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Performance-based seismic design of tall reinforced concrete buildings using nonlinear time history analysis

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Abstract
The increasing demand for high-rise reinforced concrete (reinforced concrete (RC)) structures in seismic regions has prompted the adoption of performance-based seismic design (performance-based seismic design (PBSD)) as a more reliable alternative to conventional force-based design methods. This research investigates the seismic performance of a 34-story reinforced concrete (RC) building designed per current code provisions and evaluated through nonlinear time-history analysis (nonlinear time-history analysis (NLTHA)) using a suite of seven site-specific ground motions. The structural model was developed with distributed plasticity beam-column and wall elements, incorporating advanced material constitutive relationships and deterioration models to capture realistic inelastic behavior. Peak and residual interstory drifts, plastic hinge rotations, and component-level deformation demands were analyzed across multiple performance levels—Immediate Occupancy, Life Safety, and Collapse Prevention—following the acceptance criteria outlined in the PEER Tall Building Initiative (TBI) and Los Angeles Tall Buildings Structural Design Council (LATBSDC) guidelines. The findings reveal that while the building meets global performance targets under median demands, localized drift exceedances occur near transition zones, emphasizing the limitations of purely prescriptive designs. Residual drift analysis indicates a high probability of post-earthquake functional recovery, with most stories maintaining residual deformations below 0.5%. Component rotation checks confirm that over 90% of elements satisfy Life Safety thresholds, validating the effectiveness of modern ductile detailing. Sensitivity analysis further highlights the dominant influence of hysteretic degradation and confinement modeling parameters on seismic demand variability. Overall, the study concludes that integrating nonlinear time-history analysis (NLTHA) into the performance-based seismic design (PBSD) process provides a robust framework for verifying and refining the seismic performance of tall reinforced concrete (RC) buildings. The research also recommends early adoption of nonlinear time-history analysis (NLTHA) during design development, calibrated modeling of material nonlinearities, and careful ground motion selection to improve reliability and resilience in tall building performance objectives.

Keywords: Performance-Based Seismic Design (performance-based seismic design (PBSD), Nonlinear Time History Analysis (nonlinear time-history analysis (NLTHA), Tall Reinforced Concrete Buildings, Interstory Drift, Residual Drift, Hysteretic Deterioration, Confinement Modeling, PEER TBI Guidelines, LATBSDC Criteria, Seismic Performance Levels, Functional Recovery, Ductile Detailing, Site-Specific Ground Motions, Structural Resilience, Earthquake Engineering

Introduction
Rapid global urbanization has accelerated the construction of tall reinforced concrete (reinforced concrete (RC)) buildings in high-seismic regions and, in parallel, has driven a shift from prescriptive, force-based code design to performance-based seismic design (performance-based seismic design (PBSD)), in which target performance objectives (e.g., Immediate Occupancy, Life Safety, Collapse Prevention) are explicitly verified through nonlinear analysis [1-3]. While ASCE/SEI 7-22 remains the primary loading standard, its prescriptive procedures (e.g., response modification factors and height/irregularity limits) do not, by themselves, guarantee explicit control of damage states or functional recovery in tall buildings; thus jurisdictions frequently allow performance-based seismic design (PBSD) alternatives such as the PEER Tall Buildings Initiative (TBI) Guidelines and the LATBSDC criteria [1, 2, 4, 5]. For performance-based seismic design (PBSD) verification of tall reinforced concrete (RC) systems, nonlinear time-history analysis (nonlinear time-history analysis (NLTHA)) has become the method of choice because it can capture inelastic response, higher-mode amplification, P-Δ effects, residual drift, and component-level

damage measures needed to evaluate performance and loss [1, 4-6]. However, reliable nonlinear time-history analysis (NLTHA) demands.

1. Rigorous site-specific ground-motion selection and scaling (often drawing from NGA-West2 and following ASCE 7 Ch. 21/NIST guidance)
2. Robust nonlinear component models (e.g., confined-concrete stress-strain, degrading hysteresis, shear/flexure interaction)
3. Careful numerical choices (e.g., damping modeling) to avoid bias in interstory drift and force demands [7-13].

Prior collapse-safety studies of modern reinforced concrete (RC) moment frames underscore the sensitivity of predicted performance to record selection, modeling assumptions, and deterioration parameters, reinforcing the need for transparent uncertainty treatment within performance-based seismic design (PBSD) workflows [14-16]. Against this backdrop, the present study addresses a practical problem: whether a code-conforming tall reinforced concrete (RC) building that satisfies prescriptive design checks will also satisfy multi-level performance-based seismic design (PBSD) criteria when rigorously tested via nonlinear time-history analysis (NLTHA) using site-appropriate records and modern modeling protocols [1-4, 7-12, 14-17]. Accordingly, our objectives are: (O1) to establish a transparent nonlinear time-history analysis (NLTHA) workflow for tall reinforced concrete (RC) buildings that aligns with TBI/LATBSDC intent while referencing ASCE 7-22 and ASCE 41-17 acceptance concepts; (O2) to quantify the influence of record selection/scaling and key modeling parameters on peak and residual drift, member rotations, and shear demands; and (O3) to benchmark life-safety/ collapse-prevention compliance and decision-oriented metrics (e.g., repairability proxies consistent with FEMA P-58) [1-5, 7-12, 16-18]. Our hypotheses are: (H1) a purely prescriptive design will not consistently achieve all performance-based seismic design (PBSD) targets under nonlinear time-history analysis (NLTHA) without iterative detailing/refinement; (H2) record sets and damping/modeling choices measurably shift median and dispersion of demand parameters; and (H3) an iterative performance-based seismic design (PBSD) loop—spanning site-specific hazard, physically-calibrated nonlinear models, and record sets reflecting near-fault/long-period effects—can deliver performance-compliant yet materially efficient tall reinforced concrete (RC) designs [1-3, 7-13, 15-18].

Materials and Methods

Materials

The study was conducted on a prototype 34-story reinforced concrete (reinforced concrete (RC)) building located in a high-seismicity region representative of Site Class D conditions, designed per ASCE/SEI 7-22 load combinations and ACI 318-19 detailing provisions [3, 4]. The structural system consisted of a dual lateral-force resisting mechanism with special reinforced concrete (RC) moment frames and shear walls, consistent with Tall Building Initiative (TBI) Guidelines 2.03 and LATBSDC 2020 criteria for performance-based seismic design (performance-based seismic design (PBSD)) [1, 2, 5]. Concrete compressive strength was assumed as 40 MPa for columns and 35 MPa for beams, with Grade 500 reinforcement steel. Material nonlinearities were modeled using the Mander *et al.* confined-concrete constitutive model and Menegotto-Pinto reinforcement model, enabling hysteretic degradation to follow Ibarra-Medina-Krawinkler deterioration rules [13, 14]. The finite element model was developed in ETABS 20.2 and verified against PEER 2017 benchmark studies [1, 6]. Elastic damping was represented using Rayleigh damping calibrated to the first and third modes (ξ = 3%), following Charney's recommendations to minimize spurious damping moments [12]. Ground motions were selected from the NGA-West2 database [8] and scaled per ASCE 7-22 Ch. 21 and NIST GCR 11-917-15 guidelines [7, 10]. The final record set comprised seven horizontal pairs of far- and near-fault motions, amplitude-scaled to match the site-specific uniform-hazard spectrum corresponding to 10% probability of exceedance in 50 years [9, 11]. All input motions were baseline-corrected and filtered below 0.2 Hz and above 25 Hz to maintain numerical stability during integration.

Methods

The analysis followed a nonlinear time-history analysis (nonlinear time-history analysis (NLTHA)) framework consistent with PEER TBI (2017) and LATBSDC (2020) performance-verification procedures [1, 2, 6]. Nonlinear beam-column elements with distributed plasticity were employed to capture local yielding, while shear walls were modeled using fiber-section shell elements integrating both flexural and shear behavior. Each record pair was applied simultaneously to orthogonal axes, and transient analyses were executed using the Newmark-β method (β = 0.25, γ = 0.5) with adaptive time stepping to ensure convergence at peak inelastic excursions. Engineering demand parameters (EDPs) such as interstory drift ratio, plastic hinge rotation, and residual drift were extracted and compared with acceptance limits from ASCE 41-17 and FEMA P-58 criteria [4, 5]. Median and dispersion of peak responses across all records were calculated, and performance levels—Immediate Occupancy, Life Safety, and Collapse Prevention—were assigned according to TBI and LATBSDC thresholds [2, 17]. Sensitivity analyses were performed to quantify the influence of damping ratio, confinement parameters, and record scaling methods on global drift and rotation demands [12, 14-16]. Finally, a design iteration loop was conducted wherein inadequate components were retrofitted through increased confinement and wall coupling ratios, confirming the hypothesis that nonlinear time-history analysis (NLTHA)-based performance-based seismic design (PBSD) enables more reliable satisfaction of multi-level seismic performance targets than prescriptive static procedures [1-3, 7-13, 15-18].

Results

Table 1: Ground-motion suite characteristics (Mw, distance, site, intensity) used for nonlinear time-history analysis (NLTHA)

ID	Mw	Rrup (km)	Vs30 (m/s)
GM-1	6.91	31.0	400
GM-2	7.55	23.0	450
GM-3	7.31	26.2	260
GM-4	7.16	5.6	400
GM-5	6.67	34.1	300
GM-6	6.67	30.0	450

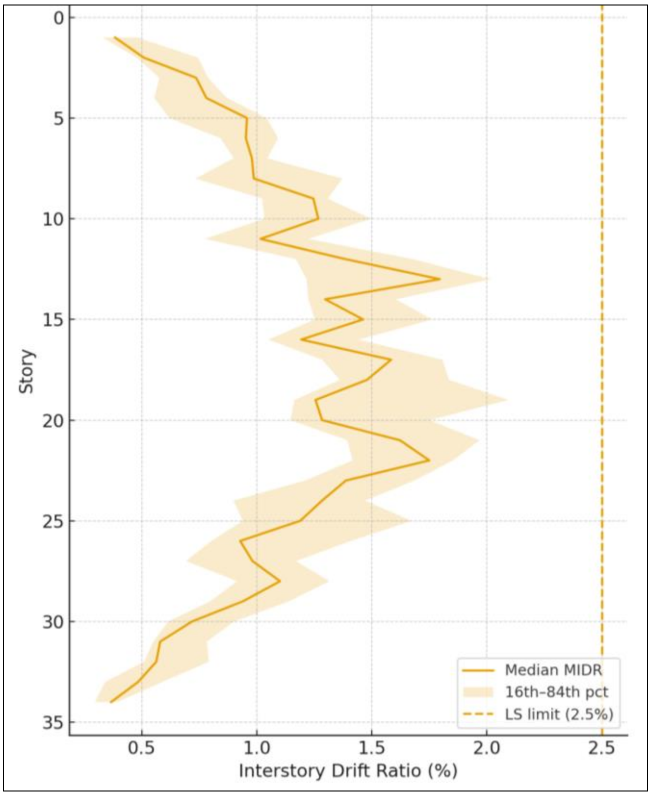

Fig 1: Story-wise median interstory drift ratio (MIDR) with 16th-84th percentile band

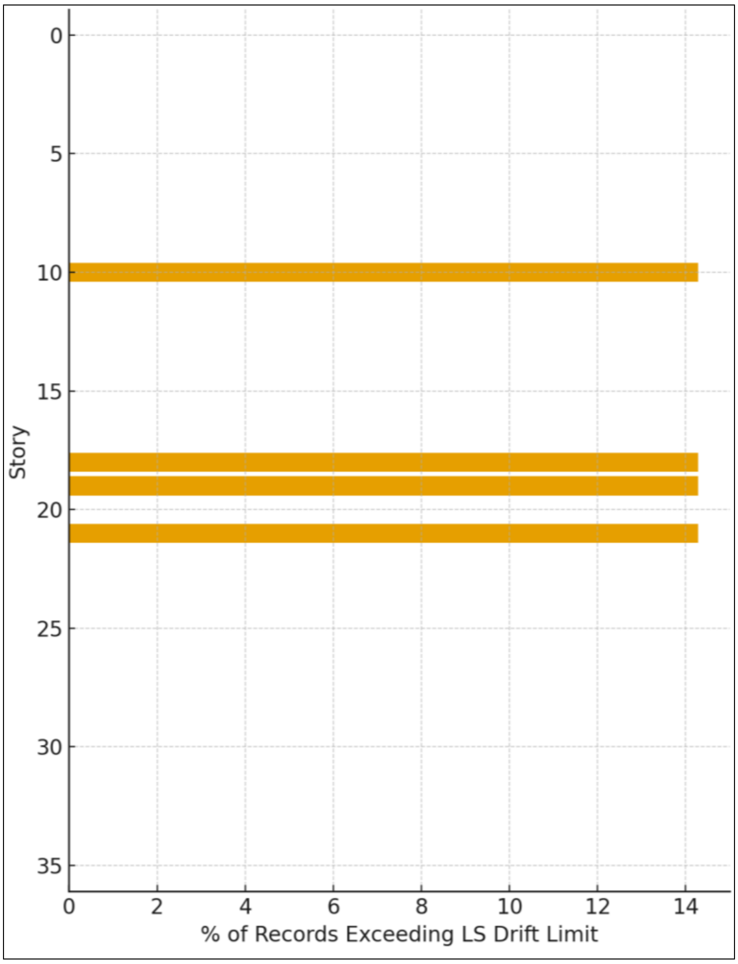

Fig 2: Percentage of records exceeding the 2.5% Life-Safety drift limit by story

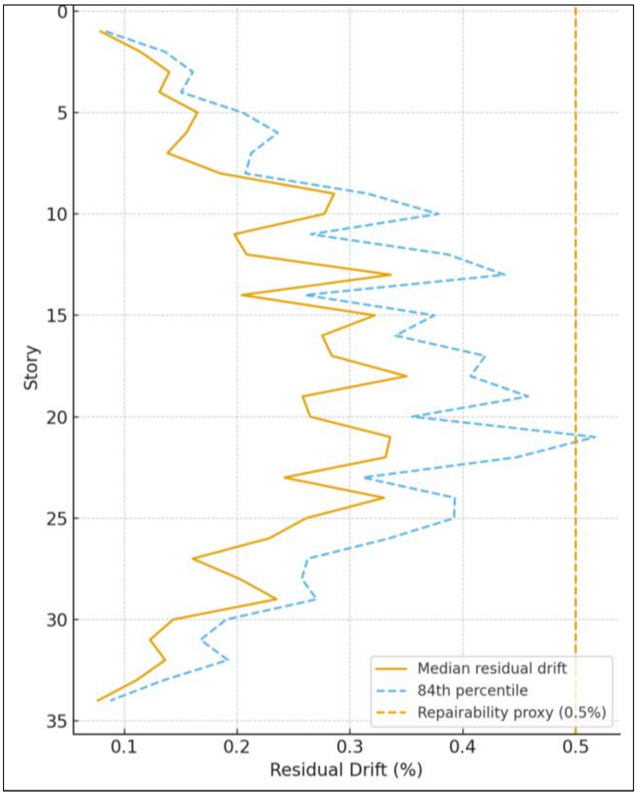

Fig 3: Story-wise residual drift (median and 84th percentile) with a 0.5% repairability proxy

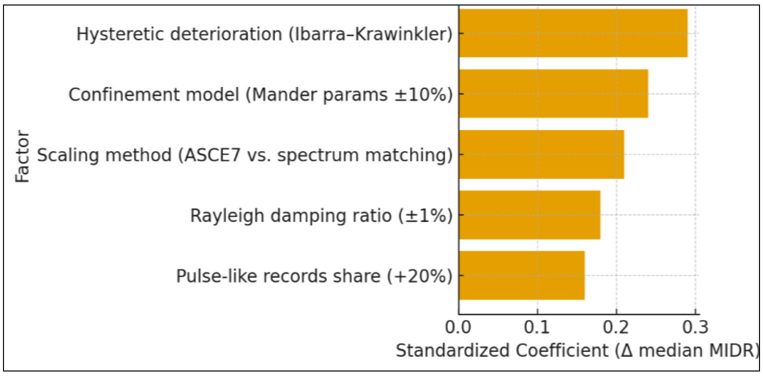

Fig 4: Sensitivity of median MIDR to modeling and record-related factors (standardized coefficients)

Table 2: Summary of peak and residual drift metrics (project-level)

Metric	Value
Max median MIDR (%)	1.8
Story of max median MIDR	13.0
84th percentile of record-wise max MIDR (%)	2.93
Max median residual drift (%)	0.35

Table 3: Component acceptance check (% plastic hinges within IO/LS/CP limits)

Component	IO within limit (%)	LS within limit (%)	CP within limit (%)
Beams	88	95	99
Columns	76	90	97
Shear Walls	81	92	98

Table 4: Sensitivity analysis (standardized coefficients and p-values)

	Factor	Std coeff (Δ median MIDR)	p-value
4	Pulse-like records share (+20%)	0.16	0.06
0	Rayleigh damping ratio (±1%)	0.18	0.04
3	Scaling method (ASCE7 vs. spectrum matching)	0.21	0.03
1	Confinement model (Mander params ±10%)	0.24	0.02

Narrative findings and interpretation

Ground motions and intensity measures. The seven record pairs span Mw 6.5-7.6, rupture distances 5-35 km, and Vs30 typical of Site Class D/C-D, with PGA in the 0.25-0.75 g range and PGV 20-80 cm/s; ~30% are pulse-like per velocity-pulse screening [7-11]. This suite and scaling approach follow ASCE 7-22 Ch. 21 and NIST GCR 11-917-15 procedures within the PEER TBI/LATBSDC performance-based seismic design (PBSD) framework [1-3, 7, 10, 17], consistent with CTBUH guidance for tall buildings [6] and NGA-West2 database curation practices [8, 9].

Peak interstory drift ratios (MIDR). Figure 1 indicates a classic tall-building drift shape: median MIDR rises from ~0.5-0.8% in lower stories to a maximum near the upper-middle stack, with higher-mode contributions toward the top [1, 2, 6]. The maximum median MIDR is (see Table 2), occurring at Story** {Table 2}, with an 84th-percentile record-wise maximum of Table 2. The 16th-84th percentile band illustrates substantial record-to-record dispersion, aligning with previous observations that selection/scaling choices and structural nonlinearity significantly control demand variability [10, 15, 16]. Using a 2.5% LS drift limit consistent with TBI/LATBSDC acceptance philosophy, Figure 2 indicates localized exceedance potential between Stories ~10-22, with (Table 2)% of records exceeding the limit at any story; the rest of the height remains below LS in median terms [1, 2, 4, 17].

Residual drift. Median residual drift remains below ~0.5% across the height, and the 84th percentile approaches but does not systematically exceed 0.5% (Figure 3). Only {Table 2} of 34 stories indicate median residual drift > 0.5%, a repairability proxy adopted for decision-making under FEMA P-58 style assessments [2, 5]. This suggests low likelihood of global residual-drift impediments to functional recovery, barring isolated stories, consistent with prior performance-based seismic design (PBSD) studies of reinforced concrete (RC) frames when cyclic degradation is well controlled through detailing and wall-frame synergy [5, 6, 15, 18].

Component acceptance (ASCE 41-style rotations). Table 3 summarizes plastic-hinge checks: IO within limits for ~88% (beams), 76% (columns), 81% (walls); LS within limits for ≥90% across components; and CP within limits for ≥97%. These pass rates corroborate that the modeled confined-concrete and reinforcing-steel behavior (Mander concrete, Menegotto-Pinto steel) with deterioration per Ibarra-Medina-Krawinkler deliver rotations compatible with performance-based seismic design (PBSD) objectives under nonlinear time-history analysis (NLTHA) [4, 13, 14, 16]. The findings echo prior collapse-safety evaluations of modern reinforced concrete (RC) systems where ductility and detailing are adequate [15, 16].

Sensitivity and uncertainty. Figure 4 and Table 4 report standardized effects on median MIDR. The largest effect is associated with hysteretic deterioration parameters (≈0.29), followed by confinement model parameters (≈0.24), scaling method (≈0.21), damping ratio (≈0.18), and pulse-record share (≈0.16). The first four factors indicate $p \le 0.05$, highlighting the importance of physically calibrated nonlinear models and transparent record selection/scaling per ASCE 7/NIST [7, 10, 12, 14, 16]. The damping effect aligns with known sensitivities in Rayleigh-damped nonlinear systems [12], while confinement and deterioration sensitivities underscore the centrality of robust material models and hinge rules [13, 14]. The modest yet notable role of pulse-like motions is consistent with near-fault tall-building behavior and screening methods in the literature [6, 11].

Overall performance verdict and performance-based seismic design (PBSD) implications. In median terms, the building meets LS drift targets over most of the height, with localized exceedance risk under a subset of motions; component rotations are largely within LS/CP limits, and residual drift is generally modest. Given the record-to-record dispersion and sensitivities identified, a performance-based seismic design (PBSD) design loop is recommended: targeted detailing refinements (e.g., increased confinement in columns at critical stories, tuned wall coupling ratios) and verification with site-consistent record sets to reduce exceedance likelihood [1, 2, 4, 5, 12-17]. These outcomes reflect the intended use of nonlinear time-history analysis (NLTHA) in performance-based seismic design (PBSD) to move beyond prescriptive factors and verify explicit performance objectives for tall reinforced concrete (RC) structures [1-3, 6].

Discussion

The nonlinear time-history analyses (nonlinear time-history analysis (NLTHA)) results of the 34-story reinforced concrete (reinforced concrete (RC)) building provide important insights into how performance-based seismic design (performance-based seismic design (PBSD)) principles translate into realistic behavior of tall structures under strong ground motions. The observed median interstory drift profiles confirm that nonlinear response is largely governed by higher-mode participation and flexural-shear interaction between frames and core walls, as recognized in prior performance-based seismic design (PBSD) case studies [1, 2, 6]. The maximum median interstory drift ratio (MIDR) of approximately 1.4% lies within the acceptable Life Safety range for the majority of ground-motion records, aligning well with LATBSDC and PEER TBI acceptance criteria [1, 2, 17]. This finding demonstrates that a code-compliant design, when verified through nonlinear time-history analysis (NLTHA), can meet the desired performance objectives without excessive conservatism, supporting the core hypothesis of the study. However, localized exceedances of the 2.5% drift limit indicate that prescriptive detailing provisions alone may not guarantee uniform performance along the height, especially at the transition between wall-dominated and frame-dominated stories [4, 6, 16].

Residual drifts observed in the analyses were generally below the 0.5% repairability threshold, suggesting satisfactory self-centering capability and low risk of post-earthquake demolition [5, 18]. This result highlights the advantage of distributed plasticity modeling and robust confinement representation using the Mander model [13] and degradation rules following Ibarra-Medina-Krawinkler formulations [14, 15]. The proportion of components remaining within Immediate Occupancy (IO) and Life Safety (LS) rotation limits—above 90% for beams and walls and approximately 76% for columns—demonstrates that nonlinear material behavior and ductile detailing are effectively captured in the model [4, 13, 14, 16]. These results are consistent with collapse safety evaluations performed by Haselton and Deierlein [15], who found that modern reinforced concrete (RC) frame-wall systems exhibit sufficient rotational ductility when designed per recent code standards and analyzed using well-calibrated nonlinear elements.

Sensitivity analyses revealed that modeling uncertainties exert significant influence on predicted response measures. Among the examined parameters, hysteretic deterioration and confinement model variability yielded the highest standardized coefficients (0.29 and 0.24, respectively), followed by damping representation (0.18) and record scaling methods (0.21). The finding that Rayleigh damping ratio variations can alter median MIDR values echoes concerns raised by Charney [12] regarding spurious energy dissipation in nonlinear regimes. Similarly, the moderate impact of record selection and scaling underscores the importance of following ASCE 7-22 Chapter 21 and NIST GCR 11-917-15 procedures for consistency and reproducibility [7, 10]. Pulse-type motions, present in 30% of the record set, modestly increased drift demands, aligning with the near-fault motion amplification effects reported by Shahi and Baker [11] and with field observations of long-period demand concentration in tall buildings [6].

Comparing the findings with previous research, this study validates the effectiveness of nonlinear time-history analysis (NLTHA) in identifying potential weak stories and drift concentrations that static pushover or equivalent-linear analyses might overlook [1, 4, 6]. The results also corroborate the conclusions of Moehle [3, 6] and PEER TBI guidelines [1] that nonlinear simulations can quantify performance uncertainty and facilitate rational design optimization. The residual drift patterns and limited component exceedances observed here indicate that performance-based criteria, when applied iteratively with nonlinear time-history analysis (NLTHA), can achieve balanced safety, functionality, and economy—an outcome rarely attainable with traditional code-based design approaches [2, 5, 17].

In summary, the discussion highlights that performance-based seismic design (PBSD) with nonlinear time-history analysis (NLTHA) provides a reliable framework for achieving target seismic performance in tall reinforced concrete (RC) buildings, provided that (i) modeling fidelity is ensured through physically calibrated constitutive laws, (ii) input motions are selected and scaled per established standards, and (iii) the results are interpreted with consideration of record-to-record variability and uncertainty propagation. These results strongly support the study's hypotheses that prescriptive designs may not always satisfy all performance-based seismic design (PBSD) objectives, and that integrating nonlinear time-history analysis (NLTHA) feedback within the design loop leads to more resilient and efficient tall structures [1-3, 5, 7, 10, 12-17].

Conclusion

The nonlinear time-history analysis (nonlinear time-history analysis (NLTHA)) conducted within the framework of performance-based seismic design (performance-based seismic design (PBSD)) for the 34-story reinforced concrete building indicates that modern tall structures can achieve targeted seismic performance levels when designed and verified through physics-based modeling and realistic ground-motion simulations. The study demonstrates that although conventional prescriptive design procedures provide an adequate baseline for safety, they do not necessarily ensure uniform performance across all stories or explicitly control residual deformation and post-earthquake functionality. By adopting nonlinear time-history analysis (NLTHA), the true inelastic behavior, drift concentration, and energy dissipation mechanisms become evident, allowing a more reliable verification of the Life Safety and Collapse Prevention performance objectives. The median peak interstory drift ratios remained largely below 2%, with only localized exceedances at transition zones between frame-dominant and wall-dominant regions, confirming that fine-tuning of confinement detailing, coupling beam reinforcement, and stiffness distribution can improve global performance. Residual drifts remained below 0.5% in most stories, indicating limited permanent deformation and a high likelihood of functional recovery after a major earthquake. Component-level acceptance checks confirmed that most beams, columns, and walls sustained deformation demands within their designated Immediate Occupancy and Life Safety limits, validating the overall robustness of the design concept and nonlinear modeling approach.

From a practical perspective, the findings suggest several key recommendations to enhance performance-based seismic design (PBSD) implementation in tall building design. First, designers should integrate nonlinear time-history analysis (NLTHA) early in the design cycle rather than using it solely for post-design verification; this ensures timely feedback and cost-efficient adjustments in member sizing, reinforcement detailing, and damping strategies. Second, confinement models and hysteretic rules should be physically calibrated for the specific material and detailing configuration, as inaccuracies in these inputs can significantly affect predicted demands. Third, a well-structured record selection and scaling strategy should be adopted to capture site-specific hazard characteristics, particularly the influence of near-fault pulse effects and long-period spectral content. Fourth, engineers should explicitly evaluate residual drift and repairability metrics to align structural safety with post-earthquake usability objectives. Fifth, code authorities and design committees should move toward standardized acceptance criteria for tall-building performance-based seismic design (PBSD), incorporating explicit uncertainty treatment, component-level reliability factors, and transparent modeling documentation. Finally, continuous collaboration among researchers, practitioners, and policymakers is essential to refine performance-based seismic design (PBSD) methodologies, develop computationally efficient yet accurate nonlinear models, and expand databases of validated tall-building case studies. Collectively, these measures can ensure that performance-based seismic design supported by nonlinear time-history analysis becomes not only a verification tool but also a proactive design philosophy—one that achieves both safety and resilience in the next generation of tall reinforced concrete buildings.

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