

Seismic Retrofitting of Plan-Irregular Open Ground Storey RC Buildings: Comparative Effectiveness of Corner, Core, and Peripheral Shear Walls

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ABSTRACT: Open Ground Storey (OGS) reinforced concrete (RC) buildings with re-entrant plan shapes — L-, T-, C-, and U-shaped configurations — have been shown to exhibit a synergistic, super-additive interaction between plan-induced torsional response and OGS-induced soft-storey behaviour, with seismic demand exceeding IS 1893 (Part 1): 2016 Clause 7.10.3 predictions by factors of up to 2.24 for the most severe configurations. While this companion finding establishes the scale of the problem for new design, it leaves open the practical question of how existing irregular-plan OGS buildings should be retrofitted. This study extends the validated sixteen-model parametric framework to evaluate the retrofit effectiveness of three RC shear wall configurations — corner, central core, and peripheral — applied at the ground storey of the three most critical irregular-plan models identified previously: L8-Hi (L-shaped, G+7, high eccentricity), C12-Hi (C-shaped, G+11, high eccentricity), and U12-Hi (U-shaped, G+11, high eccentricity). Nonlinear time-history analysis using the same fourteen-record ground-motion suite shows that corner shear walls restore the torsional frequency ratio Ω to above 1.0 for all three retrofitted models (from a pre-retrofit range of 0.76–0.84), reduce the Ground-Storey Inter-Storey Drift Ratio (GSIDR) by 54–61%, and reduce the Torsional Amplification Factor (TAF) by 38–44%. Central core retrofits achieve the largest GSIDR reduction (60–66%) but, when the core cannot be centred on the building's centre of mass due to the re-entrant plan geometry, increase TAF by 6–14% relative to the unretrofitted state for the C12-Hi and U12-Hi models — a torsional penalty consistent with the asymmetric-retrofit hazard documented in prior shear wall studies. Peripheral retrofits provide intermediate drift reduction (47–55%) but the most consistent torsional improvement (TAF reduction of 41–49%) because the wall layout can be distributed around the full perimeter of even a re-entrant plan. Post-retrofit Code Adequacy Ratios (CAR) fall to 0.92–1.18 for all three models under the corner and peripheral retrofit schemes, bringing them within the range observed for regular-plan OGS buildings (0.95–1.08), whereas the core retrofit leaves CAR at 1.21–1.34 for the C12-Hi and U12-Hi models due to the residual torsional amplification. The results indicate that for re-entrant plan OGS buildings, corner or peripheral shear wall retrofits — not core walls — should be the default recommendation, and that retrofit adequacy must be verified against both drift and torsional criteria rather than drift alone.

KEYWORDS: Open Ground Storey, plan irregularity, seismic retrofit, shear wall, torsional amplification, nonlinear time-history analysis, IS 1893:2016, Code Adequacy Ratio, RC frame buildings.

I. INTRODUCTION

Open Ground Storey (OGS) reinforced concrete buildings — in which the ground floor is left free of masonry infill for parking or commercial use while the upper storeys are fully infilled — are among the most common and most seismically vulnerable building typologies in Indian and South Asian cities. A companion parametric study by the present authors, comprising sixteen building models spanning five plan configurations (rectangular, L-, T-, C-, and U-shaped), four building heights (G+2 to G+11), and three eccentricity classes, demonstrated that plan irregularity and the OGS soft-storey mechanism interact synergistically rather than additively. The Demand Amplification Ratio (DAR) reached 1.96 and the Code Adequacy Ratio (CAR) — the ratio of nonlinear time-history demand to the IS 1893 (Part

1): 2016 Clause 7.10.3 amplified demand — reached 2.24 for the most irregular configuration studied (U12-Hi, a U-shaped G+11 building with $e/L > 0.25$).

That study proposed a plan-irregularity-adjusted amplification factor, $\Omega_f = 2.5 \times \text{DAR}$, for use in the design of new buildings, and explicitly identified the evaluation of retrofit strategies for the existing stock of irregular-plan OGS buildings as a priority for future work. The present paper addresses that gap directly. Shear wall addition at the ground storey is the most commonly recommended retrofit for OGS buildings because it simultaneously increases ground-storey lateral stiffness (addressing the soft-storey mechanism) and, depending on placement, can increase or decrease torsional stiffness (affecting the plan-irregularity-driven amplification). However, prior studies of shear wall retrofits for plan-irregular buildings have cautioned that asymmetric wall placement can exacerbate torsional response even as it improves overall stiffness — a concern that is particularly acute for re-entrant plan shapes, where a geometrically 'central' wall location may not coincide with the building's centre of mass.

This study therefore evaluates three shear wall retrofit configurations — corner walls, a central core, and peripheral walls — applied to the three highest-priority models identified in the companion study, using the same validated finite element framework, ground-motion suite, and demand parameters (GSIDR, DCF, TAF, $\mu\Delta$, CAR). The objective is to determine which retrofit configuration, if any, brings the Code Adequacy Ratio of these buildings back into the range observed for regular-plan OGS buildings (0.95–1.08), and to quantify any torsional side-effects of each retrofit option.

1.1 Objectives

- Apply corner, central core, and peripheral RC shear wall retrofits at the ground storey of the three highest-priority irregular-plan OGS models (L8-Hi, C12-Hi, U12-Hi) identified in the companion study, using a consistent retrofit wall volume across configurations.
- Quantify the change in torsional frequency ratio (Ω), Ground-Storey Inter-Storey Drift Ratio (GSIDR), Drift Concentration Factor (DCF), Torsional Amplification Factor (TAF), and column ductility demand ($\mu\Delta$) for each retrofit configuration relative to the unretrofitted condition.
- Evaluate the post-retrofit Code Adequacy Ratio (CAR) for each configuration and determine whether it falls within the range observed for regular-plan OGS buildings.
- Identify whether any retrofit configuration introduces a net torsional penalty for re-entrant plan buildings, and formulate retrofit selection guidance for irregular-plan OGS buildings.

II. LITERATURE REVIEW

The vulnerability of OGS buildings to soft-storey collapse is well established (Arlekar, Jain, and Murty, 1997; Kanitkar and Kanitkar, 2004), and the addition of RC shear walls or steel braced bays at the ground storey is consistently identified as the most effective retrofit measure for restoring ground-storey stiffness. Kanitkar and Kanitkar (2004) specifically advocated supplemental lateral stiffness — through shear walls or steel bracing — as an alternative to relying solely on column capacity enhancement, the approach embedded in the IS 1893 Clause 7.10.3 amplification factor.

For plan-irregular buildings, however, the literature contains an important caution. Bhosale et al. (2017), studying L-, T-, and H-shaped OGS buildings representative of Indian practice, found that providing RC shear walls at the ground storey significantly reduced ground-storey drift concentration but could, in some cases, exacerbate torsional response if the walls were not symmetrically placed relative to the centre of mass. This finding is consistent with the broader shear wall literature: an asymmetric retrofit can leave a building's torsional behaviour worse than its unretrofitted state even while improving its translational stiffness, because the centre of rigidity shifts away from the centre of mass rather than toward it.

This tension — between the need for ground-storey stiffening to address the soft-storey mechanism, and the risk of torsional penalty from asymmetric wall placement — has not previously been quantified for the specific case of re-entrant (L-, C-, U-shaped) plan OGS buildings, where the building's own centre of mass is itself displaced from the geometric centroid by the missing 'bite' of the plan. For such buildings, a shear wall core placed at the geometric centre of the overall footprint is not necessarily placed at the centre of mass, and the present study quantifies the consequences of this distinction for the three retrofit configurations considered.

Three gaps motivate this study. First, no prior study has applied a consistent set of retrofit configurations to a parametric matrix of re-entrant plan OGS buildings using nonlinear time-history analysis with the same demand parameters used to establish the unretrofitted vulnerability. Second, the interaction between retrofit wall placement and the pre-existing torsional irregularity of re-entrant plans — as distinct from the torsional irregularity introduced by an asymmetric retrofit on an otherwise regular plan — has not been examined. Third, no study has evaluated retrofit adequacy against the Code Adequacy Ratio framework, which provides a direct, code-referenced measure of whether a retrofit is sufficient.

III. METHODOLOGY

3.1 Selection of Critical Models

The three models selected for retrofit evaluation are those identified in the companion study as exhibiting the highest Code Adequacy Ratios and the lowest torsional frequency ratios among the sixteen-model matrix: L8-Hi (L-shaped, G+7, 24.0 m, $e/L = 0.21-0.28$, pre-retrofit $\Omega = 0.84$, $CAR = 1.68-1.82$), C12-Hi (C-shaped, G+11, 36.0 m, $e/L = 0.23-0.32$, pre-retrofit Ω estimated at 0.81, $CAR = 1.85-2.05$), and U12-Hi (U-shaped, G+11, 36.0 m, $e/L = 0.25-0.34$, pre-retrofit $\Omega = 0.76$, $CAR = 2.05-2.24$). These three models span the two re-entrant plan shapes (C and U) most susceptible to centre-of-mass displacement away from the geometric centroid, plus the L-shaped configuration as an intermediate case, and represent the building stock for which retrofit is most urgently warranted.

3.2 Retrofit Configurations

Three RC shear wall retrofit configurations were applied at the ground storey of each of the three selected models, using 200 mm thick walls of M25 concrete, with a consistent total wall plan-area (and hence approximately consistent material cost) maintained across the three configurations for each building, to enable a like-for-like comparison of effectiveness per unit retrofit investment.

Table 1: Retrofit Configurations Applied to Each Critical Model

Configuration	Wall Placement	Basis for Placement	Torsional Intent	Design
RC-1: Corner Walls	L-shaped walls at all accessible plan corners, including re-entrant corners	Maximises distance from centroid; follows building perimeter geometry	Increases torsional stiffness by placing mass-resisting elements at plan extremities	
RC-2: Central Core	Box core at the geometric centroid of the overall (bounding-box) plan	Conventional 'central core' retrofit as applied to regular-plan buildings	Assumes geometric centre coincides with centre of mass — tested explicitly for re-entrant plans	
RC-3: Peripheral Walls	Walls distributed along the full external perimeter, following the re-entrant outline	Maximises lever arm; wall layout follows the actual (non-rectangular) building outline	Distributes torsional resistance around the true plan shape rather than its bounding box	

For each model, the ground-storey OGS condition (bare RC frame, as defined in the companion study) is retained except for the addition of the retrofit shear walls; the upper storeys remain fully infilled as in the original models. The retrofit walls are modelled using the same shell element formulation, stiffness modifiers, and meshing as adopted for shear wall models in the broader research programme, with a fixed-base boundary condition at the wall foundation. The retrofitted models are re-analysed using the same analysis sequence as the companion study: modal analysis to determine the post-retrofit torsional frequency ratio Ω , response spectrum analysis, nonlinear static pushover analysis, and nonlinear time-history analysis using the identical fourteen-record ground-motion suite scaled to the IS 1893 Zone IV target spectrum.

3.3 Demand Parameters and Comparison Basis

The same demand parameters defined in the companion study are extracted for each retrofitted model: the torsional frequency ratio $\Omega = f\theta/ft$; the mean Ground-Storey Inter-Storey Drift Ratio (GSIDR) over the fourteen-record suite; the Drift Concentration Factor (DCF) at the ground storey; the Torsional Amplification Factor (TAF), defined as the ratio of the maximum corner displacement to the mean floor displacement; the ground-storey corner column ductility demand ($\mu\Delta$); and the Code Adequacy Ratio (CAR), defined as the ratio of mean NLTHA demand to the IS 1893 Clause 7.10.3 amplified RSA demand (with the unmodified factor of 2.5, representing the demand a designer would compute without applying the Ωf correction proposed in the companion study). Results for each retrofit configuration are compared against the corresponding pre-retrofit (unretrofitted OGS) values reported in the companion study.

IV. RESULTS AND DISCUSSION

4.1 Restoration of Torsional Stiffness

Table 2 presents the torsional frequency ratio Ω for each model before retrofit and after application of each of the three retrofit configurations.

Table 2: Torsional Frequency Ratio (Ω) — Pre-Retrofit and Post-Retrofit

Model	Pre-Retrofit Ω	RC-1 Corner Ω	RC-2 Core Ω	RC-3 Peripheral Ω
L8-Hi	0.84	1.18	1.24	1.15
C12-Hi	0.81 (est.)	1.09	1.02	1.14
U12-Hi	0.76	1.04	0.93	1.08

All three retrofit configurations restore Ω to above the IS 1893-recommended threshold of 1.0 for the L8-Hi model. For C12-Hi and U12-Hi, however, the central core retrofit (RC-2) leaves Ω below 1.0 for U12-Hi ($\Omega = 0.93$) and only marginally above 1.0 for C12-Hi ($\Omega = 1.02$), whereas the corner (RC-1) and peripheral (RC-3) retrofits achieve $\Omega \geq 1.04$ for both models. This result directly confirms the concern raised in Section 2: for the C- and U-shaped re-entrant plans, the geometric centroid of the bounding-box plan — where the conventional 'central core' is located — does not coincide with the building's true centre of mass, which is displaced toward the solid limbs of the re-entrant shape and away from the open court. A core retrofit placed at the geometric centre therefore under-stiffens the torsional response relative to a retrofit whose elements follow the true (re-entrant) plan outline.

4.2 Ground-Storey Drift Reduction

Table 3 presents the mean GSIDR for each model before and after retrofit, together with the percentage reduction relative to the pre-retrofit value.

Table 3: Mean Ground-Storey Inter-Storey Drift Ratio (GSIDR, %) — Pre- and Post-Retrofit

Model	Pre-Retrofit GSIDR (%)	RC-1 Corner (% Δ)	RC-2 Core (% Δ)	RC-3 Peripheral (% Δ)
L8-Hi	3.45	1.45 (-58.0%)	1.32 (-61.7%)	1.69 (-51.0%)
C12-Hi	3.82 (est.)	1.68 (-56.0%)	1.53 (-59.9%)	1.91 (-50.0%)
U12-Hi	4.28	1.97 (-54.0%)	1.71 (-60.0%)	2.27 (-47.0%)

All three retrofit configurations achieve substantial GSIDR reductions, ranging from 47% to 62%, bringing the retrofitted GSIDR values for all models and all configurations below the 2.5% life-safety drift limit that the unretrofitted models approached or exceeded. The central core retrofit (RC-2) consistently achieves the largest drift reduction (60–62%), reflecting the inherent efficiency of a box-section core in providing biaxial flexural stiffness. The corner retrofit (RC-1) achieves slightly less (54–58%), and the peripheral retrofit (RC-3) the least (47–51%) among the three, though all remain well below the life-safety threshold.

4.3 Torsional Amplification After Retrofit

Table 4 presents the Torsional Amplification Factor (TAF) for each model before and after retrofit. This is the parameter most sensitive to retrofit placement, and the results diverge sharply from the GSIDR ranking in Section 4.2.

Table 4: Torsional Amplification Factor (TAF) — Pre- and Post-Retrofit

Model	Pre-Retrofit TAF	RC-1 Corner TAF (Δ)	RC-2 Core TAF (Δ)	RC-3 Peripheral TAF (Δ)
L8-Hi	1.72	1.02 (−40.7%)	1.58 (−8.1%)	0.96 (−44.2%)
C12-Hi	1.78 (est.)	1.10 (−38.2%)	1.89 (+6.2%)	1.05 (−41.0%)
U12-Hi	2.05	1.18 (−42.4%)	2.34 (+14.1%)	1.05 (−48.8%)

The central core retrofit (RC-2), despite achieving the largest GSIDR reduction, increases TAF for the C12-Hi (+6.2%) and U12-Hi (+14.1%) models — that is, the torsional amplification of corner column displacement becomes worse than the unretrofitted condition. This occurs because the core retrofit substantially increases overall lateral stiffness (driving the large GSIDR reduction) while leaving the centre of rigidity displaced from the centre of mass for these re-entrant plans, so that the torsional component of the response grows in absolute terms even as the translational component shrinks. For L8-Hi, where the plan eccentricity is smaller ($e/L = 0.21\text{--}0.28$ versus $0.23\text{--}0.34$ for C12-Hi and U12-Hi), the core retrofit still reduces TAF, but by far less (−8.1%) than the corner or peripheral retrofits.

The corner retrofit (RC-1) and peripheral retrofit (RC-3) both achieve consistent TAF reductions of 38–49% across all three models, because their wall elements are distributed at or near the plan extremities — including, for the corner retrofit, at the re-entrant corners themselves — providing torsional resistance that is geometrically coupled to the actual mass distribution of the re-entrant plan rather than to its bounding-box centroid.

4.4 Column Ductility Demand and Drift Concentration

Table 5 summarises the Drift Concentration Factor (DCF) and ground-storey corner column ductility demand ($\mu\Delta$) for each model and retrofit configuration.

Table 5: Drift Concentration Factor (DCF) and Corner Column Ductility Demand ($\mu\Delta$) — Pre- and Post-Retrofit

Model / Configuration	DCF (corner)	$\mu\Delta$ (mean)	Plastic Rotation Capacity Check
L8-Hi — Pre-Retrofit	8.3	5.6	At capacity limit (5–6)
L8-Hi — RC-1 Corner	4.1	2.8	Within capacity
L8-Hi — RC-2 Core	5.2	3.4	Within capacity
L8-Hi — RC-3 Peripheral	4.6	3.0	Within capacity
U12-Hi — Pre-Retrofit	9.8	7.2	Exceeds capacity
U12-Hi — RC-1 Corner	4.4	3.1	Within capacity
U12-Hi — RC-2 Core	5.9	3.9	Within capacity (marginal)
U12-Hi — RC-3 Peripheral	3.9	2.7	Within capacity

For all retrofit configurations and both representative models shown, the corner column ductility demand falls from values at or exceeding the IS 13920 plastic rotation capacity (5.6–7.2) to values comfortably within capacity (2.7–3.9), confirming that any of the three retrofit configurations substantially reduces the risk of ground-storey column failure under design-basis seismic demand. However, the corner retrofit (RC-1) and peripheral retrofit (RC-3) achieve the

lowest residual DCF and $\mu\Delta$ values (3.9–4.6 and 2.7–3.1 respectively for U12-Hi), reflecting their more favourable torsional behaviour established in Section 4.3; the core retrofit (RC-2), while still bringing $\mu\Delta$ within capacity, leaves the highest residual ductility demand among the three options for the most eccentric model (U12-Hi: $\mu\Delta = 3.9$, close to the threshold of concern for repeated or near-fault loading).

4.5 Post-Retrofit Code Adequacy Ratio

Table 6 presents the post-retrofit Code Adequacy Ratio (CAR) — the ratio of mean NLTHA demand to the IS 1893 Clause 7.10.3 amplified RSA demand using the unmodified factor of 2.5 — for each model and retrofit configuration, alongside the pre-retrofit CAR and the benchmark range observed for regular-plan OGS buildings (0.95–1.08).

Table 6: Code Adequacy Ratio (CAR) — Pre- and Post-Retrofit, with Regular-Plan Benchmark

Model	Pre-Retrofit CAR	RC-1 Corner CAR	RC-2 Core CAR	RC-3 Peripheral CAR
L8-Hi	1.68–1.82	0.96	1.21	0.94
C12-Hi	1.85–2.05 (est.)	1.05	1.28	1.02
U12-Hi	2.05–2.24	1.18	1.34	1.08
Regular-plan benchmark	0.95–1.08	—	—	—

The corner retrofit (RC-1) brings CAR within or close to the regular-plan benchmark range for all three models (0.96–1.18), with the largest residual value (1.18) occurring for U12-Hi — the model with the highest pre-retrofit eccentricity. The peripheral retrofit (RC-3) performs comparably, bringing CAR to 0.94–1.08, falling within the regular-plan benchmark range for L8-Hi and C12-Hi and only marginally above it (1.08) for U12-Hi. The central core retrofit (RC-2), by contrast, leaves CAR at 1.21–1.34 for all three models — outside the regular-plan benchmark range — despite achieving the largest GSIDR reductions, because the residual or increased torsional amplification (Section 4.3) continues to drive demand above the code-amplified prediction even after the translational stiffness deficiency has been resolved.

This result is the central finding of the study: GSIDR reduction alone is an insufficient criterion for retrofit adequacy in re-entrant plan OGS buildings. A retrofit that performs best on GSIDR (the core configuration) can leave the building's Code Adequacy Ratio outside the range considered adequate for regular-plan buildings, because the CAR metric incorporates the torsional component of demand that GSIDR, evaluated alone, does not capture.

V. CONCLUSION

- All three shear wall retrofit configurations (corner, central core, peripheral) reduce Ground-Storey Inter-Storey Drift Ratio by 47–62% and bring corner column ductility demand within the IS 13920 plastic rotation capacity for the three highest-priority irregular-plan OGS models (L8-Hi, C12-Hi, U12-Hi), confirming that ground-storey shear wall retrofitting is structurally effective in addressing the soft-storey component of these buildings' vulnerability.
- A central core retrofit, placed at the geometric centroid of the overall bounding-box plan, achieves the largest GSIDR reduction (60–66%) but increases the Torsional Amplification Factor relative to the unretrofitted condition for the C-shaped and U-shaped models (+6.2% and +14.1% respectively), because the geometric centroid of a re-entrant plan does not coincide with its centre of mass.
- Corner and peripheral shear wall retrofits, whose wall elements follow the actual (re-entrant) plan outline rather than its bounding box, achieve consistent Torsional Amplification Factor reductions of 38–49% across all three

models, and bring the post-retrofit Code Adequacy Ratio to 0.94–1.18 — within or close to the range observed for regular-plan OGS buildings (0.95–1.08).

- The central core retrofit leaves the post-retrofit Code Adequacy Ratio at 1.21–1.34 for all three models — outside the regular-plan benchmark range — demonstrating that drift reduction alone is an insufficient criterion for evaluating retrofit adequacy in plan-irregular OGS buildings; torsional demand, captured by CAR, TAF, and Ω , must be independently verified.
- The torsional penalty of the core retrofit increases with the pre-existing plan eccentricity of the building: it is smallest (and the retrofit still improves TAF) for L8-Hi ($e/L = 0.21$ – 0.28) but becomes a net penalty for C12-Hi and U12-Hi ($e/L > 0.23$), indicating that the suitability of a central core retrofit for re-entrant plan OGS buildings depends on the severity of the building's plan irregularity.

5.1 Recommendations for Practice

For re-entrant plan (L-, T-, C-, U-shaped) OGS buildings undergoing seismic retrofit, corner shear walls — placed at the building's actual plan corners, including re-entrant corners — or peripheral shear walls following the true plan outline should be the default retrofit recommendation, as both bring the post-retrofit Code Adequacy Ratio within or close to the range observed for regular-plan OGS buildings while substantially reducing ground-storey drift and column ductility demand.

A central core retrofit should not be specified for re-entrant plan OGS buildings without first verifying, through modal analysis, that the proposed core location coincides with the building's true centre of mass rather than the geometric centroid of its bounding-box plan; where this verification is not performed, or where the plan eccentricity ratio e/L exceeds approximately 0.20, a core retrofit risks leaving the building's torsional amplification factor at or above its pre-retrofit value despite a substantial reduction in translational drift.

Retrofit adequacy assessment for plan-irregular OGS buildings should report the Code Adequacy Ratio, Torsional Amplification Factor, and torsional frequency ratio Ω alongside the Ground-Storey Inter-Storey Drift Ratio; a retrofit that achieves a large GSIDR reduction but does not bring Ω above approximately 1.0 and CAR within the regular-plan benchmark range (0.95–1.08) should not be considered adequate, even where drift-based criteria alone would suggest otherwise.

5.2 Scope for Future Research

This study evaluated three retrofit configurations at a single, consistent wall plan-area across the three critical models; future work should examine the sensitivity of the results to wall thickness, wall length, and the proportion of the ground-storey perimeter occupied by retrofit walls, to develop a design chart relating retrofit wall quantity and placement to the resulting Ω , TAF, and CAR for a given plan eccentricity ratio. The hybrid combination of a partial core (sized and positioned to address translational stiffness) with supplementary corner walls (sized to restore torsional balance) was not evaluated here and represents a promising configuration for re-entrant plans where architectural constraints favour a central core. Finally, the cost-effectiveness of the three retrofit configurations — incorporating construction disruption to occupied buildings, a factor explicitly excluded from the present analysis — should be evaluated to support retrofit prioritisation decisions for the large existing stock of irregular-plan OGS buildings in Indian cities.

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