Sustainable Approach to Structural Repair and Strengthening

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ABSTRACT

Reinforced Cement Concrete (RCC) structures experience progressive deterioration and cracking, which reduces their service lifetime and durability characteristics. The research investigates a dual repair method that incorporates epoxy grouting together with Carbon Fiber Reinforced Polymer (CFRP) wrapping for restoring and reinforcing RCC beams. Epoxy injection works as an internal crack treatment while CFRP wrapping reinforces structures from the outside. A critical assessment determines the joint effect of the methods on structural properties while filling a research gap because past studies evaluated them separately. In the experimental study, six RCC beams were tested under different loading conditions and different wrapping configurations, including bottom-only, U-shaped, and end-strip enhanced CFRP patterns. The results shows that the combined method significantly improves both crack resistance as well as load carrying capacity. The U-shaped wrapping provided 80% more load capacity, whereas end strips enhanced strength capability up to 140% relative to standard wrapping methods. When using two-point loading, it yields superior outcomes compared to single-point loading specimens due to optimal load distribution. The results demonstrate that the epoxy–CFRP hybrid technique provides a durable, efficient, and sustainable method for strengthening RCC members. This repair technique provides useful benefits for infrastructure maintenance purposes, especially when structures become old or show signs of damage. The study also lays a foundation for further exploration into optimized wrapping configurations under varying environmental and loading conditions.

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1. Introduction

Modern civil engineering infrastructure is based on Reinforced Cement Concrete (RCC) structures because it provides a durable solution with flexibility, strength, and cost efficiency, along with economic benefits. RCC structures find extensive use in the construction of buildings, bridges, and other essential structures. However, its performance can be compromised by natural and human-made factors, leading to structural and non-structural damage in buildings. The impacts of stress and climatic conditions cause the strength of civil engineering structures to decrease after construction. The deterioration of concrete members occurs mainly through reinforcement corrosion, cracking, and spalling, while exposing steel areas to damaged concrete structures [1].

A crack is characterized by the complete or partial division of either concrete or masonry into two or more segments, resulting from breaking or fracturing. It represents a visible discontinuity in the material's surface, often arising from internal stresses or external forces acting upon it. This damage not only reduces the lifespan of the structures but also increases the risk of human injury and property damage [2]. Cracks can vary in size, orientation, and depth, and they serve as indicators of structural distress or deterioration. It's crucial to repair concrete cracks effectively, and the choice of repair technique depends on the surrounding environmental conditions. RCC structures require immediate actions for efficient and prompt repair and strengthening techniques [3].

The conventional strengthening methods like jacketing, steel plate bonding, and section enlargement have been presented in numerous studies in the last decade, but also show the various challenges that include structural weight increase, corrosion sensitivities, and installation restrictions in confined spaces [4–7]. Advances in composite-based solutions have replaced conventional strengthening methodology because these materials provide better durability, lightweight properties, and a simplified application process. The Fiber Reinforced Polymer (FRP) composite material system has garnered worldwide interest due to its unique properties. FRP represents a class of composite materials where fibres are embedded in a polymer matrix to create a structural material with enhanced mechanical properties. FRPs find applications in various industries due to their lightweight nature, high strength-to-weight ratio, corrosion resistance, and versatility [8]. FRP systems demonstrate substantial enhancements to structural capacity by using appropriate surface treatments [9].

The mechanical performance is enhanced in concrete elements that received epoxy repairs before CFRP wrapping under diverse weather conditions, thus validating hybrid repair techniques [10]. Incorporation of various nanoparticles, such as graphene, silica, and alumina in epoxy-based nanocomposites is a promising structural repair material in recent studies, which improves mechanical strength, bonding, and durability [11–14]. The potential of silica-modified epoxy for strengthening applications may be integrated with FRP systems [15].

The application of epoxy grouting has established itself as a dependable solution for pre-repairing concrete sections that display cracking before performing structural strengthening operations. The technique of epoxy injection succeeds in filling concrete cracks of various widths, including fine and moderate ones, while maintaining high bond strength to restore monolithic concrete properties. Proper stress distribution requires epoxy to work in combination with external systems, including FRP, to enable adequate load-bearing capacity [16,17]. By integrating epoxy crack repair methods with external FRP wraps, engineers provide a comprehensive strengthening and rehabilitation sustainable solution for structural elements. This study research combines these two methods (i.e., FRP wrapping and epoxy grouting system) into one unified approach to investigate combined improvements for RCC beam performance.

2. Fiber wrapping techniques

Fiber Reinforced Polymers are high-performance composite materials that include one or more continuous fibers embedded in a polymeric resin matrix. FRPs possess high tensile strength, excellent corrosion resistance, and are easy to apply. FRPs find applications in various industries due to their lightweight nature, high strength-to-weight ratio, corrosion resistance, and versatility. There are different types of fibres available in the field, like Glass Fibre Reinforced Polymer (GFRP), Carbon Fibre Reinforced Polymer (CFRP), Aramid Fibre Reinforced Polymer (AFRP), and Basalt Fiber Reinforced Polymer [18]. The selection of the fibers depends on the application or requirement and the environmental conditions. CFRP is used for retrofitting due to its superior strength-to-weight ratio and chemical stability [19]. However, GFRP has the advantage of being a more economical alternative in alkaline environments, but it is less durable [20]. BFRP shows good thermal stability, while AFRP is known for high fatigue resistance.

There are three general techniques of FRP application in structural strengthening [19]:

- Externally Bonded Reinforcement: FRP sheet bonded onto the tension face of the concrete element by an epoxy resin.
- Near Surface Mounted: FRP rods or bars are placed in pre-cut grooves in the concrete surface and bonded with adhesive.
- Groove Enhancement with externally bonded reinforcement: This involves externally bonded reinforcement with surface preparation by grooving to enhance bonding and decrease bond failure risks.

Recently, improvements in FRP system efficiencies have been made through anchorage methods of fasteners, U-wraps, and V-wraps. Orientation and layout of FRP also play crucial roles. Various surface treatment and wrapping configurations that the researchers have studied include surface grooving, partial wrapping, and full wrapping, which can help address the issues of early debonding and improve the structural integrity of the reinforcement [21]. Side bonding increases shear capacity, while bottom-only bonding increases flexural capacity. The researchers have studied that combined loading conditions are well controlled by inclined or vertical strips [22].

There have been several studies on the comparison of the flexural strengthening effect of FRP wraps at different configurations and material combinations. According to Turki and Al-Farttoosi [23] CFRP can renew and reinforce the load-carrying capacity of damaged RC beams. According to Uz et al. [24], the ultimate capacity and the failure mode of the strengthened beams are sensitive to the CFRP orientation. Mashrei et al. [19] Introduced groove-bonded CFRP application techniques whose purpose is to prevent premature debonding and strengthen the bond. In case the beams have some preexisting damage, hybrid approaches that combine epoxy grouting and CFRP wrapping have proven particularly effective to restore mechanical continuity and yield further capacity upgrade in the beams [25].

Experimental studies have also demonstrated that bond strength between CFRP and concrete is not adversely affected by the conditions of immersion in hot and saline water, freeze and thaw cycles, and by high humidity exposures if proper application methods are used [26,27]. Additionally, crack healing and improving durability are being pursued with new techniques such as pulse electro-deposition and nano-modified CFRPs. However, these methods have yet to be validated in an experimental manner [28].

In previous studies, the independent strengthening techniques of epoxy grouting and CFRP wrapping were represented along with crack sealing with epoxy or externally bonded fiber reinforcement for flexural enhancement, with limited attention given to their integrated application on damaged RCC members. Moreover, variations in CFRP wrapping configurations have not been systematically compared when combined with prior crack treatment, especially under different loading conditions. Few studies explore how hybrid repair techniques influence structural performance parameters such as load-bearing capacity, deformation resistance, and failure modes in a comprehensive experimental framework.

This study addresses these gaps by experimentally investigating the combined effectiveness of epoxy grouting and CFRP wrapping in rehabilitating RCC beams. The experimental analysis includes studies of three different CFRP wrapping designs on broken and intact specimens, beginning with bottom-only and extending to U-shaped and bottom-with-end-strips. The objective of this study is to assess how the hybrid strengthening method improves the overall performance compared to individual techniques and determine the most effective wrapping pattern under various loading conditions. The study is helpful for the development of sustainable, cost-effective retrofitting practices for damaged concrete infrastructure.

3. Experimental program

3.1. Preparation of specimens

Six RCC beam specimens were cast, each having a span of 1.8 m and a cross-sectional area of 150 mm × 230 mm. All the specimens were designed with identical reinforcement detailing consisting of two 8 mm diameter compression bars at the top and two 8 mm tension reinforcement bars at the bottom. Shear reinforcement is provided using 8 mm diameter stirrups placed at 200 mm center to center along the length of each beam, as shown in Fig. 1. Since the beams were simply supported, the contribution of compression reinforcement was minimal, and the focus remained on flexural performance under loading [29].

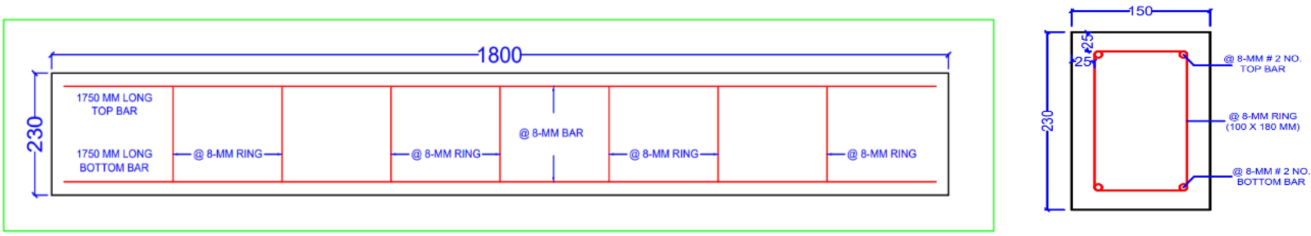


Fig. 1. Geometry and reinforcement details of the beams.

The concrete of M30 grade was used for the casting, and its mix design was prepared as per IS:10262-2019 [30]. Along with the beams, the six concrete cubes of 150 mm × 150 mm × 150 mm and three cylinders of 150 mm diameter × 300 mm height were also cast to identify the compressive and split tensile strength of concrete. The mean compressive and split tensile strength of concrete is 48 N/mm^2 and 3.2 N/mm^2, respectively. Before casting the beams, the formworks are prepared using wooden sheets to ensure uniformity and ease of demolding, as shown in Fig. 2. Steel reinforcements were placed as per the design and detailing, ensuring proper cover and anchorage. The formwork is filled with concrete in three equal layers. To avoid the effect of honeycombing on the side surface of the beam, proper compaction has to be done by the mechanical vibrator. After demolding, all the beams were cured for 28 days using continuously moistened jute bags.

Fig. 2. Casting of Beams.

3.2. Pre-loading and strengthening techniques

Out of six beams, the service load conditions were applied to three beams, which received a preload to develop visible cracks. Strengthening activities commenced after the beams experienced the first set of service loads. A combination of visual observation and crack width measurement tools tracked the formation of cracks. These damaged beams were later repaired using epoxy injection followed by CFRP wrapping. For Crack repair, Sikaguard, as an epoxy resin material, was injected into the cracks using the gravity injection method. The application occurred from the top surfaces along with side regions based on the crack alignment before the epoxy cured, leading to wrapping. The CFRP is used for strengthening purposes. As per the manufacturer's data, the modulus of elasticity of the FRP is 240 GPa, and the minimum elongation at the peak is 1.5%. There were three different methods used for carbon fibre wrapping on the beams, which are as follows:

(i) Bottom Only Wrapping: There were two different layers of carbon fibre applied on the bottom surface of the beams, as shown in Fig. 3.

Fig. 3. Two layers of FRP at the bottom surface of the beam.

(ii) U-shaped Wrapping: U-shaped wrapping was done on the bottom and side surfaces of the beams, as shown in Fig. 4.

Fig. 4. U-shaped wrapping on the beam.

(iii) Bottom wrapping with end Strips: There was a wrapping done only on the bottom surface of the beam, and then three strips of carbon fiber of 100 mm thickness were imposed over the bottom surface from both edges of the beam, as shown in Fig. 5.

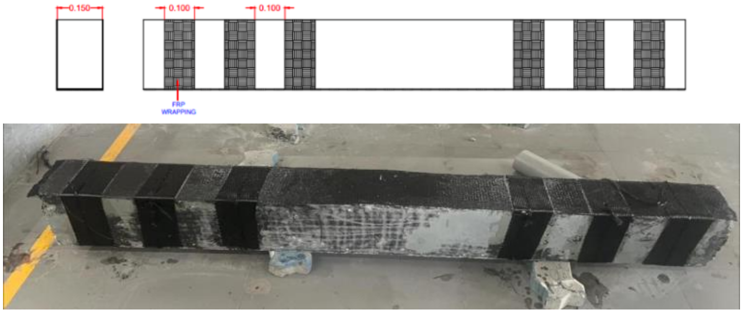


Fig. 5. FRP at the bottom layer, along with three strips of 100 mm at both supports.

There will be two specimens of a similar wrapping pattern, one with cracks (treated with epoxy resin, and carbon fibre wrapping was done) and the one without cracks (treated with the same carbon fibre wrapping pattern as its counterpart). The details of the beam specimen, FRP Wrapping pattern, and respective loading cases are presented in Table 1. The different testing conducted and various nomenclatures are given as per the flow chart shown in Fig. 6.

Table 1. Beam Details and Loading Conditions.

Beam Set	Beam ID	Crack Condition	Epoxy Treatment	FRP Wrapping Pattern	Loading Type
	B.C_1	Uncracked (Control)	No	None	
1	A.C_F(B)_1	Cracked	Yes	Bottom-only (2 layers)	Central Point Load
	F(B)_1	Uncracked	No	Bottom-only (2 layers)	
	B.C_2	Uncracked (Control)	No	None	
2	A.C_F(U)	Cracked	Yes	U-shaped	Two-Point Load at L/6
	F(U)	Uncracked	No	U-shaped	
	B.C_3	Uncracked (Control)	No	None	
3	A.C_F(S)	Cracked	Yes	Bottom + End Strips	Two-Point Load at d
	F(S)	Uncracked	No	Bottom + End Strips	

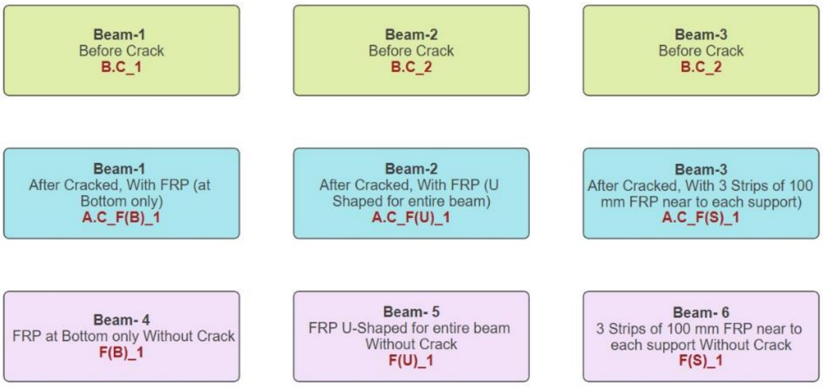


Fig. 6. Flowchart for Nomenclatures of Beams.

3.3. Experimental setup and load application

The testing system evaluated each beam using a 50-ton capacity loading frame, as shown in Fig. 7. These beams, constructed with simple support, received a precise span measurement of 1570 mm from their total length of 1800 mm when excluding the 115 mm dimensional extents at both support locations.

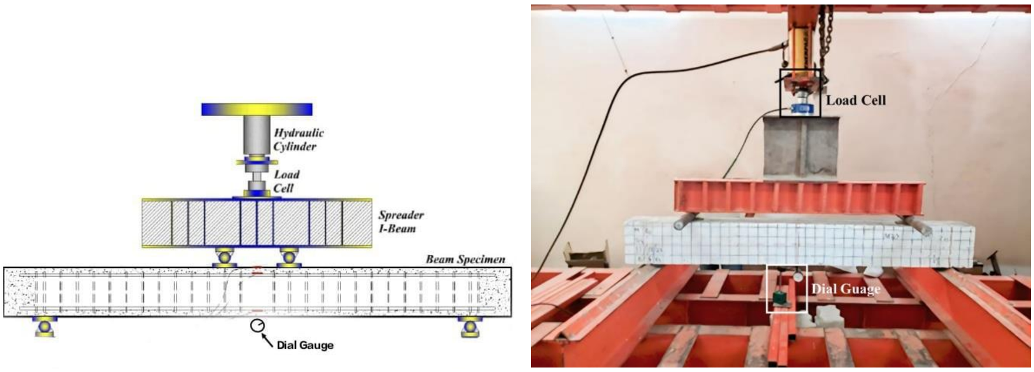


Fig. 7. Experimental Setup.

The load is applied in three different cases (i) single concentrated load at the center of the beam span. (ii) Two point loads at L/6 (260 mm) distance from each support. and (iii) Two-point loads at effective depth (d = 205 mm) from each support to test load application closer to the supports. Tests were conducted on each beam until the specimens reached failure. Performance evaluation was conducted through data collection of load-deflection behaviors to compare results between different beam arrangements.

To induce controlled cracking and simulate real-world deterioration of structures, selected RCC beams were preloaded under their service-level loading condition. All the beam specimens were tested in load-controlled conditions. The load was increased progressively by the use of a hydraulic jack in stages of 5–10 kN, with the amount of deflection recorded at each stage using a dial gauge placed in mid-span, and the flexural or shear cracks developed in the central span or adjacent to the supports. The loading was continued to failure of the beam by excessive deflections, visible crushing, or CFRP debonding. The presence and cover of cracking were confirmed using visual observation and marking of the surface using a permanent grid scheme. Crack widths were taken using a crack width gauge, and specimens with visible cracks that could be 0.2 mm to 0.5 mm were classified as damaged. These cracked beams were then epoxied under CFRP wrapping for all conditions, after which direct performance comparison with uncracked control specimens was possible.

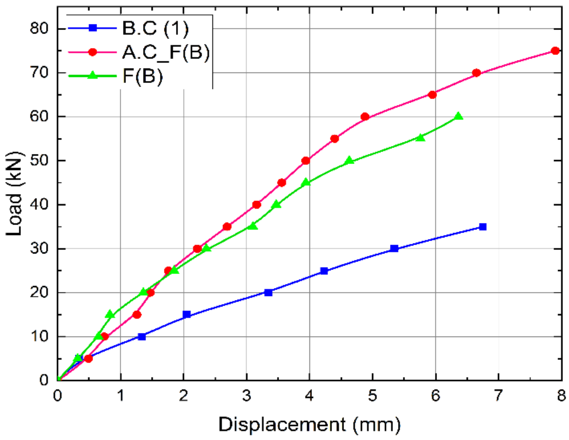
4. Results and discussion

4.1. Comparison of load and deflection for individual beams

The load-deflection response of three sets of beam specimens is provided, comparing beams under varying conditions of wrapping pattern i.e. uncracked (baseline), cracked and treated with epoxy reinforced with FRP, and uncracked but reinforced with FRP and Loading conditions like one point and two point load test The permissible deflection for each beam is 7.2 mm (i.e., span/250) according to IS 456. The failure modes of each beam are different, which depend on the cracking pattern, wrapping configuration, and loading type.

The initial experimental study includes three different sets of beams, which are as follows: (i) a controlled beam without a crack, (ii) a cracked beam repaired using epoxy injection and strengthened with two layers of CFRP on the bottom surface, (iii) an uncracked beam strengthened with the same bottom-layer CFRP configuration. The study compared deflection patterns under central point load among the tested beams. All three beams of the first set are subjected to a point load at the center. A maximum deflection of 7.9 mm was recorded in the cracked beam treated with epoxy and reinforced with FRP at a load of 75 kN, as shown in Fig. 8. The treated and reinforced beam demonstrated increased load-carrying capacity and deflection resistance compared to the baseline. Initial uncracked beams without any strengthening typically failed in flexure, which is observed by vertical cracks near mid-span under central loading.

CFRP wrapping on the tension face (bottom surface) allowed resisting the tensile stresses that would be carried by cracked concrete and is therefore effective in increasing the flexural capacity of the beam.

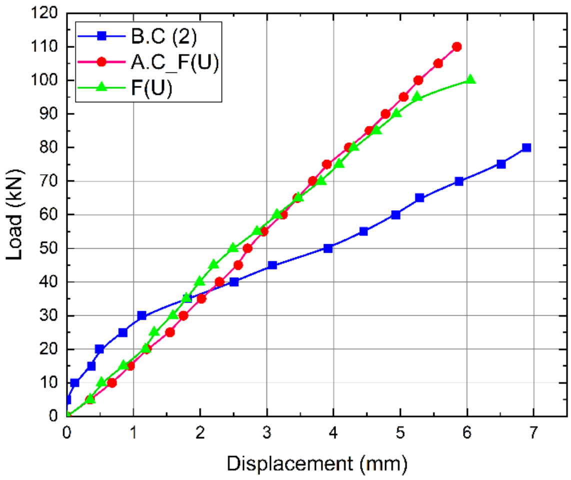


(a)

(b)

Fig. 8. Behaviour of First Set of Beams (a) Load vs Deflection (b) Deflection of Beam.

As the beam deformed under load, along the longitudinal axis, the CFRP fibers were activated, and they resisted elongation due to their high tensile modulus. This external reinforcement decreased crack widths and increased the elastic range of the load-deflection curve.



(a)

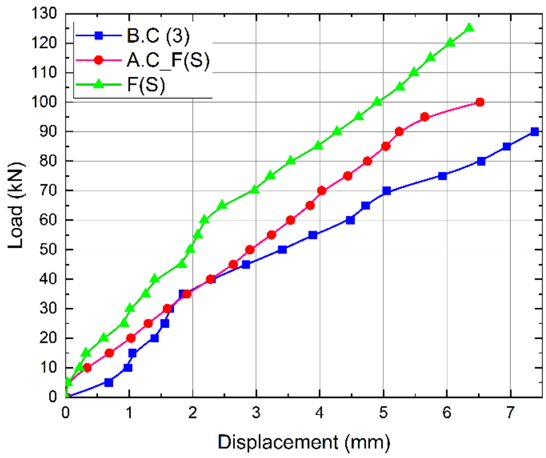
(b)

(c)

(d)

Fig. 9. Behaviour of Beams Second Set of Beams (a) Load vs Deflection (b) Cracks in Normal beam without FRP wrapping (c) Experiment of beam with wrapping (d) Failure of beam after wrapping.

In the second set of beams, a normal beam without cracks, a cracked beam treated with epoxy resin and U-shaped wrapping, and an Uncracked beam with U-shaped wrapping are considered with a two-point load test, as shown in Fig. 9. There are noticeable cracks in the concrete near the edge of the FRP wrap, which indicates that the beam is under considerable amounts of strain. In a few locations, the FRP wrap seems to be partially detached, indicating that the load has affected the structural integrity of the beams. As the material nears failure under load, this figure shows the interaction between concrete and FRP. Under an 80 kN load, the uncracked beam (without epoxy treatment) deflected 6.89 mm. The U-shaped FRP covering increased load distribution and strengthened the beam's resilience to deformation. U-shaped wrapping is not only confined to the tension face but confined along the sides of the beam as well, which increases resistance to diagonal tension and retarded shear cracking. This combination of vertical and horizontal confinement enabled the beam to resist principal tensile stresses much more effectively, converting brittle shear failure into a more ductile one. The load and deflection comparison of beam without crack (B.C_3), beam which has cracks in it and is being treated with the epoxy resin and a bottom layer of FRP was applied on the bottom surface of the beam along with the three strips of 100 mm applied near both the end supports(A.C_F(S)) and the beam without crack, just treated with the layer of FRP on the bottom surface of the beam along with the three strips of 100 mm near both the end supports (F(S)) are shown in Fig. 10. At a load of 95 kN, the uncracked, untreated beam reached a deflection of 7.92 mm. The addition of end strips of FRP reinforcement enhanced the structural integrity and load resistance of the beam. The end-strip configuration improved anchorage and crack control at the support locations where the shear stresses are greatest. These strips broke potential shear crack paths, spreading the load to a larger region and increasing shear resistance as a consequence of the localized strapping effect.



(a)

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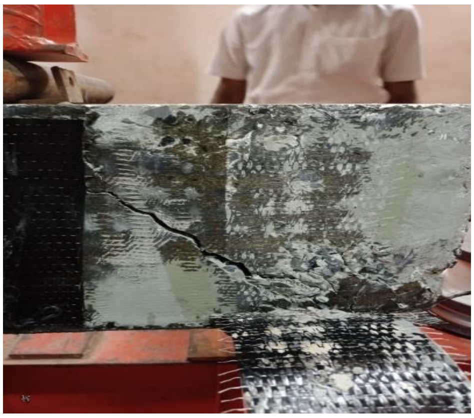

(d)

Fig. 10. Behaviour of Third Set of Beams (a) Load vs Deflection (b) Cracks in Normal Beam without Wrapping (c) Experiment of Beam with FRP Wrapping (d) Shear Failure with FRP Wrapping.

The amount of strain the beam has experienced during testing is demonstrated by the FRP's visible partial detachment in locations close to the crack. The crack indicates that the FRP helped in avoiding the ultimate failure as the beam approached its failure limit. In the case of both the second and third sets of Beams, the delayed crack propagation is observed, as shown in Fig. 9 (d) and Fig. 10 (d). The failure occurred due to demoulding of CFRP at supports or diagonal cracking, which indicates mixed flexure shear failure.

4.2. Comparison of ultimate loads for different loading conditions

The ultimate load-bearing capacity of beams under different loading arrangements is shown in Fig. 11. A single point load placed in the middle of the beam during testing resulted in an ultimate load of 35 kN. A two-point load placed L/6 from each support resulted in a significant increase in ultimate load capacity to 92 kN. Additionally, the beam's ultimate load capacity increased marginally to 100 kN when the two-point load was applied at a distance d from the supports. This load is slightly greater than the two-point load at L/6 and greater than the single-point center load condition. The beam can withstand a greater ultimate load because of the two-point load arrangement than it could under a single concentrated central load. When two points are closer to the supports (at a distance d from the supports), the ultimate load is higher compared to the marginal difference to the two-point loads with L/6 distance at the support arrangement.

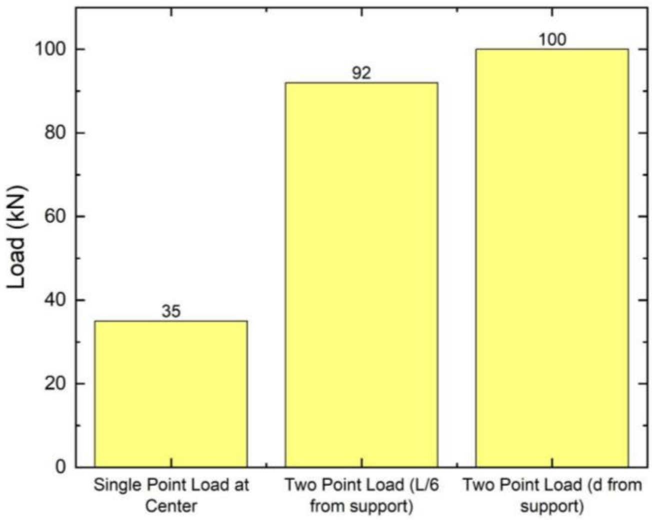

Fig. 11. Comparison of ultimate loads for different loading conditions.

4.3. Comparison of ultimate load for different frp wrapping patterns

A comparison of ultimate load capabilities for beams with different FRP wrapping patterns is shown in Fig. 12. The ultimate load capacity for the uncracked beam was 90 kN, and for the cracked beam was 80 kN when two layers of FRP were attached only on the bottom surface of the beam. Applying U-shaped wrapping along the beam increased the load capacity to 165 kN, marking an 83.33% improvement over the bottom surface-only structure. This improvement shows that U-shaped wrapping works effectively to improve resistance and strengthen the element. The application of a bottom FRP layer with three 100 mm strips near each support offered the maximum load capacity of 215 kN, which is 30% higher than the U-shaped wrapping pattern and 140% higher than the bottom surface-only wrapping pattern. Specifically at essential places close to the supports, this pattern effectively strengthens the material, hence enhancing the load-bearing capacity of the beam. The results indicate that the FRP wrapping pattern strongly affects the load-bearing performance; the bottom level and additional support strip arrangement provide excellent strength and stability.

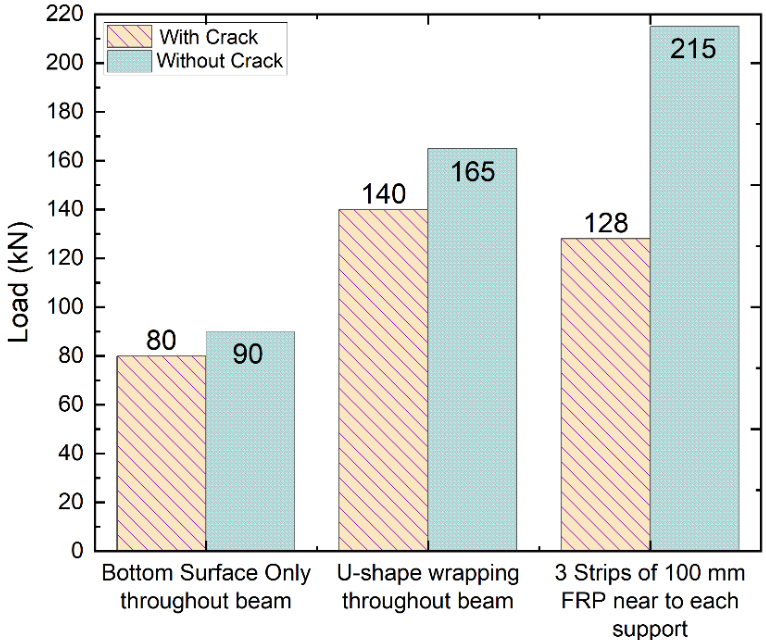

Fig. 12. Comparison of ultimate loads for different FRP wrapping patterns.

5. Key findings and discussion

RCC beams, which are subjected to a hybrid retrofitting treatment, include both epoxy and CFRP wrapping methodologies. Based on the results from the experimental study, the following key findings are identified.

- The epoxy grouting with CFRP external wrapping enhanced both structural load capacity and deformation compared to the controlled beam and single retrofitted beams.
- In the case of the bottom-layer wrapping pattern along with side strips, the maximum ultimate load of 215 kN is 140% higher than that of the bottom-layer wrapping. From the analysis, it is observed that the effect of side confinement and anchorage support is visible in U-shaped wrapping.
- Epoxy in crack beams is used to restore the internal continuity by filling the voids and microcracks with epoxy. The hardened epoxy was also found to help prevent an increase in the crack width. As a result, these beams would be able to put building areas into service to withstand flexural loads, thus delaying the formation of large deformations.
- Stress distribution was more efficient when it was conducted under two-point loading than when the load was inflicted under one central point. These maximum ultimate load capacities were observed in two-point loading in the beams, which are at a distance ‘d’ over the support points, which shows the importance of proper experimental distribution of loads.
- Based on the observation of the failed specimens, it was noted that the beams that could not be wrapped with CFRP or treated with epoxy experienced rapid failure progression owing to early flexural cracks. A delayed activation of the failure alongside better energy absorption was accompanied by improved post-cracking behavior of the retrofitted beam system.
- Retrofitted beams had reduced deflections at service loads level and their post-yield behavior was more stable with the epoxy-CFRP system retrofittings than others. It is due to the higher Flexural Stiffness and energy absorption capacity of the CFRP.
- Utilization of epoxy-CFRP hybrids will be an effective practice, which will allow their lightweight application and prevention of corrosion at a lower cost than steel jacketing processes. The system permits localized strengthening, which lowers additional dead loads. Also, suitable for old buildings in delicate zones like the wet or seismic regions.

6. Conclusions

This study aimed to determine the effectiveness of a hybrid retrofitting approach combining epoxy grouting and CFRP wrapping on RCC beams. The results of the experimental work indicate that epoxy injection has successfully restored crack continuity, and CFRP wrapping has increased both flexural and shear strength. The bottom wrapping with end strips configuration produced the most significant load capacity (215 kN) of the three configurations, followed by U-shaped wrapping (165 kN), showing a significant increase over the bottom-only wrapping. The two-point loading further maximized load distribution whilst enhancing structural response. The failure modes moved from brittle flexure or shear to more contained and ductile behavior in retrofitted specimens. These results confirm that the epoxy–CFRP hybrid solution is an efficient, durable, and cost-effective method of strengthening RCC members with damage at various loading conditions.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Vishwajisinh Zala: Investigation, Data curation, Methodology, Formal analysis.

Lwando Mwanachiwena: Investigation, Data curation, Methodology.

Dhrumit Asodariya: Investigation, Data curation, Methodology.

Devesh Poorey: Methodology, Supervision, Resources, Visualization.

Husain Rangwala: Conceptualization, Project administration, Writing – original draft, Writing – review & editing.

Amit Thoriya: Formal analysis, Writing – review & editing.

Tarak Vora: Resources, Supervision, Project administration, Validation.

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