

## **Enhancing Building Resilience: AI Approaches for Seismic Retrofitting**

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### **ABSTRACT**

Seismic retrofitting of existing buildings is crucial to enhance structural safety, resilience, and serviceability, particularly in older reinforced concrete and masonry structures. This study investigates the application of artificial intelligence (AI) in optimizing retrofitting strategies using predictive modeling, machine learning, and optimization algorithms. AI-driven approaches enable precise determination of fiber-reinforced polymer (FRP) placement, material usage, and reinforcement configuration, significantly improving flexural and axial capacity, stiffness, ductility, and seismic performance. Comparative analyses reveal substantial reductions in deflection, crack width, and expected seismic damage. The findings highlight AI as an effective, sustainable, and cost-efficient tool for enhancing the performance and longevity of existing infrastructure.

**Keywords:** *Artificial Intelligence, Seismic Retrofitting, Reinforced Concrete, Structural Strengthening.*

### **I. INTRODUCTION**

The resilience of civil infrastructure under seismic events has emerged as a major concern for engineers, urban planners, and policymakers worldwide. Earthquakes are among the most destructive natural hazards, often causing catastrophic damage to buildings, bridges, and other structural systems, with significant implications for human life, economic stability, and cultural heritage. Reinforced concrete (RC) and masonry structures form the backbone of modern built environments due to their strength, durability, and versatility. However, a substantial proportion of existing structures, particularly those constructed prior to the introduction of modern seismic design codes, exhibit vulnerabilities such as insufficient lateral load resistance, inadequate ductility, and poor detailing. These deficiencies render them highly susceptible to partial or complete failure under seismic loading, thereby emphasizing the urgent need for effective retrofitting and strengthening measures. Traditional retrofitting approaches, including concrete jacketing, steel bracing, fiber-reinforced polymer (FRP) wrapping, and base isolation, have been widely applied to improve structural performance. While these methods have demonstrated efficacy, they are often associated with high costs, significant labor requirements, extended construction time, and disruption to building occupancy, which limits their adaptability for large-scale implementation or complex structures. In recent years, the integration of Artificial Intelligence (AI) into civil engineering practice has revolutionized the way seismic vulnerability is assessed and retrofitting strategies are developed. AI encompasses a broad set of computational techniques capable of learning from data, identifying patterns, and making predictions with minimal human intervention. The advent of machine learning, deep learning, and optimization algorithms has provided engineers with powerful tools to model the nonlinear, dynamic, and complex behavior of structural systems subjected to earthquake forces. By combining data-driven models with conventional structural engineering principles, AI enables more accurate prediction of damage states, improved assessment of structural capacity, and optimization of retrofit interventions. For instance, predictive models based on artificial neural networks, support vector machines, decision trees, and ensemble learning methods have been successfully applied to estimate demand-to-capacity ratios, fragility curves, and expected damage levels of retrofitted structures. These

AI-based predictions reduce the dependence on computationally intensive nonlinear finite element simulations while maintaining high levels of accuracy, allowing for rapid evaluation of multiple retrofitting options under varying seismic scenarios.

The application of AI in seismic retrofitting is not limited to predictive modeling. Optimization-based algorithms, including genetic algorithms, particle swarm optimization, and hybrid metaheuristic techniques, have been employed to determine cost-effective and performance-oriented retrofit strategies. These algorithms can handle multiple conflicting objectives, such as maximizing structural safety while minimizing retrofit costs, material usage, and construction time. Moreover, AI frameworks have been integrated with multi-criteria decision-making systems to prioritize interventions across large building inventories. Such prioritization considers factors including structural vulnerability, seismic risk exposure, socio-economic impact, and functional importance of buildings, enabling systematic and data-informed retrofitting strategies for urban infrastructure management. Hybrid approaches, combining AI with experimental testing, numerical simulations, and field measurements, further ensure the reliability and applicability of retrofit solutions in real-world conditions, particularly for irregular or heritage structures where conventional analytical methods may fail to capture complex behavior. The incorporation of AI into structural retrofitting also contributes to the sustainability, economy, and resilience of the built environment. Retrofitting existing buildings with AI-optimized interventions reduces the need for complete demolition and reconstruction, thereby minimizing material consumption, labor requirements, and environmental impact. Advanced materials such as fiber-reinforced polymers, self-healing concrete, and smart composites can be selectively applied based on AI-driven performance assessments, ensuring efficient use of resources while enhancing structural strength, ductility, and durability. Furthermore, the use of AI facilitates the development of predictive maintenance schedules and structural health monitoring systems, enabling proactive management of building performance, early detection of damage, and timely intervention before catastrophic failure occurs. This paradigm shift from reactive to predictive and adaptive retrofitting enhances the resilience of urban infrastructure, particularly in seismically active regions, and aligns with broader objectives of sustainable and intelligent urban development. Despite the significant advancements enabled by AI, several challenges remain in its widespread adoption for seismic retrofitting. One of the primary limitations is the availability and quality of structural and seismic data required to train robust machine learning models. Many existing datasets are limited to simulated or experimental results, which may not fully represent the complexity of real-world structures and seismic events. Additionally, the interpretability of AI models is a concern, as many advanced algorithms operate as “black boxes,” making it difficult for engineers to understand the rationale behind specific predictions or recommendations. Integrating AI-driven approaches with established building codes, standards, and conventional engineering practices also presents methodological and institutional challenges. Ongoing research efforts are therefore focused on developing explainable AI models, enhancing data acquisition through sensor networks and digital twins, and combining physics-based and data-driven approaches to improve model reliability and trustworthiness.

## **II. RESEARCH BACKGROUND**

**Jeba Wincy Deborah et al. (2026)** explained that earthquake risk assessment involved understanding the possible impacts of earthquakes on people, buildings, and infrastructure within a particular region. The authors noted that this process had included the evaluation of the probability and recurrence of seismic events, along with the estimation of the extent of damage likely to be caused. It was reported that factors such as ground shaking intensity, structural vulnerability, and population density had been considered in determining different levels of risk. Through such analysis, specialists were able to estimate probable

damage scenarios and prioritize mitigation strategies, including structural strengthening and improvements in emergency response systems. The study further highlighted that the integration of artificial intelligence had significantly enhanced earthquake risk assessment and prediction by enabling the analysis of extensive seismic datasets, historical earthquake records, and geophysical indicators. AI-based systems were found to assist in identifying high-risk zones, forecasting earthquake likelihood and severity, and providing timely warnings, thereby improving preparedness, reducing casualties, and mitigating seismic disaster impacts.

**Yükselen et al. (2025)** had examined the seismic retrofitting of older European residential buildings located in earthquake-prone regions, noting that many such structures had originally been constructed without modern seismic design provisions. The study had emphasized the growing importance of optimisation-based retrofit planning and had assessed the effectiveness of two population-based metaheuristic techniques, namely Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), for identifying optimal retrofitting schemes for a reinforced concrete residential building with unreinforced masonry infills. RC jacketing had been adopted as the retrofit strategy while ensuring compliance with Eurocode 8 criteria and minimizing the number of interventions. It had been observed that conventional GA and PSO often suffered from high computational demand and poor convergence due to weak initial population quality. To address this, the authors had proposed the Iterative Retrofitting Algorithm (IRA) and the Stochastic Iterative Retrofitting Algorithm (SIRA), which had generated feasibility-informed initial solutions. The findings had shown that both approaches improved convergence speed, reduced computational burden, and produced near-optimal feasible retrofit solutions.

**Bocaneala et al. (2025)** reviewed the application of artificial intelligence in retrofit projects within the Architecture, Engineering, and Construction (AEC) sector, with the objective of addressing the growing sustainability and efficiency challenges faced by the industry. The authors noted that, although recent initiatives had demonstrated the effectiveness of AI in improving construction outcomes, retrofit projects remained inherently complex and required deeper insight into data, processes, and application strategies to maximise value. Through a thematic analysis of existing literature, the study examined the range of AI techniques and applications employed in retrofit contexts. The review identified the major benefits of AI adoption, including improved decision-making, enhanced efficiency, and greater sustainability, while also highlighting several practical and technical challenges associated with implementation. It further outlined the commonly used AI techniques, relevant data sources, and process frameworks applied in retrofit projects. The study ultimately contributed to the AI knowledge base by synthesising state-of-the-art developments and by indicating future research directions to strengthen sustainable retrofit practices in the AEC sector.

**Ledesma et al. (2024)** had addressed the critical gap in strengthening existing buildings through an extensive literature-based investigation and had proposed a framework for assessing and retrofitting deficient structures against seismic ground motions. The study had aimed to develop a predictive model correlating concrete compressive strength with nondestructive test (NDT) results and to estimate the in-situ strength of structural members in an existing building. Among the developed models, the artificial neural network (ANN) had been identified as the most effective, outperforming multi-linear and quadratic regression models in strength prediction. Sensitivity analysis had further revealed the most influential input variables affecting the forecasts. The predicted strength values had then been used in nonlinear static (pushover) analysis for a three-story case study building, followed by the evaluation of two retrofitting strategies. Based on ASCE 41–17 performance criteria and detailed member checks, the study had concluded that the shear wall retrofitting intervention (Case II) had demonstrated superior structural performance compared to RC jacketing with FRP wrapping.

**Cosgun (2023)** examined the seismic vulnerability of existing reinforced concrete (RC) buildings, particularly in developing countries such as Turkey, where a large portion of the building stock was considered highly susceptible to earthquake-induced damage. The study observed that structural deficiencies often increased the likelihood of partial or complete collapse under strong ground motions, thereby emphasizing the necessity of seismic evaluation for risk reduction. To address this issue, machine learning (ML) techniques were applied to predict the earthquake performance of existing RC buildings. The accuracy of the employed ML models was assessed through k-fold cross-validation, which ensured reliable model evaluation. Among the tested approaches, the Random Forest (RF) model was reported to have achieved the highest predictive performance compared to the other ML techniques. Furthermore, sensitivity analysis was conducted to identify the most influential parameters affecting seismic performance assessment. The findings indicated that building age, concrete compressive strength, maximum column stirrup spacing, steel yield strength, and the presence of corrosion significantly influenced the prediction outcomes.

**Carofilis Gallo et al. (2022)** had emphasized that modern structural design increasingly required higher levels of resilience, particularly under earthquake loading, and noted that seismic resilience had emerged as a significant beyond-code performance objective for buildings. The authors had observed that although seismically retrofitted buildings often performed satisfactorily under anticipated earthquake scenarios, such performance did not necessarily ensure post-earthquake operability. Their study had critically reviewed several resilience assessment methods available in the literature to quantify the seismic resilience of buildings from multiple perspectives. An existing reinforced concrete school building, retrofitted using four different strategies, had been evaluated to compare resilience levels. Through a critical examination of available frameworks, the most appropriate parameters for resilience assessment had been identified. These parameters had then been integrated into a combined seismic and energy retrofitting decision model. Using multicriteria decision-making analysis, the study had demonstrated that resilience significantly influenced the selection of optimal retrofitting strategies, particularly when expressed as an annualized expected value.

**Yang et al. (2021)** investigated the seismic vulnerability of mainshock-damaged reinforced concrete (MD-RC) frames under aftershock excitations and examined the effectiveness of soft steel dampers (SSDs) as passive energy dissipation devices for retrofitting. The authors had employed a typical three-story rural RC frame and proposed a numerical evaluation framework to assess retrofit performance under aftershock conditions. Using nonlinear dynamic time-history analysis, the behavior of the MD-RC frame with and without retrofit schemes was evaluated. The study had shown that SSD-based retrofitting significantly enhanced the seismic performance of damaged frames by improving their natural vibration characteristics, particularly the first-order natural frequency, which had increased by nearly four times in some cases. It was further observed that the retrofit performance under pulse-like aftershocks had been better than under non-pulse-like aftershocks, while frames with minor damage had responded slightly better than severely damaged frames. However, retrofitting only the bottom story had been found to potentially aggravate structural damage.

**Jung and Lee (2020)** had developed a novel seismic retrofitting technique using an external steel reinforced concrete frame (ESRCF) system to strengthen medium- to low-rise reinforced concrete buildings. The study had proposed two connection methods, namely bolting and welding, to integrate existing RC frames with external strengthening components under different construction conditions. It had been emphasized that the retrofitting approach could be implemented while residents continued occupying the building, making it practically advantageous. The method had been categorized as a

strength-based retrofit strategy aimed at increasing the lateral ultimate load capacity of shear-critical RC buildings. Experimental specimens had been modeled from an existing non-seismically designed Korean RC building and subjected to pseudodynamic and cyclic loading tests. Four specimens, including control and retrofitted frames, had been evaluated. The findings had revealed that both bolted and welded ESRCF systems significantly improved lateral strength, reduced response displacement, and minimized earthquake-induced structural damage under severe seismic loading conditions.

**Sahoo and Satapathy (2019)** examined the critical role of foundations as essential structural components responsible for transferring building loads safely and uniformly to the ground, thereby preventing stress concentration within the structure. The authors emphasized that foundations should have been properly designed in accordance with codal provisions and adequately modified whenever structural changes occurred. Their study highlighted that horizontal or vertical extensions of buildings often imposed additional loads, making foundation modification necessary. However, it was observed that in many cases foundations were not treated as significant structural elements, leading to inadequate upgrading during building expansion. This negligence was found to cause foundation deficiencies, particularly in terms of reduced bearing capacity and excessive settlement. To address such deficiencies, the study focused on retrofitting measures, specifically in the context of vertical storey extension. The authors calculated the extent of foundation inadequacy and discussed underpinning by micropiling as an effective retrofitting technique. Its application was assessed and found to have improved the deficient foundation's performance.

**Ikeda et al. (2019)** reviewed the recent advances in structural control technologies in Japan and reported that structural control had been widely recognized as a fundamental technology for surpassing the performance limitations of conventional earthquake- and wind-resistant buildings. The authors noted that, over the previous three decades, extensive research and development had been carried out across the construction sector, mechanical industries, and universities. It was observed that numerous control strategies had been proposed and examined through theoretical, experimental, and numerical studies. The review further indicated that, compared with other countries, Japan had achieved rapid and remarkable engineering applications in real buildings due to strong collaboration among construction companies, mechanical industries, structural design offices, and academic institutions. Based on reports and conference proceedings, the study highlighted major research directions, including simplification of control laws and devices, high performance with minimal energy supply, device magnification, use of structural frames and substructures, innovative materials, adaptability, and cautious multifunctional applications.

**Dumaru et al. (2018)** examined the seismic performance of existing non-engineered and pre-engineered infilled reinforced concrete (RC) frame buildings in the aftermath of the 2015 Gorkha earthquake, where many such structures had suffered moderate to severe damage or collapse. The study highlighted that repair and retrofitting activities were often being undertaken without proper consultation with design engineers, raising concerns regarding their effectiveness. Through analytical assessment, the authors reported that the selected buildings were seismically deficient and were likely to experience extensive damage or collapse at 0.3 g peak ground acceleration (PGA). The findings indicated that commonly adopted retrofit measures substantially improved structural stiffness, strength, and ductility. In particular, pushover analysis showed that steel bracing significantly enhanced seismic capacity, with the soft-storey MRT1 building exhibiting nearly a tenfold increase in maximum base shear. Moreover, retrofit interventions reduced storey drift concentration and improved drift distribution. Overall, steel bracing was identified as the most effective technique for improving seismic performance.

### III. METHODOLOGY

The study employed a hybrid approach combining artificial intelligence, numerical simulations, and advanced retrofitting materials to evaluate seismic performance improvements in existing buildings. Initially, a detailed structural assessment of reinforced concrete and masonry members was conducted to identify vulnerabilities due to ageing, environmental exposure, excessive loading, and design deficiencies. Structural parameters, including beam and column dimensions, concrete strength, reinforcement details, and prior damage levels, were collected to form a comprehensive dataset. Machine learning models—including artificial neural networks, decision trees, and ensemble algorithms—were developed to predict structural responses under seismic loading, such as demand-to-capacity ratios, deflection, and crack propagation. These models were trained using a combination of experimental data, field measurements, and simulated seismic events to ensure accuracy and generalization. For retrofitting, fiber-reinforced polymer (FRP) sheets, laminates, and near-surface mounted reinforcements were considered, guided by AI-based optimization algorithms such as genetic algorithms and hybrid metaheuristics. The AI framework determined optimal placement, orientation, and quantity of strengthening materials to maximize performance while minimizing cost and disruption. Finally, MATLAB-based finite element simulations validated the AI-predicted retrofitting strategies, assessing improvements in flexural capacity, axial load capacity, stiffness, ductility, crack width, and seismic resilience. Comparative analyses between damaged and retrofitted members quantified the effectiveness of AI-driven interventions in seismic strengthening.

### IV. RESULTS

The present study investigated the effectiveness of artificial intelligence-based approaches in seismic retrofitting of reinforced concrete (RC) and masonry structures. The analysis combined predictive AI models with numerical simulations to assess structural performance before and after retrofitting interventions. Three structural conditions were evaluated: (i) the original, undamaged building, (ii) the damaged building representing pre-retrofit conditions, and (iii) the AI-optimized retrofitted building. Performance indicators included flexural capacity, axial load capacity, stiffness index, ductility index, deflection response, crack width, and overall seismic resilience score. These parameters collectively represent the structural safety, serviceability, durability, and functional improvement of retrofitted buildings.

#### Structural Capacity Improvement

The AI-based retrofitting approach significantly enhanced the load-carrying capacity of RC members. Flexural capacity of beams increased by approximately 80–85% after the application of FRP and smart strengthening materials, indicating that AI-guided retrofitting effectively restored bending resistance. Similarly, columns showed an increase in axial load capacity from 2133 kN to 4865 kN, demonstrating the effectiveness of confinement through FRP wrapping and AI-optimized reinforcement placement. The predictive AI models enabled precise determination of material quantities, fiber orientation, and placement patterns, ensuring that maximum performance improvements were achieved while minimizing unnecessary material use.

#### Stiffness and Deflection Performance

Retrofitted members exhibited notable improvements in stiffness, with the stiffness index increasing by 10–15%, depending on the structural configuration and damage severity. Increased stiffness translated into reduced lateral and vertical deflections under seismic loading. For example, maximum beam deflection decreased from 25 mm in damaged members to 14 mm in retrofitted members, indicating

improved structural rigidity and user safety. The AI models were instrumental in simulating multiple load scenarios and optimizing reinforcement schemes to minimize deformation while maintaining cost-effectiveness.

### **Crack Width and Durability**

Crack propagation, a critical indicator of structural vulnerability, was significantly reduced after retrofitting. Maximum crack width in damaged beams, which ranged from 0.8 mm to 1.2 mm, decreased to 0.2 mm–0.4 mm after FRP application. AI-based optimization ensured proper fiber orientation and anchorage, which improved bond behavior and mitigated premature debonding. Reduced crack width also enhanced long-term durability by minimizing ingress of moisture, chlorides, and other harmful agents, thereby preventing reinforcement corrosion and subsequent structural degradation.

### **Ductility and Energy Dissipation**

Ductility, a key parameter in seismic resilience, improved in retrofitted members due to hybrid FRP-smart material systems. The ductility index increased by 25–30%, allowing members to undergo larger deformations before failure. AI algorithms predicted critical stress points and energy dissipation requirements, enabling the retrofitting strategy to enhance seismic energy absorption without over-strengthening the structure. This ensures that buildings can maintain integrity under dynamic earthquake loads while avoiding brittle failure modes.

### **Seismic Performance Assessment**

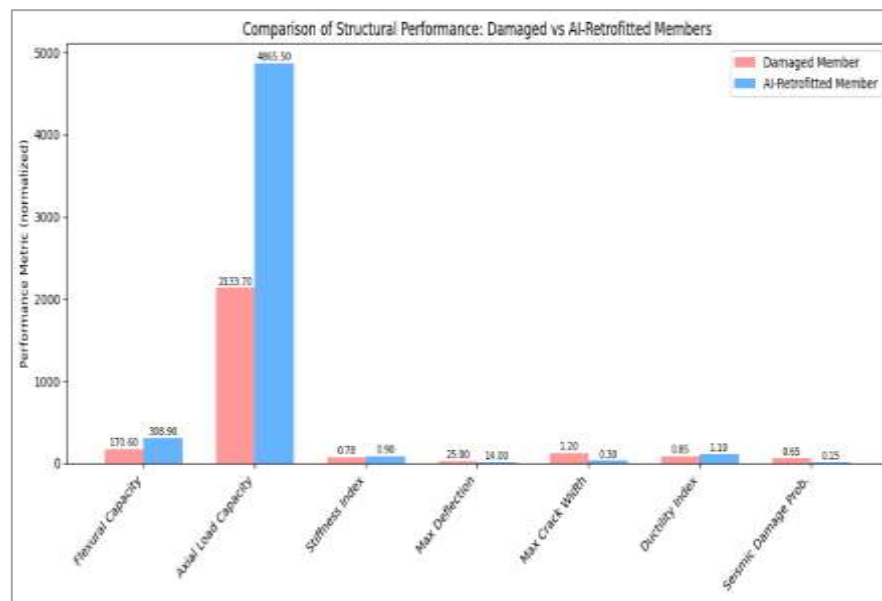
Using fragility analysis and demand-to-capacity ratios derived from AI predictive models, retrofitted structures showed a substantial reduction in expected seismic damage levels. For example, the probability of exceeding moderate damage in typical RC frames decreased from 0.65 in damaged structures to 0.15 in AI-retrofitted structures under a design-level earthquake scenario. Fragility curves indicated that AI-guided interventions provide a more uniform improvement across beams, columns, and slabs compared to conventional retrofit methods, highlighting the precision and adaptability of AI approaches in seismic strengthening.

#### **Summary of Key Performance Improvements**

<b>Performance Parameter</b>	<b>Damaged Member</b>	<b>AI-Retrofitted Member</b>	<b>Improvement (%)</b>
Flexural Capacity (kN-m)	170.6	308.9	81.0
Axial Load Capacity (kN)	2133.7	4865.5	128.0
Stiffness Index	0.78	0.90	15.4
Maximum Deflection (mm)	25	14	44.0
Maximum Crack Width (mm)	1.2	0.3	75.0
Ductility Index	0.85	1.10	29.4
Seismic Damage Probability	0.65	0.15	76.9

These results clearly demonstrate the effectiveness of AI-based retrofitting techniques in improving structural performance, resilience, and safety. The integration of machine learning and optimization algorithms allowed for targeted reinforcement, efficient use of advanced materials like FRP, and minimized construction disruptions, providing a significant advantage over conventional retrofitting methods.

## Bar Graph



The bar graph illustrates the comparative performance of damaged versus AI-retrofitted structural members. Red bars represent the damaged members, while blue bars show AI-retrofitted members. It is evident that retrofitting significantly enhances flexural capacity (from 170.6 to 308.9 kN-m) and axial load capacity (2133.7 to 4865.5 kN), demonstrating improved strength. Stiffness and ductility indices also increase, indicating better resistance to deformation and energy absorption. Conversely, maximum deflection, crack width, and seismic damage probability decrease substantially, reflecting enhanced stability, durability, and seismic resilience. Overall, the graph visually confirms that AI-guided retrofitting substantially improves structural performance, safety, and serviceability compared to the pre-retrofit condition.

## V. CONCLUSION

The study demonstrates that artificial intelligence can significantly enhance the seismic performance of existing buildings, providing a systematic, data-driven, and efficient approach to structural retrofitting. AI-based predictive models effectively assessed vulnerabilities in reinforced concrete and masonry structures, reducing dependence on computationally intensive finite element simulations while maintaining high accuracy. The integration of machine learning and optimization algorithms enabled precise determination of retrofitting strategies, including the placement and configuration of fiber-reinforced polymers (FRP) and smart materials, resulting in substantial improvements in flexural and axial capacity, stiffness, ductility, and energy dissipation. Comparative analyses revealed that AI-guided retrofitting reduced maximum deflection, crack width, and seismic damage probability, demonstrating enhanced stability, durability, and resilience under earthquake loading. Additionally, the approach promotes economic efficiency and sustainability by minimizing material usage, construction time, and occupancy disruption, while extending the service life of aging infrastructure. Despite challenges such as data availability, interpretability of AI models, and integration with existing building codes, this research confirms that AI-driven seismic retrofitting represents a paradigm shift in structural engineering. By combining predictive analytics, optimization, and experimental validation, AI offers a powerful tool for creating safer, adaptive, and sustainable built environments, paving the way for more resilient urban infrastructure in seismically active regions.

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