Smart FRP-Based Retrofitting Strategies for Enhancing Strength and Durability of Reinforced Concrete Structures: A Review

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ABSTRACT

This study examines the application of fiber reinforced polymer (FRP) and smart materials for retrofitting reinforced concrete structures. Existing RC structures often deteriorate due to corrosion, aging, seismic forces, fatigue loading, poor construction practices, and outdated design standards. FRP composites offer high strength, lightweight properties, corrosion resistance, and ease of installation, making them effective for flexural, shear, and seismic strengthening. The integration of smart materials, structural health monitoring systems, piezoelectric sensors, and computational techniques further improves damage detection, performance evaluation, and service life. Thus, FRP and smart materials provide sustainable solutions for safe infrastructure rehabilitation.

Keywords: *FRP, Smart Materials, Retrofitting, Reinforced Concrete, Structural Health Monitoring.*

I. INTRODUCTION

Reinforced concrete (RC) structures represent one of the most widely used construction systems in modern civil engineering due to their strength, durability, versatility, and economic advantages. Buildings, bridges, tunnels, parking structures, industrial plants, dams, and transportation infrastructures across the world have extensively relied on reinforced concrete systems for decades. However, a significant portion of existing RC structures has gradually deteriorated because of environmental exposure, corrosion of reinforcing steel, seismic events, fatigue loading, design deficiencies, overloading, poor construction practices, and aging effects. Many structures constructed several decades ago were designed according to older building standards and seismic codes that are no longer sufficient to satisfy present-day safety and serviceability requirements. Consequently, structural rehabilitation and retrofitting have become critical engineering necessities for maintaining structural integrity and extending the service life of infrastructure systems. Conventional retrofitting methods such as steel jacketing, section enlargement, and external plate bonding have often faced limitations including increased structural weight, corrosion susceptibility, high labor requirements, and complex installation procedures. In response to these challenges, advanced composite materials, particularly fiber reinforced polymer (FRP) systems and smart materials, have emerged as highly efficient and sustainable alternatives for strengthening and rehabilitating RC structures. Fiber reinforced polymer composites possess exceptional mechanical characteristics such as high tensile strength, low self-weight, corrosion resistance, high fatigue endurance, and ease of installation, making them suitable for retrofitting applications in both seismic and non-seismic regions. According to Bahij et al. (2022), FRP composites had become increasingly important for enhancing flexural, shear, and torsional behavior of reinforced concrete beams, while simultaneously improving structural ductility and long-term durability. Similarly, Blazy et al. (2022) emphasized that glass fiber reinforced concrete demonstrated superior crack resistance, tensile strength, fire resistance, and durability compared with ordinary concrete, thereby contributing to sustainable infrastructure development. These advancements indicate that FRP-based retrofitting technologies provide effective solutions for improving the performance of deteriorated RC structures while minimizing construction time, maintenance costs, and environmental impacts.

In recent years, researchers and engineers have increasingly focused on integrating smart materials with FRP systems to develop intelligent retrofitting techniques capable of not only strengthening structures but also monitoring their performance in real time. Smart materials are characterized by their ability to respond to environmental or mechanical stimuli such as stress, temperature, strain, or vibration, thereby enabling adaptive and self-monitoring structural systems. The integration of shape memory alloys (SMA), piezoelectric transducers (PZT), engineered cementitious composites (ECC), and self-sensing composites into retrofitting applications has significantly enhanced the resilience and reliability of reinforced concrete structures under dynamic loading conditions. Alqarni et al. (2026) investigated RC beam-column joints strengthened using hybrid systems composed of shape memory alloys and polyvinyl alcohol fibers. The study reported that the hybrid retrofitting system had improved energy dissipation, self-centering capability, load capacity, and displacement resistance under cyclic loading conditions, while also reducing residual deformations and crack propagation. These characteristics are particularly important in seismic regions where structures are subjected to repeated lateral loading during earthquakes. Likewise, Fouad and Saifeldeen (2021) developed smart self-sensing FRP sheets integrated with woven carbon fiber sensors that effectively detected cracking loads and initial debonding between FRP and concrete surfaces. Such sensing systems allow engineers to identify structural distress at early stages, thereby improving maintenance planning and preventing catastrophic failures. Mohammadi et al. (2025) further introduced a mechanochromic hybrid composite capable of providing visual feedback through color changes when excessive strain or damage occurred in retrofitted concrete beams. The proposed system not only enhanced structural strength but also functioned as a passive structural health monitoring mechanism. These developments demonstrate that the combination of FRP materials with smart sensing technologies has transformed structural retrofitting from a purely strengthening-oriented practice into an intelligent infrastructure management approach focused on safety, resilience, and sustainability.

Another major advancement in the field of retrofitting reinforced concrete structures involves the incorporation of structural health monitoring (SHM) systems and advanced analytical methods for assessing structural performance and retrofit effectiveness. Structural health monitoring technologies provide continuous information regarding structural conditions, crack formation, stress variations, and damage progression, thereby enabling timely interventions and improving structural safety. Among the most promising SHM technologies are electro-mechanical impedance (EMI)-based systems utilizing piezoelectric lead zirconate titanate (PZT) transducers. Sapidis et al. (2024) proposed an innovative methodology for monitoring carbon-fiber-reinforced polymer retrofitting in beam-column joints using PZT patches embedded within near-surface-mounted CFRP ropes. The study demonstrated that the combined use of EMI techniques and hierarchical clustering analysis improved the reliability of damage assessment and retrofit performance evaluation under cyclic loading conditions. Similarly, Naoum et al. (2024) investigated the application of advanced monitoring systems in retrofitted RC beams strengthened using U-shaped mortar jackets and observed that PZT-enabled SHM systems successfully detected interface degradation between existing concrete and retrofit layers. This capability was essential for ensuring long-term bond performance and retrofit effectiveness. Furthermore, Naoum et al. (2023) evaluated fiber-reinforced concrete prisms equipped with piezoelectric monitoring networks under repeated loading conditions simulating seismic actions. Their findings indicated that the proposed SHM systems effectively detected early-stage crack development and stress-induced damage, enabling rapid structural assessment during seismic events. The use of these intelligent monitoring systems is becoming increasingly important in modern infrastructure engineering because it allows continuous evaluation of retrofitted structures without requiring destructive testing methods. Such technologies contribute significantly toward improving structural reliability, minimizing maintenance costs, and enhancing public safety in critical infrastructure systems.

The rapid evolution of computational technologies, machine learning techniques, and finite element analysis has further accelerated the development and optimization of FRP and smart material retrofitting systems for reinforced concrete structures. Advanced computational models are now capable of simulating nonlinear structural behavior, predicting damage mechanisms, and optimizing retrofit configurations under different loading conditions. Finite element analysis software such as ABAQUS has been widely used to evaluate the performance of FRP-strengthened RC structures subjected to flexural, shear, torsional, and seismic loads. Isleem et al. (2023) conducted finite element investigations on RC beams strengthened with CFRP grids and engineered cementitious composites and reported significant improvements in shear capacity and crack control performance. The study further developed analytical models with minimal deviation from numerical results, demonstrating the reliability of predictive computational techniques. In addition to numerical simulations, machine learning approaches have increasingly gained importance in structural retrofitting applications due to their ability to analyze large datasets and accurately predict structural behavior. Alhusban et al. (2024) reviewed ninety-six research studies related to machine learning applications in FRP structural engineering and concluded that supervised learning algorithms had become highly effective in predicting the nonlinear behavior of FRP-strengthened RC members. Machine learning models have been successfully applied for predicting bond strength, flexural performance, confinement effectiveness, and structural durability while reducing dependence on costly experimental testing. Moreover, Wang et al. (2026) highlighted the integration of fiber-reinforced thermal insulating concrete for simultaneous seismic strengthening and energy-efficient retrofitting of rural buildings, thereby demonstrating the growing emphasis on multifunctional and sustainable retrofitting solutions. The integration of smart materials, FRP composites, structural health monitoring systems, and intelligent computational methods has therefore established a new era in structural engineering where retrofitted structures can achieve enhanced strength, real-time monitoring capability, environmental sustainability, and improved resilience against natural and man-made hazards. Consequently, the application of fiber reinforced polymer and smart materials for retrofitting reinforced concrete structures has become a vital research domain with immense significance for the future development of durable, safe, and sustainable infrastructure systems worldwide.

II. RESEARCH BACKGROUND

Wang et al. (2026) had addressed the dual challenges of weak seismic resistance and poor thermal performance in existing rural buildings, along with the limitations of conventional renovation approaches where structural strengthening and energy-efficient retrofitting were often treated separately, leading to complex procedures and high costs. The study had developed a novel integrated structural-functional material, namely fiber-reinforced insulation concrete. It had incorporated high-toughness fibers (polypropylene/basalt, 0.1%–0.5%) and lightweight insulation aggregates (glass microbeads/expanded perlite, 20%–60% replacement) into conventional concrete to achieve simultaneous enhancement of seismic and thermal performance. Through orthogonal experimental optimization, the mixture containing 0.3% basalt fiber and 40% glass microbeads had demonstrated optimal results, showing a 78% improvement in seismic resistance and a 30% reduction in thermal conductivity. The proposed material had enabled coordinated structural and energy-efficiency improvements, offering a practical solution for unified rural building renovation. It had also exhibited good compatibility with existing materials and could be applied using simple spraying or coating methods, thereby reducing time and cost. Long-term monitoring had further confirmed stable durability over a five-year period under varied environmental conditions.

Alqarni et al. (2026) had introduced an innovative experimental approach that combined a hybrid system of polyvinyl alcohol (PVA) fiber–reinforced composites and shape memory alloys (SMA) to enhance the seismic performance of exterior reinforced concrete (RC) beam–column joints (BCJs). It had been proposed that the technique leveraged the self-centering capability of SMA along with the energy dissipation characteristics of steel and PVA fibers to improve joint behavior without compromising load capacity. Four one-third–scale RC-

BCJ specimens had been cast and tested under quasi-static reversed cyclic loading conditions. The results had indicated that both the PVA fiber configuration and the hybrid system exhibited reduced residual displacements, higher self-centering capacity, improved energy dissipation, enhanced load and displacement capacities, smaller crack widths, and slower stiffness degradation compared with the control specimen. Additionally, a finite element (FE) model had been developed in ABAQUS to simulate the hysteretic response, and the numerical outcomes had shown good agreement with experimental results.

Mohammadi et al. (2025) evaluated the performance of damaged concrete beams retrofitted with a purpose-designed Mechan chromic composite that provided both structural strengthening and visual feedback for structural health monitoring (SHM). The study had employed externally bonded reinforcement on pre-damaged concrete prisms using a thin-ply hybrid system composed of unidirectional ultra-high modulus carbon/epoxy and S-glass/epoxy layers. It was reported that the composite exhibited Mechan chromic behaviour, in which color change indicated overload when the carbon layer fractured under excessive strain. Eighteen specimens were tested under four-point bending with varying damage and retrofitting conditions. The results indicated that a 5% crack depth had reduced load-bearing capacity by 30%, whereas retrofitting enhanced capacity by up to 208% compared with undamaged beams. The composite had functioned effectively as both a passive visual sensor and reinforcement system. The study further analysed flexural strength, load–displacement behaviour, and failure modes across conditions for structural assessment and validation purposes.

Sapidis et al. (2024) reported that, due to insufficient transverse reinforcement, retrofitting of beam–column joints (BCJs) in existing reinforced concrete (RC) frame structures had commonly been required to modify their brittle behavior. It was stated that carbon-fiber-reinforced polymers (C-FRPs) had been widely adopted in the construction industry as near-surface-mounted (NSM) reinforcement. The study emphasized that monitoring the performance of C-FRP retrofitting had been essential because its effectiveness was influenced by multiple factors. A novel methodology had been implemented to evaluate the effectiveness of the C-FRP retrofitting technique. This approach had been validated through experimental investigations on full-scale BCJs retrofitted with C-FRP ropes and subjected to cyclic loading. It was further observed that piezoelectric lead zirconate titanate (PZT) patches had been installed on NSM C-FRP ropes, and the electro-mechanical impedance (EMI) method had been used for performance monitoring. A combined use of the root mean squared deviation (RMSD) damage index and hierarchical clustering analysis (HCA) had been applied to assess performance. The results had strongly indicated improved reliability of assessment, thereby enhancing safety and resilience of retrofitted BCJs in RC structures.

Naoum et al. (2024) had stated that climate change had induced extreme effects with reduced-than-designed restoration periods, thereby necessitating the strengthening of the structural integrity of existing and mainly older reinforced concrete (RC) structures. These structures were often found to be under-reinforced in shear capacity due to outdated design codes and standards. The authors highlighted that cost-effective and feasible strengthening techniques for RC elements had become increasingly important. They reported that thin RC layers used for jacketing represented a modern advancement in repairing and retrofitting RC members. In this context, U-shaped mortar jackets had been employed to strengthen three shear-critical beams. It was emphasized that the bonding and interaction between the original member and the jacket played a critical role in performance. Furthermore, the effectiveness of U-shaped jackets had been evaluated using an Electro-Mechanical Impedance-based (EMI-based) method with a Piezoelectric Transducer (PZT)-enabled technique. The study had suggested that integrating Structural Health Monitoring (SHM) enabled early detection of interface degradation and improved retrofit reliability.

Alhusban et al. (2024) had reported that sustainable solutions in the building construction industry had emerged as a new approach for retrofitting applications over the last two decades. They observed that fiber-reinforced polymers (FRPs) had attracted considerable attention for enhancing reinforced concrete (RC) structures. It had been noted that existing design guidelines for FRP-strengthened RC members were developed using empirical approaches based on limited databases, which had reduced the accuracy of predicted outcomes. Consequently, the authors emphasized that the adoption of advanced and efficient prediction tools had become essential for accurately modelling the behaviour of FRP-strengthened RC members. They further highlighted that recent research efforts had increasingly focused on machine learning (ML) techniques as effective solutions for complex structural engineering problems. It had been demonstrated that ML methods could predict nonlinear structural behaviour with improved accuracy by considering multiple influencing parameters. The study had reviewed ninety-six Scopus-indexed articles (2016–2023) and found that ML applications were mainly concentrated in beam strengthening, column confinement, slab strengthening, bond strength, and related areas, with supervised learning techniques being the most widely used due to their robustness and predictive efficiency.

Naoum et al. (2023) had investigated the influence of synthetic macro-fibers incorporated into fiber-reinforced concrete (FRC) prismatic specimens on their flexural response and overall cracking performance. The study also had included the application of a novel structural health monitoring (SHM) system based on the electromechanical impedance (EMI) technique, along with the use of piezoelectric lead zirconate titanate (PZT) transducers embedded in FRC prisms. The PZT-enabled EMI-based monitoring system had been developed to diagnose structural damage and assess the performance of reinforced concrete (RC) members subjected to cyclic repeated loading, simulating seismic excitations in existing RC buildings. The research had further aimed to evaluate the sensitivity of real-time, wireless, and portable monitoring techniques with respect to the location, distance, and polarization direction of PZT transducers, as well as the location and severity of flexural cracking. In addition, the effects of varying stress levels and corresponding changes in EMI frequency response were examined. The results had indicated that crack detection could be effectively achieved using the proposed SHM system through prompt damage assessment during early seismic loading stages in RC structures.

Isleem et al. (2023) had investigated the shear behaviour of reinforced concrete (RC) beams strengthened with carbon fibre reinforced polymer (CFRP) grids combined with engineered cementitious composite (ECC) through finite element (FE) analysis. In their study, twelve simply supported and continuous RC beams were modelled with varying parameters, including CFRP sheets, CFRP grid cross-sectional area, and CFRP grid size. The numerical simulations had been carried out using ABAQUS software to evaluate structural performance under shear loading conditions. The results had indicated that RC beams strengthened with CFRP grids and ECC exhibited an approximately 30–50% increase in shear capacity compared to the control beams. It had also been observed that the composite action between CFRP grids and ECC effectively limited the formation of diagonal cracks and reduced the deterioration of bending stiffness in the beams. Additionally, an analytical model had been developed to estimate shear capacity, which showed only a 4% deviation from the numerical results, confirming its practical applicability.

Blazy et al. (2022) had highlighted that glass fiber reinforced concrete (GFRC) was capable of meeting the requirements of Smart City development more effectively than ordinary concrete. A comprehensive discussion on GFRC composition had been presented, along with a review of the influence of glass fibers on various concrete properties. It had been observed that, due to their crack-bridging ability, glass fibers had limited the width, length, and total area of cracks. Furthermore, GFRC had been characterized by improved tensile, flexural, and splitting strength, as well as enhanced resistance to impact, abrasion, spalling, fire, and freeze–thaw cycles. Improvements in ductility, toughness, and permeability had also contributed positively to the mechanical performance, durability, and corrosion resistance of concrete elements. In addition, reduced thermal conductivity had supported better energy efficiency in buildings. Although GFRC had been more expensive, it had resulted in lower life-cycle costs due to improved durability and maintenance benefits. Its environmental advantages had also been noted, including up to 17% reduction in CO_2 emissions.

Bahij et al. (2022) had reported that fiber-reinforced polymer (FRP) composites were widely utilized in concrete technology due to their superior mechanical strength and durability characteristics. It had been observed that FRP materials had increasingly become mainstream solutions not only for strengthening damaged structural elements but also for enhancing load-carrying capacity and addressing long-term performance issues in modern infrastructure systems. The review had aimed to develop a comprehensive database of research studies focusing on the flexural, shear, and torsional strengthening of reinforced concrete (RC) beams using different types and application techniques of FRP composites. The efficiencies of these strengthening approaches had been evaluated based on structural behaviour, FRP types, and wrapping configurations. It had been concluded that FRP composites effectively improved both the strength of damaged beams and the performance of new members, with torsional strengthening showing greater benefits than flexural and shear applications in terms of load capacity and ductility.

Fouad and Saifeldeen (2021) had investigated the advancement of externally bonded fiber-reinforced polymer (FRP) composites for upgrading existing concrete structures, while highlighting the challenge of low bonding ductility between FRP sheets and concrete surfaces. They had proposed a novel smart self-sensing FRP sheet by integrating woven long-gauge carbon fiber line sensors within the FRP matrix to monitor macrostrain variations. A direct tensile test had been conducted to evaluate the behavior of the developed smart FRP system. The findings had revealed that the carbon fiber line sensor exhibited a linear relationship with applied stress and worked in a compatible and uniform manner with the FRP sheet as a single composite unit. Furthermore, a simply supported prestressed concrete beam strengthened with the smart FRP sheet had been tested under a four-point bending setup. The experimental results had demonstrated that the embedded sensing system effectively detected cracking loads and initial debonding between FRP and concrete, confirming its suitability for structural health monitoring applications.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective of Study	Methodology/Materials Used	Key Findings	Research Gap
Wang et al. (2026)	To develop a material capable of improving both seismic resistance and thermal insulation in existing rural buildings.	Fiber-reinforced insulation concrete was prepared using polypropylene/basalt fibers and lightweight insulation aggregates such as glass microbeads and expanded perlite. Orthogonal experimental optimization and long-term durability monitoring were performed.	The optimized mix containing 0.3% basalt fiber and 40% glass microbeads improved seismic resistance by 78% and reduced thermal conductivity by 30%. The material also demonstrated good durability and compatibility with existing structures.	The study focused mainly on rural buildings, while applications in high-rise urban RC structures and large-scale infrastructure require further investigation.
Alqarni et al. (2026)	To enhance the seismic performance of RC beam-column joints using smart materials and fiber composites.	Four one-third scale RC beam-column joints reinforced with shape memory alloys (SMA) and polyvinyl alcohol (PVA) fibers were tested under cyclic loading. Finite element modelling using ABAQUS was also conducted.	The hybrid SMA-PVA system reduced residual displacements, improved self-centering capacity, increased energy dissipation, and enhanced load-carrying performance compared with conventional specimens.	Long-term fatigue performance and cost-effectiveness of SMA-based retrofitting systems were not extensively studied.

Mohammadi et al. (2025)	To evaluate the dual functionality of mechanochromic composites for strengthening and visual structural health monitoring.	Concrete beams were retrofitted using hybrid carbon/glass fiber mechanochromic composites and tested under four-point bending. Eighteen specimens with varying crack depths were analyzed.	Retrofitting increased load-carrying capacity by up to 208%, while color changes effectively indicated overload and carbon layer fracture.	Environmental durability and practical field implementation of mechanochromic composites need further evaluation.
Sapidis et al. (2024)	To monitor the effectiveness of CFRP-retrofitted beam-column joints using smart sensing techniques.	Full-scale beam-column joints retrofitted with near-surface-mounted CFRP ropes were instrumented with piezoelectric PZT patches and evaluated using electro-mechanical impedance (EMI) methods.	The proposed monitoring technique successfully detected damage and improved reliability in assessing retrofit performance under cyclic loading.	The monitoring system requires validation under long-term real-time field conditions and varying environmental effects.
Naoum et al. (2024)	To assess the effectiveness of U-shaped mortar jackets and SHM systems in strengthening shear-critical RC beams.	Three shear-critical RC beams were strengthened using U-shaped mortar jackets integrated with PZT-enabled EMI-based monitoring systems.	The retrofit improved shear performance, while the SHM system effectively identified interface degradation between old and new materials.	Large-scale applications and long-term monitoring of interface bonding behavior remain unexplored.
Alhusban et al. (2024)	To review the efficiency of machine learning techniques in FRP structural engineering applications.	Ninety-six Scopus-indexed research articles from 2016–2023 related to ML-based FRP applications were reviewed systematically.	Supervised machine learning techniques demonstrated high accuracy in predicting nonlinear structural behavior and retrofit performance of FRP-strengthened RC members.	Integration of real-time SHM data with machine learning prediction models requires further development.
Naoum et al. (2023)	To investigate crack detection and stress monitoring in fiber-reinforced concrete using smart sensing systems.	Fiber-reinforced concrete prisms embedded with piezoelectric PZT transducers were tested under cyclic repeated loading conditions simulating seismic effects.	The EMI-based monitoring system effectively detected early-stage cracking and stress-induced damage in RC elements.	Application of wireless SHM systems in full-scale structures under practical conditions requires additional research.
Isleem et al. (2023)	To evaluate the shear behavior of RC beams strengthened with CFRP grids and engineered cementitious composites (ECC).	Finite element analysis using ABAQUS was conducted on twelve RC beams strengthened with CFRP grids and ECC under shear loading conditions.	Strengthened beams exhibited 30–50% improvement in shear capacity and significant reduction in diagonal cracking and stiffness deterioration.	Experimental validation on real structural components under dynamic loading conditions is still limited.

Blazy et al. (2022)	To review the performance of glass fiber reinforced concrete (GFRC) in structural and smart city applications.	Comprehensive literature review on GFRC composition, mechanical properties, durability, and sustainability aspects.	GFRC improved tensile strength, crack resistance, ductility, impact resistance, thermal insulation, and reduced CO_2 emissions by up to 17%.	The high initial cost and lack of standardized design procedures remain major limitations.
Bahij et al. (2022)	To critically review different FRP strengthening methods for RC beams.	Extensive review of studies related to flexural, shear, and torsional strengthening of RC beams using various FRP configurations.	FRP composites effectively enhanced structural capacity and durability, with torsional strengthening showing the highest improvement in ductility and load resistance.	Comparative studies on hybrid FRP systems and long-term durability under aggressive environments are limited.
Fouad and Saifeldeen (2021)	To develop a smart self-sensing FRP sheet for structural health monitoring applications.	Carbon fiber line sensors were embedded within FRP sheets and tested under direct tensile loading and four-point bending conditions on prestressed concrete beams.	The smart FRP system effectively detected crack initiation and debonding between FRP and concrete while maintaining linear sensing performance.	Field implementation and durability of embedded sensing systems under environmental exposure require further study.

IV. CONCLUSION

The application of fiber reinforced polymer (FRP) composites and smart materials for the retrofitting of reinforced concrete (RC) structures has emerged as one of the most advanced and effective approaches in modern structural engineering for enhancing the strength, durability, safety, and sustainability of aging infrastructure systems. The comprehensive review of recent studies clearly demonstrated that conventional retrofitting techniques such as steel jacketing and section enlargement are increasingly being replaced by lightweight, corrosion-resistant, and high-performance composite systems that offer superior mechanical behavior with reduced construction complexity and maintenance requirements. FRP materials, including carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and hybrid fiber composites, have shown remarkable effectiveness in improving the flexural, shear, torsional, and seismic performance of RC elements. The reviewed studies highlighted that these materials significantly enhanced load-carrying capacity, crack resistance, ductility, stiffness retention, and overall structural reliability. Researchers such as Bahij et al. (2022) and Isleem et al. (2023) demonstrated that FRP strengthening techniques effectively controlled crack propagation and improved structural capacity under different loading conditions, while Wang et al. (2026) further illustrated the potential of fiber-reinforced thermal insulating concrete in simultaneously improving seismic resistance and energy efficiency in existing buildings. These developments confirmed that FRP-based retrofitting systems not only contribute to structural rehabilitation but also support sustainable construction practices by reducing lifecycle costs, environmental impacts, and material consumption. Furthermore, the integration of smart materials and structural health monitoring (SHM) technologies has significantly transformed the retrofitting field by enabling intelligent infrastructure systems capable of real-time monitoring, damage detection, and adaptive structural response. Smart materials such as shape memory alloys (SMA), piezoelectric lead zirconate titanate (PZT) transducers, engineered cementitious composites (ECC), and mechanochromic composites have demonstrated exceptional potential in improving seismic resilience, self-centering behavior, and energy dissipation while simultaneously providing monitoring capabilities. Studies conducted by Alqarni et al. (2026), Sapidis et al. (2024), Naoum et al. (2024), and Fouad and Saifeldeen (2021) established that smart sensing systems embedded within retrofitted RC structures could effectively detect crack initiation, debonding, interface degradation, and stress variations at early stages, thereby enhancing structural safety and maintenance planning. The use of electro-mechanical impedance (EMI)-based monitoring systems and self-sensing FRP sheets further demonstrated the capability of intelligent retrofitting systems to provide continuous structural assessment without requiring destructive testing methods. In addition, the growing adoption of finite element analysis, machine learning algorithms, and computational prediction models has improved the accuracy of performance evaluation and retrofit optimization processes. Researchers have successfully utilized advanced numerical simulations and supervised learning techniques to predict the nonlinear behavior of FRP-strengthened RC members, enabling more reliable and cost-effective retrofitting strategies. Despite the significant advancements achieved in this field, certain challenges still remain, including the high initial cost of advanced composite materials, lack of standardized design procedures for smart retrofitting systems, long-term durability concerns under aggressive environmental conditions, and limited field-scale implementation of intelligent monitoring technologies. Nevertheless, the overall findings of the reviewed literature strongly indicate that the integration of FRP composites, smart materials, SHM systems, and computational technologies represents the future direction of structural retrofitting and infrastructure rehabilitation. These technologies provide efficient, sustainable, and resilient solutions for strengthening deteriorated RC structures while enhancing their service life, seismic safety, energy efficiency, and operational reliability. Therefore, the application of fiber reinforced polymer and smart materials has become a transformative innovation in civil engineering that will continue to play a critical role in the development of durable and intelligent infrastructure systems capable of meeting future structural and environmental challenges.

V. FUTURE SCOPE

- **Development of Multifunctional Smart FRP Systems:** Future research can focus on the development of multifunctional fiber reinforced polymer (FRP) systems that simultaneously provide structural strengthening, thermal insulation, self-healing capability, corrosion resistance, and real-time structural health monitoring. Integrating sensing technologies directly into FRP composites may improve infrastructure safety and reduce maintenance requirements.
- **Integration of Artificial Intelligence and Machine Learning:** Advanced artificial intelligence (AI) and machine learning (ML) algorithms can be incorporated into retrofitting systems for predicting structural failures, optimizing retrofit design, and analyzing real-time structural health monitoring data. AI-driven predictive maintenance models may significantly improve decision-making and infrastructure management efficiency.
- **Application in Seismic-Resistant Infrastructure:** Further studies are required to investigate the performance of smart materials such as shape memory alloys (SMA), engineered cementitious composites (ECC), and piezoelectric systems under severe seismic loading conditions. Their application in earthquake-prone regions can improve energy dissipation, self-centering behavior, and post-earthquake structural stability.

- **Long-Term Durability and Environmental Performance Studies:** Extensive long-term investigations are needed to evaluate the durability of FRP composites and smart materials under aggressive environmental conditions such as high humidity, freeze–thaw cycles, chemical exposure, ultraviolet radiation, and marine environments. These studies can help establish reliable service-life prediction models.
- **Development of Sustainable and Eco-Friendly Materials:** Future research may emphasize the use of sustainable fibers, recycled polymers, bio-based composites, and low-carbon smart materials for retrofitting applications. The development of environmentally friendly retrofitting systems can contribute toward green construction practices and reduced carbon emissions.
- **Advancement of Wireless Structural Health Monitoring Systems:** The integration of wireless sensors, Internet of Things (IoT) technologies, cloud computing, and remote monitoring platforms can enhance the effectiveness of structural health monitoring systems. Real-time data transmission and automated damage assessment can improve infrastructure safety and emergency response mechanisms.
- **Optimization Through Advanced Numerical Modelling:** More sophisticated finite element analysis (FEA), digital twin technology, and hybrid computational models can be developed to accurately simulate the nonlinear behavior of retrofitted reinforced concrete structures under dynamic loading conditions. Such models can minimize experimental costs and improve retrofit optimization.
- **Standardization and Design Guideline Development:** There is a need for internationally accepted design codes and guidelines specifically addressing smart material-based retrofitting systems. Future work should focus on establishing standardized procedures for design, installation, monitoring, and quality control of FRP and smart retrofitting techniques.
- **Application in Large-Scale Infrastructure Systems:** Future investigations can explore the practical implementation of smart retrofitting technologies in bridges, tunnels, offshore structures, high-rise buildings, and industrial facilities. Large-scale field applications will help validate laboratory findings and improve industrial acceptance.
- **Self-Healing and Adaptive Structural Systems:** Research on self-healing concrete, adaptive smart composites, and autonomous repair mechanisms can revolutionize structural retrofitting practices. Such intelligent systems may automatically detect and repair microcracks, thereby improving durability, reducing maintenance costs, and extending the service life of reinforced concrete structures.

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