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Strengthening Reinforced Concrete Beams Using Fiber Reinforced Polymer (FRP) Laminates

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Abstract: The need for the rehabilitation and strengthening of aging reinforced concrete (RC) structures is increasing due to deteriorating infrastructure and higher load demands. Fiber-Reinforced Polymer (FRP) composites have emerged as a viable solution for enhancing the structural performance of RC beams.Through a review of experimental data and case studies, this paper will demonstrate that FRP strengthening is an effective, durable, and sustainable solution for enhancing RC structures. The findings provide valuable insights for civil engineers in the design and maintenance of more resilient and sustainable infrastructure.In conclusion, FRP laminates offer a promising and innovative approach to strengthening RC beams, combining efficiency, durability, and sustainability. By addressing the existing research gaps and refining application techniques, FRP technology can significantly contribute to the development of safer and more resilient infrastructure worldwide. Future research should focus on bridging these gaps to unlock the full potential of FRP in civil engineering applications.

Keywords: strengthening, reinforced, concrete, Fiber-Reinforced Polymer (FRP), RC beams, failure modes, durability, debonding

1. INTRODUCTION

Reinforced concrete (RC) beams are fundamental components in modern construction, providing essential structural support in buildings, bridges, and other infrastructure. However, over time, these beams can experience degradation due to factors such as increased load demands, environmental conditions, and material aging. To address these challenges and extend the service life of RC structures, the use of Fiber Reinforced Polymer (FRP) laminates has emerged as a highly effective strengthening technique.

FRP laminates, composed of high-strength fibers embedded in a polymer matrix, offer several advantages over traditional strengthening methods. These include high strength-to-weight ratios, resistance to corrosion, and ease of application. The application of FRP laminates to RC beams can significantly enhance their load-carrying capacity, stiffness, and overall durability. This technique involves externally bonding FRP sheets or strips to the tension face of the beams, thereby improving their flexural performance.

Numerous studies have demonstrated the efficacy of FRP laminates in strengthening RC beams. Research has shown that the use of FRP can lead to substantial increases in the ultimate load capacity and ductility of the beams. Additionally, the versatility of FRP materials allows for tailored solutions to meet specific structural requirements, making them suitable for a wide range of applications.

2. LITERATUTE REVIEW

Baiet al. (2024) presented experimental study of the flexural performance of reinforced concrete (RC) beams externally bonded with hybrid fiber-reinforced polymer (FRP) laminates made of carbon and polyethylene terephthalate (PET) fibers. Ten beam specimens were subjected to four-point bending tests, with a focus on assessing the effects of the stacking sequence and the elastic modulus of hybrid carbon-PET FRP laminates on the flexural performance of the strengthened beams. The failure modes, load-bearing capacities, displacement ductility of the specimens and strain distributions in the FRP laminates were examined and discussed.

Assad et al. (2024) presented investigate the flexural behavior of externally strengthened RC beams with CFRP laminates and anchored at end with CFRP spike anchors. The results of anchored beams was compared with unanchored specimens in terms of load-deflection response, strain in the FRP laminates, and failure modes. Results showed that anchorage of CFRP laminates with CFRP splay anchors positively affected the flexural capacity of the specimens. An average increase in the load-carrying capacity of 19 % was portrayed in the anchored specimens compared to the unanchored specimen. Anchorage of FRP laminates resulted in the mitigation of debonding failure and thus, enhanced strain utilization in laminates

Makhloufet al. (2024) presented create composite sheets made of local natural fibers (jute fiber), which are cheap, environmentally friendly, and sustainable, and a new local epoxy resin (NOVO BOND EB) with high strength, especially in bonding to concrete, and low cost for use in shear strengthening of R.C. structures. In the experimental programme, the sheets were made from jute fiber-reinforced polymer (JFRP). Three samples of JFRP were tested to determine the mechanical properties of this material. Twelve RC specimens of beams were prepared to study the effect of the variables of laminate manufactured from the JFRP, namely: number of layers (1-2–4), “wrapping configuration (strips – full length sheet) wrapping”, angle of strengthening (90°–45°), and shape (U–U with top cap–box).

Mussaet al. (2024) presented investigate the behaviour of reinforced concrete (RC) beams strengthened by Carbon Fibre-Reinforced Polymer (CFRP) under static and impact loads. A series of RC beams were tested and categorized into four groups, namely, unstrengthened RC beams (B1), RC beams strengthened with a CFRP longitudinal strip in the tension zone (B2), RC beams wrapped with CFRP fabric (B3), and RC beams strengthened with a combination of both CFRP longitudinal strips and wraps (B4). The results show that the average load–displacement capacity of RC beam group (B4) was improved by 84.88% as compared with the unstrengthened beam (B1) under static loads. The dynamic test results demonstrated an increase in the deflection resistance of RC beam group (B4) by −57.89% as compared with unstrengthened RC beam group (B1) under identical drop weights of 1 m. In addition, a collapse failure mode was noticed in the unstrengthened beams, while minor damage was recorded mainly in the case of RC beam group (B4). Furthermore, the numerical analysis conducted using LS-DYNA software (V 971 R6.0.0) proved that the adopted numerical models can efficiently predict the behaviour of RC beams under dynamic loads, with maximum differences reaching up to −12.5% compared with the experimental test results.

Shi et al. (2024) presented the effect of incorporating multi-wall carbon nanotubes (MWCNTs) in epoxy resin on the flexural behavior of reinforced concrete (RC) beams strengthened with basalt fiber-reinforced polymer (BFRP) sheets through four-point bending beam tests. Experimental results indicated that the flexural behavior was significantly improved by the MWCNT-modified epoxy. The BFRP sheets bonded by the MWCNT-modified epoxy more effectively mitigated the debonding failure of BFRP sheets and constrained crack development as well as enhanced the ductility and flexural stiffness of strengthened beams. When the beam was reinforced with two-layer BFRP sheets, the yielding load, ultimate load, ultimate deflection, post-yielded flexural stiffness, energy absorption capacity and deflection ductility of beams strengthened using MWCNT-modified epoxy increased by 7.4%, 8.3%, 18.2%, 22.6%, 29.1% and 14.3%, respectively, in comparison to the beam strengthened using pure epoxy. It could be seen in scanning electron microscopy (SEM) images that the MWCNTs could penetrate into concrete and their pull-out and crack bridging consumed more energy, which remarkably enhanced the flexural behavior of the strengthened beams. Finally, an analytical model was proposed for calculating characteristic loads and characteristic deflections of RC beams strengthened with FRP sheets, which indicated a reasonably good correlation with the experimental results.

Pour et al. (2024) presented the efficiency of different strengthening techniques to advance the flexural characteristics of reinforced concrete (RC) beams using glass fiber-reinforced polymer (GFRP) laminates, including externally bonded reinforcement (EBR), externally bonded reinforcement on grooves (EBROG), externally bonded reinforcement in grooves (EBRIG), and the near-surface mounted (NSM) system. A new NSM technique was also established using an anchorage rebar. Then, the effect of the NSM method with and without externally strengthening GFRP laminates was studied. Twelve RC beams (150 × 200 × 1500 mm) were manufactured and examined under a bending system. One specimen was designated as the control with no GFRP laminate.

Khan et al. (2024) presented data-driven estimation models, an extensive collection of experimental data on FRP-strengthened RC beams was compiled from the experimental studies. For the assessment of the accuracy of developed models, various statistical indicators were utilized. The machine learning (ML) based models were compared with empirical and conventional linear regression models to substantiate their superiority, providing evidence of enhanced performance. The GEP model demonstrated outstanding predictive performance with a correlation coefficient (R) of 0.98 for both the training and validation phases, accompanied by minimal mean absolute errors (MAE) of 4.08 and 5.39, respectively.

Zhang et al. (2024) presented a novel method of laying a composite layer of fiber reinforced polymer (FRP) grid reinforced with engineering cementitious composite (ECC), designated as FGRE, and applied at the soffit of reinforced concrete (RC) beams to improve its flexural performance. Experimental studies were conducted on RC beams with different strengthening configurations to validate the effectiveness of the proposed strengthening method. In addition, analysis on the working mechanism and a parametric analysis were performed for the composite strengthened beam using nonlinear finite element modeling.

Gaberet al. (2024) presented experimental investigation on the improvement of the torsional resistance of reinforced concrete beams using fiber-reinforced polymer (FRP) fabric. The experimental program outlines a comprehensive analysis of the combined effects of shear and torsion on the torsional strengthening of four rectangular reinforced concrete beams with externally bonded glass fiber-reinforced polymer (GFRP) sheets.

Iyappanet al. (2024) presented the performance of Reinforced Concrete (RC) beams enhanced in shear using basalt fiber and glass fiber. After curing the beams were wrapped with fibers other than the conventional. All the 12 beams were tested under the same loading condition with the four-point loading. The shear deficient RC beams do not have required shear reinforcement and hence they fail by shear first. FRP strengthening in the shear zones can increase the shear strength of the beams and hence these strengthened beams fail in flexure first or sometimes as flexure-shear failure.

3. RESEARCH GAP

1. **Limited Long-Term Performance Data:** Although many studies focus on the short-term benefits of FRP strengthening, such as improved load capacity and stiffness, there is insufficient data on the long-term durability of FRP in various environmental conditions, particularly in aggressive environments like high humidity or chemical exposure.
2. **Inconsistent Bonding Techniques:** Research on the effectiveness of different bonding techniques and the impact of surface preparation on bond strength between FRP and concrete remains fragmented. More studies are needed to develop standardized bonding methods to ensure reliable performance across different applications.
3. **Comprehensive Failure Mode Analysis:** Existing research tends to focus primarily on flexural strengthening, but the understanding of failure modes (e.g., debonding, shear failure) in FRP-strengthened beams, especially under complex load conditions, requires further investigation.
4. **Limited Comparative Studies on FRP Types:** There is a lack of comparative studies evaluating different types of FRP materials (e.g., carbon, glass, aramid) under the same experimental conditions. This limits the ability to provide definitive recommendations for selecting the most appropriate FRP material for specific applications.
5. **Numerical Modeling Validation:** While some studies have explored numerical modeling of FRP-strengthened RC beams, more work is needed to validate these models with experimental data, particularly in predicting long-term performance and failure mechanisms.

Addressing these gaps would help advance the understanding of FRP-strengthened RC beams and improve the reliability and efficiency of FRP applications in structural rehabilitation.

4. CONCLUSION

The application of Fiber Reinforced Polymer (FRP) laminates for strengthening reinforced concrete (RC) beams has emerged as an effective solution to address the challenges of aging infrastructure and increasing load demands. This review has highlighted the significant advancements in the field, showcasing the potential of FRP materials such as carbon, glass, and aramid fibers to enhance the structural performance of RC beams. Key benefits include improved flexural and shear capacity, increased stiffness and ductility, and resistance to environmental degradation, making FRP a versatile and sustainable material for structural rehabilitation.

However, the review also identifies several areas requiring further investigation. The long-term durability of FRP under varying environmental conditions, optimization of bonding techniques, and comprehensive understanding of failure mechanisms are critical for ensuring the reliability of FRP applications. Additionally, comparative studies on different FRP types and advanced numerical modeling validated by experimental data are needed to standardize design practices and improve predictive capabilities.

In conclusion, FRP laminates offer a promising and innovative approach to strengthening RC beams, combining efficiency, durability, and sustainability. By addressing the existing research gaps and refining application techniques, FRP technology can significantly contribute to the development of safer and more resilient infrastructure worldwide. Future research should focus on bridging these gaps to unlock the full potential of FRP in civil engineering applications.

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