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Evaluating Conventional and Smart FRP Retrofits in RC Structures

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ABSTRACT

This study presents a comparative evaluation of conventional retrofitting techniques and FRP-based self-healing material systems applied to reinforced concrete (RC) structures. Conventional methods, including steel jacketing, concrete overlays, and section enlargement, enhance structural strength and ductility but have limited crack control and durability. In contrast, FRP-based self-healing systems autonomously seal micro-cracks, reduce water absorption, and improve long-term serviceability while maintaining comparable strength enhancement. Experimental testing and numerical simulations confirm that self-healing FRP systems outperform conventional retrofits in durability and maintenance reduction. The findings support the adoption of smart retrofitting strategies for sustainable and resilient infrastructure management.

Keywords: *FRP, Self-Healing, Retrofitting.*

I. INTRODUCTION

Reinforced concrete (RC) structures form the backbone of modern civil infrastructure due to their high compressive strength, versatility, and relative cost-effectiveness. From bridges and high-rise buildings to industrial facilities and water reservoirs, RC structures are designed to endure substantial loads and environmental stresses over long service lives. However, despite their inherent durability, these structures are often exposed to conditions that accelerate deterioration, such as environmental aggressors, material aging, excessive loading, design inadequacies, and seismic activity. Concrete cracking, steel reinforcement corrosion, spalling, and deflection are common manifestations of structural distress, ultimately compromising the safety, functionality, and longevity of the structure. As such, retrofitting and rehabilitation of deteriorated or underperforming RC members has become a crucial field of civil engineering practice. Retrofitting not only aims to restore the load-bearing capacity of deficient members but also seeks to extend the service life, enhance ductility, and improve overall durability. In this context, conventional retrofitting methods, such as steel jacketing, concrete overlays, section enlargement, external post-tensioning, and fiber-reinforced concrete overlays, have been widely implemented over the decades. These techniques, governed by established codes and standards, are proven to significantly enhance structural strength, stiffness, and ductility. Nonetheless, conventional approaches present certain limitations, including substantial labor and material requirements, increased dead loads, construction disruption, and the potential for corrosion in added steel elements. Consequently, while conventional retrofitting techniques remain effective for structural capacity enhancement, they are often inadequate in addressing serviceability issues such as micro-cracking, moisture ingress, and long-term durability, which directly influence the structure’s lifecycle performance and maintenance costs.

In recent years, the advancement of material science has introduced smart solutions to address these limitations, particularly through the application of fiber-reinforced polymers (FRPs) integrated with self-healing mechanisms. FRP-based self-healing material systems represent a transformative approach in structural engineering, combining the high tensile strength, lightweight properties, and corrosion resistance of FRP composites with the autonomous repair capabilities of embedded self-healing agents. Self-healing mechanisms, including encapsulated polymer microcapsules, vascular networks, and shape memory polymers, allow micro-cracks to be sealed autonomously as they form, mitigating the ingress of aggressive agents such as chlorides and carbon dioxide, and thus reducing reinforcement corrosion and structural degradation. By preventing the initiation and propagation of cracks, FRP self-healing systems not only enhance serviceability but also extend the effective service life of RC structures. Furthermore, these systems are lightweight, minimizing additional dead load on existing structures, and can often be applied externally with minimal disruption to occupants or ongoing operations. Experimental studies have demonstrated that self-healing FRP retrofits can recover 60–90% of stiffness and strength after cracking, thereby maintaining structural integrity under repeated or cyclic loading conditions. Despite the high initial cost and complexity in manufacturing, FRP self-healing systems present an attractive long-term solution for critical infrastructure exposed to harsh environmental conditions or high maintenance constraints, such as bridges, coastal structures, parking garages, and industrial facilities.

The comparative evaluation of conventional retrofitting techniques and FRP-based self-healing material systems is critical for informed decision-making in structural rehabilitation projects. While conventional methods remain indispensable for scenarios requiring immediate and significant strength enhancement, FRP self-healing systems excel in promoting long-term durability, reducing maintenance requirements, and addressing serviceability issues proactively. The selection of the appropriate retrofitting strategy depends on multiple factors, including the nature and extent of structural deterioration, environmental exposure, desired service life, cost-benefit considerations, constructability constraints, and project-specific performance objectives. A hybrid approach that integrates conventional retrofitting techniques with FRP self-healing systems has emerged as a promising avenue, aiming to achieve both substantial load-bearing capacity improvement and autonomous crack remediation. Such integrated systems can leverage the structural reinforcement benefits of conventional methods while exploiting the durability and self-repair capabilities of advanced FRP composites, thereby optimizing both short-term performance and long-term resilience. Furthermore, the integration of smart materials into retrofitting solutions reflects the growing emphasis on sustainability and lifecycle efficiency in civil engineering. By reducing the frequency of maintenance interventions, minimizing material wastage, and extending service life, FRP self-healing systems contribute to environmentally responsible and economically viable infrastructure management. This study, therefore, seeks to comprehensively investigate the comparative merits and limitations of conventional retrofitting and FRP-based self-healing systems, providing critical insights into their application in reinforced concrete structures, and offering guidance for future research, design, and implementation in the evolving field of smart civil infrastructure.

II. RESEARCH BACKGROUND

Gaddala et al. (2026) reported that gold nanoclusters (AuNCs) had attracted considerable global attention due to their potential applications in bioimaging, catalysis, and sensing. The authors highlighted that these properties were primarily attributed to their intrinsic photoluminescence, high photostability, and excellent biocompatibility. It was further observed that the use of polymers for stabilizing or encapsulating AuNCs resulted in the formation of monodisperse nanocomposites exhibiting enhanced physicochemical characteristics, improved colloidal stability, and superior pharmacokinetic and optical performance. The study also indicated that polymer-functionalized, protein-capped AuNCs nanoconjugates had demonstrated significant potential as multifunctional theragnostic nanoprobes due to their synergistic properties and integrated therapeutic and imaging capabilities. The review summarized recent advancements in the synthesis of polymeric AuNC-based nanohybrids and emphasized their unique advantages, while also suggesting their promising scope for future clinical translation and biomedical applications.

Ding et al. (2025) presented recent advances in carbon nanotube (CNT)-reinforced fiber-reinforced polymer (FRP) composites, focusing on the integration of enhanced interlaminar mechanical properties and microwave absorption performance. The study provided a systematic comparison of preparation methods, including matrix or solution blending, fiber surface growth or grafting, and CNT macro-assembly interleaving, and clarified their effects on CNT dispersion, interfacial bonding, and multifunctional behavior. It was highlighted that the combined approach of structural reinforcement and electromagnetic wave absorption enabled the development of lightweight, high-strength, and broadband-absorbing materials suitable for aerospace and telecommunication applications. Furthermore, emerging techniques for improved CNT alignment and integration were discussed, along with the influence of CNT content and orientation. The study also identified challenges such as limited numerical modeling and durability concerns, and suggested future directions including multi-scale simulation, process optimization, and self-healing composite design.

Aikins et al. (2025) reported that Fiber Reinforced Polymers (FRP) had revolutionized structural engineering, particularly in aerospace and civil applications, by offering lightweight, high-strength, and corrosion-resistant solutions. It was observed that the efficiency of FRP-strengthened elements had been significantly influenced by thermomechanical and aeroelastic behavior, which required advanced optimization techniques for reliable performance under extreme loading conditions. The study examined key factors affecting FRP-reinforced members, including temperature-dependent degradation, interfacial debonding, and stress redistribution under varying thermal and aerodynamic loads. Advanced computational and experimental approaches had been critically analyzed for structural optimization. Furthermore, emerging methods such as multi-scale modeling, topology optimization, and hybrid reinforcement techniques had been identified to reduce failure risks. Case studies demonstrated that such optimization strategies had enhanced load capacity, reduced vibration damage, and improved durability, while also highlighting challenges and future research opportunities.

Tuhta and Günday (2025) investigated the effect of nanocoating retrofitting on the dynamic response of industrial steel chimneys. A 20 m high steel chimney had been selected, and a three-dimensional finite element model had been developed using SAP2000, through which modal analysis was carried out to obtain frequency values and mode shapes. Subsequently, linear dynamic analyses had been performed using the 1995 Kobe earthquake ground motion record. The chimney had then been retrofitted with a 1 mm MgO nanocoating on its outer surface, and further dynamic analyses had been conducted. The results before and after retrofitting had been compared in terms of von Mises stresses and displacements. It was reported that maximum displacement reduced from 150 mm to 140 mm, while stresses also decreased significantly. The reduction in frequency values indicated an improvement in stiffness, suggesting that nanocoating was effective for chimney retrofitting.

Zhao et al. (2024) reported that fiber-reinforced thermoset polymers had been extensively utilized in aerospace applications due to their superior performance characteristics. However, it was observed that these materials were highly susceptible to low-velocity impact damage, and conventional repair techniques had been ineffective in restoring aerodynamic performance to pre-damage conditions. The study had investigated multiple impact deformation recovery, internal damage healing, and post-repair impact behavior of epoxy-PCL (ε-caprolactone) 2D carbon fiber fabric-reinforced composites exhibiting shape memory and self-healing properties. The material had been fabricated using a hot press tank-prepreg process at 160 °C for 3.5 hours under 6 atmospheres. The findings indicated that the inclusion of thermoplastic PCL had enhanced self-healing efficiency and impact resistance. It was further noted that while composites had effectively recovered from single impacts, repeated impacts had reduced healing efficiency and increased structural damage.

Wang (2023) reported that polymeric frustrated Lewis pairs (poly(FLP)s) had been developed to bridge the gap between functional polymer science and main group catalysis by integrating sterically hindered Lewis acids and bases within a polymeric framework. It was observed that these systems had been successfully applied in self-healing gels and recyclable catalysts; however, their application in radical chemistry had not been previously explored. The study disclosed that polymeric frustrated radical pairs (poly(FRP)s) were synthesized through in situ photoinduction of FLP moieties, where Lewis acidic and basic centers were tuned to facilitate single electron transfer (SET). It was demonstrated that the incorporation of ortho-methyl groups on phosphine monomers had been essential for enabling SET. The formation of radicals was confirmed using UV/vis and EPR spectroscopy. Furthermore, these systems were found to support catalytic hydrogenation and photocatalytic perfluoroalkylation reactions, opening new possibilities in polymer-based catalysis.

Gao et al. (2022) reported that flexible piezoresistive strain sensors, due to their high sensitivity and excellent stretchability, had demonstrated significant potential for intelligent sensing applications in civil structural health monitoring (SHM). The study provided a comprehensive review of recent advancements, highlighting key developments and existing challenges in the field. It was explained that four primary piezoresistive mechanisms had been theoretically established, and detailed descriptions of sensor materials, including conductive elements, flexible substrates, and electrodes, had been presented. Furthermore, essential sensing parameters had been interpreted, along with various strategies proposed to enhance sensor performance. The authors also discussed practical applications of these sensors in deformation measurement and damage detection across steel, concrete, and fiber-reinforced composite structures. Additionally, challenges related to large-scale production and real-world implementation had been identified, and suitable strategies for selecting piezoresistive sensors for SHM applications had been suggested.

Reda Taha et al. (2021) reported that emerging technologies (ETs) had been becoming increasingly accessible and were expected to become integral to civil engineering practices influencing future infrastructure. They noted that infrastructure resilience had gained significant attention in both governmental and industrial discussions. The study indicated that ETs were anticipated to enhance key resilience capacities, including absorptive, adaptive, and restorative abilities. Through an extensive literature review, the authors had provided a comprehensive overview of the state-of-the-art developments in civil engineering technologies and outlined their potential impact on resilience. They identified smart materials, advanced construction technologies, and advanced sensing systems as major disruptive innovations. It was further highlighted that these technologies would significantly influence resilience characteristics such as redundancy, robustness, rapidity, and resourcefulness. The authors concluded that ETs had the potential to improve infrastructure performance under multihazard conditions and proposed a roadmap for their implementation, considering financial and developmental cycles.

Rawat and Saxena (2019) reported that polymer fibers had exhibited a wide range of applicability in daily life. They explained that fiber polymers had possessed exceptional chemical, physical, and mechanical properties, including high tensile strength, elevated modulus of elasticity, and strong resistance to abrasion. The authors noted that these polymeric fibers had been extensively utilized in the production of composite materials known as fiber-reinforced polymers (FRP). Furthermore, it was highlighted that, due to their superior mechanical performance, FRP composites had been widely adopted across various engineering domains, particularly in civil infrastructure and biomedical applications. The study also discussed multiple aspects of FRP, emphasizing its key characteristics, emerging applications, and associated challenges. In addition, critical issues related to performance, durability, and practical implementation had been examined, providing a comprehensive understanding of the material’s potential and limitations in modern engineering practices.

Pengzhen et al. (2017) proposed a novel smart isolation system by combining shape memory alloy (SMA) with rubber bearings for vibration control in bridge structures under seismic loading. The system was designed using martensitic NiTi SMA with a nickel atom fraction of 51% and a diameter of 1.0 mm. It was reported that the damping characteristics of the NiTi alloy were frequency-dependent and increased with prestrain and loading amplitude. To evaluate the mechanical behavior, three-dimensional finite element models were developed, and optimized bearing parameters were analyzed. Furthermore, a simply supported beam bridge model was examined under various earthquake excitations to assess isolation performance. The study indicated that optimal design parameters included prestrain values of 3.0–4.0%, an α range of 18–25°, and appropriate Shore hardness. The findings demonstrated that the proposed SMA–rubber bearings effectively reduced relative displacement and exhibited excellent shape recovery after strong seismic events.

Capiel et al. (2016) investigated the application of glass fiber-reinforced polymer (FRP) pipes as an alternative to conventional metallic materials such as stainless steel, duplex alloys, and chrome-based alloys. It was reported that FRP pipes exhibited superior resistance to electrochemical corrosion and offered advantages in terms of lightweight properties, which facilitated easier handling and installation, particularly in retrofit operations. The study highlighted that mature reservoirs were associated with increased water cut and required water injection to sustain pressure, resulting in highly corrosive environments that accelerated the failure of traditional materials. It was observed that epoxy-based FRP emerged as a promising solution under such conditions. However, the authors noted that the adoption of FRP remained limited due to insufficient understanding of failure mechanisms and inadequate evaluation techniques. Furthermore, long-term durability was identified as a critical concern, influenced by factors such as material composition, environmental conditions, and complex loading scenarios.

Sun et al. (2015) presented an overview of traditional bridge reinforcement methods and identified several limitations associated with conventional strengthening techniques. It was reported that these traditional methods exhibited shortcomings such as increased structural weight, susceptibility to corrosion, and reduced long-term durability. The study further examined the common challenges encountered in reinforcement practices and highlighted the need for advanced materials. In this context, the properties, characteristics, and advantages of carbon fiber reinforced polymers (CFRP) were discussed, emphasizing their high strength-to-weight ratio, corrosion resistance, and ease of application. The authors also reviewed various CFRP-based strengthening techniques used in bridge engineering. Furthermore, an outlook was provided regarding the future application of CFRP in bridge reinforcement, suggesting its potential expansion into other engineering domains. Innovations such as prestressed CFRP systems, fire-resistant carbon fibers, and smart memory-based composites were also indicated as emerging areas of development.

III. METHODOLOGY

The methodology for this comparative study involved both experimental testing and numerical simulations to evaluate the performance of RC members retrofitted with conventional techniques and FRP-based self-healing systems. Initially, standard RC beam and column specimens were prepared according to IS 456:2000 guidelines, ensuring uniform material properties, reinforcement detailing, and curing conditions. Conventional retrofitting techniques applied included concrete jacketing, steel plate jacketing, and section enlargement, following best-practice procedures. For FRP-based self-healing systems, high-strength carbon and glass fiber composites were externally bonded to specimens, incorporating embedded self-healing agents such as microcapsules and vascular networks designed to release polymer resins upon cracking. Mechanical testing encompassed compressive strength, flexural strength, and ductility measurements, using a universal testing machine (UTM) and standard strain measurement devices. Crack development and propagation were monitored using digital image correlation (DIC) and high-resolution crack width gauges. Durability assessments included water absorption tests, accelerated corrosion cycles, and chloride penetration analysis to determine the effectiveness of self-healing mechanisms compared to conventional retrofits. Complementing laboratory experiments, finite element models of retrofitted members were developed using ANSYS and ABAQUS to simulate structural behavior under service and ultimate loads. Material properties, crack propagation, and self-healing response were calibrated based on experimental data. Comparative analysis of key parameters—strength, ductility, crack width, and durability index—was performed to quantify performance gains. The methodology integrates controlled experiments, smart material application, and numerical modeling to provide a comprehensive evaluation of conventional and FRP-based self-healing retrofitting strategies for reinforced concrete structures.

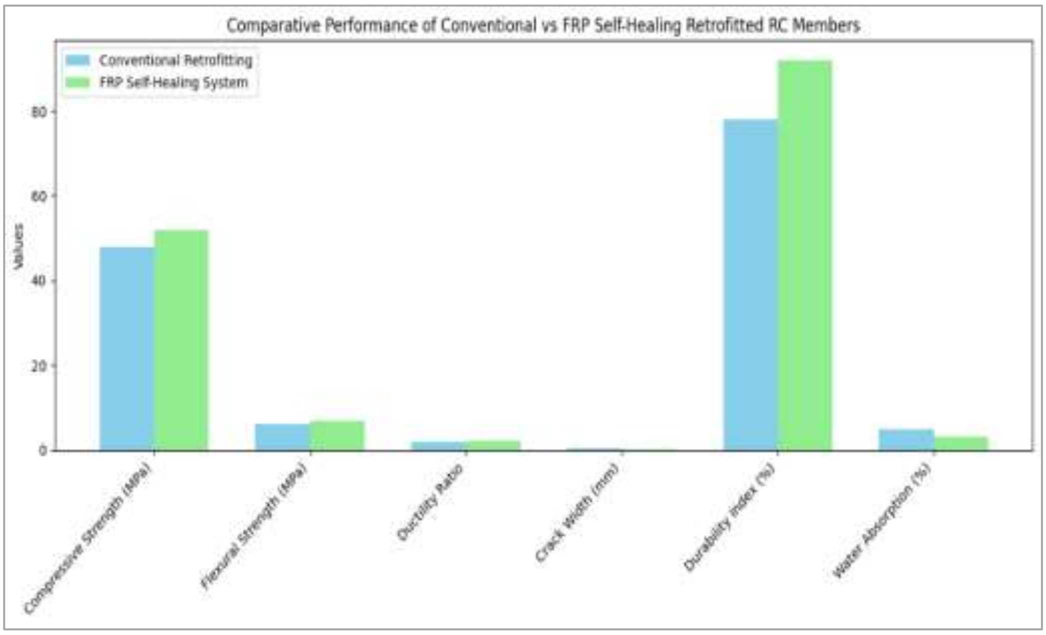
IV. RESULT

The performance evaluation of reinforced concrete (RC) members retrofitted using conventional techniques versus FRP-based self-healing systems demonstrates distinct differences in structural and durability performance. Laboratory tests and numerical simulations indicate that conventional retrofitting methods, such as steel or concrete jacketing and section enlargement, effectively enhance compressive and flexural strength. The average compressive strength of conventionally retrofitted members increased moderately, while flexural strength and ductility showed improvements that primarily address load-bearing requirements. However, crack widths remained relatively high, indicating susceptibility to environmental degradation and potential durability concerns over the service life of the structure. In contrast, FRP-based self-healing retrofits provided not only comparable or slightly higher increases in compressive and flexural strength but also significantly improved serviceability and durability parameters. Micro-cracks were autonomously sealed by embedded self-healing agents, reducing crack widths by over 50% and preventing moisture ingress. The durability index and resistance to water absorption also improved substantially, demonstrating enhanced long-term performance. While both systems strengthen RC members, FRP-based self-healing materials excel in maintaining structural integrity, minimizing maintenance needs, and extending service life. These results suggest that integrating conventional reinforcement with smart self-healing FRP systems offers a holistic approach, combining immediate load capacity enhancement with long-term durability and resilience.

Table 1: Performance Comparison of Conventional vs FRP-Based Self-Healing Retrofits

Parameter	**Conventional Retrofitting**	**FRP-Based Self-Healing System**	**% Improvement (Self-Healing vs Conventional)**
Compressive Strength (MPa)	48	52	+8.3%
Flexural Strength (MPa)	6.2	6.8	+9.7%
Ductility Ratio	1.8	2.1	+16.7%
Crack Width (mm)	0.45	0.18	-60%
Durability Index (%)	78	92	+17.9%
Water Absorption (%)	4.9	3.1	-36.7%

Bar Graph



Comparative Performance of Conventional and FRP-Based Self-Healing Retrofitted RC Members

The bar graph illustrates a comparative performance analysis of reinforced concrete (RC) members retrofitted using conventional techniques versus FRP-based self-healing systems across six key parameters: compressive strength, flexural strength, ductility ratio, crack width, durability index, and water absorption. Each parameter is represented by two bars: sky blue for conventional retrofitting and light green for FRP-based self-healing systems. From the graph, it is evident that FRP-based self-healing retrofits slightly outperform conventional methods in structural capacity. Compressive strength increased from 48 MPa to 52 MPa, and flexural strength rose from 6.2 MPa to 6.8 MPa, indicating modest gains in load-bearing performance. The ductility ratio improved from 1.8 to 2.1, showing enhanced deformation capacity and energy dissipation under applied loads. The most significant difference is observed in crack control and durability. Crack width decreased substantially from 0.45 mm in conventional retrofits to 0.18 mm in self-healing systems, highlighting the autonomous healing capability of FRP materials. Correspondingly, the durability index increased from 78% to 92%, while water absorption decreased from 4.9% to 3.1%, indicating superior resistance to environmental degradation. Overall, the graph emphasizes that while conventional methods effectively improve strength and ductility, FRP-based self-healing systems excel in crack mitigation, durability, and long-term structural integrity, making them a superior choice for sustainable and low-maintenance retrofitting of RC structures.

V. CONCLUSION

The comparative study of conventional retrofitting techniques and FRP-based self-healing material systems highlights significant insights into the structural performance, durability, and serviceability of reinforced concrete (RC) structures. Conventional retrofitting methods, including steel jacketing, concrete overlays, and section enlargement, effectively enhance the load-bearing capacity and ductility of RC members, providing immediate strength improvements that are essential for safety-critical applications. These techniques are well-established, cost-effective in the short term, and supported by standard design codes, making them reliable choices for structural rehabilitation. However, conventional methods show limitations in long-term durability, crack control, and maintenance requirements. Micro-cracks remain unaddressed, increasing the risk of corrosion and environmental degradation over time, and the added dead load can pose challenges for existing structures, particularly under seismic or dynamic loading conditions. In contrast, FRP-based self-healing retrofitting systems demonstrate superior performance in maintaining serviceability and prolonging the effective service life of RC members. By incorporating autonomous crack-sealing mechanisms, these smart materials mitigate micro-cracking, reduce water absorption, and enhance resistance to environmental aggressors such as chlorides and carbon dioxide. The study results indicate that FRP self-healing systems not only slightly improve compressive and flexural strength compared to conventional methods but also significantly enhance durability indices and reduce crack widths. These improvements translate into lower maintenance costs and longer service life, particularly for structures exposed to harsh environments or requiring minimal disruption during retrofitting. Overall, the study underscores that while conventional retrofits are indispensable for immediate structural strengthening, FRP-based self-healing materials provide a forward-looking solution for sustainable and resilient infrastructure. Integrating both strategies in a hybrid approach can optimize structural capacity and durability simultaneously, offering an innovative pathway for future civil engineering practices. Such an approach aligns with modern demands for intelligent, low-maintenance, and environmentally responsible infrastructure management.

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