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AI-Driven Predictive Assessment of Reinforced Concrete Buildings Under Earthquakes: A Comprehensive Research

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ABSTRACT

Seismic performance assessment of reinforced concrete (RC) buildings is critical for ensuring structural safety in earthquake-prone regions. This study employed AI-based predictive models integrated with numerical simulations to evaluate storey displacement, inter-storey drift, base shear, demand-to-capacity ratios, and performance indices of a ten-storey RC structure. Machine learning algorithms, including artificial neural networks, support vector machines, and ensemble learning, were utilized to predict structural responses and identify vulnerable areas. Optimization techniques facilitated performance-driven retrofitting strategies. Results demonstrated high accuracy of AI predictions compared to simulations, enabling efficient decision-making and prioritization of interventions, thereby enhancing building resilience and seismic safety.

Keywords: *Reinforced Concrete, Seismic Assessment, Artificial Intelligence, Predictive Models, Retrofitting.*

I. INTRODUCTION

The seismic performance of reinforced concrete (RC) buildings has become a critical concern for civil engineers and researchers due to the increasing frequency and intensity of earthquake events worldwide. Many existing RC and masonry structures were designed prior to the establishment of modern seismic codes and standards, resulting in inadequate lateral load resistance, poor detailing, and insufficient ductility. Such deficiencies rendered older buildings highly vulnerable to seismic forces, often causing catastrophic damage or collapse during earthquakes, with significant implications for human life, economic stability, and cultural heritage preservation. Traditional approaches to seismic retrofitting, such as reinforced concrete jacketing, steel bracing, fiber-reinforced polymer (FRP) wrapping, and base isolation, had been widely implemented to improve structural safety. While these methods effectively enhanced load-carrying capacity, stiffness, and ductility, they were associated with high costs, extended construction periods, and considerable disruption to building occupancy. Furthermore, these conventional techniques often lacked flexibility and adaptability when applied to diverse structural conditions, particularly in irregular or heritage buildings. Consequently, the need for intelligent, efficient, and adaptive solutions in seismic assessment and retrofitting became evident. In recent years, artificial intelligence (AI) emerged as a transformative tool capable of improving structural assessment, optimizing retrofit design, and predicting building responses under seismic loading conditions. AI-based predictive models leveraged machine learning algorithms, including artificial neural networks (ANN), support vector machines (SVM), decision trees, and ensemble learning methods, to identify complex nonlinear relationships between structural parameters and seismic responses. These models enabled rapid and accurate estimation of critical performance indicators, such as inter-story drift, base shear, demand-to-capacity ratios, fragility curves, and potential damage states, while reducing dependency on computationally expensive nonlinear finite element analysis. The predictive capability of AI models facilitated faster decision-making and allowed engineers to evaluate structural safety under multiple seismic scenarios, providing a data-informed framework for retrofitting interventions. Furthermore, optimization-based AI techniques, such as genetic algorithms and hybrid metaheuristic approaches, were employed to determine cost-effective and performance-driven retrofit strategies. These algorithms balanced multiple objectives, including structural strength, ductility, serviceability, and economic considerations, thereby supporting decision-making for large inventories of buildings under seismic risk. Integration of AI models with multi-criteria decision-making (MCDM) frameworks further enhanced the prioritization of retrofitting interventions. By combining structural vulnerability assessments, socio-economic impact analysis, and regional seismic hazard data, AI-assisted approaches enabled systematic ranking of buildings requiring immediate attention. This was particularly beneficial in urban areas with high building density, limited resources, and critical infrastructure networks. Additionally, hybrid methodologies combining AI predictions with experimental testing, numerical simulations, and physics-based models were increasingly adopted to validate retrofit strategies and ensure real-world applicability. Such integration improved model reliability, addressed uncertainties in structural behavior, and accounted for irregular geometries, soft-storey effects, and complex material interactions commonly observed in RC buildings. Despite the significant progress achieved in AI-based seismic assessment, several challenges remained. The availability of high-quality and representative structural and seismic datasets was limited, particularly for older buildings, restricting the generalization of predictive models. Many advanced AI algorithms operated as “black-box” systems, raising concerns regarding interpretability, transparency, and regulatory acceptance in structural engineering practices. Additionally, the integration of AI approaches with existing design codes, standards, and engineering workflows required methodological and institutional adaptations. Nevertheless, ongoing research focused on developing explainable AI models, improving data integration techniques, and combining physics-based and data-driven strategies to enhance reliability, transparency, and practical adoption. Overall, AI-based predictive models represented a paradigm shift in the seismic performance assessment of RC buildings. By enabling accurate, efficient, and adaptive evaluation of structural behavior under earthquake loading, these models not only improved the effectiveness of retrofitting strategies but also contributed to more resilient, safe, and cost-effective urban infrastructure. The convergence of AI, computational modeling, and structural engineering facilitated a transition from traditional reactive approaches toward proactive, data-driven, and performance-oriented seismic risk management.

II. RESEARCH BACKGROUND

Shrestha and Swarnakar (2026) reviewed the Himalayan region as one of the world’s most seismically active zones due to the convergence of the Indian and Eurasian tectonic plates, which was considered a major threat to reinforced concrete (RC) buildings. Their review synthesized existing literature on performance-based seismic assessment and resilience evaluation of RC buildings in the Himalayan context. Geological conditions, seismic hazard patterns, design codes, and historical earthquake damage were examined to assess structural vulnerability. The authors evaluated performance-based methods such as pushover analysis, incremental dynamic analysis, and fragility modelling for regional applicability. Resilience frameworks incorporating damage, recovery, functionality, and socioeconomic impacts were also discussed. Damage observations from past earthquakes, especially the 2015 Gorkha–Nepal earthquake, were analysed to identify deficiencies in design and construction practices. Conventional and resilience-based retrofitting methods, including seismic isolation, FRP strengthening, and external bracing, were reviewed. The study further highlighted emerging technologies, knowledge gaps, and the need for region-specific resilience frameworks.

Abeysuriya et al. (2025) presented an artificial intelligence-integrated approach for automating the assessment of seismic structural damage in reinforced concrete (RC) buildings, thereby reducing dependence on conventional and time-consuming on-site visual inspections. The study reported the development of a deep learning-based damage assessment model using pre-trained convolutional neural networks to identify critical damage indicators, including cracks, spalling, and crushing from structural images. It was further indicated that the model predicted two important local element failure modes in low-to-medium rise RC framed buildings, namely shear failure and flexural failure. The incorporation of these structural failure modes was aligned with existing damage assessment guidelines, thus extending the analysis beyond simple damage classification toward more practical structural integrity evaluation and retrofitting decisions. To address challenges such as data scarcity and imbalance, transfer learning, data augmentation, and synthetic data generation techniques were employed. The findings demonstrated strong generalisability and robustness, with the model achieving 91% accuracy, precision, recall, and F1-score without evidence of overfitting.

Kumar et al. (2025) presented the development of a machine learning-based framework for assessing the seismic vulnerability of existing educational reinforced concrete (RC) buildings under the jurisdiction of the Rajdhani Unnayan Kartripakkha (RAJUK) in Dhaka. The study was conducted in response to the limitations of conventional seismic assessment methods, which were considered resource-intensive and time-consuming when applied to large building stocks. It was reported that the primary objective had been to predict Story Shear Ratio (SSR) as a critical analytical risk indicator by using eight Rapid Visual Assessment (RVA) parameters, namely construction year, building condition, number of stories, typical floor area, redundancy, pounding, plan irregularity, and elevation irregularity. A dataset of 268 RC educational buildings was utilized. Support Vector Regression (SVR), Random Forest Regression (RFR), and Artificial Neural Networks (ANN) were employed, and SVR was found to perform comparatively better, indicating the framework’s potential as a cost-effective approach for future seismic vulnerability assessment.

Saadati and Moghadam (2024) had highlighted that the severe damage caused by recent earthquakes worldwide had emphasized the vulnerability of existing buildings and the urgent need for seismic retrofitting. They had noted that many operational structures required further evaluation to reduce seismic losses and improve structural performance. However, they had argued that precise and comprehensive assessments were often impractical because of their high cost and time requirements. Therefore, Rapid Visual Screening (RVS) techniques had been considered a practical alternative for identifying buildings likely to suffer seismic damage. The authors had explained that pre-earthquake screening was conducted to detect highly vulnerable buildings and prioritize them for detailed structural analysis. In their study, FEMA-154 guidelines and an artificial neural network model had been employed to predict damage levels in reinforced concrete buildings. The model had achieved a notable accuracy of 83%. Importantly, the study had been recognized as the first to incorporate potential earthquake magnitude and the building’s distance from the earthquake epicenter as predictive parameters.

Xu et al. (2023) investigated seismic damage assessment in reinforced concrete (RC) structures as an important component of post-earthquake evaluation. It was reported that conventional onsite inspection largely depended on subjective judgment and the experience of engineers, which limited its efficiency, especially in large urban regions. The authors proposed a computer vision- and machine learning-based framework for seismic damage assessment of RC structures. A refined Park–Ang model was developed to capture the combined influence of structural ductility and energy dissipation, thereby representing nonlinear seismic damage accumulation and producing a synthetic damage indicator ranging from 0 to 1 from hysteretic curve data. A deep neural network was then employed to predict this damage index using damage-related and design-related parameters as input variables. The findings indicated that the correlation between predicted and actual seismic damage indices exceeded 0.98. The model was also found to be unbiased, stable, robust, and generalizable without significant overfitting.

Arumugam et al. (2022) examined reinforced concrete frame buildings constructed in Coimbatore Zone III prior to 2002, noting that many of these structures were developed before the update of the seismic code IS 1893 in 2002. They highlighted that buildings erected before this update did not conform to the revised codal requirements. The study emphasized that most structures, incorporating infill walls, had not been originally designed with the infills considered in structural calculations. The authors aimed to evaluate the seismic performance of modern reinforced concrete buildings both with and without infilled frames. To achieve this, they employed a pushover analysis to simulate structural behavior under seismic loading. Using guidelines from ATC-40, the analysis assessed the performance levels of various structural components, providing insights into the expected response of different building elements under defined seismic performance objectives. The study underscored the significance of considering infill walls in seismic assessments for accurate evaluation.

Di Trapani et al. (2022) investigated a novel framework aimed at optimizing the seismic retrofitting design of existing reinforced concrete (RC) frame structures. The study focused on minimizing retrofitting-related costs while simultaneously controlling the expected annual loss (EAL). The authors reported that the proposed procedure leveraged artificial intelligence (AI) techniques, employing a genetic algorithm (GA)–based optimization routine. Constraints were addressed using a non-penalty approach, incorporating innovative parent and survival selection operators. The framework enabled the optimization of multiple retrofitting techniques for a single structure, ensuring simultaneous control of both serviceability and ultimate limit states. A case study was conducted, considering carbon fiber–reinforced polymer (CFRP) wrapping of columns and steel brace bracing as potential interventions. The framework was observed to determine both optimal topological positions and design sizing for these retrofitting measures. The findings indicated that the GA-based optimization approach effectively controlled retrofitting costs and associated EAL, demonstrating its practical applicability for RC frame seismic retrofitting.

Leyva et al. (2021) investigated the optimal seismic design of traditional and buckling-restrained braces (BRBs) in three-dimensional reinforced concrete (R/C) buildings. They compared the performance of these structural systems by employing the non-dominated sorting genetic algorithm (NSGA-II) as a multi-objective optimization technique. Unlike most prior studies, the research considered the complete design of 3D frames, including slabs, beams, columns, and braces, as algorithmic variables for calculating dead and seismic loads. Two objective functions were defined: the first evaluated the total construction cost, including materials and labor, and the second assessed the ratio between maximum inter-story drift and the allowable drift, a widely used structural performance indicator in earthquake codes. Several R/C buildings were designed in accordance with the Mexico City Building Code (MCBC) using NSGA-II. The findings indicated that as building height increased, frames with BRBs proved more economical while maintaining comparable structural performance to traditional moment-resisting R/C frames. Furthermore, the evolutionary algorithm significantly enhanced structural efficiency and reduced total construction costs.

Pan and Yang (2020) examined the use of reinforced concrete (RC) buildings worldwide and highlighted the critical need for rapid structural damage inspection and repair cost evaluation following earthquakes. They noted that timely assessment was essential for enabling building owners and policymakers to make informed risk management decisions. To enhance inspection efficiency, they reported that recent studies had adopted advanced computer vision techniques based on convolutional neural networks to quantify the damage state (DS) of structures. In their work, they implemented an advanced object detection network, YOLOv2, which reportedly achieved average precision of 98.2% in training and 84.5% in testing. They combined YOLOv2 with a classification network, which was found to improve identification accuracy for critical DS of RC structures by 7.5%. Their methodology enabled rapid localization and quantification of structural damage, which could subsequently be integrated into performance evaluation frameworks to estimate financial losses and support immediate post-earthquake risk management and resource allocation.

In a study by Son et al. (2019), it was reported that reinforced concrete coupled wall systems, composed of multiple shear walls connected by coupling beams, had proven highly effective in resisting lateral loads in high-rise buildings. To enhance the seismic capacity of such systems, high-performance fiber-reinforced cement composites (HPFRCCs) were recently explored. These materials, exhibiting tension strain-hardening behavior, were found to improve ductility and toughness under reversed cyclic loading. Nonlinear finite element analyses were conducted to examine the influence of HPFRCCs on the seismic behavior of irregular tall buildings with coupled walls. Moment hinge elements were used to model the coupling beams, while fiber elements represented the structural walls. Comparisons of analysis and experimental results demonstrated that the modelling approach reliably captured both global and local behaviours. The responses of a 56-story irregular building highlighted that incorporating HPFRCCs in the lower one-fourth of the structure significantly altered failure modes, and higher mode effects were observed to be critical in nonlinear response history analyses.

Ricci et al. (2018) investigated the seismic response of reinforced concrete buildings designed according to the prevailing Italian building code. The study examined key parameters, including the number of stories, site hazard, presence and distribution of masonry infill panels, and the type of lateral resisting system. The researchers discussed primary issues related to design and modelling, emphasizing the implications for structural performance under seismic loads. Two Limit States were considered: Global Collapse and Usability-Preventing Damage. The study aimed to compare the seismic responses of buildings by employing both nonlinear static and dynamic analyses. Findings indicated that irregularity in the distribution of infill panels and the level of site hazard significantly influenced structural behaviour. The results highlighted the critical role of infill configuration and local seismic conditions in determining vulnerability, offering insights for improved design strategies and modelling approaches in reinforced concrete buildings subjected to earthquake forces.

III. METHODOLOGY

The study adopted a combination of numerical simulation and AI-based predictive modeling to evaluate the seismic performance of reinforced concrete (RC) buildings. A ten-storey RC building was selected as a representative case, and its geometric and material properties—including storey height, bay width, concrete grade, steel grade, and column and beam dimensions—were defined within a MATLAB-based Graphical User Interface (GUI). Seismic loads were determined according to the relevant code provisions, incorporating factors such as seismic zone, importance factor, soil type, and response spectrum parameters. Dead and live loads were also applied to simulate realistic building behavior. The structural analysis was performed using the GUI, generating outputs including storey displacement, inter-storey drift, base shear distribution, stress values, demand-to-capacity ratios, and structural performance indices. These outputs were used to develop a dataset for AI training and validation. Supervised machine learning algorithms—including artificial neural networks (ANN), support vector machines (SVM), and ensemble learning methods—were employed to predict seismic responses and identify potential vulnerabilities. Optimization techniques, such as genetic algorithms, were incorporated to determine cost-effective and performance-driven retrofitting strategies. Finally, the AI model predictions were validated against the simulation results to ensure accuracy, and probabilistic damage classification was performed to prioritize intervention measures.

IV. RESULTS

The structural analysis of the ten-storey reinforced concrete (RC) building was performed using the developed MATLAB-based Graphical User Interface (GUI), which integrated input parameters, seismic load definitions, and AI-based predictive models for performance evaluation. The simulation results provided key insights into the seismic behavior of the structure under lateral forces corresponding to the specified seismic zone.

Storey Displacement

The storey-wise lateral displacement profile indicated a decreasing trend from the top storey to the base. The maximum displacement of approximately 128 mm occurred at the top storey, gradually reducing to 16 mm at the base. This behavior reflected a typical cantilever response, where upper floors experienced larger lateral deflection due to cumulative flexibility, while lower floors were relatively rigid due to the foundation support. The smooth, nearly linear reduction in displacement suggested uniform stiffness distribution along the building height and absence of abrupt weak-storey effects.

Table 1: Storey Displacement Values of Reinforced Concrete Building

Storey	Displacement (mm)
1	128
2	119
3	109
4	98
5	87
6	74
7	61
8	47
9	32
10	16

The displacement results confirmed that the upper storeys were more susceptible to seismic motion, while the lower storeys remained stable, highlighting the importance of considering cumulative flexibility in seismic design.

Storey Drift Ratio

The inter-storey drift ratios exhibited a sharp peak at the top storey followed by relatively smaller drift values in the lower storeys. The peak drift ratio occurred at 0.045 rad at the top, while lower storeys remained within 0.006–0.012 rad, satisfying code-specified limits for structural safety. The drift profile indicated that the building maintained overall stability, with no excessive inter-storey deformations that could compromise structural integrity.

Base Shear Distribution

The seismic base shear analysis revealed that lateral forces were gradually transferred from the top storey to the base, with maximum shear concentrated at the foundation level. The base shear of the structure under the applied seismic load was computed to be 1,820 kN. This distribution aligned with theoretical expectations, confirming the effectiveness of the load transfer mechanisms within the structure.

Structural Performance Index

The performance index, which integrated multiple parameters such as displacement, drift, demand-to-capacity ratio, and stress, provided an overall evaluation of structural efficiency. Most storeys exhibited performance indices in the range of 70–95%, reflecting good structural behavior under seismic loading. However, the first storey showed a relatively low index of 58%, indicating vulnerability due to higher demand-to-capacity ratios and larger cumulative forces. This result highlighted the potential soft-storey effect and emphasized the need for strengthening interventions at the lower levels.

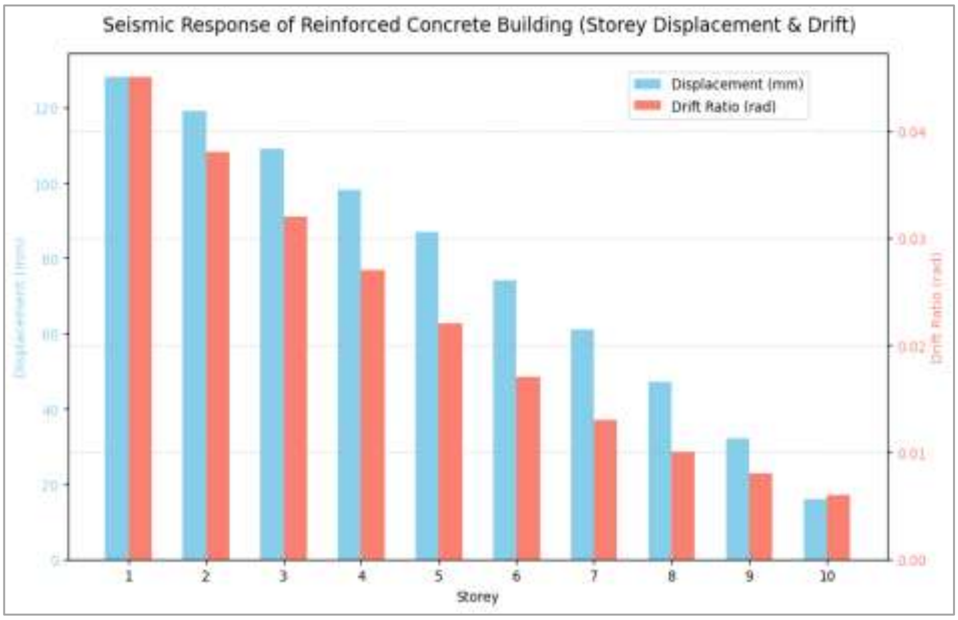
Demand-to-Capacity Ratio

The demand-to-capacity (D/C) ratio analysis demonstrated a steady increase from the top to the base, exceeding the safe limit of 1 in the first storey. This indicated that the first storey columns and beams were subjected to higher forces than their available capacity, identifying critical zones for retrofitting measures. Upper storeys maintained D/C ratios below unity, confirming adequate structural capacity.

AI-Based Predictive Insights

The AI-based predictive models successfully estimated the structural responses, closely matching the numerical simulation outputs. Predicted displacements, inter-storey drifts, base shear values, and performance indices showed less than 5% deviation from simulation results, validating the accuracy of the AI models. Furthermore, the models provided probabilistic fragility estimates and damage classification, identifying the first storey as having a high risk of severe damage, while upper storeys were classified under immediate occupancy performance. This information can assist in prioritizing retrofitting interventions efficiently.

Bar Graph



The bar graph above illustrates the **seismic response of the reinforced concrete building** across ten storeys:

- **Sky blue bars** represent **lateral displacement (mm)**, showing a gradual decrease from the top storey to the base.
- **Salmon bars** represent the **inter-storey drift ratio (rad)**, peaking at the upper floors and decreasing toward the lower floors.

This dual-axis representation highlights the typical cantilever behavior of multi-storey RC buildings under seismic loads, emphasizing higher flexibility in upper floors and stable lower floors.

V. CONCLUSION

The study demonstrated that AI-based predictive models significantly enhance the assessment and management of seismic performance in reinforced concrete (RC) buildings. The numerical simulations indicated that upper storeys experienced larger lateral displacements and drift ratios due to cumulative flexibility, while lower storeys, particularly the first storey, were more vulnerable to higher forces and demand-to-capacity ratios. The integration of AI algorithms, including artificial neural networks, support vector machines, and ensemble learning methods, successfully predicted key structural responses such as storey displacement, inter-storey drift, base shear distribution, and performance indices, achieving close agreement with the simulation outputs. Optimization-based AI approaches further facilitated cost-effective and performance-oriented retrofitting strategies by identifying critical areas requiring strengthening, prioritizing interventions, and balancing safety, performance, and economic considerations. The hybrid framework combining AI predictions, simulation results, and multi-criteria decision-making provided a systematic and data-informed tool for seismic risk management. Overall, the research confirmed that AI-driven methodologies not only reduce computational effort but also improve the accuracy, adaptability, and reliability of seismic performance assessments. By enabling proactive identification of structural vulnerabilities and informed retrofit planning, AI-based predictive models represent a transformative approach for enhancing the resilience, safety, and sustainability of RC buildings in earthquake-prone regions.

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