A Study on Seismic Reliability of Multi-Storeyed Buildings with Complex Plan and Vertical Irregularities

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Abstract

Buildings with re-entrant corners, projecting wings, and asymmetric plan forms are increasingly common in contemporary urban construction, yet such configurations depart from the uniform mass and stiffness distribution on which conventional seismic design provisions are based. This study evaluates the seismic reliability of four six-storey (G+5) reinforced-concrete special moment-resisting frame buildings possessing L-, C-, T-, and cruciform (+) plan shapes, each incorporating an open ground storey. Three-dimensional models with equal floor area and comparable structural quantities were developed in ETABS and analysed for Seismic Zone V in accordance with IS 1893 (Part 1): 2002, using both the Equivalent Static Method (ESM) and the Response Spectrum Method (RSM). Lateral displacement, storey drift, storey shear, torsional response, storey stiffness, modal periods, and overturning moment were compared across the four configurations. The equivalent static results were closely grouped across models, differing by only 8-9%, whereas the dynamic (RSM) results varied far more widely - up to 47% between configurations - showing that plan shape has a much stronger influence on true dynamic behavior than on code-based static estimates. The C-shaped plan (Model 2) consistently produced the largest dynamic displacement, drift, and base shear, identifying it as the most seismically demanding configuration, while the L-shaped plan (Model 1) developed the largest torsional moment, concentrated in members adjacent to its re-entrant corner. All models satisfied the permissible storey-drift limit of IS 1893 (Part 1): 2002. The results demonstrate that reliance on equivalent static analysis alone can substantially understate the seismic demand on irregular multi-storeyed buildings, and that response spectrum analysis, combined with explicit torsional checks at re-entrant corners, is essential for the reliable seismic design of complex plan-irregular structures.

Keywords: seismic reliability; plan irregularity; vertical irregularity; re-entrant corner; equivalent static method; response spectrum method; storey drift; torsion; ETABS; IS 1893:2002

I. INTRODUCTION

Earthquake ground motion imparts inertial forces to a building in proportion to its mass and the acceleration experienced at each floor level. Because the base of a structure moves with the ground while the upper floors respond with a time lag governed by the building's own dynamic characteristics, every storey above the foundation is subjected to relative inertial force. In a building whose mass and stiffness are distributed uniformly in plan and elevation, these forces act through a well-defined load path and the resulting response can be estimated with reasonable confidence using simplified code procedures. In practice, however, architectural, functional, and site-related requirements frequently produce buildings that depart markedly from this idealised uniform condition.

Structural irregularities are generally classified into plan (horizontal) irregularities and vertical irregularities. Plan irregularities include torsional irregularity, re-entrant corners, diaphragm discontinuity, out-of-plane offsets of vertical elements, and non-parallel lateral-load-resisting systems. Vertical irregularities include stiffness irregularity (soft storey), setback or geometric irregularity, mass irregularity, in-plane discontinuity of vertical elements, and strength discontinuity (weak storey). These irregularities disturb the direct transfer of lateral force, introduce eccentricity between the center of mass and the center of rigidity, and give rise to additional torsional demand that is not present in regular structures.

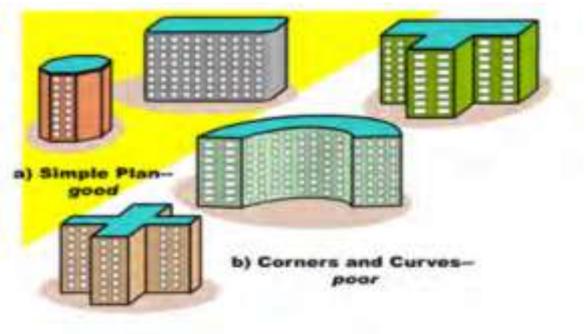

Fig. 1: Examples of regular and irregular plan configurations

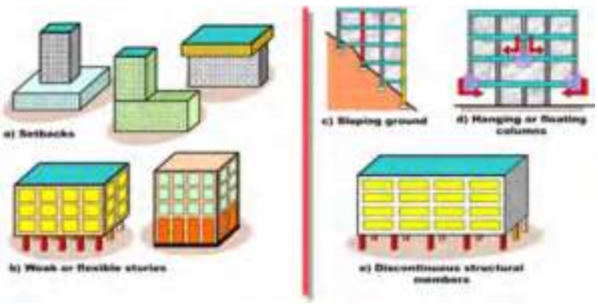

Fig. 2: Common forms of vertical irregularity

A large proportion of buildings constructed in dense urban plots incorporate L-, T-, C-, U-, H-, or cruciform plans to satisfy setback rules, natural-lighting requirements, or aesthetic considerations, almost always combined with an open ground storey for parking - a common vertical (soft-storey) irregularity in Indian practice. Quantifying how such combined plan and vertical irregularity affects seismic reliability, relative to a common structural basis, is therefore of direct practical importance to structural designers, particularly in high seismic zones.

II. LITERATURE REVIEW

A substantial body of research has examined the seismic behavior of plan- and vertically-irregular reinforced-concrete buildings. Alavi and Srinivasa Rao investigated five-storey buildings with re-entrant corners of varying severity and found that torsional response increased markedly with the degree of plan irregularity, even in the absence of a dual lateral-load-resisting system. Yousuf et al. compared symmetric and irregular G+5 buildings and concluded that dynamic (response-spectrum) analysis is essential for irregular and tall buildings because simplified static procedures do not reliably capture the true distribution of lateral force. Dubay et al. highlighted those torsional moments generated at re-entrant and T-shaped plan discontinuities can substantially increase column shear demand, and further noted that open or soft ground storeys compound this vulnerability.

Ravikumar et al. combined geometric and diaphragm discontinuities with setbacks and sloping-ground conditions and reported that the equivalent static method, being largely empirical, did not adequately capture the influence of irregularity, whereas pushover analysis revealed higher hinge formation in low-rise irregular models. Modakwar et al. examined cross- and L-shaped plans on a uniform structural grid and found that column shear and bending moment near re-entrant corners increased significantly, particularly on upper floors, recommending targeted strengthening at these locations. Sultan and Peera, and separately Khan et al., studied taller (G+15) rectangular, L-, C-, and H-shaped buildings and identified the C-shaped configuration as the most seismically vulnerable among the plans considered - a finding directly consistent with the present study. Sakale et al. demonstrated that shear walls become progressively more necessary for irregular plans as seismic-zone severity increases, while Gonzalez Herrera and Gomez Soberon confirmed, using elastic analysis of real urban plan forms, that seismic vulnerability rises with the degree of irregularity, although linear analysis alone may underestimate inter-storey drift once the structure enters the inelastic range.

Collectively, the reviewed literature establishes three consistent themes: (i) equivalent static analysis is frequently unable to represent the true seismic demand on plan-irregular buildings; (ii) torsional demand concentrates strongly in members adjacent to re-entrant corners; and (iii) no single irregular plan shape is universally the most critical - the outcome depends on the specific geometry, height, and response parameter examined. However, comparatively few studies have evaluated multiple complex plan shapes (L, C, T, cruciform) side by side, on an equal floor area and identical structural basis, while simultaneously incorporating a vertical irregularity (open ground storey) and comparing both ESM and RSM across the full set of response parameters - displacement, drift, shear, torsion, stiffness, modal properties, and overturning moment. This combined and controlled comparison is the specific gap addressed by the present study.

III. RESEARCH SIGNIFICANCE AND OBJECTIVES

The objectives of the present investigation are as follows:

- To develop three-dimensional ETABS models of G+5 reinforced-concrete special moment-resisting frame buildings having L-, C-, T-, and cruciform plan configurations, each incorporating an open ground storey.
- To analyse each model using the Equivalent Static Method and the Response Spectrum Method in accordance with IS 1893 (Part 1): 2002 for Seismic Zone V.
- To compare the seismic performance of the four configurations on an equal floor area and comparable structural basis, isolating the influence of plan geometry.

To evaluate and compare lateral displacement, storey drift, storey shear, torsional response, storey stiffness, modal periods and frequencies, and overturning moment, and to identify the configuration(s) that govern seismic reliability.

IV. THEORETICAL BASIS AND METHODS OF ANALYSIS

4.1 Earthquake-Resistant Design Basis

Seismic design under IS 1893 (Part 1): 2002 is founded on a life-safety philosophy: structures are expected to withstand minor and moderate shaking without significant damage, and severe shaking without collapse, while accepting a controlled level of structural and non-structural damage. The design seismic base shear, VB, in a given direction is obtained as

$$VB = Ah\ W$$

where Ah is the design horizontal seismic coefficient and W is the total seismic weight of the building. Ah itself depends on the zone factor (Z), importance factor (I), response reduction factor (R), and the spectral acceleration coefficient (Sa/g) appropriate to the fundamental period and soil type:

$$Ah = (Z/2)(I/R)(Sa/g)$$

The approximate fundamental period for a bare moment-resisting RC frame (Clause 7.6.1) is Ta = 0.075 h0.75, where h is the total height of the building above the base.

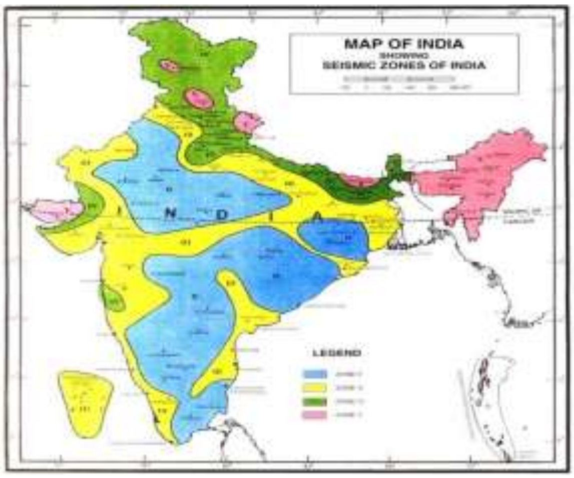

Fig. 3: Seismic zones of India [IS 1893 (Part 1): 2002]

4.2 Equivalent Static Method (ESM)

The equivalent static method represents earthquake action through a set of static horizontal forces distributed over the building height in proportion to storey mass and the square of storey height above the base, approximating the response of the fundamental mode. It is computationally simple and generally reliable for regular, low- to medium-rise buildings whose response is dominated by a single mode, but its underlying empirical distribution may not represent the true force pattern in buildings with significant plan or vertical irregularity, torsional eccentricity, or discontinuities in mass and stiffness.

4.3 Response Spectrum Method (RSM)

The response spectrum method performs a free-vibration (eigenvalue) analysis on the assembled mass and stiffness matrices of the structure to obtain natural periods, frequencies, and mode shapes. Peak modal responses are read from the design spectrum and combined - using the Complete Quadratic Combination (CQC) rule for closely spaced modes - to obtain the total design response. A sufficient number of modes is included to capture at least 90% of the total participating mass. Because RSM explicitly incorporates the modal characteristics of the specific structure, it captures the influence of irregular mass and stiffness distribution far more realistically than ESM, and IS 1893 accordingly mandates its use for irregular framed buildings beyond specified height limits.

V.METHODOLOGY -DESCRIPTION OF ANALYTICAL MODELS

Four G+5 (ground plus five upper storeys) reinforced-concrete special moment-resisting frame buildings were modelled in ETABS, each with a uniform storey height of 3 m and a total structural height of 18 m, representing L-shaped (Model 1), C-shaped (Model 2), T-shaped (Model 3), and cruciform (Model 4) plans. Every model was assigned an equal floor area together with an identical number of beams, columns, slab panels, and wall panels, so that differences in seismic response could be attributed to plan geometry rather than to differences in structural quantity. An open ground storey (vertical stiffness irregularity) was included in every model, and the stiffness contribution of masonry infill was represented only through equivalent gravity loading, not as a structural element.

Table 1. Structural element details common to all models

Parameter	Value
Number of storeys	G+5 (6 levels)
Storey height	3.0 m
Column size (typical floors, C1)	230 mm x 450 mm
Column size (ground storey, C2)	450 mm x 450 mm
Beam size	230 mm x 450 mm
Slab thickness	125 mm
Masonry wall thickness	230 mm
Concrete grade	M25 (fck = 25 MPa, E = 25,000 MPa)
Reinforcement grade	Fe415 (fy = 415 MPa)
Seismic zone / Zone factor	Zone V, Z = 0.36
Importance factor, I	1.0 (residential occupancy)

Parameter	Value
Response reduction factor, R	5.0 (Special RC Moment-Resisting Frame)
Soil type / damping	Medium soil (Type II), 5% damping

Table 2. Description of the four plan configurations

Model	Plan shape	Columns	Beams	Floor panels	Wall panels
Model 1	L-shaped	360	606	252	505
Model 2	C-shaped	360	606	252	505
Model 3	T-shaped	360	606	252	505
Model 4	Cruciform (+)	360	606	252	505

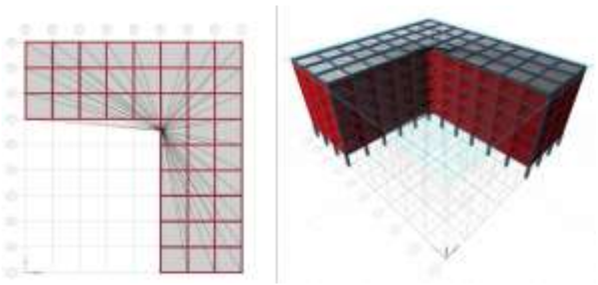

Fig. 4: Plan and elevation of Model 1

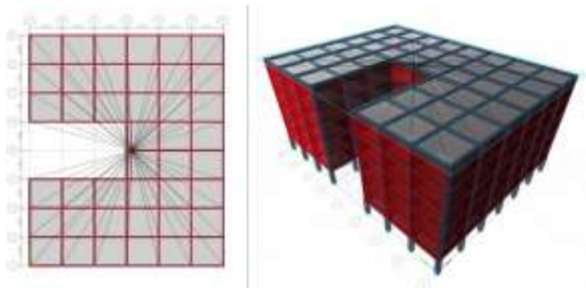

Fig. 5: Plan and elevation of Model 2

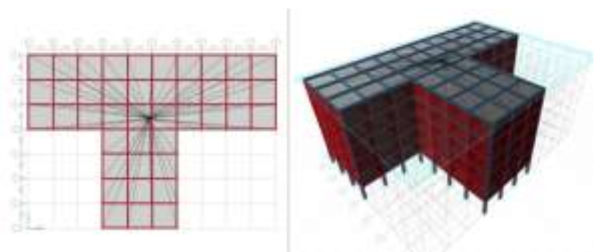

Fig. 6: Plan and elevation of Model 3

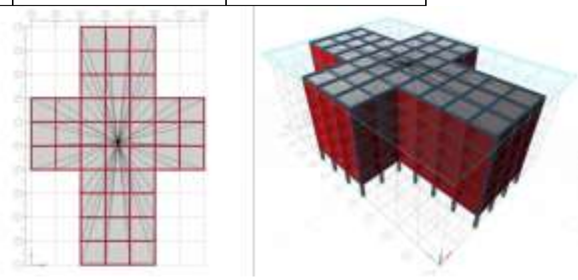

Fig. 7: Plan and elevation of Model 4

Gravity loads comprised self-weight (computed automatically by ETABS), a superimposed dead load of 2 kN/m² for floor finish and waterproofing, a masonry wall load of 14.635 kN/m applied on beams, and an imposed floor load of 2 kN/m² per IS 875 (Part 2). Seismic weight combined the full dead load with the applicable fraction of imposed load per IS 1893 Clause 7.4.2. Each model was analysed for the governing IS 456 / IS 1893 load combinations under both ESM and RSM, and the response was extracted at every storey level.

VI. RESULTS AND DISCUSSION

The response of the four models is compared below in terms of lateral displacement, storey drift, storey shear and base shear, torsional response, storey stiffness, modal properties, and overturning moment.

6.1 Lateral Displacement

Table 3 summarises the top-storey (Storey 6) lateral displacements obtained from ESM and RSM in the principal X and Y directions.

Table 3. Top-storey lateral displacement (mm)

Model	ESM - Ux	ESM - Uy	RSM - Ux	RSM - Uy
Model 1 (L)	20.0	22.2	13.1	14.9
Model 2 (C)	19.4	21.9	17.2	26.4
Model 3 (T)	19.1	23.8	12.2	14.1
Model 4 (+)	21.1	22.2	11.8	14.1

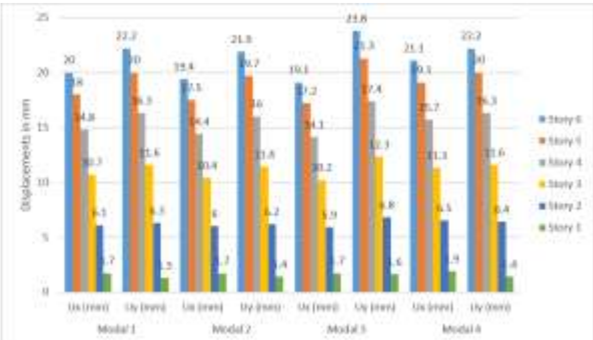

Fig.8: Variation of storey displacements in X and Y directions obtained from static analysis with models

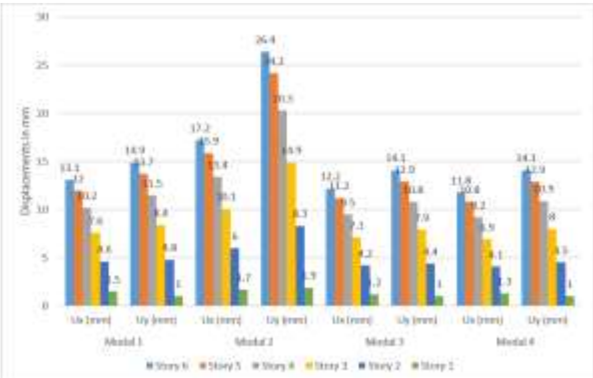

Fig. 9: Variation of storey displacements in X and Y directions from dynamic analysis with models

The equivalent static displacements were closely grouped across the four models, varying by only about 8% in the X direction and 9.4% in the Y direction, because the models share equal seismic weight and comparable structural quantities. Under RSM, however, the spread widened sharply to roughly 31% (X) and 47% (Y), and RSM values differed from the corresponding ESM values by 40-44% overall. Model 2 (C-shaped) produced the largest dynamic displacement, most pronounced in the Y direction, whereas Model 4 (cruciform) produced the largest displacement under the static comparison. This divergence shows that a plan configuration which appears unremarkable under simplified static analysis can, in reality, be considerably more flexible dynamically - underscoring why RSM is indispensable for irregular buildings.

6.2 Storey Drift

Storey drift - the relative lateral displacement between consecutive floors - is limited by IS 1893 to 0.004 times the storey height, i.e. 12 mm for the adopted 3 m storey height. None of the four models exceeded this limit under either analysis method.

Table 4. Maximum storey drift (mm), intermediate storeys

Model	ESM - Ux	ESM - Uy	RSM - Ux	RSM - Uy
Model 1 (L)	4.58	5.25	3.12	3.75
Model 2 (C)	4.44	5.17	4.21	6.56
Model 3 (T)	4.36	5.60	2.97	3.48

Model	ESM - Ux	ESM - Uy	RSM - Ux	RSM - Uy
Model 4 (+)	4.81	5.25	2.86	3.53

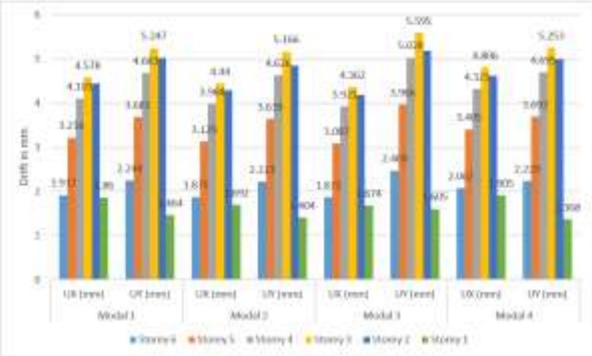

Fig. 10: Comparison of storey drift of all storeys in X and Y direction obtained using static analysis with models

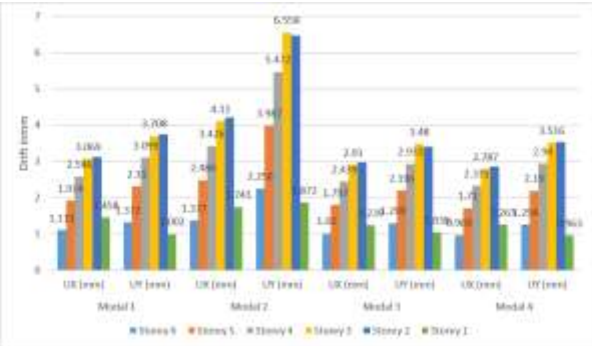

Fig. 11: Comparison of storey drift of all storeys in X and Y direction obtained using dynamic analysis with models

At the top storey, ESM drift varied by only about 7.6% (X) and 9.2% (Y) between models, while the RSM drift spread widened to approximately 32% (X) and 47% (Y). Model 2 again developed the largest drift in both directions, reflecting lower effective lateral stiffness and a stronger coupling between translational and torsional response arising from its C-shaped plan. The largest drifts in all models occurred at intermediate storeys (broadly Storeys 2-3), identifying these levels - rather than the ground or roof storey - as requiring particular attention during member design and detailing.

6.3 Storey Shear and Base Shear

Table 5. Base shear (Kn)

Model	ESM - Vbx	ESM - Vby	RSM - Vbx	RSM - Vby
Model 1 (L)	1455.6	1155.9	1104.1	907.4
Model 2 (C)	1405.9	1175.5	1673.8	1612.4
Model 3 (T)	1403.5	1181.7	1150.3	934.5
Model 4 (+)	1429.0	1155.9	1183.9	912.6

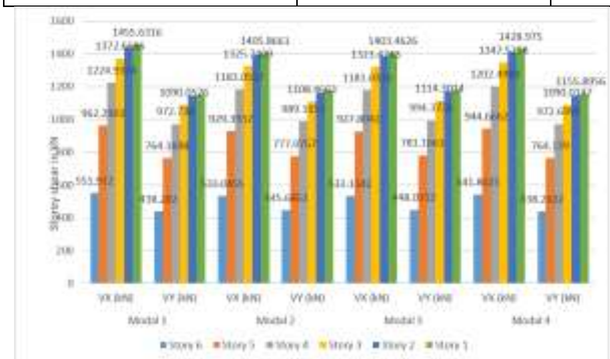

Fig. 12: Comparison of Storey Shears of all storeys in X and Y direction obtained, using Static analysis with all models

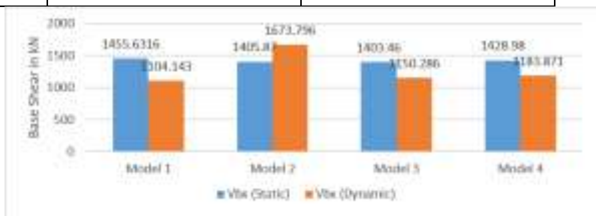

Fig 13: Comparison of Base shear of all models in X direction for Static and Dynamic Method

Equivalent static base shear was similar across all four models, again a direct consequence of their equal seismic weight. Dynamic (RSM) base shear, in contrast, varied substantially: Model 2 developed the highest dynamic base shear in both principal directions - roughly 19% and 46% higher than the L-shaped

Model 1 in the X and Y directions, respectively - confirming that its C-shaped plan mobilises a stronger dynamic response than the equivalent static procedure would suggest.

6.4 Torsional Response

Torsion was evaluated from the eccentricity between the centre of mass and centre of rigidity, combined with the accidental eccentricity prescribed by IS 1893 Clause 7.9.

Table 6. Design eccentricity and maximum torsional moment (top storey)

Model	ed - X (m)	ed - Y (m)	Tx (kN-m)	Ty (kN-m)
Model 1 (L)	2.288	2.088	1263	915
Model 2 (C)	2.149	1.749	1146	780
Model 3 (T)	1.729	2.329	920	1043
Model 4 (+)	2.051	1.451	1111	636

Fig. 14: Comparison of values of torsion due to force obtained from X direction

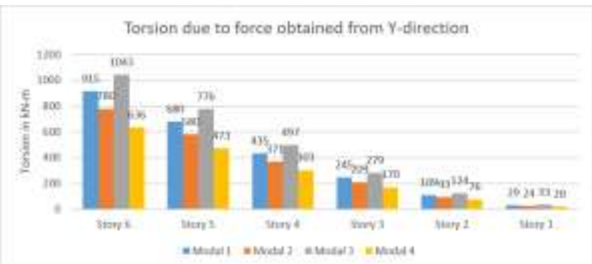

Fig. 15: Comparison of values of torsion due to force obtained from Y direction

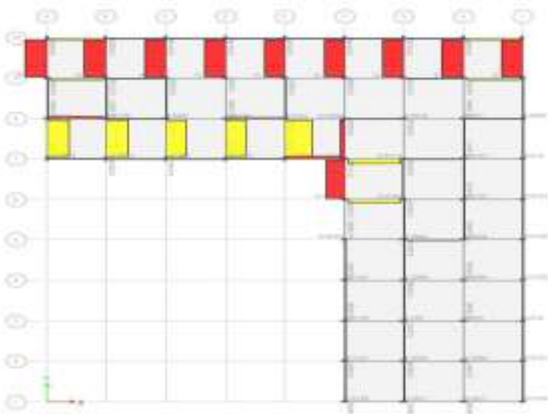

Fig. 16: Torsion in members of Model 1 due to dynamic earthquake load in X direction

Model 1 (L-shaped) developed the largest torsional moment in the X direction and Model 3 (T-shaped) the largest in the Y direction, each consistent with its respective design eccentricity. In every model, member-level torsion contours showed the largest positive and negative moments concentrated in beams and columns immediately adjacent to the re-entrant corner, under both static and dynamic seismic load cases - with the response spectrum results showing a more distinct variation between configurations than the static results. This confirms that re-entrant-corner members require torsion-specific verification and detailing regardless of which plan shape governs the global displacement or shear response.

6.5 Storey Stiffness

Fig.17 Comparison of Storey stiffness of all storeys in X direction by RSM and ESM with all models

Storey stiffness varied only modestly among the four models, since each contains an equal number of columns of identical cross-section; the ground storey showed markedly higher stiffness than the upper storeys in every model, consistent with its larger (450 mm x 450 mm) column size, while the open ground-storey condition still produced a visible relative softening compared with the floors immediately above.

6.6 Modal Periods and Frequencies

Table 7. Fundamental modal periods (first three modes, seconds)

Model	Mode 1	Mode 2	Mode 3
Model 1 (L)	0.894	0.755	0.710
Model 2 (C)	0.879	0.759	0.735
Model 3 (T)	0.875	0.781	0.736
Model 4 (+)	0.894	0.754	0.723

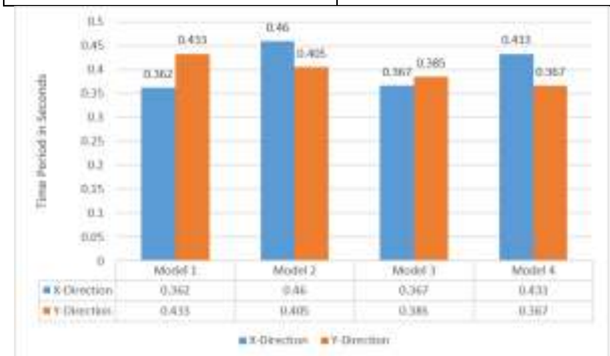

Fig. 18: Fundamental natural periods of all models evaluated in accordance with IS 1893 (Part 1): 2002

The fundamental periods of the four models were closely comparable, ranging from 0.875 s (Model 3) to 0.894 s (Models 1 and 4), with Model 2 recording an intermediate value of 0.879 s. Despite this narrow grouping in period, Model 2 exhibited a markedly stronger dynamic response in displacement, drift, and base shear (Sections 6.1-6.3). This indicates that Model 2's dynamic sensitivity arises primarily from the participation of its C-shaped plan in coupled lateral-torsional mode shapes, rather than from a simple elongation of the fundamental period - a distinction that a designer relying on period alone could easily overlook.

6.7 Overturning Moment

Fig. 19: Comparison of overturning moments at all storey levels with all models due to DL

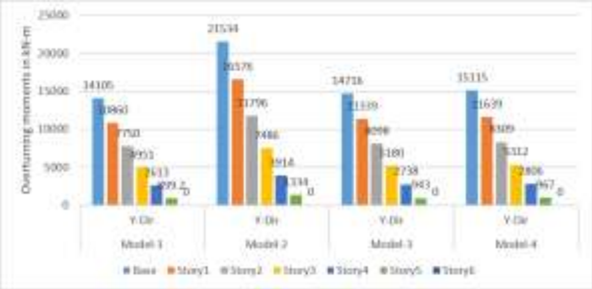

Fig. 20: Comparison of overturning moments at all storey levels with all models due to RSM-X

The overturning moment generated by dead load was, as expected, an order of magnitude larger than the seismic-only overturning moment, reflecting the gravity-load moment convention reported by the software rather than any seismic vulnerability. Among the seismic (RSM) results, Model 2 again developed the largest dynamic overturning moment, consistent with its governing role in displacement, drift, and base shear, confirming the C-shaped plan as the critical configuration when the response-spectrum results are considered.

VII. CONCLUSION

- For Models 1, 3, and 4, the equivalent static method produced larger displacement and drift than the response spectrum method; Model 2 (C-shaped) did not follow this trend and instead developed a stronger dynamic response, reflecting the influence of its plan geometry on modal participation.

- Equivalent static displacement, drift, shear, and stiffness varied only slightly (about 8-9%) among the four models because their seismic weight and structural quantities were held equal; the corresponding dynamic (RSM) results varied far more widely (up to about 47%), showing that plan configuration governs true dynamic behaviour much more strongly than it governs the simplified static estimate.

- The C-shaped plan (Model 2) consistently governed the seismic-critical response - the largest RSM displacement, drift, base shear, and overturning moment among the four configurations - and should be treated as the most seismically demanding of the shapes examined.

- All storey drifts in all four models remained within the IS 1893 permissible limit of 0.004 times the storey height, with the largest drifts occurring at intermediate storeys rather than at the base or roof, identifying these levels for particular attention in detailing.

- The L-shaped plan (Model 1) developed the largest torsional moment in the X direction and the T-shaped plan (Model 3) the largest in the Y direction; in every model, torsion concentrated strongly in members adjacent to the re-entrant corner under both static and dynamic seismic cases, confirming re-entrant corners as critical locations for torsion-specific design checks irrespective of which plan governs the global response.

- Fundamental periods were closely grouped across all four models (0.875-0.894 s); Model 2's markedly stronger dynamic response therefore originates from coupled lateral-torsional mode participation associated with its plan shape, not from a longer fundamental period, illustrating that period alone is an insufficient indicator of seismic vulnerability for plan-irregular buildings.

Overall, the results demonstrate that seismic reliability of complex plan-irregular multi-storeyed buildings cannot be reliably assessed from equivalent static analysis alone; response spectrum analysis, together with explicit torsional verification at re-entrant corners, is necessary to identify the true governing configuration and critical member locations.

VIII. SCOPE FOR FUTURE WORK

- Extending the comparison to nonlinear static pushover and nonlinear time-history analysis to evaluate yielding, damage progression, and collapse mechanisms.

- Repeating the study for taller buildings and a wider range of height-to-plan proportions to assess higher-mode effects.

- Introducing shear walls, coupled walls, or other lateral systems at varying locations to identify arrangements that most effectively control translation and torsion in these plan shapes.

- Explicitly modelling the in-plane stiffness, strength, and potential degradation of masonry infill walls, rather than representing them only as gravity loads.
- Examining a broader range of plan and vertical irregularities in combination, including diaphragm openings, setbacks, mass discontinuities, and transfer storeys.

Extending comparable investigations to structural-steel, composite, and precast framing systems.

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