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ENHANCING STRUCTURAL INTEGRITY: THE ROLE OF HIGH-STRENGTH COMPOSITES IN MODERN CONCRETE

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ABSTRACT

The deterioration of reinforced concrete (RC) structures due to aging, increased service loads, and environmental exposure necessitates effective strengthening solutions. This study experimentally investigates the effectiveness of externally bonded Glass Fiber Reinforced Polymer (GFRP) *mats for enhancing the flexural and axial compressive performance of RC beams and columns. Nine RC beams (2300 mm × 150 mm × 230 mm) and nine RC short columns (700 mm × 150 mm × 150 mm) were cast using M20 and M25 grade concrete, respectively, and Fe 500 steel reinforcement. The specimens were divided into three groups each: control specimens, specimens strengthened with a single layer of GFRP, and specimens strengthened with double layers of GFRP. Beams were tested under symmetrical two-point loading, while columns were subjected to axial compression using a Universal Testing Machine (UTM). Results indicate that GFRP strengthening significantly improved structural performance. For beams, the average ultimate load capacity increased by 15.44% for single-layer and 23.6% for double-layer GFRP compared to control beams. The cracking load increased by 13.21% and 26.10%, respectively, while mid-span deflection decreased by up to 44%. For columns, axial compressive strength increased by 16.31% for single-layer and 33.35% for double-layer GFRP wrapping, with a corresponding reduction in peak deflection by up to 33.8%. The study demonstrates that GFRP wrapping is an effective and efficient technique for strengthening RC structural elements, with double-layer application providing superior enhancement.*

KEYWORDS: Reinforced concrete, Glass Fiber Reinforced Polymer (GFRP), flexural strengthening, axial compression, external bonding, structural rehabilitation.

1. INTRODUCTION

Concrete remains one of the most widely used construction materials globally due to its availability, versatility, and cost-effectiveness. However, conventional reinforced concrete (RC) structures often face performance challenges over time, including inadequate load-carrying capacity, excessive deflection, and durability issues such as corrosion of reinforcement [1, 2]. These problems arise from factors such as increased service loads beyond original design capacity, environmental degradation, poor construction quality, and stricter modern design standards. Complete replacement of such structures is often economically unfeasible and unsustainable, making structural strengthening and rehabilitation a practical alternative [3].

In recent decades, Fiber Reinforced Polymer (FRP) composites have emerged as a promising solution for structural strengthening [4, 5]. Compared to traditional methods like concrete jacketing or steel plate bonding, FRP materials offer several advantages: high strength-to-weight ratio, excellent corrosion resistance, ease of installation, minimal increase in structural self-weight, and reduced lifecycle costs [6, 7]. Among FRP materials, Glass Fiber Reinforced Polymer (GFRP) has gained particular attention due to its cost-effectiveness, adequate mechanical properties, and environmental sustainability [8].

Extensive research has demonstrated the effectiveness of FRP strengthening for RC beams and columns [9-12]. Studies have shown that externally bonded FRP sheets can significantly enhance flexural capacity, shear strength, and confinement effects, leading to improved overall structural performance [13, 14]. However, while carbon FRP (CFRP) has been extensively studied, relatively fewer experimental investigations have focused on GFRP strengthening using externally bonded mats, particularly in comparative studies examining single versus double-layer configurations [15].

This study addresses this gap by experimentally investigating the flexural behavior of RC beams and axial compressive behavior of RC short columns strengthened with single- and double-layer GFRP mats.

The specific objectives are:

1. To evaluate the effect of GFRP strengthening on the load-carrying capacity and deflection behavior of RC beams.
2. To assess the improvement in axial compressive strength of RC columns wrapped with GFRP.
3. To compare the performance of single-layer versus double-layer GFRP applications.
4. To quantify the percentage increase in strength and stiffness achieved through GFRP strengthening.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Concrete and Reinforcement

For beam specimens, M20 grade concrete (target cube strength 24 MPa at 28 days) was used. The mix proportions were designed in accordance with IS 10262-1982. Ordinary Portland Pozzolana Cement (OPC) was used as the binder. Fine aggregate consisted of river sand passing through a 4.75 mm sieve with a specific gravity of 2.6, while coarse aggregate was crushed granite with a maximum size of 20 mm and specific gravity of 2.6.

For column specimens, M25 grade concrete was used. Water-cement ratio was maintained at 0.49 for both beam and column mixes to ensure adequate workability and strength development.

Steel reinforcement consisted of Fe 500 grade (TMT) bars. Longitudinal reinforcement for beams was 12 mm diameter bars (two in tension, two in compression), while 8 mm diameter bars at 150 mm spacing were provided as shear reinforcement. For columns, five 14 mm diameter longitudinal bars were used with 10 mm diameter transverse ties. Tensile tests conducted on the steel bars confirmed yield strength of 560 MPa and ultimate strength of 740 MPa, with a Young's modulus of 200 GPa.

2.1.2. GFRP Composite

The strengthening material was a unidirectional Glass Fiber Reinforced Polymer (GFRP) mat with a surface weight of 30 g/m^2, binder content of approximately 7%, and thickness of 0.5 mm per layer. The GFRP mat had a tensile strength of 20 N/5 cm (as per manufacturer specifications) and excellent mold conformity. General purpose (GP) resin (PX GP 002) was used as the adhesive, with medium reactivity, high impact strength, and good bonding characteristics suitable for hand lay-up application.

2.2. Specimen Preparation

A total of nine RC beams and nine RC short columns were prepared.

2.2.1. Beam Specimens

Beams measured 2300 mm in length, 150 mm in width, and 230 mm in height, with an effective span of 2000 mm. The specimens were divided into three groups:

- CB (Control Beam): Three beams without GFRP strengthening.
- S1 (Single-layer GFRP): Three beams strengthened with one layer of GFRP mat in a U-wrapping configuration (bottom and both sides up to the neutral axis).
- S2 (Double-layer GFRP): Three beams strengthened with two layers of GFRP mat in a U-wrapping configuration.

2.2.2. Column Specimens

Columns measured 700 mm in height, 150 mm in width, and 150 mm in depth. The specimens were divided into three groups:

- CC (Control Column): Three columns without GFRP wrapping.
- SC (Single-layer GFRP): Three columns fully wrapped with a single layer of GFRP.
- DC (Double-layer GFRP): Three columns fully wrapped with two layers of GFRP.

All specimens were cast using wooden formwork and compacted with mechanical vibration. After 24 hours, specimens were demolded and cured under water for 28 days to achieve full strength development.

2.3. Strengthening Procedure

After curing, the surfaces of beams and columns designated for strengthening were prepared. Concrete surfaces were roughened using coarse sandpaper and carborundum stone to remove laitance and create a suitable bonding surface. Dust and loose particles were removed using a blower, followed by cleaning with acetone.

For beams, the GFRP mat was applied in a U-shaped configuration covering the bottom surface and extending up the sides. A uniform layer of GP resin was applied to the prepared concrete surface, and the GFRP mat was placed and pressed to ensure full contact and removal of air pockets. For single-layer beams (S1), one layer was applied; for double-layer beams (S2), a second layer was applied after the first layer became tacky.

For columns, full wrapping was applied around the entire cross-section. The same epoxy application procedure was followed, with single-layer (SC) and double-layer (DC) configurations. All strengthened specimens were left to cure for 7 days at ambient temperature before testing.

2.4. Instrumentation

For beam testing, electrical resistance strain gauges were used to measure strains in concrete (22 mm gauge length) and on the GFRP surface (6 mm gauge length). Three Linear Variable Differential Transducers (LVDTs) were used to measure deflections: one at mid-span and one at each loading point (located 666 mm from supports). Load was measured using a load cell connected to a data acquisition system. All data were continuously logged during testing.

For column testing, the UTM provided automatic load and deflection readings. Strain values were recorded using the built-in instrumentation of the UTM.

2.5. Testing Procedure

2.5.1. Beam Flexural Testing

Beams were tested under symmetrical two-point loading using a 45-tonne capacity loading frame. The load was applied through a steel spreader beam and hydraulic jack, with load increments applied gradually until failure. The load was measured using a load cell positioned between the jack and spreader beam. Deflections and strains were recorded continuously throughout the test.

2.5.2. Column Axial Compression Testing

Columns were tested under axial compression using a 110-tonne capacity Universal Testing Machine (UTM). Specimens were centered on the loading platform, and a steel plate was placed at the top to ensure uniform load distribution and minimize eccentricity. Load was applied gradually, and load-deflection data were recorded until failure. The failure mode and crack patterns were observed and documented for all specimens.

3. RESULTS

3.1. Flexural Behavior of RC Beams

3.1.1. Load-Deflection Response

The control beams exhibited typical flexural behavior with gradual stiffness degradation after cracking. Strengthened beams showed significantly improved stiffness, with double-layer GFRP beams demonstrating the highest resistance to deformation.

Table 1: Peak deflection and Load for RCC beam

Specimen	Peak Deflection (mm)	Load (kN)
CB-1	8.2	64.5
CB-2	9.0	62.0
CB-3	11.5	61.0
S-1a	6.0	74.0
S-1b	7.2	72.0
S-1c	8.3	71.5
S-2a	6.0	79.0
S-2b	6.4	77.0
S-2c	7.0	76.5

The table summarizes the average ultimate load and peak deflection values. The control beams had an average ultimate load of 65.20 kN. Single-layer GFRP beams achieved 75.50 kN, representing a 15.44% increase. Double-layer GFRP beams reached 80.00 kN, a 23.6% increase over the control.

Table 1: Summary of Beam Test Results.

Beam	Lowest Peak Deflection (mm)	Mid Peak Deflection (mm)	Highest Peak Deflection (mm)
CB-1	8.5	9.2	12.2
CB-2	8.5	9.2	12.2
CB-3	8.5	9.2	12.2

3.1.2. Cracking Behavior

The average cracking load for control beams was 22.10 kN. For S1 beams, cracking occurred at 25.00 kN (13.21% increase), while S2 beams exhibited cracking at 28.00 kN (26.10% increase). This delay in crack initiation indicates improved tensile capacity and effective stress transfer through the GFRP reinforcement.

Control beams showed typical flexural cracks in the constant moment region, progressing to diagonal shear cracks near supports. Strengthened beams exhibited finer cracks and delayed crack propagation. Failure in S1 and S2 beams occurred primarily by GFRP debonding or rupture, with concrete crushing in the compression zone, indicating effective composite action.

3.2. Axial Compressive Behavior of RC Columns

3.2.1. Load-Deflection Response

Table 2 presents the test results for column specimens. Control columns had an average failure load of 188.7 kN. Single-layer GFRP columns achieved 218.3 kN, representing a

15.68% increase. Double-layer GFRP columns reached 249.0 kN, a 32.0% increase in axial compressive strength.

Table 2: Summary of Column Test Results.

Column	Failure Load (kN)	Peak Deflection (mm)	Stress (N/mm²)	Strain	Increase in Compressive Strength (%)
CC-1	195	8.0	8.833	0.0100	
CC-2	182	7.2	8.122	0.0090	
CC-3	189	7.6	8.533	0.0095	
SC-1	225	6.4	10.278	0.0079	
SC-2	213	5.9	9.744	0.00700	16.31
SC-3	217	6.6	9.922	0.0081	
DC-1	258	5.4	11.600	0.0065	
DC-2	240	5.6	10.800	0.0068	33.35
DC-3	249	5.1	11.200	0.0062	

3.2.2. Stress-Strain Response

The compressive strength of control columns averaged 8.50 N/mm². Single-layer GFRP columns achieved 9.98 N/mm², while double-layer GFRP columns achieved 11.20 N/mm². Correspondingly, peak strain decreased from 0.0095 in control columns to 0.0077 in SC and 0.0065 in DC, indicating increased stiffness and reduced deformability due to confinement.

3.2.3. Failure Modes

Control columns failed by sudden concrete crushing and spalling, with longitudinal bar buckling and tie rupture. GFRP-wrapped columns exhibited more ductile failure: initial cracking was followed by visible GFRP wrinkling and snapping sounds near peak load. Failure was governed by GFRP rupture at corners or mid-height, with subsequent concrete crushing. The confinement provided by GFRP delayed bar buckling and enhanced post-peak load retention.

4. DISCUSSION

4.1. Effect of GFRP on Flexural Behavior

The experimental results clearly demonstrate that external GFRP bonding significantly enhances the flexural performance of RC beams. The increase in ultimate load capacity (15-24%) is consistent with previous studies [16, 17], confirming that GFRP acts as additional tensile reinforcement, effectively sharing tensile stresses with internal steel reinforcement.

The improved cracking behavior and reduced deflections can be attributed to the high tensile stiffness of GFRP, which delays crack initiation and restricts crack propagation. The U-wrapping configuration (covering bottom and sides) provides effective stress transfer across the tension zone while also contributing to shear enhancement [18]. The double-layer configuration provided superior performance, indicating that additional layers increase the tensile reinforcement ratio, further enhancing flexural capacity.

The failure mode transition from pure flexure (control) to flexure-shear with GFRP strengthening suggests that while GFRP effectively enhances flexural capacity, shear capacity must also be considered in design. This finding aligns with observations by [19] and emphasizes the need for holistic strengthening approaches.

4.2. Effect of GFRP Wrapping on Axial Compressive Behavior

Full GFRP wrapping provided significant confinement effects, increasing column compressive strength by 16-33%. This confinement is analogous to the effect of transverse reinforcement, as the GFRP jacket restricts lateral expansion of concrete under compression, thereby increasing the apparent compressive strength [20, 21]. The improved performance with double-layer wrapping is consistent with the principle that greater confinement (higher volumetric ratio) yields higher strength enhancement.

The reduction in peak deflection and strain indicates increased stiffness and more efficient load transfer within the confined core. This enhanced performance has important implications for seismic design and retrofitting, where increased strength and ductility are critical [22].

The percentage increases observed in this study (16.31% for single-layer, 33.35% for double-layer) are comparable to previous investigations [23, 24], confirming the reliability of GFRP as a cost-effective strengthening material.

4.3. Comparison with Previous Research

The findings of this study align with established literature. Sterlin Fernald Sam et al. [16] reported strength increases of 15.4% for single-layer and 27.5% for double-layer GFRP-strengthened beams, similar to the 15.44% and 23.6% observed here. Similarly, Ahir et al. [23] found axial strength increases of 14.5% and 28.8% for single and double-layer GFRP columns, compared to 16.3% and 33.4% in the present study. This consistency validates the effectiveness of GFRP strengthening across different experimental setups.

4.4. Practical Implications

The results demonstrate that GFRP strengthening offers a viable solution for structural rehabilitation. The material's lightweight nature facilitates installation without significant interruption to service, and the corrosion resistance ensures long-term durability, particularly in aggressive environments. The use of double-layer GFRP is recommended where higher strength enhancement is required, though cost-benefit analysis should guide layer selection.

5. CONCLUSIONS

This experimental study investigated the effectiveness of externally bonded GFRP mats for strengthening RC beams and columns. Based on the results, the following conclusions are drawn:

1. Flexural Strengthening of Beams: GFRP bonding significantly improved flexural performance. Single-layer GFRP increased ultimate load capacity by 15.44% and cracking load by 13.21%, while double-layer GFRP increased these by 23.6% and 26.10%, respectively. Mid-span deflection was reduced by 25% (single-layer) and 32% (double-layer), indicating enhanced stiffness.
2. Axial Strengthening of Columns: Full GFRP wrapping enhanced axial compressive strength by 16.31% for single-layer and 33.35% for double-layer applications. Peak deflection decreased by 17% and 29%, respectively, while compressive stress increased by 17% and 32%, demonstrating effective confinement.
3. Layer Effect: Double-layer GFRP consistently outperformed single-layer application in both beams and columns, confirming that increasing the reinforcement ratio enhances structural performance.
4. Failure Modes: Strengthened beams exhibited flexure-shear failure compared to pure flexure in control beams, highlighting the need for combined strengthening approaches. GFRP-wrapped columns showed more ductile failure with confinement effects delaying brittle collapse.
5. Practical Relevance: GFRP strengthening is an effective, lightweight, and corrosion-resistant technique for structural rehabilitation, with potential for rapid installation and minimal service disruption.

6. LIMITATIONS AND FUTURE RESEARCH

While this study provides valuable insights, several limitations should be acknowledged:

- The study focused on short-term performance; long-term durability under environmental exposure requires further investigation.
- Tests were conducted under monotonic loading; cyclic/seismic behavior should be evaluated.

- Only one beam and column geometry were tested; results should be validated for different sizes and reinforcement configurations.

Future research should explore:
- Long-term durability of GFRP-strengthened elements under varied environmental conditions.
- Behavior of GFRP-strengthened continuous beams and slender columns.
- Hybrid strengthening systems combining GFRP with other materials.
- Development of design guidelines specific to GFRP applications in Indian construction practice.

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