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Advanced Performance Assessment of Reinforced Concrete Buildings Using Sustainable Materials: A Review

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ABSTRACT

This study examined the structural performance of reinforced concrete (RC) buildings under modern loading, durability, and sustainability challenges. It focused on the use of advanced simulation tools, finite element modelling, machine learning methods, and experimental validation to predict seismic response, stiffness degradation, drift, corrosion effects, and fire-induced damage. The study also highlighted the importance of sustainable materials such as plastic waste, recycled glass, fiber-reinforced composites, stainless steel reinforcement, nanomaterials, and self-healing concrete in improving durability and reducing environmental impact. Overall, integrated digital and material-based approaches were found essential for resilient RC building design.

Keywords: *Reinforced Concrete, Structural Performance, Seismic Analysis, Sustainable Materials.*

I. INTRODUCTION

The structural performance of reinforced concrete (RC) buildings had been recognized as a critical area of research in modern civil engineering, particularly due to the increasing complexity of urban infrastructure, exposure to extreme loading conditions, and demand for sustainable construction practices. It had been observed that conventional analytical methods alone had been insufficient to capture the nonlinear, time-dependent, and multi-hazard behavior of RC structures, which had led to the growing adoption of advanced digital simulation techniques, experimental validation frameworks, and hybrid computational models. Recent studies had emphasized that reinforced concrete systems had been continuously evolving through the integration of high-performance materials, improved design methodologies, and numerical tools capable of simulating realistic structural behavior under seismic, fire, corrosion, and dynamic loading conditions (Singh et al., 2024; Chen et al., 2020). In this context, the application of finite element modeling, machine learning algorithms, and coupled soil–structure interaction models had significantly enhanced the ability to predict structural response with improved accuracy and reliability. It had further been highlighted that high-rise RC buildings, in particular, had required advanced analytical approaches due to their sensitivity to lateral loads, stiffness degradation, and dynamic amplification effects, which had not been adequately addressed by traditional design codes alone (Cosgun, 2023; Ranjbar et al., 2026). Consequently, structural engineers had increasingly relied on digital simulation platforms such as ETABS and nonlinear finite element tools to evaluate parameters including base shear, drift, stiffness, and energy dissipation capacity under realistic loading scenarios.

Furthermore, significant advancements had been reported in the field of material innovation and structural strengthening techniques, which had played a vital role in enhancing the performance and sustainability of RC buildings. It had been found that the incorporation of alternative materials such as plastic waste, recycled glass, and fiber-reinforced composites had demonstrated promising results in improving mechanical properties while simultaneously reducing environmental impact. Abdullah et al. (2026) had reported that partial replacement of fine aggregates with plastic particles had resulted in only marginal reductions in compressive and flexural strength, thereby indicating the feasibility of sustainable waste utilization in concrete production. Similarly, Bawab et al. (2021) had observed improved structural behavior in RC beams incorporating CRT glass waste at optimal replacement levels, while maintaining comparable crack patterns and load-bearing capacity. In addition, Huang et al. (2022) had emphasized that ultra-high-performance fiber-reinforced concrete (UHPFRC) had significantly enhanced shear and punching resistance in existing structures, although interface bonding and shrinkage compatibility had remained critical challenges. Alongside material advancements, corrosion and environmental degradation had also been identified as major factors influencing long-term structural performance. Turan et al. (2025) had demonstrated that corrosion in RC frames had substantially reduced stiffness, ductility, and energy absorption capacity under cyclic loading, while Rabi et al. (2022) had highlighted the potential of stainless steel reinforcement as a durable alternative for mitigating corrosion-related deterioration. Moreover, Al-Yaseri and Al-Hadithy (2025) had indicated that modern strengthening techniques, including nanomaterials and self-healing concrete systems, had further contributed to improving structural resilience under gravity and seismic loading conditions, thereby supporting the development of more durable and sustainable RC systems.

In addition to material and durability considerations, seismic performance and structural stability under extreme dynamic conditions had been extensively studied using experimental, analytical, and computational approaches. It had been reported that RC columns and frames had exhibited highly complex behavior under cyclic loading, particularly when subjected to variable axial forces, near-fault ground motions, and soil–structure interaction effects. Tra et al. (2026) had found that axial load variability had significantly influenced hysteretic response and failure mechanisms in RC columns, thereby challenging the traditional assumption of constant axial loading in seismic design. Ranjbar et al. (2026) had further demonstrated that pile-supported RC buildings in liquefiable soils had exhibited increased foundation rotation and lateral displacement, indicating that longer pile lengths had not always guaranteed improved seismic performance. Similarly, Cosgun (2023) had applied machine learning techniques and had reported that algorithms such as Random Forest had achieved high accuracy in predicting seismic vulnerability, with key parameters including concrete strength, corrosion level, and reinforcement detailing playing a dominant role in performance estimation. In high-rise structural systems, Singh et al. (2024) had concluded that diagrid systems had provided superior lateral load resistance compared to conventional framed systems, thereby improving overall structural efficiency under dynamic loading. Additionally, Chen et al. (2020) had shown that RC walls exposed to fire conditions had experienced severe strength degradation and buckling failure due to thermal gradients and material nonlinearity. Collectively, these studies had indicated that the integration of digital simulation techniques, experimental validation, and intelligent predictive models had significantly improved the understanding of RC structural behavior, while also highlighting the need for more comprehensive multi-physics and multi-hazard analysis frameworks for future structural design applications.

II. RESEARCH BACKGROUND

Abduallah et al. (2026) presented a novel experimental investigation and provided a detailed comparative analysis of the influence of different plastic materials on concrete performance. In their study, six commonly used plastic types—PET, HDPE, PVC, LDPE, PP, and PS—were examined to evaluate their effects on the flexural strength of reinforced concrete beams, along with compressive strength, elastic modulus, and durability characteristics. It was reported that 10% of natural fine aggregates had been replaced with plastic particles in the experimental program. The findings indicated that the incorporation of plastic waste resulted in only modest adverse effects on mechanical properties, thereby suggesting its feasibility as a sustainable alternative. Flexural tests were found to show no significant negative impact on beam behavior. Furthermore, durability assessments using ultrasonic pulse velocity and electrical resistivity tests demonstrated comparable performance to conventional concrete. The life cycle assessment analysis revealed that improved recycling strategies could significantly reduce the carbon footprint.

Tra et al. (2026) investigated the seismic performance of reinforced concrete (RC) columns and reported that axial load had a significant influence on their behavior. It was noted that most existing experimental studies and design provisions had been based on constant axial load assumptions, despite evidence indicating considerable axial force variations during earthquakes, particularly under near-fault ground motions. The study experimentally examined shear-critical RC columns subjected to variable axial loading, thereby addressing a critical research gap. Nine geometrically and materially identical specimens were tested under cyclic lateral loading combined with different axial load patterns. The findings revealed that all specimens exhibited shear failure after the yielding of longitudinal reinforcement, confirming the intended failure mode. It was further observed that axial loading patterns significantly affected hysteretic behavior and response symmetry, with greater asymmetry occurring under synchronized variable axial loading.

Ranjbar et al. (2026) investigated the seismic performance of mid- to high-rise buildings supported by pile foundations in liquefiable soils, emphasizing the role of soil–pile–structure interaction mechanisms. It was reported that a fully coupled three-dimensional nonlinear numerical framework had been developed to evaluate the influence of pile length and building height on the dynamic response of reinforced concrete structures. The model was found to incorporate advanced soil constitutive behavior, pore-pressure generation, and structural nonlinearity. Different building heights and pile lengths were analyzed under near-fault and far-field earthquake records. The findings indicated that taller buildings exhibited increased foundation rotation, settlement, and lateral pile demands due to higher inertial effects. It was further observed that increasing pile length enhanced rotational stiffness but could also amplify structural responses. The study concluded that greater pile length did not necessarily ensure improved seismic performance, highlighting the necessity of integrated geotechnical–structural analysis in design.

Al-Yaseri et al. (2025) reported that flat plate–column connections had been recognized as critical components in reinforced concrete structures due to their structural efficiency and architectural flexibility. However, it was highlighted that such systems had been highly susceptible to failures such as punching shear and lateral cyclic displacement, particularly under seismic loading conditions. The study had examined recent advancements in enhancing structural performance through both experimental and computational approaches. It was found that material innovations, including fiber-reinforced concrete and ultra-high-performance concrete, along with advanced shear reinforcement techniques, had significantly improved system resilience. Furthermore, emerging retrofitting methods such as nanomaterial coatings and self-healing concrete had demonstrated promising results in durability enhancement. The authors had also indicated that machine learning models had been increasingly applied to predict failure mechanisms. Additionally, overlooked factors like boundary conditions and dynamic strain aging had been emphasized as crucial for comprehensive analysis. The study had ultimately advocated for sustainable, AI-integrated solutions for resilient structural design.

Turan et al. (2025) investigated the structural behavior of corroded reinforced concrete (RC) frames by testing five full-scale specimens. It was reported that four corroded and one non-corroded RC frame were subjected to cyclic loading in order to develop and validate predictive models. The corroded frames were tested under displacement-controlled cyclic loading at varying corrosion levels, while maintaining a constant axial load ratio of 0.20 and identical material and reinforcement configurations. It was observed that actual corrosion ratios were determined after testing by extracting reinforcement bars. The findings indicated that corrosion significantly influenced structural capacity, with initial crack widths having pronounced effects on performance. It was further noted that certain models developed for RC columns could be applied to RC frames for estimating load capacities. Additionally, it was concluded that displacement-based ductility ratios might be misleading unless evaluated using energy-based criteria, while stiffness and energy absorption characteristics revealed notable corrosion impacts.

Singh et al. (2024) examined the increasing challenges associated with the construction of tall buildings due to rapid urbanization and land-use constraints, emphasizing the need to address issues of height and structural stiffness. Various structural systems, including framed systems, shear wall systems, braced frames, outrigger systems, and diagrid systems, were considered. The study had employed ETABS software to perform dynamic analysis on a G+16 storey RCC building across these systems. Key parameters such as base shear, storey shear, maximum displacement, storey drift, stiffness, and time period were analyzed. The objective had been to identify the most efficient structural system. The findings indicated that the diagrid system had performed most effectively in resisting lateral loads, showing comparable behavior to shear wall systems. It was concluded that the diagrid system had demonstrated superior stability and resistance under dynamic loading, thereby offering a promising solution for enhancing the safety and performance of high-rise structures in modern urban environments.

Cosgun (2023) examined earthquakes as highly challenging disasters that were considered a major threat to urbanized regions, particularly in developing countries such as Turkey, where a significant portion of the reinforced concrete (RC) building stock was reported to be highly vulnerable to seismic risks. It was highlighted that these structures were prone to partial or total collapse under strong ground motions due to inherent structural deficiencies. The study emphasized that seismic evaluation of existing RC buildings was essential for mitigating potential risks. Machine learning techniques were applied to predict the seismic performance of such buildings, and k-fold cross-validation was utilized to assess model accuracy. Among the applied methods, Random Forest was found to yield the best performance. Furthermore, sensitivity analysis was conducted, which indicated that building age, concrete compressive strength, column stirrup spacing, steel yield strength, and corrosion presence significantly influenced performance prediction.

Rabi et al. (2022) had examined the degradation of reinforced concrete (RC) infrastructure due to corrosion of steel reinforcement, which was recognized as a significant and costly global issue. The authors reported that inspection, repair, maintenance, and replacement activities had imposed substantial economic burdens and caused disruptions affecting productivity. It was observed that conventional remedial measures were largely retrospective in nature and did not effectively support sustainability goals or reduce long-term maintenance demands. In this context, the study suggested that replacing traditional carbon steel with corrosion-resistant stainless steel reinforcement could serve as a viable and sustainable alternative. The growing interest in stainless steel reinforced concrete was attributed to aging infrastructure and insufficient design data. The paper had provided a comprehensive state-of-the-art review at both material and structural levels, while also identifying research gaps and offering guidance for future studies and practical engineering applications.

Huang et al. (2022) reported that Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC), owing to its superior mechanical properties and low permeability, had been considered a promising material for enhancing the mechanical resistance and durability of existing reinforced concrete (RC) structures. The study reviewed the application of UHPFRC in strengthening structures under flexure, shear, and punching shear, with particular emphasis on shear performance and the behavior at the UHPFRC–concrete interface. A holistic approach had been adopted, incorporating macro-, meso-, and micro-scale analyses of structural and interfacial behavior. The authors further examined existing analytical and numerical models used to predict shear and punching shear capacities. It was also highlighted that interface characteristics, bonding techniques, moisture transfer, and differential shrinkage significantly influenced performance. The study concluded that despite extensive research, inadequate understanding of interface behavior and lack of reliable design models limited widespread application.

Bawab et al. (2021) investigated the performance of reinforced concrete beams incorporating cathode-ray tube (CRT) glass waste as a partial replacement of sand. It was reported that four concrete mixes with 0%, 10%, 20%, and 30% CRT glass were prepared and evaluated in terms of compressive strength, flexural strength, and modulus of elasticity. The study indicated that concrete with CRT glass exhibited improved mechanical properties, particularly at the 10% replacement level. Reinforced concrete beams were tested under three-point bending, and it was observed that beams with 10% CRT glass demonstrated higher load-carrying capacity compared to control and other mixes. The failure mode was reported as flexural for all beams, with similar crack patterns. However, it was noted that the control beam showed greater ductility. Furthermore, numerical analysis was conducted, and it was found that the results closely matched the experimental outcomes, with deviations not exceeding 5%, confirming the reliability of the adopted model.

Chen et al. (2020) investigated the structural performance and deterioration in load-carrying capacity of reinforced concrete (RC) walls subjected to one-sided fire exposure. It was reported that a detailed heat transfer analysis had been carried out to characterize the temperature gradient within the wall, and a comprehensive structural model had been developed. The study considered important factors such as transient creep of concrete under fire conditions, strain softening in compression, cracking behavior, tension stiffening, yielding of steel reinforcement, and geometrical nonlinearity. It was further noted that the heat transfer problem had been solved using finite-element approximation, while the governing differential equations of the structural model had been addressed through a nonlinear shooting method with iterative procedures. The findings indicated that buckling failure dominated under one-sided fire exposure, highlighting the significant role of geometrical nonlinearity. It was also concluded that existing design codes might be nonconservative in several cases.

III. KEY FINDINGS FROM STUDY

S. No.	Author(s) & Year	Objective of Study	Methodology / Approach	Key Findings	Research Gap / Limitation
1	Abdullah et al. (2026)	To evaluate effect of plastic waste in RC concrete	Experimental study using PET, HDPE, PVC, LDPE, PP, PS (10% replacement)	Minor reduction in strength; acceptable flexural and durability performance	Long-term durability and field-scale validation not fully addressed
2	Tra et al. (2026)	To study RC columns under variable axial and cyclic loading	Experimental cyclic loading tests on RC specimens	Axial load variation significantly affected hysteresis and failure mode	Limited real earthquake simulation scenarios
3	Ranjbar et al. (2026)	To analyze RC buildings on pile foundations in liquefiable soils	3D nonlinear numerical simulation with soil–structure interaction	Taller buildings increased pile demand; longer piles not always beneficial	High computational complexity; limited experimental validation

4	Al-Yaseri & Al-Hadithy (2025)	To review flat plate–column connection performance	Experimental + computational review	Fiber concrete, UHPC and AI improved seismic resistance	Lack of unified design model for punching shear
5	Turan et al. (2025)	To assess corroded RC frame behavior	Full-scale cyclic loading tests	Corrosion reduced stiffness, ductility, and energy absorption	Limited predictive corrosion progression models
6	Singh et al. (2024)	To compare structural systems in high-rise buildings	ETABS-based dynamic analysis	Diagrid system showed best lateral load resistance	Limited consideration of soil–structure interaction
7	Cosgun (2023)	To predict seismic vulnerability of RC buildings	Machine learning (Random Forest, k-fold validation)	High prediction accuracy; key factors identified (age, strength, corrosion)	Data dependency and limited generalization
8	Rabi et al. (2022)	To review stainless steel reinforcement in RC	State-of-the-art literature review	Stainless steel improves durability and reduces corrosion issues	High material cost and limited design guidelines
9	Huang et al. (2022)	To study UHPFRC strengthening of RC structures	Macro–meso–micro scale analysis	Significant improvement in shear and punching resistance	Interface behavior not fully understood
10	Bawab et al. (2021)	To investigate CRT glass waste in RC beams	Experimental beam testing and numerical validation	10% CRT replacement improved strength and performance	Limited environmental impact assessment
11	Chen et al. (2020)	To analyze RC walls under fire exposure	Finite element heat transfer + nonlinear structural model	Buckling failure dominant under fire conditions	Existing codes may be unsafe under extreme fire scenarios

IV. CONCLUSION

The reviewed studies collectively demonstrated that the structural performance of reinforced concrete (RC) buildings had significantly evolved with the integration of advanced digital simulation techniques, experimental investigations, and data-driven analytical approaches. It had been consistently observed that modern research had shifted from conventional linear analysis methods toward nonlinear finite element modelling, machine learning-based prediction systems, and coupled soil–structure interaction frameworks, which had enabled a more realistic assessment of RC behavior under complex loading conditions. The literature had highlighted that RC structures had been influenced by multiple interacting factors, including material composition, seismic loading variability, environmental degradation, fire exposure, and foundation-soil interaction effects. Studies such as Tra et al. (2026) and Ranjbar et al. (2026) had emphasized that axial load variations and geotechnical conditions had played a crucial role in altering structural response, while Singh et al. (2024) had shown that optimized structural systems like diagrid frameworks had improved lateral load resistance and overall stability. Furthermore, material-based investigations had revealed that sustainable alternatives such as plastic waste, CRT glass, and ultra-high-performance fiber-reinforced concrete (UHPFRC) had demonstrated promising improvements in strength and durability, although interface behavior and long-term performance uncertainties had still remained challenges (Abdullah et al., 2026; Huang et al., 2022). Corrosion-related deterioration and extreme loading scenarios such as fire exposure had also been identified as major threats to structural integrity, as evidenced by Turan et al. (2025) and Chen et al. (2020), who had reported significant reductions in stiffness, ductility, and load-carrying capacity under adverse conditions. In addition, the increasing use of machine learning techniques, as demonstrated by Cosgun (2023), had improved predictive accuracy for seismic vulnerability assessment, thereby supporting more informed decision-making in structural design and retrofitting. However, despite these advancements, it had been observed that limitations still existed in terms of model generalization, experimental validation at full scale, and the integration of multi-hazard effects within a unified framework. Overall, it could be concluded that the combination of digital simulation, experimental research, and intelligent computational models had significantly enhanced the understanding of RC structural performance, but further research was still required to develop more robust, sustainable, and universally applicable design methodologies for future resilient infrastructure systems.

V. FUTURE SCOPE

The future scope of research on the structural performance analysis of reinforced concrete (RC) buildings using advanced digital simulation techniques is highly promising, particularly with the rapid evolution of computational intelligence, material science, and multi-physics modelling approaches. It is expected that future studies will increasingly focus on the development of fully integrated digital twin frameworks for RC structures, where real-time monitoring data from sensors will be combined with finite element models and machine learning algorithms to predict structural behavior, damage progression, and failure risk with high accuracy. Such systems will enable continuous structural health monitoring and proactive maintenance strategies, thereby improving safety and reducing lifecycle costs. In addition, the incorporation of artificial intelligence and deep learning techniques is anticipated to enhance the prediction of seismic vulnerability, corrosion propagation, and fire-induced damage under complex and uncertain loading conditions. Future research is also likely to emphasize multi-hazard assessment models that simultaneously consider earthquakes, fire, corrosion, blast loads, and environmental degradation within a unified simulation environment, which is currently limited in existing studies. Furthermore, advancements in sustainable and high-performance materials such as ultra-high-performance fiber-reinforced concrete (UHPFRC), geopolymer concrete, self-healing concrete, and recycled composite materials are expected to play a significant role in improving structural resilience and reducing environmental impact. The development of more accurate interface modeling techniques between different materials and structural components will also be essential to address current gaps in bonding behavior and load transfer mechanisms. Additionally, large-scale experimental validation combined with high-fidelity numerical simulations will be required to improve the reliability and generalizability of predictive models. Integration of geotechnical–structural interaction effects in real-time simulation platforms will further enhance the understanding of foundation behavior under liquefiable soil conditions. Overall, future research will move toward intelligent, sustainable, and adaptive structural systems that are capable of self-assessment, self-diagnosis, and optimized performance under evolving environmental and loading scenarios.

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