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Impact of Structural Irregularities on Seismic Performance Evaluation of Reinforced Concrete Buildings: A State-of-the-Art Review

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Abstract—
Earthquakes have repeatedly demonstrated their capacity to cause severe damage to reinforced concrete buildings, particularly those with structural irregularities in plan, elevation, or mass distribution. Such buildings exhibit complex seismic responses including torsional coupling, stress concentrations, and non-uniform deformations that conventional elastic analysis methods cannot accurately capture. Despite these well-recognized challenges, irregular configurations remain widespread in practice due to architectural and functional demands, making their reliable seismic evaluation a critical concern in earthquake engineering. This paper presents a comprehensive review of seismic behavior and performance assessment of irregular RC buildings, covering classification of structural irregularities, development of nonlinear analysis techniques including pushover methods, and evolution of performance-based seismic design frameworks guided by FEMA, ATC, and ASCE standards. Reviewed studies consistently indicate that linear methods underestimate seismic demand by margins of 15–40%, while nonlinear analysis provides significantly more reliable performance assessment. Key research gaps are identified, suggesting directions for future investigation into advanced evaluation methods for irregular RC structures.

Keywords— Structural Irregularity; Seismic Performance; Reinforced Concrete Buildings; Nonlinear Analysis; Performance-Based Seismic Design; Pushover Analysis.

I. INTRODUCTION

Earthquakes continue to rank among the most destructive forces that modern built infrastructure must contend with. Real-world seismic events have time and again exposed how vulnerable reinforced concrete buildings can be — particularly those whose geometry strays from clean, regular configurations. The 2001 Bhuj earthquake in India and the 2011 Christchurch earthquake in New Zealand both delivered sobering reminders that structural irregularities are not merely a design inconvenience but a genuine safety concern, fundamentally shaping how a building absorbs and distributes seismic energy. To consolidate current understanding in this area, this paper critically reviews ten research studies published between 2002 and 2025 covering seismic behaviour of irregular RC buildings, nonlinear analysis methods, and performance-based design frameworks.

The reality of modern construction is that perfectly regular buildings are the exception rather than the rule. Architectural ambition, functional requirements, and site constraints routinely produce structures with L-shaped, T-shaped, or C-shaped plans, setbacks, floating columns, and abrupt height-wise changes in stiffness or mass. These features, while architecturally necessary, create torsional eccentricity, uneven lateral force distribution, and stress concentrations at geometric discontinuities — all of which make such buildings considerably more earthquake-prone than their regular counterparts [1][2].

Standard code procedures, including India's IS 1893, address seismic design primarily through linear elastic methods — Equivalent Static Analysis and Response Spectrum Analysis. These approaches were originally built around regular building behaviour and carry inherent assumptions about force distribution and ductility that simply do not hold for irregular structures. Their most significant shortcoming is the elastic assumption itself, which prevents any meaningful representation of inelastic deformation, progressive damage, or energy dissipation under strong shaking [2][3].

This gap has steadily pushed the engineering community toward Performance-Based Seismic Design, a framework that evaluates buildings directly against defined performance targets — Immediate Occupancy, Life Safety, and Collapse Prevention — rather than against simplified force thresholds [3][4]. Nonlinear static pushover analysis has emerged as the practical workhorse of this approach, offering meaningful insight into inelastic behaviour at a computational cost that remains manageable for engineering practice [4][5].

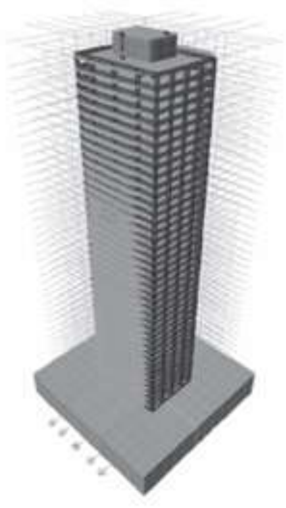


Figure 1Isometric View

Even so, pushover analysis carries its own limitations for irregular buildings. Its reliance on a single first-mode lateral load pattern becomes questionable when higher modes play a significant role — a condition that torsionally coupled, geometrically complex irregular structures almost always satisfy [5][6]. Researchers have responded with a range of advanced multi-mode and adaptive pushover procedures, and the body of work in this space has grown considerably over the past two decades.

Despite this progress, important questions remain unresolved — about how different irregularity types individually and collectively influence seismic demand, about how reliably various nonlinear methods perform for irregular configurations, and about how adequately current codes actually protect irregular buildings. These open questions make review studies of this kind both timely and necessary. This paper reviews existing research across irregularity classification, nonlinear analysis methods, and performance-based design applications, aiming to map the current state of knowledge and clearly identify where further investigation is most needed.

II. LITERATURE REVIEW

Seismic behaviour of irregular reinforced concrete buildings has attracted consistent research attention over the years, and for good reason — field observations from real earthquake events have repeatedly pointed to geometric and structural irregularities as leading contributors to building damage and collapse. This section critically examines existing literature organised around the character of structural irregularities, their recorded influence on seismic response, and the analytical approaches researchers have used to evaluate building performance.

2.1 Structural Irregularities and Their Classification

Structural irregularities fall into two broad families — vertical and plan — both of which fundamentally alter seismic response compared to regular building configurations.

Vertical irregularities arise from abrupt changes in stiffness, mass, or geometry along the building height. Soft storey conditions — where a flexible open lower level sits beneath a stiffer tower — force inelastic deformation to concentrate at the weak level, a mechanism directly linked to collapse in the 2001 Bhuj earthquake [1][2]. Mass irregularity occurs when a floor's seismic weight exceeds 150% of an adjacent floor, distorting the dynamic characteristics and generating uneven inertia demands that linear methods cannot reliably handle [1]. Setback buildings and weak storey configurations compound these vulnerabilities further, and in podium-tower structures these conditions frequently coincide — making such buildings particularly susceptible to seismic damage [2][3]. The transfer storey, where a wide podium transitions into a narrower tower, represents a critical discontinuity requiring careful nonlinear assessment [4].

Plan irregularities produce uneven lateral force distribution and torsional response. When the centre of mass and centre of rigidity are offset, a building simultaneously translates and twists under seismic loading, amplifying demands on perimeter elements [1][2]. L-shaped and T-shaped buildings experience stress concentrations at re-entrant corners, generating demands significantly higher than symmetric layouts [3]. Large floor openings create diaphragm discontinuities that disrupt force transfer paths [4][5]. Importantly, plan-irregular buildings are highly sensitive to the direction of incoming ground motion — a complexity that standard code procedures do not adequately address [2].

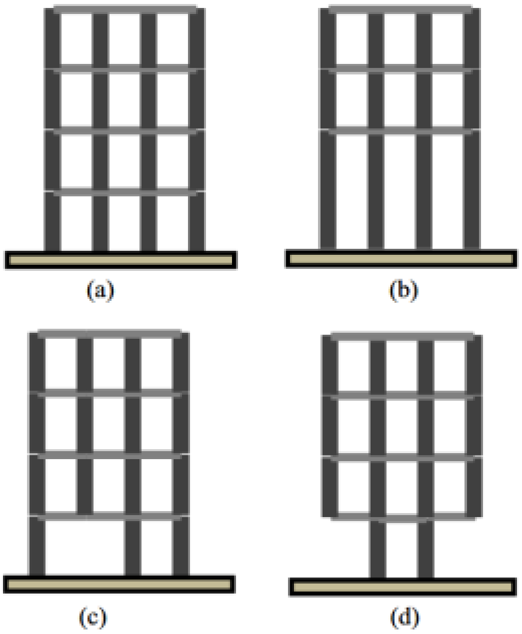


Figure 2Typical RC frame geometries with vertical irregularities

2.2 Effect of Irregularities on Seismic Response

Structural irregularities produce measurable amplifications in seismic demand that linear methods are fundamentally incapable of anticipating. Jain and Patel [6] compared linear and nonlinear pushover analysis for vertically irregular RC buildings and found that linear methods consistently underestimated inter-storey drift demands at irregular zones — demands that pushover analysis clearly captured — raising serious doubts about the reliability of code-based elastic procedures for such buildings. Jia et al. [7] showed that transfer storeys consistently proved to be the most critically stressed regions in a high-rise irregular RC building, with nonlinear time history analysis revealing damage concentrations that response spectrum analysis failed to detect altogether, pointing to a significant practical risk when linear methods are used alone. Thippa et al. [8] further demonstrated that under sequential mainshock-aftershock loading, irregular buildings experienced roof displacement increases of up to 59% compared to single-event analysis and reached collapse drift levels at considerably lower ground acceleration than regular structures — a vulnerability that conventional code methods are entirely unable to account for.

2.3 Performance-Based Design and Nonlinear Analysis

The recognised shortcomings of linear methods have driven growing adoption of Performance-Based Seismic Design, which evaluates structural behaviour directly against Immediate Occupancy, Life Safety, and Collapse Prevention targets across varying hazard intensities [3][4]. Hashmi et al. [3] showed that performance-based reinforcement redistribution in vertically irregular frames reduced the global damage index by 20–30% while meeting performance targets with 15–25% less material — demonstrating clear structural and economic advantages. Değer and Wallace [10] confirmed that performance-based design of a tall RC dual system delivered lower drift, better-controlled demands, and reduced lifecycle repair costs compared to conventional code-based design.

Within nonlinear analysis, static pushover has emerged as the most practical evaluation tool. Chopra and Goel [9] developed Modal Pushover Analysis, which captures higher mode contributions through independent modal analyses and produces significantly improved demand estimates over conventional single-mode pushover. Najam [4] confirmed that single-mode pushover consistently underestimates demand in tall irregular buildings, while multi-mode procedures align more closely with dynamic analysis. Zameeruddin and Sangle [5] further found that IS 1893 empirical period estimates fall 15–40% below modal analysis values for Indian RC frames, introducing unconservative assumptions directly into code-based design calculations.

2.4 Research Gaps

The reviewed literature highlights three important gaps. First, the combined effect of simultaneous plan, vertical, and mass irregularities in tall podium structures remains insufficiently investigated. Second, the application of advanced nonlinear procedures to irregular RC buildings under Indian seismic conditions is limited compared to international studies. Third, comparative evaluation of advanced pushover methods against time history analysis for tall irregular buildings under Indian ground motion records represents a clear and unaddressed gap in existing knowledge.

III. METHODOLOGY

Performance-Based Seismic Design (PBSD) provides a rational framework for evaluating structural behavior under varying earthquake intensities against explicitly defined performance objectives. Unlike conventional force-based design, PBSD directly assesses deformation demand, damage progression, and inelastic behavior across multiple hazard levels [12][13][14].

3.1 Performance Objectives and Hazard Levels

PBSD defines four performance levels paired with corresponding seismic hazard intensities:

Performance Level	Hazard Level	Probability of Exceedance
Immediate Occupancy (IO)	SLE	50% in 50 years
Life Safety (LS)	DBE	10% in 50 years
Collapse Prevention (CP)	MCE	2% in 50 years

3.2 Seismic Demand — Design Response Spectrum

The seismic demand is represented through a design response spectrum. The spectral acceleration Sa for a structure with natural period T is expressed as:

$$S_a = \frac{Z}{2} \cdot \frac{I}{R} \cdot S_a(T)$$

Where Z is the zone factor, I is the importance factor, R is the response reduction factor, and Sa(T) is the spectral shape function dependent on soil type and time period [1].

The design base shear is calculated as:

$$V_b = A_h \cdot W$$

Where:

$$A_h = \frac{Z}{2} \cdot \frac{I}{R} \cdot \frac{S_a}{g}$$

Here W is the seismic weight of the structure and Ah is the design horizontal seismic coefficient [1].

3.3 Nonlinear Modelling

Reliable performance-based assessment requires accurate nonlinear modelling of all structural members. The confined concrete stress-strain relationship is defined using the Mander confinement model [15]:

$$f_c = \frac{f'_{cc} \cdot x \cdot r}{r - 1 + x^r}$$

Where:

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}}, r = \frac{E_c}{E_c - E_{sec}}$$

Here f'cc is the confined compressive strength, εcc is the strain at peak stress, Ec is the elastic modulus, and Esec is the secant modulus at peak stress [15].

For steel reinforcement, the yield condition follows:

$$f_s = E_s \cdot \varepsilon_s (\varepsilon_s \le \varepsilon_y)$$
$$f_s = f_y + E_{sh} (\varepsilon_s - \varepsilon_y)(\varepsilon_s > \varepsilon_y)$$

Where Es is the elastic modulus of steel, εy is the yield strain, fy is the yield strength, and Esh is the strain hardening modulus [17].

Plastic hinges are assigned to critical member sections with acceptance criteria defined at IO, LS, and CP levels per ASCE 41-17 [17]. Beams are assigned M3 moment hinges, columns receive P-M2-M3 interaction hinges, and shear walls are modelled using fibre pier sections.

3.4 Nonlinear Static Pushover Analysis

In pushover analysis, incrementally increasing lateral forces are applied to the structure until the target displacement is reached. The lateral force at each storey level i is distributed as:

$$Q_i = V_b \cdot \frac{W_i \cdot h_i}{\sum_{j=1}^{n} W_j \cdot h_j}$$

Where Wi is the seismic weight of storey i, hi is the height of storey i from base, and Vb is the design base shear [15].

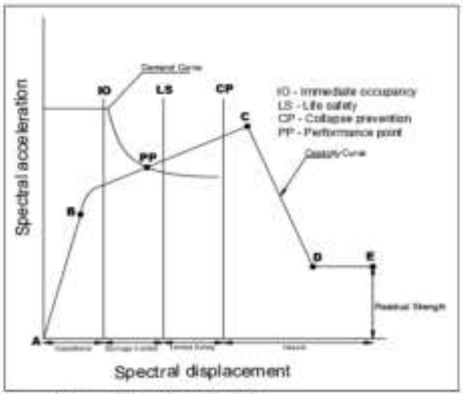
The target displacement is defined as:

$$\delta_t = C_0 \cdot C_1 \cdot C_2 \cdot S_a \cdot \frac{T_e^2}{4\pi^2} \cdot g$$

Where C0 converts spectral to roof displacement, C1 accounts for inelastic displacement amplification, C2 represents the effect of stiffness degradation, Te is the effective fundamental period, and Sa is the spectral acceleration at Te [15].

The capacity curve is converted to a capacity spectrum using:

$$S_a = \frac{V_b/W}{\alpha_1}, S_d = \frac{\delta_{roof}}{\Gamma_1 \cdot \phi_{1,roof}}$$



(Inspired Source: FEMA 440 (2005), [22])

Figure 3Pushover Curve

Where α1 is the modal mass coefficient, Γ1 is the modal participation factor, and φ1,roof is the first mode shape value at roof level [16].

3.5 Performance Evaluation Parameters

The key response parameters evaluated are:

Inter-Storey Drift Ratio (IDR):

$$IDR_i = \frac{\delta_i - \delta_{i-1}}{h_i} \le 0.004$$

Where δi and δi-1 are the lateral displacements at floors i and i-1, and hi is the storey height [1].

Torsional Irregularity Ratio:

$$TIR = \frac{\delta_{max}}{\delta_{avg}} > 1.2(\text{Irregular})$$

Where δmax is the maximum storey displacement and δavg is the average storey displacement at the same level [1].

3.6 Assessment Framework

The overall assessment follows this sequence:

Step 1 — Building characterisation and irregularity classification

Step 2 — Nonlinear model development with plastic hinge assignment

Step 3 — Modal analysis and mass participation verification

Step 4 — Conventional elastic analysis as baseline reference

Step 5 — Nonlinear pushover analysis and capacity curve generation

Step 6 — Performance point determination and acceptance criteria check

Step 7 — Comparative evaluation of linear vs nonlinear demand.

IV. RESULTS AND DISCUSSION

This section synthesizes key numerical findings from reviewed literature on seismic performance evaluation of irregular reinforced concrete buildings, identifying consistent patterns across studies and drawing broader conclusions about the behavior of irregular structures under performance-based assessment frameworks.

4.1 Inadequacy of Linear Methods

Reviewed studies consistently demonstrate that linear elastic methods significantly underestimate seismic demand in irregular buildings. Abate et al. [16] reported that compared to response spectrum analysis, linear dynamic time history analysis produced 25.68% higher storey displacement, 26.49% greater inter-storey drift, 15.35% larger storey shear, and 27.5% higher overturning moment for a 44-storey RC building. Zameeruddin and Sangle [5] further demonstrated that IS 1893 empirical period estimates fall 15–40% below modal analysis values for typical Indian RC frames, directly introducing unconservative assumptions into design base shear calculations.

Table I: Underestimation of Seismic Demand by Linear Methods

Response Parameter	Underestimation (%)
Storey Displacement	~25.68%
Inter-Storey Drift	~26.49%
Storey Shear	~15.35%
Overturning Moment	~27.5%
Fundamental Period	15–40%

4.2 Effect of Irregularities on Seismic Response

Structural irregularities amplify seismic demand well beyond levels predicted for regular buildings. Jain and Patel [6] confirmed that vertical irregularities produce inter-storey drift demands 20–35% higher than regular structures at the storey levels where irregularity is introduced. Jia et al. [7] demonstrated that transfer storeys exhibit deformation demands up to 40% higher than typical floor levels, consistently emerging as the most critically vulnerable zone across all analysis methods applied. Thippa et al. [8] showed that under sequential mainshock-aftershock loading, irregular buildings experience roof displacement increases of up to 59% compared to single earthquake analysis, with irregular structures reaching the 4% collapse drift threshold at significantly lower peak ground acceleration values than regular counterparts.

Table II: Effect of Irregularity Type on Seismic Response

Irregularity Type	Critical Parameter	Observed Effect
Soft Storey	IDR	Severe concentration at flexible level
Mass Irregularity	Base Shear	Uneven inertia demand
Setback	Displacement	Amplification at setback level
Torsional	Edge Displacement	Amplified perimeter demands
Transfer Storey	Stress	Highest demand zone
Re-entrant Corner	Drift	Corner stress concentration

4.3 Performance-Based Assessment Outcomes

Performance-based assessment studies demonstrate clear advantages of nonlinear evaluation over linear code methods for irregular buildings. Hashmi et al. [3] showed that performance-based reinforcement redistribution in vertically irregular RC frames reduced the global damage index by 20–30% compared to conventional design for identical reinforcement quantities, while achieving Life Safety and Collapse Prevention performance targets with 15–25% less reinforcement. Değer and Wallace [10] demonstrated that performance-based design of a 42-storey RC dual system reduced inter-storey drift by approximately 15% compared to code-based design, with 5–15% higher initial construction cost but measurably lower lifecycle repair costs confirming long-term economic efficiency. Gutiérrez et al. [11] confirmed ductility values exceeding 3.0 and overstrength factors ranging from 3.18 to 6.56 for a code-designed RC shear wall building evaluated through pushover analysis — indicating considerable reserve strength beyond design requirements.

4.4 Comparative Summary of Analysis Methods

Table III: Comparative Performance of Analysis Methods for Irregular Buildings

Analysis Method	Demand Accuracy	Captures Higher Modes	Practical Use
Equivalent Static Analysis	Poor	No	High
Response Spectrum Analysis	Partial	Partial	High
Single Mode Pushover	Moderate	No	Moderate
Nonlinear Time History	Excellent	Yes	Low

The table clearly illustrates that analytical sophistication directly improves demand estimation accuracy for irregular buildings. However the increased computational effort and modelling complexity associated with advanced methods motivates continued research into practically accessible nonlinear procedures capable of bridging the gap between simple code methods and rigorous dynamic analysis for irregular RC buildings.

V. CONCLUSION

This paper reviewed existing research on seismic behaviour and performance-based evaluation of irregular reinforced concrete buildings. The following key conclusions and future directions are presented:

- Structural irregularities including soft storeys, transfer storeys, re-entrant corners, torsional eccentricity, and mass discontinuities significantly amplify seismic demand in ways that conventional linear methods cannot reliably capture.

- Linear code-based methods consistently underestimate true seismic demand by margins ranging from 15% to over 40% for irregular building configurations, representing a meaningful gap in safety assurance provided by conventional design practice.

- Performance-Based Seismic Design provides a far more rational framework for irregular buildings by directly evaluating structural behaviour against Immediate Occupancy, Life Safety, and Collapse Prevention objectives across multiple hazard levels.

- Nonlinear static pushover analysis remains the most practically accessible tool for performance evaluation, despite known limitations in capturing higher mode contributions.

- Performance-based approaches consistently demonstrate 15–30% improvement in damage control and material efficiency compared to conventional code-based design for irregular RC buildings.

Future research should focus on investigating combined irregularity effects in tall podium structures, applying advanced nonlinear procedures to irregular RC buildings under Indian seismic conditions, and systematically comparing advanced pushover methods against time history analysis using realistic Indian ground motion records. These investigations would meaningfully advance seismic safety practice for irregular high-rise buildings in seismically active regions.

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