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SEISMIC PERFORMANCE EVALUATION OF REINFORCED CONCRETE BUILDINGS IN HIGH-RISK ZONES

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Abstract

Reinforced concrete (RC) buildings remain the dominant structural form in seismically active high-risk zones, yet they continue to exhibit significant vulnerabilities during major earthquakes due to limitations in traditional design and evaluation approaches. This study presents a comprehensive review of contemporary seismic performance assessment methodologies for RC buildings, highlighting the shift from force-based to performance-based engineering paradigms. Key topics include the comparative advantages and limitations of linear (Equivalent Static and Response Spectrum) versus nonlinear (pushover, time-history, and incremental dynamic) analysis procedures; the critical influence of structural irregularities, masonry infill configurations (including soft-story and short-column effects), and soil-structure interaction (SSI); and the implications of mainshock-aftershock sequences on collapse capacity and residual drift. The paper examines international seismic evaluation standards (ASCE 41, Eurocode 8), forensic lessons from recent devastating events (Türkiye 2023, Japan 2024, Nepal 2015), and emerging resilience-enhancing technologies such as FRP/TRM jacketing, viscous dampers, shape memory alloys, and base isolation. Additionally, the transformative role of machine learning techniques (e.g., XGBoost, Random Forest, SVR) combined with interpretability tools (SHAP) for rapid regional vulnerability assessment is discussed. The synthesis underscores the necessity of holistic, nonlinear, and probabilistic frameworks that integrate structural, geotechnical, and non-structural factors to achieve improved seismic resilience in high-risk regions.

1. INTRODUCTION

The structural integrity of the built environment in seismically active regions represents a critical intersection of public safety, economic stability, and engineering innovation. Reinforced concrete (RC) buildings, as the predominant structural typology globally, have undergone rigorous scrutiny following successive catastrophic seismic events (Makhoul et al., 2024). The evaluation of these structures in high-risk zones has evolved from simple strength requirements into a complex assessment of displacement capacity, ductility, and the intricate interaction between structural and non-structural components (Elqudah et al., 2025). This report provides a comprehensive review of current evaluation methodologies, the impact of structural irregularities, the role of soil-structure interaction, and the emerging influence of machine learning and advanced retrofitting technologies in enhancing seismic resilience (Najar et al., 2025).

2. Evolutionary Paradigms in Seismic Analysis Methodologies

The transition from force-based to performance-based seismic engineering marks a fundamental shift in how RC buildings are evaluated (Choudhury, 2024). Traditional force-based design, which relies on linear elastic analysis and response reduction factors, has been found insufficient for capturing the true inelastic behavior of structures during severe earthquakes (Causevic & Mitrovic, 2011). In high-risk zones, where seismic demand often drives the structure deep into the nonlinear range, the limitations of linear methods become stark (Guan et al., 2025).

2.1. Linear versus Nonlinear Analytical Procedures

Linear methodologies, including Equivalent Static Analysis (ESA) and Response Spectrum Analysis (RSA), are frequently used for their lower computational requirements (Ruggieri & Uva, 2024). However, recent studies highlight significant accuracy gaps in high-seismicity scenarios. For instance, RSA can overestimate base reactions, such as moments and shear forces, by as much as 250% in high-risk zones because linear models do not "cap" forces at the point of material yielding (MDPI, 2024).

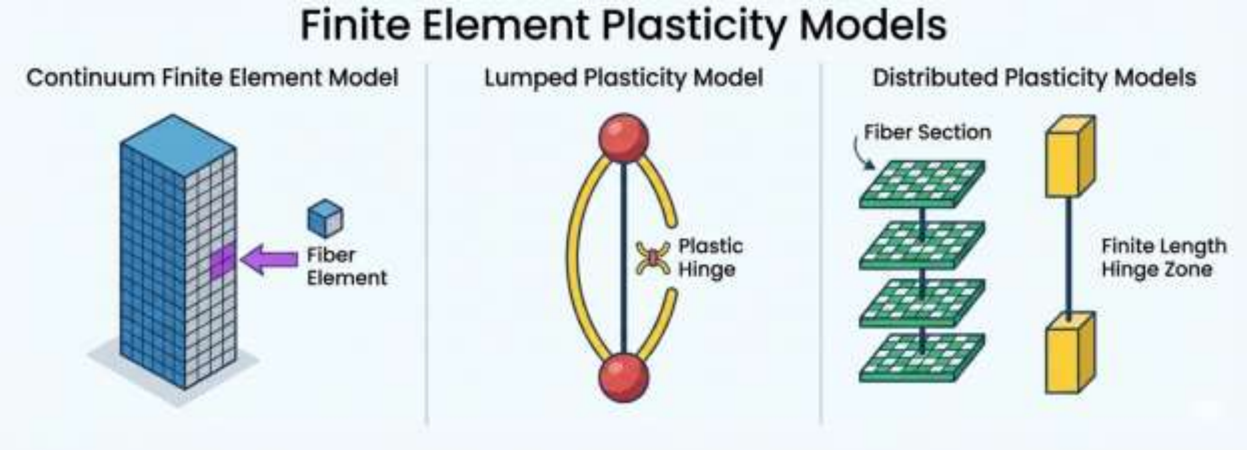

Figure 1: Classification of Numerical Modeling Approaches for Inelastic Seismic Analysis: From Continuum Finite Element to Distributed Plasticity Fiber Models.

Conversely, nonlinear procedures provide a more realistic estimation of structural response. The Nonlinear Static Procedure (NSP), or pushover analysis, allows engineers to visualize the sequence of hinge formation (Tesfamariam & Goda, 2015). While NSP is effective for buildings where the fundamental mode dominates, it often provides misleading results beyond an inter-story drift ratio of 1% (Luk, 2025). For complex buildings, Nonlinear Time-History Analysis (NLTHA) is the benchmark for accuracy, explicitly accounting for material nonlinearities and geometric P-Delta effects (Khatiwada, 2025).

Table 1. Comparison of Seismic Analysis Methodologies and Computational Demands

Analysis Methodology	Computational Demand	Primary Metric	Applicability
Equivalent Static Analysis	Low	Force/Base Shear	Regular, low-rise buildings (MDPI, 2024)
Response Spectrum Analysis	Moderate	Modal Combination	Standard practice for regular structures (Ye et al., 2015)

Nonlinear Static Procedure	Moderate-High	Capacity Curve	Assessment of failure mechanisms (Ye et al., 2015)
Nonlinear Time-History	High	Time-varying Response	Research benchmarks and complex structures (MDPI, 2024)
Incremental Dynamic Analysis	Very High	Fragility/Collapse	Probabilistic risk assessment (Ye et al., 2015)

2.2. Probabilistic Frameworks and Sequence Effects

Advanced frameworks now incorporate the probabilistic nature of seismic demand. Incremental Dynamic Analysis (IDA) involves scaling ground motion records to determine the probability of a structure reaching limit states such as Life Safety (LS) and Collapse Prevention (CP) (Singh 2021). A critical development is the consideration of mainshock-aftershock (MSAS) sequences. Research indicates that low-rise buildings (e.g., 2-story) can experience a 13% reduction in median collapse capacity when aftershocks are considered (Isufaj, 2024). Furthermore, MSAS sequences have a profound impact on residual inter-story drift ratios (ResISDR), which can increase by up to 100% compared to single-mainshock records (Rashid & Nishio, 2024).

3. Structural Irregularities and the Impact of Masonry Infills

Architectural requirements often lead to structural configurations that are inherently vulnerable. Irregularities in plan and elevation create complex load paths that traditional methods may overlook (Madav et al., 2025).

3.1. Hilly Terrain and Geometric Asymmetry

Buildings on sloping terrains, particularly in the Himalayas, face unique challenges. Step-back configurations lead to varying column heights, inducing the "short-column effect" (Roshan et al., 2023). Because shorter columns are stiffer, they attract a higher share of seismic shear, often leading to brittle failure. Studies have shown that step-back buildings without infill walls are 83% more susceptible to displacement in certain directions than those with infill walls (YH, 2024).

3.2. Structural Contribution of Masonry Infills

While often treated as non-structural, masonry infill walls act as diagonal struts that significantly increase initial stiffness and energy dissipation. A fully infilled frame can exhibit up to 70% higher stiffness than a bare frame (Shrestha et al., 2024). However, discontinuous infills, such as an open ground story (pilotis), create a soft-story mechanism where ground floor columns are subjected to extreme ductility demands, often leading to collapse (Manoukas et al., 2023).

Table 2. Influence of Masonry Infill Configurations on Structural Response and Risk

Infill Wall Configuration	Effect on Period (Tn)	Effect on Base Shear (Vb)	Structural Risk Factor
Bare Frame	Longest	Lowest	High drift instability (Shrestha et al., 2024)
Fully Infilled Frame	Shortest	Highest	Potential for brittle column shear (Shrestha et al., 2024)
Open Ground Story	Intermediate	High	Soft-story collapse (Sindhushree et al., 2025)
Partially Infilled Frame	Variable	Moderate	Short-column effects (MDPI, 2024)

4. Soil-Structure Interaction (SSI) and Foundation Flexibility

The fixed-base assumption in structural design is a simplification that can lead to erroneous evaluations, especially on soft soils. Soil-structure interaction (SSI) involves a feedback loop where ground motion influences building vibration, and the buildings response alters the soil behavior (Krishnan & Sivakumar, 2024).

4.1. Kinematic and Inertial Interaction Mechanisms

In high-risk zones with soft soils (Vs < 150 m/s), base flexibility increases the building's fundamental period and changes its damping characteristics (Akash, 2025). While a longer period may reduce base shear by moving the structure to a lower-acceleration region of the spectrum, the associated increase in inter-story drift can lead to severe damage and exacerbate second-order P-Delta effects (Xue et al., 2025).

4.2. Comparative SSI Modeling Approaches

Evaluating SSI requires a choice between the sub-structure method (Winkler springs) and the direct finite element method (FEM). Direct FEM models are more accurate in representing complex nonlinear soil laws but require significantly more vibration modes to reach 90% mass participation sometimes up to 30 modes compared to 3 for spring models (Krishnan et al., 2024). Research on tall structures (15 to 40 stories) indicates that soft soils can increase residual displacements by as much as 60% compared to fixed-base assumptions (Alisawi, 2021).

5. International Seismic Standards and Performance Levels

Seismic risk mitigation is codified in standards like ACI 318, ASCE 41, and Eurocode 8. These codes define performance levels based on the building's intended functionality after an earthquake (Shumak, 2023).

5.1. Comparative Acceptance Criteria: ASCE 41 vs. Eurocode 8

ASCE 41-17 and Eurocode 8-3 both use performance-based evaluation, classifying structural elements as flexure-controlled or shear-controlled. ASCE 41 utilizes levels like Immediate Occupancy (IO) and Collapse Prevention (CP), while Eurocode 8 uses Damage Limitation (DL) and Near Collapse (NC) (Güneş & Ulucan, 2021). A key divergence is the treatment of shear-controlled walls; Eurocode 8-3 can occasionally lead to brittle failure predictions that significantly underestimate a structure's actual deformation capacity compared to ASCE 41-17 (Ascencio, 2022).

Table 3. Correspondence of Seismic Performance Levels and Objectives

Standard	Performance Level (Low Damage)	Performance Level (Moderate Damage)	Performance Level (High Damage)
ASCE 41-17	Immediate Occupancy (IO)	Life Safety (LS)	Collapse Prevention (CP)
Eurocode 8-3	Damage Limitation (DL)	Significant Damage (SD)	Near Collapse (NC)
Performance Goal	Retain original strength/stiffness	Prevent loss of life; repairable	Prevent total collapse; unrepairable

5.2. Drift Limits and Design Philosophy

Codes reflect local tectonic hazards. For instance, Japanese codes prioritize high stiffness to minimize drift, resulting in structural wall densities that far exceed Turkish or American practice. Surveys found that 89% of recently built Turkish buildings had a Priority Index (stiffness measure) below 0.3%, whereas Japanese buildings typically exceed these thresholds to prevent P-Delta instability (Istanbul Technical University, 2024).

6. Forensic Engineering and Failure Mechanisms in Recent Events

Recent earthquakes in Türkiye (2023), Japan (2024), and Nepal (2015) provide forensic data that challenges existing assumptions (Gülbaz et al., 2026).

6.1. Türkiye 2023: Detailing and Stiffness Deficits

The 2023 Türkiye sequence revealed vulnerabilities in buildings supposedly designed to modern standards. Surveys by ACI Committee 133 identified several failure modes, including lap splice failures at column ends and a lack of confinement (crossties) that failed to prevent the buckling of longitudinal bars (Antoniou, 2023). Furthermore, "dog-leg" offsets at the top of foundations were frequent sites of fracture under high-intensity ground motions (Shi et al., 2023).

6.2. Japan 2024 and Nepal 2015: Site Effects and Ground Deformation

The 2024 Noto Peninsula earthquake demonstrated the impact of liquefaction and crustal uplift on RC performance. While many modern buildings survived structural collapse due to high robustness, non-structural damage remained prevalent (Vescovo et al., 2025). In Nepal, the 2015 Gorkha earthquake highlighted that buildings designed with old codes were the most likely to collapse, often due to local site characteristics and the amplification of ground motion (Acharya et al., 2022).

7. Advanced Retrofitting and Seismic Resilience Technologies

Retrofitting is moving away from traditional jacketing toward high-performance materials and passive energy dissipation systems (Qader et al., 2024).

7.1. High-Performance Composites: FRP and TRM

Fiber-Reinforced Polymers (FRP) can increase lateral load capacity by up to 40% and ductility by 100-200% (Wan et al., 2025). Textile-Reinforced Mortar (TRM) is an innovative alternative that uses a cementitious matrix, offering improved fire resistance and compatibility with historic substrates (Varma et al., 2025). TRM jackets effectively confine columns, changing failure modes from brittle shear to ductile flexure (TRM Review, 2025).

7.2. Supplemental Damping and Self-Centering Systems

1. **Viscous Fluid Dampers (VFD):** These devices can reduce inter-story drift by 33-37% without increasing structural stiffness (Elqudah et al., 2025).
2. **Shape Memory Alloys (SMA):** SMA-based retrofits can recover up to 8% strain, reducing post-earthquake residual deformations by 70% (Najar et al., 2025).
3. **Base Isolation:** By decoupling the structure from the ground, base isolation can reduce inter-story drift by 50-75%, though initial costs remain high, often 20-50% of the total project cost (Rashid & Nishio, 2024).

Table 4. Effectiveness and Limitations of Advanced Retrofit Technologies

Retrofit Technology	Strength Increase	Ductility Increase	Damage Reduction	Barrier to Adoption
FRP Jacketing	40%	100-200%	Moderate	High material cost; fire risk (Qader et al., 2024)
SMA Reinforcement	Minimal	High	70% (Residual)	Material cost; design complexity (Qader et al., 2024)
Viscous Dampers	Minimal	High	40%	Maintenance requirements (Qader et al., 2024)
Base Isolation	Minimal	Very High	40-60%	Extremely high initial cost (Qader et al., 2024)
TRM Jacketing	Moderate	High	Moderate	Skilled labor requirement (TRM Review, 2025)

8. Machine Learning and the Future of Seismic Assessment

Artificial Intelligence (AI) and Machine Learning (ML) are revolutionizing regional vulnerability assessments. Traditional engineering analysis is resource-intensive, but ML models offer a scalable alternative (Güneş & Ulucan, 2021).

8.1. Rapid Vulnerability Assessment via ML

Algorithms like XGBoost and Random Forest can predict damage levels with accuracies exceeding 85% (Luk, 2025). In Dhaka, a framework using Support Vector Regression (SVR) achieved significant predictive performance for the Storey Shear Ratio based on eight rapid visual parameters, including construction year and floor area (Zhang et al., 2025).

8.2. Interpretability and SHAP Analysis

A major advancement is the use of SHAP (SHapley Additive exPlanations) values to interpret model predictions. SHAP analysis allows engineers to identify which features such as soft stories or high axial load ratios are the primary drivers of vulnerability, ensuring transparency in AI-driven tools (Kadhim & Craifaleanu, 2025).

9. Synthesis of Seismic Performance Evaluation

The seismic performance evaluation of RC buildings in high-risk zones is an evolving discipline that recognizes the limitations of deterministic and linear approaches. Evidence suggests that robustness characterized by high lateral stiffness is as essential as ductility in preventing global collapse (Istanbul Technical University, 2024). The evaluation process must now move toward a holistic framework that integrates nonlinear structural behavior, the influence of soil-structure interaction, and the contribution of masonry infills (Guan et al., 2025). Ultimately, the goal is to ensure the long-term functionality and safety of the built environment through advanced modeling, sophisticated tools, and validated experimental data (Madav et al., 2025).

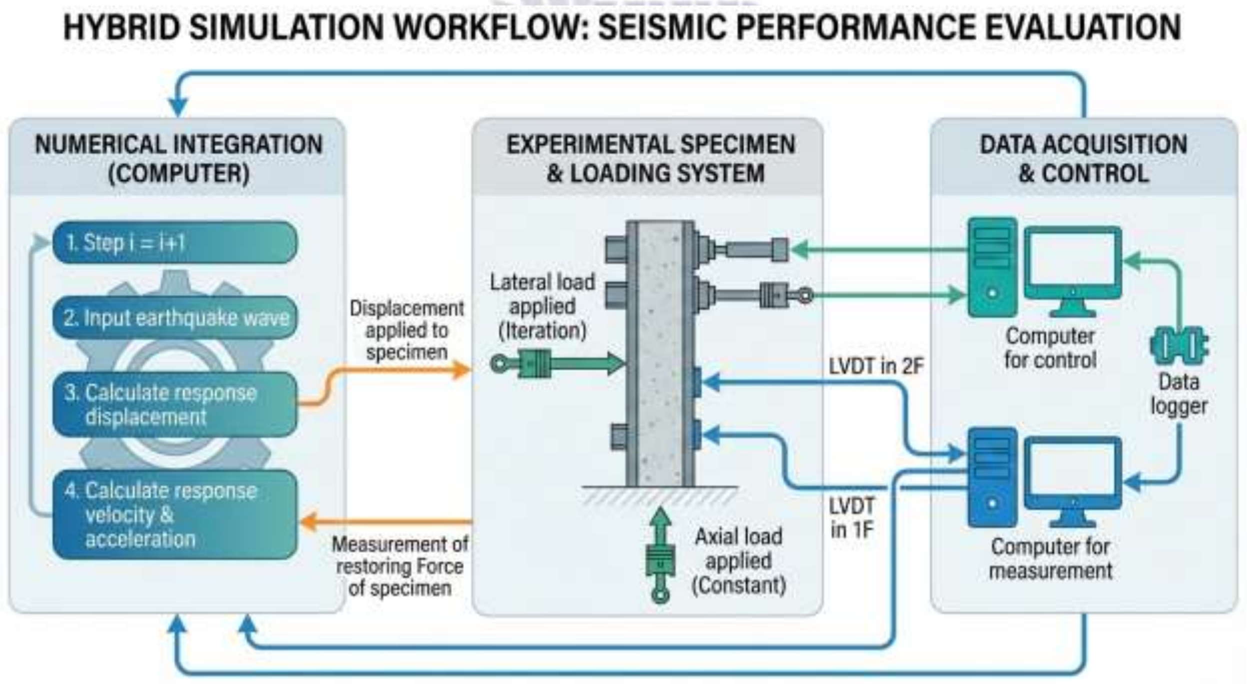

Figure 2: Experimental-Numerical Hybrid Simulation Framework for Validating Seismic Performance and Restoring Force of Structural Components.

Conclusion

The seismic performance evaluation of reinforced concrete buildings in high-risk zones has evolved considerably from conventional force-based methods toward sophisticated performance-based and probabilistic frameworks that better capture inelastic behavior, displacement demands, and realistic failure mechanisms. This review demonstrates that linear analysis techniques, while computationally efficient, frequently fail to predict actual structural response in severe seismic scenarios, particularly when structural irregularities, discontinuous masonry infills, soft-story mechanisms, short-column effects, and soil-structure interaction are present. Recent earthquakes in Türkiye (2023), Japan (2024), and historical events such as Nepal (2015) have repeatedly exposed detailing deficiencies, stiffness irregularities, and the devastating consequences of ignoring aftershock effects and site amplification. Advanced retrofitting solutions incorporating high-performance composites (FRP, TRM), supplemental damping devices, self-centering systems (SMA), and base isolation offer promising pathways to substantially enhance ductility, reduce residual deformations, and prevent collapse. Concurrently, machine learning-based approaches enable rapid, large-scale vulnerability screening with high predictive accuracy, while tools like SHAP improve interpretability and engineering trust in AI-driven assessments. Ultimately, achieving long-term seismic resilience requires moving beyond deterministic code compliance toward integrated, multi-hazard, and holistic evaluation strategies that account for nonlinear structural response, geotechnical interaction, non-structural components, and post-mainshock damage accumulation. Future research and practice should prioritize validation through large-scale experimental testing, real-time structural health monitoring integration, and region-specific fragility model development to ensure safer, more sustainable built environments in earthquake-prone regions worldwide.

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