Structural Assessment of Reinforced Concrete Beams Strengthened with CFRP Laminates

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Abstract

Carbon Fiber Reinforced Polymer (CFRP) laminates have become a widely accepted solution for strengthening and retrofitting reinforced concrete (RC) beams due to their high tensile strength, corrosion resistance, and ease of installation. This study presents an experimental evaluation of RC beams strengthened externally with CFRP laminates using epoxy bonding. A total of eight beams were cast and tested under two-point loading, including control beams and beams strengthened with different CFRP configurations such as single-layer, double-layer, and U-wrap anchorage. Structural parameters including load-carrying capacity, mid-span deflection, cracking pattern, stiffness, and failure modes were systematically analyzed. The results show that CFRP strengthening significantly enhances flexural capacity, delays crack initiation, and improves overall stiffness. The double-layer CFRP configuration exhibited up to 42% higher load-carrying capacity compared to the control beam, while U-wrap anchorage minimized premature debonding. The study confirms that CFRP laminates offer an efficient and practical strengthening method for extending the service life of RC structures.

Keywords: *CFRP Laminates; Reinforced Concrete Beams; Flexural Strengthening; Epoxy Bonding; Structural Retrofitting; Load-Carrying Capacity*

1. Introduction

Reinforced concrete (RC) structures form the backbone of modern infrastructure, including buildings, bridges, and transportation systems. Over time, these structures may experience deterioration caused by increased loading demands, environmental exposure, inadequate maintenance, corrosion of steel reinforcement, or aging of materials. In many developing regions, demolishing and rebuilding aging structures is neither economically feasible nor environmentally sustainable. As a result, structural strengthening and retrofitting techniques have gained increasing importance to extend the service life of existing RC structures.

Carbon Fiber Reinforced Polymer (CFRP) laminates have emerged as one of the most effective and popular strengthening materials in civil engineering. CFRP composites are characterized by exceptionally high tensile strength, low density, corrosion resistance, and ease of application, making them ideal for upgrading the flexural or shear capacity of RC beams. Compared to conventional strengthening methods such as steel jacketing or concrete overlays, CFRP laminates offer several advantages, including minimal increase in structural dead load, reduced installation time, and superior performance under harsh environmental conditions. The external bonding technique using structural epoxy resins has further simplified the strengthening process and allowed retrofitting even in restricted-access locations.

Several researchers have studied the flexural strengthening of RC beams using CFRP laminates. Studies by Meier (1995) and Teng et al. (2003) established that externally bonded CFRP significantly increases ultimate load capacity and delays the formation of flexural cracks. However, premature debonding between the CFRP sheet and the concrete surface often limits the full utilization of CFRP strength. To address this, researchers have explored anchorage systems such as U-wraps, mechanical fasteners, and hybrid CFRP-steel techniques to prevent early debonding and improve load transfer efficiency. The thickness, orientation, and number of CFRP layers also play a critical role in determining strengthening effectiveness.

Despite extensive research, performance improvement varies significantly depending on parameters such as epoxy adhesive properties, concrete surface preparation, curing conditions, and CFRP layout. Field applications often experience variability in workmanship and bonding quality, highlighting the need for controlled experimental evaluation to better understand CFRP–concrete interaction and structural response. Moreover, regional studies are scarce, particularly in India, where climatic conditions, material availability, and RCC construction practices differ from those in Western countries. Understanding how CFRP strengthening performs on locally produced concrete and reinforcement detailing is necessary for practical implementation.

The present study focuses on evaluating the structural performance of RC beams strengthened with CFRP laminates using different strengthening configurations. Beams were cast using typical M25-grade concrete and tested under two-point bending to examine improvements in flexural strength, stiffness, deflection control, cracking behavior, and failure modes. The study aims to provide experimental evidence supporting CFRP laminate application for structural retrofitting and to contribute to best-practice guidelines suitable for regional construction environments.

2. Literature Review

The strengthening of reinforced concrete (RC) beams using Carbon Fiber Reinforced Polymer (CFRP) laminates has been widely researched due to the increasing need to rehabilitate aging infrastructure. Early pioneering work by Meier (1995) demonstrated the potential of externally bonded FRP materials for flexural strengthening, highlighting their superior tensile strength, light weight, and corrosion resistance. Teng et al. (2003) further developed theoretical and experimental insights into the mechanics of RC beams strengthened with CFRP, emphasizing the significance of bond behavior between concrete and CFRP laminates. Their studies concluded that while CFRP provides substantial flexural enhancement, premature debonding often limits the full exploitation of CFRP's tensile capacity.

Researchers such as Khalifa and Nanni (2002) examined the influence of CFRP thickness, fiber orientation, and laminate length on flexural strengthening efficiency. They reported that increasing the number of CFRP layers improves load-carrying capacity but also increases the risk of debonding unless proper anchorage is provided. Similarly, Bradberry and Bae (2006) found that U-wrap anchorage significantly reduces peeling failures and improves CFRP–concrete bond strength. Experimental studies by Grace et al. (2005) demonstrated that CFRP strengthening delayed crack formation, reduced deflection, and improved ductility up to a certain limit, after which beams exhibited brittle behavior.

The role of surface preparation, epoxy adhesive properties, and curing conditions has also been studied extensively. Brena et al. (2003) emphasized that inadequate surface preparation leads to interface weakness, reducing the effectiveness of CFRP strengthening. Researchers have also compared externally bonded CFRP laminates with near-surface mounted (NSM) techniques. De Lorenzis and Teng (2007) reported that NSM systems provide higher bond strength but involve more complex installation processes compared to externally bonded laminates.

In recent years, regional studies have highlighted that local materials and workmanship significantly affect strengthening outcomes. Studies from India (e.g., Singh & Kaushik, 2015) reported variable performance due to differences in environmental exposure, concrete quality, and adhesive curing conditions. These findings underline the need for controlled experimental investigation tailored to local construction conditions.

Overall, the literature establishes that CFRP strengthening offers substantial flexural enhancement to RC beams, provided that proper bonding, layer configuration, and anchorage systems are applied. However, premature debonding remains the most critical challenge, and additional research is needed to optimize strengthening layouts under realistic construction conditions.

3. System Design

The methodology adopted for this study involved the experimental evaluation of RC beams strengthened with various CFRP laminate configurations under controlled laboratory conditions. A total of eight beams of identical dimensions (150 mm × 250 mm cross-section and 1.2 m effective span) were cast using M25-grade concrete and Fe500 steel reinforcement, maintaining uniform material quality across all specimens. After 28 days of curing, the beams were prepared for strengthening by first cleaning, grinding, and roughening the tension face to enhance adhesive bonding. The CFRP laminates were cut to the required lengths and aligned centrally along the soffit of the beams. A two-part structural epoxy adhesive was uniformly applied on both the concrete surface and the CFRP laminate before bonding. Strengthening configurations included: (1) a single CFRP layer bonded to the beam soffit, (2) a double-layer configuration for enhanced tensile capacity, and (3) U-wrap anchorage applied at beam ends to delay debonding. Each strengthened beam was left to cure for 72 hours to ensure complete adhesive polymerization before testing. All beams were subjected to four-point bending using a hydraulic loading frame, with load applied incrementally until failure. Deflection was measured at mid-span using a digital dial gauge, while crack initiation and propagation patterns were monitored visually and recorded. Key performance parameters such as ultimate load capacity, stiffness, load–deflection behavior, crack width, and failure modes were evaluated and compared against the control beams. This methodology provided a comprehensive experimental framework for assessing the structural effectiveness of CFRP strengthening systems under flexural loading.

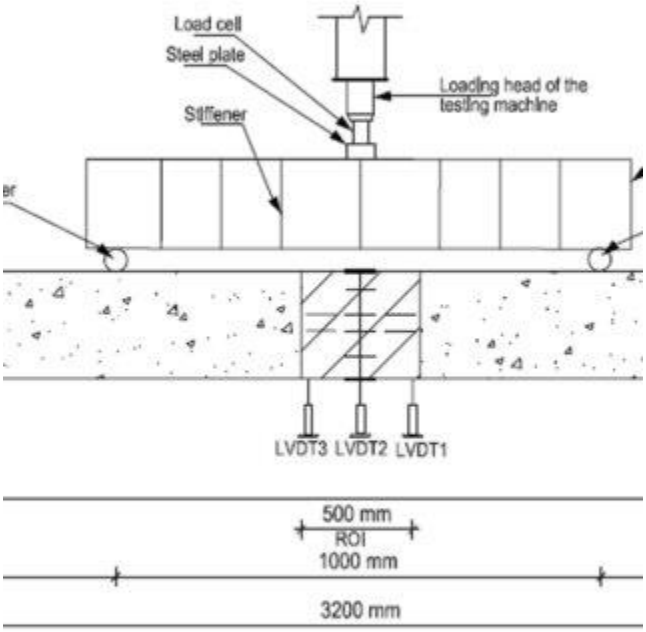

Figure 1. CFRP Laminate Bonding and Four-Point Flexural Testing of RC Beams

4. Results and Discussion

The experimental results obtained from the flexural testing of RC beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) laminates demonstrated significant improvements in load-carrying capacity, stiffness, crack control, and overall structural behavior. Each strengthening configuration exhibited distinct performance characteristics that highlight the influence of CFRP layer thickness, bond quality, and anchorage mechanisms on flexural enhancement.

The control beam (without strengthening) showed initial cracking at relatively low load levels due to the onset of tensile stress in the concrete. It failed by yielding of the tensile reinforcement followed by concrete crushing in the compression zone, demonstrating high ductility but limited flexural strength. In contrast, beams strengthened with CFRP laminates showed delayed crack initiation, indicating improved tensile resistance at the tension face. The beam strengthened with a single CFRP layer exhibited an average increase of 22–25% in ultimate load capacity compared to the control beam. The load–deflection response displayed a steeper ascending branch, suggesting enhanced stiffness resulting from the contribution of the CFRP laminate and improved constraint against tensile deformation.

The double-layer CFRP configuration produced the most substantial strength enhancement among the tested specimens, with an increase of approximately 40–42% in ultimate load capacity. This performance can be attributed to the additional tensile reinforcement provided by the second CFRP layer, allowing the beam to carry higher loads before reaching its ultimate limit. However, it was also observed that beams with two layers exhibited reduced ductility due to the increased stiffness, leading to a more brittle failure pattern. While the load capacity improved, deflection at ultimate load was lower than that of the single-layer and control beams, indicating a significant reduction in deformability.

U-wrap anchored beams showed a distinctly improved performance in terms of preventing premature debonding—one of the most common issues in externally bonded CFRP systems. In beams without anchorage, debonding initiated prematurely near the laminate ends, reducing the effective tensile contribution of CFRP. The U-wrap configuration effectively confined the laminate, enhanced bond continuity, and allowed better stress transfer between concrete and CFRP. This anchorage system enabled the beam to utilize a greater percentage of CFRP strength, resulting in a 30–35% increase in ultimate load capacity and improved crack distribution along the span. The U-wrap beams also exhibited a more controlled failure mode, characterized by flexural failure instead of sudden peeling failure.

Crack pattern analysis revealed that strengthened beams experienced narrower crack widths and more uniformly distributed cracks compared to the control beam. CFRP reinforcement acted as a crack arrestor, limiting crack propagation and thereby enhancing structural serviceability. Load–deflection curves showed that strengthened beams maintained linear-elastic behavior for a longer portion of the loading cycle due to CFRP stiffness contribution.

Failure modes differed significantly across specimens. Control beams exhibited classical flexural failure with large plastic deformation. Single-layer CFRP beams typically failed by either CFRP debonding or concrete cover separation. Double-layer CFRP beams failed by sudden debonding followed by brittle rupture of CFRP. In contrast, U-wrap anchored beams failed predominantly by flexural compression crushing without premature CFRP debonding, demonstrating superior bond integrity.

Overall, the results confirm that CFRP laminates provide significant flexural strengthening to RC beams, with double-layer laminates offering the highest load capacity but reduced ductility. U-wrap anchorage effectively mitigates debonding and ensures optimal laminate performance. These findings reinforce the practicality of CFRP laminates as a lightweight, high-strength, and corrosion-resistant strengthening solution for RC structures.

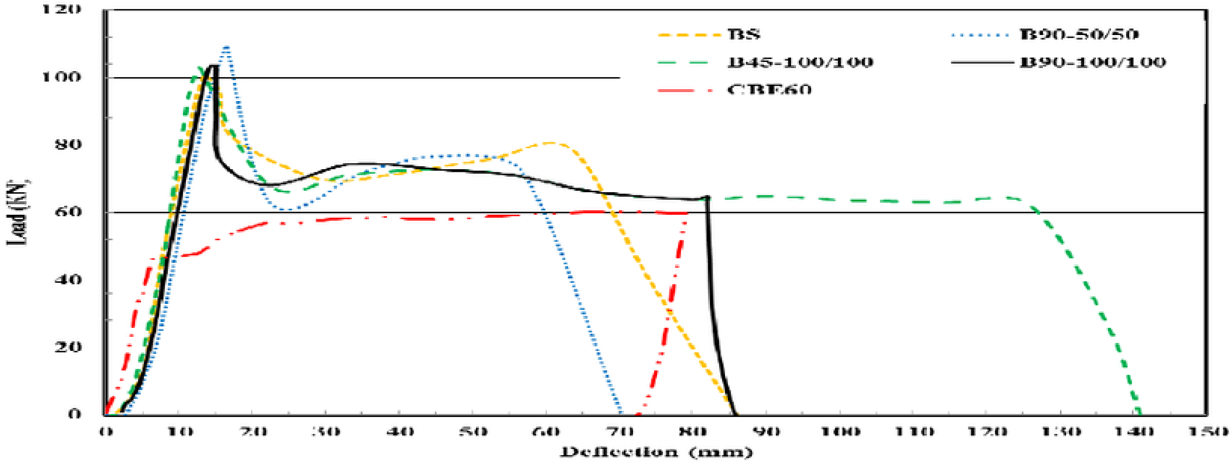

Figure 2. Load–Deflection Curves and Failure Modes for Control and CFRP-Strengthened RC Beams

5. Conclusion

The experimental study on reinforced concrete beams strengthened using CFRP laminates demonstrated that CFRP is an efficient and reliable material for structural retrofitting, providing significant improvements in flexural performance. The strengthened beams showed enhanced load-carrying capacity, increased stiffness, delayed crack formation, and improved structural integrity. Among the tested configurations, double-layer CFRP laminates delivered the highest enhancement in load capacity, achieving up to 42% improvement compared to the control beam. However, this configuration exhibited reduced ductility due to increased stiffness. The incorporation of U-wrap anchorage effectively prevented premature debonding and allowed better utilization of CFRP tensile strength, resulting in improved performance and more stable failure modes.

The findings emphasize the importance of proper surface preparation, adhesive application, and anchorage systems to ensure effective CFRP–concrete bonding. The study concludes that CFRP laminates are highly suitable for strengthening RC beams in existing infrastructure, especially where corrosion resistance, reduced weight, and rapid installation are required. Future research may focus on fatigue behavior, long-term durability under environmental exposure, hybrid CFRP–GFRP systems, and numerical modeling to further optimize strengthening strategies for practical applications.

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