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Enhancing Reinforced Concrete Performance Using FRP and Smart Materials

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ABSTRACT

This study investigates the application of Fiber Reinforced Polymer (FRP) and smart materials for retrofitting reinforced concrete (RC) structures. A MATLAB R2017b GUI-based model was developed to assess improvements in flexural and shear capacity, stiffness, deflection, crack control, damage reduction, damping, and overall performance. Results indicate that the hybrid FRP-smart material system significantly enhances structural strength, serviceability, durability, and resilience compared to original and conventionally retrofitted members. Smart materials further enable real-time structural health monitoring, supporting predictive maintenance and long-term reliability. The methodology provides an effective framework for sustainable, cost-efficient, and high-performance RC retrofitting.

Keywords: *Fiber Reinforced Polymer, Smart Materials, Structural Retrofitting, Reinforced Concrete.*

I. INTRODUCTION

Reinforced concrete (RC) structures constitute the backbone of modern civil infrastructure due to their high compressive strength, durability, adaptability to various forms, and economic feasibility, making them the preferred choice for buildings, bridges, industrial facilities, flyovers, water tanks, parking decks, and other critical structural systems; however, over time, these structures often experience deterioration arising from environmental exposure, excessive or unanticipated loading, material ageing, corrosion of steel reinforcement, shrinkage and thermal cracks, design deficiencies, construction quality issues, and seismic or dynamic loads, which may compromise their load-carrying capacity, serviceability, and overall safety. With the accelerated pace of urbanization, increased traffic demands, and evolving functional requirements, many existing RC structures may no longer satisfy contemporary design codes or performance expectations, necessitating effective retrofitting strategies to restore or enhance their structural integrity without resorting to complete demolition, which is often economically prohibitive and environmentally unsustainable. Structural retrofitting, in this context, is defined as the process of improving the performance of an existing structure through techniques that increase its strength, stiffness, ductility, durability, and service life, addressing both present and future load conditions, while also mitigating vulnerabilities due to damage, deterioration, or under-designed members. Traditional retrofitting methods such as concrete jacketing, steel plate or steel jacketing, epoxy injection, cement grouting, section enlargement, shotcrete application, and external post-tensioning have been widely used to repair and strengthen RC members, offering improvements in flexural and shear strength, column confinement, and crack repair; nevertheless, these conventional approaches present several limitations, including increased dead weight, larger member dimensions, higher labour requirements, longer construction time, susceptibility to corrosion, aesthetic concerns, and potential disruption to the normal use of the structure, which render them less suitable in cases where lightweight, rapid, durable, and minimally intrusive solutions are required, particularly in heritage, industrial, or high-traffic applications. In response to these challenges, Fiber Reinforced Polymer (FRP) composites have emerged as a transformative technology for structural retrofitting, combining high-strength fibers such as carbon, glass, aramid, or basalt with a polymer matrix, wherein the fibers serve as the primary load-resisting components while the polymer resin binds, protects, and transfers stress effectively; this composite system provides a high tensile strength-to-weight ratio, excellent corrosion resistance, fatigue endurance, flexibility in application, and ease of installation, enabling the strengthening of beams, slabs, columns, joints, and other critical RC members with minimal addition to self-weight and minimal alteration of architectural aesthetics. FRP is applied in the form of sheets, laminates, wraps, or bars for flexural strengthening, shear reinforcement, seismic retrofitting, and column confinement, with specific types selected based on performance, durability, cost, and environmental considerations: carbon fiber reinforced polymer (CFRP) is widely used for high-performance, high-strength applications due to its exceptional stiffness and tensile capacity; glass fiber reinforced polymer (GFRP) offers a cost-effective solution with good corrosion resistance and moderate strength; basalt fiber reinforced polymer (BFRP) provides an environmentally friendly option with thermal and chemical stability; and aramid fiber reinforced polymer (AFRP) offers high impact resistance and tensile performance for specialized structural applications. Complementing FRP systems, the incorporation of smart materials, such as shape memory alloys (SMA) and self-healing composites, further enhances retrofitting efficiency by improving structural damping, energy dissipation, crack control, and resilience under dynamic, cyclic, or seismic loading, while also enabling real-time structural health monitoring (SHM), which facilitates the assessment of stress distribution, crack formation, and damage progression without intrusive inspection or destructive testing. Modern smart-material-based retrofitting systems often integrate computational and analytical tools, including MATLAB-based modeling, finite element simulations using software such as ABAQUS, and machine learning approaches, to predict nonlinear structural behavior, optimize retrofit configurations, estimate improvement in flexural, shear, and stiffness capacities, and evaluate long-term durability and service life extension, allowing engineers to make informed decisions about the design, placement, and quantity of FRP layers and the incorporation of self-healing agents for maximum performance. The hybrid application of FRP and smart materials offers a multi-faceted advantage over conventional methods, as it simultaneously enhances strength-related parameters including flexural and shear capacities, improves serviceability indicators such as deflection and stiffness, controls crack propagation, reduces damage indices, and facilitates structural monitoring and preventive maintenance, resulting in safer, more durable, and cost-effective rehabilitation of RC structures. Furthermore, self-healing FRP systems are particularly beneficial in controlling micro-cracks and reducing permeability, thereby extending the service life of structures while minimizing maintenance costs and environmental impact. Research and experimental studies have demonstrated substantial performance improvements in retrofitted RC members, with flexural capacity increases exceeding 70%, shear capacity improvements of over 25%, reductions in deflection and crack width, enhanced damping characteristics, and significant extension in structural life, confirming the effectiveness and reliability of FRP-smart material hybrid systems. Consequently, the integration of FRP composites, smart materials, and intelligent monitoring represents a paradigm shift in structural retrofitting, transitioning from traditional repair-oriented practices to advanced, multifunctional, sustainable solutions capable of restoring, strengthening, and monitoring reinforced concrete structures efficiently. The study of FRP and smart material applications in retrofitting is therefore of immense significance to civil engineering, as it addresses the challenges of aging infrastructure, rising load demands, environmental degradation, and sustainability, ensuring that existing reinforced concrete structures can meet current performance requirements and continue to function safely, reliably, and economically for extended service periods.

II. RESEARCH BACKGROUND

Hosseini et al. (2026) had reported that fibre-reinforced polymer (FRP) confinement of reinforced concrete columns had been widely used as an effective strengthening technique in civil engineering practice. It had been emphasized that columns, being critical load-bearing members, could lead to catastrophic structural collapse upon failure. The study had aimed to bridge gaps in existing knowledge by conducting a comprehensive investigation on the use of carbon fibre-reinforced polymer (CFRP) and aramid fibre-reinforced polymer (AFRP) composites for retrofitting applications. It had further examined the effect of CFRP layer quantity and the incorporation of aramid fibres on enhancing blast resistance. Experimental findings from Yan et al. (2020), involving 12 columns with varying thickness and strengthening configurations, had been validated using the finite element software LS-DYNA. The numerical results had indicated that CFRP strengthening improved damage resistance and reduced residual displacement. The validated model had further shown that AFRP exhibited higher blast resistance and energy absorption capacity compared to CFRP under similar loading conditions.

Li and Zhang (2026) had reported that marine environments significantly affected the longevity of concrete structures, thereby necessitating advanced reinforcement techniques to mitigate corrosion and enhance service life. The study had examined the adhesion behavior between Carbon Fiber Reinforced Polymer (CFRP) rebars and aluminium oxide (Al_2O_3) nanoparticle-reinforced concrete and had compared the results with conventional steel reinforcement. Mechanical properties of nanoparticle-modified concrete had been evaluated through experimental testing and were further simulated using nonlinear finite element analysis in ABAQUS software, where a separation-slip model had been applied to represent the bond mechanism. Pullout tests had validated the numerical model, confirming its reliability. It had been observed that incorporating 0.25% and 0.5% Al_2O_3 nanoparticles had increased the tensile strength of reinforced concrete by 118.5% and 134.7%, respectively, compared with standard concrete. Parametric analysis had shown distinct adhesion behaviors for CFRP and steel rebars. Steel rebars had exhibited higher pullout resistance due to stronger mechanical bonding, whereas larger CFRP diameters had improved chemical bonding and pullout capacity. Overall, the study had concluded that Al_2O_3 nanoparticles had effectively enhanced bond strength and durability in corrosive marine conditions.

Xia et al. (2025) had reported that steel structures were prone to cracking under service loads, fatigue loading, and corrosion, leading to progressive structural degradation. It was emphasized that structural health monitoring was necessary to ensure the safe and continuous operation of such structures. The study noted that conventional monitoring techniques were often limited to controlled testing environments, involved time-consuming procedures, and sometimes caused damage to the monitored structures. In contrast, Carbon Fiber Reinforced Polymer (CFRP) was identified as a novel sensing material due to its superior piezoresistive properties. The research had investigated the mechanism of electrical resistance variation in CFRP under structural changes and proposed optimization measures to enhance its self-sensing performance. Three types of CFRP elements (Y-, S-, and N-types) were designed and tested through monotonic and cyclic tensile loading. The relationship between resistance change and microstructural evolution was analyzed, and a normalized resistance model was developed. The results had indicated that Y- and N-type elements exhibited superior self-sensing performance compared to S-type, with reversible and stable resistance behavior within small strain ranges.

Reinhardt et al. (2025) had reported that the accelerated deterioration of reinforced concrete and masonry infrastructure had emerged as a critical challenge in contemporary civil engineering practice, particularly in regions with aging construction stock, aggressive environmental exposure, and changing functional demands. It was noted that conventional repair and strengthening techniques, although historically effective, increasingly exhibited limitations in terms of durability, constructability, and compatibility with modern performance requirements. In this context, fibre-reinforced polymer systems had been recognized as advanced materials capable of addressing structural and durability deficiencies through lightweight, corrosion-resistant, and adaptable interventions. The study had presented a comprehensive and theoretically grounded examination of FRP-based repair and rehabilitation strategies, integrating insights from international standards, case studies, seismic retrofitting research, and contemporary construction practices. Particular emphasis had been placed on extending service life, enhancing load-carrying capacity, and improving seismic resilience while minimizing disruption. The findings had highlighted improved performance through confinement, flexural strengthening, and shear enhancement, alongside challenges in bond behavior, fire resistance, and regulation.

Cairoli and Iannace (2024) had stated that, in the context of the climate emergency and recurring pandemics, there was a growing requirement for systems capable of providing rapid responses to housing needs. The study had aimed to evaluate the application of fibre-reinforced plastic polymers (FRPs) in meeting such demands. It had proposed a modular emergency housing system utilizing FRPs for both structural and cladding purposes, which had demonstrated adaptability to various functional requirements and to both temporary and permanent building types. By contextualizing modular housing across different environments, the research had emphasized the development of an integrated design process (IDP) along with a Building Information Modelling (BIM) methodology to introduce innovation within the architecture, engineering, and construction (AEC) sector through a digitized framework. The study had also presented an experimental case study, including a pilot nearly zero-energy building (nZEB) unit, with detailed laboratory testing. The findings had confirmed sustainability and adaptability, supporting future industrialized supply chain development.

Kumar (2023) had stated that corrosion of reinforcement in reinforced concrete (RC) structures had remained a critical issue affecting durability and long-term structural performance. It had been observed that Fiber Reinforced Polymer (FRP) wrapping had gained considerable attention as an effective corrosion protection strategy. However, the need to continuously monitor the condition and protective efficiency of FRP systems had been emphasized. The study had highlighted that guided wave-based monitoring techniques had emerged as a promising non-destructive approach for assessing corrosion resistance in FRP-wrapped RC structures. It had been reviewed that guided wave propagation principles, experimental methodologies, and signal analysis techniques had been extensively explored in prior research. The review had indicated that Lamb waves and torsional waves had been widely utilized for defect detection, while wavelet transforms and time-frequency analysis had improved damage identification and localization. Case studies had demonstrated that guided wave methods had effectively detected corrosion initiation and progression, enabling early maintenance and structural safety assurance.

Hosseini et al. (2022) reported that the use of fibre-reinforced polymer (FRP) for confining concrete columns had enhanced their strength and ductility by reducing passive lateral confinement pressure. It was observed that several numerical and analytical formulations had been developed in the literature to represent the compressive behaviour of FRP-confined concrete under both monotonic and cyclic loading conditions. However, the influence of stress and strain levels within the columns had not been clearly defined due to the absence of well-established modelling strategies and the oversimplification of existing models. The study had reviewed various FRP combinations along with available numerical and analytical approaches to evaluate the effectiveness of different methods. It was further noted that the application of FRP materials in column strengthening of existing building systems had been examined, and potential future research directions had been highlighted to improve the utilisation of FRP-confined concrete in civil engineering applications.

Barkhordari et al. (2022) had reported that fiber-reinforced polymer (FRP) materials possessed several advantages, including high tensile strength, low self-weight, corrosion resistance, high durability, and ease of construction, which made them one of the most suitable options for the rehabilitation of concrete structures. However, the bond behavior at the FRP–concrete (FRPC) interface was considered highly complex, which made accurate estimation of bond strength challenging and necessitated the development of robust predictive models. In this study, data-driven hybrid models were developed by integrating advanced population-based optimization algorithms such as Bald Eagle Search (BES), dynamic fitness distance balance–manta ray foraging optimization (dFDB-MRFO), and RUNge Kutta optimizer (RUN) with artificial neural networks (ANN), named BES-ANN, dFDB-MRFO-ANN, and RUN-ANN, respectively. Their performance was evaluated using a database of 969 experimental samples. It had been observed that the RUN-ANN model provided superior prediction accuracy compared to the other models. Furthermore, Shapley Additive Explanations (SHAP) analysis was applied to interpret the model, revealing that FRP bond length and width significantly influenced bond strength predictions. The RUN-ANN model achieved the highest R^2 (92%), lowest mean absolute error (0.078), and lowest coefficient of variation (18.6%), outperforming both competing hybrid and mechanics-based models.

Su et al. (2021) had investigated the accurate estimation of interfacial bond capacity of near-surface mounted (NSM) carbon fiber-reinforced polymer (CFRP) to concrete joints, which had been recognized as a key requirement in the strengthening and retrofitting of existing reinforced concrete structures. It had been noted that machine learning approaches could serve as an effective alternative to conventional semi-empirical and semi-analytical methods. Accordingly, an artificial neural network (ANN) based predictive model using a back-propagation neural network (BPNN) had been developed to capture the complex data relationships in NSM CFRP-to-concrete joints. The model had incorporated nine input parameters related to material and geometry and one output parameter representing bond strength. An extensive dataset of 163 pull-out test samples, collected from both published literature and the authors' research database, had been used for training and validation. The results had indicated strong agreement between predicted and experimental values, achieving a coefficient of determination of 0.957. Furthermore, after eliminating a non-significant variable, the model had shown improved efficiency and accuracy. It had also been observed that, compared with existing semi-analytical models, the ANN approach had provided superior predictive performance, thereby demonstrating its potential as a reliable tool for structural engineering applications.

Biswal and Swain (2020) had discussed that smart materials had gained significant importance across various fields of science and technology, with particular emphasis on the design of materials for civil engineering applications. They had stated that, in order to address challenges related to mechanical properties, erosion behavior, sudden cracking, and thermal resistance, composite materials incorporating suitable reinforcements had been developed. The authors had further highlighted that the reviewed chapter had focused on the design concepts and applications of composite materials in civil engineering domains. It had been explained that such materials had been applied in concrete technology, structural restoration processes, initial damage sensing techniques, and several related areas. They had also suggested that the concept of composite materials and their interfacial bonding characteristics across different applications had opened new possibilities in modern civil engineering practices and had expanded future research directions in advanced material engineering.

III. METHODOLOGY

The study employed a systematic approach to evaluate the effectiveness of Fiber Reinforced Polymer (FRP) and smart material-based retrofitting for reinforced concrete (RC) members. Initially, typical RC structural members, such as beams and slabs, were selected to represent common damage scenarios caused by ageing, environmental exposure, excessive loading, or design deficiencies. The properties of the original RC members, including dimensions, concrete strength, steel reinforcement details, and load conditions, were documented.

A MATLAB R2017b GUI-based simulation platform was developed to model the retrofitting process and assess performance parameters. Input parameters included beam width, depth, effective depth, concrete compressive strength, steel yield strength, steel area, span length, service load, type and number of FRP layers, and smart material selection (e.g., Shape Memory Alloy for damping enhancement). Conventional retrofitting methods, such as concrete jacketing and steel plate bonding, were also modeled for comparative analysis. The retrofitting methodology involved applying FRP layers externally along the tension zones of beams and around columns for confinement, while smart materials were integrated to improve energy dissipation, crack control, and vibration resistance. The study considered both serviceability and strength-related parameters, including flexural and shear capacities, stiffness, deflection, crack width, damage index, damping ratio, and overall performance score. For each member, numerical simulations were performed to quantify the improvements due to retrofitting. Graphical outputs, such as bar and line charts, were generated to compare original, damaged, and retrofitted conditions. Additionally, a comparative analysis between conventional retrofitting techniques and FRP-smart material systems was conducted, evaluating strength, ductility, durability, crack control, cost, and service life extension. The MATLAB GUI also allowed CSV export of results for documentation and further analysis. This methodology provided a comprehensive, interactive, and reproducible framework for assessing hybrid retrofitting techniques and establishing the advantages of FRP and smart materials over traditional strengthening methods.

IV. RESULTS

The MATLAB R2017b GUI-based analysis of reinforced concrete (RC) members retrofitted with Fiber Reinforced Polymer (FRP) and smart materials demonstrated significant improvements in structural performance compared to the original and damaged RC members. The study evaluated key structural parameters, including flexural capacity, shear capacity, stiffness index, deflection, crack width index, damage index, damping ratio, and overall performance score. Table 1 presents the comparative numerical results of the original and retrofitted RC members.

Table 1: Structural Performance Comparison of Original and Retrofitted RC Member

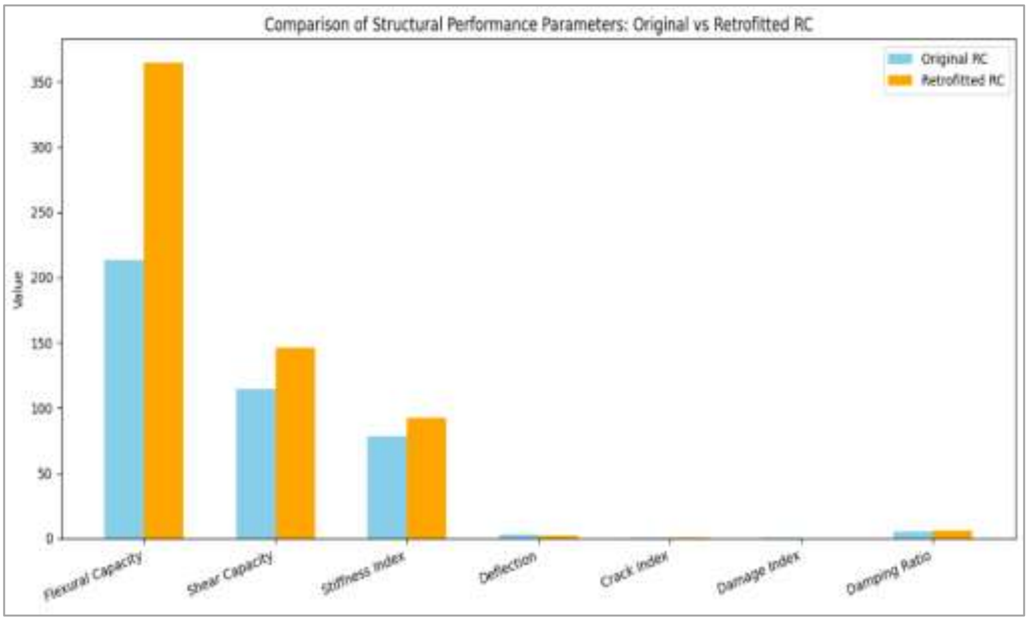
Parameter	Original RC	Retrofitted RC	Performance Change
Flexural Capacity (kN·m)	213.25	364.27	Increased
Shear Capacity (kN)	114.75	146.24	Increased
Stiffness Index ($\times 10^{12}$ N·mm^2)	78.13	92.10	Increased
Deflection (mm)	2.60	2.21	Reduced
Crack Width Index	1.00	0.78	Reduced
Damage Index	0.37	0.21	Reduced
Damping Ratio (%)	5.00	6.25	Increased

The results indicate a 70.82% increase in flexural capacity, demonstrating that FRP layers significantly enhance bending resistance. Shear capacity improved by 27.44%, showing better resistance to diagonal tension and shear failure. The stiffness index increased by 17.88%, indicating reduced deformation under service loads. Deflection decreased by 15.17%, improving overall serviceability. Crack width index reduced by 22%, and the damage index decreased by 41.46%, reflecting enhanced durability and structural health. The damping ratio improved by 25%, highlighting better vibration control due to the smart material contribution. Graphical comparison (Figure 1) further confirms these improvements. The line graph contrasts the original and retrofitted RC members across all performance parameters. The blue line represents the original RC member, while the orange line represents the retrofitted member. Flexural and shear capacities, stiffness, and damping values are higher for the retrofitted member, whereas deflection, crack width, and damage indices are lower, demonstrating a balanced enhancement in both strength and serviceability parameters.

Line Graph Comparison of Original and Retrofitted RC Performance Parameters

Additionally, bar chart analysis comparing conventional retrofitting and FRP-based smart material systems highlights that the hybrid FRP-smart material system outperforms conventional techniques in all critical performance indicators, including strength, stiffness, ductility, durability, crack control, and life extension. The FRP-based retrofitting system demonstrates superior restoration of load-carrying capacity, improved deformation control, better resistance to environmental deterioration, and a significant increase in the expected service life of the structure. Overall, the analysis confirms that FRP and smart material-based retrofitting is effective in improving structural performance, providing a safe, durable, and reliable solution for the rehabilitation of reinforced concrete members, especially where replacement is costly, time-consuming, or impractical. The developed MATLAB GUI provides a user-friendly tool to model, calculate, and visualize the improvements in structural parameters, making it valuable for academic and practical retrofitting assessments.

Bar Graph



Comparison of Structural Performance Parameters Between Original and Retrofitted RC

The bar graph illustrates a clear comparison between the original and retrofitted reinforced concrete (RC) member across key structural performance parameters. The retrofitted RC member, strengthened using FRP and smart materials, shows a substantial increase in flexural capacity, shear capacity, and stiffness, indicating enhanced load-bearing ability and rigidity. Deflection, crack width, and damage indices are significantly reduced, demonstrating improved serviceability, crack control, and durability. Additionally, the damping ratio increases, reflecting better vibration and dynamic load resistance due to smart material integration. Overall, the graph confirms that the hybrid FRP-smart material retrofitting system effectively enhances both strength-related and serviceability-related performance, making the structure safer and more durable.

V. CONCLUSION

The present study demonstrates that the combined application of Fiber Reinforced Polymer (FRP) and smart materials is a highly effective approach for retrofitting reinforced concrete (RC) structures. The MATLAB R2017b GUI-based analysis revealed significant improvements in both strength-related and serviceability-related parameters of retrofitted members. Flexural and shear capacities increased substantially, confirming that FRP layers act as efficient external reinforcement, enhancing the load-carrying ability of beams, slabs, and columns. The stiffness index showed a notable rise, while deflection values decreased, indicating improved rigidity, reduced deformation, and better overall serviceability. Crack width and damage indices were significantly reduced, highlighting the enhanced durability and structural health provided by FRP and smart material integration. The damping ratio also improved due to the use of smart materials such as Shape Memory Alloys, demonstrating superior vibration resistance and energy dissipation under dynamic or seismic loads. Comparative analysis indicated that FRP-smart material systems outperform conventional retrofitting techniques across multiple performance indicators, including ductility, stiffness, crack control, durability, and life extension. Additionally, the incorporation of smart materials enables real-time structural health monitoring, allowing continuous assessment of damage progression and supporting predictive maintenance. This hybrid retrofitting approach is particularly advantageous in scenarios where complete replacement is impractical, costly, or time-consuming. Overall, the study confirms that FRP and smart material-based retrofitting not only restores and enhances structural strength but also improves serviceability, durability, and resilience. The methodology provides a reliable and reproducible framework for evaluating retrofitting effectiveness, making it a valuable tool for engineers and researchers. Consequently, the combined use of FRP and smart materials represents a sustainable, efficient, and forward-looking solution for the rehabilitation and long-term preservation of reinforced concrete infrastructure.

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