

Artificial Intelligence in Seismic Retrofitting: Enhancing Building Resilience and Retrofit Design Optimization

Saurabh Sharma

M. Tech. in Structural Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Jaswant Singh

A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

Seismic retrofitting of existing buildings has become crucial due to the vulnerability of infrastructure to earthquakes. Traditional retrofitting methods are costly and complex, prompting research into more efficient approaches. Artificial Intelligence (AI) has emerged as a transformative tool in this field, enhancing structural assessment, optimizing retrofit design, and improving seismic performance prediction. AI-driven methods, including machine learning, optimization algorithms, and data-driven modeling, have reduced reliance on expensive simulations while improving accuracy. However, challenges such as limited datasets, model interpretability, and integration with existing codes remain. AI represents a paradigm shift in seismic strengthening, promoting resilience and sustainability.

Keywords: *Seismic Retrofitting, Artificial Intelligence, Machine Learning, Structural Assessment.*

I. INTRODUCTION

Seismic retrofitting and strengthening of existing buildings had become a critical area of structural engineering research due to the increasing global vulnerability of built infrastructure to earthquake hazards. A significant proportion of existing reinforced concrete (RC) and masonry structures worldwide had been designed prior to the introduction of modern seismic design codes, resulting in inadequate lateral load resistance, poor detailing, and insufficient ductility. These deficiencies had made older buildings highly susceptible to damage or collapse during seismic events, thereby posing serious risks to human life, economic stability, and cultural heritage preservation. In response to these challenges, traditional retrofitting techniques such as reinforced concrete jacketing, steel bracing, fiber-reinforced polymer (FRP) wrapping, and base isolation had been widely implemented. However, these methods had often been associated with high costs, construction complexity, disruption to building occupancy, and limited adaptability to diverse structural conditions. Consequently, researchers had increasingly focused on developing more efficient, intelligent, and adaptive approaches for seismic strengthening. Within this context, artificial intelligence (AI) had emerged as a transformative technology capable of enhancing structural assessment, optimizing retrofit design, and improving predictive accuracy in seismic performance evaluation. Studies had indicated that AI-based systems, when integrated with structural engineering principles, had enabled faster decision-making, reduced computational effort, and improved reliability in assessing seismic vulnerability and retrofit effectiveness (Salama, 2024; Singh et al., 2025; Hoang et al., 2021).

The application of AI in seismic retrofitting had been strongly supported by advancements in machine learning, optimization algorithms, and data-driven structural modeling. Researchers had demonstrated that machine learning techniques such as artificial neural networks, support vector machines, decision trees, and ensemble learning methods had been effectively used to predict structural responses under seismic loading conditions. These approaches had reduced dependency on computationally expensive nonlinear finite element analysis while maintaining high levels of accuracy. For instance, predictive

models had been developed to estimate demand-to-capacity ratios, fragility curves, and damage states of retrofitted structures, enabling engineers to evaluate structural safety more efficiently. Optimization-based AI techniques, including Genetic Algorithms and hybrid metaheuristic methods, had also been widely applied to determine optimal retrofit strategies by balancing cost, performance, and safety requirements. In addition, AI-driven frameworks had been integrated with multi-criteria decision-making systems to prioritize retrofitting interventions across large building inventories based on structural vulnerability, socio-economic impact, and seismic risk exposure. These developments had demonstrated that AI was not only enhancing computational modeling but also transforming seismic risk management into a more systematic and data-informed process (Nigro et al., 2023; Noureldin et al., 2022; Cao et al., 2020). Furthermore, hybrid approaches combining AI with experimental testing and numerical simulation had been increasingly adopted to validate retrofit techniques and ensure real-world applicability, particularly in complex structural systems such as irregular buildings and heritage masonry structures.

Despite these advancements, several challenges had remained in the widespread adoption of AI-based seismic retrofitting approaches. One major limitation had been the availability and quality of structural and seismic datasets required for training robust machine learning models. Many existing studies had relied on simulated or limited experimental data, which had restricted the generalization ability of predictive models when applied to real-world conditions. Additionally, the interpretability of AI models had remained a concern, as many advanced algorithms operated as “black-box” systems, making it difficult for engineers to fully understand the underlying decision mechanisms. This had raised issues related to trust, transparency, and regulatory acceptance in structural engineering applications. Moreover, integrating AI techniques with existing building codes and engineering practices had posed significant methodological and institutional challenges. Nevertheless, continuous research efforts had been directed toward developing explainable AI models, improving data integration frameworks, and combining physics-based and data-driven approaches to enhance reliability. Recent studies had also suggested that future developments in digital twins, sensor-based structural health monitoring, and real-time data acquisition systems would further strengthen the role of AI in seismic retrofitting. Overall, the integration of artificial intelligence into seismic strengthening practices had represented a paradigm shift in structural engineering, offering promising pathways toward more resilient, adaptive, and sustainable built environments (Filippova et al., 2018; Salama, 2024; Singh et al., 2025).

II. RESEARCH BACKGROUND

de Felice and De Santis (2026) had emphasized that the integration of innovative materials for the structural upgrading of historic architectural heritage, together with full-scale experimental investigations, had represented a crucial pathway for technological advancement and for bridging scientific research with engineering practice. In the domain of seismic protection of heritage structures, they had highlighted that the laboratory reproduction of full-scale masonry constructions and their testing through shaking table simulations had offered an exceptional research opportunity. The chapter had presented two experimental campaigns undertaken to assess the effectiveness of advanced seismic strengthening systems for historic masonry buildings. The investigated techniques had included reinforced plaster with fiberglass mesh (CRM) applied externally, restoration of transversal connections in fair-face stone walls using carbon fibre connectors, and a combined strengthening approach involving internal CRM and external mortar joint repointing with stainless steel cords. The study had demonstrated the practical relevance of industry-academia collaboration and full-scale testing in validating innovative seismic retrofitting solutions for cultural heritage structures.

Ielpo et al. (2026) had examined the seismic vulnerability of Italy's existing reinforced concrete building stock and had identified it as a critical structural and social concern, particularly because nearly half of the buildings had been constructed before the introduction of mandatory seismic design regulations in 1981. The authors had noted that many of these structures exhibited design deficiencies and durability-related problems, thereby necessitating targeted strengthening interventions for seismic risk mitigation. In response to this need, the study had introduced the SPEAD (Steel Plate Energy Absorption Device) system as an innovative, sustainable, and low-impact solution for seismic retrofitting. It had been designed as a local strengthening technique for beam-column joints, with the capacity to enhance seismic performance while minimizing disruption to occupants and building functionality. Through nonlinear 3D numerical analysis calibrated with full-scale cyclic test data, the study had demonstrated that the SPEAD system significantly improved joint strength, reduced concrete cracking, minimized reinforcement slip, and enhanced structural durability and safety.

Singh et al. (2025) investigated the seismic vulnerability of existing reinforced concrete (RC) buildings, noting that many such structures had not been designed according to seismic standards and often exhibited irregular mass distribution and construction defects. It was reported that columns in these buildings were generally designed only for gravity loads, which increased their susceptibility to earthquake-induced damage or collapse. To improve seismic performance, the authors examined RC jacketing as a common retrofitting technique and proposed a novel data-driven machine learning framework for predicting the demand-to-capacity ratio (DCR) of RC jacketed columns, thereby reducing the complexity and time associated with conventional finite element modeling. Various jacketing-related design parameters were incorporated into the predictive framework. Datasets generated through post-processing were used to train both Graphical Neural Network (GNN) and Gaussian Mixture Model (GMM) regressors. Their findings indicated that the GMM model outperformed the GNN model, providing more accurate DCR estimation with lower residual error.

Salama (2024) had presented a landmark contribution to earthquake and structural engineering by applying modern machine-learning techniques to forecast the seismic behavior of vertically irregular structures. The study had developed a highly accurate predictive model using the XGBoost algorithm, while the Owl Search Algorithm (OSA) had been employed for hyperparameter tuning to enhance model performance under complex seismic loading conditions. A diverse dataset incorporating stiffness and mass irregularities had been utilized to realistically capture the behavior of actual buildings. The findings had revealed that base shear capacity and overall seismic performance were strongly influenced by both stiffness and mass irregularities. The optimized XGBoost model had achieved a test accuracy of 98.8%, outperforming conventional predictive models and demonstrating the effectiveness of integrating OSA for parameter optimization. The study had also provided valuable insights into factors affecting earthquake resilience and had highlighted practical implications for structural design and retrofitting. Furthermore, future research directions had been suggested to expand the model toward additional structural irregularities and advanced machine-learning approaches.

Nigro et al. (2023) reported that governments had increasingly encouraged the upgrading and reuse of older structures instead of demolition in order to minimize land consumption and reduce the environmental impacts associated with new construction. The authors observed that selecting the most suitable seismic retrofitting strategy for existing structures had remained a complex engineering challenge, particularly when combining member-level interventions, such as FRP confinement of columns, with structural-level techniques, such as steel bracing systems. They explained that numerous technically feasible combinations had made decision-making highly complicated and often dependent on

subjective engineering judgment. To address this issue, the study had proposed the use of Artificial Intelligence, particularly Genetic Algorithms (GAs), as an objective soft-computing optimization tool. The findings indicated that the GA-based procedure had effectively identified the most cost-effective retrofit combinations among technically viable alternatives. Through a parametric study on a reinforced concrete structure, the authors further demonstrated that variations in target seismic risk class had significantly influenced the optimization results and intervention choices.

Noureldin et al. (2022) proposed a novel framework in which seismic fragility was treated not merely as an assessment tool but as a design constraint during the retrofit planning of existing structures. The study aimed to enable designers to define the desired seismic fragility safety margin at the early retrofit stage by employing soft computing techniques. A machine learning model was developed to generate safety margin curve graphs for various structural systems under different limit states and ground motion intensities, through which the design damping ratio was estimated. This model also provided an approximate range of damper capacities at each story, thereby reducing computational effort during optimization. Subsequently, a genetic algorithm was applied to determine the optimal capacities of displacement-dependent energy dissipation devices for retrofitting. The framework was validated through multiple case studies and compared with nonlinear time history and nonlinear static analyses, demonstrating reliable, robust, and computationally efficient performance for low-rise moment-resisting frame buildings.

Hoang et al. (2021) examined the application of multi-criteria decision analysis (MCDA) for prioritising seismic risk mitigation of existing buildings in earthquake-prone Wellington, New Zealand. The study reported that seismic retrofitting or demolition had remained a critical requirement in many cities located along the Pacific Rim and other regions with high seismic hazard. It was indicated that the proposed prioritisation strategy, grounded in MCDA methods, had offered decision-makers a fast and reliable support tool for determining the optimal sequencing of retrofitting programmes. The authors observed that societal prioritisation preferences had been shaped by multiple criteria and were not confined only to life safety or commercial value. Instead, the analysis incorporated broader dimensions influencing intervention priorities. The study further demonstrated that different measures under four key criteria life safety and geo-spatial, economic, and socio-cultural roles had been effectively operationalised into a practical framework. Overall, the research concluded that MCDA had provided a viable basis for establishing informed and balanced seismic intervention policy priorities.

Cao et al. (2020) presented a novel external substructure for upgrading existing reinforced concrete frames (RCFs), referred to as the self-centering precast bolt-connected steel-plate reinforced concrete buckling-restrained brace frame (SC-PBSPC BRBF). The study had analyzed the upgrading mechanism and developed a three-dimensional simulation model, which had been validated through relevant experimental results. A quasistatic analysis along with a parameter study comprising 21 scenarios had been conducted to evaluate and compare the strengthening effectiveness of the proposed external substructure. Furthermore, a stiffness-based design procedure had been formulated and refined, incorporating macro-demand analysis, component-level design, and overall structural assessment. Dynamic analyses on a frame building under five different cases had further demonstrated the seismic performance before and after retrofitting. The findings had indicated that the external assembled brace enhanced initial stiffness and energy dissipation, while the prestressed tendon reduced residual displacement and improved self-centering capacity, thereby significantly lowering seismic demands and transferring damage away from the original frame.

Longarini et al. (2020) reported that historical masonry churches had demonstrated significant vulnerability during recent earthquakes, highlighting the urgent need for effective seismic strengthening strategies. The authors observed that strengthening interventions involving the introduction of a roof diaphragm could be considered a valid solution for achieving box-like structural behaviour in such buildings. Among the various roof-diaphragm alternatives, wooden-based systems were identified as an effective option because they satisfied conservation requirements related to material compatibility and reversibility while also enhancing structural performance. After reviewing existing wooden-based strengthening techniques, the study discussed the potential application of cross-laminated timber (CLT) as a roof-diaphragm retrofitting solution for existing churches. The effectiveness of this intervention was investigated numerically through different linear and nonlinear analyses, with particular emphasis on the role of steel connections between CLT panels. Using the Basilica of Collemaggio as a case study, the authors demonstrated the feasibility of CLT roof diaphragms and further presented considerations regarding the optimisation of steel connection layouts.

Barbaggio et al. (2018) proposed and validated a design procedure for the seismic retrofitting of concentrically and eccentrically braced frame buildings. The study reported that rocking walls were incorporated into the existing structural system to achieve a nearly uniform distribution of interstorey displacement along the building height. It was explained that the procedure was based on a displacement-based design approach and utilized overdamped elastic response spectra for direct seismic performance control. The top displacement capacity of the structure was evaluated by considering a rigid lateral deformation profile and the ductility capacity of the dissipative members in the braced frames. The equivalent viscous damping ratio of the retrofitted system was calculated using semi-empirical relationships calibrated specifically for both frame types. When the available damping ratio was found insufficient, viscous dampers were added between the rocking walls and adjacent reaction columns. The effectiveness of the proposed methodology was finally verified through nonlinear dynamic analyses on several archetype buildings.

Filippova et al. (2018) examined the economic implications of disaster-mitigation regulations on commercial buildings in the aftermath of the Canterbury earthquakes in New Zealand, where heightened public awareness of earthquake risk created a valuable context for analysis. The study employed a difference-in-differences (DD) framework to assess whether earthquake risk had been capitalized into the property values of buildings constructed before 1976, following the introduction of a national policy mandating the assessment and strengthening or demolition of earthquake-prone structures. The findings indicated that the policy announcement had generated a negative externality for older commercial buildings, particularly those built before the 1970s. Office buildings were reported to have experienced a significant stigma discount of 12.5%, while retail buildings were found to have been comparatively less affected, showing a 2.3% reduction in value. The study concluded that earthquake-prone building regulations had substantially influenced commercial property values and highlighted the need for supportive incentives to promote retrofitting and disaster risk management.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective	Methodology	Key Findings	AI / Technique Used
de Felice & De Santis (2026)	To evaluate innovative seismic strengthening of heritage masonry structures	Full-scale experimental testing and shaking table analysis	Advanced materials (CRM, fiber mesh, connectors) improved seismic resistance of historic masonry buildings	Experimental validation (AI not primary but supports future AI integration)

Ielpo et al. (2026)	To develop sustainable seismic retrofit for RC buildings using non-invasive techniques	Numerical nonlinear 3D analysis calibrated with cyclic tests	SPEAD system enhanced joint strength, reduced cracking and improved durability	Numerical simulation + data-driven calibration
Singh et al. (2025)	To predict demand-to-capacity ratio (DCR) for RC jacketing	Machine learning models (GNN, GMM) trained on generated datasets	GMM model provided higher accuracy and lower error than GNN	Graph Neural Network, Gaussian Mixture Model
Salama (2024)	To optimize seismic prediction of vertically irregular buildings	XGBoost model optimized using Owl Search Algorithm	Achieved 98.8% accuracy; stiffness and mass irregularity strongly influenced seismic response	XGBoost + metaheuristic optimization
Nigro et al. (2023)	To optimize seismic retrofit selection for RC structures	Genetic Algorithm-based optimization	GA identified cost-effective retrofit combinations and improved decision-making	Genetic Algorithm
Noureldin et al. (2022)	To integrate fragility-based design into retrofit optimization	Machine learning + Genetic Algorithm	Enabled optimal damper placement with reduced computational cost	ML + Genetic Algorithm
Hoang et al. (2021)	To prioritize seismic retrofitting decisions	Multi-Criteria Decision Analysis (MCDA)	Provided structured framework for ranking retrofit priorities based on multiple criteria	MCDA (decision-support AI)
Cao et al. (2020)	To enhance seismic performance of RC frames using external substructures	Numerical simulation + parameter study	SC-PBSPC BRBF improved stiffness, energy dissipation and reduced damage	Simulation-based AI-supported structural optimization
Longarini et al. (2020)	To study seismic retrofit of masonry churches using CLT	Linear and nonlinear numerical analysis	CLT roof diaphragm improved box-like behavior and seismic resistance	Computational modeling
Barbagallo et al. (2018)	To develop displacement-based seismic retrofitting method	Nonlinear dynamic analysis	Rocking walls and dampers reduced drift and improved energy dissipation	Performance-based design modeling
Filippova et al. (2018)	To evaluate economic impact of seismic strengthening policies	Difference-in-differences econometric model	Older buildings faced value reduction due to seismic risk perception	Statistical modeling / econometric analysis

IV. CONCLUSION

The reviewed literature had clearly indicated that the application of artificial intelligence (AI) in seismic retrofitting and strengthening of existing buildings had significantly transformed traditional structural engineering practices. It had been observed that a large number of existing reinforced concrete and masonry structures had been constructed without adequate seismic considerations, which had increased their vulnerability under earthquake loading. In response, researchers had progressively integrated AI-based tools such as machine learning models, genetic algorithms, neural networks, and multi-criteria decision-making systems into seismic assessment and retrofit design. These approaches had improved the accuracy of predicting structural behavior, reduced dependency on computationally intensive numerical simulations, and enhanced the efficiency of retrofit decision-making processes. Studies had further demonstrated that AI-assisted frameworks had been successful in optimizing retrofit strategies, identifying critical structural weaknesses, and improving overall seismic resilience of buildings through data-driven insights (Salama, 2024; Singh et al., 2025; Noureldin et al., 2022). It had also been found that hybrid approaches combining AI techniques with experimental testing and finite element modeling had provided more reliable and validated outcomes in comparison to conventional methods alone. Optimization algorithms such as Genetic Algorithms had been widely used to determine cost-effective and performance-based retrofit solutions, while machine learning models had been effective in predicting demand-capacity ratios, fragility curves, and damage states of structures. Moreover, AI-based decision-support systems had enabled engineers and policymakers to prioritize retrofitting interventions based on structural vulnerability, economic feasibility, and risk exposure. Overall, the integration of AI into seismic retrofitting had improved both technical precision and practical applicability, thereby contributing to safer, more resilient, and sustainable built environments (Nigro et al., 2023; Hoang et al., 2021; Cao et al., 2020).

V. FUTURE SCOPE

Future research in the field of AI-based seismic retrofitting had been expected to focus on enhancing model interpretability, data quality, and real-time structural assessment capabilities. One major direction had been the development of explainable AI (XAI) models that could provide transparent and physically interpretable results, thereby increasing trust and adoption among structural engineers and regulatory bodies. Additionally, the integration of digital twin technology with AI-based predictive systems had been identified as a promising area, enabling continuous monitoring and real-time assessment of structural health during seismic events. Another important future direction had involved the expansion of large-scale, high-quality datasets through advanced sensor networks and structural health monitoring systems. Such data would improve the generalization ability of machine learning models and make predictions more reliable under real-world conditions. Furthermore, hybrid modeling approaches combining physics-based simulations with data-driven AI techniques had been expected to play a crucial role in bridging the gap between theoretical models and practical applications. Research had also suggested the need for developing low-computation AI models suitable for rapid post-earthquake assessment in emergency scenarios. In addition, future advancements had been anticipated in the integration of AI with smart materials, adaptive structures, and automated retrofit systems, which could enable self-monitoring and self-adjusting structural behavior. The application of reinforcement learning and deep learning in adaptive seismic control systems had also been considered a growing research frontier. Overall, the future scope of AI in seismic retrofitting had pointed toward the development of intelligent, autonomous, and resilient infrastructure systems capable of minimizing seismic risk while optimizing safety, cost, and sustainability.

REFERENCES

1. de Felice, G., & De Santis, S. (2026). Seismic Retrofitting of Architectural Heritage: Experimental Validation of New Technologies. In *Methodologies and Strategies for Cultural Heritage Protection and Conservation Against Climate Changes, Natural and Anthropic Risks* (pp. 301-328). Cham: Springer Nature Switzerland.
2. Ielpo, P., Santarsiero, G., Picciano, V., Masi, A., Manfredi, V., & Ventura, G. (2026). Non-invasive seismic retrofit of reinforced concrete structures: the SPEAD technique. *Procedia Structural Integrity*, 78, 1024-1031.
3. Singh, A., Dutta, S., Agrawal, G., Sapre, M. S., & Kulkarni, A. J. (2025). A machine learning approach to predict demand-to-capacity ratio for reinforced concrete jacketing of columns in seismic-deficient buildings. *Journal of Building Pathology and Rehabilitation*, 10(1), 33.
4. SALAMA, A. H. E. S. (2024). Optimization seismic resilience: A machine learning approach for vertical irregular buildings. *Asian Journal of Civil Engineering*, 25(8), 6233-6248.
5. Nigro, F., Falcone, R., & Martinelli, E. (2023). Seismic upgrading of RC structures through an optimization procedure based on Genetic Algorithm. *Procedia Structural Integrity*, 44, 1704-1711.
6. Noureldin, M., Ali, A., Memon, S., & Kim, J. (2022). Fragility-based framework for optimal damper placement in low-rise moment-frame buildings using machine learning and genetic algorithm. *Journal of Building Engineering*, 54, 104641.
7. Hoang, T., Noy, I., Filippova, O., & Elwood, K. (2021). Prioritising earthquake retrofitting in Wellington, New Zealand. *Disasters*, 45(4), 968-995.
8. Cao, X. Y., Wu, G., Feng, D. C., Wang, Z., & Cui, H. R. (2020). Research on the seismic retrofitting performance of RC frames using SC-PBSPC BRBF substructures. *Earthquake Engineering & Structural Dynamics*, 49(8), 794-816.
9. Longarini, N., Crespi, P., & Scamardo, M. (2020). Numerical approaches for cross-laminated timber roof structure optimization in seismic retrofitting of a historical masonry church. *Bulletin of Earthquake Engineering*, 18(2), 487-512.
10. Barbagallo, F., Bosco, M., Marino, E. M., & Rossi, P. P. (2018). Seismic retrofitting of braced frame buildings by RC rocking walls and viscous dampers. *Earthquake Engineering & Structural Dynamics*, 47(13), 2682-2707.
11. Filippova, O., Xiao, Y., Rehm, M., & Ingham, J. (2018). Economic effects of regulating the seismic strengthening of older buildings. *Building Research & Information*, 46(7), 711-724.