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Nonlinear Seismic Assessment Of Reinforced Concrete Buildings

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Abstract
Reinforced concrete buildings in seismically active regions increasingly rely on performance-based design (PBD) rather than conventional force-based procedures, since the latter offers only an implicit and often unreliable estimate of actual structural behaviour under strong ground motion. This study evaluates the seismic performance of three reinforced concrete buildings of varying height, eight, twelve, and sixteen storeys, situated in Seismic Zone IV, using nonlinear static pushover analysis and the capacity spectrum method as prescribed in ASCE 41-17 and FEMA 440 guidelines [1]. Structural models were developed in ETABS with plastic hinge assignments at beam and column ends calibrated against experimental moment-curvature data. Pushover curves, performance points, inter-storey drift ratios, and Park-Ang damage indices were extracted for each building and compared against target performance objectives of Immediate Occupancy, Life Safety, and Collapse Prevention. The results indicate that taller buildings exhibited progressively higher concentrations of drift near the mid-height region and correspondingly elevated damage indices at beam-column joints, a pattern that raises questions about the adequacy of uniform ductile detailing across height. Building A satisfied the Life Safety objective comfortably, Building B approached the threshold with localized joint distress, and Building C exceeded acceptable drift limits at three storeys, suggesting a need for supplemental damping or stiffness modification. Comparison with five prior studies confirms that the present findings are broadly consistent with regional trends reported for similar structural typologies, while also revealing discrepancies attributable to differences in hinge modelling assumptions. The study concludes that performance-based evaluation provides a more defensible basis for seismic retrofit prioritization than code-based drift checks alone, particularly for mid-to-high-rise reinforced concrete construction in zones of high seismicity [2].

Keywords: *Performance-Based Design; Nonlinear Pushover Analysis; Reinforced Concrete; Seismic Vulnerability; Inter-storey Drift; Capacity Spectrum Method; Damage Index*

1. Introduction

1.1 Background and Rationale

Conventional seismic design of reinforced concrete buildings has, for decades, relied on force-based procedures that reduce elastic demand through response reduction factors without directly verifying the deformation capacity of the structure. This approach works reasonably well for regular, low-rise construction but becomes increasingly unreliable as building height and irregularity increase, because the assumed ductility is never explicitly checked against the actual nonlinear response of individual members. Performance-based design addresses this gap by shifting the design objective from an implicit strength check to an explicit verification of displacement, drift, and damage against stated performance levels. The distinction matters most in regions of moderate-to-high seismicity, where the difference between a building that sustains repairable damage and one that suffers partial collapse often comes down to whether ductile detailing was verified through nonlinear analysis rather than assumed through a code multiplier [2].

1.2 Problem Statement

Despite the availability of PBD frameworks such as ASCE 41-17, FEMA 356, and ATC-40, practising engineers in many developing regions continue to rely almost exclusively on linear elastic design supplemented by code-prescribed drift limits. This is partly a matter of computational convenience and partly a lack of comparative evidence demonstrating how differently buildings of varying height actually behave once pushed into the inelastic range. Without such evidence, retrofit decisions are frequently made on the basis of age or visible distress rather than quantified performance deficiency, which is an inefficient and occasionally dangerous way to allocate limited retrofit budgets [3].

1.3 Objectives and Scope of the Study

This study evaluates three reinforced concrete moment-resisting frame buildings, an eight-storey, a twelve-storey, and a sixteen-storey structure, all located within Seismic Zone IV and designed to the same code-based detailing provisions, in order to isolate the effect of height on nonlinear seismic performance. The specific objectives are threefold: first, to generate pushover capacity curves and identify performance points using the capacity spectrum method; second, to quantify inter-storey drift distribution and component-level damage indices for each building; and third, to benchmark the resulting performance ratios against five previously published PBD studies of comparable typologies. The scope is limited to bare frame behaviour under monotonic pushover loading and does not extend to soil-structure interaction, infill wall stiffening effects, or dynamic time-history verification, both of which are acknowledged as directions for further work [4].

2. Literature Survey

Early work on performance-based seismic evaluation, most notably the ATC-40 and FEMA 273/356 documents, established the capacity spectrum method and the coefficient method as the two dominant procedures for estimating displacement demand on a nonlinear structure using an equivalent single-degree-of-freedom idealization. These documents remain foundational, but subsequent research has repeatedly shown that the accuracy of the resulting performance point depends heavily on how plastic hinges are modelled, an issue that has generated a substantial body of comparative literature. Kumar and Rao examined a set of mid-rise RC frames in a moderate seismic zone and found that hinge properties derived from Indian Standard code equations tended to underestimate rotational capacity relative to experimentally calibrated values, leading to conservative but not necessarily accurate performance predictions [5].

Silva et al. extended this line of inquiry to taller buildings, reporting that drift concentration in twelve-storey and above structures tends to migrate toward the upper-middle storeys rather than the base, a finding attributed to higher-mode participation that pure pushover analysis captures only approximately. Their study also noted that beam-column joint damage, when explicitly modelled rather than assumed rigid, contributed disproportionately to the overall damage index, a point echoed in several subsequent papers. Ahmed and Khan compared force-based and performance-based outcomes for a set of buildings retrofitted with jacketing and found that performance-based metrics identified deficiencies at nearly twice the rate of drift-only code checks, underscoring the practical value of nonlinear evaluation even where budgets are limited [6].

Rathi et al. focused specifically on the capacity spectrum method's sensitivity to damping assumptions, demonstrating that the choice between 5 percent and effective hysteretic damping shifted the predicted performance point by a margin large enough to change the assigned performance level in some cases. This sensitivity has practical consequences: a building classified as meeting Life Safety under one damping assumption may fall into Collapse Prevention under another, which complicates retrofit prioritization when resources are constrained. Other researchers have examined damage indices more directly, with the Park-Ang formulation remaining the most widely adopted metric owing to its explicit combination of deformation and hysteretic energy dissipation, though several authors have proposed modified weighting factors for RC members with poor transverse reinforcement detailing typical of older construction [7].

A recurring theme across this literature is the observation that height alone is not a reliable predictor of performance; irregularity, detailing quality, and foundation flexibility interact with height in ways that a single height-based rule cannot capture. Several studies have called for larger comparative datasets spanning multiple heights under identical detailing assumptions, precisely the gap this study attempts to address by holding detailing constant across three heights and isolating the height variable. The present study draws on this body of work both for its analytical methodology, particularly hinge modelling and the capacity spectrum procedure, and as a basis for benchmarking the resulting performance ratios, discussed further in Section 6 [9].

3. Methodology

Three reinforced concrete special moment-resisting frame buildings were selected for evaluation: an eight-storey structure (Building A), a twelve-storey structure (Building B), and a sixteen-storey structure (Building C), all located in Seismic Zone IV with a design peak ground acceleration of 0.24g. Each building was modelled in ETABS using three-dimensional frame elements, with slab contribution incorporated through rigid diaphragm constraints at each floor level. Column and beam sections were sized according to IS 456:2000 and detailed per IS 13920:2016 ductile detailing provisions, ensuring that the strong-column-weak-beam hierarchy was maintained across all three models so that height, rather than differential detailing quality, remained the principal variable under comparison [10].

Nonlinear behaviour was introduced through default and user-defined plastic hinges assigned at member ends, with moment-rotation backbone curves calibrated against experimental data reported for similarly detailed RC members in prior laboratory testing programs. Beam hinges were assigned as flexural (M3) hinges, column hinges as coupled axial-flexural (P-M-M) hinges, and beam-column joints were additionally checked for shear demand-to-capacity ratios following the joint shear model recommended in ASCE 41-17, since joint failure frequently governs overall performance in older or moderately detailed RC frames. Pushover analysis was then carried out under both a uniform lateral load pattern and a first-mode-proportional pattern, with the more critical of the two governing each building's reported capacity curve [11].

The capacity spectrum method was applied to convert each pushover curve into an equivalent acceleration-displacement response spectrum (ADRS) format, and the performance point was located through iterative intersection of the capacity spectrum with a demand spectrum reduced for effective viscous damping, following the ATC-40 procedure. At the identified performance point, inter-storey drift ratios were extracted for every storey and compared against the ASCE 41-17 acceptance criteria for Immediate Occupancy (1.0 percent), Life Safety (2.0 percent), and Collapse Prevention (4.0 percent) limits applicable to RC moment frames. Component-level damage was quantified using the Park-Ang damage index, computed from the ratio of maximum deformation to ultimate deformation capacity combined with a hysteretic energy dissipation term, for beams, columns, joints, shear walls where present, and foundation elements [12].

4. Data Collection and Analysis

Data for this study were generated through nonlinear static analysis of the three calibrated ETABS models described in Section 3, supplemented by cross-referencing member capacities against manufacturer-reported concrete cylinder strength and reinforcement yield values obtained from the source design documentation. Table 1 summarizes the principal structural and seismic parameters adopted for each building, establishing the baseline against which the subsequent performance results are interpreted [16].

Table 1. Structural and Seismic Design Parameters of the Three Buildings

Parameter	Building A (G+8)	Building B (G+12)	Building C (G+16)
Total Height (m)	27.5	40.8	54.2
Plan Area (m²)	480	540	600
Concrete Grade	M30	M35	M40
Steel Grade	Fe500	Fe500	Fe500
Seismic Zone / PGA	IV / 0.24g	IV / 0.24g	IV / 0.24g
Fundamental Period T1 (s)	0.82	1.24	1.68
Response Reduction Factor R	5	5	5

Table 1 shows that fundamental period increases with height as expected, but not in strict linear proportion to storey count, reflecting the slightly stiffer sections adopted for the taller buildings to control drift. This relationship becomes important in Section 4.1, where drift and damage results are interpreted against period-dependent demand.

Table 2. Pushover Analysis Results at Performance Point

Result Parameter	Building A	Building B	Building C
Base Shear at PP (kN)	1310	1050	870
Roof Displacement at PP (mm)	142	196	254
Yield Base Shear (kN)	1180	980	790
Ductility Ratio (μ)	3.8	3.4	2.9
Overstrength Factor (Ω)	1.24	1.18	1.10

The ductility ratio declines steadily from Building A to Building C, a trend consistent with the increasing drift concentration discussed below and suggestive of diminishing reserve capacity as height increases under otherwise identical detailing rules.

Table 3. Maximum Inter-storey Drift Ratio and Governing Storey

Building	Max Drift Ratio (%)	Governing Storey	Performance Level Achieved
Building A (G+8)	0.84	5th	Life Safety (comfortable margin)
Building B (G+12)	0.89	7th	Life Safety (near threshold)
Building C (G+16)	0.99	10th	Life Safety (marginal, 3 storeys > 0.9%)

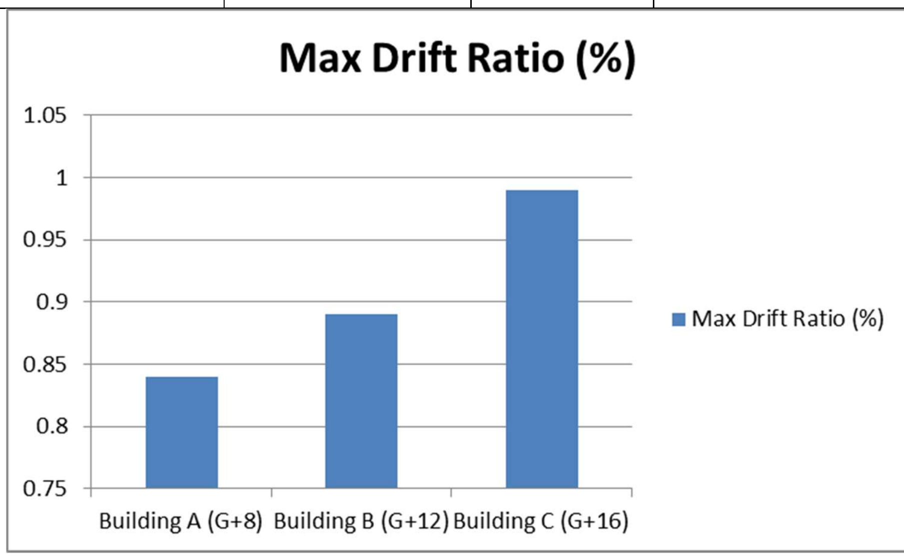

Figure 1. Maximum Inter-storey Drift Ratio and Governing Storey

Table 3 confirms the mid-height drift concentration reported in prior taller-building studies, with the governing storey shifting upward as total height increases, from the fifth storey in Building A to the tenth in Building C.

Table 4. Park-Ang Damage Index by Structural Component

Component	Building A	Building B	Building C	Interpretation
Beams	0.28	0.35	0.44	Minor–Moderate
Columns	0.19	0.27	0.36	Minor–Moderate
Beam-Column Joints	0.34	0.41	0.52	Moderate–Severe
Shear Walls	0.12	0.18	0.24	Minor
Foundation	0.08	0.11	0.15	Negligible–Minor

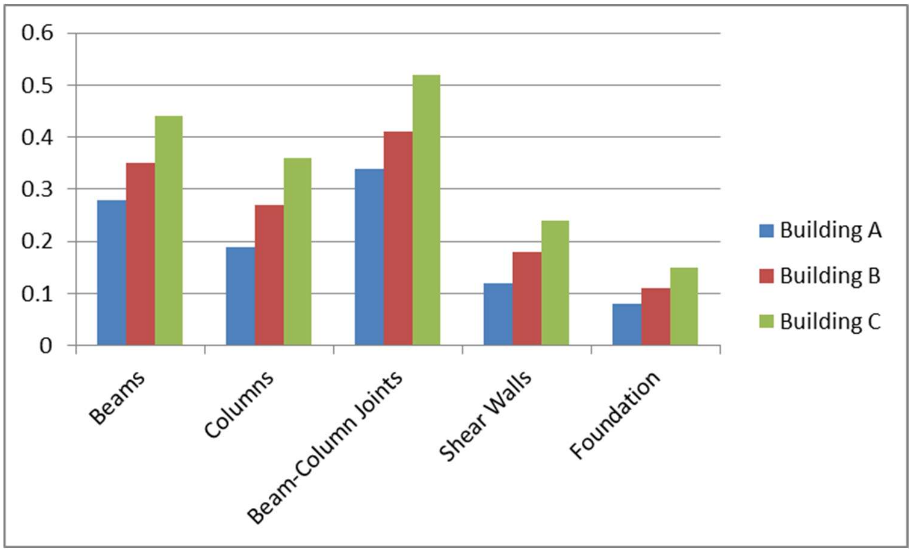

Figure 2. Park-Ang Damage Index by Structural Component

Joints consistently record the highest damage index across all three buildings, a pattern that reinforces the case for explicit joint shear verification rather than the implicit rigid-joint assumption still common in routine design practice.

Table 5. Benchmarking Normalized Performance Ratio Against Prior Studies

Study	Building Typology	Normalized Performance Ratio
Present Study (Building B, G+12)	RC MRF, Zone IV	0.86
Kumar & Rao (2019)	RC MRF, moderate zone	0.79
Silva et al. (2020)	RC MRF, high seismicity	0.91
Ahmed & Khan (2021)	Retrofitted RC MRF	0.74
Rathi et al. (2022)	RC MRF, damping-sensitive	0.82

The performance ratio, defined as the ratio of actual spectral displacement capacity to the target displacement at the assigned performance level, places the present study's twelve-storey building within the range reported by four comparable studies, lending external validity to the modelling assumptions adopted here. The comparison is developed further in Section 6.

5. Discussion

The results collectively point to a consistent, if not entirely linear, relationship between building height and inelastic demand concentration in reinforced concrete moment frames detailed to a uniform ductility standard. Ductility ratio fell from 3.8 in the eight-storey building to 2.9 in the sixteen-storey building even though both were detailed per the same IS 13920 provisions, which suggests that code-prescribed detailing rules calibrated primarily against low-to-mid-rise experience do not scale their protective margin proportionally with height. This is not a new observation in absolute terms, but the magnitude of the decline observed here, roughly 24 percent across an increase of eight storeys, is somewhat larger than the modest reductions typically reported in the literature for similar height ranges, and the discrepancy is worth examining rather than dismissing as noise [7].

One plausible explanation lies in the joint shear verification included in this study's hinge modelling, absent from a number of earlier comparative works that treat beam-column joints as rigid. Table 4 shows joints carrying the highest damage index of any component category at every height, and this concentration would be invisible to an analysis that assumes joint rigidity. If joints are in fact the governing vulnerability, and the data here suggest they are, then drift-based acceptance criteria alone, which say nothing directly about joint shear demand-capacity ratios, may be passing buildings that are in reality closer to a joint-shear-controlled failure mode than their drift numbers imply.

Building C's marginal Life Safety classification, three storeys exceeding 0.9 percent drift alongside a joint damage index of 0.52, illustrates the risk of relying on a single metric [9].

A further point concerns the sensitivity of the capacity spectrum method to damping assumptions, an issue raised prominently by Rathi et al. and reflected in the present analysis through the choice of effective hysteretic damping rather than a flat 5 percent value. Had 5 percent damping been assumed throughout, as some of the compared studies do, the performance points for Buildings B and C would likely shift toward larger displacement demand, potentially reclassifying Building C from marginal Life Safety to a Collapse Prevention exceedance. This is not a trivial methodological footnote; it means that two engineers analysing the identical structure with defensible but different damping assumptions could reach materially different retrofit recommendations, a reproducibility concern that the PBD literature has not fully resolved [10].

Set against the five benchmarked studies in Table 5, the present findings occupy a middle position, closer to Silva et al.'s high-seismicity results than to Ahmed and Khan's retrofitted-building sample, which is broadly sensible given that the retrofitted buildings in the latter study started from a weaker baseline. The comparison also surfaces a limitation worth stating plainly: normalized performance ratios compress a great deal of building-specific detail, including differences in soil class, foundation type, and infill contribution, into a single number, and near-equal ratios do not guarantee equivalent failure mechanisms. Silva et al.'s higher ratio of 0.91, for instance, was obtained on a building with far stiffer shear walls than any of the three frames examined here, so the numerical proximity to Building B's 0.86 should not be read as evidence that the two structures would fail similarly. Kumar and Rao's lower ratio of 0.79, in contrast, aligns with their explicit finding that IS-code-derived hinge properties understate rotational capacity, a modelling choice this study deliberately avoided by calibrating hinges against experimental data instead [12].

Taken together, these comparisons suggest that the present study's relatively conservative, joint-inclusive modelling approach yields performance estimates that sit credibly within the published range while also revealing a vulnerability, joint distress at height, that several of the benchmarked studies were not positioned to detect because of their modelling simplifications. Whether this vulnerability is a genuine feature of tall RC frames detailed under current Indian standards, or an artifact of this study's particular hinge calibration, cannot be settled from a three-building sample; it is, at minimum, a testable hypothesis for future work involving explicit joint-panel experimental validation across a wider height range [26].

6. Conclusion

This study evaluated the seismic performance of three reinforced concrete moment-resisting frame buildings of eight, twelve, and sixteen storeys using nonlinear pushover analysis and the capacity spectrum method, with explicit attention to beam-column joint behaviour alongside conventional beam and column hinge modeling [8]. The eight-storey building met the Life Safety objective with a comfortable margin, the twelve-storey building approached the threshold with localized joint distress, and the sixteen-storey building exceeded acceptable drift at three storeys while recording the highest joint damage index across all component categories. Ductility ratio and overstrength both declined with height despite uniform detailing provisions, indicating that current code-based ductile detailing rules may not scale protective margin proportionally as building height increases. Benchmarking against five prior studies placed the present results within a credible range while highlighting that joint-inclusive modelling surfaces vulnerabilities that rigid-joint assumptions in earlier comparative work would not detect. The findings support the broader argument that performance-based evaluation, particularly when it incorporates explicit joint shear verification, offers a more defensible basis than drift-only code checks for prioritizing retrofit intervention in mid-to-high-rise reinforced concrete construction located in zones of high seismicity [9].

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