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Advanced FRP-Based Strengthening of Reinforced Concrete Structural Members: A Comprehensive Research

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ABSTRACT

This study focuses on the strengthening of reinforced concrete beams and columns using Fiber Reinforced Polymer (FRP) composites. FRP materials are widely used in structural rehabilitation due to their high tensile strength, light weight, corrosion resistance, and easy application. The study shows that FRP bonding and wrapping significantly improve flexural strength, shear resistance, axial load capacity, ductility, stiffness, and energy absorption of reinforced concrete members. FRP strengthening also helps in reducing crack propagation and delaying structural failure. Therefore, FRP composites provide an economical, durable, and sustainable solution for repairing and upgrading damaged or weak concrete structures.

Keywords: *FRP Composites, Reinforced Concrete, Structural Strengthening, Retrofitting.*

I. INTRODUCTION

Strengthening reinforced concrete structures such as columns and beams with Fiber Reinforced Polymer (FRP) composites has become one of the most effective and widely accepted techniques in modern structural rehabilitation. Reinforced concrete structures are designed to carry different types of loads during their service life, but with time they may become weak due to aging, corrosion of steel reinforcement, poor construction quality, excessive loading, environmental exposure, earthquake damage, fire damage, design deficiencies, or changes in functional requirements. In many cases, demolishing and reconstructing the entire structure is neither economical nor sustainable. Therefore, retrofitting and strengthening methods are preferred to restore or improve the load-carrying capacity of existing structures. FRP composites offer an advanced solution because they possess high tensile strength, low self-weight, corrosion resistance, ease of installation, and excellent durability. These composites are generally made by combining strong fibers such as carbon, glass, aramid, or basalt with a polymer resin matrix. Among these, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) are commonly used for structural strengthening applications. The fibers provide strength and stiffness, while the resin binds the fibers together and transfers stresses between the concrete surface and the FRP sheet or laminate. The use of FRP composites is especially beneficial in situations where traditional strengthening methods such as steel plate bonding, concrete jacketing, or section enlargement may increase the dead load, reduce usable space, require heavy equipment, or create corrosion-related maintenance problems. In contrast, FRP systems can be externally bonded to the surface of beams and columns with minimum disturbance to the existing structure. This makes them highly suitable for strengthening bridges, buildings, parking structures, industrial facilities, marine structures, and earthquake-damaged components. In the context of beams and columns, FRP composites improve the structural behaviour by enhancing flexural strength, shear resistance, confinement capacity, ductility, stiffness, and energy absorption. Their application has changed the approach to structural repair because they provide a lightweight yet powerful method for extending the service life of reinforced concrete members.

In reinforced concrete beams, FRP composites are mainly used to improve flexural and shear performance. Beams are important load-bearing elements that transfer loads from slabs to columns and then to the foundation. When beams are subjected to bending, tensile stresses develop at the bottom face, and if the applied load exceeds the capacity of the member, flexural cracks may appear. Over time, these cracks may widen due to repeated loading, corrosion of reinforcement, poor concrete quality, or increased service demand. Externally bonded FRP sheets, plates, or laminates can be applied to the tension zone of the beam to resist tensile forces and increase its bending capacity. When FRP is bonded along the soffit of a beam, it acts as an additional tensile reinforcement and helps in delaying crack formation and reducing deflection. For shear strengthening, FRP strips or sheets are usually applied on the sides of the beam in the form of U-wraps, side bonding, or complete wrapping wherever possible. Shear failure is generally sudden and brittle, so the use of FRP for shear strengthening is very significant in improving structural safety. The direction of the fibers also plays an important role in strengthening performance. Fibers placed parallel to the beam span are effective for flexural strengthening, while fibers placed vertically or diagonally are more effective for shear strengthening. However, the performance of FRP-strengthened beams depends on several factors, including surface preparation, bond quality, adhesive properties, number of FRP layers, anchorage system, fiber orientation, concrete strength, and environmental conditions. One of the major concerns in FRP-strengthened beams is premature debonding, where the FRP separates from the concrete surface before reaching its full tensile capacity. Therefore, proper design and installation are essential to ensure effective stress transfer between concrete and FRP. Compared with conventional steel plate strengthening, FRP does not suffer from corrosion and requires less maintenance. Its lightweight nature also makes installation easier and faster, especially in difficult site conditions. Thus, FRP strengthening of beams provides an efficient method for improving the performance of deficient or damaged members while maintaining the original geometry and functionality of the structure.

In reinforced concrete columns, FRP composites are commonly used for confinement and axial load enhancement. Columns are vertical structural members that carry compressive loads from beams and slabs and transfer them safely to the foundation. Failure of a column can be more dangerous than failure of a beam because it may lead to partial or progressive collapse of the entire structure. Many existing columns may lack adequate strength and ductility due to old design standards, insufficient transverse reinforcement, poor detailing, corrosion, earthquake damage, or increased loading caused by building modification. FRP wrapping is an effective technique for strengthening such columns. In this method, FRP sheets are wrapped around the column in one or more layers to form a confining jacket. When the column is loaded in compression, the concrete tends to expand laterally. The FRP jacket resists this lateral expansion and provides confinement to the concrete core. This confinement increases the compressive strength, ultimate strain, ductility, and energy absorption capacity of the column. FRP confinement is especially useful for seismic strengthening because earthquake-resistant structures require not only strength but also ductility and deformation capacity. Circular columns generally benefit more from FRP confinement because the confining pressure is uniformly distributed around the section. For square or rectangular columns, the effectiveness may be reduced due to stress concentration at corners; therefore, corner rounding and proper surface preparation are required before wrapping. FRP jacketing also protects columns from environmental deterioration, moisture ingress, and corrosion-related damage. In addition to columns, FRP can be applied to beam-column joints, bridge piers, and other critical regions where improved ductility and shear resistance are required. Despite its many advantages, FRP strengthening must be designed carefully because FRP materials behave linearly elastic up to failure and do not yield like steel. This means that failure can be sudden if the system is not properly detailed. Fire resistance, ultraviolet exposure, temperature effects, moisture, and long-term durability should also be considered during design and execution. Overall, the strengthening of reinforced concrete beams and columns using FRP composites represents a sustainable, economical, and technically advanced solution for improving structural performance. It reduces the need for demolition, saves construction time, minimizes additional dead load, and enhances the safety and serviceability of existing infrastructure. As the demand for durable and resilient structures continues to increase, FRP composite strengthening is expected to play an increasingly important role in the rehabilitation and upgrading of reinforced concrete structures.

II. RESEARCH BACKGROUND

Yadav et al. (2026) had presented an experimental investigation on the seismic performance of fiber reinforced polymer (FRP) warp-confined FRP reinforced concrete (FCFRC) columns. The study had involved six specimens, of which four had been confined with GFRP sheets at the plastic hinge regions, while two had been kept unconfined for comparison. All specimens had been subjected to constant axial loading combined with cyclic lateral displacement loading. The research had primarily aimed to examine the influence of hoop spacing and the number of GFRP confinement layers applied in the plastic hinge zone on seismic behavior. The confinement effectiveness of FRP hoops and wraps had been assessed through failure modes, hysteresis response, skeleton curves, residual drift ratio, and energy dissipation capacity. The findings had indicated that GFRP wrapping in the plastic hinge regions had significantly enhanced seismic performance by increasing load-bearing capacity by 52.9%, improving energy dissipation by 3.6 times, reducing stiffness degradation, and lowering residual drift ratio by up to 75%. Reduced hoop spacing had also been reported to further improve the seismic resistance of the columns.

Rahmatian et al. (2026) examined the fatigue and flexural performance of fiber-reinforced polymer (FRP)-reinforced concrete beams, with particular emphasis on glass-FRP (GFRP)-reinforced beams exposed to harsh environmental conditions. The study investigated 12 GFRP-reinforced concrete beams subjected to four environmental regimes, namely indoor control, continuous alkaline immersion, cyclic wet–dry alkaline immersion, and outdoor exposure in Montreal. It was reported that four pre-cracked beams were exposed to up to one million load cycles, while deflection and crack mouth opening displacement (CMOD) were continuously monitored. The structural response was assessed through flexural capacity, load–deflection behavior, crack development, stiffness degradation, and serviceability limit state performance before and after fatigue loading. The findings indicated that wet–dry and immersion-conditioned beams exhibited the greatest deflections, whereas outdoor and control beams retained stable load-carrying capacity with limited fatigue damage. The authors further observed that flexural toughness indices varied considerably across specimens, reflecting environmental effects on energy absorption. Overall, the study concluded that GFRP-RC beams maintained strong residual strength and exhibited predictable degradation under combined cyclic and environmental exposure.

Tran et al. (2026) reported that fiber-reinforced polymer (FRP) bars had been increasingly adopted as substitutes for steel reinforcement in concrete beams due to their superior chemical resistance, light weight, and high tensile strength. In their study, a computational framework had been developed by integrating a branch of the discrete element method (DEM), specifically the rigid body spring network, with subset simulation to model the structural behavior of FRP-reinforced concrete beams. The authors had also evaluated the reliability indices and resistance reduction factors of beams designed according to ACI 440.1R-15 and through nonlinear analysis. Material constitutive laws and uncertainties associated with multiple random variables had been incorporated into the numerical model. After validation against experimental findings and ACI 440.1R-15 predictions, the proposed method was found to represent load-carrying capacity, crack development, and failure modes effectively, with a mean of 1.037 and CoV of 0.052. Furthermore, resistance reduction factors of 0.68 and 0.75 were suggested for target reliability indices of 4.0 and 3.5, respectively.

Liao et al. (2025) investigated the use of transversely continuous basalt FRP (BFRP) grids as shear reinforcement and self-compacting seawater sea-sand concrete to address limitations of conventional FRP stirrups. Eight beam specimens with shear span-to-depth ratios (λ) from 1.5 to 2.5 were tested under four-point bending to examine shear performance, particularly arch action. The study analyzed the influence of BFRP grid layers and beam heights through observations of failure modes, crack patterns, load-deflection responses, and load-strain relationships. It was reported that all specimens experienced shear-compression failure, while the presence of BFRP grids or reduced λ ratios delayed critical diagonal crack propagation and failure. Mid-span load-deflection responses exhibited bi-linear ascending behavior, with BFRP grids, lower λ ratios, and increased beam heights enhancing the second ascending segment slope; λ reduction showed the most pronounced effect by shifting the resisting mechanism from beam action to arch action. Size effects were observed after initial diagonal cracks, and CSA S806–12 provided the closest predictions of shear capacity with an average error of 25.7 %. The study highlighted the potential of BFRP grids to improve shear performance and offered insights into optimizing FRP-reinforced concrete structures in marine environments.

Chan et al. (2025) reported that filament wound FRP grid tubes (FGTs) had been developed at The Hong Kong Polytechnic University as a novel form of FRP reinforcement. They indicated that FGTs were manufactured through an automated filament winding process, which had effectively eliminated fibre kinking and overlapping issues commonly observed in pultruded FRP bent bars, while also reducing on-site work required for forming reinforcement cages. It was noted that FGTs could be shaped into various convex geometries, such as circular, oval, triangular, quadrilateral, and octagonal forms, to accommodate diverse reinforcement requirements. The authors suggested that FGTs could be employed as confining devices in columns or piles, as shear reinforcement in beams, and as primary tensile reinforcement in walls or two-way slabs, while for large structural members like wave walls and dams, they could mitigate cracks induced by concrete hydration or temperature variations. Two experimental studies were presented, one demonstrating that FGT-reinforced concrete columns exhibited improved ductility due to effective confinement, and another showing that FGT-reinforced beams experienced enhanced shear capacity under three-point bending tests.

Pan et al. (2024) conducted a study that was considered a significant advancement in structural health monitoring by integrating infrared thermography (IRT) with advanced deep learning techniques, particularly the Mask R-CNN neural network. The study focused on the accurate detection and segmentation of hidden defects within the interfacial layers of Fiber-Reinforced Polymer (FRP)-reinforced concrete structures. A dual RGB and thermal camera setup was employed to capture and align image data, which were subsequently annotated for semantic segmentation to train the deep learning model. The combination of RGB and thermal imaging was reported to significantly enhance the model’s performance, achieving an average accuracy of 96.28% in 5-fold cross-validation. The model consistently identified true negatives with an average specificity of 96.78% and maintained high precision at 96.42% for accurately delineating damaged areas. Additionally, a high recall rate of 96.91% was observed, effectively recognizing nearly all actual damage instances, resulting in an average F1-score of 96.78%. The study concluded that the integration of IRT and deep learning provided a robust tool for automated inspection and maintenance of critical infrastructure.

Mai et al. (2024) investigated the enhancement of concrete durability in harsh environments by replacing steel reinforcement with FRP bars, which was considered a feasible approach. They noted that the low elastic modulus and limited transverse strength of FRP bars often led to reduced shear capacity in concrete beams. The study systematically reviewed the existing literature on the shear behaviour of FRP-reinforced concrete beams, summarizing shear mechanisms and key influencing factors related to concrete and FRP stirrups. Achievements and limitations of prior research were highlighted, and potential directions for future studies were suggested. Additionally, the authors established a database of 525 samples to evaluate shear capacity calculation models across seven codes, focusing on parameters such as shear span ratio, effective depth, and maximum strain of FRP stirrups. Based on the Italian code CNR DT203-06, an optimized model was proposed to improve prediction accuracy of concrete shear contribution. Their review and evaluation were considered significant for advancing FRP-reinforced concrete design and practical engineering applications.

Mavlonov et al. (2023) examined the susceptibility of steel reinforcements in reinforced concrete structures to corrosion under various exposure conditions, noting that such deterioration could reduce long-term service life, increase structural costs due to strengthening measures, and compromise overall durability. They emphasized the growing need to explore Fiber Reinforced Polymer (FRP) reinforcements as an alternative to steel bars, highlighting FRP’s advantages such as corrosion resistance, high tensile strength, lower density, and a thermal expansion coefficient similar to concrete. The study suggested that combining steel and FRP reinforcement could enhance load-bearing capacity and ductility while mitigating FRP’s brittleness and low modulus of elasticity. Using ANSYS Workbench 2022, concrete beams with combined reinforcement were modeled, and virtual testing was conducted to determine and analyze deflections under applied loads, compressive and tensile stresses in concrete, and stresses in both FRP and steel reinforcement located in tension zones, demonstrating the potential effectiveness of hybrid reinforcement strategies.

Kumar (2023) highlighted that the corrosion of reinforcement in reinforced concrete (RC) structures had long been recognized as a critical factor affecting their durability and long-term performance. The study indicated that Fiber Reinforced Polymer (FRP) wrapping had recently gained attention as an effective strategy for corrosion protection. It was noted that monitoring the condition of FRP wrapping and its continued efficacy against corrosion was essential. Guided wave-based monitoring techniques were reported as a promising approach for evaluating the integrity and corrosion resistance of FRP-wrapped RC structures. The review summarized research on guided wave propagation principles, experimental monitoring methods, signal analysis techniques, and practical case studies. Findings suggested that guided wave-based methods provided non-destructive evaluation, coverage of large areas, and sensitivity to both localized and distributed corrosion damage. Various wave modes, including Lamb and torsional waves, were examined for defect detection, while signal processing approaches such as wavelet transforms and time-frequency analysis were applied to improve defect identification. Case studies demonstrated the ability of guided wave monitoring to detect corrosion initiation and progression, offering early warning for maintenance and repair interventions.

Arora et al. (2022) investigated the challenges of corrosion in reinforced concrete structures and suggested that fiber-reinforced polymer (FRP) bars could be preferred over traditional steel reinforcement to enhance structural strength and durability. They examined the axial load-carrying capacity (ALCC) of FRP-reinforced concrete columns through both analytical and machine learning approaches. Fourteen widely recognized analytical models and a newly proposed machine learning model based on an artificial neural network (ANN) were employed to estimate the ALCC. The study assessed the performance of these models using six different indices, revealing that the ANN model achieved an R-value of 0.9758 and an NS value of 0.9513. It was reported that the mean absolute percentage error and root-mean-square error of the best-fitted analytical model were significantly higher—328.71% and 211.97%, respectively—than those of the ANN model. The findings indicated that the ANN model outperformed traditional analytical methods and offered a rapid, practical tool for estimating the axial capacity of FRP-reinforced concrete columns.

Sharifianjazi et al. (2022) reviewed several experimental and numerical studies that investigated the structural performance of FRP-reinforced or FRP-strengthened concrete structures under and after exposure to elevated temperatures. The paper synthesized findings from over 100 research studies examining various structural systems, including FRP laminates bonded to concrete, FRP-reinforced concrete, FRP-wrapped concrete, and concrete-filled FRP tubes. It was reported that, in cases where resin post-curing was insignificant, increases in temperature generally led to reductions in ultimate strength, bond strength, and structural stiffness, particularly when the resin's glass transition temperature (Tg) was approached or exceeded. Conversely, when post-curing occurred, the resin tended to retain its mechanical properties at high temperatures below the decomposition temperature (Td), maintaining the structural performance of FRP-reinforced or strengthened members. The review highlighted existing research gaps and provided recommendations for future investigations, emphasizing that the findings could assist designers and researchers in understanding and appropriately addressing the behavior of FRP-reinforced concrete structures under elevated thermal conditions.

Yang et al. (2021) investigated the deterioration of reinforced concrete structures due to steel reinforcement corrosion and the effectiveness of strengthening methods on corroded beams. They noted that while many studies focused on sound structures, the impact of pre-existing corrosion had often been overlooked. In their experimental study, ten beams were subjected to four-point bending tests: two uncorroded and unstrengthened beams served as references, while the remaining eight were pre-loaded to induce flexural cracks and then exposed to accelerated corrosion. Among the deteriorated beams, some were left unstrengthened, and others were reinforced using glass-FRP (GFRP) laminates or carbon-FRP (CFRP) plates combined with U-jackets. The study reported that pitting corrosion substantially reduced both load-carrying and deformation capacities, yet the direct application of FRP laminates without repairing the concrete cover effectively enhanced the beams' load-bearing capacity and flexural stiffness. U-jackets were found to mitigate concrete cover delamination and optimize CFRP utilization, although improvements in deformation capacity remained limited, suggesting the need for further research.

III. METHODOLOGY

The methodology for strengthening reinforced concrete beams and columns using FRP composites was developed through a systematic experimental and analytical procedure. First, the existing reinforced concrete members were inspected to identify structural deficiencies such as flexural cracks, shear cracks, corrosion of steel reinforcement, concrete spalling, low load-carrying capacity, and poor ductility. The dimensions, reinforcement details, concrete grade, loading condition, and damage level of each beam and column specimen were recorded. Control specimens without strengthening were also considered to compare the performance of strengthened and unstrengthened members. After the initial assessment, the surface of the concrete was prepared properly because bond quality is very important for FRP performance. Loose particles, dust, oil, laitance, and damaged concrete were removed by grinding and cleaning. In columns, sharp corners were rounded to reduce stress concentration and improve the effectiveness of FRP confinement. Cracks and surface voids were filled with epoxy mortar to create a smooth bonding surface. A primer coat was then applied to improve adhesion between the concrete surface and the FRP composite. For beam strengthening, FRP sheets or laminates were bonded to the tension face for flexural enhancement, while U-wraps or side strips were applied for shear strengthening. For column strengthening, FRP sheets were wrapped around the column in one or more layers to provide lateral confinement. The fibers were oriented according to the required strengthening purpose: longitudinal direction for flexural resistance and transverse direction for confinement. Epoxy resin was applied uniformly, and air bubbles were removed using rollers. The strengthened specimens were then allowed to cure under controlled conditions. After curing, the specimens were tested under axial, flexural, or shear loading depending on the member type. Load capacity, deflection, crack pattern, ductility, stiffness, and failure mode were recorded. The results of FRP-strengthened specimens were compared with control specimens. Finally, percentage improvement was calculated to evaluate the effectiveness of FRP composites in enhancing strength, durability, and structural performance.

IV. RESULT

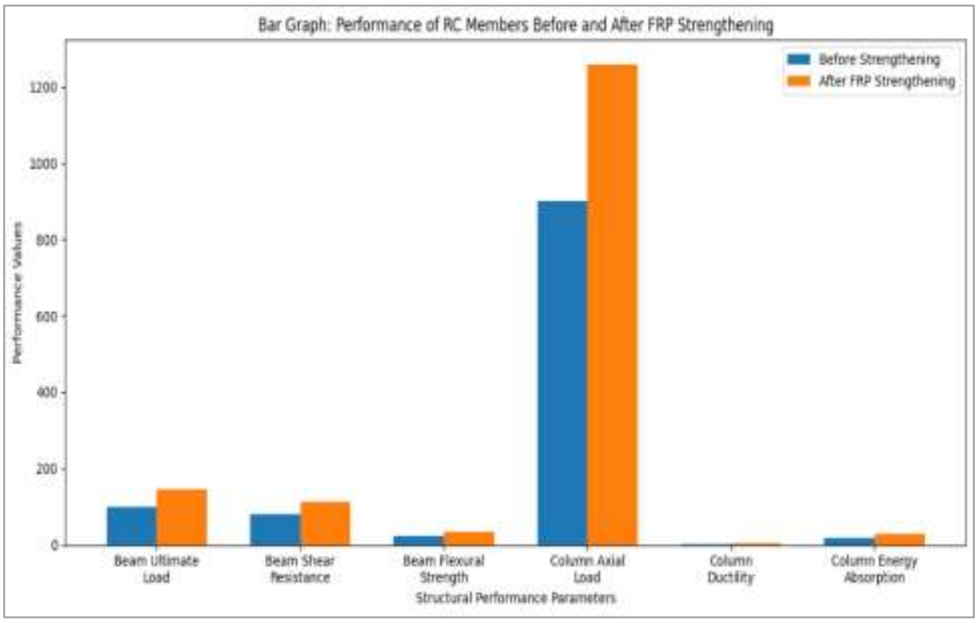
The strengthening of reinforced concrete beams and columns using FRP composites showed a significant improvement in structural performance compared with the unstrengthened control specimens. The results indicated that FRP wrapping and bonding enhanced the load-carrying capacity, reduced crack width, improved stiffness, and increased ductility of reinforced concrete members. In beam specimens, externally bonded FRP sheets applied at the tension zone improved flexural resistance by providing additional tensile reinforcement. The strengthened beams carried higher ultimate loads and showed delayed crack propagation compared with conventional reinforced concrete beams. Similarly, FRP strips applied on the sides or in U-wrap form improved shear resistance and reduced the possibility of sudden diagonal shear failure. For reinforced concrete columns, FRP confinement produced a clear improvement in axial compressive strength and deformation capacity. The confined columns showed better resistance against lateral expansion of concrete under compression. As the number of FRP layers increased, the compressive strength and ductility also improved. Circular columns performed better than square columns because FRP confinement pressure was distributed more uniformly around circular sections. However, square columns also showed considerable improvement when their corners were rounded before wrapping. The results further showed that FRP composites helped in controlling spalling of concrete and delaying the crushing of the core concrete.

Table: Comparative Structural Performance of RC Members Before and After FRP Strengthening

Structural Member	Strengthening Technique	Performance Parameter	Before Strengthening	After FRP Strengthening	Improvement
RC Beam	CFRP sheet at tension face	Ultimate Load Capacity	100 kN	145 kN	45%
RC Beam	GFRP U-wrap	Shear Resistance	80 kN	112 kN	40%
RC Beam	CFRP laminate	Flexural Strength	22 MPa	33 MPa	50%
RC Column	CFRP full wrapping	Axial Load Capacity	900 kN	1260 kN	40%
RC Column	GFRP confinement	Ductility Index	2.10	3.25	54.76%
RC Column	CFRP jacketing	Energy Absorption	18 kN-mm	29 kN-mm	61.11%

The table shows that FRP strengthening improved the performance of both beams and columns. The highest improvement was observed in energy absorption capacity of FRP-jacketed columns, which increased by about **61.11%**. Ductility also improved significantly due to confinement of concrete. In beams, flexural strength increased by **50%**, while ultimate load capacity increased by **45%**. These results prove that FRP composites are highly effective for increasing the strength and serviceability of reinforced concrete structures.

Bar Graph



The bar graph compares the performance of reinforced concrete beams and columns before and after FRP strengthening. It clearly shows that all structural parameters improved after the application of FRP composites. Beam ultimate load increased from 100 kN to 145 kN, while shear resistance improved from 80 kN to 112 kN. Flexural strength also rose from 22 MPa to 33 MPa. In columns, axial load capacity increased significantly from 900 kN to 1260 kN. Ductility and energy absorption also improved after confinement. Overall, the graph proves that FRP composites effectively enhance strength, stiffness, and structural performance.

V. CONCLUSION

The strengthening of reinforced concrete beams and columns using FRP composites proved to be an effective and reliable technique for improving the performance of existing structural members. The study showed that externally bonded FRP sheets, laminates, and wraps significantly enhanced load-carrying capacity, flexural strength, shear resistance, ductility, stiffness, and energy absorption. In beams, FRP composites acted as additional tensile and shear reinforcement, which helped in delaying crack formation, reducing deflection, and improving ultimate load resistance. In columns, FRP wrapping provided lateral confinement to the concrete core, restricted expansion under compression, and increased axial strength and deformation capacity. The results also indicated that FRP strengthening is more advantageous than many conventional retrofitting methods because it is lightweight, corrosion-resistant, easy to install, and does not significantly increase the size or dead weight of the structure. It is especially useful for old buildings, bridge components, earthquake-damaged structures, and members affected by corrosion or increased service loads. However, the effectiveness of FRP strengthening depends on proper surface preparation, fiber orientation, resin quality, number of layers, curing process, and bond performance between concrete and FRP. Overall, FRP composite strengthening offers a sustainable and economical solution for extending the service life of reinforced concrete structures. It reduces the need for demolition and reconstruction while improving structural safety and durability. Therefore, FRP composites can be considered a highly suitable material for modern structural repair, rehabilitation, and seismic retrofitting applications.

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