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Investigating the structural integrity of glass fiber reinforced polymer (GFRP) composite-striated reinforced concrete beams

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ABSTRACT

This experimental study investigates the structural performance of reinforced concrete (RC) beams retrofitted with Glass Fiber-Reinforced Polymer (GFRP) composites. Retrofitting existing concrete structures has gained attention as an environmentally and economically viable method to enhance load-bearing capacity and extend lifespan. The study involves comprehensive experiments on RC beams with GFRP composites to improve the structural behavior of deteriorated or under-designed beams. RC beams representing common structural configurations, such as those with insufficient flexural capacity or corrosion, were fabricated. GFRP retrofitting involved applying sheets or strips to the tension and shear faces to enhance flexural strength and ductility. Parameters included the number of GFRP layers, their orientation, and bonding methods. Performance variables like load-carrying capability, deflection, cracking patterns, and failure modes were meticulously monitored. The research also explored the impact of GFRP retrofitting on environmental resistance and long-term endurance. Results are expected to provide insights into the effectiveness of GFRP composites for RC beam retrofitting, offering practical guidelines for engineers and researchers in rehabilitating and strengthening concrete structures, and advancing sustainable solutions for aging infrastructure.

Keywords: GFRP; Retrofitting; Laminate; Debonding; Structural integrity.

1. INTRODUCTION

The need for sustainable and efficient infrastructure has led to a continuous exploration of innovative materials and techniques for enhancing the performance and longevity of reinforced concrete (RC) structures. Retrofitting existing RC beams to improve their load-carrying capacity and ductility has emerged as a viable solution to address the challenges of aging infrastructure [1, 2]. Retrofitting damaged structures has developed as a critical necessity and a widely used technology. Fiber reinforced polymer composites are utilized for retrofitting. They are employed in a wide range of work domains due to their positive characteristics. Fiber reinforced polymers provide a high strength-to-weight ratio [3–5]. In this context, Glass Fiber Reinforced Polymer (GFRP) composites have gained significant attention due to their exceptional mechanical properties and resistance to corrosion.

This study delves into the realm of structural engineering, focusing on the experimental investigation of RC beams retrofitted with Glass FRP polymers 200 Gsm. The primary objective of this research is to assess and compare the structural behavior of these retrofitted beams against a control beam under various loading conditions [6, 7]. The investigation involves a comprehensive analysis of load-deflection responses, stiffness, and deflection ductility of the beams to provide valuable insights into their performance.

The motivation behind this study is multifaceted. Firstly, the deteriorating state of existing RC structures poses a considerable challenge to infrastructure resilience and safety. Retrofitting techniques using advanced materials like GFRP offer an effective means of extending the service life and enhancing the structural performance of these aging assets [8–10].

Secondly, the environmental benefits associated with GFRP materials are significant. The use of GFRP composites reduces the reliance on conventional materials like steel, which can be resource-intensive to produce and prone to corrosion. This aligns with the broader goals of sustainable construction practices and reduced carbon footprint in the construction industry [11]. Glass fiber reinforced polymer sheets (GFRP) have the benefit

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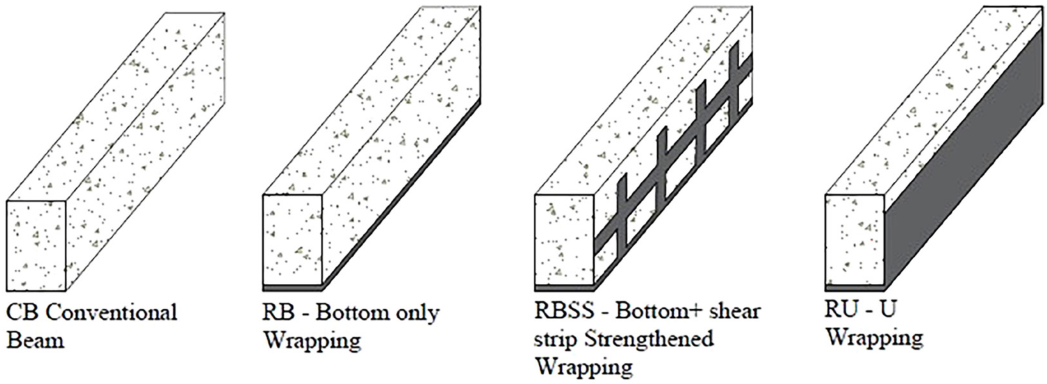

Figure 1: Retrofitting layout.

of being easy to mold into any shape, having mechanical strength that is so strong and rigid for its weight that it can outperform most other materials, being low maintenance, anti-magnetic, and fire resistant, electrically insulating, and waterproof [12].

Numerous investigations on the strengthening of RC beams demonstrated that U-wrapping outperformed all other forms of wrapping schemes. The effect of various wrapping strategies and GFRP layer counts for strengthening RC beams was previously studied [6, 13, 14]. The majority of studies explored U wrapping, Bottom wrapping, and Side wrapping as ways for strengthening the RC beam. Where U wrapping outperforms all other forms of wrapping. Thus, the focus of my research is on strengthening the tension zone by wrapping it entirely and the shear zone by wrapping it partially as shown in Figure 1.

Moreover, the comparative analysis of allows for a nuanced understanding of how variations in the type and quantity of GFRP affect the structural behavior of retrofitted beams. Such insights can guide to selecting the most suitable GFRP materials for specific retrofitting projects based on load requirements and desired structural characteristics.

The research methodology involves subjecting the RC beams, including the control beam and those preloaded beam retrofitted with GFRP200, to a series of loading tests. These tests include the determination of initial crack load, yield load, and ultimate load, along with corresponding deflection measurements. Additionally, stiffness and deflection ductility are calculated to assess the beams behavior under different loading scenarios [14–16]. The results obtained from these experiments will be meticulously analyzed and compared to draw meaningful conclusions regarding the effectiveness of GFRP retrofitting in enhancing the load-carrying capacity and ductility of RC beams.

This paper is structured to provide a comprehensive understanding of the experimental study on the structural behavior of RC beams retrofitted with Glass FRP polymer. This research contributes to the growing body of knowledge in structural engineering and retrofitting practices while promoting sustainable construction solutions. The findings of this study hold the potential to inform retrofitting decisions and advance the field of structural rehabilitation, ultimately leading to safer, more resilient, and environmentally responsible infrastructure.

2. MATERIAL CHARECTIRIZATION

2.1. Materials

2.1.1. Cement

Beams were cast using Portland Pozzolana Cement (PPC) 43-grade. The cement that was utilized complied with IS 8112: 1988. 3.07 was the specific gravity. 30 minutes was the first setting time and 600 minutes was the last setting time.

2.1.2. Coarse aggregate

Concrete was cast using locally accessible crushed stones and basalt stone. Aggregates of 20 mm were employed. The content complied with IS 383-1970. Twenty millimeters had specific gravities of 2.7, respectively. It absorbed 0.75% of the water [17].

2.1.3. Fine aggregates

Locally accessible M-sand that fell inside zone II was used in accordance with IS: 383-1970 provisions. The coarse aggregate (CA) exhibited a specific gravity of 2.6 and a water absorption rate of 1.5%.

Table 1: Mechanical characteristics of GFRP.

SL.NO	DESCRIPTION	GLASS 200 GSM
1	Yield force (N)	1216.07
2	Yield elongation (mm)	6.17
3	Break force (N)	1265.3
4	Break elongation (mm)	6.32
5	Flexural strength at yield (N/mm^2)	14.55
6	Flexural strength at break (N/mm^2)	14.73
7	Impact load (Joule)	0.552

2.1.4. Water

For both concrete casting and concrete curing, tap water was utilized. According to IS 456-2000, water should meet all standards.

2.1.5. Epoxy resin

Pre-polymers with a low molecular weight are epoxy resins. Epoxy resins are utilized in the civil engineering sector for coating and bonding purposes [16]. Epoxy resin is a two-part system consisting of a catalyst-containing hardener and sticky resin. In this investigation, utilized Araldite LY. 556 resin and Hardener HY. 951.

2.1.6. Fiber sheet

E-glass was the fiber sheet employed in the current experiment. It was an undirectionally woven glass fiber mat by nature. When utilized in composites, glass fibers are substantially less brittle and far less expensive [18]. A common reinforcing ingredient for polymer goods is glass fiber. It is utilized to create fiber reinforced polymer (FRP) composite materials, which are comparatively lightweight and extremely strong [11, 19–21].

The mechanical properties of Glass Fiber Reinforced Polymer (GFRP) composites are shown in Table 1. The Glass 200 GSM laminate exhibited a yield force of 1216.07 N and a yield elongation of 6.17 mm. The yield force is the most significant force that a laminate can sustain before undergoing plastic deformation, demonstrating its ability to resist applied loads. The corresponding yield elongation reflects the extent of deformation at this critical point, providing insights into the material's ductility. The break force and break elongation values were determined as 1265.3 N and 6.32 mm, respectively. These parameters signify the maximum force sustained by the laminate before failure and the associated elongation. Understanding the break force and elongation is vital for assessing the laminate's structural integrity and failure mechanisms. Flexural strength, both at yield and break, was calculated for the Glass 200 GSM laminate. The flexural strength at yield was found to be 14.55 N/mm^2, while the flexural strength at break was slightly higher at 14.73 N/mm^2. These values highlight the laminate's capacity to withstand bending loads and its structural performance under different loading conditions. The impact load resistance of the Glass 200 GSM laminate was measured at 0.552 Joules. This parameter is critical for understanding the material's ability to absorb energy during sudden dynamic loads, which is particularly relevant in real-world applications where structures may experience impact events. The mechanical properties of the Glass 200 GSM laminate suggest favorable characteristics for GFRP retrofitting applications. The high yield force and elongation values indicate good ductility, which is essential for accommodating deformation in structural elements. The comparable flexural strengths at yield and break suggest that the laminate maintains its structural integrity even under severe loading conditions. Furthermore, the impact load resistance of 0.552 Joules signifies the laminate's ability to absorb energy during impact events, which is crucial for structures exposed to potential dynamic loads. To note that these values are particular to the materials tested and provide an overview of the mechanical characteristics of the Glass Fiber Reinforced Polymer composites. These mechanical properties collectively contribute to the effectiveness of Glass 200 GSM laminate in enhancing the structural behavior of RC beams when used as a retrofitting material. The comprehensive analysis of the mechanical properties of Glass 200 GSM laminate provides valuable insights into its suitability for GFRP retrofitting applications.

2.2. Mix proportion

Design mix of M20 concrete is done by IS 10262 2009.

Cement = 358.47 kg/m^3

Fine aggregates = 736.90 kg/m^3

Coarse aggregates = 1176.88 kg/m^3

Water = 197.16 kg/m^3

Final mix proportion as 1: 2.055 : 3.283 at 0.55 W/C

2.3. Specimen layout

In this experimental inquiry, three beams were cast using M20 concrete grade and Fe 500 grade of steel. The beams were named Controlled Beam, Preloaded Beam wrapped using GFRP 200 gsm, and Preloaded Beam wrapped using GFRP 400 gsm. Every beam had the same dimensions. The beam has a cross sectional size of 100 mm by 150 mm and is 2000 mm long. Two High Yield Strength Deformed (HYSD) bars with a diameter of 8 mm were used throughout as the main reinforcement in the beams and two bars with a diameter of 8 mm were used throughout as hanging bars, and two legged stirrups made of 6 mm diameter bars at 150 mm C/C as shown in Figure 2. The two steel grades, D6 and D8, have different properties. The yield stress, ultimate stress, and elastic modulus of D6 steel are 425.16 MPa, 435.30 MPa, and 204.0 GPa, respectively. On the other hand, the D8 steel exhibits an elastic modulus of 226.2 GPa, a yield stress of 425.16 MPa, and an ultimate stress of 435.30 MPa. The main flexural reinforcement in each beam has a 20 mm clear concrete cover to prevent failure from splitting bond [22–24]. The purpose of applying this layer was to maintain the bond between the surrounding concrete and the reinforcement. The beams were left for 28 days to cure before the initial phase of testing started. Prior to beginning the experiments, this curing procedure made sure the concrete achieved the strength.

2.4. Mixing of concrete

For the current project, nominal and design mixed M20 grade concrete was made using Portland Pozzolana Cement (PPC).Concrete raw materials should be mixed in a certain way to provide a consistent level of quality. The design mix was used to weigh the raw materials, which were then placed into the tray. To get a consistent texture, the components were first combined for a while without the addition of water. Water was then gradually added after that. Three batches of the mix were made to ensure the right consistency. The top surface of the beam was finished using a mixture made of cement and sand [25].

2.5. RC beams undergoing retrofitting

The RC beams subjected to testing were removed from the testing apparatus for reinforcement using Glass FRP. The retrofitting process involved employing the wrapping method to address venule shear and tensile cracks. Epoxy injection was also attempted to patch these cracks and restore the integrity of the investigated RC beams. The concrete surfaces underwent roughening with a wire brush, followed by meticulous cleaning with water to remove any contaminants before the application of the GFRP

After the tested RC beams were allowed to dry for 24 hours, ensuring a dust-free surface, epoxy was utilized to enhance adhesion between the GFRP and the concrete. The GFRP sheets were cut into specific patterns, covering both shear zone and the tension zone, In addition, the tension zone. exclusively targeting the GFRP effectively covered the shear zone and the tension zone of the preloaded control beam.

For the flexural strengthening with GFRP, an epoxy mixture of resin and hardener, according to the manufacturer's specifications, was prepared [26–28]. To establish a robust bond between the concrete surface

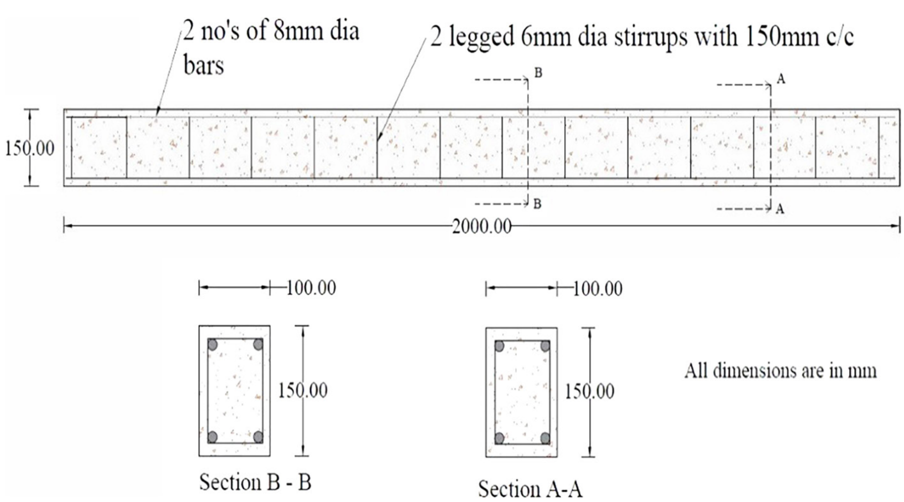

Figure 2: Reinforcement detailing of concrete beam.

and the glass fiber matrix, a 2 mm thick layer of epoxy glue was initially applied to the tested RC beam. The glass fiber matrix was then applied to the epoxy-coated concrete surface in the exposed region. Subsequently, discrete epoxy coatings were applied on top of the glass fiber matrix to create the GFRP laminate. This laminate served as the retrofitting element over the beam, especially when subjected to a moderate proportion of moment corresponding to its own dead load.

2.6. Experimental set up

For this experiment, four specimens are made using cement, fine and coarse aggregate, and the calculated mix proportion. Two High Yield Strength Deformed (HYSD) bars with a diameter of 8 mm were used throughout as the main reinforcement in the beams and two bars with a diameter of 8 mm were used throughout as hanging bars, and two legged stirrups made of 6 mm diameter bars at 150 mm C/C as shown in Figure 2. Beam specimens for the CB control beam and the preloaded wrapped beams are made of GFRP (200 gsm). After being cured for 28 days, beams were given a cleaning with water to reveal any cracks as shown in Figure 3. A two-point loading configuration was employed to test the beams.

The two steel rollers with their bearings spaced 75 mm apart from each other were positioned above the beam. The specimen was crushed to get the peak, from which the strength was measured. A linearly variable differential transducer LVDT was utilized to monitor the midspan displacement, the stacking maximum is 500 kN. By placing a two-point static load on the specimen. The beams were tested with two supports at 600 mm intervals across an 1800 span as shown in Figure 4 [29, 30]. The GFRP wrapping process involved the application

Figure 3: Casting of RC beam specimens.

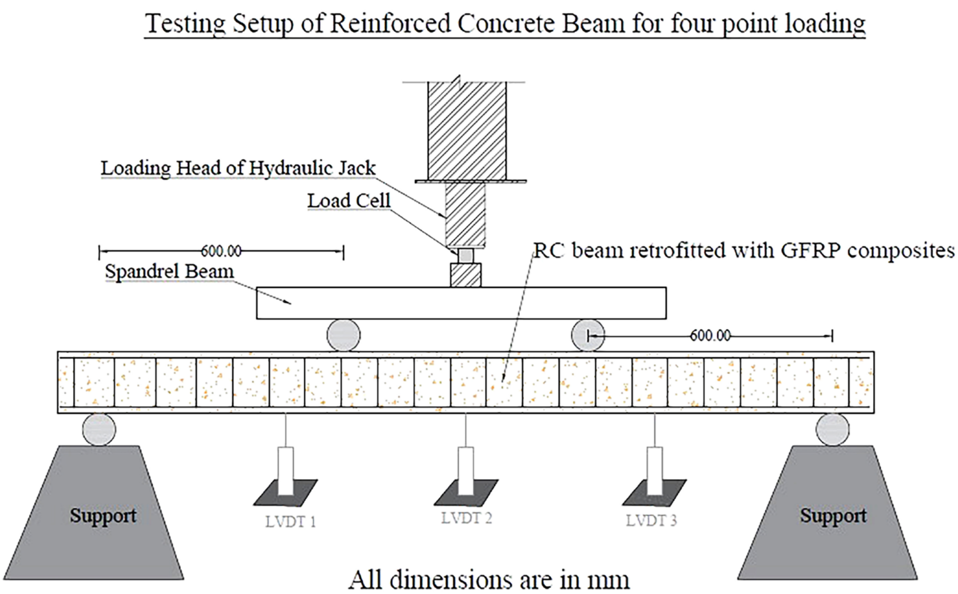

Figure 4: Test setup for beam.

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of GFRP sheets to the preloaded beams. This step was performed with precision to ensure proper bonding and coverage, which is essential for evaluating the effectiveness of GFRP in enhancing the structural performance of the beams. Each specimen was then subjected to a series of tests to measure various performance metrics, including load-bearing capacity, deflection, and failure modes. By adhering to this detailed experimental setup and process, the study aims to provide a comprehensive understanding of the structural integrity of GFRP composite-striated reinforced concrete beams. This methodical approach ensures that the findings are robust, reliable, and applicable to real-world engineering scenarios [5].

3. RESULT AND DISCUSSION

3.1. Control beam testing

The method termed "Preloading of RC beams" can be applied to mimic the strain and stress levels experienced by a beam in real-world conditions. This procedure involves subjecting the beam to a preload before conducting the actual test as indicated in the Figure 5. To replicate damage prior to retrofitting, RC beams are preloaded with a load using the same configuration. The load necessary to initiate cracking in the RC beams was identified as 23.7 kN through testing control beams. Then, in a controlled way, the weight is progressively withdrawn to allow for the observation of any flaws that may have developed during the testing of the beam. Initial Crack Stage. At the initial crack stage, the control beam exhibited a load of 9.4 kN, with a corresponding deflection of 4 mm. The initiation of cracking is a critical stage in structural behaviour, and the control beam's response serves as a baseline for comparison with retrofitted configurations. This stage provides a glimpse into the inherent crack resistance of the unreinforced beam. Upon reaching the yield stage, The load-displacement graph in Figure 6-a shows that yielding occurred in the member at 20.9 kN, accompanied by a deflection of 9.7 mm. The yield point signifies the onset of plastic deformation in the structure. The retrofitted beams, when compared to the control, are expected to showcase improvements in load-carrying capacity and ductility, providing insights into the effectiveness of GFRP in delaying the onset of yielding. At the ultimate failure stage, the control beam failed at a load of 25.5 kN, with a deflection of 30.5 mm. This stage represents the maximum load-carrying capacity of the control beam before failure. The retrofitted beams are anticipated to exhibit enhanced performance, delaying failure and potentially increasing the overall load-carrying capacity and deformability of the structure. The beam shows no indications of shear cracking or deboning.

3.2. Tests on retrofit beams

Each retrofitted beam was tested using the same approach as the initial load application, as seen in Figure 6(c). As indicated in the test configuration, a two-point flexural monotonous load of about 1800 mm was placed to

Figure 5: Testing of beam.

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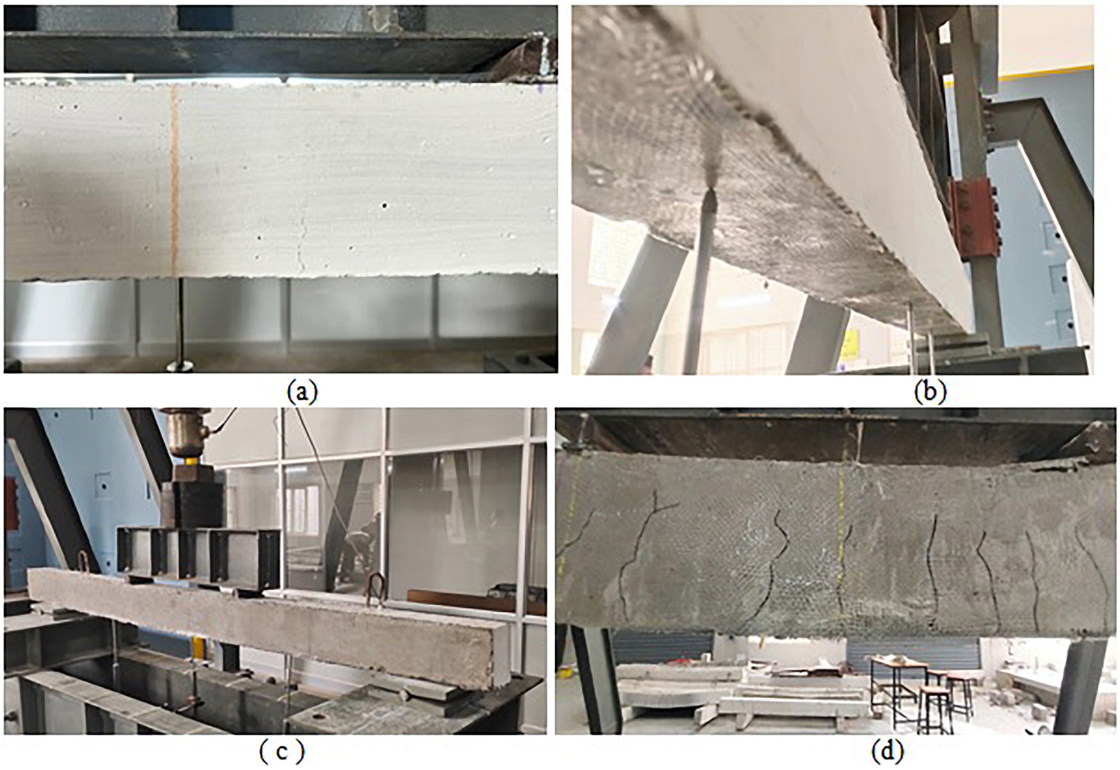

Figure 6: (a) Initial crack test (b) GFRP RC beam. (c) U- shaped beam testing (d) U wrapped beam failure.

each retrofitted beam. A hydraulic jack was used to apply the load, which was positioned beneath a distributed 600 mm steel I-beam. The applied load was measured using a carefully calibrated load cell, ensuring exact readings [16, 31, 32]. The usage of LVDTs, which stand for linear variable differential transformers, was necessary in order to accurately quantify the deflection that was produced throughout the testing operation. For each redesigned beam, load was applied until it broke under the pressure. The utilization of this testing strategy makes it possible to investigate the greatest ultimate load bearing capacity of every retrofitted arrangement [33]. The results of the experimental testing provided valuable insights into the testing technique as well as the failure patterns that were discovered in the entirely retrofitted beams (RU) showing in Figure 6(d). When the members reached their maximum load capacity, the failure occurred as a result of tearing at the mid-span of the RU beams [34]. The debonding of the modified GFRP laminates took place as the ultimate load was imparted to the RB beams. The beam's structural integrity is put in jeopardy as a result of this debonding occurrence. As the RBSS beams approached their maximum weight, the concrete in the beams began to split, which ultimately led to the members' catastrophic failure. As a result of these discoveries, the numerous failure mechanisms that are associated with each retrofitting strategy are brought to light, and essential data are provided for the purpose of further inquiry and the development of retrofitting methodology.

3.3. Research observations

The results of an experimental investigation comparing the efficiency of different retrofitting patterns on the initial tested RC beam are shown in the table 2. Several retrofitting categories were explored, including RU, RB, and RBSS [35].

The results from the initial crack load tests revealed a noteworthy enhancement in load-bearing capacity with the implementation of GFRP retrofitting. The control beam exhibited an initial crack load of 9.4 kN, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with shear strip strengthened wrapping demonstrated load capacities of 14.3 kN, 9.9 kN, and 11.1 kN, respectively. This indicated the effectiveness of U-wrap configuration in significantly increasing the load-carrying capacity, an essential attribute for delaying the onset of structural deterioration.

Moving to the yield load tests, the control beam yielded at 20.9 kN show in the Figure 7(a), whereas GFRP200 with U-wrap showcased an increased yield load of 23.8 kN shown in the Figure 7(b). Similarly, the bottom wrap and bottom wrap with partial shear strip exhibited yield loads of 17.4 kN and 19.4 kN, respectively

Table 2: Details of load-deflection for test specimens.

BEAM	INITIAL CRACK		YIELD		ULTIMATE		STIFFNESS
	LOAD (KN)	DEFLECTION (mm)	LOAD (KN)	DEFLECTION (mm)	LOAD (KN)	DEFLECTION (mm)	
CB	9.4	4	20.9	9.7	25.5	45	0.6
RU	14.3	3.5	23.8	14	31.3	52.5	0.6
RB	9.9	5	17.4	9.2	26.2	38	0.7
RBSS	11.1	3.8	19.4	11	30.4	48.4	0.6

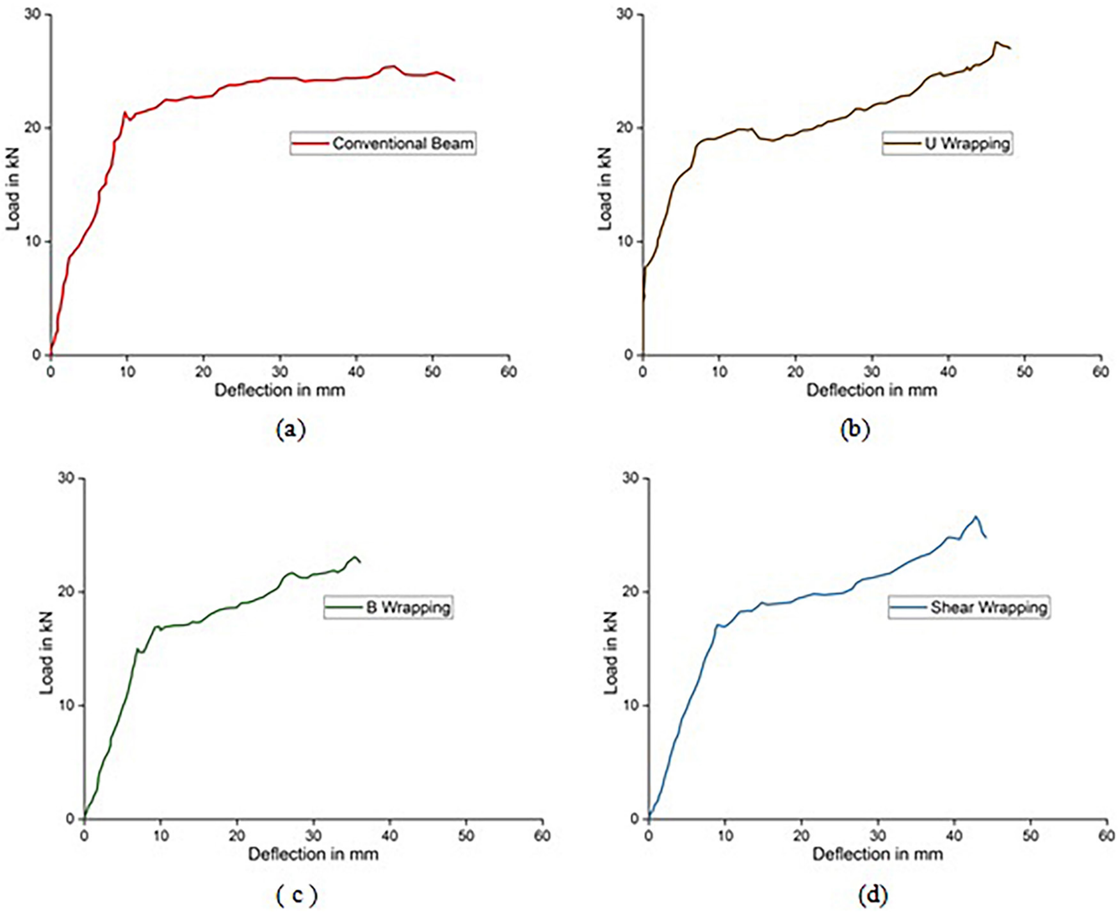

Figure 7: (a) Load vs Deflection of CB. (b) Load vs Deflection of RU. (c) Load vs Deflection of RB. (d) Load vs Deflection of RBSS.

indicated in the Figure 7(c) and Figure 7(d). This highlights the potential of GFRP retrofitting to enhance the beam's resistance to yielding, crucial for ensuring the structural integrity under varying loading conditions.

Further exploration of the ultimate load tests demonstrated the substantial effectiveness of GFRP retrofitting in preventing structural failure. The control beam reached an ultimate load of 25.5 kN, whereas GFRP200 with U-wrap exhibited the highest ultimate load at 31.3 kN. The bottom wrap and bottom wrap with partial shear strip also showed significant improvements, with ultimate loads of 26.2 kN and 30.4 kN, respectively [36].

Examining the deflection results, the GFRP retrofitting introduced increased deflection, as expected. The control beam exhibited a deflection of 45 mm at ultimate load, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with shear strip demonstrated deflections of 52.5 mm, 40.2 mm, and 48.4 mm, respectively. This increased deflection, while a trade-off for improved load-bearing capacity, indicates a more ductile behavior, crucial for mitigating potential failure modes evident in the Figure 8 load deflection behaviour of retrofitted RC beams.

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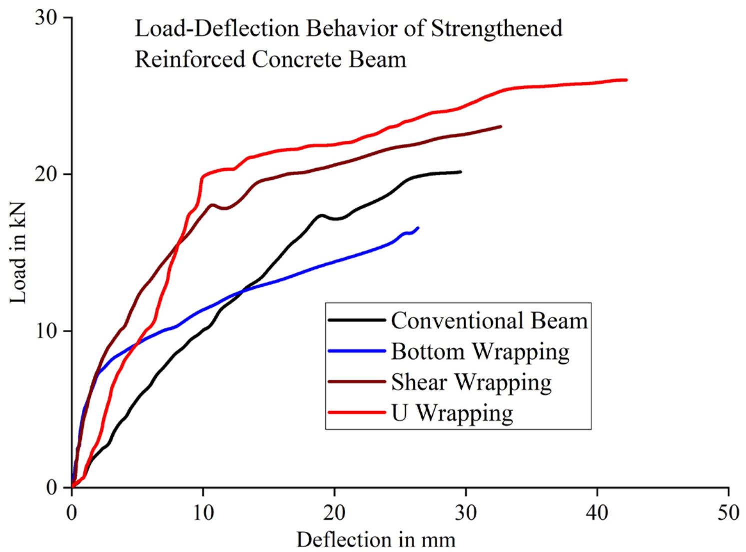

Figure 8: Load vs Deflection for CB, RU, RB, RBSS.

Table 3: Structural parameters of test specimens

BEAM	DEFLECTION DUCTILITY	ENERGY UPTO YIELD POINT	ENERGY UPTO ULTIMATE POINT	ENERGY DUCTILITY
CB	4.6	116.5	621.3	5.3
RU	3.8	81.5	469.6	5.8
RB	4.1	47.9	282.3	5.9
RBSS	4.4	56.5	314.8	5.6

Considering the stiffness values, the control beam exhibited a stiffness of 0.57, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with shear strip demonstrated stiffness values of 0.60, 0.7, and 0.63, respectively. The reduction in stiffness, though expected with the introduction of GFRP retrofitting, is a reasonable compromise for the improved ductility and load-carrying capacity. The U-wrap configuration emerges as particularly effective, showcasing significant improvements in load-bearing capacity, yield load, and ultimate load, albeit with an expected increase in deflection and reduction in stiffness, which are justifiable trade-offs for improved ductility and structural performance.

It has been observed that enhancing the deflection ductility, bending capacity, and energy ductility of reinforced concrete beams can be achieved through the retrofitting technique involving U-shaped wrapping. The performance of RB beams, in particular, exhibited deficiencies in terms of cracking, yield, and maximum load. On the contrary, CB beams demonstrated superior initial cracking load and deflection, while RU beams showed enhanced yield load, maximum load, and deflection. Although there were slight variations in stiffness values among the beams, the RB beam appeared to be marginally stiffer compared to the others.

The information provided in Table 3 gives valuable insights into the structural characteristics of various beams, including retrofitting, deflection ductility, and energy ductility. Beginning with the CB beam, it signifies the lack of any retrofitting measures.

The assessment of deflection ductility is crucial for understanding the ability of the retrofitted RC beam to deform under loading conditions. The control beam demonstrated a deflection ductility of 4.6, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with partial shear strip exhibited ductilities of 3.8, 4.1, and 4.4, respectively. The decrease in ductility with U-wrap indicates a more controlled and predictable response, while the other configurations maintain or slightly enhance ductility. This suggests that the GFRP retrofitting, particularly with bottom wrap and partial shear wrap, contributes to the beam's ability to undergo substantial deformation before failure.

The energy absorption capability up to the yield point is critical for understanding the material's ability to dissipate energy before undergoing permanent deformation. The control beam absorbed 116.5 units of energy, whereas GFRP200 with U-wrap, bottom wrap, and bottom wrap with partial shear wrap absorbed 81.5, 47.85, and 56.5 units of energy, respectively. The reduction in energy absorption with GFRP retrofitting suggests that the material contributes to controlled energy dissipation, preventing sudden and catastrophic failure. The U-wrap configuration demonstrates a more significant reduction, indicating a more efficient utilization of energy absorption mechanisms.

Evaluating energy absorption up to the ultimate point provides insights into the retrofitting's effectiveness in enhancing the overall structural performance and preventing catastrophic failure. The control beam absorbed 621.25 units of energy, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with partial shear wrap absorbed 469.6, 282.25, and 314.75 units of energy, respectively. The results indicate that the GFRP retrofitting not only contributes to increased energy absorption but also ensures a more controlled failure mode, preventing sudden and brittle failure. The U-wrap configuration stands out as particularly effective in enhancing the energy absorption capacity of the retrofitted beam.

Energy ductility combines the aspects of both deflection ductility and energy absorption, providing a comprehensive measure of the structure's ability to deform and absorb energy before failure. The control beam exhibited an energy ductility of 5.3, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with partial shear wrap demonstrated ductilities of 5.8, 5.9, and 5.6, respectively. The increase in energy ductility with GFRP retrofitting indicates a positive impact on the overall performance of the structure, ensuring a more controlled and gradual failure mode.

The area of retrofitting is a critical parameter reflecting the extent of GFRP material application on the beam. The control beam had no retrofitting, while GFRP200 with U-wrap, bottom wrap, and bottom wrap with partial shear strip had retrofitting areas of 8000 cm^2, 2000 cm^2, and 4600 cm^2, respectively. The considerable area of retrofitting demonstrates the effective utilization of GFRP materials, contributing to the enhanced load-carrying capacity and overall structural performance.

The detailed examination of deflection ductility, energy absorption up to yield and ultimate points, and energy ductility underscores the positive influence of GFRP retrofitting on the structural behavior of RC beams. The U-wrap configuration stands out for its efficiency in controlling deformation and enhancing energy absorption, while other configurations also contribute to improved ductility and energy dissipation.

The table outlines the retrofitting zones for different beams along with their deflection ductility and energy ductility. These results provide valuable perspectives on the structural characteristics and retrofitting efficacy of the beams, facilitating well-informed decision-making in the field of structural engineering.

3.4. The contribution of GFRP

The structural behaviour of the retrofitted beams is greatly influenced by the use of Glass FRP, which is included in the retrofitting procedure and is explained with experimental findings in Table 2. Several beneficial characteristics of glass FRP improve the beams' strength and performance. The strength and functionality of the beams are enhanced by a number of advantageous properties of glass FRP. This reinforcement successfully inhibits the formation and spread of fractures, avoiding or postponing failure mechanisms such as steel yielding or concrete crushing. In addition, Glass FRP exhibits significant fatigue resistance, enabling the retrofitted beams to endure numerous loading cycles without experiencing a discernible decline in operational efficiency. This characteristic proves to be especially advantageous in scenarios where the beams encounter dynamic or periodic loading circumstances. Additionally, GFRP has weight to strength ratio is low, which means that despite greatly enhancing the beams' ability to resist loads, it adds very little extra weight to them. This feature reduces the additional dead weight placed on the existing structures, making it particularly helpful for retrofitting applications. Additionally, Glass FRP exhibits outstanding resistance to corrosion, rendering it a favorable option for upgrading beams in challenging environments or structures exposed to chemical pollutants. The corrosion inhibitor in Glass FRP guarantees the enduring strength and longevity of the modified beams. In summary, integrating Glass FRP into the retrofitting procedure enhances the beams' load-bearing capacity, reinforces their resistance to wear and cracks, reduces additional weight, and guards against corrosion. Glass FRP demonstrates remarkable resistance to corrosion, rendering it a suitable selection for retrofitting purposes. Owing to its advantages, Glass FRP emerges as an enticing option for retrofitting applications, notably improving the longevity and efficiency of the retrofitted beams.

3.5. Failure modes

In varied retrofitting patterns, RC beams retrofitted using GFRP laminates demonstrated distinct mechanisms of failure. The experimental findings reveal that using GFRP laminates in shear zones has no significant effect on the flexural strength of the members. This implies that while GFRP may enhance certain performance aspects, it may not universally improve all structural characteristics. The study identifies several key failure mechanisms associated with the use of GFRP laminates in RC beams, including debonding, rupture, delamination, concrete crushing, and shear failure. Debonding occurs when the bond between the Glass FRP and the concrete substrate is interrupted, resulting in a reduced load transfer capacity and compromised performance. This type of failure is often attributed to inadequate surface preparation, poor adhesive quality, or improper installation techniques. As illustrated in Table 2, debonding can significantly diminish the effectiveness of the retrofitting, leading to early failure of the structure under load. Although GFRP laminate materials exhibit high tensile strength, they are susceptible to rupture or shattering when subjected to excessive stress. The experimental results indicate that rupture failure of beams retrofitted with different GFRP configurations, such as RB (retrofit bottom), RBSS (retrofit bottom with side strips), and RU (retrofit U-wrap), occurred at the ultimate load. The proportion of FRP rupture varies based on factors like the type of GFRP used and the applied load. Reported failure rates range from 10% to 30%, highlighting the variability in performance based on material properties and load conditions.

Delamination, the separation of layers within a GFRP laminate, is another critical failure mode. This issue is influenced by the quality of the adhesive, surface preparation, and installation practices. Delamination can lead to a significant loss of structural integrity, as it prevents the effective transfer of loads across the laminate layers. Experimental data show that delamination failure in retrofitted beams has been reported between 5% and 15%. Ensuring proper adhesive application and curing processes can mitigate this risk. Concrete crushing failure, particularly under compression-dominated loading, is another concern in retrofitted beams. The proportion of concrete fracture depends on factors such as the compressive strength of the concrete and the applied loads. Failure rates reported in studies range between 10% and 20%. This type of failure underscores the importance of considering the overall material properties and load distribution when designing retrofitting solutions. Shear failure can occur at the interface of the GFRP and concrete or within the concrete itself. This type of failure is particularly concerning as it can lead to sudden and catastrophic collapse. Reported failure rates for shear failure range between 10% and 25%, emphasizing the need for careful design and installation of shear reinforcement. The interface between the GFRP and the concrete must be meticulously prepared to ensure a strong bond and prevent premature failure.

Experimentation on GFRP retrofitted beams has identified various failure modes, including debonding of FRP composites after reaching maximum load. In RB-type retrofitting, where the bottom face is exclusively retrofitted, GFRP composites may experience rupture failure, leading to catastrophic collapse. Factors such as the type of GFRP and applied stress levels influence the failure mechanisms of retrofitted beams. The use of epoxy in retrofitting, without adequate fiber reinforcing, can result in brittle behavior. Proper preparation of test specimens and caution in removing sharp edges precede epoxy application.

Furthermore, the mentioned figures are approximate and based on general findings. Actual failure types and percentages may vary depending on project specifics, material qualities, and installation standards. For a detailed understanding of failure modes and associated risks, a thorough examination of design standards and comprehensive structural analysis is recommended. The integration of detailed failure analysis into the design and retrofitting process can significantly enhance the reliability and safety of GFRP-retrofitted RC beams, ensuring their long-term performance and durability. This approach not only helps in addressing the immediate structural concerns but also in planning for future maintenance and monitoring strategies.

4. CONCLUSION

The experimental study on the structural behavior of RC beams retrofitted with Glass FRP has provided valuable insights into the efficacy of this retrofitting technique. The inclusion of GFRP in the retrofitting process has demonstrated significant improvements in various key aspects of structural performance.

The experimental results indicate that GFRP retrofitting effectively enhances the load-carrying capacity of RC beams. The beams retrofitted with GFRP, especially those with U-wrap and bottom wrap configurations, exhibited increased initial crack loads, yield loads, and ultimate loads compared to the control beam. This enhancement in load capacity is crucial for the structural integrity and resilience of the retrofitted beams under different loading conditions.

Moreover, the study revealed that GFRP retrofitting contributes to improved ductility in the retrofitted beams. Despite the expected increase in deflection, the beams retrofitted with GFRP, particularly in the U-wrap and bottom wrap configurations, displayed higher deflection ductility values. This suggests that GFRP retrofitting allows the beams to undergo larger deformations while maintaining structural integrity, which is essential for withstanding dynamic or seismic loading.

Additionally, the energy absorption characteristics of the retrofitted beams were examined. The results indicated that GFRP retrofitting led to controlled energy absorption up to the yield and ultimate points. While there was a reduction in energy absorption compared to the control beam, this is attributed to the enhanced stiffness introduced by GFRP, indicating a more controlled failure mechanism and increased safety.

The area of retrofitting, as shown in the experimental results, highlights the effective utilization of GFRP materials. The considerable retrofitting area, especially in the U-wrap configuration, emphasizes the material's ability to significantly contribute to the overall strength and performance of the retrofitted beams.

In summary, the experimental study underscores the positive impact of GFRP retrofitting on the structural behavior of RC beams. The incorporation of GFRP enhances load-carrying capacity, improves ductility, and ensures controlled energy absorption. The results presented enhance the existing structural engineering knowledge base and provide valuable practical perspectives for engineers and researchers engaged in the enhancement of reinforced concrete structures through the application of Glass FRP. The findings affirm the effectiveness of GFRP as a valuable and sustainable material for reinforcing and retrofitting existing structures, promoting their longevity and resilience against various loading conditions. Additionally, future researchers may investigate GFRP's durability and resistance to environmental factors to further substantiate the study's findings and contribute to a more thorough evaluation of its potential applications in structural retrofitting.

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