# Response Spectrum Analysis of an I-Shaped Building with Mass, Stiffness and Geometrical Vertical Irregularities

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**Abstract:** ***Vertical irregularities in multi-storey reinforced concrete buildings can modify the spreading of mass, lateral stiffness and geometry along the height, thereby altering the dynamic characteristics and concentrating seismic demand. This paper presents a systematic comparative study of the influence of mass, stiffness, vertical geometric and combined irregularities on the seismic response of a G+15 RC special moment-resisting frame (SMRF) with an L-shaped plan. Thirteen 3D finite-element models were developed in ETABS and analysed using linear response spectrum analysis in accordance with IS 1893 (Part 1): 2016. One regular reference model and twelve irregular variants were considered, with irregularities introduced individually and in combination at one, two and three storey levels. The fundamental period, base shear, storey displacement, inter-storey drift ratio and storey acceleration were extracted in the two principal horizontal directions. The mass-irregular model with discontinuities at three levels recorded the maximum fundamental period of 2.134s, the maximum base shears of 25795.12kN (X) and 25103.29kN (Y), and the maximum X-direction roof displacement of 47.25mm. The vertical geometric-irregular model with discontinuities at two levels produced the maximum Y-direction displacement of 54.04mm and the largest floor accelerations of 949.9mm/s$^2$ (X) and 960.5mm/s$^2$ (Y). The combined-irregularity models governed the Y-direction drift ratio, reaching 0.00169. The findings show that no single irregularity type controls every response quantity, and that lower base shear does not necessarily indicate lower demand. Seismic evaluation of vertically irregular RC frames should therefore employ multiple response parameters simultaneously.***

**Keywords:** Seismic response, Mass irregularity, Stiffness irregularity, Vertical geometric setback, Combined irregularity, Response spectrum analysis, ETABS

## 1. Introduction

### 1.1. Background and motivation

The accelerated pace of urbanisation and the scarcity of usable land in fast-growing economies have transformed the way modern buildings are conceived. Contemporary high-rise structures are frequently required to accommodate mixed uses within a single vertical envelope, combining parking podiums, commercial floors, residential storeys and mechanical levels. These functional demands, together with aesthetic and site-related constraints, often result in departures from the idealised regular building form. Such departures introduce vertical or plan irregularities that influence the way a structure responds to earthquake ground motion [8, 12].

A structurally regular building possesses a relatively uniform distribution of mass, stiffness, strength and geometry over its height and plan. Under seismic excitation, such a configuration tends to distribute inertia forces smoothly along the load path and to dissipate seismic energy in a controlled manner. When irregularities are present, however, the smooth transfer of lateral forces is disrupted. Abrupt changes in storey mass, lateral stiffness or plan dimension create local zones of high demand, amplify inter-storey drift and can promote localised damage or, in extreme cases, partial collapse [21]. Field observations following major earthquakes have repeatedly confirmed that buildings with pronounced vertical discontinuities perform less favourably than their regular counterparts.

### 1.2. Classification of irregularities

Modern seismic codes explicitly define and limit irregularities. IS 1893 (Part 1): 2016 [6] identify several categories of vertical irregularity, including stiffness (soft-storey) irregularity, mass irregularity, vertical geometric (setback) irregularity, in-plane discontinuity of lateral-force-resisting elements and strength (weak-storey) irregularity. Plan irregularities such as torsional irregularity, re-entrant corners, diaphragm discontinuities and nonparallel systems are treated separately.

For the present investigation, three vertical irregularity types are of primary interest:

- Mass irregularity: A storey is considered mass-irregular when its effective seismic mass exceeds a specified multiple of that of an adjacent storey. This condition typically arises from heavy equipment floors, water-retaining structures or storage levels.
- Stiffness (soft-storey) irregularity: A storey is soft when its lateral stiffness is significantly lower than that of the storey above or of the average of the storeys above. Open ground floors and tall lobby levels are common sources.

- Vertical geometric irregularity (setback): A sudden change in the horizontal dimension of the lateral-force-resisting system along the height leads to a stepped profile with abrupt changes in both mass and stiffness.

When these irregularities occur simultaneously, their interaction can either amplify or, in some cases, partially mitigate the seismic response. The complexity of this interaction motivates a systematic parametric investigation.

### 1.3. Research gap and objectives

Although numerous studies have examined individual irregularity types, comparatively fewer have combined a consistent parametric framework with a systematic examination of the influence of the number and location of irregular storeys on multiple response quantities in both principal directions of an asymmetric plan. Moreover, conclusions drawn from a single response indicator, such as base shear or roof displacement, can be misleading because a configuration that is critical for one measure may be benign for another. The objectives of this study are therefore to:

1) Develop a regular G+15 L-shaped RC SMRF reference model and twelve vertically irregular variants;
2) Introduce mass, stiffness and vertical geometric irregularities individually and in combination at one, two and three storey levels;
3) Quantify the fundamental period, base shear, storey displacement, inter-storey drift ratio and storey acceleration in both principal horizontal directions;
4) Identify the configurations that govern force demand, deformation demand and acceleration demand; and
5) Provide interpretation and design-oriented observations relevant to the seismic assessment of vertically irregular RC frames.

### 1.4. Scope

The investigation is limited to linear elastic response spectrum analysis in accordance with IS 1893 (Part 1): 2016 [6]. A single building height, plan configuration and soil category are considered. Nonlinear behaviour, soil- structure interaction and infill contribution are outside the present scope but are identified as directions for future work.

## 2. Literature Review

### 1.5. Studies on mass irregularity

Mass irregularity has been widely investigated because heavy floors change the vertical distribution of inertia forces and shift the effective centre of mass. Tiwari and Adhikari [22] modelled a ten-storey RC frame with varying mass and stiffness and reported that concentrating mass at upper storeys markedly increased the top-storey lateral demand, whereas placing heavy or soft floors near the base reduced overall displacement and reinforcement demand. Raajan et al. [16] studied a G+4 building resting on a sloped surface and observed that the storey at which the additional mass was applied did not necessarily experience the maximum drift; the adjacent storey often did. These findings highlight that the location of the mass irregularity within the height is at least as influential as its magnitude.

### 1.6. Studies on stiffness and combined irregularity

Soft-storey behaviour remains one of the most damaging vertical irregularities because it draws large rotational demand into the columns of the flexible storey. Divya and Murali [10] analysed G+15 RC models with horizontal, vertical, stiffness and mass irregularities, with and without shear walls, and concluded that the introduction of shear walls substantially improved performance, with vertically irregular frames being the most vulnerable in the absence of walls. Raj et al. [17] performed pushover-based fragility analyses and found that combined stiffness and mass irregularities produced the most fragile seismic response, exhibiting the highest displacements and lowest base-shear capacity among the cases studied. Similar conclusions regarding the severity of combined irregularities were drawn in broader reviews of irregular-building behaviour [23].

### 1.7. Studies on vertical geometric (setback) irregularity

Setback structures possess abrupt reductions in plan area over the height, causing localised stress concentration and modified modal behaviour. Sarkar et al. [18] proposed a quantitative regularity index for stepped frames and derived a modified empirical period formula, demonstrating that standard code equations tend to underpredict the fundamental period when vertical geometric irregularity is present. Bohlouli and Poursha [4] evaluated setback steel moment frames and emphasised the importance of considering higher mode and dynamic characteristics for such configurations. Le-Trung et al. [15] similarly reported that vertical geometric irregularities strongly influence the distribution of demand in special moment frames.

### 1.8. Code comparisons and response parameters

Comparative code studies indicate that the choice of design standard can materially affect the computed demand for irregular frames. Investigations comparing IS 1893 with Eurocode 8 for vertically geometric-irregular frames have shown notable differences in design base shear and drift arising mainly from different response-modification assumptions. Studies on floor response and acceleration-sensitive components [20, 14] further demonstrate that acceleration demand may be governed by different configurations than those governing displacement or drift. Recent work on structural period estimation using detailed finite-element models [11] reinforces the need to evaluate multiple dynamic parameters rather than relying on a single simplified predictor. Evaluations of response-modification factors for vertically irregular moment frames [1] and comparative analyses of regular versus irregular multistorey structures [19, 3, 7, 13] collectively support the multi-parameter perspective adopted in the present study.

### 1.9. Summary of findings from the literature

The reviewed literature supports several observations that frame the present investigation:

- Mass irregularity influences global force demand and the vertical distribution of inertia forces;
- Stiffness irregularity primarily modifies the deformation pattern and local drift concentration;

- Vertical geometric irregularity alters dynamic characteristics and can govern acceleration and directional displacement; and
- Combined irregularities frequently produce the most critical, and least predictable, response, underscoring the value of a systematic multiparameter comparison.

## 2. Methodology

### 2.1. Overview of the analytical framework

A structured five-phase numerical framework was adopted: (i) model setup and code selection; (ii) definition of structural geometry and elements; (iii) load application, mass source definition and dynamic parameters; (iv) modelling of the irregularity configurations; and (v) computational execution, verification and comparative evaluation. All models were constructed and analysed in ETABS [9].

### 2.2. Reference building configuration

The reference structure is a G+15 RC SMRF building with an L-shaped plan and a total height of 48m. A uniform storey height of 3m was maintained. The principal modelling parameters are summarised in Table 1.

**Table 1:** Principal parameters of the analytical building model.

| Parameter | Specification |
|---|---|
| Structural system | RC special moment-resisting frame |
| Number of storeys | G+15 |
| Total building height | 48m |
| Typical storey height | 3m |
| Plan envelope | 60m × 60m |
| Typical bay spacing | 6m |
| Beam section | 600mm × 450mm |
| Column section | 900mm × 900mm |
| Slab thickness | 150mm |
| Concrete grade | M35 |
| Reinforcement grade | Fe500 |
| Floor finish load | 1.0kN/m$^2$ |
| Imposed (live) load | 3.0kN/m$^2$ |
| Wall load | 14kN/m |
| Seismic zone | Zone V |
| Zone factor, Z | 0.36 |
| Importance factor, I | 1.2 |
| Response reduction factor, R | 5 |
| Soil type | Type II (medium) |
| Damping ratio | 5% |
| Analysis method | Response spectrum analysis |
| Design code (concrete) | IS 456:2000 |
| Seismic code | IS 1893 (Part 1):2016 |

### 2.3. Finite-element idealisation

Beams and columns were modelled as one-dimensional frame elements with axial, flexural, shear and torsional stiffness. Floor slabs were represented by shell elements and assigned as rigid diaphragms at each level to constrain in-plane translations and rotation to a master node, consistent with common practice for RC floor systems. Cracked-section stiffness modifiers were applied to reflect the effective flexural stiffness of RC members under seismic action, using representative values of $0.35I_g$ for beams and $0.70I_g$ for columns. Column bases were assumed fixed.

The modulus of elasticity of concrete was computed as

$$E_c = 5000\sqrt{f_{ck}} \quad [\text{MPa}] \tag{1}$$

with a Poisson's ratio of 0.2. The elastic modulus of the reinforcing steel was taken as $2.0 \times 10^5$ MPa.

### 2.4. Loading and mass source

Gravity loads comprised the self-weight of members, superimposed dead load from finishes and walls, and imposed floor loads assigned in accordance with IS 875 (Part 2) [5]. The seismic mass source combined the dead load and a code-stipulated fraction of the imposed load:

$$M = 1.0DL + 1.0SIDL + \alpha LL \tag{2}$$

where α is the imposed-load participation factor (0.25 for imposed loads not exceeding 3.0kN/m$^2$ and 0.50 otherwise). The mass was lumped at the diaphragm levels, and accidental eccentricity was incorporated in accordance with the code.

### 2.5. Response spectrum analysis

Linear modal response spectrum analysis was performed in both principal horizontal directions. The design horizontal seismic coefficient for each mode was obtained from

$$A_h = \frac{Z}{2} \cdot \frac{I}{R} \cdot \frac{S_a}{g} \tag{3}$$

where $S_a/g$ is the spectral acceleration coefficient corresponding to the modal period, damping and soil classification. A sufficient number of modes were extracted so that the cumulative modal mass participation exceeded 90% in each translational direction. Modal responses were combined using the complete quadratic combination (CQC) rule to account for closely spaced modes and translational-torsional coupling:

$$\lambda = \sqrt{\sum_{i=1}^{N}\sum_{j=1}^{N} \lambda_i \, \rho_{ij} \, \lambda_j} \tag{4}$$

where $\lambda_i$ and $\lambda_j$ are modal peak responses and $\rho_{ij}$ is the cross-modal correlation coefficient. Directional effects were combined using the standard 100% + 30% rule. Where the dynamic base shear fell below the equivalent static base shear $V_b = A_h(T_a)W$, all dynamic response quantities were scaled by the ratio $V_b/\bar{V}_B$ in accordance with the code.

### 2.6. Load combinations

Ultimate and serviceability load combinations incorporating gravity and orthogonal seismic actions were considered, as summarised in Table 2.

**Table 2:** Representative seismic load combinations.

| No. | Load combination |
|---|---|
| 1 | $1.2[DL + LL + (EQ_x + 0.3EQ_y)]$ |
| 2 | $1.5[DL + LL + (EQ_x + 0.3EQ_y)]$ |
| 3 | $0.9DL + 1.5LL + (EQ_x + 0.3EQ_y)$ |
| 4 | $1.2[DL + LL + (0.3EQ_x + EQ_y)]$ |
| 5 | $1.5[DL + LL + (0.3EQ_x + EQ_y)]$ |
| 6 | $0.9DL + 1.5LL + (0.3EQ_x + EQ_y)$ |

### 2.7. Irregularity configurations

Thirteen models were analysed. Model M1 is the regular reference. Models M2-M4 introduce mass irregularity, M5-M7 introduce stiffness irregularity, M8-M10 introduce vertical geometric irregularity, and M11-M13 introduce combined irregularities. In each group, the irregularity is applied at one, two and three storey levels, respectively (12th; 12th and 9th; 12th, 9th and 6th). Table 3 lists the configurations.

**Table 3:** Description of the thirteen analysed models.

| Model | Irregularity type | Affected storey level(s) |
|---|---|---|
| M1 | Regular reference | None |
| M2 | Mass | 12th |
| M3 | Mass | 12th, 9th |
| M4 | Mass | 12th, 9th, 6th |
| M5 | Stiffness | 12th |
| M6 | Stiffness | 12th, 9th |
| M7 | Stiffness | 12th, 9th, 6th |
| M8 | Vertical geometric | 12th |
| M9 | Vertical geometric | 12th, 9th |
| M10 | Vertical geometric | 12th, 9th, 6th |
| M11 | Combined (mass + stiffness + geometric) | 12th |
| M12 | Combined (mass + stiffness + geometric) | 12th, 9th |
| M13 | Combined (mass + stiffness + geometric) | 12th, 9th, 6th |

### 2.8. Amplification factor

To benchmark irregular behaviour against the regular model, an amplification factor was defined as

$$\kappa = \frac{\text{Responseirregular}}{\text{Response}_{\text{regular}}} \quad (5)$$

This ratio was used to interpret the relative severity of each configuration for a given response quantity.

### 2.9. Model verification

Before result extraction, each model was verified by inspecting analysis logs for numerical warnings, confirming equilibrium between total applied load and base reactions, checking mode-convergence to the required modal mass participation, and confirming that dynamic base shear satisfied the code scaling requirement.

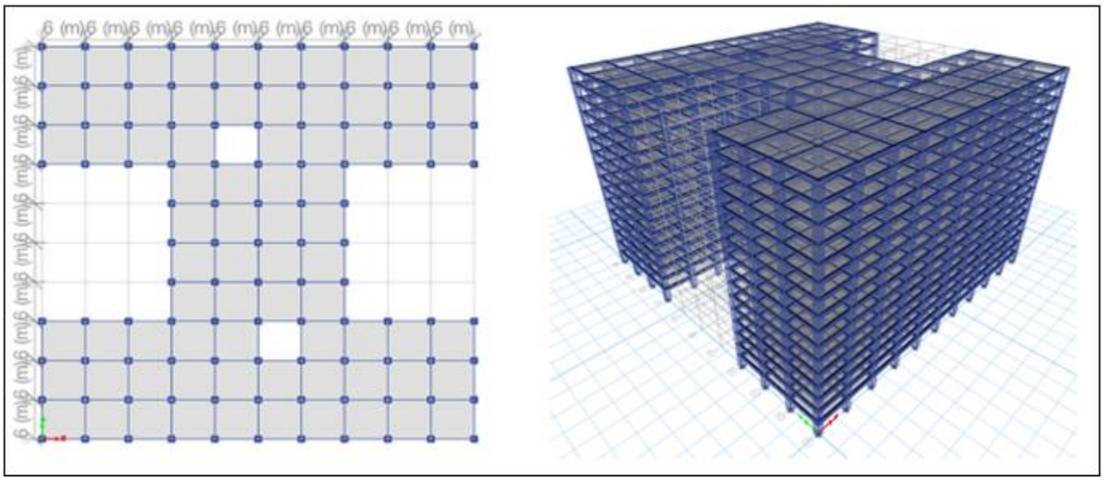

**Figure 1:** Analytical model of the G+15 L-shaped RC SMRF building

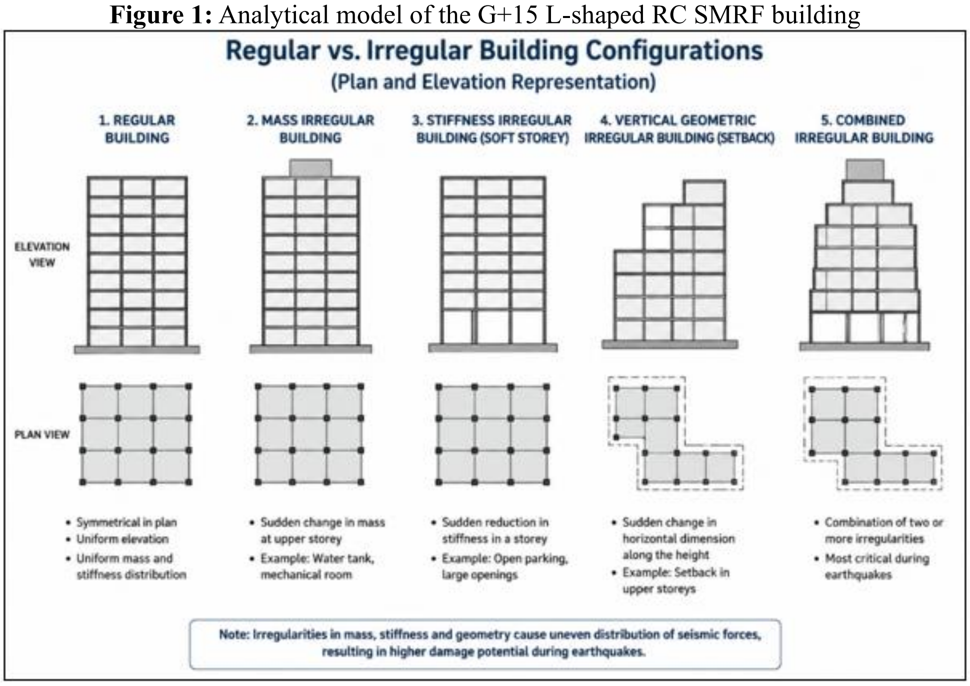


**Figure 2:** Schematic representation of the irregularity configurations

## 3. Results

The complete set of extracted response quantities is presented in Table 4.

The following subsections discuss each response parameter in turn.

**Fundamental natural period**

The fundamental period ranged from 1.936s (M9) to 2.134s (M4). The mass-irregular models exhibited a progressive increase in period with the number of irregular levels, reflecting the added flexibility associated with the redistributed mass.

**Table 4:** Comparative summary of seismic response quantities for Models M1-M13.

| Model | Period | Base shear X | Base shear Y | Max disp. X | Max disp. Y | Max drift X | Max drift Y | Max acc. X | Max acc. Y |
|---|---|---|---|---|---|---|---|---|---|
| | (s) | (kN) | (kN) | (mm) | (mm) | (-) | (-) | (mm/s2) | (mm/s2) |
| M1 | 2.022 | 24111.98 | 23398.51 | 44.52 | 46.23 | 0.00141 | 0.00145 | 827.0 | 819.2 |
| M2 | 2.054 | 24377.25 | 23560.72 | 44.93 | 46.84 | 0.00142 | 0.00146 | 820.1 | 813.8 |
| M3 | 2.076 | 24110.81 | 23397.49 | 45.33 | 47.35 | 0.00143 | 0.00148 | 826.1 | 813.5 |
| M4 | 2.134 | 25795.12 | 25103.29 | 47.25 | 49.29 | 0.00151 | 0.00155 | 823.8 | 805.5 |
| M5 | 2.036 | 23991.97 | 23313.36 | 44.81 | 46.65 | 0.00129 | 0.00133 | 790.9 | 775.5 |
| M6 | 2.051 | 24059.65 | 23409.44 | 44.55 | 46.52 | 0.00140 | 0.00144 | 783.3 | 772.1 |
| M7 | 2.055 | 24095.27 | 23442.93 | 44.22 | 46.17 | 0.00141 | 0.00145 | 797.7 | 781.3 |
| M8 | 1.962 | 23895.03 | 21557.00 | 43.49 | 52.82 | 0.00139 | 0.00166 | 948.6 | 934.0 |
| M9 | 1.936 | 23107.55 | 19894.63 | 43.48 | 54.04 | 0.00134 | 0.00167 | 949.9 | 960.5 |
| M10 | 1.943 | 22127.51 | 19421.00 | 43.89 | 53.89 | 0.00126 | 0.00163 | 940.5 | 944.8 |
| M11 | 2.008 | 23892.48 | 21610.12 | 44.30 | 48.62 | 0.00140 | 0.00165 | 884.5 | 868.2 |
| M12 | 2.017 | 23357.41 | 20126.51 | 44.36 | 47.82 | 0.00136 | 0.00169 | 884.3 | 893.4 |
| M13 | 2.027 | 22552.88 | 19544.76 | 44.54 | 47.24 | 0.00130 | 0.00169 | 882.6 | 887.5 |

In contrast, the vertical geometric-irregular models displayed the lowest periods, consistent with the reduction in participating mass at the upper setback levels. The stiffness-irregular and combined models produced intermediate values close to the reference. Notably, the shortest period model (M9) did not yield the smallest seismic demand, confirming that period alone is an incomplete indicator of severity.

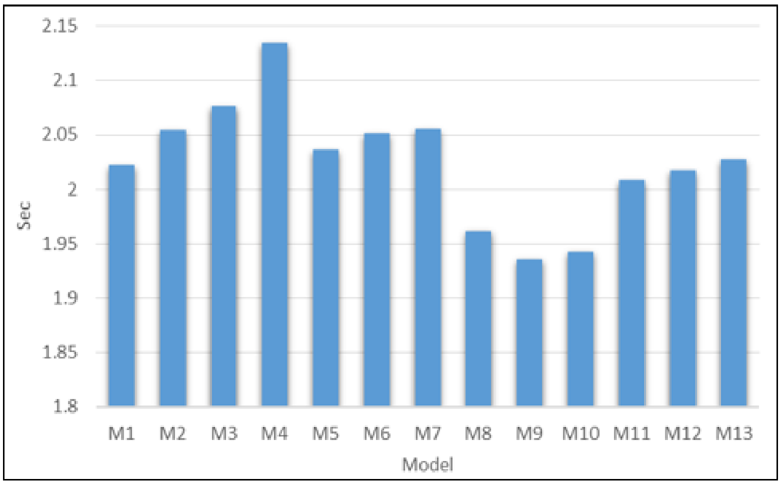


**Figure 3:** Fundamental natural period across Models M1-M13

### 3.1. Base shear

Model M4 produced the largest base shear in both directions, reaching 25795.12kN in X and 25103.29kN in Y, an increase of approximately 7% over the reference in each direction. This confirms that mass irregularity distributed across three levels increases the overall seismic force demand. Several vertical geometric-irregular and combined models (M9, M10, M13) developed lower base shear than the reference, yet, as shown below, these same models produced elevated displacement or acceleration demands. Base shear is therefore a necessary but insufficient basis for comparison.

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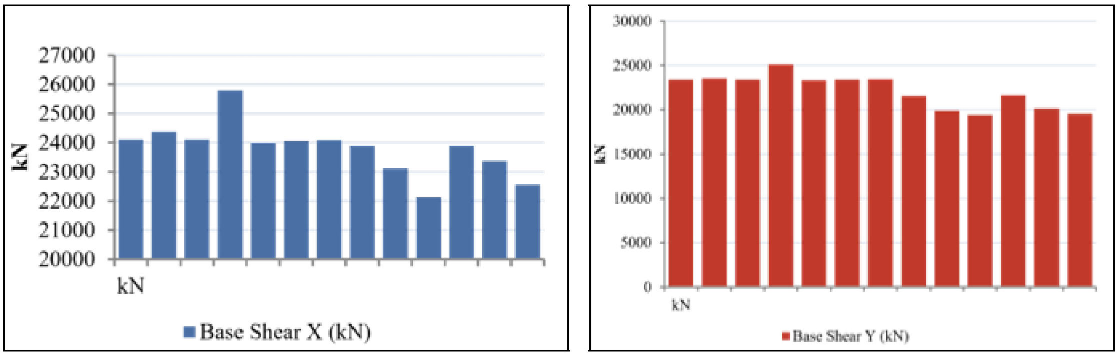


**Figure 4:** Base shear comparison in the X and Y directions.

### 3.2. Storey displacement

Roof displacement increased with height in all models, with the maximum occurring near the upper storeys. In the X direction, the maximum displacement of 47.25mm was recorded for M4. In the Y direction, the maximum displacement of 54.04mm occurred in M9. The larger Y-direction sensitivity of the vertical geometric-irregular models reflects the interaction between the setback and the asymmetric L-shaped plan, which reduces effective lateral resistance along the shorter leg of the plan.

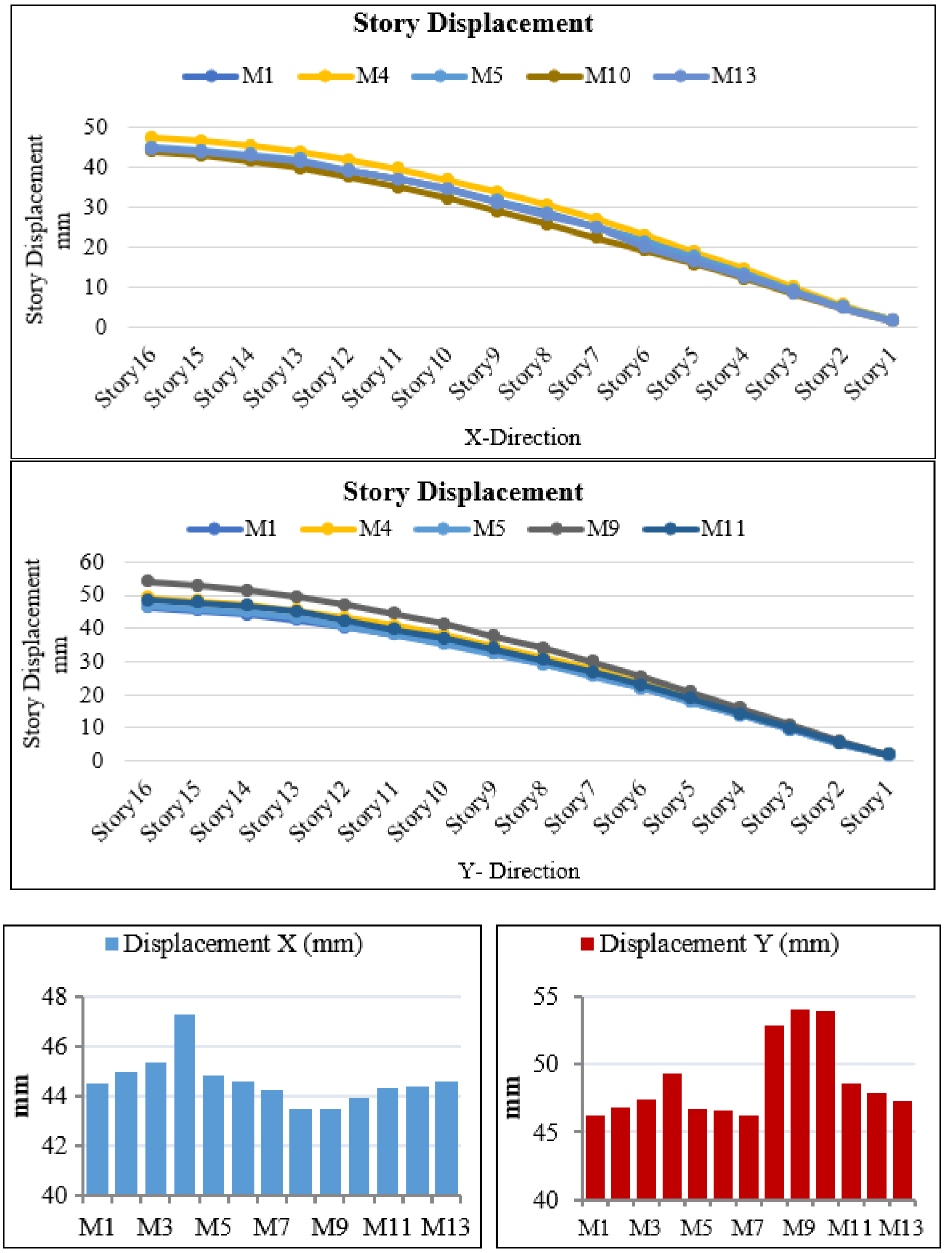


**Figure 5:** Storey displacement profiles and maximum-displacement comparison

### 3.3. Inter-storey drift

The maximum X-direction drift ratio of 0.00151 was obtained for M4, consistent with its governing role for X-direction deformation. The maximum Y-direction drift ratio of 0.00169 was produced by both M12 and M13, the combined-irregularity models at two and three levels. The equality of the peak drift in M12 and M13 is significant: it indicates that the addition of a further irregular level did not proportionally increase the governing drift. This demonstrates that the interaction of the irregularities with the overall stiffness distribution, rather than the mere number of irregular storeys, controls the drift demand.

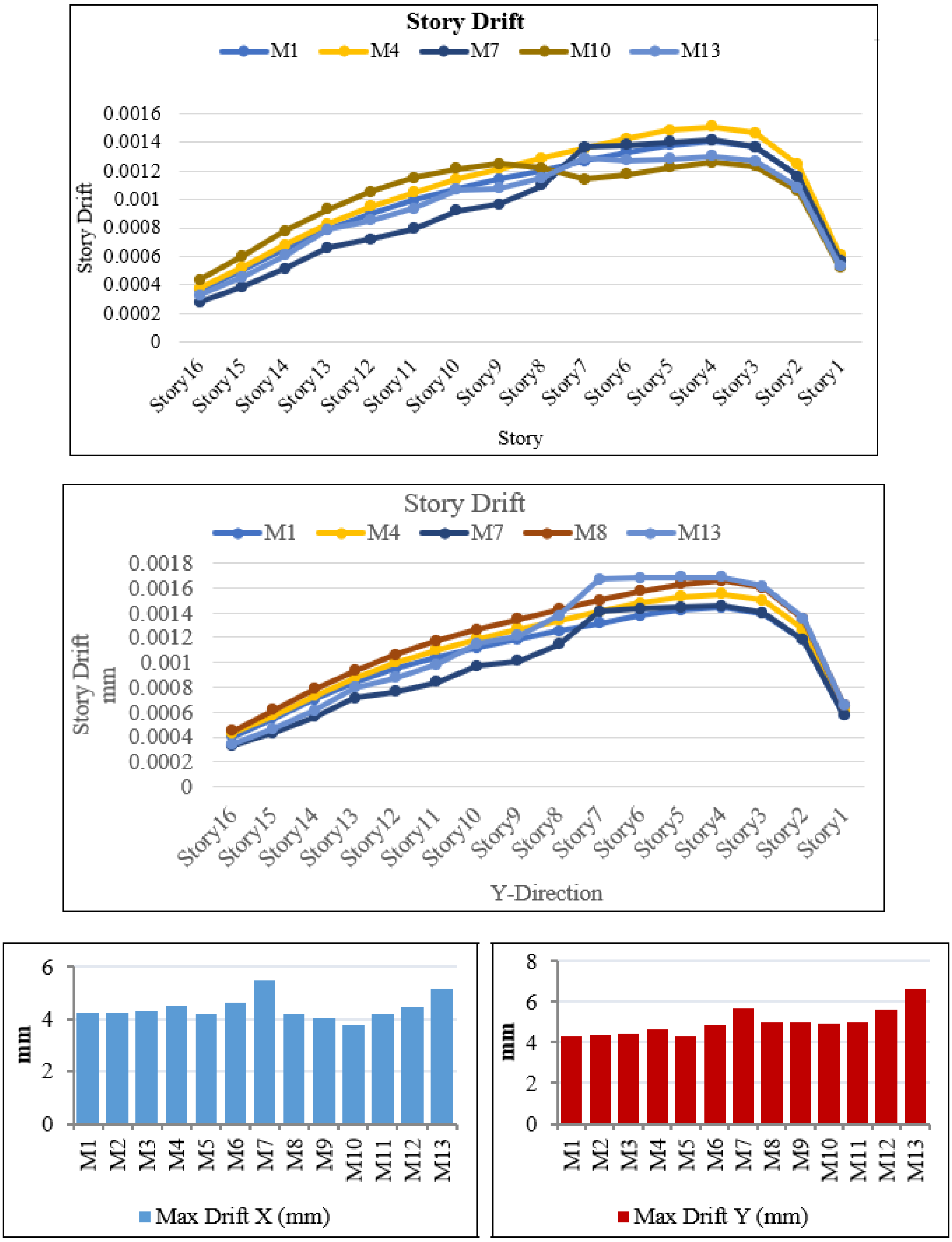


**Figure 6:** Inter-storey drift profiles and maximum-drift comparison

### 3.4. Storey acceleration

The storey acceleration response was dominated by the vertical geometric irregular models. Model M9 recorded the maximum accelerations of 949.9mm/s$^2$ in X and 960.5mm/s$^2$ in Y. The vertical geometric-irregular group (M8- M10) consistently exhibited higher accelerations than the mass- and stiffness irregular groups, indicating that abrupt geometric discontinuities excite dynamic amplification that is particularly relevant for acceleration-sensitive non-structural components and contents.


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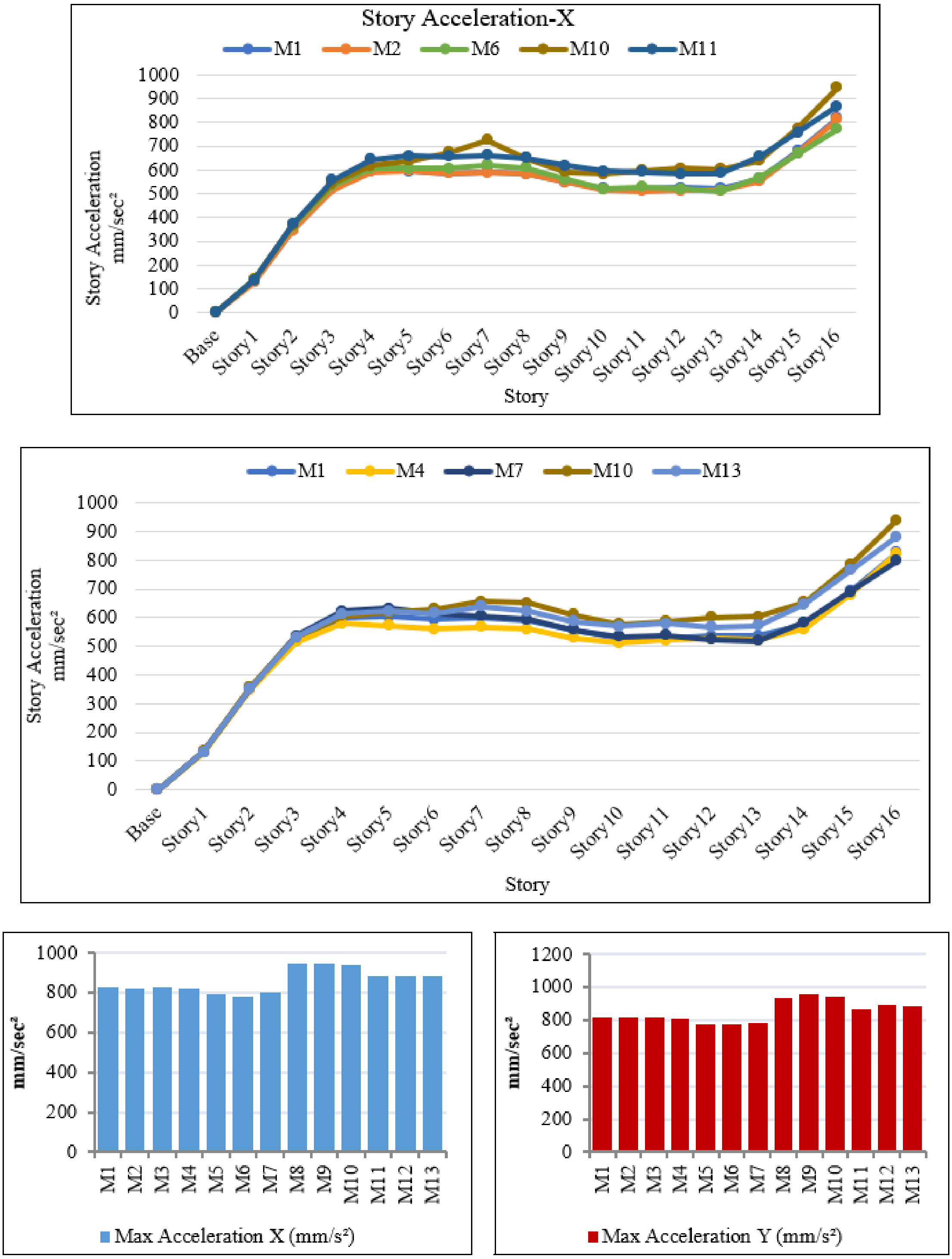


**Figure 7:** Storey acceleration profiles and maximum-acceleration comparison

## 4. Discussion

### 5.1 Effect of individual irregularities

The results indicate distinct roles for the three individual irregularity types. Mass irregularity (M2-M4) was the dominant driver of global force demand and X-direction deformation. As the number of mass-irregular levels increased from one to three, the fundamental period rose from 2.054s to 2.134s, and the base shear, X-direction displacement and X-direction drift attained their overall maxima in M4. This behaviour is consistent with earlier observations that added mass increases both the inertial demand and the overall flexibility of the system [22, 16].

Stiffness irregularity (M5-M7) did not govern any global maximum in this study. The X-direction displacements of these models remained close to or below the reference, and their accelerations were lower than those of the geometric-irregular group. Nevertheless, the stiffness-irregular models altered the deformation distribution, and their drift patterns differed from the reference. This confirms that soft-storey effects must still be evaluated carefully at the local level, even when global indicators appear benign; the potential for local drift concentration remains a concern consistent with previous soft-storey studies [10].

Vertical geometric irregularity (M8-M10) produced the most pronounced dynamic effects. Despite having the lowest fundamental periods, these models governed the acceleration response and Y-direction displacement. This apparent paradox, in which a stiffer, shorter-period structure exhibits higher acceleration demand, is characteristic of setback frames in which higher-mode participation and abrupt geometric transitions amplify the dynamic response [18, 4, 15]

### 5.2 Effect of combined irregularities

The combined-irregularity models (M11-M13) did not maximise the fundamental period, base shear or overall displacement, but they governed the Y-direction inter-storey drift, reaching 0.00169 in both M12 and M13. Because inter-storey drift is the primary indicator of relative deformation and damage potential between adjacent storeys, this outcome is of considerable practical importance. The results demonstrate that the interaction of mass, stiffness and geometric discontinuities can shift the governing response parameter compared with the individual cases, in agreement with fragility-based findings that identify combined irregularities as particularly critical [17, 23].

### 5.3 Direction dependence and the role of plan asymmetry

A recurring theme in the results is the direction dependence of the response. Mass irregularity governed the X-direction response, whereas vertical geometric irregularity governed the Y-direction response. This behaviour is attributable to the asymmetric L-shaped plan, in which the lateral stiffness and effective resisting width differ between the two directions. Consequently, a configuration that is critical in one direction may be sub-critical in the perpendicular direction. This observation underscores the necessity of bidirectional evaluation for plan-asymmetric buildings.

### 5.4 Displacement versus drift

The comparison between M9 and the combined models illustrates the distinction between total displacement and relative drift. M9 produced the highest roof displacement in the Y direction, yet M12 and M13 produced the highest Y-direction drift. Total displacement reflects the cumulative lateral movement of a storey relative to the base, whereas drift reflects the differential movement between adjacent storeys. From a damage-assessment perspective, the two measures can identify different critical models, and both should be reported.

### 5.5 Implications of lower base shear

An important practical implication is that a lower base shear cannot be interpreted as improved seismic performance. Models M9, M10 and M13 exhibited base shears below the reference while simultaneously developing elevated displacement, drift or acceleration. Reliance on base shear alone would therefore misclassify these configurations as favourable. The findings support a multi-parameter assessment philosophy for irregular RC frames.

### 5.6 Amplification factors

Expressing the peak responses relative to the reference model using Equation (5) provides a compact severity measure. For the governing cases, the approximate amplification factors are $\kappa \approx 1.07$ for X-direction base shear (M4), $\kappa \approx 1.17$ for Y-direction displacement (M9), $\kappa \approx 1.17$ for Y-direction acceleration (M9), and $\kappa \approx 1.17$ for Y-direction drift (M12/M13). These factors indicate that even moderate irregularities can increase specific demands by roughly 7-17% relative to the regular frame, with the deformation- and acceleration-related demands more sensitive than the global force demand.

## 5. Conclusions

A comparative response spectrum study of a G+15 L-shaped RC SMRF building with mass, stiffness, vertical geometric and combined irregularities was conducted using ETABS in accordance with IS 1893 (Part 1): 2016. Thirteen models were analysed, and five seismic response parameters were evaluated in both principal directions. The principal conclusions are:

1) The fundamental period varied between 1.936s and 2.134s. The maximum period occurred in the mass-irregular model M4 (three levels), and the minimum in the vertical geometric-irregular model M9 (two levels).
2) Mass irregularity governed the global force demand and X-direction deformation. Model M4 produced the maximum base shears of 25795.12kN (X) and 25103.29kN (Y), the maximum X-direction displacement of 47.25mm, and the maximum X-direction drift ratio of 0.00151.
3) Vertical geometric irregularity governed the acceleration response and Y-direction displacement. Model M9 produced the maximum Y-direction displacement of 54.04mm and the largest accelerations of 949.9mm/s$^2$ (X) and 960.5mm/s$^2$ (Y), despite having the lowest fundamental period.
4) Combined irregularities governed the Y-direction inter-storey drift. Models M12 and M13 both reached a drift ratio of 0.00169, and the equality of these values shows that increasing the number of irregular storeys does not necessarily increase the governing response proportionally.
5) The seismic response was strongly direction-dependent for the asymmetric L-shaped plan, with different irregularity types controlling the X and Y directions. Bidirectional assessment is therefore essential.
6) A lower base shear did not indicate improved performance, as several configurations with reduced base shear developed elevated displacement, drift or acceleration demand.
7) No single irregularity configuration governed all response parameters. Consequently, the seismic assessment of vertically irregular RC frames should employ fundamental period, base shear, displacement, drift and acceleration simultaneously rather than relying on any single criterion.

## 6. Limitations and Future Work

The present study is confined to linear elastic response spectrum analysis of a single building height, plan configuration, soil category and seismic zone. Masonry infill contribution, soil-structure interaction and explicit torsional irregularity effects were not modelled. Future investigations may extend the framework to nonlinear static (pushover) and nonlinear time-history analyses using recorded ground motions, incorporate infill and soil-structure interaction, examine additional building heights and plan shapes, and assess the effectiveness of mitigation measures such as shear walls or bracing for controlling the demands identified herein. Such extensions would enable a more comprehensive characterisation of post-elastic behaviour and damage concentration near irregular storeys.

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