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Performance-Based Seismic Evaluation of Reinforced Concrete Structures under Near-Fault and Long-Duration Earthquakes: Damage Control and Resilience Implications

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ABSTRACT

Performance-based seismic engineering (PBSE) has evolved to prioritize displacement control, damage limitation, and functional recovery over traditional force-based prescriptive approaches, particularly for reinforced concrete (RC) structures vulnerable to extreme ground motion characteristics. This study reviews the distinct hazards of near-fault ground motions (NFGMs), featuring velocity pulses, directivity effects, and fling-step permanent displacements, which impose impulsive, high-energy demands leading to early nonlinear response and potential collapse in RC moment-resisting frames (MRFs) and shear wall systems. In contrast, long-duration earthquakes (LDEs) from subduction zones cause cumulative cyclic fatigue, stiffness degradation, period elongation, and amplified damage under mainshock-aftershock sequences. Conventional code-based assessments (ASCE 41) often prove overly conservative or insufficient for these specialized demands, while probabilistic frameworks like FEMA P-58 better quantify consequences such as repair costs, downtime, and casualties. Advanced mitigation techniques, including seismic isolation, viscous dampers, buckling-restrained braces (BRBs), and rocking systems, offer enhanced drift control and re-centering capabilities, though challenges persist under pulse-like or prolonged shaking. The Park-Ang damage index effectively captures combined deformation and energy demands, with deformation dominating in NFGMs and energy in LDEs. Drawing on recent events and updated standards (ASCE 41-23), the paper emphasizes the shift toward "safe-to-fail" philosophies and resilience-based design targeting rapid recovery. Recommendations include mandatory incorporation of pulse-like records in hazard analysis, adoption of dual systems for superior performance, and integration of functional recovery metrics

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(REDi, Seismic Resilience Index) to achieve community-level resilience.

Keywords: Performance-Based Seismic Engineering, Reinforced Concrete Structures, Near-Fault Ground Motions, Long-Duration Earthquakes, Velocity Pulse, Directivity Effects, Seismic Resilience, Damage Index, Base Isolation, Supplemental Damping, ASCE 41, FEMA P-58

Introduction

The conceptual landscape of seismic engineering has undergone a profound metamorphosis over the last five decades, transitioning from a reliance on prescriptive, force-based methodologies to the contemporary framework of performance-based seismic engineering (PBSE) (Choudhury, 2024). This evolution was primarily driven by the realization that structural integrity during a seismic event is not solely a function of a building's capacity to resist lateral forces but is more accurately a problem of controlling earthquake-induced displacements (Khatiwada, 2025). Early seismic provisions, such as those in the 1961 Uniform Building Code (UBC), simplified earthquake demand as a static lateral load equivalent to a small percentage of a building's weight, often failing to account for the complex dynamic interactions between ground motion and structural response (Anwar, 2023). The nearly annual occurrence of damaging earthquakes in the Western United States during the late 20th century, coupled with stakeholder demands for a clearer understanding of the benefits of seismic retrofitting, necessitated a more realistic approach to risk assessment (Moehle, 2024).

Modern performance-based design (PBSD) permits the construction and evaluation of reinforced concrete (RC) structures with a reliable understanding of the risks associated with life safety, occupancy, and economic loss (Chiluka & Oggu, 2023). By categorizing building performance into discrete levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) engineers can tailor structural systems to meet specific performance goals defined by owners or regulators (Speicher & Harris, 2023). Despite these advancements, reinforced concrete moment-resisting frames (MRFs) and shear wall systems remain highly vulnerable to specialized ground motion characteristics, particularly those originating from near-fault ruptures or subduction zone events of long duration (Kazaz et al., 2023).

The technical challenge lies in the fact that reinforced concrete is a material inherently prone to degradation under cyclic loading. When subjected to the impulsive, high-energy demands of near-fault ground motions (NFGMs) or the sustained, fatigue-inducing cycles of long-duration earthquakes (LDEs), conventional RC structures often exhibit damage patterns that are not fully captured by standard code-prescribed performance checks (Khademi et al., 2024). Consequently, the industry is shifting toward a "safe-to-fail" design philosophy, where the focus extends beyond preventing collapse to ensuring rapid functional recovery and long-term community resilience (Almufti & Willford, 2014). Recent 2025 guidelines have introduced standardized "Ready-to-Use" detailing (RUD) to specifically bolster the resilience of low-rise RC buildings in areas with limited engineering oversight (Beyer, 2025).

Figure 1: Conceptual illustration of earthquake-induced ground motion and the

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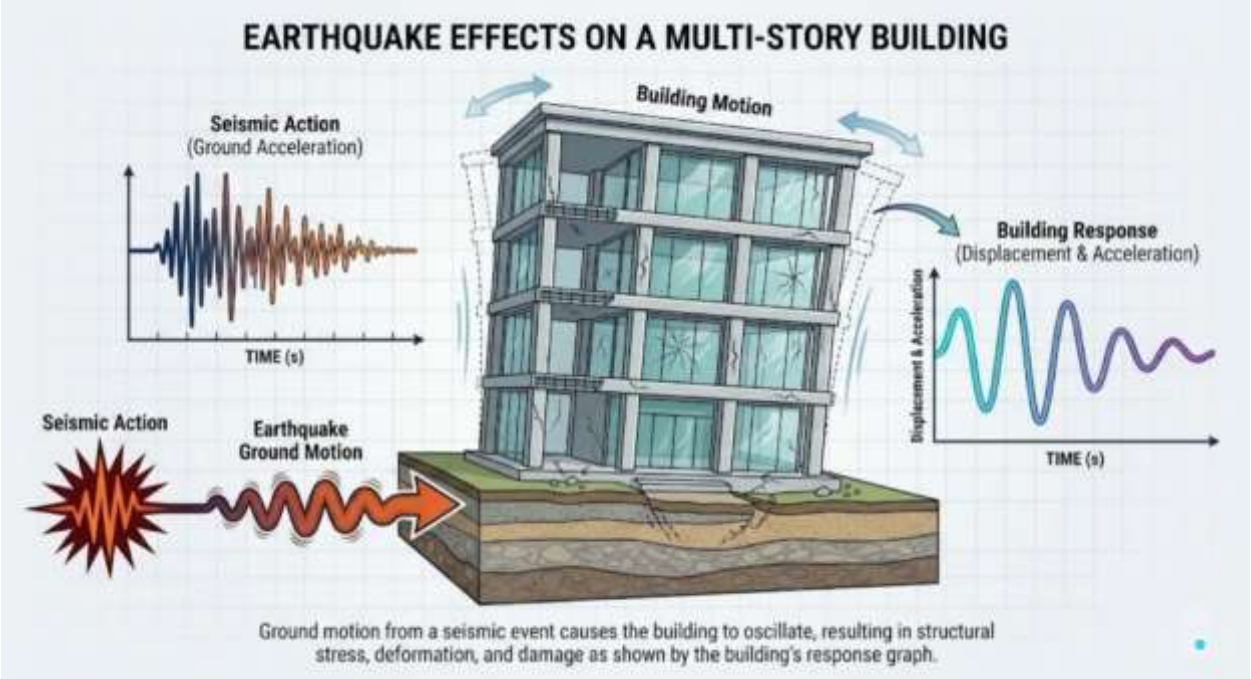
resulting dynamic structural response in a multi-story building.



Characterization of Near-Fault Ground Motion Hazards

Near-fault ground motions occur in close proximity to the causative fault, typically within a distance of 10 to 20 kilometers, and are characterized by physics fundamentally different from far-field records (Hidayat et al., 2026). These motions are often dominated by a large-amplitude, long-period velocity pulse in the beginning of the record, which results from the constructive interference of the radiated seismic waves (Ghahari & Abadi, 2004). This phenomenon, known as rupture directivity, occurs when the fault ruptures toward the site at a velocity approaching the shear wave velocity of the surrounding material (Mollaioli et al., 2013).

Directivity and Pulse-Like Phenomena

Rupture directivity effects are most pronounced on the component of motion perpendicular to the fault strike, often referred to as the fault-normal component. These velocity pulses transmit large amounts of energy to the structure in a very short duration, often forcing the system to undergo its maximum nonlinear response or even collapse at the onset of the pulse (Harrington & Liel, 2020). The period of these pulses (Tp) generally increases with the earthquake magnitude and plays a critical role in the structural demand. If the natural period of a structure (T) is close to or slightly smaller than the pulse period, the structure enters a state of quasi-resonance, leading to catastrophic displacement demands (Daei, 2021).

Fling-Step and Permanent Ground Deformation

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In addition to dynamic pulses, near-fault motions may exhibit a "fling-step," which represents the permanent geodetic offset of the ground associated with the fault rupture. Fling-step is characterized by a one-sided, monotonic displacement pulse that occurs parallel to the slip direction of the fault (Su & Billah, 2024). While dynamic pulses affect the inertia of the structure, fling-step can impose significant differential displacements on foundations, particularly for large-scale infrastructure like long-span bridges or industrial complexes (Ruiz-García, 2024).

Table 1: Seismic Parameters of Near-Fault and Far-Field Motions

Seismic Parameter	Near-Fault (Pulse-Like)	Far-Field (Non-Pulse)
Energy Arrival	Concentrated in early, large pulse (Khademi et al., 2024)	Distributed over duration (Khademi et al., 2024)
PGV/PGA Ratio	High (Low frequency dominated) (Ghahari & Abadi, 2004)	Low (High frequency dominated) (Ghahari & Abadi, 2004)
Residual Displacement	Potentially very large (Choi & Saiidi, 2010)	Generally negligible (Choi & Saiidi, 2010)
Frequency Content	Rich in both high and low frequencies (Khademi et al., 2024)	High frequencies often damped out (Khademi et al., 2024)
Demand Type	Impulsive, single-cycle energy dissipation (Mollaioli et al., 2013)	Cyclic, multi-cycle fatigue (Ghahari & Abadi, 2004)

Long-Duration Earthquakes and Cumulative Degradation

Long-duration earthquakes (LDEs) are primarily associated with subduction zone events, where the rupture of vast fault segments can generate ground motions lasting several minutes (Hassan & Elnashai, 2025). Unlike near-fault motions, where the primary threat is the peak demand of a single pulse, the hazard in LDEs is cumulative. For reinforced concrete structures, which exhibit significant strength and stiffness degradation under repeated reversed cycles, the duration of shaking is a critical determinant of the final damage state (Khoshraftar & Govindhan, 2013).

Cyclic Fatigue and Period Elongation

During the initial phase of strong ground shaking, RC elements may yield, causing the effective stiffness of the building to decrease. This leads to an elongation of the fundamental structural period (T). As the period elongates, the structure becomes sensitive to different frequency contents of the ground motion, often moving into a region of higher spectral acceleration (Torghabeh, 2023). In long-duration events, the structure remains in this softened, vulnerable state for a prolonged period, leading to an accumulation of plastic deformations that may eventually trigger global instability or collapse (Alam, 2023).

Mainshock-Aftershock Sequences

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The impact of long-duration hazards is further compounded by the occurrence of aftershocks. A structure damaged by a mainshock is rarely repaired before the arrival of subsequent aftershocks. These sequential events significantly increase the cumulative damage, effectively shifting the fragility curves of the building to the left, meaning the probability of failure increases at lower intensity levels (Di Sarno & Pugliese, 2020). Research has demonstrated that total cumulative damage is a combination of the damage states from all events in the sequence, and neglecting this in design can lead to constructing buildings that are fundamentally unsafe (Santos-Santiago et al., 2022).

Table 2: Long-Duration Earthquake Characteristics and Structural Impacts

Feature of Long Duration	Structural Impact	Causal Relationship
Many Loading Cycles	Increased cumulative energy dissipation (Ruiz-García, 2024)	Leads to bond-slip and concrete crushing (Khoshraftar & Govindhan, 2013)
Sustained Shaking	Prolonged exposure to inelastic demands (Hassan & Elnashai, 2025)	Prevents structural redistribution (Di Sarno & Pugliese, 2020)
Stiffness Degradation	Permanent structural softening (Hassan & Elnashai, 2025)	Elongates T into sensitive spectral zones (Hassan & Elnashai, 2025)
Sequential Hazards	Additive damage from aftershocks (Beyer, 2025)	Mainshock weakens system before next pulse (Beyer, 2025)

Performance-Based Seismic Evaluation Frameworks

The systematic evaluation of RC structures requires robust analytical frameworks. Currently, the industry relies on standards such as ASCE 41 and FEMA P-58 for deterministic and probabilistic performance assessment (Padalu et al., 2024).

ASCE 41: Component-Based Deterministic Evaluation

ASCE 41 is the current state-of-practice for the assessment and rehabilitation of existing structures. It employs a three-tiered process: Tier 1 (Screening), Tier 2 (Deficiency-Based), and Tier 3 (Systematic Analysis) (ASCE, 2023). A critical limitation of ASCE 41 is its reliance on component-based acceptance criteria. A building "fails" if even a small percentage of its components exceed rotation or force limits, regardless of whether those components are critical to overall stability (Speicher & Harris, 2023). Benchmarking studies show that ASCE 41 tends to be overly conservative, predicting failure at intensities lower than those observed to cause collapse in tests (Sattar et al., 2021).

FEMA P-58: Consequence-Based Probabilistic Assessment

FEMA P-58 represents "next generation" design, focusing on system-level metrics such as repair cost, repair time, and casualties. Using a Monte Carlo simulation approach, FEMA P-58 generates a distribution of potential outcomes for a given

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seismic scenario. This provides stakeholders a clearer picture of resilience (Safiey et al., 2021).

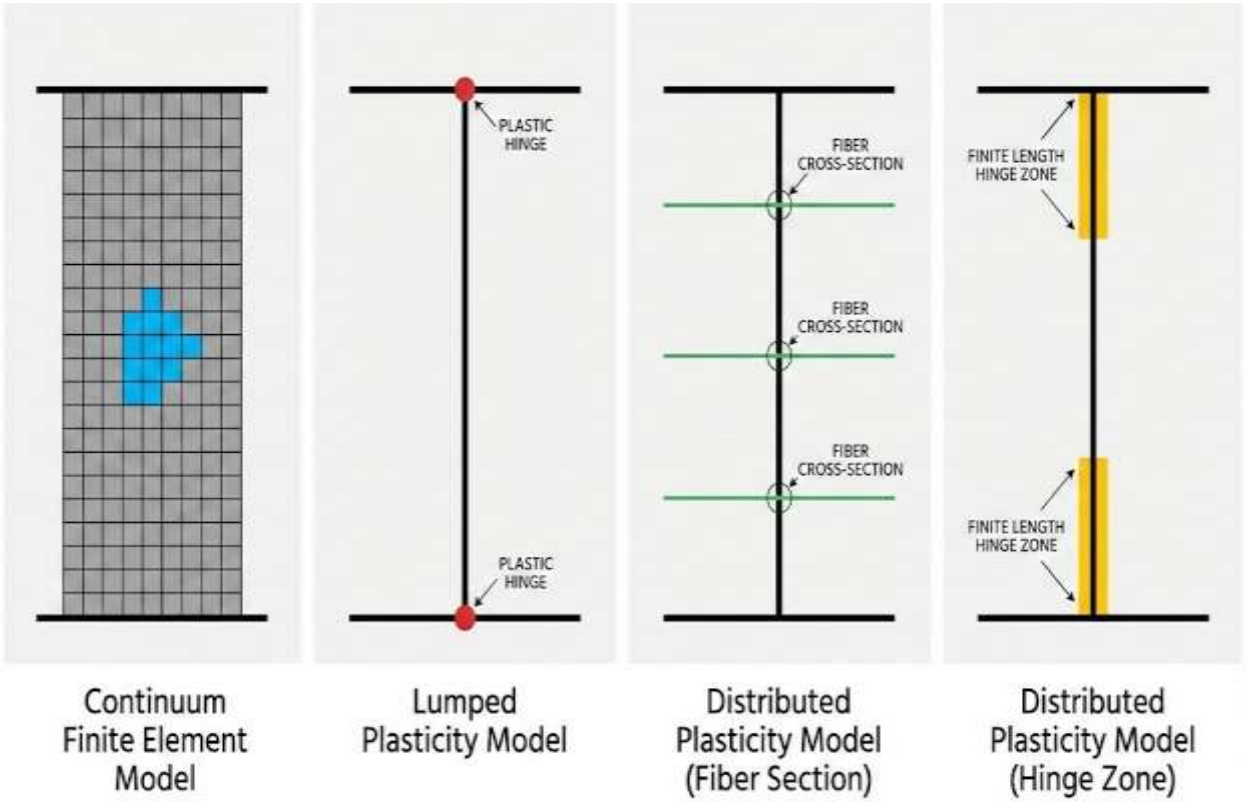
Updates in ASCE 41-23

The ASCE 41-23 standard incorporates significant updates to reduce conservatism and align with the latest USGS hazard models. These updates include revised concrete wall provisions that offer a less conservative assessment for older buildings. The 2023 update also aligns with multi-point response spectra for more accurate hazard representation (Pekelnicky, 2023).

Structural Behavior of RC Systems under Extreme Demands

The response of RC structures is governed by the interaction of moment-resisting frames and shear walls (Sococol et al.,2022).

Figure 2: Comparative modeling approaches for nonlinear structural analysis, ranging from Continuum Finite Element to Lumped and Distributed Plasticity models.



RC Moment-Resisting Frames (MRFs)

RC MRFs dissipate energy through plastic hinges. Under near-fault pulses, these frames face extremely high peak demands in a single cycle, which can result in roof drifts exceeding 4% and potential "soft-story" mechanisms (Hidayat et al., 2026).

RC Shear Wall Systems

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Shear walls provide essential stiffness, but NFGMs can increase the risk of collapse if the ratio of the pulse period to the first-mode period is unfavorable. Recent 2025 studies emphasize that dual systems (shear wall-frame) significantly outperform pure frame systems by controlling lateral drifts under extreme pulses (Yön et al., 2025).

RC Bridge Columns and Residual Displacements

In bridge engineering, pulse-like motions can cause large residual displacements or permanent "tilt" that make the bridge unserviceable. Increasing reinforcement is not always sufficient to reduce these residual displacements (Vahed & Habibi, 2025).

Damage Modeling and the Park-Ang Index

The Park-Ang damage index (DI) is the most widely used metric for RC, accounting for both maximum deformation and cumulative energy (Khoshraftar & Govindhan, 2013).

The index is expressed as:

DI = (Maximum displacement / Ultimate displacement) + (Beta / (Yield strength * Ultimate displacement)) * (Cumulative dissipated energy)

A DI value of 0.4 marks severe damage, while DI greater than or equal to 1.0 connotes total failure. For long-duration earthquakes, the energy term dominates, while for near-fault pulses, the deformation term governs (Ruiz-García, 2024).

Advanced Mitigation: Base Isolation and Damping Systems

Seismic Isolation

Base isolation decouples the structure from the ground, shifting the fundamental period. Lead-Rubber Bearings (LRB) and Friction Pendulum Bearings (FPB) are common. While effective, near-fault pulses can cause excessive displacements at the isolation interface (Harris, 2011).

Supplemental Damping and Retrofit

Dampers like Fluid Viscous Dampers (FVDs) are effective in reducing drifts. Furthermore, retrofitting existing buildings with RC jacketing and fiber-reinforced polymer (FRP) wrapping can increase ultimate capacity by over 180% (Sindhushree et al., 2025).

Table 3: Performance of Mitigation Technologies under Pulse-Like and Long-Duration Demands

Mitigation Technology	Primary Mechanism	Pulse-Like Response	Long-Duration Response
Base Isolation	Period Shifting	High displacement demand (Kazaz et al., 2023)	Risk of isolator degradation (De Domenico et al., 2020)
Viscous Dampers	Velocity Damping	Controls early-peak drift (Sindhushree et al., 2025)	Continuous energy dissipation (De Domenico et al., 2020)
BRB Systems	Hysteretic	Prevents story	High cumulative

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	Energy	mechanisms (Khademi et al., 2024)	ductility (Khademi et al., 2024)
Rocking Walls	Re-centering	Minimizes residual drift (Daei, 2021)	Maintains elastic response (Daei, 2021)

Resilience Implications and Functional Recovery

Seismic resilience focuses on the dimension of time and functional recovery. A resilient structure can return to normal functionality within an acceptable timeframe (Almufti & Willford, 2014).

Quantifying Resilience: The SRI and Functionality Curves

The Seismic Resilience Index (SRI) tracks functionality over time. The REDi Rating System provides a framework for resilience-based design, accounting for "impeding factors" like inspection and financing delays that contribute to downtime (Chen & Wang, 2026).

Case Study: 2023 Turkey-Syria Earthquake

The 2023 Turkey-Syria earthquake provided a critical data set for PBSE methodologies. The sequence featured motions with distinct near-fault features. In Antakya, roof drifts of mid-rise RC MRFs exceeded 4%, aligning with nonlinear dynamic analysis predictions. This event highlighted the importance of accurate standards for evaluating older, non-conforming RC structures (Pekelnicky, 2023).

Conclusion

The transition to performance-based seismic engineering represents a paradigm shift in the design and evaluation of reinforced concrete structures, moving from simplistic force-based criteria to sophisticated displacement- and consequence-focused approaches that better address real-world risks. Near-fault ground motions impose severe impulsive demands through velocity pulses and fling-step effects, often triggering early inelastic excursions, soft-story mechanisms, and elevated collapse probabilities in conventional RC moment-resisting frames and shear walls. Long-duration earthquakes exacerbate cumulative degradation via repeated cycles, stiffness loss, period elongation, and unmitigated aftershock damage, leading to fatigue-dominated failure modes not adequately captured by standard far-field assumptions. Established frameworks such as ASCE 41 provide deterministic component-level checks but tend toward conservatism, while FEMA P-58 enables probabilistic, system-level resilience quantification essential for informed decision-making on life safety, operability, and economic impacts. Damage metrics like the Park-Ang index remain valuable for integrating peak deformation and hysteretic energy dissipation, with distinct dominance patterns under pulse-like versus sustained shaking. Mitigation strategies ranging from base isolation and velocity-dependent dampers to innovative low-damage systems demonstrate substantial reductions in demands (e.g., >80% base shear reduction) and residual drifts, though performance under extreme near-fault or long-duration inputs requires careful calibration. The 2023 Turkey-Syria earthquake underscored these vulnerabilities in existing non-ductile RC stock, validating the need

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for updated provisions (e.g., ASCE 41-23) and "Ready-to-Use" detailing for resilient low-rise construction. Ultimately, achieving earthquake resilience demands holistic integration of hazard-specific ground motion selection, nonlinear dynamic analysis, advanced energy dissipation devices, and time-dependent recovery objectives. Future engineering practice should prioritize dual lateral systems, functional recovery targets via frameworks like REDi, and reduced conservatism in evaluation standards to ensure structures not only survive but rapidly regain functionality, minimizing societal disruption in high-seismic regions.

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