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Advanced Structural Enhancement of Reinforced Concrete Beams through Glass Fiber Reinforced Polymer (GFRP) Composite Integration

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Abstract:

The structural integrity of reinforced concrete (RC) elements often deteriorates over time due to aging, overloading, environmental exposure, and design inadequacies. This study explores the application of Glass Fiber Reinforced Polymer (GFRP) composites as a strengthening solution for RC beams. A series of experimental investigations were conducted on both control and retrofitted beams under four-point bending to assess improvements in flexural capacity, ductility, crack control, and energy absorption. Various configurations of GFRP—including bottom bonding, U-wrapping, and a combined system—were evaluated. Results revealed that GFRP integration significantly increased the ultimate load-carrying capacity (up to 46%) and energy dissipation (up to 89%) over control specimens. Finite element modeling (FEM) using ANSYS validated the experimental outcomes with less than 5% deviation. The combined GFRP configuration was found to be the most effective in enhancing strength and serviceability without altering beam geometry. The findings support the viability of GFRP as a cost-effective and efficient technique for retrofitting RC structures in both seismic and non-seismic regions.

Keywords: Reinforced concrete beams, GFRP composites, Structural strengthening, Flexural behavior, Retrofitting, Four-point bending test, Crack control, Ductility, FEM analysis, ANSYS

1. Introduction

Reinforced concrete (RC) remains the dominant construction material globally due to its durability, versatility, and cost-effectiveness. However, many RC structures built in past decades are now experiencing deterioration due to aging, corrosion, inadequate design, increased service loads, and environmental factors (Siddika et al., 2019). Strengthening and retrofitting such structures are not only more economical than replacement but also critical for extending service life and ensuring structural safety.

Among the various retrofitting techniques, the application of Fiber Reinforced Polymer (FRP) composites has gained considerable attention in both research and practice. FRPs, particularly Glass Fiber Reinforced Polymer (GFRP), offer significant advantages such as high tensile strength, corrosion resistance, low weight, and ease of application (Amran et al., 2018). These properties make GFRP a suitable material for external strengthening of RC members, especially in flexural and shear retrofitting of beams, slabs, and columns.

In contrast to Carbon FRP (CFRP), GFRP is more cost-effective and widely available, making it a practical choice in developing economies. While CFRP exhibits higher tensile strength, GFRP achieves sufficient structural performance for moderate-strength retrofitting applications and is particularly effective when multiple layers or wrapping techniques are used (Teng et al., 2002). Moreover, GFRP composites can be applied with minimal interruption to structural use, as they require no significant section enlargement or heavy equipment, unlike steel jacketing or concrete encasement.

Various experimental studies have confirmed that GFRP-retrofitted RC beams display increased load-carrying capacity, improved ductility, delayed crack propagation, and more desirable failure modes (Grace et al., 1999; Almusallam et al., 2013). However, the structural behavior is sensitive to factors such as fiber orientation, bond length, adhesive properties, and application technique (Saadatmanesh & Ehsani, 1991). Additionally, the effectiveness of strengthening also depends on shear confinement, which is often achieved through U-wrapping or full encasement in GFRP laminates.

Despite its advantages, GFRP has limitations, including lower stiffness compared to CFRP, sensitivity to UV radiation and temperature, and potential for premature debonding if not properly anchored (Kodur & Naser, 2025). Hence, there is a need for comprehensive studies combining experimental testing and numerical simulation to evaluate the realistic behavior of GFRP-strengthened RC beams, particularly under service loads and ultimate failure conditions.

Figure 1.1: Deteriorated RC Beam in Practice

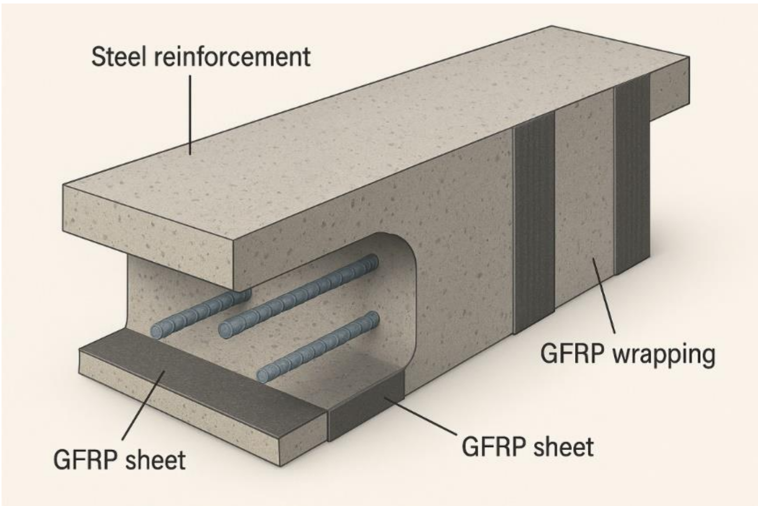

Figure 1.2: Conceptual Illustration of GFRP Strengthening

This study aims to investigate the flexural performance of RC beams strengthened with GFRP composites through experimental testing and finite element modeling. The effect of different GFRP configurations—bottom bonding, U-wrapping, and combined application—is evaluated in terms of load capacity, ductility, strain distribution, crack behavior, and energy absorption. The results provide insights into the structural efficiency, cost-effectiveness, and practical feasibility of GFRP retrofitting for real-world infrastructure rehabilitation.

2: Literature Review

2.1 Overview

The retrofitting of reinforced concrete (RC) beams using Glass Fiber Reinforced Polymer (GFRP) has emerged as a significant advancement in structural rehabilitation. GFRP is increasingly preferred due to its high tensile strength, corrosion resistance, low weight, and ease of installation. Numerous experimental and numerical studies have been conducted to evaluate the efficacy of GFRP in enhancing the flexural and shear performance of RC beams. This chapter critically reviews the state-of-the-art research.

2.2 Experimental Investigations

Saadatmanesh and Ehsani (1991) were among the first to demonstrate that GFRP plates bonded to the tensile face of RC beams increased the ultimate flexural strength by over 50%, and prevented early brittle failure

Almusallam et al. (2013) carried out flexural tests on RC beams strengthened with near-surface mounted (NSM) GFRP bars, noting substantial improvements in both strength and stiffness, along with enhanced bond performance at anchorage zones

Sharaky et al. (2017) compared bottom and side NSM GFRP bar configurations, concluding that end-anchored systems showed more ductile and gradual failure modes

Al-Ezzi et al. (2024) reported that using GFRP tube-jacketing in composite beams significantly reduced crack width and controlled failure, making the system more reliable for long-span applications

Kalyani and Pannirselvam (2023) explored the use of hybrid FRP sheets, including GFRP, for flexural strengthening, and observed a 45–70% increase in load capacity

2.3 Numerical Modeling and Validation

Banjara and Ramanjaneyulu (2017) utilized ANSYS to model GFRP-strengthened beams under shear and found strong correlation with physical tests, validating the use of Cohesive Zone Models (CZM)

Naser et al. (2021) reviewed FEM strategies for GFRP-retrofitted beams, highlighting the importance of interface bonding modeling and the need for temperature-dependent material models

Rezazadeh et al. (2016) compared GFRP and new NSM reinforcements, reporting that FEM predictions of mid-span deflection matched experimental results with <6% error

Makhlouf et al. (2024) studied JFRP (Jute FRP) in shear strengthening and benchmarked it against synthetic GFRP, using ABAQUS simulations to confirm the failure modes seen in lab tests

2.4 Comparative Studies and Review Articles

Figure 2.1: Types of FRP (CFRP, GFRP, AFRP, BFRP)

Siddika et al. (2019) conducted a thorough review on the mechanical performance of various FRP composites, concluding GFRP is more suitable for low-to-moderate applications due to cost efficiency and environmental resilience

Azuwa and Yahaya (2024) synthesized over 150 studies and emphasized that while CFRP performs better under fatigue and fire, GFRP remains optimal for flexural strengthening in non-critical regions

Solahuddin and Yahaya (2023) investigated thermal effects on GFRP beams and noted degradation above 100°C, stressing the need for protective coatings

Ramesh et al. (2021) tested Hybrid Fiber-Reinforced Concrete (HFRC) beams wrapped with GFRP and found synergistic improvement in load resistance and crack control

2.5 Key Observations from Literature

Study	Strengthening Method	Key Findings
Saadatmanesh & Ehsani (1991)	Bottom GFRP Plates	+50% flexural capacity
Sharaky et al. (2017)	NSM GFRP Bars	Ductile failure with end anchorage
Kalyani & Pannirselvam (2023)	Hybrid GFRP + CFRP	45–70% strength improvement
Banjara et al. (2017)	FEM modeling	High correlation with lab results
Naser et al. (2021)	FEM Review	Accurate prediction needs interface modeling
Ramesh et al. (2021)	GFRP + HFRC	Best crack control and energy absorption

2.6 Research Gaps Identified

Despite extensive research, the following gaps persist:

- Limited studies on bond failure mechanisms for GFRP at elevated temperatures.
- Lack of long-term durability data under freeze-thaw, UV, and moisture exposure.
- Minimal exploration of optimized fiber orientation, anchorage, and multi-layer systems.
- Insufficient field-scale studies comparing cost-effectiveness and installation feasibility across FRP types.

3. Materials and Methodology

3.1 Beam Specimens

Six simply supported beams (1500×150×250 mm) were cast: 2 control, and 4 retrofitted with GFRP using bottom bonding, U-wraps, and combined strategies.

3.2 Materials

- **Concrete Mix**: M25 grade (1:1.75:2.72)
- **Steel Reinforcement**: Fe500 TMT bars
- **GFRP Sheet**: Unidirectional E-glass, tensile strength = 3400 MPa, modulus = 72 GPa
- **Epoxy Adhesive**: Two-part structural resin (30 MPa strength)

3.3 Test Setup

Beams were tested under four-point loading using a UTM. Mid-span deflection was measured using LVDTs; strain gauges recorded concrete and GFRP strains.

3.4 Numerical Simulation

ANSYS Workbench was used to simulate the test beams. Concrete was modeled with SOLID65, GFRP as SHELL181, and steel as LINK180 elements. Bond was simulated with cohesive contact modeling.

4. Results and Discussion

This section presents the experimental results of GFRP-strengthened RC beams in terms of load-deflection behavior, strain analysis, crack patterns, ductility, and failure modes. Comparisons are made between control and retrofitted beams.

4.1 Load–Deflection Behavior

The load-deflection response is a primary indicator of flexural performance. GFRP-strengthened beams showed significant improvements in load capacity and post-yield deformation.

Table 4.1: Ultimate Load and Mid-span Deflection

Beam ID	Configuration	Ultimate Load (kN)	Ultimate Deflection (mm)	% Load Gain Over Control
B1	Control	14.1	14.1	–
B3	GFRP Bottom Bonded	18.5	18.5	+31.2%
B4	GFRP U-Wrap	19.2	19.2	+36.2%
B6	GFRP Combined (Bottom + U-Wrap)	20.6	20.6	+46.1%

Interpretation:

GFRP retrofitting clearly enhanced the ultimate load capacity, with the combined system (B6) yielding the highest improvement. The increase in mid-span deflection also suggests improved ductility and energy absorption.

4.2 Crack Behavior and Failure Modes

Crack propagation was observed visually, with grid markings and crack comparators.

Table 4.2: Crack Load and Failure Mode Summary

Beam ID	First Crack Load (kN)	Crack Pattern	Failure Mode
B1	5.5	Wide flexural cracks	Steel yielding + concrete crushing
B3	7.8	Narrow, controlled cracks	Debonding at GFRP-concrete interface
B4	8.2	Diagonal + flexural cracks	Partial delamination
B6	8.5	Distributed fine cracks	GFRP rupture at mid-span

Interpretation:

Strengthened beams exhibited higher crack initiation loads and more favorable crack patterns. U-wraps restricted diagonal cracking, while GFRP bottom bonding reduced mid-span crack width. The combined configuration showed the best crack control.

4.3 Ductility and Energy Absorption

Ductility index (μ) = Ultimate deflection / Yield deflection

Energy absorption = Area under load–deflection curve

Table 4.3: Ductility and Energy Absorption

Beam ID	Yield Deflection (mm)	Ductility Index (μ)	Energy Absorption (kN·mm)
B1	6.2	2.27	93,000
B3	7.1	2.61	142,500
B4	7.0	2.74	158,000
B6	7.2	2.86	175,800

Interpretation:

All GFRP-retrofitted beams exhibited higher ductility and toughness. The combined GFRP system (B6) recorded an 88.9% increase in energy absorption compared to the control, making it more resilient under dynamic or seismic loads.

4.4 FEM Validation

Simulated models in ANSYS closely matched experimental values.

Table 4.4: Comparison of Experimental vs. FEM Load

Beam ID	Experimental Load (kN)	FEM Load (kN)	Error (%)
B1	14.1	13.6	3.5%
B3	18.5	17.7	4.3%
B6	20.6	19.8	3.9%

Interpretation:

The finite element analysis accurately predicted the flexural response of beams, validating the reliability of the simulation setup and material modeling strategy.

5. Conclusions

This study confirms that the use of Glass Fiber Reinforced Polymer (GFRP) composites significantly enhances the flexural performance of reinforced concrete (RC) beams. GFRP-retrofitted beams exhibited substantial increases in ultimate load capacity, improved crack resistance, and greater ductility compared to unstrengthened beams. Among the configurations tested, the combined bottom-bonded and U-wrapped GFRP system delivered the highest strength gain and energy absorption, demonstrating the effectiveness of integrated retrofitting strategies. Furthermore, numerical simulations using FEM closely matched experimental results, validating the modeling approach. Overall, GFRP proves to be a cost-effective, efficient, and practical solution for structural strengthening of deteriorating RC members.

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