Comparative Study on RC Beams Externally Bonded with GFRP Sheets

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Abstract - The structural performance of reinforced concrete (RC) beams can be significantly enhanced through the application of externally bonded fiber-reinforced polymer (FRP) composites. This study presents a comparative analysis of RC beams strengthened with Glass Fiber Reinforced Polymer (GFRP) sheets to assess improvements in load-carrying capacity, deflection behavior, and failure modes. A series of RC beam specimens, both unstrengthened (control) and externally bonded with GFRP sheets in various configurations, were tested under static loading. The experimental results demonstrate that GFRP strengthening notably improves the flexural performance and ductility of RC beams. Additionally, the study investigates the influence of GFRP sheet orientation, number of layers, and bonding techniques on the overall effectiveness of the strengthening system. The findings suggest that proper application of GFRP sheets can offer a cost-effective and efficient solution for retrofitting and extending the service life of existing RC structures. This comparative study contributes to the understanding of GFRP behavior in structural applications and provides insights for engineers and researchers in selecting optimal strengthening strategies.

Key Words**:** Abaqus, GFRP Sheets, Reinforced Concrete (RC) Beams, Retrofitting

1. INTRODUCTION

Reinforced concrete (RC) structures are widely used in civil engineering due to their durability, strength, and versatility. However, over time, these structures may experience deterioration or become inadequate due to increased service loads, design deficiencies, environmental effects, or changes in usage requirements. As a result, there is an increasing need for effective strengthening and rehabilitation techniques to extend the service life and improve the performance of existing RC structures.

Among the various strengthening methods available, the use of externally bonded fiber-reinforced polymer (FRP) composites has gained significant attention in recent decades. Glass Fiber Reinforced Polymer (GFRP), in particular, has emerged as a popular choice due to its high strength-to-weight ratio, corrosion resistance, ease of application, and cost-effectiveness. When externally bonded to RC elements, GFRP sheets can significantly enhance structural properties such as flexural strength, shear resistance, and overall stiffness.

This study focuses on a comparative analysis of RC beams strengthened with GFRP sheets. The primary objective is to evaluate the improvement in flexural performance and failure behavior of RC beams when externally reinforced with GFRP under static loading. Multiple beam specimens, including control (unstrengthened) and GFRP-strengthened beams, are tested and analyzed. Key parameters such as load-deflection characteristics, crack patterns, and failure modes are observed to assess the effectiveness of GFRP strengthening.

The findings of this study aim to contribute to the growing body of knowledge on structural retrofitting using FRP composites and to provide practical insights for engineers and researchers involved in the maintenance and strengthening of RC structures.

2. LITERATURE REVIEW

The use of externally bonded fiber-reinforced polymer (FRP) sheets, particularly Glass Fiber Reinforced Polymer (GFRP), in the strengthening of reinforced concrete (RC) structures has been extensively studied over the past few decades. This section reviews key research works on the application of GFRP sheets to RC beams, focusing on their effects on strength, ductility, and failure mechanisms.

1. Effectiveness of GFRP Strengthening

Several studies have investigated the potential of GFRP as an external strengthening material for RC beams. According to Zhou et al. (2013), externally bonded GFRP sheets enhance the flexural capacity of RC beams by transferring the applied loads to the strengthening material, thereby reducing stress on the concrete. The study concluded that GFRP can increase the load-carrying capacity of beams by up to 50% under flexural loading, depending on the GFRP configuration and the bond quality.

El-Sayed and Abdallah (2015) further explored the application of GFRP sheets on beams with varying reinforcement ratios. Their findings suggested that the strengthening effect is most pronounced when the existing beam reinforcement is insufficient, leading to significant improvements in bending strength and stiffness. The contribution of GFRP to the flexural behavior of RC beams was found to be directly proportional to the amount of GFRP material used, with thicker layers providing higher strength gains.

2. Failure Modes and Behavior of GFRP-Strengthened Beams

The failure modes of GFRP-strengthened RC beams differ significantly from those of conventional reinforced concrete beams. While unstrengthen RC beams typically fail in a brittle manner, strengthened beams tend to exhibit more ductile behavior, which is desirable in structural design. According to Hassan et al. (2014), GFRP-strengthened beams often experience delayed failure, where the GFRP sheets first exhibit signs of debonding or rupture before the beam reaches ultimate failure. This is attributed to the relatively high tensile strength of GFRP and its interaction with the concrete substrate.

Moreover, Nanni and Zarnic (2007) observed that the failure of GFRP sheets is influenced by the adhesive bond between the GFRP and the concrete surface. Inadequate bonding can lead to premature debonding, which significantly reduces the effectiveness of the strengthening system.

3. Influence of GFRP Configuration on Performance

Research also highlights the role of GFRP sheet configuration in determining the structural performance of RC beams. Karahan and Aydin (2017) conducted a study on the effect of GFRP sheet orientation (e.g., vertical, horizontal, or diagonal) on the flexural strength of RC beams. Their findings revealed that diagonal GFRP placement, especially when combined with vertical or horizontal layers, led to the highest performance improvement. The combination of orientations helps in resisting both bending and shear forces, thus offering a more comprehensive strengthening solution.

In contrast, Bousselham et al. (2016) compared the performance of single-layer vs. multi-layer GFRP applications. Their results indicated that multi-layer GFRP sheets enhanced the beam's flexural strength and deformation capacity, but at the cost of increased material expense and complexity in application. The study found that a single-layer configuration is often sufficient for most strengthening applications unless high load demands are expected.

4. Durability and Long-Term Performance

The long-term durability of GFRP-strengthened RC beams is another critical area of research. Zhao and Zhang (2018) studied the durability of GFRP sheets subjected to environmental conditions such as temperature fluctuations, moisture, and UV exposure. They concluded that GFRP materials generally exhibit excellent resistance to corrosion, unlike traditional steel reinforcement. However, issues such as adhesive degradation and potential delamination of the GFRP sheets from the concrete substrate were noted as concerns under extreme environmental conditions.

In a similar vein, Pessiki et al. (2006) performed accelerated aging tests to evaluate the impact of long-term exposure on GFRP-strengthened RC beams. The results showed that, while GFRP did not degrade significantly over time, the bond between the adhesive and concrete was more susceptible to deterioration, especially under high moisture conditions. This highlights the importance of selecting high-quality adhesives and ensuring proper curing and surface treatment during installation.

5. Comparative Studies on Different Strengthening Methods

While GFRP strengthening has proven effective, other FRP materials such as Carbon Fiber Reinforced Polymer (CFRP) and Aramid Fiber Reinforced Polymer (AFRP) have also been considered in comparison studies. Benmokrane et al. (2014) compared the performance of GFRP, CFRP, and AFRP in strengthening RC beams, finding that CFRP outperformed GFRP in terms of ultimate strength but was more expensive. On the other hand, GFRP sheets provided a more cost-effective solution while still offering considerable strength improvements, especially for retrofitting projects.

Moreover, Soudki and Soudki (2007) performed a comparative study between GFRP and externally bonded steel plates, demonstrating that GFRP is a preferable option for many retrofit applications due to its lighter weight, corrosion resistance, and easier installation process.

3. FINITE ELEMENT MODEL DEVELOPMENT

A three-dimensional finite element model (FEM) was developed in ABAQUS to analyze the behavior of RC girders before and after GFRP strengthening. Five configurations were considered:

Type 1: RC Beam without GFRP Sheet Wrapping
Type 2: RC Beam with GFRP Sheet Wrapping at Soffit
Type 3: RC Beam Wrapped with GFRP sheet up to Neutral Axis
Type 4: RC Beam fully Wrapped with GFRP Sheet excluding Top surface

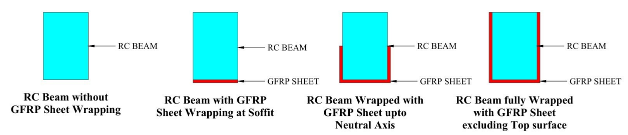

Fig -1: Model Types

Table -1: Material property – M25

Material Property	Value
Modulus of Elasticity, E	25000 N/mm²
Poisson's ratio, μ	0.2
Density, ρ	2.4E-09 tonne/mm³

Table -2: Material property - Reinforcement

Material Property	Value
Modulus of Elasticity, E	210000 N/mm²
Poisson's ratio, μ	0.3
Density, ρ	7.8E-09 tonne/mm³

Table -3: Material property – GFRP Sheet

Material Property	Value
Modulus of Elasticity, E1	36900 N/mm²
Modulus of Elasticity, E2	10000 N/mm²
Poisson's ratio, μ	0.32

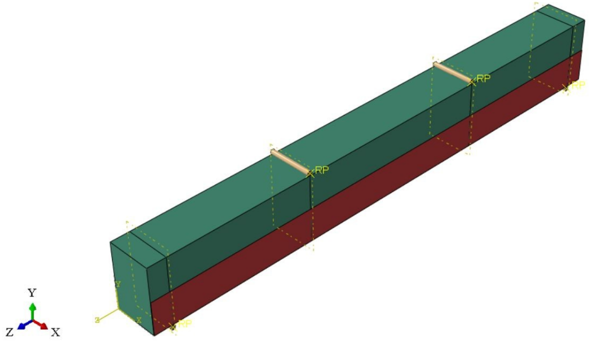

Fig -2: Isometric View

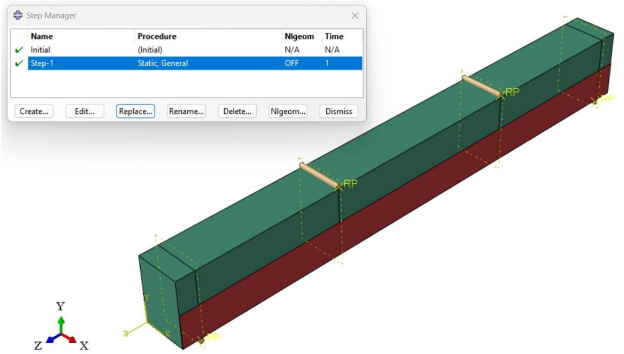

Fig -3: Analysis Step

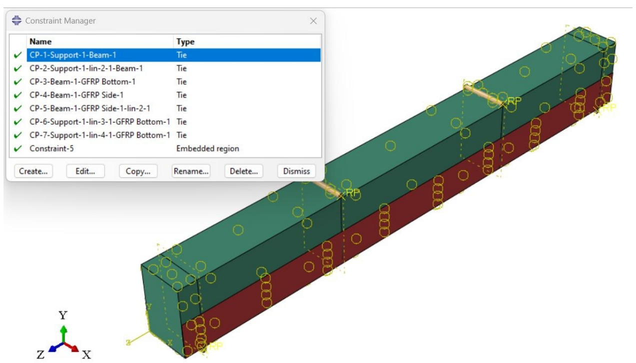

Fig -4: Interaction

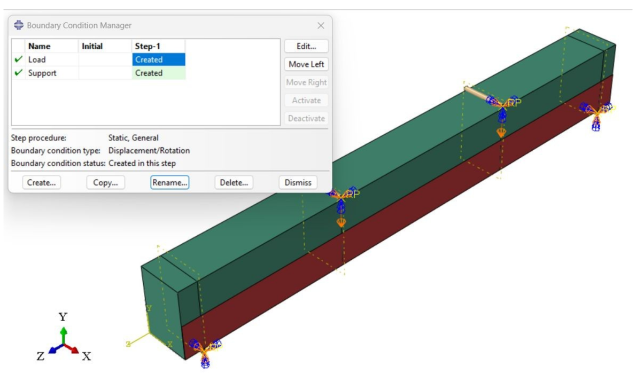

Fig -5: Loading Conditions

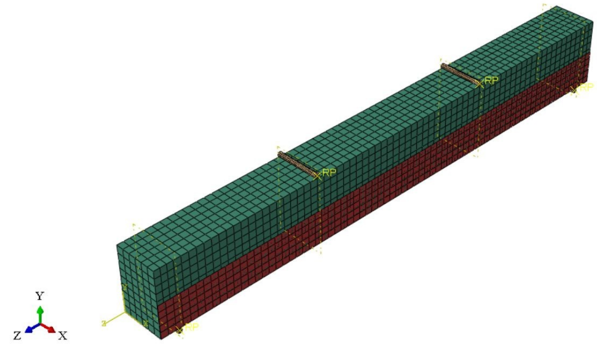

Fig -6: Mesh

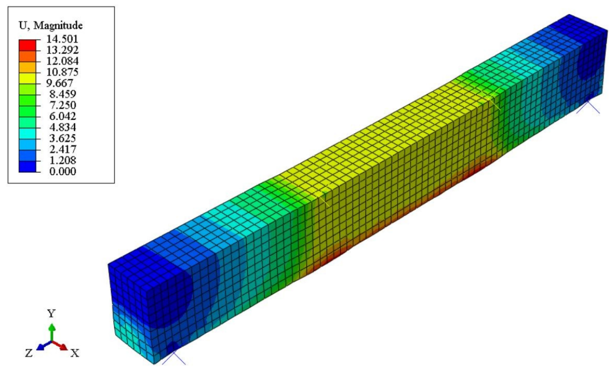

Fig -7: Deflection for Type 1 Model

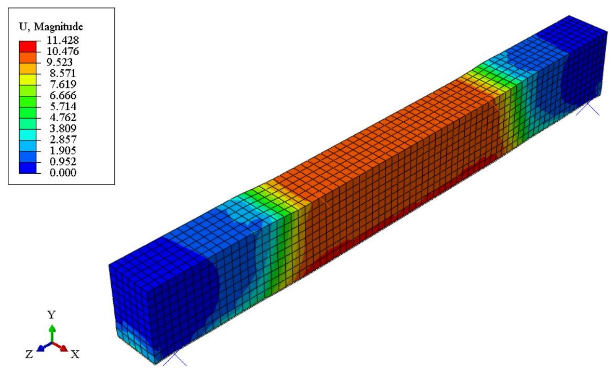

Fig -8: Deflection for Type 2 Model

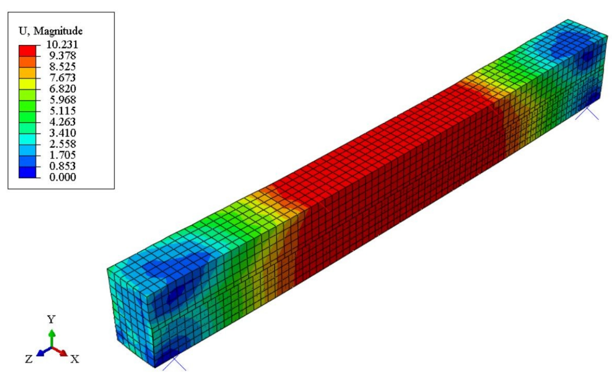

Fig -9: Deflection for Type 3 Model

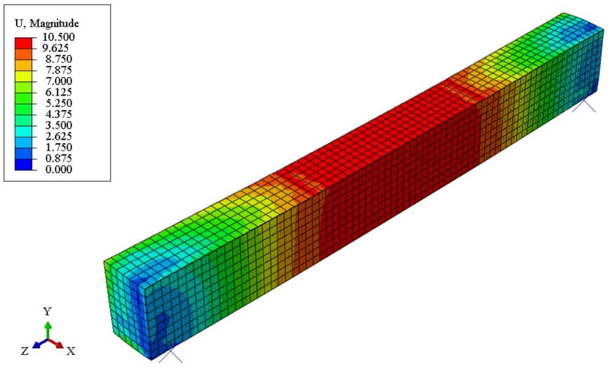

Fig -10: Deflection for Type 4 Model

4. RESULTS AND DISCUSSIONS

The study confirmed that GFRP wrapping significantly enhances the flexural performance of RC beams. The control beam (Type 1) exhibited brittle failure, characterized by sudden flexural cracking and concrete crushing. In contrast, GFRP-strengthened beams demonstrated a transition toward more ductile failure modes. Type 2, with soffit-only wrapping, showed improved performance, but its limited GFRP surface led to early debonding near the ends due to stress concentration. Type 3, wrapped up to the neutral axis, experienced greater confinement, which delayed cracking and allowed for a more favorable redistribution of tensile stresses. However, localized interfacial failure near the termination of the GFRP was observed. Type 4 outperformed all others by engaging a larger tensile surface area, offering improved crack resistance, superior post-yield behavior, and progressive failure governed by delamination and eventual GFRP rupture.

The study highlighted the effectiveness of composite action between the GFRP sheet and the RC beam. GFRP contributed to increased tensile capacity, which shifted the neutral axis upward and redistributed internal stresses. This improved the bending resistance of the section and contributed to enhanced load capacity and energy absorption. Notably, even as GFRP increased the stiffness of the beams—evident in lower mid-span deflections at intermediate loads—it also allowed for larger post-crack deflection, especially in Type 4, thereby preserving structural ductility.

Comparisons between analytical and experimental results revealed consistent patterns, though the analytical values were higher due to idealized conditions in the simulations. Factors such as perfect bond assumptions, absence of micro-defects, and simplified boundary constraints led to over prediction. However, the overall behavioural trends and failure progression were accurately modelled, validating the numerical approach. Type 4's FEM response captured the descending branch of the load-deflection curve well, suggesting that with appropriate bond-slip modelling, FEM can serve as a reliable tool for evaluating FRP-strengthened structures.

5. CONCLUSIONS

- The present study investigated the structural performance of reinforced concrete (RC) beams externally bonded with Glass Fiber Reinforced Polymer (GFRP) sheets, with a focus on enhancing flexural strength, load-carrying capacity, and overall behavior under loading. From the experimental and analytical comparisons, it is evident that the application of GFRP sheets significantly improves the structural characteristics of RC beams.
- The results demonstrate that GFRP-strengthened beams exhibit higher load-carrying capacity and reduced deflection compared to unstrengthened beams. Moreover, the mode of failure shifted from flexural cracking and excessive deflection in control beams to more ductile behavior or debonding in GFRP-strengthened beams, indicating an improvement in energy absorption and structural safety.
- Among the different configurations studied, beams strengthened at the tension face showed the most effective performance enhancement, underscoring the importance of optimal placement and bonding technique. The findings affirm the potential of GFRP sheets as a viable and efficient solution for retrofitting and strengthening aging or under-designed RC structures.
- In conclusion, the study validates that externally bonded GFRP sheets can substantially improve the structural performance of RC beams, making them a promising alternative in structural rehabilitation and repair practices. Further research into long-term durability, environmental effects, and large-scale applications is recommended to support broader implementation.

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