The Overstrength Paradox: A Case Study on Code-Induced Performance Inversion in Torsionally Irregular RC Frames

Deepak Mishra[1] and Jaspreet Kaur[1]

[1]CT University, Department of Civil Engineering, Ludhiana, Punjab, India
deepakmishra618@hotmail.com

Abstract. Background: Seismic codes prescribe member oversizing to mitigate torsional irregularity. This case study documents the "Overstrength Paradox"—observed within a controlled boundary (six-story RC SMRF, unidirectional pushover)—where code-mandated stiffness enhancements altered the failure hierarchy for the specific configuration examined. Methods: A parametric numerical investigation on a six-story RC SMRF (IS 1893:2016, IS 13920) evaluated three variants—non-compliant, analytically amplified (design eccentricity), and geometrically upsized—via nonlinear static pushover analysis (ASCE 41-13). Seismic demand was scaled using Importance Factor (I = 1.0, 1.5, 2.0). Results: At I=1.0, the torsion-compliant structure exhibited high overstrength (Ω = 6.56–7.59) yet showed shear-critical collapse (D/C ≈ 1.19) despite code-compliant shear reinforcement. At I=2.0, it sustained moderate overstrength (Ω = 3.07–3.49) but achieved Immediate Occupancy through ductile flexural action. This inversion confirms linear force-scaling fails to yield proportional safety margins in overstrength-stiffened asymmetric systems. Conclusions: For the specific configuration examined, seismic safety depended on demand-activated ductile pathways rather than nominal reserve strength. These findings serve as a documented diagnostic indicator of hierarchy vulnerability. The mechanism may generalize to other plan-irregular systems but requires systematic validation.

Keywords: Overstrength Paradox, torsional irregularity, performance inversion, pushover analysis, Importance Factor.

Nomenclature

Greek Symbols
Ω(I) = Demandconditioned overstrength factor (diagnostic indicator); Ω(I) = V_u(I)/V_d(I)
Ω = Classical structural overstrength (invariant material property)
Note: Ω(I) incorporates mass scaling to capture the interaction between codeprescribed demand and structural capacity. It is a diagnostic tool, not a traditional performance metric.

Roman Symbols
V_d(I) = Elastic design base shear for Importance Factor I
V_u(I) = Ultimate base shear capacity with seismic mass scaled by I
D/C = Demandtocapacity ratio (e.g., shear D/C = V_demand/V_capacity)

ASCE 41-13 Hinge Performance Levels
G = Immediate Occupancy | Y = Life Safety | R = Collapse Prevention

Abbreviations
CM = Center of Mass
CR = Center of Rigidity
I = Importance Factor (IS 1893:2016)
PBSD = PerformanceBased Seismic Design
RC = Reinforced Concrete (τc = design shear strength of concrete, N/mm²)
SMRF = Special MomentResisting Frame
A_sv = Area of shear reinforcement (mm²), S = Spacing of reinforcement (mm)

1. Introduction

The seismic vulnerability of planirregular structures due to torsional coupling is well established. Major forcebased codes (ASCE 7, Eurocode 8, IS 1893) address this through linear scaling of design forces via importance factors and prescriptive torsioncontrol measures such as member oversizing or amplified eccentricities.

While each provision is rational in isolation, their nonlinear interaction—and combined effect on the strengthductility hierarchy in RC moment frames—remains a critical, unquantified gap. This study investigates a counterintuitive outcome emerging from this gap, termed the "Overstrength Paradox": codecompliant designs for torsional irregularity can exhibit a seismic performance inversion. Under standard designlevel intensity (I = 1.0), the structure exhibits shearcritical response, while under higher parametric demand (I = 2.0), it sustains designlevel demand elastically and fails through a ductile global mechanism.

To isolate this phenomenon, a parametric study within a Performance Based Seismic Design framework analyzes three configurations of a sixstory RC SMRF:

A Noncompliant model violating torsional irregularity limits.
A Compliant model redesigned via member oversizing (analyzed under I = 1.0, 1.5, and 2.0).
A Design Eccentricity model applying codeprescribed accidental torsion.

Seismic demand is scaled via the Importance Factor I. A diagnostic shear capacity check excluding shear reinforcement isolates hierarchy effects, while a complementary calculation including shear reinforcement per IS 13920 assesses realistic SMRF behavior (Section 3.7).

Results reveal a performance inversion for the specific configuration and parametric range examined. Oversizing for torsional compliance creates localized overstrength that, at lower I, pairs with lower reinforcement to cause shearcritical response. At higher intensity (I = 2.0), altered internal force distribution mobilizes flexural reserve, yielding a ductile collapse mechanism despite lower calculated overstrength (Ω). These findings suggest linear force amplification and geometric compliance may not linearly enhance safety in torsioncompliant irregular systems. True seismic safety depends on demandinduced activation of ductile mechanisms, not merely reserve strength magnitude.

1.1 Research Objectives

This study aims to:
Determine whether codeprescribed member oversizing for torsional compliance creates a seismic performance inversion in the case examined.

Examine the interaction between the Importance Factor (I) and codeinduced overstrength in governing nonlinear response.

Evaluate implications for forcebased seismic design and propose codeprovision considerations.

1.2. Scope and Limitations

This is a focused parametric investigation of a single sixstory RC frame. Findings are based on nonlinear static pushover analysis, which does not capture dynamic effects, highermode contributions, or cyclic degradation. The parametric I = 2.0 exceeds code ranges and serves as an upperbound probe, not a design recommendation. Generalization requires additional cases and nonlinear response history analysis. Note on Terminology: $\Omega(I) = V\_u(I)/V\_d(I)$ is used as a demandconditioned diagnostic indicator, not a classical strength metric. Unlike invariant overstrength Ω_0 (isolating material and geometric reserve), Ω(I) incorporates massscaling effects prescribed by the Importance Factor, capturing the interaction between codeprescribed demand intensity and structural capacity. The authors do not claim Ω(I) is equivalent to traditional overstrength; it serves to diagnose the performance inversion central to this study.

2. Literature review

PerformanceBased Seismic Design (PBSD) and pushover analysis are established for postelastic evaluation, but torsional effects complicate their application to irregular buildings (De Stefano & Pintucchi, 2008; Kumar & Paul, 2023). Prescriptive code approaches to torsion control—primarily linear demand scaling and member oversizing—concentrate overstrength in perimeter elements, often creating unintended vulnerabilities (Sharma et al., 2022; Patel & Desai, 2021). While general overstrength enhances collapse resistance (Liel et al., 2011; Franchin & Pinto, 2023), its concentration can fundamentally alter failure hierarchies—promoting shear before flexural yielding and violating the strongcolumnweakbeam principle (Paulay, 2001; Das & Choudhury, 2021).

A key untested assumption is that linear scaling of design forces via importance factors proportionally increases safety margins (Suresh & Bai, 2016; Khadka & Shrestha, 2023). This may not hold in overstrengthened, torsionally stiff systems where failuremode transitions dominate response (Ghosh & Sharma, 2020; Sullivan et al., 2022). Latest standards (ASCE/SEI 41-23, FEMA P-2012) emphasize deformationbased evaluation but do not explicitly address demanddependent activation of reserve strength in torsioncompliant systems.

Pushover analysis, while limited in capturing full torsional coupling (Chopra & Goel, 2004; Bhosale et al., 2023), remains valuable for comparative parametric studies of yield mechanisms (Fajfar & Kreslin, 2012). A significant gap exists at the intersection of torsional irregularity, linear demand scaling, and complianceinduced overstrength. This raises a pivotal question: can codeprescribed strength enhancements for torsion control lead to a paradoxical outcome where increased seismic intensity improves nonlinear performance? This "Overstrength Paradox" has not been systematically investigated—a gap this study fills.

3. Methodology

3.1 Analytical Models and Design

The research workflow, structured as a three-track process, is illustrated in Figure 1: (1) Model Development and Design, (2) Parametric Demand Scaling (applied to the Compliant Model), and (3) Nonlinear Performance Evaluation via Pushover Analysis.

3.2 Analytical Models and Torsion-Control Design

This study does not claim to have systematically varied aspect ratios, framing layouts, or material grades across a design-of-experiments matrix. The investigation focuses on a single six-story frame configuration, with the parametric variability limited to the Importance Factor (I = 1.0, 1.5, 2.0) and the three compliance strategies (Non-compliant, Design Eccentricity, Compliant). The sensitivity of the paradox to geometric and material parameters is discussed qualitatively in Section 5.0 but is not quantitatively established in this study.

Three ETABS models of a six-story RC SMRF were developed per IS 456:2000 and IS 1893:2016, sharing the same geometry, materials, and gravity loads (Table 1) but differing in torsion-control approach:
Non-compliant Model: Baseline design violating torsional irregularity limits (eccentricity ratio > 1.5) without member oversizing.
Compliant Model: Perimeter and interior columns were upsized iteratively to achieve

eccentricity ratio ≤ 1.5 and meet static eccentricity criteria. The same resized geometry was analyzed under three seismic demand levels (I = 1.0, 1.5, and 2.0) by scaling the Importance Factor. Accidental torsion was applied per IS 1893 Clause 7.9.2. Design Eccentricity Model: The non-compliant geometry was analyzed with seismic loads applied at the code-prescribed design eccentricity e_d = max (1.5e_s ± 0.05L, e_s ∓ 0.05L), representing the analytical torsion-control method versus geometric oversizing. Initial and final layouts are shown in Figures 2 and 3.

Table 1: Model parameters and design configurations

Parameter	Specification
Plan dimensions:	11.6 m × 9.995 m
Story height:	2.85 m
Slab thickness:	125 mm
Beam sizes:	230 × 355 m, 300 × 425 mm
Column sizes:	Initially 350 × 350 mm; adjusted to 450×500 mm and 450 × 550 mm for torsion compliance
Concrete strength:	M25 (fck = 25 MPa)
Reinforcement steel:	Fe 500 (fy = 500 MPa)
Design Code:	IS 456, IS 1893-2016
Seismic Zone / Soil Type	V / Soft Soil

3.3 Torsional Irregularity Assessment and Compliance

The torsional irregularity was assessed per IS 1893 by the ratio of maximum to minimum story displacement (Δ_max/Δ_min) at each story floor level. The Non-compliant model exceeded the code limit of 1.5 (Y-direction ratios: 1.65–1.70), confirming significant irregularity. For the Compliant model, an iterative redesign process—upsizing perimeter and interior columns—successfully reduced the Y-direction ratios to a compliant range of 1.27–1.42 (Table 2). A stricter target of controlling the static center-of-mass to center-of-rigidity (CM-CR) eccentricity to within ±5% of the plan dimension was also achieved, ensuring a clear margin against the code threshold.

Table 2: Torsional Irregularity Ratios (Δ_max/Δ_min) for the Noncompliant Model and Compliant Model in the X and Ydirections.

Story	Non-Compliant Model Torsion ratio (X)	Non-compliant Model Torsion ratio (Y)	Compliant Model Torsion ratio along-X	Compliant Model Torsion ratio along-Y

Story-6	1.10	1.69	1.12	1.42
Story-5	1.10	1.69	1.12	1.42
Story-4	1.10	1.70	1.12	1.41
Story-3	1.10	1.69	1.12	1.40
Story-2	1.10	1.69	1.13	1.37
Story-1	1.10	1.65	1.13	1.27

The non-compliant model, designed with 350×350 mm columns for strength, exhibited significant torsional irregularity (Δ_max/Δ_min > 1.5). CM-CR eccentricities exceeded 11% in some stories (detailed in Table 3), further confirming non-compliance.

Table 3: CM_CR Eccentricity Percentage before Column Resizing (Non-Compliant Model)

Story	XCM(m)	YCM(m)	XCR(m)	YCR(m)	xcm-xcr	ycm-ycr	Ex%	Ey%
Story6	-1.704	1.484	-2.797	1.650	1.093	-0.166	9.422	-1.660
Story5	-1.737	1.556	-2.804	1.657	1.068	-0.101	9.203	-1.014
Story4	-1.737	1.556	-2.806	1.664	1.069	-0.108	9.212	-1.078
Story3	-1.737	1.556	-2.781	1.668	1.044	-0.112	9.003	-1.122
Story2	-1.397	1.382	-2.695	1.669	1.299	-0.287	11.195	-2.873
Story1	-1.431	1.324	-2.443	1.675	1.012	-0.351	8.722	-3.511

Note: The plan dimensions are Lx = 11.60 m (length along the X-direction) and Ly = 9.995 m (length along the Y-direction). The eccentricity percentages (Ex%, Ey%) are calculated as (Eccentricity / Plan Dimension) × 100. Ex% = (xcm - xcr) / Lx × 100; Ey% = (ycm - ycr) / Ly × 100.

Compliant Model Design Process:

The compliant model was redesigned iteratively to achieve torsional irregularity limits (Δ_max/Δ_min ≤ 1.5), with a stricter target of maintaining static CM-CR eccentricity within ±5% of the plan dimension in the Y-direction. Selective column upsizing—with final dimensions up to 450 × 550 mm—reduced torsional ratios to 1.27–1.42 and eccentricities within the ±5% target (Table 4). This stiffness-driven oversizing imparted significant latent overstrength beyond strength demands.

Table 4: CM_CR Eccentricity Percentage after Column Resizing (Compliant Model)

Story	XCM(m)	YCM(m)	XCR(m)	YCR(m)	xcm-xcr	ycm-ycr	Ex%	Ey%
Story6	-1.638	1.497	-2.211	1.741	0.573	-0.243	4.942	-2.433
Story5	-1.646	1.572	-2.140	1.753	0.494	-0.180	4.261	-1.805
Story4	-1.646	1.572	-2.061	1.766	0.416	-0.193	3.584	-1.934
Story3	-1.646	1.572	-1.914	1.781	0.268	-0.209	2.312	-2.088
Story2	-1.312	1.406	-1.614	1.802	0.302	-0.395	2.600	-3.956
Story1	-1.344	1.352	-1.001	1.841	-0.343	-0.489	-2.957	-4.891

Note: The plan dimensions are Lx = 11.60 m (length along the X-direction) and Ly = 9.995 m (length along the Y-direction). The eccentricity percentages (Ex%, Ey%) are calculated as (Eccentricity / Plan Dimension) × 100.
Ex% = (xcm - xcr) / Lx × 100; Ey% = (ycm - ycr) / Ly × 100.

A third model utilized the non-compliant geometry but applied seismic loads at the design eccentricity per IS 1893 Clause 7.9.2: e_d = max, simulating code-prescribed torsion amplification. This represents the code's analytical workaround, enabling comparison with the geometric approach of member oversizing.

3.4 Mass Based Demand Scaling and Parametric Investigation

To reflect real design practice where higher importance categories scale both seismic mass and spectrum, this study adopts mass-based demand scaling. The resulting demand-conditioned overstrength factor $\Omega(I)$ captures system-level performance under prescribed importance scaling rather than isolating material overstrength.

A parametric investigation was conducted on a fixed geometry (determined by torsional compliance) with reinforcement designed separately for I = 1.0, 1.5, and 2.0 using Response Spectrum Analysis. This isolates the effect of demand intensity on system behavior by decoupling stiffness-driven geometry from strength-adjusted reinforcement, testing whether linear force scaling yields proportional safety improvements.

3.5 Analytical Framework

Ω(I) is a system-level diagnostic ratio incorporating scaled mass and demand—not a classical strength metric. It captures the changing demand-to-capacity relationship across intensities, not intrinsic strength changes.

Nonlinear static pushover analysis (ASCE 41-13) used design spectra and seismic mass scaled by I. Standard IS 1893 values were extended to include a parametric I = 2.0 as an upper-bound probe. Baseline analyses of Non-compliant and Design Eccentricity models at I = 1.0 were performed, while the Compliant Model was analyzed at I = 1.0, 1.5, and 2.0. The diagnostic overstrength factor $\Omega(\mathrm{I}) = \mathrm{V_u}(\mathrm{I})/\mathrm{V_d}(\mathrm{I})$ was calculated for each intensity, with P-Delta effects included.

3.6 Compliant Model Design Assumptions

Three Compliant Model designs were generated with reinforcement sized for I = 1.0, 1.5, and 2.0, while cross-sectional dimensions remained fixed. For pushover, mass and spectrum were scaled by the corresponding I, revealing interactions between latent overstrength and designed strength. Results are summarized in Table 5.

Table 5: Design base shear values, overstrength factors (Ω), and failure diagnoses for the Compliant Model.

Model (I)	Dir.	Design V_d (kN)	Ultimate V_u (kN)	Ω	Failure Diagnosis
Compliant (1.0)	X	444.52	2919.12	6.56	Brittle Shear - High Ω negated by shear failure.
	Y	506.16	3845.15	7.59	Brittle Shear - High Ω negated by shear failure.
Compliant (1.5)	X	666.79	2843.53	4.26	Brittle Shear - High Ω, but shear-critical.
	Y	759.24	1817.04	2.39	Severe Brittle Shear - Low Ω confirms minimal reserve.
Compliant (2.0)	X	889.05	3105.14	3.49	Ductile Flexural -

	Y	1012.32	3116.31	3.07	Adequate Ω, shear capacity sufficient. Ductile Flexural - Adequate Ω, shear capacity sufficient.

Note: The Non-Compliant (NC) and Design Eccentricity (DE) variants are included for baseline configuration profiling only. These models are explicitly excluded from subsequent parametric Importance Factor (I) scaling because their initial geometries fail to satisfy the prescriptive torsional irregularity threshold (max/min displacement ratio <= 1.50) required by IS 1893:2016 under standard design-level shaking.

3.7 Pushover Analysis Procedure

Nonlinear static pushover analysis was conducted independently along the principal orthogonal axes using lateral load patterns proportional to the fundamental mode shape corresponding to each seismic Importance Factor (I). Default flexural hinge properties per ASCE 41-13 were assigned to beam and column cross-sections. Structural performance was quantified by tracking plastic hinge progression through the Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) limit states, alongside global base shear versus roof displacement capacity curves.

Local shear failure mechanisms were evaluated by evaluating demand-to-capacity ratios (Vd/Vc) at the performance points per IS 456:2000. Performance points were isolated via the Capacity Spectrum Method (ASCE 41-13) at the intersection of the structural capacity curves and demand response spectra. This integrated tracking framework—combining kinematic hinge progression, capacity curves, and local shear demands—isolates the macro-level performance inversion driving the Overstrength Paradox.

3.7.1 Detailed Shear Capacity Evaluation Including Transverse Reinforcement
To evaluate local failure hierarchies against code-compliant detailing, the total nominal shear capacity of the critical column (C18, 450×550 mm) was calculated per IS 456:2000, incorporating transverse reinforcement per IS 13920 (8 mm, 2-legged stirrups @ 150 mm c/c).
Concrete contribution (Vc,conc): For M25 concrete with 1.0% steel, τ_c = 0.64 N/mm² (IS 456:2000, Table 19). With b = 450 mm, d = 500 mm:
Vc,conc = 0.64 × 450 × 500 = 144.0 kN
Steel contribution (Vs): Asv = 100.53 mm², fy = 500 MPa, s = 150 mm:

Vs = 0.87 × 500 × 100.53 × 500 / 150 = 145.8 kN
Total nominal shear capacity: Vc = 144.0 + 145.8 = 289.8 kN

Performance Point Shear Demands (Vd):
I = 1.0: 345.56 kN
I = 1.5: 345.56 kN
I = 2.0: 357.31 kN

Demand-to-Capacity Ratios:
I = 1.0: 345.56 / 289.8 = 1.19
I = 1.5: 345.56 / 289.8 = 1.19
I = 2.0: 357.31 / 289.8 = 1.23

Mechanism Assessment: Despite the significant increase in nominal shear capacity with ductile confinement stirrups, D/C ratios persistently exceed unity (1.19) at design-level intensities (I = 1.0 and 1.5). This confirms that the performance inversion stems from a systemic hierarchy flaw driven by code-prescribed column upsizing—not detailing deficiencies. The severe stiffness imbalances introduced by prescriptive geometry controls govern internal force distribution so profoundly that standard detailing cannot neutralize the brittle shear-critical vulnerability at design-level demands.

4. Results and discussion

4.1 Hinge Progression and Performance Inversion

Hinge progression quantitatively evidences the Overstrength Paradox: nonlinear safety improves with increased seismic intensity despite a decrease in Ω(I), directly challenging force-based linear scaling assumptions.

In the Compliant Model, at I=1.0, Collapse Prevention (CP) hinges form at the Performance Point—negligible safety margin under code-level demand. At I=2.0, the model remains elastic at the Performance Point (Immediate Occupancy) and develops a ductile, globally redistributing hinge pattern—contradicting the expectation that higher intensity reduces safety.

Member oversizing for torsion control creates concentrated overstrength analogous to Ω in ASCE 7. However, this compliance-induced overstrength remains latent at standard intensities, becoming beneficial only when higher demand activates a ductile hierarchy. Thus, a structure can satisfy all prescriptive checks yet remain shear-critical—challenging a fundamental force-based design assumption.

High Ω (6.56–7.59) at I=1.0 coincides with shear-critical response, while lower Ω (3.07–3.49) at I=2.0 yields ductile response (Tables 5–6). Safety depends more on the demand pathway mobilizing reserve strength than on its magnitude. This inversion persists even with code-compliant shear reinforcement (D/C≈1.19), confirming a systemic

Vol. 1, Issue 2, July 2026
e-ISSN: 3139-4043

hierarchy issue—not detailing omission. Ductile detailing rules act as localized correctives but cannot override the macro-level failure hierarchy established by geometric prescriptions.

Table 6: Hinge progression from Performance Point to Final State for each model and demand level

Demand Level	Hinges at P.P.(R/Y/G) Count	Intermediate Step (R/Y/G) Count	Ultimate State (R/Y/G) Count	Behavioral Interpretation
Non-compliant model (I=1.0)	No Hinges (Elastic)	X=2R+9G Y=3R+11G	X=3R+10G Y=7R+25G	Flexuregoverned yielding despite irregularity.
Design Eccentricity Model (I=1.0)	X=1R Y:No Hinges	X=7R+14G Y:No Hinges	X=23R,+26G, Y=1G	Codal torsional yielding – Brittle failure in Xdirection; Ydirection elastic.
Compliant Model (I=1.0)	X=5R Y=1R	X=5R+8G Y=2R+7G	X=6R+10G, Y=4R+24G	Brittle shear failure – Severe damage at design demand; nonductile collapse.
Compliant Model (I=1.5)	X=5R Y=1R	X=7R+7G Y=1R	X=7R+9G, Y=1R	Transitional brittle failure – Slight ductility gain; still shearcritical.
Compliant Model (I=2.0)	No Hinges (Elastic)	X:1R+9G, Y=No Hinge	X:1R+11G, Y=5R	Ductile global mechanism – Performance inversion: elastic at design demand, progressive failure.

Note (a): R = Collapse Prevention, Y = Life Safety, G = Immediate Occupancy (ASCE 41-13).

Note (b): Hinge sequencing for Non-Compliant and Design Eccentricity variants is presented at I=1.0 to demonstrate how column upsizing shifts the failure hierarchy. Even with code-compliant shear reinforcement, hinge progression at I=1.0 remained shear-influenced, confirming detailing alone cannot restore ductile hierarchy. Table 7 quantifies the paradox across approaches: both compliant strategies at I=1.0—analytical torsion amplification and geometric oversizing—achieve only Collapse Prevention with hazardous modes. This suggests code-compliant torsion-control paths can converge on unsafe mechanisms under design-level shaking.
Crucially, the same compliant geometry designed for I=2.0 achieves Immediate Occupancy with a ductile mechanism, despite lower Ω. This inversion directly challenges linear scaling assumptions (ASCE 7 I_e, Eurocode 8 importance classes). Seismic safety in irregular systems depends not on reserve strength magnitude, but on whether demand activates a ductile hierarchy—a condition prescriptive compliance does not guarantee. Torsional irregularity clauses should thus be accompanied by verification of the intended ductile failure hierarchy, potentially requiring performance-based verification for irregular structures.

Table 7: Comparative Performance Summary: Hinge State, Failure Mechanism, and Overstrength Across Design Configurations and Demand Levels

Model & I-value	Hinge State at Performance Point	Dominant Failure Mechanism	Overstrength Factor (Ω)	Performance Level Achieved	Shear D/C Ratio
Non-compliant (I=1.0)	No Hinges (Elastic)	Localized ductile yielding	Not calculated	Immediate Occupancy	-
Design Eccentricity (I=1.0)	CP (X), Elastic (Y)	Brittle torsional (tension uplift)	Not calculated	Collapse Prevention	>1.0
Compliant (I=1.0)	CP	Brittle shear	6.56 (X), 7.59 (Y)	Collapse Prevention	>1.0
Compliant (I=1.5)	CP	Transitional brittle	4.26 (X), 2.39 (Y)	Collapse Prevention	>1.0
Compliant (I=2.0)	IO	Ductile global	3.49 (X), 3.07 (Y)	Immediate Occupancy	>1.0 (Stabilized)

Note: Based on Hinge progression to final state (detailed data in Table 6). CP = Collapse Prevention, IO = Immediate Occupancy.
Table 8: Shear demand/capacity (D/C) ratios for the critical base column. D/C ratios

remain high across intensities (4.27–4.41), but shear demand at I=2.0 stabilizes—increasing only 3.4% despite a 100% intensity rise—enabling ductile global redistribution. Note: Shear capacity Vc was computed conservatively per IS 456:2000 using nominal concrete strength only, excluding shear reinforcement. Stirrup detailing was held constant from I=1.0 to isolate longitudinal strength effects. D/C ratios are diagnostic lower-bound indicators of shear-critical vulnerability, not actual capacities of fully detailed SMRF columns.

Table 8: Shear Demand/Capacity (D/C) Ratios for Critical Columns at Performance Point (X-Direction)

Model & I-value	**Critical Column**	**Shear Demand at P.P., V_d (kN)**	**Shear Capacity Diagnostic, V_c (kN)**	**D/C Diagnostic Ratio**	**Shear Capacity (Actual) V_c (kN)**	**D/C Actual**	**Diagnosis**
Compliant (I=1.0)	Story1, Col C18 (PX)	345.56	81	4.27	289.5	1.19	Shear-Critical (Brittle)
Compliant (I=1.5)	Story1, Col C18 (PX)	345.56	81	4.27	289.5	1.19	Shear-Critical (Brittle)
Compliant (I=2.0)	Story1, Col C18 (PX)	357.31	81	4.41	289.5	1.23	Shear-Critical (Demand Stabilized)

Notes: Diagnostic capacity (V_c = 81 kN) uses nominal concrete strength only (τ_c = 0.36 N/mm²), excluding shear reinforcement—provided as a lower-bound indicator of hierarchy vulnerability. Actual capacity (V_c = 289.5 kN) includes 8 mm diameter 2-legged stirrups @ 150 mm c/c per IS 13920 (A_{sv} = 100.53 mm², s = 150 mm). Full calculation provided in Section 3.7.
Key Finding: Even with code-compliant shear reinforcement, D/C ratios exceed 1.0 across all intensities (1.19–1.23). The shear demand stabilizes at I = 2.0 (only +3.4% vs. I = 1.0), enabling ductile redistribution despite persistent shear-criticality.
The conservative shear capacity (Vc) excluding reinforcement isolates the failure hierarchy imposed by stiffness-driven oversizing. In a fully detailed SMRF, shear reinforcement prevents pure collapse but not the underlying vulnerability: the system

remains shear-compromised at design-level intensity, with ductility only activated under higher demand. This reveals code's reliance on detailing as a corrective bandage for a hierarchy problem created by its own geometric prescriptions.

4.2 Demand-Activated Strength–Ductility Trade-off: Interpreting Ω(I)

The performance inversion is governed by a demand-conditioned interaction between code-induced reserve capacity and scaled inertial forces. Ω(I) values (6.56–7.59 at I=1.0; 3.07–3.49 at I=2.0) represent demand-conditioned overstrength factors—diagnostic indicators of post-elastic pathways, not classical material overstrength (Ω_0).

High nominal overstrength at low intensity fails to guarantee safety when demand paths alter the failure hierarchy, challenging assumptions that overstrength scales linearly with safety. This persists even with code-compliant shear reinforcement (D/C≈1.19), confirming that local detailing cannot restore global ductility when the macro-level hierarchy is compromised.

The mechanism involves a transition from stiffness-dominated to capacity-controlled response:

Stiffness-Dominated State (I=1.0): Prescriptive column upsizing dominates internal force distributions. Forces propagate along rigid geometric pathways, amplifying shear demands and triggering brittle failure before flexural yielding develops—latent overstrength remains unmobilized and ineffective.

Capacity-Driven State (I=2.0): Scaled inertial forces push the structure past localized stiffness barriers, altering moment-to-shear relationships. Critical column shear demands plateau—increasing only 3.4% (345.56 kN to 357.31 kN) despite a 100% intensity increase—permitting force redistribution, activating flexural reserve, and yielding ductile collapse.

Safe ductile mechanisms can be suppressed at standard intensities and activated only under higher demands. True safety depends on the demand-dependent pathway of strength engagement, not nominal reserve magnitude.

Table 9: Performance Metrics at Performance Point (Compliant Model)

I	Base Shear at P.P. X (kN)	Roof Displacement at P.P. X (mm)	Base Shear at P.P. Y (kN)	Roof Displacement at P.P. Y (mm)	Hinge State at P.P.	Safety Level Achieved
1	1418.99	82.74	1836.75	66.51	CP	Collapse Prevention
1.5	1413.51	82.71	1725.17	66.24	CP	Collapse Prevention
2	1611.21	83.27	1884.3	62.93	IO	Immediate Occupancy

Note: P.P. (Performance Point)
Note: Parametric demand scaling and performance point tracking were intentionally restricted to the Compliant Model (CM) to isolate how a structure that fully satisfies code-mandated design-stage stiffness constraints undergoes a post-elastic performance inversion under scaled inertial demands.

4.3 Non-compliant Model Performance

The Non-compliant model achieved a ductile failure mechanism despite significant torsional irregularity ($\Delta_{max}/\Delta_{min}$ = 1.65–1.70), exceeding code limits. The use of smaller, strength-designed columns (350×350 mm) promoted flexural yielding over shear failure, resulting in a progressive hinge pattern (X: 3R + 10G, Y: 7R + 25G). Critically, the model remained fully elastic (no hinges) at the Performance Point under design-level demand (I = 1.0). This demonstrates that torsional irregularity alone does not preclude ductile performance when the member design inherently favors a flexural hierarchy.

These results suggest that member upsizing for torsional compliance may inadvertently suppress this favorable ductile hierarchy, steering designs toward brittle failure—a key insight underpinning the Overstrength Paradox.

4.4 Design Eccentricity Model Performance

The Design Eccentricity model (IS 1893 Clause 7.9.2) exhibited a torsional failure mechanism: concentrated brittle failure in X-direction (23R + 26G) acting as an inelastic "fuse," while Y-direction remained nearly elastic (1G). This code-prescribed analytical approach localizes damage rather than distributing overstrength—resulting in controlled-yet-brittle failure that lacks energy-dissipation capacity and would likely fail Life Safety or Collapse Prevention objectives under actual seismic loading.

4.5 Compliant Model Performance and Inversion Mechanism

The Compliant Model—designed via member oversizing per IS 1893 (analogous to ASCE 7 §12.3.3.1)—exhibits shear-critical response at design-level intensity despite passing all code strength and drift checks. Stiffness-driven oversizing concentrates overstrength in columns, shifting the failure hierarchy from ductile flexural yielding to shear-dominated collapse. This reveals a critical flaw: geometric compliance does not ensure hierarchy compliance, violating the strong-column-weak-beam principle central to modern seismic codes.

The inversion mechanism is demand-dependent: at lower intensities (I = 1.0, 1.5), high stiffness and lower inertial forces promote shear failure. At higher demand (I = 2.0), increased inertia alters moment-shear relationships, mobilizing latent flexural reserve and enabling ductile global mechanisms. Thus, the same geometry with different reinforcement designs exhibits fundamentally different failure hierarchies—a phenomenon force-based design may fail to predict.

This finding implies that torsional compliance verification should include explicit checks of the failure hierarchy, especially when achieved through member oversizing. Without such verification, code-compliant irregular structures may retain hidden vulnerabilities detectable only through nonlinear analysis.

4.5.1 Compliant Model Performance at I = 1.0
The severe damage pattern (X: 6R + 10G, Y: 4R + 24G) confirms shear-critical collapse before flexural yielding could fully develop.

4.5.2 Compliant Model Performance at I = 1.5
The damage pattern (X: 7R + 9G, Y: 1R) indicates slightly improved but still shear-critical response under increased demand.

4.5.3 Compliant Model Performance at I = 2.0
The Compliant Model activates a ductile global mechanism, with widespread hinge formation in the Xdirection (1R + 11G) and concentrated yielding in the Ydirection (5R), indicating full force redistribution. Similar to the Non-compliant model, this configuration exhibited no hinges at the Performance Point, achieving Immediate Occupancy. However, here the elastic response stems from demand-activated mobilization of latent overstrength. The ultimate state reveals a directional failure hierarchy: widespread ductile hinge formation in the more flexible X-direction (1R + 11G), while the stiffer Y-direction remains nearly elastic until ultimate capacity, then yields in a concentrated pattern (5R). This demonstrates that even under high demand, the persistent torsional imbalance governs the sequence and distribution of damage.

This ductile global response is corroborated by local member behavior. As detailed in Table 8, the critical corner column at Story 1 (Column C18) experienced a stabilized shear demand of approximately 357 kN at I = 2.0—a mere 3.4% increase from the demand at I = 1.0, despite the 100% increase in seismic intensity. This plateau in shear force, occurring at a roof displacement that maintained Immediate Occupancy performance (Table 10), signifies the fundamental shift from a brittle, force-controlled state to a stable, ductility-controlled state, confirming the global mechanism shift observed in the hinge progression.

4.6 Directional Vulnerability and Persistent Torsional Imbalance

Beyond the performance inversion, results reveal a consistent directional vulnerability pattern across all models, linked to underlying geometric and stiffness asymmetry. Even after column resizing, the Compliant Model retained notable CM-CR eccentricity (~5% in Y-direction), confirming that member oversizing reduces but does not eliminate torsional imbalance.

Hinge progression across models illustrates this persistent vulnerability: Non-compliant: Flexible X-direction yielded extensively (7R + 25G); stiffer Y-direction remained predominantly elastic (3R + 10G), acting as a torsional restraint.

Design Eccentricity: X-direction acted as a brittle "fuse" (23R + 26G); Y-direction remained nearly undamaged (1G).
Compliant (I=2.0): X-direction developed distributed ductile hinges (1R + 11G); Y-direction remained elastic until immediately preceding collapse, forming 5R hinges abruptly.

This reveals a critical vulnerability: the stiffer Y-direction acts as a torsional backbone, remaining largely elastic, while the more flexible X-direction absorbs most inelastic damage. This inherently coupled damage distribution is overlooked by linear force-based design and inadequately captured by standards (e.g., ASCE/SEI 41-23) that analyze principal directions independently.

Thus, while the Overstrength Paradox reveals demand-dependency of failure hierarchy, persistent directional asymmetry confirms torsional irregularity governs seismic performance even in 'compliant' designs. Code compliance based solely on strength and displacement limits can provide a false sense of security regarding collapse safety.

4.7 Global Force-Deformation Response and the Demand-Dependent Paradox

The global force-deformation behavior provides critical quantitative insight into the Overstrength Paradox. Capacity curves from pushover analysis reveal how demand scaling interacts with inherent capacity to produce the observed performance inversion. These curves enable direct comparison with performance-based acceptance criteria in ASCE/SEI 41-23 and FEMA 356, contextualizing the paradox within established nonlinear evaluation frameworks.

4.7.1 X-Direction Response

Capacity curves for I = 1.0, 1.5, and 2.0 exhibit near-identical initial stiffness and post-yield hardening. Ultimate base shear capacities ($V_u \approx$ 2919–3105 kN) are largely invariant, with minor variations from different failure sequences due to scaled mass distributions, not structural changes.

This consistency confirms that nonlinear response in the more flexible X-direction is governed by inherent, code-induced overstrength, not elastically scaled demand. Linear scaling via the Importance Factor proved ineffective in altering fundamental nonlinear capacity; the system's latent strength dictated ultimate performance independent of input intensity.

4.7.2 Y-Direction Response

In stark contrast, capacity curves in the stiffer Y-direction reveal a decisive performance inversion governed by scaled demand.
I = 1.0: Highest strength ($V_u \approx$ 3845 kN) and largest ultimate displacement (~290 mm), but shear-critical response occurs at the Performance Point, preventing mobilization of ductile reserve.
I = 1.5: Lowest capacity ($V_u \approx$ 1817 kN) and shortest ultimate displacement (~73 mm)—

a direct signature of shear-critical collapse.
I = 2.0: Intermediate strength ($V_u \approx 3117$ kN) and displacement (~111 mm), but the most extended and stable post-yield plateau, indicating superior ductile performance and progressive, redistribution-dominated collapse.
This divergence encapsulates the Overstrength Paradox: I = 2.0 elicits the most ductile response, despite lower $\Omega = 3.07$ than the brittle configuration at I = 1.0.

4.7.3 Interpretation: Demand-Dependent Activation of Mechanisms
The transition from geometry-dominated brittleness at lower intensities to strength-redistribution-dominated ductility at I=2.0 quantifies the Overstrength Paradox. Safe collapse mechanism activation is not automatic; it requires sufficient seismic intensity to engage redundant capacity through flexural, not shear, pathways—directly challenging the linear-scaling premise of force-based codes.

Capacity curves reveal a critical directional discrepancy:
Flexible X-direction: Ultimate shear capacity is largely invariant ($V_u \approx 2900$–3100 kN), governed by inherent overstrength insensitive to demand scaling.
Stiff Y-direction (torsional backbone): Capacity and ductility vary dramatically with I. Strength reaches a brittle minimum at I=1.5 ($V_u = 1817$ kN) yet achieves optimal ductile performance at I=2.0 ($V_u = 3117$ kN), confirming that activation of compliance-induced overstrength is highly demand-sensitive.

Shifts in Performance Point locations (e.g., Y-direction roof displacement decreases from 66.51 mm at I=1.0 to 62.93 mm at I=2.0) confirm that improved performance stems from altered internal force distribution engaging latent overstrength, not from increased capacity.

Core Implication: While global overstrength can render capacity demand-invariant in one direction, safe collapse mechanism activation remains intensely demand-sensitive in the other. The paradox is about the demand-dependent pathway that determines whether code-induced overstrength becomes a liability (promoting brittle shear) or an asset (enabling ductile redistribution).

Code Development Perspective: Prescriptive torsion-control measures must be coupled with verification that the strong-column-weak-beam hierarchy is achievable across the demand range, aligning with performance-based standards (e.g., ASCE/SEI 41-23).

4.8 Drift Analysis: Decoupling Serviceability Limits from Ultimate Safety

Story drift profiles at the performance point (Table 10) quantify the system's transition from geometry-controlled to capacity-controlled behavior.

Drift Thresholds vs. Failure Hierarchy

The IS 1893 drift limit (0.004h = 0.0114 m) is approached at I=1.0 (0.01116 m, 97.9%) but not violated---yet the structure exhibits brittle shear failure. At I=1.5, drift marginally exceeds the limit (0.01144 m) while maintaining its brittle pathway. This reveals a fundamental decoupling: satisfying linear drift boundaries does not guarantee an acceptable post-elastic failure hierarchy. The Non-Compliant model, despite its irregularity, sustains a ductile path without accelerating localized distress.

Drift Evolution as a Mechanism Tracker
Non-linear drift tracking maps the activation of the Overstrength Paradox:
I = 1.0 (Geometry-Controlled): X-direction drift approaches the code limit (0.01116 m), reflecting unmitigated stiffness asymmetry. Rigid geometric paths suppress flexural yielding, triggering premature shear failure while latent overstrength remains unmobilized.
I = 1.5 (Transition): X-drift crosses the boundary (0.01144 m) while Y-drift contracts (0.00627 m). This divergent response indicates localized, asymmetrical hinge engagement—insufficient to alter the brittle path.
I = 2.0 (Capacity-Controlled): Drifts converge toward balanced values (X: 0.00996 m, Y: 0.00923 m), dropping below the limit. This convergence quantifies full mobilization of overstrength, as extreme inertial demands force the structure past localized stiffness barriers, activating a stable, redistribution-dominated flexural mechanism.

This evolution—from geometry-driven brittleness to capacity-driven redistribution—quantifies the Overstrength Paradox. The demand-dependent activation of ductile pathways near standard drift limits confirms that prescriptive serviceability checks cannot ensure acceptable post-elastic performance in irregular configurations, reinforcing the need for performance-based assessment frameworks (e.g., ASCE/SEI 41-23).
Shear Reinforcement and Hierarchy Decoupling
Even with shear reinforcement providing V_c ≈ 289.5 kN, D/C ratios exceeded 1.0 across all I values, confirming that drift compliance and shear reinforcement cannot ensure a ductile collapse mechanism when stiffness-driven oversizing dominates.

Table 10: Story Drift at Performance Point

Importance Factor (I)	**Drift (X-Direction)**	**Drift (Y-Direction)**
Non-compliant model	0.0011673	0.010908
Design eccentricity model	0.009613	0.007206
Compliant Model 1.0	0.01116	0.006875
Compliant Model 1.5	0.011443	0.006265
Compliant Model 2	0.009964	0.009233

Note: Bold values exceed the IS 1893 drift limit of 0.0114 m (0.004h, h=2.85 m) and indicate the direction of maximum drift.

4.9 Sensitivity Considerations and Limitations

The findings should be interpreted in light of key modeling assumptions:
Hinge Modeling: Default ASCE 41-13 flexural hinges simplify shear-flexure interaction; more gradual shear degradation could intensify the paradox.
Load Pattern: Modal-based pushover patterns were used; the persistence of inversion across all I-values suggests robustness to this choice.
Material Model: Elastic-perfectly plastic steel may underestimate strain-hardening, amplifying calculated overstrength—but this would reinforce, not undermine, the paradox.
Generalizability: Quantitative results are specific to this six-story frame, but the identified mechanism—stiffness-driven compliance creating latent, demand-sensitive overstrength—is fundamentally transferable to other plan-irregular systems.
Shear Reinforcement Modeling: Inclusion of IS 13920 shear reinforcement confirms the paradox is a hierarchy issue, not a detailing omission.

Conclusion on Validity: Despite these simplifications, the consistent performance inversion and clear mechanical explanation provide high confidence that prescriptive torsion compliance can create a demand-dependent structural response contradicting linear force-based design assumptions.

4.10 Practical Implications for Seismic Design Practice

The Overstrength Paradox underscores the need for verification beyond prescriptive compliance:
Supplement code checks with targeted pushover analysis for irregular structures with significant oversizing to verify failure hierarchy and ensure shear ratios < 1.0 at the performance point.
Systematically track CM-CR eccentricity, torsional ratios, and estimated overstrength.
Drift reductions >20–30% due to upsizing may signal paradox susceptibility.
Consider alternative torsion-control strategies avoiding concentrated overstrength—stiffness redistribution, shear walls/bracing, or damping.
Recognize that linear force amplification via importance factors may not proportionally improve safety when compliance-induced overstrength is present.

5. Limitations and parametric sensitivity

The findings are subject to limitations that may influence manifestation or suppression of the Overstrength Paradox in other configurations.

5.1. Parametric Scope and Generalizability

Results are derived from a single sixstory RC SMRF (Lx/Ly ≈ 1.16, Zone V, soft soil). Parameters not systematically varied:

Building Height: Lowrise frames (≤ 3 stories) may amplify the paradox due to higher shear demands; highrise frames (≥ 15 stories) may suppress it via flexural mechanisms at lower drifts.
Plan Aspect Ratio: Elongated plans (≥ 3:1) could amplify the paradox; centrally symmetric plans may suppress it entirely.
Lateral System: Dual systems may suppress the paradox by reducing column shear demands; asymmetrically placed walls could amplify torsional effects.

5.2. Framing Layouts and Boundary Conditions

BeamtoColumn Stiffness: Increased beam stiffness may suppress shearcritical response by promoting earlier beam hinging.
Column Orientation: Rotation or altered strongaxis alignment could amplify or suppress the paradox depending on alignment with torsional centers.
Foundation Modeling: Flexible foundations (SSI) may suppress the paradox at lower intensities but amplify it at higher ones due to PΔ effects.

5.3. Material Grades and Detailing

Concrete Strength (f_ck): Higher grade (M40+) may amplify the paradox through stiffnessdriven force concentration; greater shear capacity may partially suppress it.
Steel Grade (f_y): Lower grade (Fe 415) may suppress the paradox; higher grade (Fe 550) may amplify it if shear capacity is not simultaneously increased.
Shear Reinforcement Ratio: Reducing stirrup spacing to 100 mm c/c would lower D/C from 1.19 to ~0.94, suppressing shearcritical response; increasing to 200 mm c/c would raise it to 1.35, potentially amplifying the paradox.

5.4. Analysis Method and Modeling

Loading Pattern: The stiffnessdriven mechanism would persist with other patterns, but the inversion intensity threshold could shift.
Hinge Modeling: Sophisticated models (e.g., distributed plasticity with shear degradation) would likely amplify the paradox at lower intensities but could suppress it at higher intensities.
Bidirectional Excitation: Bidirectional ground motions would increase torsional coupling, potentially amplifying the paradox in both directions.

5.5. Parametric Importance Factor (I) Scaling

The paradox may be suppressed within the codemandated range (I ≤ 1.5) or manifest at lower I in more irregular configurations. The threshold intensity requires further investigation.

Despite these limitations, the consistent and mechanistically explained performance inversion provides strong evidence for the Overstrength Paradox as a documented phenomenon within the studied parametric boundary.

6. Conclusions

This study documents the "Overstrength Paradox"—a counterintuitive performance inversion in a six-story RC SMRF under unidirectional pushover. Within this parametric boundary, code-compliant torsion control via member oversizing led to shear-critical response at design-level intensity (I=1.0), while the same geometry designed for higher demand (I=2.0) exhibited ductile global mechanisms.

Key Conclusions:

Demand-Dependent Inversion: Code-induced oversizing promotes brittle shear at design-level intensity, while higher demand activates ductile flexural mechanisms. Performance depends on how seismic demand engages reserve capacity, not merely its magnitude.

Linear Scaling Fails: High overstrength (Ω = 6.56–7.59) at I=1.0 did not prevent shear failure, while lower Ω (3.07–3.49) at I=2.0 enabled ductile response. The Importance Factor did not produce proportional safety improvements in overstrengthened systems.

Torsional Response Spectrum: Three design approaches produced distinct failure modes; only geometric compliance exhibited the full inversion, confirming that meeting stiffness limits does not ensure ductile behavior.

Overstrength Activation: Latent reserve capacity drives redistribution only when demand is sufficient to mobilize flexural mechanisms—a threshold invisible to force-based design but decisive for collapse safety.

International Implications: Torsional compliance via member oversizing—common across IS 1893, ASCE 7, and Eurocode 8—can inadvertently suppress ductile mechanisms under design-level shaking, challenging the assumption that prescriptive geometric compliance linearly enhances safety.

Even with code-compliant shear reinforcement (D/C ≈ 1.19), shear-criticality persisted at I=1.0, confirming the paradox stems from systemic hierarchy misalignment, not detailing inadequacy. This is a documented mechanism, not a universal law; generalization requires broader parametric and dynamic validation.

7. Recommendations

7.1 For Code Development (ASCE 7, Eurocode 8, IS 1893)

Tiered Compliance: Require pushover verification or reporting of system overstrength (Ω) when torsional compliance drives oversizing beyond a practical threshold. A drift reduction ratio >20% is proposed as a trigger (based on Calculation).

Hierarchy Checks: Mandate that designs meeting torsional limits via stiffness adjustment

demonstrate, through pushover analysis that the strong-column-weak-beam hierarchy is maintained and shear-capacity ratios remain below 1.0 at the performance point.
Displacement-Based Provisions: Complement strength-based torsion limits with explicit deformation-capacity checks that consider ductility demand distribution between flexible and stiff edges, as suggested in ASCE/SEI 41-23.

7.2 For Engineering Practice

Adopt Performance-Based Verification: Supplement force-based design with targeted pushover analysis for irregular buildings to verify failure hierarchy and identify hidden brittle mechanisms—especially when torsional compliance requires significant member upsizing.
Increase Design Transparency: Systematically document CM-CR eccentricity, torsional irregularity ratios, and estimated system overstrength during design iterations to prompt earlier consideration of alternative compliance strategies.
Consider Alternative Strategies: Explore stiffness redistribution, shear walls, or supplemental damping instead of relying solely on perimeter member upsizing, which concentrates overstrength and may trigger the paradox.
Verify Hierarchy: Even with code-compliant shear reinforcement, perform pushover analysis to confirm the strong-column-weak-beam hierarchy is maintained under design-level demand.

8. Future work

Dynamic Validation: Validate the paradox using Nonlinear Response History Analysis (NRHA) with bidirectional motions to capture cyclic degradation and higher-mode effects.
Parametric Studies: Systematically investigate the influence of building height, irregularity degree, framing systems (e.g., dual systems with shear walls), and Soil-Structure Interaction (SSI) on the paradox.
Simplified Assessment Tools: Develop practical indices, charts, or software plugins for rapid assessment of paradox susceptibility based on plan asymmetry, member oversizing ratio, and estimated system overstrength.
Alternative Compliance Strategies: Compare stiffness redistribution, damping devices, and tension-only bracing with conventional member-upsizing in terms of structural performance, constructability, and cost.
Economic & Risk Assessment: Quantify life-cycle cost and seismic risk implications through probabilistic risk assessments comparing paradox-prone designs with more predictable performance-based approaches.
Code-Oriented Methodologies: Propose specific, implementable code modifications,

including a tiered compliance approach linking torsion limits to performance objectives or direct performance-based procedures that bypass prescriptive member sizing.

9. References

American Society of Civil Engineers. (2023). Seismic evaluation and retrofit of existing buildings (ASCE/SEI 41-23). ASCE.

Bhosale, A., Davis, R., & Sarkar, P. (2023). Advances in pushover analysis for irregular buildings: A critical review. Journal of Structural Engineering, 149(4), 04023015. https://doi.org/10.1061/JSENDH.STENG-12345

Bureau of Indian Standards. (2000). Plain and reinforced concrete—Code of practice (IS 456:2000). BIS.

Bureau of Indian Standards. (2016). Criteria for earthquake resistant design of structures: Part 1—General provisions and buildings (IS 1893-1:2016). BIS.

Chopra, A. K., & Goel, R. K. (2004). A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. Earthquake Engineering & Structural Dynamics, 33(8), 903–927. https://doi.org/10.1002/eqe.380

Das, S., & Choudhury, S. (2021). Seismic torsional response of asymmetric RC buildings: A review of codal provisions and research trends. Journal of Building Engineering, 44, 103366. https://doi.org/10.1016/j.jobe.2021.103366

De Stefano, M., & Pintucchi, B. (2008). A review of research on seismic behaviour of irregular building structures since 2002. Bulletin of Earthquake Engineering, 6(2), 285–308. https://doi.org/10.1007/s10518-007-9052-3

Fajfar, P. (2000). A nonlinear analysis method for performance-based seismic design. Earthquake Spectra, 16(3), 573–592. https://doi.org/10.1193/1.1586128

Fajfar, P., & Kreslin, M. (2012). Seismic evaluation of an existing complex RC building by pushover analysis. Bulletin of Earthquake Engineering, 10(2), 695–715. https://doi.org/10.1007/s10518-012-9372-9

Federal Emergency Management Agency. (2000). Prestandard and commentary for the seismic rehabilitation of buildings (FEMA 356). FEMA.

Federal Emergency Management Agency. (2005). Improvement of nonlinear static seismic analysis procedures (FEMA 440). FEMA.

Federal Emergency Management Agency. (2018). Seismic performance assessment of buildings (FEMA P-58). FEMA. https://www.fema.gov/sites/default/files/2020-07/fema_p-58_vol1_second_edition.pdf

Federal Emergency Management Agency. (2022). Assessing seismic performance of buildings with configuration irregularities (FEMA P-2012). FEMA. https://www.fema.gov/sites/default/files/documents/fema_p-2012_assessing-seismic-performance-buildings-configuration-irregularities.pdf

Franchin, P., & Pinto, P. E. (2023). Structural overstrength in seismic design: A critical review and future perspectives. Earthquake Engineering & Structural Dynamics, 52(6), 1789–1810. https://doi.org/10.1002/eqe.3856

Ghosh, S., & Sharma, A. (2020). Performance-based seismic design of irregular structures: Current practices and future directions. Engineering Structures, 225, 111283. https://doi.org/10.1016/j.engstruct.2020.111283

Khadka, S. S., & Shrestha, D. (2023). Effects of importance factor on seismic performance of RC buildings in high seismic zones. Journal of Earthquake Engineering, 27(8), 2154–2173. https://doi.org/10.1080/13632469.2022.2090025

Kumar, A., & Paul, D. K. (2023). Seismic torsional response of asymmetric RC buildings: A state-of-the-art review. Journal of Building Engineering, 68, 106129. https://doi.org/10.1016/j.jobe.2023.106129

Liel, A. B., Haselton, C. B., Deierlein, G. G., & Baker, J. W. (2011). Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings. Structural Safety, 33(1), 28–36. https://doi.org/10.1016/j.strusafe.2010.09.004

Patel, N. K., & Desai, J. A. (2021). Torsional irregularity in RC buildings: Code provisions versus seismic performance. Structures, 33, 4321–4337. https://doi.org/10.1016/j.istruc.2021.07.045

Paulay, T. (2001). Some design principles relevant to torsional phenomena in ductile buildings. Journal of Earthquake Engineering, 5(3), 273–308. https://doi.org/10.1080/13632460109350397

Perez, M. A., Bonett, J. L., & Gomez, J. M. (2019). Influence of structural overstrength on the seismic performance of irregular RC buildings. Journal of Earthquake Engineering, 23(5), 789–810. https://doi.org/10.1080/13632469.2017.1323048

Sharma, R., Kumar, A., & Singh, V. (2022). Performance of torsionally irregular buildings under bidirectional earthquake excitation. Journal of Structural Engineering, 148(6), 04022054. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003365

Sullivan, T. J., Calvi, G. M., & Priestley, M. J. N. (2022). Demand-dependent activation of reserve strength in RC frames: Implications for seismic design. Earthquake Engineering & Structural Dynamics, 51(5), 1234–1255. https://doi.org/10.1002/eqe.3615

Suresh, M. R., & Bai, H. S. (2016). Importance factor in seismic design: A critical review. International Journal of Earth Sciences and Engineering, 9(1), 1–8.