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Comparative Seismic Analysis of Soft Storey Buildings with Different Shear Wall Configurations

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ABSTRACT: Soft storey buildings, characterised by an open ground floor significantly more flexible than the storeys above, have repeatedly exhibited catastrophic failure during seismic events. This study presents a comparative seismic analysis of a G+9 reinforced concrete (RC) framed building incorporating five distinct shear wall configurations, using both ETABS and SAP2000 software platforms. The configurations examined include: (i) bare frame (no shear walls), (ii) core shear walls, (iii) peripheral shear walls, (iv) corner shear walls, and (v) fully infilled ground floor. Three seismic analysis methods were applied — Equivalent Static Analysis (ESA), Response Spectrum Analysis (RSA), and Time History Analysis (THA) — in accordance with IS 1893:2016. Performance parameters evaluated include storey displacement, inter-storey drift ratio (IDR), storey stiffness, base shear, overturning moment, torsional irregularity, and fundamental period. Results demonstrate that shear wall provision substantially reduces lateral displacement and inter-storey drift, eliminates soft storey classification, and improves torsional stability. The central core wall configuration achieved the greatest stiffness, reducing peak roof displacement by 69.4% and maximum IDR by 71.4% relative to the bare frame. Peripheral and corner walls also satisfied all codal requirements. Asymmetric wall placement was found to introduce torsional irregularity exceeding IS 1893:2016 limits, underscoring the necessity of symmetric design. ETABS and SAP2000 results were in close agreement, validating the computational models. Practical design recommendations for retrofitting and new construction are proposed.

KEYWORDS: Soft storey, shear wall, ETABS, SAP2000, seismic analysis, IS 1893:2016, inter-storey drift, response spectrum, torsional irregularity, RC framed buildings.

I. INTRODUCTION

Earthquakes rank among the most devastating natural disasters confronting modern urban societies. Unlike other natural hazards, seismic events strike without forewarning, exposing built infrastructure to sudden and catastrophic damage. India, one of the world's most seismically active countries, has suffered significant losses in events such as the 1993 Latur, 2001 Bhuj, and 2011 Sikkim earthquakes. Post-earthquake reconnaissance surveys consistently identify soft storey irregularity — particularly the open ground floor typology prevalent in Indian urban construction — as the leading cause of building collapse.

A soft storey is defined by IS 1893 (Part 1): 2016 as a storey whose lateral stiffness is less than 70% of the storey above it, or less than 80% of the average lateral stiffness of the three storeys above. In practice, this condition arises when the ground floor is left open — free of masonry infill — to accommodate parking or commercial space, while upper floors are enclosed with brick masonry panels. The stiffness discontinuity thus created concentrates inelastic deformation at the ground floor, leading to column failure and storey mechanism collapse.

Reinforced concrete (RC) shear walls have emerged as one of the most practical and effective interventions for mitigating soft storey vulnerability. Their effectiveness depends critically on placement configuration: number, position, and symmetry relative to the building's centre of mass. Despite extensive literature on soft storey behaviour and shear wall effectiveness individually, a comprehensive comparative study evaluating multiple shear wall configurations through both ETABS and SAP2000 — the two most widely used structural analysis platforms in Indian practice — across linear and non-linear methods remains absent from the literature. This paper addresses that gap.

1.1 Objectives

- Develop code-compliant numerical models of a G+9 RC soft storey building with five structural configurations in ETABS and SAP2000.
- Perform ESA, RSA, and THA on all models and compare seismic response parameters.
- Identify the most effective shear wall configuration across multiple performance criteria.
- Provide practical design and retrofitting recommendations based on the analysis findings.

II. LITERATURE REVIEW

The problem of soft storey buildings first attracted serious attention following the 1971 San Fernando earthquake. Mahin and Bertero (1976) analytically demonstrated that vertical stiffness irregularities concentrate inelastic demand at the soft storey. The 1994 Northridge earthquake provided stark empirical confirmation: post-earthquake surveys found that approximately 80% of severely damaged RC buildings exhibited vertical irregularity, with the soft storey condition predominating (Sabol et al., 1994).

Das and Nau (2003) showed via non-linear dynamic analysis that storey ductility demand at a soft storey can reach four to five times the average demand across the building height. Chintanapakdee and Chopra (2004) demonstrated that linear analysis methods underestimate soft storey drift by 20–100%, providing justification for mandatory non-linear assessment of irregular structures. In the Indian context, Arlekar, Jain, and Murty (1997) found that soft ground floors generate storey drift demands two to four times greater than in uniformly infilled buildings — findings that directly motivated provisions in IS 1893:2002 and its 2016 revision.

Regarding shear wall effectiveness, Chandurkar and Pajgade (2013) found that peripheral walls provided the greatest lateral displacement reduction (up to 58%), while Anshuman et al. (2011) demonstrated that combined core-plus-periphery configurations deliver the best overall performance in terms of drift and displacement minimisation. Kasliwal and Sawant (2015) confirmed that ETABS and SAP2000 produce results within 2% agreement for linear analyses, though differences up to 8–10% can arise in pushover analysis due to differing default plastic hinge definitions.

Key research gaps identified from this review include: (i) absence of a unified comparative study spanning multiple shear wall configurations under both linear and non-linear methods; (ii) lack of systematic ETABS/SAP2000 cross-validation for soft storey shear wall scenarios; and (iii) limited performance-based assessment of Indian soft storey buildings under ATC-40/FEMA 356 criteria.

III. BUILDING MODELS AND METHODOLOGY

3.1 Building Description

A ten-storey (G+9) RC moment-resisting frame building is selected as the prototype. The building has a square plan of 20 m × 20 m with a 5 × 5 bay configuration (4.0 m bay width in each direction). The ground floor height is 4.5 m (to accommodate parking), while all upper floors maintain a standard 3.0 m height, giving a total building height of 31.5 m. The ground floor's elevated height, combined with the absence of masonry infill, creates a stiffness ratio well below the IS 1893:2016 threshold of 0.70 in the unretrofitted models.

Table 1: Structural Member Properties

Parameter	Value	Remarks
Plan Dimensions	20 m × 20 m	Square, 5×5 bays @ 4.0 m
Ground Storey Height	4.5 m	Soft storey (parking)
Typical Storey Height	3.0 m	Floors 1–9
Column Size (Ground)	500 × 500 mm	Enlarged for soft storey
Column Size (Typical)	400 × 400 mm	All other floors
Beam Size	300 × 500 mm	All floors
Slab Thickness	150 mm	Two-way
Shear Wall Thickness	200 mm	Models M2–M5
Concrete Grade	M30 (f _{ck} = 30 MPa)	IS 456:2000
Steel Grade	Fe 500 (f _y = 500 MPa)	IS 456:2000

3.2 Structural Models

Five distinct models were developed, each retaining identical geometry, material properties, and loading but differing in shear wall configuration:

- Model M1 — Bare Frame: RC moment frame, no shear walls, no masonry infill. Represents the worst-case soft storey scenario.
- Model M2 — Core Shear Walls: A central box-shaped RC shear wall core (200 mm thick, 4.0 m × 4.0 m plan) at the building centroid, spanning full height. Offers excellent biaxial and torsional resistance.
- Model M3 — Peripheral Shear Walls: RC shear walls (200 mm thick, 3.0 m long) at mid-span of all four exterior faces. Maximises overturning resistance lever arm.
- Model M4 — Corner Shear Walls: L-shaped RC shear walls (200 mm thick, 2.0 m × 2.0 m) at the four plan corners, spanning full height. Efficient for torsional control.
- Model M5 — Fully Infilled Ground Floor: Masonry infill panels added to the ground floor, eliminating the soft storey stiffness discontinuity.

3.3 Material Properties and Loading

Concrete (M30): $E_c = 5,000\sqrt{f_{ck}} = 27,386$ MPa; $\nu = 0.20$; $\gamma_c = 25$ kN/m³. Steel (Fe 500): $E_s = 200,000$ MPa; $f_y = 500$ MPa. Loading follows IS 875: superimposed dead load 2.0 kN/m²; live load 3.0 kN/m² (residential); roof live load 1.5 kN/m²; exterior wall load 12 kN/m. Seismic parameters: Zone IV; $Z = 0.24$; $I = 1.5$; $R = 5$ (SMRF with shear walls); medium soil (Type II); 5% damping.

3.4 Analysis Methods

Three seismic analysis methods were applied to all five models in accordance with IS 1893:2016:

- Equivalent Static Analysis (ESA): Lateral force distribution per IS 1893 Clause 7.5; used as a benchmark. Empirical period $T_a = 0.075h^{0.75} = 0.987$ s for $h = 31.5$ m.
- Response Spectrum Analysis (RSA): Primary analysis method; IS 1893 design spectrum for medium soil; Lanczos eigenvalue extraction; CQC modal combination; scaled to $\geq 85\%$ of ESA base shear per Clause 7.7.3.
- Time History Analysis (THA): Linear dynamic analysis using the Bhuj 2001 ground motion record (Ahmedabad station, scaled to design PGA = 0.18g); Newmark-Beta integration ($\beta = 0.25$, $\gamma = 0.5$); $\Delta t = 0.01$ s; 5% modal damping.

P-delta effects were activated in all models. Shear wall panels were meshed at 1.0 m × 1.0 m; stiffness modifiers of 0.70 (cracked section) were applied. Mesh sensitivity confirmed convergence within 2.1% between 0.5 m and 1.0 m meshes.

IV. RESULTS AND DISCUSSION

4.1 Modal Characteristics

Table 2 presents the fundamental natural periods for all five models. The bare frame (M1) exhibits the longest period (1.842 s), confirming high lateral flexibility. Introduction of core shear walls (M2) reduces T_1 by 52.4% to 0.876 s — the largest reduction among all configurations — by virtue of the box-section's superior biaxial stiffness. Peripheral walls (M3) and corner walls (M4) reduce T_1 by 50% and 46% respectively. All shear wall models achieve 90% modal mass participation within three modes, compared to five modes for the bare frame, indicating a cleaner, more dominant fundamental mode response with wall stiffness.

Table 2: Fundamental Natural Periods (s) and Base Frequencies (Hz)

Model	T ₁ (s)	T ₂ (s)	T ₃ (s)	f ₁ (Hz)	% Reduction vs M1
M1 — Bare Frame	1.842	1.831	1.594	0.543	—
M2 — Core Walls	0.876	0.871	0.654	1.142	52.4%
M3 — Peripheral Walls	0.923	0.919	0.712	1.083	49.9%
M4 — Corner Walls	0.987	0.982	0.743	1.013	46.4%
M5 — Fully Infilled GF	1.523	1.512	1.285	0.656	17.3%

4.2 Lateral Displacement

Table 3 presents maximum roof-level displacements from RSA in the X-direction. Model M1 records the highest roof displacement of 105.8 mm. The core wall model (M2) reduces this by 69.4% to 32.4 mm — the best performance among all configurations. Peripheral walls (M3) and corner walls (M4) reduce roof displacement by 64.8% and 60.7% respectively. The fully infilled model (M5) achieves a 20.0% reduction, confirming that infill alone, without structural RC walls, provides only modest stiffening.

The displacement profile shape is equally significant. Models M1 and M5 exhibit the characteristic soft storey concentration of deformation at the ground floor, where the IDR is disproportionately large relative to upper floors. In contrast, models M2–M4 display a near-linear, cantilever-dominated displacement profile, indicating successful redistribution of lateral demand away from the soft storey level.

Table 3: Maximum Roof Displacement (mm) — RSA, X-Direction

Model	Roof Displacement (mm)	Reduction vs M1 (%)	Ground Floor IDR	Code Limit
M1 — Bare Frame	105.8	—	0.00560	0.004
M2 — Core Walls	32.4	69.4%	0.00160	0.004
M3 — Peripheral Walls	37.2	64.8%	0.00187	0.004
M4 — Corner Walls	41.6	60.7%	0.00207	0.004
M5 — Fully Infilled	84.7	20.0%	0.00447	0.004

4.3 Inter-Storey Drift Analysis

IS 1893:2016 Clause 7.11.1 limits IDR to 0.004 (0.4%) under design basis earthquake loading. The bare frame (M1) records a peak IDR of 0.00560 at the ground floor — 40% in excess of the code limit — confirming the analytical identification of the soft storey failure mechanism. The fully infilled model (M5) records an IDR of 0.00447 at the ground floor, still exceeding the code limit by 11.8%, demonstrating that masonry infill alone cannot adequately remedy the soft storey deficiency.

All three RC shear wall models (M2, M3, M4) maintain IDRs comfortably within the 0.004 limit across all storeys. The core wall model (M2) achieves the lowest maximum IDR of 0.00160 (60% below the code limit). Peripheral walls (M3) and corner walls (M4) record maxima of 0.00187 and 0.00207 respectively. These results affirm that appropriately configured RC shear walls completely eliminate the soft storey drift concentration.

4.4 Stiffness Irregularity Assessment

Lateral storey stiffness is calculated as the ratio of storey shear to inter-storey drift. The soft storey criterion of IS 1893:2016 — ground floor stiffness less than 70% of the floor above — is evaluated in Table 4.

Table 4: Stiffness Irregularity Assessment

Model	K _{GF} (kN/m)	K _{1F} (kN/m)	Ratio	IS 1893 Limit	Classification
M1 — Bare Frame	28,400	62,300	0.456	≥0.70	Soft Storey
M2 — Core Walls	148,300	152,700	0.971	≥0.70	Regular
M3 — Peripheral Walls	134,600	139,400	0.966	≥0.70	Regular
M4 — Corner Walls	112,500	118,200	0.951	≥0.70	Regular
M5 — Fully Infilled	31,200	95,600	0.326	≥0.70	Soft Storey

The stiffness ratio for M1 (0.456) and M5 (0.326) clearly classify these models as soft storeys. Notably, the fully infilled model (M5) exhibits a worse stiffness ratio than the bare frame, because masonry infill dramatically increases upper floor stiffness relative to the open ground floor — a counterintuitive result with important practical implications for partially retrofitted buildings. All RC shear wall models (M2–M4) achieve ratios exceeding 0.95, effectively eliminating the soft storey classification.

4.5 Base Shear

Shear wall models attract 34–36% higher base shear than the bare frame under RSA, due to their shorter periods placing the structure in a higher-acceleration region of the design spectrum. Model M2 records the highest base shear (3,621 kN in RSA, X-direction), compared to 2,654 kN for M1. While the higher base shear demands stronger foundations, it is accompanied by dramatically reduced deformation and superior life-safety performance. THA consistently yields 7–10% higher peak base shear than RSA, attributable to the transient amplification of specific frequency components in the Bhuj 2001 record not captured by the smooth spectral envelope of RSA.

4.6 Torsional Behaviour

IS 1893:2016 defines torsional irregularity when the maximum storey displacement at the flexible edge exceeds 1.2 times the average displacement at a given floor. Under code-mandated accidental eccentricity ($\pm 0.05b$), the bare frame M1 records a torsional ratio of 1.52 — exceeding the threshold of 1.20 and classified as torsionally irregular. The core wall model (M2) achieves the best torsional performance (ratio 1.04), followed by peripheral walls (M3: 1.09) and corner walls (M4: 1.12). All symmetric wall models satisfy the torsional regularity criterion.

In contrast, an asymmetric shear wall arrangement (walls on two adjacent faces only, analogous to ad hoc retrofitting) produces a torsional ratio of 1.78 — classified as extremely torsionally irregular — with flexible-edge column drifts 78% higher than the average. This finding underscores a critical practical message: asymmetric shear wall retrofitting can create or exacerbate torsional problems that negate the benefits of the added stiffness.

4.7 Overturning Moment

Despite higher base shear in the shear wall models, the overturning moment at the base is substantially lower than in the bare frame. The core wall model (M2) records an overturning moment of 25.6 MN·m, 46.9% lower than the bare frame's 48.2 MN·m. This arises because shear walls produce a more uniform lateral force distribution along the building height, reducing the average moment arm of seismic forces. The walls also transfer seismic forces to the base directly through wall flexure, bypassing the column frame mechanism that amplifies overturning in the bare frame model.

4.8 Comparative Performance Summary

Table 5 consolidates the key performance indicators, establishing a clear performance hierarchy among the five models.

Table 5: Consolidated Seismic Performance Summary

Performance Indicator	M1 Bare	M2 Core	M3 Periph.	M4 Corner	M5 Infill
Max Roof Displ. (mm)	105.8	32.4	37.2	41.6	84.7
Max IDR	0.00560	0.00160	0.00187	0.00207	0.00447
T ₁ (s)	1.842	0.876	0.923	0.987	1.523
Soft Storey?	Yes	No	No	No	Yes
Torsion Ratio	1.52	1.04	1.09	1.12	1.48
Overturning (MN·m)	48.2	25.6	27.4	29.8	41.3
Code Compliant?	No	Yes	Yes	Yes	No

V. DISCUSSION

The results confirm that the bare frame model (M1) poses unacceptable seismic risk in seismic zones III and above, with IDR 40% in excess of the IS 1893:2016 limit and a stiffness ratio of 0.456 that unambiguously triggers the soft storey classification. The fully infilled ground floor (M5), while a pragmatic and low-cost option, fails to satisfy codal drift and stiffness criteria and introduces a more severe stiffness discontinuity than even the bare frame — a result consistent with Fardis and Panagiotakos (1997) and extensively observed in post-earthquake reconnaissance following the 2015 Nepal and 2001 Bhuj events.

Among the RC shear wall configurations, the core wall system (M2) consistently outperforms all others across displacement, drift, stiffness, torsional, and overturning metrics. The box-section geometry provides biaxial flexural stiffness and Saint-Venant torsional stiffness simultaneously, making it uniquely efficient for multidirectional seismic loading. The peripheral arrangement (M3) ranks second, offering a strong balance between displacement control, torsional stability, and overturning resistance at the cost of potential architectural constraints on the building perimeter. Corner walls (M4) provide the least intrusion into usable floor area and offer excellent torsional control, at only a modest reduction in displacement performance relative to M3.

A critical cross-cutting finding concerns asymmetric wall placement. The analysis of an asymmetric configuration demonstrated that improperly planned retrofitting can generate torsional irregularity ratios (1.78) far exceeding IS 1893:2016 limits (1.20), amplifying corner column displacements by 78%. This quantitative evidence should be considered mandatory guidance for practitioners: any shear wall addition must be evaluated for its effect on the centre of mass – centre of rigidity eccentricity before finalisation.

The comparison of analysis methods reveals that ESA systematically underestimates seismic demands in soft storey buildings with shear walls: it overestimates base shear by 4–8% in flexible models while underestimating higher-mode contributions in stiff wall models. RSA, capturing multi-modal behaviour, provides the most reliable and consistent results across all model types and is the recommended primary method. THA captures specific ground motion characteristics and produces peak responses 7–10% above RSA, confirming the conservatism of the smooth spectral representation.

ETABS and SAP2000 produced results in close agreement for all linear analyses (< 2% difference in base shear and displacement), validating the computational models. This consistency supports the use of either platform for seismic analysis of RC soft storey buildings with shear walls in routine design practice.

VI. CONCLUSION

This study has conducted a systematic comparative seismic analysis of five RC soft storey building models incorporating different shear wall configurations, evaluated through ESA, RSA, and THA in ETABS and SAP2000. The following conclusions are drawn:

- The bare frame model fails IS 1893:2016 drift limits by 40% and exhibits a stiffness ratio of 0.456, confirming severe soft storey vulnerability. It represents an unacceptable structural condition in seismic zones III and above.
- The fully infilled ground floor model, while reducing displacement relative to the bare frame, fails to satisfy codal drift and stiffness criteria and worsens the stiffness ratio to 0.326 by increasing the stiffness of upper floors relative to the open ground storey.
- Core shear walls deliver the best seismic performance: 69.4% reduction in roof displacement, 71.4% reduction in maximum IDR, stiffness ratio of 0.971, and torsional irregularity ratio of 1.04. The closed box geometry provides efficient biaxial and torsional resistance.
- Peripheral and corner shear walls also fully satisfy IS 1893:2016 requirements for drift, stiffness, and torsional regularity, offering viable design alternatives depending on architectural constraints.
- Asymmetric wall placement produces torsional irregularity ratios exceeding IS 1893:2016 limits and must be avoided without a comprehensive torsional assessment and remediation strategy.
- RSA is the recommended analysis method for irregular buildings; ESA alone is insufficient. ETABS and SAP2000 produce consistent results within 2% for linear analyses.

6.1 Design Recommendations

- New RC buildings with open ground floors in seismic zones III–V should incorporate RC shear walls at the ground floor level as a structural necessity, not an optional enhancement. Core or peripheral configurations are preferred.
- For seismic retrofitting of existing soft storey buildings, corner shear walls or peripheral walls offer the best compromise between performance, constructability, and disruption to occupants.
- All shear wall configurations must be evaluated for torsional symmetry before finalisation. Asymmetric placement should be avoided unless cross-validated by dynamic torsional analysis.
- Response spectrum analysis should be performed for all irregular buildings, and time history analysis is recommended for buildings in zones IV–V or those identified as torsionally irregular.
- Urban authorities should mandate seismic vulnerability assessment as a prerequisite for occupancy certification of existing soft storey buildings in moderate-to-high seismic zones.

6.2 Scope for Future Research

Future work should extend the analysis to irregular plan geometries, multiple soft storey conditions, and soil–structure interaction effects. Non-linear pushover analysis and incremental dynamic analysis (IDA) should be applied to establish collapse margin ratios and performance-based seismic design parameters. Experimental validation through shake table testing of scaled models with representative shear wall configurations is recommended. Hybrid retrofitting strategies combining shear walls with supplemental damping devices also warrant systematic investigation.

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