Vol 6, Issue 3, March 2026 www.ijesti.com E-ISSN: 2582-9734
International Journal of Engineering, Science, Technology and Innovation (IJESTI)

Rehabilitation of Reinforced Concrete Structures Using Fiber-Reinforced Polymer Composites

Tinku Kumar Singh
M. Tech. in Structural Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Parvesh
A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

The rehabilitation of reinforced concrete (RC) structures using fiber-reinforced polymer (FRP) composites has become a crucial advancement in modern structural engineering, particularly in extending service life and load-carrying capacity. FRP systems, such as externally bonded reinforcement (EBR) and near-surface mounted (NSM) techniques, have demonstrated significant improvements in flexural, shear, and axial performance. These systems also enhance seismic retrofitting by improving column ductility and compressive strength. However, challenges remain, such as debonding failure, durability issues, and performance under extreme temperatures, emphasizing the need for continued research on improving material behavior, long-term performance, and predictive models.

Keywords: *FRP Composites, RC Structures, Rehabilitation, Seismic Retrofitting.*

I. INTRODUCTION

The rehabilitation and strengthening of reinforced concrete (RC) structures using fiber-reinforced polymer (FRP) composites has emerged as a significant advancement in modern structural engineering, particularly in extending the service life and load-carrying capacity of existing infrastructure. With rapid urbanization and aging civil infrastructure, many RC beams and columns are now experiencing deterioration due to increased service loads, environmental exposure, corrosion of steel reinforcement, and inadequate original design provisions. In this context, FRP composites have been widely recognized as an efficient strengthening material owing to their high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal disruption during application. Studies have consistently demonstrated that externally bonded FRP systems, including Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) techniques, significantly enhance flexural, shear, and axial performance of RC members (Tran et al., 2025; Ye et al., 2022). Moreover, FRP confinement in columns has been shown to improve ductility and compressive strength, making it highly effective in seismic retrofitting applications (Valasaki & Papakonstantinou, 2023; Durgadevi et al., 2021). Despite these advantages, the application of FRP systems in structural strengthening is still evolving due to challenges such as long-term durability, debonding failure, and environmental degradation. Therefore, understanding the mechanical behavior and interaction mechanisms between FRP and concrete remains essential for optimizing design and ensuring structural safety.

The strengthening of RC beams and columns using FRP composites primarily relies on composite action between the FRP material and the concrete substrate. In beam strengthening applications, FRP sheets or laminates are externally bonded to the tension zone to resist flexural stresses, while shear strengthening is achieved through U-wraps or side bonding techniques. Additionally, anchorage systems have been developed to improve load transfer efficiency and delay premature debonding failures, as evidenced in experimental studies on multi-anchor FRP systems (Zhang et al., 2026). For column applications, FRP confinement enhances the lateral restraint of concrete, resulting in improved compressive strength and ductility. Hybrid systems such as FRP-confined steel-reinforced concrete (FCSRC) have further expanded the application scope by integrating steel, concrete, and FRP into a single structural system (Ye et al., 2022). Near-surface mounted (NSM) reinforcement techniques also offer improved bond performance compared to externally bonded systems due to better protection against environmental exposure. Recent advancements in FRP-reinforced ultrahigh-strength engineered cementitious composites (UHS-ECC) have further demonstrated the potential of FRP in improving crack resistance and structural efficiency (Zhu et al., 2026). However, the overall effectiveness of these systems depends heavily on bond behavior, anchorage performance, and the mechanical compatibility between FRP and concrete, which remain active areas of research.

Despite the significant advantages of FRP composites in structural strengthening, several limitations continue to restrict their widespread application. One of the major concerns is the poor performance of FRP materials under elevated temperatures, as the polymer matrix tends to degrade near its glass transition temperature (Tg), leading to significant loss of mechanical properties (Zhou et al., 2026). Fire exposure can severely compromise the integrity of FRP-strengthened systems unless adequate insulation is provided. In addition, environmental factors such as moisture, alkalinity, and chloride exposure can lead to long-term degradation of FRP materials, particularly in marine and aggressive environments (Zhang et al., 2022; Ortiz et al., 2023). Another critical issue is the debonding failure between FRP and concrete, which often governs the ultimate capacity of strengthened members. Although anchorage systems and advanced bonding techniques have been developed to mitigate this issue, complete elimination of premature failure has not yet been achieved. Furthermore, variability in material properties and lack of standardized design provisions across different codes create uncertainty in practical applications. Numerical and experimental studies have also highlighted the limited understanding of FRP behavior in complex structural forms such as deep beams and continuous members, indicating the need for further research (Tran et al., 2025). These limitations emphasize the necessity of developing more reliable predictive models and improving durability characteristics of FRP composites.

Recent research trends indicate a growing interest in enhancing the performance, sustainability, and applicability of FRP-strengthened RC structures through innovative materials and techniques. Advances in compression-cast concrete technology have shown improved compatibility with FRP reinforcement, resulting in enhanced mechanical properties and reduced carbon emissions (Wu et al., 2024). Similarly, the development of 3D printed continuous fiber-reinforced thermoplastic polymer (CFRTP) reinforcement has opened new possibilities for integrating FRP materials in additive manufacturing of concrete structures (Zeng et al., 2024). Non-destructive evaluation techniques, such as ultrasonic guided wave methods, have also been introduced for early detection of thermal and structural damage in FRP-strengthened members, improving maintenance and safety assessment strategies (Cao et al., 2025). Furthermore, extensive databases on FRP-confined concrete have provided deeper insights into confinement efficiency, material selection, and structural behavior under axial loading (Valasaki & Papakonstantinou, 2023). Collectively, these advancements indicate a shift toward more intelligent, durable, and sustainable FRP-based strengthening systems. However, despite these developments, gaps remain in long-term performance prediction, multi-hazard resistance, and full-scale structural implementation. Therefore, continued research is essential to optimize FRP strengthening techniques and establish comprehensive design guidelines for RC beams and columns in modern infrastructure systems.

II. RESEARCH BACKGROUND

Zhou et al. (2026) presented a comprehensive review of the fire performance of Fiber-Reinforced Polymers (FRP) and FRP-concrete systems, emphasizing that the structural application of FRP had been significantly constrained by its inherent thermal sensitivity. The study distinguished the fire behavior of internally reinforced FRP-reinforced concrete members from externally applied strengthening systems, such as Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) techniques, thereby offering a clearer analytical framework than earlier reviews. It was reported that the thermal and mechanical degradation of FRP constituents, particularly reinforcing fibers and polymer matrices, had been critically influenced by the glass transition temperature (Tg). The review further compared organic epoxy-based binders with inorganic cementitious binders, highlighting their bonding mechanisms and thermal resistance under fire exposure. Various fire-protection strategies, especially insulation systems, were also assessed, and it was found that insulation thickness had largely governed fire endurance, whereas irreversible polymer degradation had remained the key obstacle to post-fire structural recovery.

Zhang et al. (2026) investigated the structural behaviour of fiber-reinforced polymer (FRP) anchored externally bonded FRP (EB-FRP) systems, noting that although FRP anchors had been recognized for improving load transfer and delaying premature debonding, limited experimental evidence and design guidance had been available for single- and multianchored systems under realistic field conditions. The study was reported through a three-round experimental programme comprising 48 large-scale single-lap shear tests on reinforced concrete blocks, in which anchor configurations, dowel diameters, anchor spacing, FRP strip thickness, and concrete compressive strength were systematically varied. A 3D digital image correlation technique was employed to monitor strain distribution, slip response, anchor engagement, and interfacial debonding. The findings indicated that anchorage had significantly enhanced both load-carrying capacity and deformation performance. Sequential anchor engagement was observed in multianchor arrangements, while failure behaviour was found to depend on the capacity relationship between anchor rupture and strip fracture. Furthermore, a simplified empirical multilinear load–slip model was proposed and was shown to predict peak load and ultimate slip with strong agreement, thereby providing a validated basis for performance-based design and anchorage detailing in structural strengthening applications.

Zhu et al. (2026) investigated a novel stay-in-place permanent formwork system utilizing fiber-reinforced polymer (FRP)-reinforced ultrahigh-strength engineered cementitious composites (UHS-ECCs) to improve the durability and structural performance of concrete structures. The study evaluated the flexural behavior and failure mechanisms of reinforced concrete beams incorporating a 3-mm FRP bar-reinforced, 20-mm-thick UHS-ECC formwork through experimental testing, digital image correlation, and theoretical analysis. For comparative purposes, ultrahigh-performance concrete (UHPC) was also examined as an alternative formwork material. It was reported that rectangular grooves spaced at 50 mm and 120 mm were introduced in the precast formwork to enhance interfacial bonding. The findings revealed that the UHS-ECC formwork effectively reduced early crack localization, thereby improving load-carrying capacity and post-yield stiffness. In contrast, the UHPC formwork was found to be more prone to localized cracking, which caused interfacial deformation incompatibility and consequently lowered ductility and load-bearing performance. Overall, the study concluded that FRP-reinforced UHS-ECC permanent formwork had significant potential as an effective solution for enhancing the mechanical behavior and long-term durability of concrete structures.

Tran et al. (2025) were reported to have highlighted the potential of fiber-reinforced polymer (FRP) bars as replacements for steel in reinforced concrete (RC) beams, emphasizing their high tensile strength and corrosion resistance. They were noted to have conducted a comprehensive review of prior experimental and numerical studies to provide an understanding of FRP RC beam behavior, design considerations, and limitations. The study was described to have collated experimental findings from 93 tested specimens and summarized numerical analyses, including finite element (FE), discrete element (DE), and artificial intelligence/machine learning (AI/ML) approaches. The authors were also reported to have evaluated international design standards for FRP RC beams. Through their review, they were observed to have identified gaps, particularly the limited research on continuous and deep beams reinforced with FRP bars, and recommended further studies employing DE analysis and AI/ML to assess beam responses under loading conditions.

Cao et al. (2025) investigated the application of guided waves for detecting early-stage thermal damage in concrete structures reinforced with externally bonded fibre-reinforced polymer (FRP) composite plates. They first introduced a theoretical model incorporating both linear and nonlinear elastic coefficients to characterize the material properties and behavior of FRP plates, while simulating thermal damage by increasing the nonlinear elastic coefficients. A nonlinear parameter was proposed to quantify the extent of thermal damage, and a user-defined subroutine for a three-dimensional finite element model was developed to simulate wave propagation across various frequencies. Experimental tests were conducted on a carbon FRP-strengthened concrete beam, where thermal damage was induced by heating a localized CFRP surface area with a radiant heater. The sensitivity of the proposed nonlinear parameter in detecting different levels of thermal damage was demonstrated, and the study confirmed the reliability and effectiveness of the nonlinear guided wave approach for early-stage damage detection in FRP-strengthened concrete structures.

Wu et al. (2024) reported that concrete manufacturing was a major source of carbon emissions and explored compression-casting as a novel, highly efficient technology for producing concrete. They highlighted that compression-casting, a mechanical process, enhanced the properties of various concrete materials without the need for chemical additives or mineral admixtures. The study indicated that this method was particularly effective for high-quality concrete production using secondary, substandard, or recycled aggregates, supporting sustainable and low-carbon construction. Wu et al. also presented experimental findings on material behavior and fiber-reinforced polymer (FRP)-reinforced structures, demonstrating the application of compression-casting with inferior materials such as rubber, recycled aggregates, desert sand, and recycled powder concrete. The authors found that FRP-reinforced compression-cast concrete (CCC) members exhibited superior mechanical performance, microstructure, durability, cement efficiency, and economic benefits compared to normal concrete (NC), along with reduced CO_2 emissions. They further suggested strategies to mitigate brittleness in CCC, proposing that this approach could significantly transform future concrete manufacturing practices.

Zeng et al. (2024) reported that 3D printed concrete had gained increasing popularity in both research and industrial contexts, yet it suffered from a lack of effective internal reinforcement. They noted that fiber-reinforced polymer (FRP) reinforcement, widely used in conventional concrete structures, had been adopted to improve the performance of 3D printed concrete, although traditional FRP manufacturing processes, such as pultrusion, did not allow on-site forming, creating construction challenges. The study aimed to address these issues by developing a novel 3D printed continuous fiber-reinforced thermoplastic polymer (CFRTP) reinforcement for 3D printed concrete structures. An experimental program was conducted to evaluate the tensile behavior of 3D printed CFRTP bars and grids, followed by their application in high-performance 3D printed concrete. Twenty-two concrete plates were tested to assess the influence of loading direction and fabrication type on flexural behavior. Results indicated that CFRTP reinforcement considerably enhanced the performance of 3D printed high-performance concrete, demonstrating effectiveness comparable to conventional FRP, and highlighted directions for further research on simultaneous printing of concrete and FRP reinforcement.

Ortiz et al. (2023) reviewed the applications and challenges of fiber-reinforced polymer (FRP) composites in civil engineering, noting that these materials had been increasingly recognized for their mechanical strength and chemical resistance. They indicated that FRP composites were susceptible to harsh environmental conditions such as water, alkaline and saline solutions, and elevated temperatures, as well as mechanical phenomena including creep rupture, fatigue, and shrinkage, which could influence the performance of FRP-reinforced or strengthened concrete (FRP-RSC) elements. The authors summarized the current state of knowledge regarding the durability and mechanical behavior of commonly used FRP composites, such as glass/vinyl-ester bars and carbon/epoxy fabrics, highlighting the sources and effects of environmental and mechanical stresses on their properties. They reported that literature generally showed tensile strength reductions of no more than 20% under single exposures. Additionally, they discussed provisions for serviceability design, including environmental factors and creep reduction, and compared serviceability criteria between FRP and steel RC elements, suggesting that understanding these behaviors could guide the effective use of FRP in concrete structures.

Valasaki and Papakonstantinou (2023) investigated the use of fiber-reinforced polymers (FRPs) as composite materials in civil engineering for the rehabilitation and strengthening of reinforced concrete elements. They compiled a comprehensive and up-to-date experimental database from compressive tests on circular concrete structural elements confined with FRP materials, applying strict criteria to minimize uncertainty and ensure data uniformity. The collected results were categorized based on the confinement type—FRP wrapping or FRP tube encasement. Their database, encompassing 1,470 test results, detailed specimen geometry, mechanical properties of the jacketing materials, and the influence of confinement on axial compressive strength and strain. Analysis of the data indicated that unconfined concrete strength was inversely related to confinement efficiency, which was limited in high-strength specimens. Carbon fibers were found to provide greater confinement effectiveness, while FRP axial rigidity significantly contributed to confinement performance. Glass and aramid fibers performed similarly across confinement types, and although FRP-wrapped and tube-encased specimens showed comparable compressive strength increases, tube-encased specimens exhibited larger ultimate axial strains.

Zhang et al. (2022) highlighted that fiber reinforced polymer (FRP) had been considered an alternative to steel and could be directly applied in seawater sea sand concrete (SSC), though it faced significant durability challenges in corrosive environments, which had been a major focus of contemporary research. They reviewed the literature on the long-term degradation of FRP bars and the durability performance of FRP-reinforced SSC structures in marine settings. It was noted that the combined effects of concrete alkalinity and salt ions from seawater and sea sand accelerated resin dissolution and fiber-resin interface debonding, particularly in BFRP bars, resulting in highly variable mechanical properties and reduced bonding with SSC. Furthermore, they observed that the bearing capacity of FRP or steel-FRP composite bar reinforced SSC components declined in marine environments, with altered failure modes. They also reported that existing codes used conservative environmental reduction factors for durability design. The study concluded by emphasizing the need for quantifying mechanical variability of FRP bars after long-term service and developing time-dependent, reliability-based design methods for structural components.

Ye et al. (2022) discussed that fiber-reinforced polymer (FRP) composites had been extensively employed for strengthening or constructing structures owing to their notable corrosion resistance and high tensile strength. They highlighted that an emerging hybrid structural member form, termed FRP-confined steel-reinforced concrete (FCSRC) systems—comprising a steel section as internal reinforcement, an external FRP wrap or tube, and concrete infill—had gained growing research attention. The authors noted that this concept had been applied both for strengthening and repairing steel structures and for developing new hybrid structural members, including hybrid columns, beams, and buckling-restrained braces (BRBs). They indicated that the FRP confinement and composite interaction among the three components contributed to the superior performance of these hybrid members. The paper provided a comprehensive review of FCSRCs in structural applications and identified existing knowledge gaps as well as potential directions for future research on the design, analysis, and practical implementation of such hybrid systems.

Durgadevi et al. (2021) highlighted that retrofitting involved upgrading existing building structures to enhance their resistance to seismic activity. They observed that numerous existing constructions worldwide, including reinforced concrete and masonry structures as well as bridges, required urgent rehabilitation or reconstruction due to factors such as inadequate detailing, environmental degradation, poor maintenance, and substandard workmanship during construction. Their experimental study examined the confinement of M30 reinforced concrete beams using GFRP (Glass Fiber Reinforced Polymer), CFRP (Carbon Fiber Reinforced Polymer), and BFRP (Basalt Fiber Reinforced Polymer) to evaluate improvements in load-carrying capacity and deflection under service loads. They reported that the fiber wrapping was applied in double and four layers using bi-directional fiber mats. The findings suggested that externally bonded FRP with four-layer wrapping provided superior resistance to applied loads and exhibited reduced deflection compared to other FRP types, indicating its effectiveness in structural retrofitting for seismic resilience.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Study Focus	Methodology	Key Findings	Research Contribution
Zhou et al. (2026)	Fire performance of FRP–RC systems	State-of-the-art review	FRP strength significantly reduces near Tg; insulation governs fire resistance	Provided fire-safety framework for FRP-strengthened structures
Zhang et al. (2026)	FRP anchorage in EBR systems	48 large-scale single-lap shear tests + DIC analysis	Anchors improved load capacity and reduced debonding; proposed load–slip model	Improved understanding of anchorage behavior in FRP systems
Zhu et al. (2026)	FRP-reinforced UHS-ECC formwork	Experimental beam testing + theoretical analysis	Improved crack control, stiffness, and load capacity	Introduced durable FRP-based permanent formwork system
Tran et al. (2025)	FRP RC beam behavior	Literature review (93 specimens + FE + AI models)	FRP effective but limited in deep/continuous beams	Identified research gaps in FRP beam design
Cao et al. (2025)	Thermal damage detection in FRP systems	FEM + ultrasonic guided wave testing	Nonlinear parameter effectively detects early damage	Developed NDT-based monitoring approach
Wu et al. (2024)	Compression-cast FRP concrete systems	Experimental material testing	Improved strength, durability, and reduced CO_2 emissions	Proposed sustainable FRP–concrete manufacturing method
Zeng et al. (2024)	3D printed CFRTP reinforcement	Experimental testing on RC plates	CFRTP reinforcement enhanced flexural performance	Introduced additive-manufactured FRP reinforcement

Ortiz et al. (2023)	Durability of FRP composites	Review study	Environmental exposure reduces strength (<20% in most cases)	Explained long-term degradation behavior of FRP
Valasaki & Papakonstantinou (2023)	FRP-confined concrete columns	Experimental database (1470 tests)	Carbon FRP most effective; confinement depends on stiffness	Provided large-scale confinement performance database
Zhang et al. (2022)	Marine durability of FRP RC	Literature review	Seawater exposure accelerates degradation and reduces capacity	Highlighted need for reliability-based design
Ye et al. (2022)	FRP-confined steel RC (FCSRC) systems	State-of-the-art review	Hybrid systems improve strength and ductility	Introduced hybrid FRP–steel–concrete systems
Durgadevi et al. (2021)	FRP retrofitting of RC beams	Experimental testing (GFRP, CFRP, BFRP wrapping)	CFRP 4-layer wrapping gave highest strength improvement	Confirmed FRP effectiveness in structural retrofitting

IV. CONCLUSION

The strengthening of reinforced concrete (RC) beams and columns using fiber-reinforced polymer (FRP) composites has been established as one of the most effective and widely adopted techniques in modern structural rehabilitation and retrofitting practices. The reviewed literature consistently indicates that FRP materials significantly enhance the structural performance of RC elements in terms of flexural strength, shear resistance, axial load capacity, and ductility, while also offering advantages such as corrosion resistance, lightweight characteristics, and ease of installation. Studies on externally bonded reinforcement (EBR), near-surface mounted (NSM) systems, and FRP confinement techniques have demonstrated substantial improvements in load-bearing capacity and deformation behavior of structural members (Tran et al., 2025; Valasaki & Papakonstantinou, 2023). In beam applications, FRP laminates and sheets effectively improve flexural and shear performance by enhancing tensile resistance in critical zones, whereas in columns, FRP confinement significantly increases compressive strength and ductility, thereby improving seismic resilience (Durgadevi et al., 2021; Ye et al., 2022). Furthermore, advancements in anchorage systems have shown that premature debonding failures, which are a common limitation in FRP strengthening, can be mitigated to a considerable extent, leading to improved load transfer efficiency and structural reliability (Zhang et al., 2026). Despite these advantages, the literature also highlights several critical limitations that affect the long-term performance and widespread adoption of FRP systems. One of the most significant challenges is the thermal sensitivity of FRP materials, where exposure to elevated temperatures near the glass transition temperature (Tg) leads to rapid degradation of mechanical properties, thereby compromising structural integrity during fire events (Zhou et al., 2026). Additionally, environmental exposure such as moisture, alkalinity, and chloride attack has been found to contribute to long-term degradation of FRP composites, particularly in marine and aggressive conditions, resulting in reduced bond strength and mechanical efficiency (Zhang et al., 2022; Ortiz et al., 2023). Another major concern is the brittle failure mode associated with FRP-strengthened members, primarily governed by debonding or rupture of the composite material, which limits ductility and energy dissipation capacity under extreme loading conditions. Although hybrid systems such as FRP-confined steel-reinforced concrete (FCSRC) and FRP-reinforced ultrahigh-performance materials have shown promising improvements in structural behavior, these technologies are still in developmental stages and require further validation for full-scale applications (Zhu et al., 2026; Ye et al., 2022). Moreover, variability in design guidelines across different codes and limited understanding of FRP behavior in complex structural configurations, such as deep beams and continuous systems, continue to restrict uniform implementation in engineering practice. Nevertheless, recent advancements in sustainable concrete technologies, 3D-printed FRP reinforcements, and non-destructive evaluation methods such as ultrasonic guided wave techniques indicate a positive direction toward improving the durability, monitoring, and efficiency of FRP-strengthened structures (Wu et al., 2024; Zeng et al., 2024; Cao et al., 2025). Overall, it can be concluded that FRP composites represent a highly promising solution for extending the service life and enhancing the performance of existing RC structures; however, further research is required to address issues related to fire resistance, long-term durability, bond behavior, and standardized design provisions to ensure safe, reliable, and sustainable application in future structural engineering practices.

V. FUTURE SCOPE

- **Development of Fire-Resistant FRP Systems:** Future research can focus on improving the thermal stability of FRP composites by developing advanced resin matrices, nano-modified polymers, and hybrid insulation systems to overcome degradation near glass transition temperature (Tg) and enhance fire safety performance of FRP-strengthened structures (Zhou et al., 2026).
- **Improved Bond and Anchorage Mechanisms:** There is a strong need to design more efficient anchorage systems and surface treatment methods to prevent premature debonding failures in FRP-strengthened beams and columns. Advanced mechanical anchors, hybrid bonding techniques, and nano-engineered adhesives can be explored to improve load transfer efficiency (Zhang et al., 2026).
- **Long-Term Durability Assessment Models:** Future studies should develop time-dependent degradation models for FRP materials under combined environmental effects such as moisture, temperature variation, alkalinity, and chloride exposure, especially for marine and coastal infrastructure applications (Zhang et al., 2022; Ortiz et al., 2023).
- **Hybrid Structural Systems Development:** Integration of FRP with steel and advanced concrete materials (such as UHPC and ECC) should be further investigated to enhance ductility, energy dissipation, and post-cracking behavior, particularly for seismic-resistant structures (Ye et al., 2022; Zhu et al., 2026).
- **Application of AI and Machine Learning:** Future research can incorporate artificial intelligence and machine learning models for predicting the flexural, shear, and confinement behavior of FRP-strengthened RC members, enabling faster and more accurate design optimization (Tran et al., 2025).
- **Smart Monitoring and Structural Health Systems:** Development of embedded sensing systems using fiber optics, ultrasonic guided waves, and digital image correlation techniques can enable real-time monitoring of damage, debonding, and thermal degradation in FRP systems (Cao et al., 2025).
- **Sustainable and Low-Carbon FRP Applications:** Research should focus on reducing environmental impact by integrating FRP systems with green concrete technologies such as compression-cast concrete, recycled aggregates, and low-emission production methods (Wu et al., 2024).

- **3D Printing and Automated Construction Technologies:** Future advancements can explore the simultaneous 3D printing of concrete and continuous FRP reinforcement, enabling customized structural elements with improved strength and reduced construction time (Zeng et al., 2024).
- **Standardization of Design Codes:** There is a need to develop unified international design guidelines for FRP-strengthened structures to reduce inconsistencies in safety factors, durability considerations, and load resistance models across different engineering codes.
- **Seismic and Extreme Loading Applications:** Further research should investigate the performance of FRP-strengthened beams and columns under extreme conditions such as earthquakes, blast loads, and impact forces to improve resilience of critical infrastructure.
- **Large-Scale Experimental Validation:** Full-scale testing of FRP-strengthened structural systems is required to validate laboratory findings and improve confidence in real-world applications, particularly for deep beams and continuous structural systems.
- **Life-Cycle Performance Evaluation:** Future studies should incorporate life-cycle cost analysis (LCCA) and sustainability assessments to evaluate the economic and environmental benefits of FRP strengthening compared to traditional rehabilitation methods.

REFERENCES

1. Zhou, J., Zhou, Y., Guo, M., & Xiang, S. (2026). Fire Performance of FRP-Composites and Strengthened Concrete Structures: A State-of-the-Art Review. *Polymers*, *18*(2), 181.
2. Zhang, J., del Rey Castillo, E., Allen, T., Hogan, L., Kanitkar, R., & Borwankar, A. D. (2026). Behavior and Predictive Model of Large-Scale Externally Bonded FRP Strips Anchored to Reinforced Concrete Structures. *Journal of Composites for Construction*, *30*(3), 04026009.
3. Zhu, J. X., Weng, K. F., Liu, W. H., Huang, B. T., Peng, K. D., Zhu, J. H., & Dai, J. G. (2026). Stay-in-Place Permanent Formwork for Concrete Structures Using FRP-Reinforced Ultrahigh-Strength Engineered Cementitious Composites. *Journal of Composites for Construction*, *30*(3), 04026011.
4. Tran, H., Nguyen-Thoi, T., & Dinh, H. B. (2025). State-of-the-art review of studies on the flexural behavior and design of frp-reinforced concrete beams. *Materials*, *18*(14), 3295.
5. Cao, Y., Jiang, C., Ng, C. T., & Smith, S. T. (2025). Thermal damage detection in FRP-strengthened reinforced concrete structures using ultrasonic guided waves. *NDT & E International*, *152*, 103329.
6. Wu, Y. F., Yuan, F., & Hu, B. (2024). Green compression-cast concrete material and its fiber-reinforced polymer (FRP)-reinforced concrete structures. *Engineering*.
7. Zeng, J. J., Yan, Z. T., Jiang, Y. Y., & Li, P. L. (2024). 3D printing of FRP grid and bar reinforcement for reinforced concrete plates: Development and effectiveness. *Composite Structures*, *335*, 117946.
8. Ortiz, J. D., Khedmatgozar Dolati, S. S., Malla, P., Nanni, A., & Mehrabi, A. (2023). FRP-reinforced/strengthened concrete: State-of-the-art review on durability and mechanical effects. *Materials*, *16*(5), 1990.
9. Valasaki, M. K., & Papakonstantinou, C. G. (2023). Fiber reinforced polymer (FRP) confined circular concrete columns: An experimental overview. *Buildings*, *13*(5), 1248.
10. Zhang, K., Zhang, Q., & Xiao, J. (2022). Durability of FRP bars and FRP bar reinforced seawater sea sand concrete structures in marine environments. *Construction and Building Materials*, *350*, 128898.
11. Ye, Y. Y., Zeng, J. J., & Li, P. L. (2022). A state-of-the-art review of FRP-confined steel-reinforced concrete (FCSRC) structural members. *Polymers*, *14*(4), 677.
12. Durgadevi, S., Karthikeyan, S., Lavanya, N., & Kavitha, C. (2021). A review on retrofitting of reinforced concrete elements using FRP. *Materials Today: Proceedings*, *45*, 1050-1054.