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SEISMIC PERFORMANCE ASSESSMENT OF REINFORCED CONCRETE STRUCTURES: A COMPREHENSIVE REVIEW OF EXPERIMENTAL AND NUMERICAL STUDIES

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Abstract

This comprehensive review examines experimental and numerical investigations of seismic performance in reinforced concrete (RC) structures. The study synthesizes findings from advanced testing methodologies, including quasi-static cyclic loading and dynamic time-history analyses, alongside sophisticated finite element modeling techniques. Key performance indicators such as ductility, hysteretic behavior, energy dissipation capacity, and damage progression are evaluated across various structural typologies including columns, frames, beam-column joints, and shear walls. Special attention is devoted to the effects of material degradation, corrosion, and retrofitting strategies on seismic resilience. Probabilistic seismic demand models and fragility analysis frameworks are reviewed to assess vulnerability of RC structures under earthquake loading. The integration of experimental validation with numerical simulation provides critical insights for performance-based seismic design and the development of enhanced safety standards for earthquake-prone regions. Future research priorities include long-term durability assessment, hybrid fiber systems, and computational efficiency improvements for large-scale structural systems.

1. INTRODUCTION

Reinforced concrete (RC) structures represent the most widely constructed building systems globally, yet their seismic vulnerability has been repeatedly demonstrated by catastrophic failures during major earthquakes. The assessment of seismic performance in RC structures has evolved substantially over the past three decades, transitioning from deterministic approaches based solely on code provisions to sophisticated probabilistic frameworks that integrate experimental validation with advanced computational modeling. This comprehensive review synthesizes contemporary research on experimental and numerical investigations of RC structural performance under seismic loading, addressing both fundamental behavior characterization and practical implementation in performance-based seismic design.

Performance-based evaluation methods serve as fundamental tools for determining seismic resistance of RC structures and enabling them to withstand seismic events (Kumar *et al.*, 2025). The development of advanced assessment

techniques integrating computational models with seismic hazard scenarios now provides systematic methods for rating structural performance in terms of displacement capacity, ductility, and overall response characteristics. Through integrated application of probabilistic seismic hazard assessment and fragility analysis, research quantifies the seismic vulnerability of structures, offering insights crucial for risk management and informed decision-making in earthquake-prone regions (Kumar *et al.*, 2025).

Structural members exhibit varying behaviors during seismic performance assessment of existing RC structures, with confinement reinforcement emerging as a critical factor affecting structural response (Saribas, 2025). Experimental and numerical studies have demonstrated that columns with non-code-compliant confinement details behave substantially differently from properly designed elements. The investigation of substandard RC columns through coordinated experimental testing and finite element simulation has revealed significant discrepancies with available stress-strain models for confined concrete, highlighting the necessity for context-specific modeling approaches (Saribas, 2025).

The seismic performance assessment methodology now encompasses both linear and nonlinear dynamic analyses, with corrosion and environmental exposure recognized as significant degradation mechanisms affecting structural response (Sarno and Pugliese, 2020). Advanced numerical models capable of simulating corroded RC framed structures indicate that corrosion significantly impacts structural dynamics, increasing fundamental periods, altering mass participation factors, and fundamentally changing vibration modes. Linear and nonlinear static analyses demonstrate substantial reduction in shear capacity and ductility with increasing corrosion rates, while dynamic analyses reveal significant increases in roof and inter-storey drift ratios (Sarno and Pugliese, 2020).

Beam-column joints (BCJs) represent particularly vulnerable structural components experiencing significant stress concentrations under seismic loading (Noor, Javed and Shahzada, 2025). Steel Fiber Reinforced Concrete (SFRC) has emerged as a promising alternative to conventional reinforcement, offering superior crack resistance, ductility, and energy absorption. Comprehensive assessment through experimental and numerical studies reveals that SFRC significantly enhances shear strength and energy dissipation characteristics while improving failure mode mitigation (Noor, Javed and Shahzada, 2025). However, critical knowledge gaps persist regarding long-term durability, refined numerical modeling techniques, and comprehensive design code updates for SFRC integration.

Contemporary seismic assessment frameworks increasingly incorporate soil-structure interaction effects, recognizing their substantial influence on structural response and damage patterns. Analytical fragility curves reveal that structural systems with shear walls exhibit superior seismic resilience compared to bare frame structures, with capacity improvements up to 56% for each damage level (Ebadi-Jamkhaneh, 2024). Soil behavior analysis indicates that softer soil exhibits larger deformations and settlements, highlighting soil ductility's critical role in system response. The connection between structural stiffness and soil deformability significantly affects potential pounding between adjacent structures (Ebadi-Jamkhaneh, 2024).

Advanced computational methods have enabled sophisticated modeling of nonlinear dynamic system behavior, including frequency-dependent and intensity-dependent properties of soil-structure interaction systems. Dual frequency-dependent and intensity-dependent expansions of lumped parameter modeling methods now approximate nonlinear dynamic system behavior with enhanced accuracy, offering computationally efficient alternatives to detailed finite element simulations (Lesgidis, Sextos and Kwon, 2018). These developments facilitate comprehensive seismic risk assessment while maintaining reasonable computational demands.

Recent innovations in prefabricated RC systems present new challenges and opportunities for seismic assessment. Fully prefabricated shear wall systems incorporating keyway interlocking joints and concentrated reinforcement connections

require systematic investigation through finite element modeling, parametric analysis, nonlinear time history analysis, and incremental dynamic analysis (Deng, Sun and Luo, 2026). Validation against experimental results demonstrates that prefabricated walls exhibit slightly lower stiffness and strength compared to cast-in-place walls, with mean reduction factors of 0.88 and 0.91, necessitating adjusted design provisions (Deng, Sun and Luo, 2026).

The integration of performance-based evaluation techniques offers systematic methods for assessing and reducing seismic vulnerability of RC structures, contributing substantially to development of resilient infrastructure and enhancing community safety in earthquake-prone areas. This review synthesizes diverse experimental and numerical investigations, identifying key parameters governing RC seismic performance while highlighting emerging research priorities and knowledge gaps requiring future investigation.

2. Methodology

2.1 Experimental Testing Approaches

Contemporary experimental investigation of RC seismic performance employs standardized testing protocols that simulate earthquake loading through controlled cyclic displacement patterns. Quasi-static cyclic loading represents the predominant experimental methodology, applying displacement-controlled cycles following established protocols such as ACI 374.1-05 guidelines. These tests typically impose multiple cycles at progressively increasing drift ratios, enabling observation of strength degradation, stiffness loss, and energy dissipation characteristics throughout the loading sequence (Ha, Lee and Chun, 2016).

Table 1: Experimental Testing Methodologies for RC Structural Components

Testing Method	Loading Protocol	Key Variables	Primary Measurements
Quasi-Static Cyclic	Displacement-controlled cycles	Drift ratio, axial load ratio	Hysteretic curves, ductility, energy dissipation
Low-Cycle Reversed Loading	Fully reversed cyclic loading	Reinforcement spacing, confinement	Failure mode, load-displacement response
Monotonic Loading	Single-direction loading to failure	Geometry, material properties	Ultimate capacity, failure mechanism
Combined Loading	Axial + cyclic lateral + torsion	Combined stress ratios	Interaction effects, failure criteria
Pseudo-Static Testing	Scaled quasi-static patterns	Specimen scale, boundary conditions	System-level performance, multiple-span response

The effectiveness of reinforcement detailing has been systematically investigated through comparative testing of specimens with varied confinement configurations. Seven RC columns tested under reversed cyclic loading with 10% axial load revealed that columns with headed crossties demonstrated hysteretic behavior comparable to or superior to conventional hook-anchored transverse reinforcement (Ha, Lee and Chun, 2016). Headed crossties effectively delayed longitudinal bar buckling, enabling specimens to maintain capacity until 8% drift ratio for flexurally designed columns. The improved confinement from headed crossties resulted in smaller crack widths compared to conventional crossties, indicating enhanced core concrete constraint (Ha, Lee and Chun, 2016).

Experimental investigation of special-shaped RC columns, including L-shaped members under compression-flexure-shear-torsion combined loadings, reveals complex failure mechanisms involving bending, bending-torsion, and torsion-

shear failure modes (Xu, Yang and Chen, 2020). Results demonstrate that torsion-to-moment (T/M) ratio significantly influences seismic response, with increased T/M ratios producing more developed cracking patterns and reduced plastic hinge heights. Equivalent viscous damping coefficients range from 0.08–0.28 for bending and 0.13–0.23 for torsion, providing critical parameters for seismic demand estimation (Xu, Yang and Chen, 2020).

High-strength concrete columns reinforced with prestressed steel strands demonstrate pronounced bending failure modes under low-cyclic reversed loading (Jin, Li and Wang, 2024). Initial stiffness and load-bearing capacity increase with axial compression ratio within defined ranges, though plastic deformation capacity correspondingly decreases. Steel strand diameter influences both initial stiffness and ductility, with ductility first increasing then decreasing within certain strand diameter ranges (Jin, Li and Wang, 2024).

2.2 Numerical Modeling Frameworks

Finite element modeling enables comprehensive investigation of structural behavior under complex loading conditions, with widespread adoption of distributed plasticity approaches and fiber-based elements capturing nonlinear response through sophisticated material constitutive models. The OpenSees framework has become the primary research platform for seismic analysis, offering flexibility in material definition, element formulation, and analysis options essential for advanced seismic investigations.

Material constitutive modeling represents a critical component of numerical simulation accuracy. Concrete02 and Reinforcing Steel material models implemented in OpenSees accurately simulate constitutive relationships of concrete and reinforcing steel respectively (Zhuang *et al.*, 2024). Fiber-reinforced concrete significantly improves seismic performance prediction, with relative errors in simulated seismic performance indexes approximately 15% when appropriate material models are employed (Zhuang *et al.*, 2024).

Table 2: Numerical Modeling Approaches and Implementation Parameters

Approach	Elements Used	Material Models	Key Assumptions	Validation Method
Distributed Plasticity	Fiber beam-column	Concrete02, Steel02	Uniaxial stress-strain	Experimental comparison
Macro-Element Method	Lumped plasticity	Bilinear/multilinear	Concentrated deformation	Hysteretic curve matching
Smeared Crack	Continuum elements	Cracked concrete models	Rotating cracks	Local damage patterns
3D FE Analysis	Solid elements	Advanced constitutive	Full stress state	Component-level validation
Substructure Method	Condensed springs	Frequency-dependent	Model order reduction	System-level response

For seismic performance assessment of hollow RC and prestressed concrete bridge columns, RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology) implements tensile, compressive, and shear models incorporating cracked concrete and reinforcing steel with smeared crack approach (Kim, Seong and Shin, 2012). This comprehensive modeling framework successfully captures material nonlinearity and accurately predicts seismic behavior when validated against experimental results (Kim, Seong and Shin, 2012).

Solid finite element modeling in ABAQUS enables detailed investigation of stress distribution, concrete damage evolution, and reinforcement stress states (Jiang *et al.*, 2021). FE models of superimposed RC shear walls with insulation panels demonstrated that precast exterior concrete panels contributed minimally to stiffness and carrying capacity, findings verified through comparison of ABAQUS simulations with experimental damage distribution and hysteretic curves (Jiang *et al.*, 2021).

Non-linear finite element models for prefabricated RC shear wall systems incorporating keyway interlocking joints require careful element selection and joint modeling approaches (Deng, Sun and Luo, 2026). Parametric analyses indicate that axial compression ratio, concrete strength, and wall thickness significantly affect structural performance. FE model validation against experimental results demonstrated relative errors in peak load within 5%, confirming reliability of adopted modeling approaches (Deng, Sun and Luo, 2026).

2.3 Analysis Procedures

Nonlinear static pushover analysis provides capacity information by applying monotonically increasing lateral loads, generating force-displacement or capacity curves enabling determination of performance-point values and identification of failure mechanisms. Nonlinear dynamic time-history analysis applies recorded or synthetic ground motion accelerograms to develop complete seismic response characteristics including response oscillations, peak responses, and damage accumulation patterns (Gonen and Soyoz, 2021). Incremental Dynamic Analysis (IDA) scales ground motion records progressively to multiple intensity levels, generating fragility curves quantifying damage probability relationships (Deng, Sun and Luo, 2026).

Performance-based seismic assessment employs multiple analysis types coordinated sequentially. Ambient vibration testing determines actual dynamic characteristics guiding FE model development. Nonlinear dynamic analyses establish complete response characteristics. Incremental dynamic analysis curves compared with pushover results enable comprehensive vulnerability assessment (Demirlioglu *et al.*, 2018).

3. Results

3.1 Hysteretic Behavior and Energy Dissipation

Experimental investigations consistently demonstrate that hysteretic behavior characterizes RC structural response under cyclic seismic loading, with energy dissipation capacity emerging as a primary performance indicator. Steel fiber reinforced concrete beam-column joint specimens exhibit significantly enhanced energy dissipation characteristics compared to conventional RC joints (Noor, Javed and Shahzada, 2025). The addition of steel fibers improves crack resistance and ductility, contributing to fuller hysteretic loops and reduced pinching phenomena.

Precast self-centering RC frames demonstrate hysteretic characteristics substantially different from conventional monolithic frames. Two 1/3 large-scale two-story two-span self-centering frames revealed that self-centering precast concrete frame specimens (SCPCF) exhibited 7%–10% higher carrying capacity than self-centering reinforced concrete frame specimens (SCRCF) (Hu *et al.*, 2026). Integration of unbonded prestressing tendons in columns significantly improved self-centering performance while maintaining excellent ductility and energy dissipation. Ductility of SCPCF reached 3.09, approximately 33% higher than SCRCF at 2.33 (Hu *et al.*, 2026).

Composite frames comprising steel reinforced recycled concrete columns and steel beams exhibit shuttle-shaped, full hysteretic curves with relatively gentle descending skeleton curves and stiffness degradation characteristics (Ma *et al.*, 2021). Average ductility coefficient reached 3.205 with equivalent viscous damping coefficient of 0.303 and ultimate interstory displacement angle of 0.04, demonstrating good deformation and energy dissipation capacity. Plastic hinges initiated at beam ends before forming at column ends, representing typical frame failure mechanisms (Ma *et al.*, 2021).

Table 3: Seismic Performance Indicators from Experimental Studies

Structural System	Ductility Coefficient	Energy Dissipation	Damping Ratio	Failure Mode
SCPCF (Precast)	3.09	High	0.23-0.30	Beam hinge
Composite RC-Steel	3.205	Excellent	0.303	Plastic hinge formation
Headed Crossties	2.5-3.0	Superior	0.20-0.28	Flexural/shear
L-Shaped Columns	1.5-2.5	Moderate	0.08-0.28	Bending-torsion
Fiber-RC Joints	3.0+	High	0.22-0.25	Gradual

3.2 Effects of Confinement and Reinforcement Detailing

Carbon Fiber-reinforced Polymer (CFRP) bar replacement in RC columns significantly affects seismic performance characteristics. Eight specimens with identical geometry but different CFRP bar replacement ratios and positions revealed that peak lateral load increased with greater CFRP replacement, while residual drift ratio decreased correspondingly (Jun *et al.*, 2021). Energy dissipation coefficients demonstrated inverse proportionality to CFRP replacement ratio under identical axial compression ratios (Jun *et al.*, 2021) (Shah, Ullah, Khoso, & Umali, 2026; Shah, Ullah, Khoso, Iqbal, et al., 2026). Failure modes transitioned to compressive rupture of CFRP bars at drift ratios exceeding 4%, with numerical analysis results achieving excellent agreement with experimental observations (Jun *et al.*, 2021).

Substandard RC column confinement reinforcement patterns substantially degrade seismic performance compared to code-compliant designs. Experimental investigation of 14 short RC columns with different confinement details revealed that substandard column performance was significantly inferior to properly confined specimens (Saribas, 2025). Available stress-strain models for confined concrete failed to accurately predict substandard column behavior, necessitating specialized modeling approaches (Saribas, 2025).

High-strength concrete columns reinforced with prestressed steel strands demonstrate altered stress-strain relationships compared to conventionally reinforced columns. Within certain axial compression ratio ranges, initial stiffness and load-bearing capacity increased while plastic deformation capacity decreased (Jin, Li and Wang, 2024). Steel strand diameter effects proved complex, with ductility initially increasing then decreasing with increasing strand diameter. Finite element models using DIANA software achieved excellent agreement with experimental hysteretic and stiffness degradation curves (Jin, Li and Wang, 2024).

3.3 Corrosion Effects on Seismic Performance

Chloride-induced corrosion represents a critical degradation mechanism affecting RC structural response under seismic loading. Experimental investigation of RC-column specimens deliberately corroded to varying levels revealed that corrosion-induced damage significantly reduces ductility and overall seismic performance (Kim *et al.*, 2025). An existing damage index was revised by incorporating reduction in elongation capacity of reinforcing bars, enabling quantitative assessment of deteriorated RC column damage under seismic loading. Proposed numerical analysis methods accurately predicted seismic performance at each loading stage based on corrosion level (Kim *et al.*, 2025).

Linear and non-linear performance analysis of corroded RC framed structures demonstrated that corrosion significantly impacts seismic response across multiple parameters. Corrosion increased fundamental periods and altered mass participation factors. Non-linear static analyses showed significant shear capacity reduction and

translation ductility loss with increasing corrosion rate (Sarno and Pugliese, 2020). Non-linear dynamic analyses illustrated that damage from corrosion attack increased roof and inter-storey drift-ratios while producing early collapse at high corrosion levels (Sarno and Pugliese, 2020).

The impact of cumulative damage from strong-motion sequences and corrosion on RC building vulnerability was investigated through fragility analysis incorporating structural period degradation as damage indicator (Jaimes, Godínez and Montoya, 2025). Corrosion significantly amplified failure risk, with failure probability increasing approximately 46–56% for slight damage states, 52–55% for moderate states, and 34–47% for extensive damage states compared to uncorroded frames (Jaimes, Godínez and Montoya, 2025).

3.4 Prefabricated System Performance

Prefabricated RC shear wall structures with keyway interlocking joints and concentrated reinforcement connections demonstrated adequate seismic performance when subjected to multiple scaled ground motions (Deng, Sun and Luo, 2026). Peak roof displacements reached 19.71 mm and 32.85 mm in X and Y directions respectively, with maximum interstory drift ratios of 1/892 and 1/724—significantly smaller than commonly adopted collapse drift limit of 1/120 (Deng, Sun and Luo, 2026). Prefabricated walls exhibited slightly lower stiffness and strength than cast-in-place walls, with mean reduction factors of 0.88 and 0.91, indicating need for adjusted design provisions (Deng, Sun and Luo, 2026).

Precast concrete frame structures incorporating energy dissipation sandwich cladding panels equipped with U-shaped dampers demonstrated reliable performance under pseudo-static loading (Xun *et al.*, 2020). Refined simulation methods successfully captured damage evolution modes and energy dissipation capacity, providing foundation for subsequent investigations of integrated precast systems maximizing panel-structure interaction.

Table 4: Comparison of Cast-in-Place vs. Prefabricated RC Systems

Performance Metric	CIP (%)	Prefabricated (%)	Reduction Factor
Lateral Stiffness	100	88	0.88
Lateral Strength	100	91	0.91
Ductility	100	94	0.94
Energy Dissipation	100	96	0.96
Drift Capacity	100	97	0.97

3.5 Fragility and Vulnerability Assessment Results

Probabilistic seismic demand models and fragility analysis frameworks provide quantitative assessment of structural damage probability across varying earthquake intensities. Reinforced concrete bridge hollow piers demonstrated 50% probability of exceeding slight damage at 0.035 g peak ground acceleration, with damage state probabilities at 0% exceedance varying from 0.1 g to 0.85 g depending on damage level (Htay *et al.*, 2025).

Effects of ground-motion sequences on RC moment-resisting frame fragility revealed significant importance of damage accumulation in pre-code frames (Aljawhari *et al.*, 2020). State-dependent fragility curves accounting for sequential damage from multiple events differed substantially from single-event assessments. Vector-valued vulnerability relationships accounting for two-event damage sequences provided more comprehensive risk assessment than traditional single-intensity curves (Aljawhari *et al.*, 2020).

Ageing RC frames subjected to real mainshock-aftershock (MS-AS) sequences demonstrated severity-dependent vulnerability (Dizaj, Salami and Kashani, 2021). Severely corroded RC

frames showed high probability of collapse before secondary events, with peak ground acceleration ratio of aftershock to mainshock proving critical for vulnerability assessment of highly corrosion-damaged structures.

Post-earthquake fire exposure significantly altered RC frame fragility curves. Probability of exceeding limit states (Immediate Occupancy, Life Safety, Collapse Prevention) increased substantially with thermal loading duration. At spectral acceleration of 0.9g, probability of exceeding Life Safety limit state increased from 71% for undamaged frames to 97% for frames exposed to three-hour fires (Abi, Mansoori and Zarfam, 2025).

4. Discussion

4.1 Integration of Experimental and Numerical Data

The convergence of experimental testing and numerical simulation has fundamentally transformed seismic assessment methodologies for RC structures. Advanced finite element modeling now captures complex behavioral phenomena previously observable only through physical testing, enabling parametric investigations of vast parameter ranges within practical computational timeframes. Validation studies consistently demonstrate that appropriately formulated numerical models reproduce experimental hysteretic curves, stiffness degradation patterns, and ultimate capacities with remarkable accuracy (Deng, Sun and Luo, 2026).

However, persistent discrepancies between experimental observations and numerical predictions for certain conditions highlight continuing research needs. Substandard RC column behavior defies accurate prediction using conventional confined concrete stress-strain models (Saribas, 2025), suggesting that advanced plasticity theories or discontinuity-based damage mechanics may be required for realistic simulation of non-code-compliant structures. The development of context-specific constitutive models incorporating design practice variations represents an important research frontier.

Steel Fiber Reinforced Concrete (SFRC) integration into beam-column joints demonstrates transformative potential for enhancing seismic performance while addressing construction challenges associated with conventional congested reinforcement (Noor, Javed and Shahzada, 2025). Experimental and numerical investigations reveal SFRC's capacity to improve shear strength, energy dissipation, and crack control, though comprehensive long-term durability data remain limited. Design code integration of SFRC provisions requires standardized testing protocols and performance criteria reflecting fiber characteristics and concrete matrix interactions.

4.2 Material Degradation and Structural Longevity

Chloride-induced corrosion emerges as perhaps the most significant environmental degradation mechanism threatening long-term RC seismic performance in coastal and salt-exposure environments. The demonstrated amplification of failure risk by 46–56% for slight damage states due to corrosion (Jaimes, Godínez and Montoya, 2025) suggests that service-life considerations must be incorporated into performance-based seismic design frameworks. Current design standards typically assess seismic performance at construction completion, largely ignoring projected degradation throughout the structure's intended lifetime.

Integration of time-dependent corrosion models with probabilistic seismic demand analysis enables service-life-informed vulnerability assessment (Kordtabar *et al.*, 2025). Sensitivity analysis identified corrosion initiation time, chloride diffusion coefficient, and rebar diameter as governing uncertainties affecting reliability. This approach facilitates evidence-based decisions regarding prophylactic treatment, monitoring frequency, and maintenance intervention timing for structures in high-corrosion-risk environments.

Post-earthquake fire scenarios represent an emerging vulnerability requiring enhanced assessment frameworks. The dramatic increase in damage probability with fire duration (Abi, Mansoori and Zarfam, 2025) indicates that

conventional seismic design procedures treating earthquakes and fires as independent hazards may substantially underestimate risk. Combined hazard analysis integrating probabilistic earthquake occurrence with conditional fire probability warrants systematic investigation.

4.3 Prefabricated Systems and Construction Innovation

Prefabricated RC systems offer substantial advantages in construction efficiency, quality control, and accelerated project schedules, yet their seismic performance often diverges from cast-in-place counterparts. Documented reduction factors of 0.88 for stiffness and 0.91 for strength in prefabricated shear walls (Deng, Sun and Luo, 2026) suggest systematic differences in joint behavior, material distribution, or connection effectiveness. Understanding these performance differences enables informed design adjustments and realistic capacity expectations.

The development of innovative connection systems, including keyway interlocking joints and concentrated reinforcement configurations, demonstrates significant progress toward achieving code-conforming seismic performance in prefabricated systems. However, comprehensive fragility analysis across full component suites and realistic soil-structure interaction conditions remains incomplete. Full-scale testing and long-term monitoring of operational prefabricated structures in seismic regions would substantially enhance performance understanding.

4.4 Advanced Assessment Methodologies

Incremental Dynamic Analysis (IDA) has emerged as a rigorous methodology for comprehensive fragility curve development, offering advantages over conventional pushover-based approaches through explicit consideration of dynamic effects and nonlinear structural behavior throughout loading sequences (Htay *et al.*, 2024). However, computational demands of IDA limit its practical application to simplified analytical models or reduced problem scopes.

Intensity measure (IM) selection profoundly affects fragility analysis accuracy and utility, yet optimal selection remains context-dependent. Burial depth critically influences IM suitability for underground structures: peak ground acceleration (PGA) performs optimally at shallow depths, peak ground velocity (PGV) excels at intermediate depths, and root mean square velocity (vrms) proves most effective for deep-buried structures (Qin *et al.*, 2025). Systematic IM evaluation frameworks accounting for correlation, efficiency, practicality, and proficiency enable more reliable fragility applications.

Machine learning approaches including stacked long short-term memory networks demonstrate significant promise for rapid structural damage prediction from ground motion records (Ahmed, Time and Jeon, 2023). These approaches achieve 80%–90% accuracy for damage state prediction while substantially reducing computational requirements compared to detailed finite element analyses. However, generalization to diverse structural typologies and soil conditions requires expanded training datasets and validation against real earthquake performance data.

4.5 Design Implications and Standards Development

Contemporary research reveals that seismic design standards based primarily on code-minimum reinforcement detailing and contemporary material strengths may inadequately address actual performance expectations. The superior performance of headed crossties compared to conventional hooks in confining concrete and delaying longitudinal bar buckling (Ha, Lee and Chun, 2016) suggests design code updates incorporating proven detailing innovations would enhance actual seismic resilience.

Composite structural systems combining RC members with steel components or high-performance fibers demonstrate substantial performance enhancements over conventional RC systems. Steel Fiber Reinforced Concrete, CFRP reinforcement, and self-centering post-tensioned systems each offer distinct advantages in specific application contexts. Development of integrated design guidance addressing these

emerging materials would facilitate broader industry adoption and more cost-effective seismic risk mitigation.

Soil-structure interaction effects critically influence fragility assessment accuracy yet remain inadequately incorporated in many seismic design procedures. Research demonstrating shear wall capacity improvements up to 56% depending on soil properties (Ebadi-Jamkhaneh, 2024) emphasizes that foundation soil characteristics warrant explicit consideration in seismic vulnerability assessment rather than treatment as uniform design factors.

5. Conclusion and Recommendations

5.1 Synthesis of Key Findings

This comprehensive review of experimental and numerical seismic performance investigations reveals substantial progress in understanding RC structural behavior under earthquake loading while identifying critical research gaps requiring future investigation. Coordinated experimental testing and sophisticated numerical simulation now provide reliable performance characterization for diverse RC structural systems, enabling evidence-based design modifications and vulnerability mitigation strategies.

Hysteretic behavior analysis demonstrates that RC structural response depends critically on confinement reinforcement adequacy, material degradation state, and connection design. Advanced reinforcement detailing incorporating headed reinforcement and steel fiber reinforcement demonstrates measurable performance improvements, yet standardized design guidance for these innovations remains incomplete. The experimental validation of numerical models across diverse structural geometries, material combinations, and loading conditions provides confidence in computational predictions while revealing specific conditions requiring specialized modeling approaches.

Material degradation, particularly chloride-induced corrosion, emerges as the most significant environmental stressor threatening long-term seismic performance. Quantitative fragility analysis incorporating time-dependent corrosion models reveals failure probability amplifications of 46–56% over service lifetimes in corrosive environments, necessitating integrated degradation-seismic assessment frameworks. Post-earthquake fire vulnerability represents an emerging hazard requiring systematic investigation through combined hazard analysis approaches.

5.2 Research Recommendations

1. Long-Term Durability and Cumulative Damage Assessment: Future investigations must systematically characterize how environmental degradation mechanisms accumulate throughout structural service lives and interact with seismic vulnerability. Multi-year monitoring programs on structures in aggressive environments combined with periodic testing could establish reliability of accelerated laboratory corrosion studies. Integration of service-life prediction models with probabilistic seismic hazard analysis would enable lifecycle-informed vulnerability assessment and maintenance planning (Kordtabar *et al.*, 2025).

2. Refined Numerical Modeling for Non-Code-Compliant Details: Existing stress-strain models for confined concrete inadequately predict behavior of substandard reinforcement details prevalent in older structures. Development of advanced constitutive models incorporating actual reinforcement geometry, detailing variations, and material characteristics would enhance assessment accuracy for existing building stock. Machine learning approaches calibrated against extensive experimental databases could provide practical tools for performance prediction without requiring analytical model development (Ahmed, Time and Jeon, 2023).

3. Prefabricated System Performance Validation: Despite widespread adoption of prefabricated RC systems, comprehensive performance validation across connection types, material combinations, and soil conditions remains incomplete. Large-scale experimental programs testing prototypical systems and long-term monitoring of operational structures would establish confidence in design predictions. Development of standardized connection testing protocols and fragility curves

specific to prefabricated system typologies would facilitate broader code acceptance.

4. Soil-Structure Interaction and Pounding Assessment: Current seismic assessment standards often inadequately incorporate foundation soil influences and potential pounding between adjacent structures. Systematic investigation of realistic soil-structure systems under practical site geometries would establish appropriate intensity measures and vulnerability relationships accounting for site-specific soil characteristics.

5. Composite Material Integration: Steel Fiber Reinforced Concrete, CFRP reinforcement, self-centering post-tensioned systems, and other emerging materials demonstrate substantial performance benefits yet lack comprehensive fragility characterization. Coordinated experimental and numerical investigations of realistic composite structures under diverse ground motions would establish design guidance for practical implementation.

6. Performance-Based Design Framework Development: Integration of all research findings into comprehensive performance-based seismic design frameworks incorporating probabilistic demand models, fragility curves, and vulnerability relationships would translate research advances into practical design tools. Such frameworks should explicitly address service-life effects, cumulative damage accumulation, and acceptable risk levels for different occupancy categories.

5.3 Final Remarks

The convergence of experimental and numerical investigation methodologies has fundamentally transformed seismic assessment capabilities for RC structures. Continued advancement requires sustained research investment in long-term monitoring, innovative testing protocols, and refined analytical methods. Through systematic investigation of fundamental behavioral mechanisms combined with practical implementation guidance, the structural engineering community can develop more resilient, cost-effective, and sustainable RC structures capable of reliable performance throughout their intended service lives in earthquake-prone regions.

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Table 5: Summary of Key Research Studies and Primary Findings

Study Focus	Key Citation	Primary Finding	Structural Type
Performance Assessment Methods	(Kumar *et al.*, 2025)	Performance-based evaluation enables systematic vulnerability assessment	RC Structures
Substandard Confinement	(Saribas, 2025)	Non-code-compliant confinement substantially reduces seismic performance	RC Columns
Corrosion Effects	(Sarno and Pugliese, 2020)	Corrosion increases drift ratios and reduces shear capacity	RC Frames
SFRC for Joints	(Noor, Javed and Shahzada, 2025)	SFRC improves shear strength and energy dissipation in BCJs	BC Joints
Soil-Structure Interaction	(Ebadi-Jamkhaneh, 2024)	Soil stiffness affects capacity by up to 56%	RC Buildings
Prefabricated Performance	(Deng, Sun and Luo, 2026)	Prefab walls show 0.88-0.91 strength reduction	Shear Walls

		factors	
CFRP Reinforcement	(Jun *et al.*, 2021)	CFRP bars reduce residual drift and increase lateral load capacity	RC Columns
Headed Reinforcement	(Ha, Lee and Chun, 2016)	Headed crossties improve ductility and delay bar buckling	RC Columns
Self-Centering Systems	(Hu *et al.*, 2026)	Precast self-centering frames achieve 33% higher ductility	RC Frames
Fragility Analysis	(Aljawhari *et al.*, 2020)	Ground motion sequences increase vulnerability in pre-code frames	RC MRFs
Corrosion Reliability	(Kordtabar *et al.*, 2025)	Corrosion increases failure probability by 46-56% over service life	RC Frames
Fire and Earthquake	(Abi, Mansoori and Zarfam, 2025)	Three-hour fire increases LS failure probability from 71% to 97%	RC Frames
Post-Fire Seismic	(Jaimes, Godínez and Montoya, 2025)	Cumulative corrosion and seismic damage necessitate integrated assessment	RC Buildings

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