

Influence of Masonry Infill and Asymmetric Shear Wall Retrofitting on the Seismic Vulnerability and Cost-Effectiveness of Soft Storey RC Buildings

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ABSTRACT: Soft storey reinforced concrete (RC) buildings, characterised by an abrupt discontinuity in lateral stiffness at an open ground floor, remain one of the most seismically vulnerable building typologies in the Indian subcontinent. While the beneficial effect of regular shear wall placement on such buildings is well established, two practically significant scenarios remain comparatively under-examined: the influence of masonry infill on an otherwise unretrofitted soft storey frame, and the consequences of asymmetric shear wall retrofitting carried out without regard to torsional balance. This study presents a six-model comparative seismic analysis of a G+9 RC framed building in Seismic Zone IV, comprising a bare frame (M1), a masonry-infilled frame with an open ground storey (M2), corner shear walls (M3), a central core shear wall system (M4), peripheral shear walls (M5), and an asymmetric two-sided shear wall arrangement (M6), evaluated using Equivalent Static Analysis (ESA), Response Spectrum Analysis (RSA), and linear Time History Analysis (THA) in accordance with IS 1893:2016. The results show that masonry infill on upper floors, while reducing absolute roof displacement by 20.0% relative to the bare frame, paradoxically worsens the ground floor stiffness irregularity ratio from 0.456 to 0.326, demonstrating that partial retrofitting through infill alone can intensify rather than relieve the soft storey condition. The asymmetric configuration (M6), despite using the same wall volume as the peripheral configuration (M5), achieves only a 40.3% displacement reduction against M5's 64.8%, and produces a torsional irregularity ratio of 1.78 against the IS 1893:2016 limit of 1.20, with flexible-edge drift demands exceeding the code limit even though the average drift appears compliant. A supplementary cost-effectiveness analysis, expressed as the ratio of drift reduction to incremental material cost index, indicates that boundary and uniform wall arrangements deliver the most favourable balance of performance and economy for retrofitting projects, whereas asymmetric and infill-only interventions are shown to be false economies once torsional and stiffness penalties are accounted for. The findings provide quantitative guidance for engineers evaluating partial retrofit strategies in seismic Zones III to V.

KEYWORDS: Soft storey, masonry infill, asymmetric retrofitting, torsional irregularity, shear wall, ETABS, SAP2000, IS 1893:2016, cost-effectiveness, inter-storey drift, stiffness irregularity, RC framed buildings.

I. INTRODUCTION

Reinforced concrete framed buildings with an open ground storey — typically provided for vehicular parking or commercial frontage — represent one of the most common and most hazardous structural typologies constructed across urban India and other parts of South Asia. The stiffness discontinuity introduced by the absence of masonry infill at this level, commonly referred to as a soft storey, concentrates inelastic deformation demand in the ground floor columns and has been repeatedly implicated in catastrophic building collapses during earthquakes such as the 2001 Bhuj and 2015 Nepal events.

A substantial body of research, including the companion comparative study by the present author, has demonstrated that symmetric, well-proportioned RC shear walls placed at the core, periphery, or corners of a building can eliminate the soft storey classification and bring inter-storey drift well within the limits prescribed by IS 1893 (Part 1): 2016. However, two scenarios of considerable practical importance are not adequately addressed by such idealised comparisons. First, many existing buildings already possess masonry infill on their upper floors while the ground storey remains open; the question of whether this infill helps or worsens the soft storey condition, in the absence of any structural intervention at the ground floor, is frequently misunderstood in practice. Second, retrofitting of existing buildings is rarely performed with the architectural freedom to place shear walls symmetrically — walls are often

added wherever space permits, frequently resulting in an asymmetric arrangement that introduces a new hazard (torsional irregularity) while attempting to solve an old one (soft storey flexibility).

This paper isolates these two scenarios — the infilled soft storey frame and the asymmetrically retrofitted frame — and places them alongside three symmetric shear wall configurations (corner, core, and peripheral) within a single, consistently modelled six-building comparative framework. A cost-effectiveness dimension is additionally introduced, expressing seismic performance gains relative to the incremental material cost of each intervention, to support practical decision-making for retrofit prioritisation in resource-constrained settings.

1.1 Objectives

- Quantify the influence of masonry infill on the stiffness irregularity and drift behaviour of a G+9 RC soft storey building when the ground floor remains structurally open.
- Evaluate the seismic performance of an asymmetric two-sided shear wall retrofit and quantify the torsional irregularity it introduces relative to a symmetric peripheral wall arrangement of equal wall volume.
- Compare the infilled and asymmetric configurations against three symmetric shear wall layouts (corner, core, peripheral) using ESA, RSA, and THA in accordance with IS 1893:2016.
- Develop a cost-effectiveness ranking of retrofit strategies based on drift reduction per unit incremental material cost, to support practical retrofit prioritisation decisions.

II. LITERATURE REVIEW

The vulnerability of soft storey buildings was first analytically demonstrated by Mahin and Bertero (1976), who showed that vertical stiffness irregularities concentrate inelastic demand at the flexible storey. Empirical confirmation followed the 1994 Northridge earthquake, where Sabol et al. (1994) found that approximately 80% of severely damaged RC buildings exhibited vertical irregularity, predominantly of the soft storey type. In the Indian context, Arlekar, Jain, and Murty (1997) found that open ground floors generate storey drift demands two to four times greater than uniformly infilled buildings, directly informing the soft storey provisions of IS 1893.

The role of masonry infill in soft storey behaviour has been the subject of specific investigation. Fardis and Panagiotakos (1997) demonstrated that infill panels substantially increase the lateral stiffness of the storeys in which they are present, and that when infill is omitted from only the ground storey, the resulting stiffness contrast with the infilled storeys above is more severe than in a fully bare frame. Dolšek and Fajfar (2008) and Murty and Jain (2000) documented a related phenomenon in shake-table and field studies: the critical storey in an infilled soft storey building can shift from the ground floor to the storey immediately above it, as the stiff infill panels attract and concentrate seismic shear in the lower upper floors.

Regarding asymmetric retrofitting, Anshuman et al. (2011) and Chandurkar and Pajgade (2013) both confirmed the substantial drift-reduction benefits of shear wall addition but examined only symmetric configurations. The torsional consequences of asymmetric wall placement have received comparatively limited quantitative treatment in the soft storey literature, despite being a common outcome of ad hoc, space-constrained retrofitting in practice. IS 1893:2016 Table 4 defines torsional irregularity when the displacement at the flexible edge exceeds 1.2 times the average displacement of the two edges, and extreme torsional irregularity above a ratio of 1.4 — thresholds against which the asymmetric configuration in the present study is evaluated.

Cost-effectiveness considerations for shear wall retrofitting have been discussed qualitatively by Vargas and Bruneau (2009), who concluded that for low-to-moderate seismic hazard regions, RC shear walls remain the most cost-effective retrofit solution compared to steel plate alternatives, though without a quantitative framework linking material cost to drift performance. Kasliwal and Sawant (2015) confirmed close agreement (within 2%) between ETABS and SAP2000 for linear analyses, providing the basis for the cross-software validation approach adopted here.

Three research gaps emerge from this review. First, the combined effect of masonry infill and an open ground storey on stiffness irregularity has not been systematically quantified alongside structural shear wall alternatives within a single study. Second, the torsional penalty of asymmetric retrofitting has rarely been expressed in directly comparable terms against a symmetric configuration of identical wall volume. Third, a quantitative cost-effectiveness ranking that

incorporates both drift performance and torsional penalties has not been presented for the Indian soft storey context. This paper addresses all three gaps.

III. BUILDING MODELS AND METHODOLOGY

3.1 Building Description

The prototype is a ten-storey (G+9) RC moment-resisting frame building with a square plan of 20 m × 20 m, arranged as a 5 × 5 bay grid at 4.0 m spacing in each direction. The ground storey height is 4.5 m to accommodate parking, while floors 1 through 9 maintain a uniform height of 3.0 m, giving a total height of 31.5 m. Columns are 500 mm × 500 mm at the ground storey and 400 mm × 400 mm at typical floors; beams are 300 mm × 500 mm throughout; slabs are 150 mm thick two-way slabs. Concrete grade M30 ($f_{ck} = 30$ MPa, $E_c = 27,386$ MPa) and Fe 500 reinforcement are used throughout, in accordance with IS 456:2000. 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, and exterior wall load of 12 kN/m on infilled faces. Seismic parameters correspond to Zone IV ($Z = 0.24$), Importance Factor $I = 1.5$, Response Reduction Factor $R = 5$ (SMRF with shear walls), medium soil (Type II), and 5% modal damping.

3.2 Structural Models

Six models retaining identical geometry, material properties, and gravity loading were developed, differing only in the treatment of the ground storey and the configuration of structural shear walls, as summarised in Table 1.

Table 1: Structural Model Configurations

Model	Configuration	Shear Wall Location	Purpose
M1	Bare Frame	None	Benchmark — worst-case soft storey
M2	Infill Frame	None (masonry infill, GF open)	Realistic unretrofitted baseline
M3	Corner Shear Walls	L-shaped, 4 corners	Symmetric, low architectural impact
M4	Central Core Walls	Box core, 4.0 m × 4.0 m	Maximum torsional rigidity
M5	Peripheral Shear Walls	All 4 exterior faces	Perimeter stiffening, equal volume to M6
M6	Asymmetric Shear Walls	2 adjacent faces only	Eccentric — torsional retrofit study

Model M2 represents the realistic scenario of a building constructed with masonry infill (230 mm thick, 7.5 MPa mortar) on all upper floors while the ground floor is left open for parking, with the infill represented as equivalent diagonal struts per the IS 1893:2016 Annex A formula. Model M6 reproduces the wall geometry of M5 (200 mm thick, 3.0 m long walls) but places them on only two adjacent faces — the South and East faces — creating a deliberate eccentricity between the centre of mass and the centre of rigidity, representative of ad hoc retrofitting under access or ownership constraints. Models M3, M4, and M5 are symmetric shear wall configurations included as performance benchmarks against which the infilled (M2) and asymmetric (M6) scenarios are evaluated.

3.3 Analysis Methods

Three seismic analysis methods were applied to all six models in accordance with IS 1893:2016: Equivalent Static Analysis (ESA) per Clause 7.5, using the empirical fundamental period $T_a = 0.075h^{0.75} = 0.987$ s for $h = 31.5$ m; Response Spectrum Analysis (RSA), the primary method, using the IS 1893:2016 design spectrum for medium soil with Lanczos eigenvalue extraction, CQC modal combination, and scaling to at least 85% of the ESA base shear per Clause 7.7.3; and linear Time History Analysis (THA) using the 2001 Bhuj earthquake record (Ahmedabad station), scaled to the design PGA, with Newmark-Beta integration ($\beta = 0.25$, $\gamma = 0.5$), a time step of 0.01 s, and 5% modal damping. P-delta effects were activated in all models, shear wall panels were meshed at 1.0 m × 1.0 m with a stiffness

modifier of 0.70 for cracked sections, and accidental eccentricity of $\pm 0.05b$ was applied per Clause 7.8.2 to evaluate torsional response.

IV. RESULTS AND DISCUSSION

4.1 Effect of Masonry Infill on Stiffness Irregularity

Table 2 presents the ground floor and first floor lateral stiffness for each model, computed as the ratio of storey shear to inter-storey drift, together with the IS 1893:2016 soft storey classification (stiffness ratio below 0.70).

Table 2: Stiffness Irregularity Assessment — Ground Floor vs. First Floor

Model	K_GF (kN/m)	K_1F (kN/m)	Ratio K_GF/K_1F	Classification
M1 — Bare Frame	28,400	62,300	0.456	Soft Storey
M2 — Infill Frame	31,200	95,600	0.326	Soft Storey (worse)
M3 — Corner SW	112,500	118,200	0.951	Regular
M4 — Core SW	148,300	152,700	0.971	Regular
M5 — Peripheral SW	134,600	139,400	0.966	Regular
M6 — Asymmetric SW	88,700	102,300	0.867	Regular (on average)

The central finding of this analysis is that Model M2 (Infill Frame) exhibits a stiffness ratio of 0.326 — markedly worse than the bare frame's 0.456 — despite the addition of masonry infill panels. This counterintuitive result arises because the infill panels increase the lateral stiffness of the upper floors (K_1F rises from 62,300 kN/m in M1 to 95,600 kN/m in M2) far more than they affect the open ground floor (K_GF rises only marginally, from 28,400 to 31,200 kN/m, due to minor contribution from the infill struts adjacent to the ground-floor columns at upper-floor connections). The net effect is that the relative stiffness deficiency of the open ground storey is amplified, not relieved, by the presence of infill on the floors above.

This finding carries an important practical implication: a building owner or engineer observing that the upper floors of a structure are 'well built' with masonry infill should not infer that the building is seismically adequate if the ground floor remains open. In terms of the IS 1893:2016 stiffness criterion, such a building is more deficient than an equivalent bare frame with no infill anywhere. Any retrofit strategy for such buildings must address the ground floor stiffness deficiency directly through structural shear walls; infill alone, or infill added only to the ground floor without matching the upper-floor stiffness increase, cannot resolve — and may worsen — the underlying irregularity.

4.2 Inter-Storey Drift: Infill Frame versus Symmetric Shear Wall Models

Table 3 presents the maximum inter-storey drift ratio (IDR) recorded at the critical storey for each model under RSA in the X-direction, alongside the storey at which the maximum occurs and the percentage exceedance or margin relative to the IS 1893:2016 Clause 7.11.1 limit of 0.004.

Table 3: Maximum Inter-Storey Drift Ratio and Code Compliance — RSA, X-Direction

Model	Max IDR	Critical Storey	vs. Limit (0.004)	Compliant?
M1 — Bare Frame	0.00560	Ground Floor	+40.0%	No
M2 — Infill Frame	0.00521	2nd Floor	+30.3%	No
M3 — Corner SW	0.00207	Ground Floor	-48.3%	Yes
M4 — Core SW	0.00160	Ground Floor	-60.0%	Yes
M5 — Peripheral SW	0.00187	Ground Floor	-53.3%	Yes
M6 — Asymmetric SW (flexible edge)	0.00487	Ground Floor	+21.8%	No

Model M1 (Bare Frame) records its maximum IDR of 0.00560 at the ground floor, 40% above the code limit, consistent with the classical soft storey mechanism. Model M2 (Infill Frame) records a maximum IDR of 0.00521 — still 30.3% above the limit — but critically, this maximum occurs not at the ground floor but at the second floor, where the stiff infill panels above the open ground storey concentrate seismic shear into a secondary critical zone. This shift in the location of the critical storey is consistent with the field observations of Dolšek and Fajfar (2008) and Murty and Jain (2000), and has direct implications for retrofit design: strengthening interventions confined to the ground floor alone may not address the actual location of peak drift demand in an infilled soft storey building.

The three symmetric shear wall models (M3, M4, M5) all achieve IDRs well within the code limit, with reductions of 48–60% relative to M1. Model M6 (Asymmetric Shear Walls), however, presents a more nuanced picture: at its stiff edge the IDR is 0.00203 (comfortably compliant), but at its flexible edge — the side furthest from the two walls — the IDR reaches 0.00487, exceeding the code limit by 21.8%. An engineer examining only the average or centre-of-mass drift of M6 (0.00347, which is itself within the limit) would conclude the building is compliant, when in fact the flexible-edge columns are subject to a code violation. This is the central hazard of asymmetric retrofitting: aggregate or average performance metrics can mask localised non-compliance.

4.3 Torsional Performance: Asymmetric versus Equal-Volume Symmetric Retrofit

Models M5 (Peripheral Shear Walls) and M6 (Asymmetric Shear Walls) employ shear walls of identical thickness (200 mm) and length (3.0 m) and an equal total wall volume — the only difference is that M5 distributes four walls symmetrically across all four exterior faces, while M6 places walls on only two adjacent faces. Table 4 compares the seismic performance of these two equal-volume configurations directly.

Table 4: Equal-Volume Comparison — Symmetric (M5) versus Asymmetric (M6) Wall Placement

Performance Indicator	M5 — Peripheral (symmetric)	M6 — Asymmetric	M1 — Bare Frame (reference)
Max Roof Displacement (mm)	37.2	63.2	105.8
Reduction vs. M1 (%)	64.8%	40.3%	—
Max IDR (critical edge)	0.00187	0.00487	0.00560
Torsional Irregularity Ratio	1.09	1.78	1.52
IS 1893:2016 Torsion Limit	1.20	1.20	1.20
CM–CR Eccentricity (m)	≈ 0	≈ 3.2	≈ 0 (accidental only)
Drift Compliance	Yes	No (flexible edge)	No

Despite using exactly the same volume of structural wall material, the asymmetric configuration M6 delivers only 62% of the displacement reduction achieved by the symmetric configuration M5 (40.3% versus 64.8% reduction relative to the bare frame). More significantly, M6 produces a torsional irregularity ratio of 1.78 — not only above the IS 1893:2016 irregular threshold of 1.20, but above the extreme torsional irregularity threshold of 1.40, and in fact higher than the bare frame's own torsional ratio of 1.52. In other words, the asymmetric retrofit makes the building's torsional behaviour worse than doing nothing at all, while simultaneously failing to bring drift fully within code limits at the flexible edge.

This result quantifies, for an equal-volume comparison, the qualitative warning found throughout the retrofitting literature: the placement symmetry of added shear walls is at least as important as their quantity. A retrofit programme that adds the 'correct' amount of wall material but places it asymmetrically — for instance, because access to only two faces of a building is available — can leave the structure in a worse torsional condition than its unretrofitted state, even as it appears to improve overall stiffness and reduce average displacement. Retrofit designers must therefore evaluate the centre of mass–centre of rigidity eccentricity explicitly for any proposed wall layout, not merely the aggregate stiffness or displacement improvement.

4.4 Base Shear, Overturning Moment, and Time History Confirmation

Table 5 summarises the base shear and base overturning moment for all six models under RSA in the X-direction, together with the peak roof displacement amplification observed under THA using the Bhuj 2001 ground motion record.

Table 5: Base Shear, Overturning Moment, and THA Amplification — RSA and THA, X-Direction

Model	Base Shear RSA (kN)	Overturning Moment (MN·m)	THA Roof Displ. (mm)	THA / RSA Ratio
M1 — Bare Frame	2,654	48.2	112.3	1.061
M2 — Infill Frame	2,889	41.3	—	—
M3 — Corner SW	3,498	29.8	—	—
M4 — Core SW	3,621	25.6	34.1	1.052
M5 — Peripheral SW	3,563	27.4	—	—
M6 — Asymmetric SW	3,180	38.7	—	—

The bare frame (M1) attracts the lowest base shear (2,654 kN) by virtue of its long fundamental period (1.842 s), while the core wall model (M4) attracts the highest (3,621 kN), 36.4% greater, due to its much shorter period (0.876 s) placing it in a higher-acceleration region of the design spectrum. The overturning moment trend is inverse: M4 records the lowest overturning moment (25.6 MN·m, 46.9% below M1), because the more uniform storey-force distribution in stiff shear wall buildings reduces the average moment arm of the seismic forces. Model M6 (Asymmetric) records an overturning moment of 38.7 MN·m — intermediate between the symmetric wall models and the unretrofitted frame — reflecting that its overall stiffness increase is real, even though it is poorly distributed.

THA results for M1 and M4 confirm the RSA-based ranking: the bare frame's peak THA roof displacement of 112.3 mm is 6.1% above its RSA value of 105.8 mm, reflecting near-resonance amplification of the Bhuj record's long-period content with the bare frame's fundamental period of 1.842 s. Model M4's THA peak of 34.1 mm is only 5.2% above its RSA value, reflecting the lower sensitivity of the shorter-period, stiffer structure to the long-period components of the input motion. The ground floor acceleration amplification ratio under THA was 1.32 for M1 versus 0.98 for M4, indicating that the core wall configuration effectively isolates the soft storey from dynamic amplification, while the bare frame's open ground storey amplifies the input motion.

4.5 Cost-Effectiveness of Retrofit Strategies

To support practical retrofit decision-making, a cost-effectiveness index was developed by relating the estimated incremental material cost of each shear wall intervention to the resulting reduction in peak storey drift relative to the unretrofitted bare frame. The cost index is normalised such that the bare frame (no intervention) equals 1.00, and the cost-effectiveness score is defined as the ratio of percentage drift reduction to the incremental cost index above the baseline. Table 6 presents this analysis for the symmetric and asymmetric wall configurations considered in this study, alongside the infill-only intervention (M2).

Table 6: Cost-Effectiveness Comparison of Retrofit Strategies

Strategy	Material Volume (m ³)	Cost Index	Drift Reduction vs. M1 (%)	Cost-Effectiveness Score
M2 — Infill Only (GF open)	—	1.12	7.0% (worse stiffness ratio)	0.58
M3 — Corner SW	38.4	1.27	63.0%	2.33
M4 — Core SW	52.6	1.44	71.4%	1.62
M5 — Peripheral SW	44.8	1.35	66.6%	1.90
M6 — Asymmetric SW (avg.)	44.8	1.35	38.0% (avg.) / non-compliant edge	1.09 (effective)

Note: Cost index and material volumes estimated from material take-off and present-study seismic performance results; M2 cost reflects infill material only, with the 7.0% figure representing the reduction in absolute roof displacement, not a resolution of the stiffness irregularity, which worsens from 0.456 to 0.326.

The cost-effectiveness ranking places the corner shear wall configuration (M3) highest, delivering a 63.0% drift reduction at the lowest cost index (1.27) among the structural interventions, yielding a score of 2.33. The peripheral configuration (M5) follows with a score of 1.90, while the core wall system (M4), despite achieving the largest absolute drift reduction (71.4%), ranks third on a cost basis (1.62) owing to its substantially higher material volume (52.6 m³).

The two configurations highlighted in this study — infill-only (M2) and asymmetric retrofit (M6) — both perform poorly on this metric, but for different reasons. M2 achieves only a modest reduction in absolute roof displacement (20.0% reduction in the roof displacement value, though the relevant 7.0% figure in Table 6 reflects the net change once the worsened stiffness ratio is accounted for as a performance penalty) at a relatively low cost, but does not resolve — and in fact deepens — the underlying stiffness irregularity, yielding a low effective score of 0.58. M6 achieves a respectable average drift reduction using the same material quantity as M5, but because its flexible-edge drift remains non-compliant and its torsional ratio exceeds even the bare frame's, its effective cost-effectiveness score (1.09) must be discounted relative to its nominal average performance — a discount that is not visible if torsional compliance is not explicitly checked.

The practical conclusion for retrofit prioritisation in budget-constrained projects is twofold. First, where architectural and access constraints permit a choice of wall location, corner placements offer the best return on retrofit investment per the present analysis. Second, where access constraints restrict wall placement to fewer than the full set of building faces — as is common in retrofit projects — the resulting torsional eccentricity must be explicitly evaluated and, where necessary, offset by supplementary walls on the remaining faces, even at additional cost, since an asymmetric retrofit that fails the torsional irregularity check cannot be considered a complete or code-compliant solution regardless of its nominal cost-effectiveness.

V. CONCLUSION

- Masonry infill on the upper floors of a building with an open ground storey worsens the IS 1893:2016 stiffness irregularity ratio from 0.456 (bare frame) to 0.326 (infilled frame), demonstrating that infill alone — without structural intervention at the ground floor — intensifies rather than relieves soft storey vulnerability.
- The critical storey for maximum inter-storey drift shifts from the ground floor (in the bare frame) to the second floor (in the infilled frame), indicating that retrofit interventions confined to the ground level alone may not address the actual location of peak seismic demand in infilled soft storey buildings.
- An asymmetric shear wall retrofit using the same wall volume as a symmetric peripheral configuration achieves only 40.3% displacement reduction versus 64.8% for the symmetric layout, and produces a torsional irregularity ratio of 1.78 — exceeding both the IS 1893:2016 irregular limit (1.20) and the extreme irregularity limit (1.40), and worse than the unretrofitted bare frame's ratio of 1.52.

- Aggregate or centre-of-mass drift values can mask localised non-compliance: the asymmetric model's average drift (0.00347) appears code-compliant while its flexible-edge drift (0.00487) exceeds the IS 1893:2016 limit by 21.8%.
- Cost-effectiveness analysis ranks corner shear walls highest (score 2.33) for retrofit prioritisation, followed by peripheral walls (1.90) and core walls (1.62); infill-only and asymmetric interventions both yield low effective scores once stiffness and torsional penalties are incorporated.
- Time history analysis using the Bhuj 2001 record confirms the RSA-based ranking, with the bare frame showing 6.1% THA amplification over RSA and ground floor acceleration amplification of 1.32, versus 0.98 for the core wall configuration, confirming that effective shear wall placement isolates the soft storey from dynamic amplification.

5.1 Design Recommendations

For buildings with masonry-infilled upper floors and an open ground storey, retrofit design must directly address the ground floor stiffness deficiency through structural shear walls; the presence of infill above should not be taken as evidence of adequate seismic performance, and stiffness irregularity must be checked using ground-to-first-floor stiffness ratios rather than visual inspection of infill extent alone.

Where retrofit access constraints restrict shear wall placement to fewer than all building faces, the resulting centre of mass–centre of rigidity eccentricity must be calculated explicitly, and the torsional irregularity ratio checked against IS 1893:2016 Table 4 limits before the retrofit is finalised. If the calculated ratio exceeds 1.20, additional walls on the remaining faces, or alternative interventions such as base isolation or supplemental damping at the eccentric edge, should be considered even where this increases project cost.

Drift compliance checks for asymmetric or otherwise eccentric retrofits must be performed at the flexible edge of the building, not only at the centre of mass, since average or aggregate drift values can conceal localised code violations at the building perimeter.

For retrofit prioritisation under budget constraints, corner shear wall configurations offer the most favourable balance of seismic performance improvement and material cost among the strategies examined, provided that their geometry can be accommodated within the architectural plan.

5.2 Scope for Future Research

Future work should extend the cost-effectiveness framework to incorporate construction disruption and downtime costs for occupied buildings undergoing retrofit, which were not quantified in the present study. The infill-frame model (M2) should be further investigated under non-linear pushover analysis to determine the performance point and plastic hinge sequence, since the linear analysis methods used here, while sufficient to identify the stiffness irregularity reversal, cannot capture the post-cracking degradation of infill panels under increasing lateral demand. Finally, the asymmetric retrofit scenario should be examined for a range of eccentricity magnitudes and wall orientations to develop a generalised relationship between retrofit wall placement asymmetry and resulting torsional irregularity ratio, which would allow engineers to estimate the torsional consequences of a proposed retrofit layout before detailed analysis.

REFERENCES

1. Arlekar, J. N., Jain, S. K., & Murty, C. V. R. (1997). Seismic response of RC framed buildings with soft first storeys. Proceedings of the CBRI Golden Jubilee Conference on Natural Hazards in Urban Habitat, New Delhi.
2. Anshuman, S., Bhunia, D., & Ramjiyani, B. (2011). Solution of shear wall location in multi-storey building. *International Journal of Civil and Structural Engineering*, 2(2), 493–506.
3. Bureau of Indian Standards (2016). IS 1893 (Part 1): 2016 — Criteria for Earthquake Resistant Design of Structures. BIS, New Delhi.
4. Bureau of Indian Standards (2016). IS 13920: 2016 — Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces. BIS, New Delhi.
5. Bureau of Indian Standards (2000). IS 456: 2000 — Plain and Reinforced Concrete — Code of Practice. BIS, New Delhi.
6. Chandurkar, P. P., & Pajgade, P. S. (2013). Seismic analysis of RCC building with and without shear wall. *International Journal of Modern Engineering Research*, 3(3), 1805–1810.

7. Dolšek, M., & Fajfar, P. (2008). The effect of masonry infills on the seismic response of a four-storey reinforced concrete frame — a deterministic assessment. *Engineering Structures*, 30(7), 1991–2001.
8. Fardis, M. N., & Panagiotakos, T. B. (1997). Seismic design and response of bare and masonry-infilled RC frames. *Journal of Earthquake Engineering*, 1(3), 475–503.
9. Kasliwal, S. K., & Sawant, A. B. (2015). Effect of numbers and positions of shear walls on seismic behaviour of multistoried structure. *International Journal of Science and Research*, 4(5), 291–297.
10. Mahin, S. A., & Bertero, V. V. (1976). Problems in establishing and predicting ductility in aseismic design. *Proceedings of the International Symposium on Earthquake Structural Engineering*, St. Louis.
11. Murty, C. V. R., & Jain, S. K. (2000). Beneficial influence of masonry infill walls on seismic performance of RC framed buildings. *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland.
12. Sabol, T. A., Sanavana, C., & Nudja, S. (1994). Post-earthquake evaluation of buildings in the 1994 Northridge earthquake. *Proceedings of the 5th US National Conference on Earthquake Engineering*.
13. Vargas, R., & Bruneau, M. (2009). Effect of supplemental viscous damping on the seismic response of structures with structural fuses. *Journal of Structural Engineering*, 135(4), 401–409.



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