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Seismic Analysis of Regular and Irregular-Shaped RC Buildings of Varying Heights with Shear Wall at Different Locations (STAAD Pro.)

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Abstract: The effect of plan irregularity on buildings of varying heights and the mitigation of additional torsion through the strategic placement of shear walls are explored in this study using Response Spectrum Analysis in STAAD Pro. This research focuses on the performance and behaviour of concrete buildings, especially under seismic loading, by varying the location and orientation of shear walls along the building plan to determine their optimal positions. Several structural models, including regular structures and those with plan irregularities, such as L- and T-shaped buildings of various heights, incorporate shear walls at various locations and orientations along the building plan. Studies were then conducted on their structural behaviour and analyzed to yield valuable insights into the effects of plan irregularity and the effective use of shear walls. Results demonstrated that placing a shear wall at the center of the perimeter walls provided better resistance to torsional motion due to plan eccentricity and to lateral displacement, whereas placing a shear wall at the building core provided better resistance to vertical ground displacement. These findings provide valuable insights into structural design optimization, offering a potential pathway to the development of aseismic structures.

Keywords: Seismic Analysis; Shear Wall; Response Spectrum; Storey Drift; Plan Irregularity; Concrete Buildings; Structural Designs; Ground Displacement; Aseismic Structures.

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1. Introduction

Earthquakes are naturally occurring phenomena that can cause catastrophic damage to human life, infrastructure, and the environment. This establishes the need to understand the effects of earthquakes and their impact on structures to ensure structural safety and protect human life. A Detailed Study of the effects of earthquakes on structures not only provides knowledge of their damaging effects but also offers valuable means to mitigate them and incorporate them into our aseismic design. As a Structural Engineer, it is crucial to understand the various parameters of a building that can significantly improve its seismic efficiency. Regular buildings are always symmetrical, have uniform dimensions, and generally respond more

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predictably to seismic forces. On the other hand, Irregular Buildings have geometrical or mass irregularities that result in torsional motion, uneven force distribution, and potential failure points. Plan irregularity refers to buildings with structural or mass distribution irregularities in their plan view (such as non-rectangular shapes and asymmetric layouts), leading to less predictable and unique behaviour under seismic loads. Shear Walls are vertical structural plate elements designed to resist lateral forces and play a crucial role in stabilizing a building and limiting its lateral displacement. The location of shear walls within the structure has a major impact on the building's structural performance under seismic loading.

The height of a building widely influences its seismic response. Taller and Slender buildings tend to experience more lateral displacement than shorter, rigid buildings. The dynamic behaviour of buildings changes with height and must be carefully considered when designing structures. The position and orientation of shear walls significantly influence a building's lateral resistance to seismic forces, as the building's response varies with their relative positions and orientations. An incorrect placement can lead to twisting movements and other structural issues. However, the optimal placement of shear walls in buildings with plan irregularities, particularly in varying height scenarios, is not well documented. Building height is a critical factor in seismic performance, as taller buildings generally experience greater lateral forces. However, the manner in which this height interacts with plan irregularity has not been sufficiently studied, leaving a knowledge gap regarding the most effective design strategies for such structures. While the effects of shear wall and building geometry on seismic performance are well known, a detailed optimization model that accounts for both plan irregularity and varying heights across different locations remains lacking. Designers often rely on simplified methods and do not use advanced Structural Analysis tools such as STAAD Pro to analyze these factors comprehensively.

2. Role of Plan Irregularity and Height in Buildings

Regular buildings usually exhibit predictable behaviour under seismic loads. However, structures with plan irregularity exhibit unpredictable seismic behaviour due to torsional effects arising from the eccentricity between the building's center of mass and its center of rigidity (Figure 1).

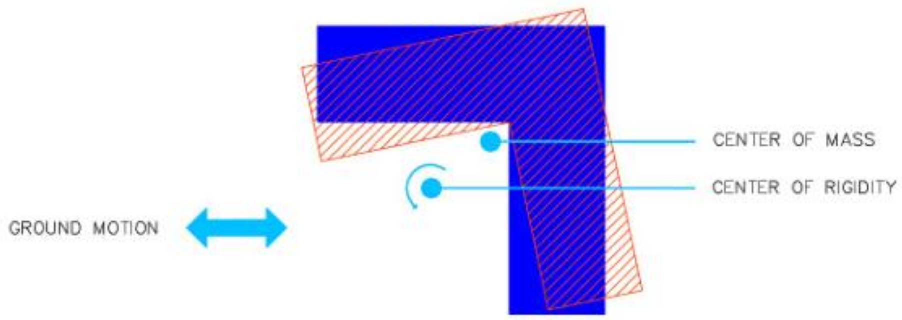

Figure 1: Torsional irregularity due to offset between the center of mass and center of rigidity in seismic response

These additional torsions, when coupled with normal ground shaking, tend to cause devastating effects on the structure, which require further research and documentation. Moreover, the height of a building plays a major role in its structural behaviour. Although seismic base shear increases with building height, the effect of height on the building's structural performance needs further investigation, especially in cases with plan irregularity.

3. Literature Review

In structural engineering, ensuring that buildings can withstand seismic activity is crucial, as earthquakes remain a major threat to infrastructure. Numerous researchers have thoroughly examined how factors such as building design, shear wall positioning, structural irregularities, and analytical methods influence seismic resilience. Together, these studies offer important insights into both conceptual planning and advanced modeling, laying the groundwork for constructing buildings that are both safer and more cost-effective. Dražić and Vatin [1] emphasized that the initial configuration of a building plays a decisive role in determining its seismic behavior. They argued that a well-conceived conceptual plan at the preliminary design stage significantly improves seismic performance. Standard building structures with regular configurations are easier to model, analyze, and design for seismic resistance, making them more economical while ensuring safety. In contrast, irregular structures often exhibit highly complex, unpredictable behavior during earthquakes, making their seismic responses difficult to predict with accuracy. For such cases, early involvement of structural engineers is crucial. By equipping architects with knowledge of seismic design principles and construction technologies, it is possible to balance aesthetics with safety, ensuring that design choices do not compromise structural stability.

Building on the importance of configuration, Sadraddin et al. [2] explored the role of shear walls in enhancing the seismic resistance of high-rise reinforced concrete buildings. Using stochastic methods to account for uncertainties, they compared four 12-storey buildings with identical plan dimensions but different lateral load-resisting systems. Incremental dynamic analyses were performed under selected ground motions, and fragility curves were developed for three boundary states. The findings indicated that incorporating shear walls substantially improves structural performance under seismic forces. Moreover, shear walls located internally provided better seismic resistance than those placed externally, highlighting the importance of placement in structural design. Complementing this perspective, Wdowicki and Wdowicka [3] presented an analytical algorithm for three-dimensional structures with shear walls that uses a cross-partition continuous connection method. Their approach incorporated limitations on the derivative of the shear strength function. The method's validity was tested against experimental results, yielding a high degree of correlation. This confirmed that robust computational methods can simulate complex shear wall behavior with reasonable accuracy, thereby aiding design optimization. Similarly, Coull and Smith [4] analyzed deep shear walls subjected to lateral loads in one-storey structures using one-dimensional finite difference methods. Their experimental investigations of masonry wall and reinforced concrete frames highlighted the stabilizing effect of floor slabs, wall-panel interactions, and joint performance under seismic loading.

These studies collectively underscore that both analytical and experimental methods are essential in capturing the multifaceted behavior of shear wall systems. Case studies of real earthquakes further illustrate the importance of shear walls. Ozkul et al. [5] investigated two buildings in Van, Turkey, affected by the 2011 earthquake. Nonlinear time-history analysis, performed using SAP2000 and real earthquake records, showed stark differences in performance. One building, which had inadequate shear wall provisions, suffered severe damage, while the other—designed according to updated seismic codes—sustained considerably less damage. Retrofitting and strengthening strategies involving shear walls were proposed to enhance the resilience of the damaged building. This study emphasized the critical role of code compliance and realistic nonlinear modeling in evaluating seismic vulnerability. More recently, Zhang and Mueller [6] proposed a novel methodology to identify optimal shear wall patterns for tall buildings, ensuring that structural requirements align with architectural constraints. Their system automates the design of reinforced concrete structures, reducing computational time and storage requirements while effectively handling irregular shear wall configurations. By addressing both engineering and architectural concerns, this approach represents a step toward integrating performance-based design with practical construction requirements. While shear walls substantially improve structural stiffness and drift control, irregularities in building configurations introduce additional complexities. Alecci et al. [7] examined torsional irregularities in reinforced concrete school buildings and assessed the applicability of ASCE code provisions.

Nonlinear analyses revealed that the prescribed code threshold values may not always reflect actual torsional demands, sometimes underestimating or overestimating the irregularity effects. Similarly, Khanal and Chaulagain [8] studied L-shaped buildings subjected to seismic excitations at varying angles of incidence. Using finite element methods, they found that irregular buildings exhibited mixed translational and rotational modes, resulting in higher seismic demands than in regular buildings. The inter-storey drift was most pronounced at the first floor, demonstrating that lower stories are more vulnerable in irregular configurations. Further extending this line of inquiry, Abdel Raheem et al. [9] highlighted that floor irregularities in moment resisting frame (MRF) buildings significantly influence seismic demands. Irregular structures require higher resistance values, and conventional code-based combination rules may be inadequate for capturing torsional effects. Their findings stressed the necessity of close collaboration between architects and structural engineers to ensure structural safety. Neglecting torsional and irregularity-induced demands can lead to unsafe designs and increased vulnerability. Finally, Simon et al. [10] reiterated that shear walls are effective in reducing lateral displacements and inter-storey drifts under earthquake loading, while simultaneously increasing structural stiffness. Importantly, shear walls must be strategically placed in both principal directions of the building to maximize efficiency. This insight is consistent with earlier findings, underscoring that while the inclusion of shear walls is essential, their orientation and distribution are equally critical.

Taken together, the reviewed literature highlights several recurring themes. First, conceptual design and regularity in building configuration remain fundamental to seismic safety, as emphasized by Dražić and Vatin [1]. Second, shear walls are consistently shown to improve seismic performance, but their placement, configuration, and design methodology play critical roles in determining effectiveness [2]; [5]; [6]; [10]. Third, irregular buildings, especially those with torsional or geometric complexities, demand more rigorous analysis and often exceed the provisions of standard codes [7]-[9]. Fourth, the synergy between experimental investigations, computational modeling, and real-world case studies enhances the reliability of design approaches [4]. Finally, collaboration between architects and engineers is indispensable for achieving both aesthetic and structural objectives in earthquake-resistant buildings [5]. The literature affirms that achieving seismic resilience requires a multifaceted approach—beginning with thoughtful conceptual design, reinforced by structural systems such as shear walls, validated through advanced modeling and experimental methods, and finally implemented through adherence to seismic codes and collaborative practices [3]. As urbanization drives the construction of taller and more complex buildings, these insights serve as guiding principles for future research and practice in earthquake engineering.

4. Methodology

Figure 2 shows the step-by-step process used in this study, starting with identifying the problem, the research goals, and the main hurdles. After that, the input parameters are standardized to ensure the variables used in the modeling process are consistent, accurate, and reliable. After that, parametric models are developed to show how inputs and the expected system behavior are mathematically and computationally related.

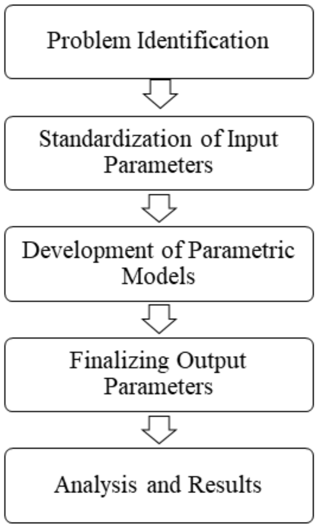

Figure 2: Flow chart for design methodology

The next step is to finalize the output parameters, including the performance indicators and evaluation criteria. Finally, the procedure ends with analysis and findings, during which the outputs are reviewed, understood, and checked to ensure they support useful conclusions. This systematic technique guarantees logical advancement, reproducibility, and the resilience of the comprehensive study framework.

5. Modelling and Analysis in STAAD Pro

Base models of three structural shapes with the same plan area (400 sqm) were selected for study (Figure 3):

- R0-rectangular building with plan dimensions 20x20 m.
- L0-L shaped building with plan dimensions 25x25 m (Overall).
- T0-T Shaped Building with plan dimension 20x30 m (Overall).

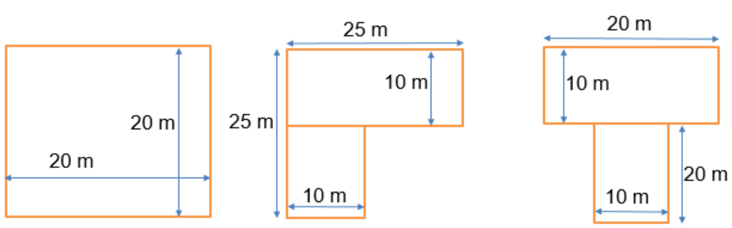

Figure 3: Base models of three structural shapes

The basic plan shapes are chosen so that the models exhibit regularity, plan irregularity along one axis, and plan irregularity along both axes (Figure 4).

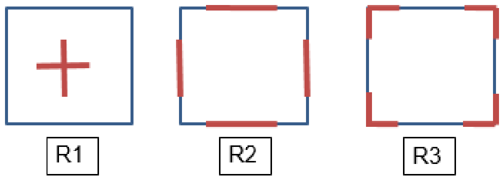

Figure 4: Rectangular models with shear wall at different locations

Based on these three base models of defined structural shapes, an additional 10 models incorporating shear walls at different orientations are developed, ensuring that the volume or area of the shear wall is the same across the models (Figure 5).

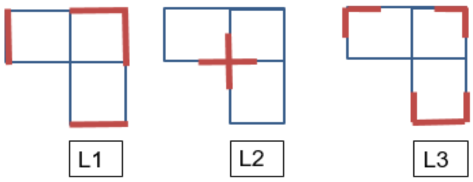

Figure 5: L-Shaped models with shear wall at different locations

Then the storey height of these models is increased by 5 stories, in increments of 5 stories. The building height variation was considered relative to the chosen area, with H/D ranging from 0.75 to 2.25. The shear wall locations are confined to several areas along the building, including the center, edges, and corners (Figure 6).

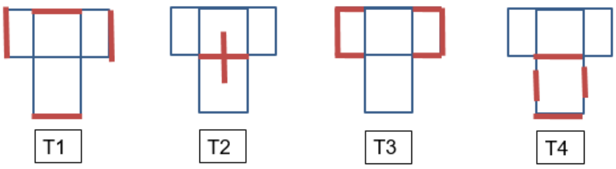

Figure 6: L-Shaped models with shear wall at different locations

The locations of the shear walls are also chosen so that the resistance offered by the shear walls in the X and Z directions across the models for comparison shall be equal.

5.1. Modelling

The beam and columns are modelled in STAAD Pro as beam elements. The shear walls are modelled as plate elements (Figure 7).

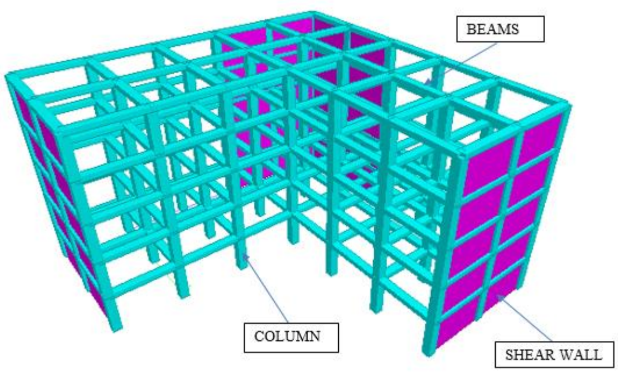

Figure 7: STAAD model showing beam, column, and shear wall

5.2. Property Specification

The following properties are assigned in STAAD for all model types based on the number of storeys (Table 1).

Table 1: Cross-section of beam and column

Elements	Up to 5 Storeys	From 6th Storey to 10th Storey	From 10th Storey to 15th Storey
5 Storey Building			
Column	0.60x0.60m	NA	NA
Beam	0.35x0.60m	NA	NA
Shear Wall	0.3m (Thick)	NA	NA
10 Storey Building			
Column	0.80x0.80m	0.60x0.60m	NA
Beam	0.40x0.80m	0.35x0.60m	NA
Shear Wall	0.4m (Thick)	0.4m (Thick)	NA
15 Storey Building			
Column	1.00x1.00m	0.80x0.80m	0.60x0.60m
Beam	0.50x1.00m	0.40x0.80m	0.35x0.60m
Shear Wall	0.5m (Thick)	0.5m (Thick)	0.5m (Thick)

The above-mentioned member profiles are used for all model types based on the number of storeys, ensuring that dead load and live load are standardized across models. The choice of the above member sizes is based on preliminary assumptions.

5.3. Specifications

- Property reduction factor of 0.7 for Columns and 0.35 for beams is chosen as per IS 1893-Part 1 Cl. 6.4.3.1.
- Floor Diaphragm is defined for the nodes of all floors to account for the un-modelled Slab element.

5.4. Support Assignment

Fixed Supports are assigned for all column bases to account for the end conditions.

5.5. Load Assignment

5.5.1. Dead Load

- The self-weight of the structure and unmodelled load of the slab are applied in Load case 1: DL.
- The self-weight of the structure is applied using the self- weight command in STAAD with a factor of -1.

The dead load for the unmodelled concrete floor is applied as a floor load of 3.75 kN/m2, calculated as shown below:

Load per unit area = Specific Wt. of Concrete x Thickness of Slab = 25*0.15 = 3.75 kN/m^2

5.5.2. Live Load

Live Load of magnitude 2kN/m2 is applied for all floors of the building, including the roof.

5.5.3. Reference Load

The reference load accounts for the application of mass (Seismic weight) in three directions required for response spectrum analysis. The seismic weight is applied as 100% dead load and 50% live load.

5.5.4. Seismic Load – Lateral Direction

- Seismic Loads in the X and Z directions are applied as response-spectrum loads in STAAD Pro.
- The following factors are considered for the application of Seismic Load.
- Seismic Zone Factor Z = 0.24 (Seismic Zone IV)
- Importance Factor = 1.2

- Response Reduction Factor = 5 (Special moment resisting frames)
- The Earthquake load is applied as a response spectrum load using IS 1893 (Part 1): 2016, with the spectrum table defined for Medium Soil Conditions and a damping of 5%.

The direction factor in the respective X or Z directions is calculated as follows:

Direction Factor X or Z = Z/2*I/R=0.24/2*1.2/5 = 0.0288

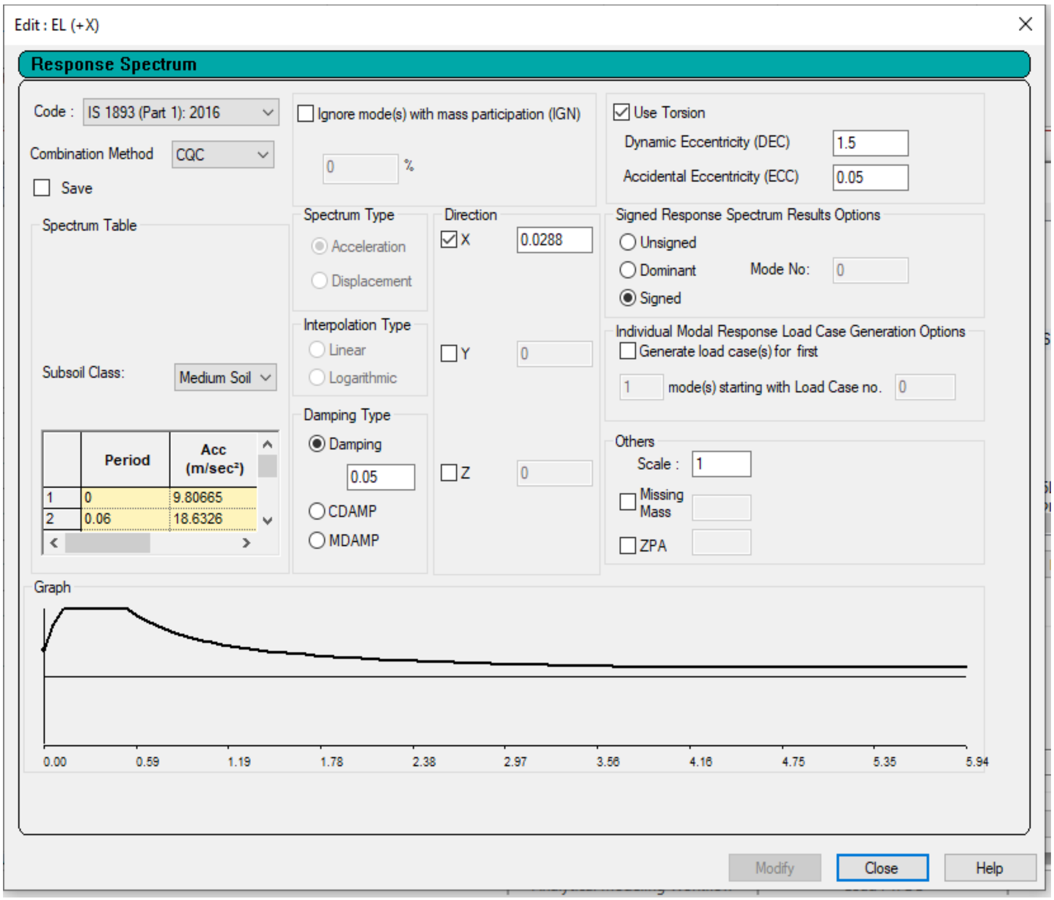

Figure 8: Seismic load application for X direction

Figure 8 displays the Response Spectrum description for the EL (+X) seismic stress example used in structural analysis software based on IS 1893 (Part 1): 2016. The Complete Quadratic Combination (CQC) approach is chosen for modal combination because it works well for vibration modes that are close together. The analysis is conducted for medium soil conditions with a damping ratio of 5%, indicative of standard seismic design specifications. To see how the structure will respond to earthquakes, researchers examine torsional effects using a dynamic eccentricity of 1.5 and an accidental eccentricity of 0.05. The response spectrum graph at the bottom shows how spectral acceleration changes over time. This is used to determine the seismic forces acting on the building.

5.5.5. Seismic Load – Vertical Direction

For Seismic Load in the Vertical direction, the factors considered for Seismic Load in the lateral direction are applied. However, the direction factor in the Y direction is calculated as follows:

Direction Factor Y=2/3*Z/2*I/R*2.5=0.048

Torsional effects are not considered for the vertical seismic loads (Figure 9).

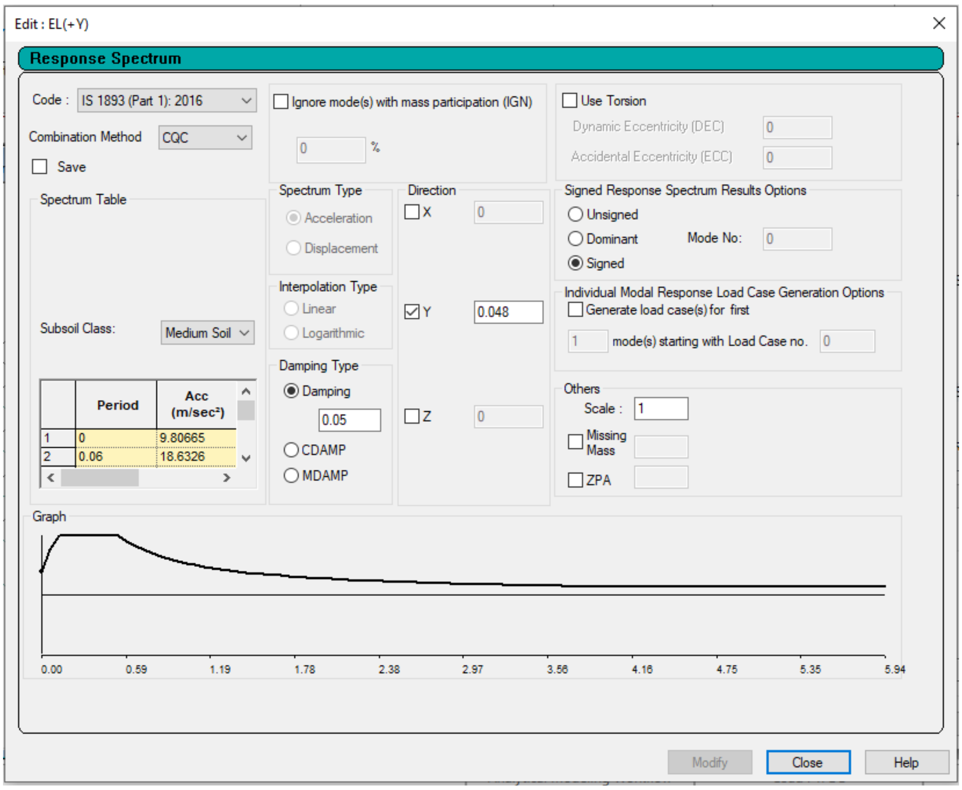

Figure 9: Seismic load application for the Y direction

5.5.6. Load Combinations

Load Combinations are applied as per IS 456 and IS 1893. The method for combining earthquake loads in mutually perpendicular directions is applied in accordance with the clause. 6.3.4.1 of IS 1893, such that when the maximum response occurs in one direction, the responses in the other two directions are 30% of their respective maximums (Table 2).

Table 2: Load combinations

No.	Load Combinations
Strength Combinations	
1	1.5 (DL + LL)
2	1.2 (DL + LL + EL)
3	1.5 (DL + EL)
4	0.9 DL + 1.5 EL
Serviceability Combinations	
1	1 (DL + LL)
2	1 (DL + EL)
3	1 DL + 0.8 LL + 0.8 EL

6. Results and Discussion

The results from STAAD, which are compared, include storey lateral displacement, vertical displacement, base shear, storey shear, and additional torsion per storey.

6.1. Storey Lateral Displacement

- The provision of shear walls greatly reduces the building's deflection.
- The models with shear walls at the peripheral walls (Model R2, L1, T1) are found to be more effective at controlling deflection than the models with shear walls at the corners (Model R3, L3, T3).
- The models with a shear wall at the central core (Model R1, L2, T2) experience greater deflection.

- The displacement of Model T4 is found to be higher than that of Model T3.
- The effectiveness of deflection control with shear walls at corners decreases with increasing height.

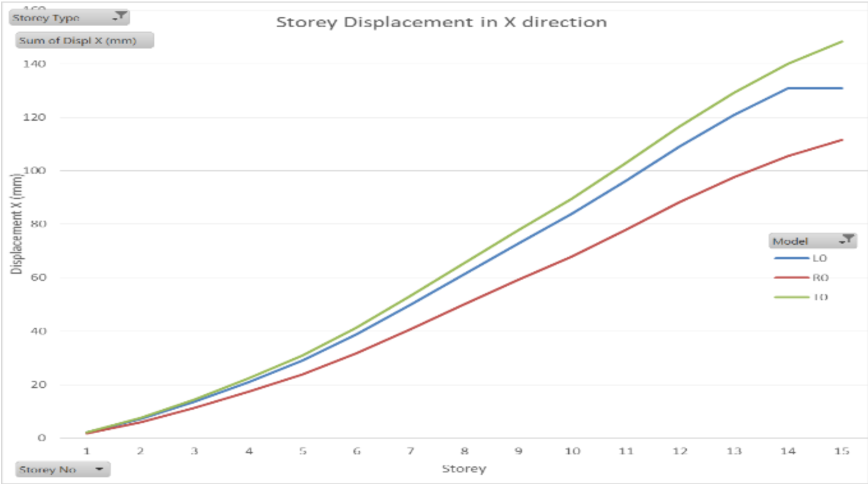

Figure 10: Graph showing comparison of displacement x - models without shear wall for a 15-story building

Figure 10 shows how the storey moves in the X direction for four distinct structural models (L1–L4) across 15 storeys. As the storey height increases, the displacement gradually increases. The biggest displacement happens at the top storey. L2 has the greatest displacement among the models, indicating it is less rigid than the others.

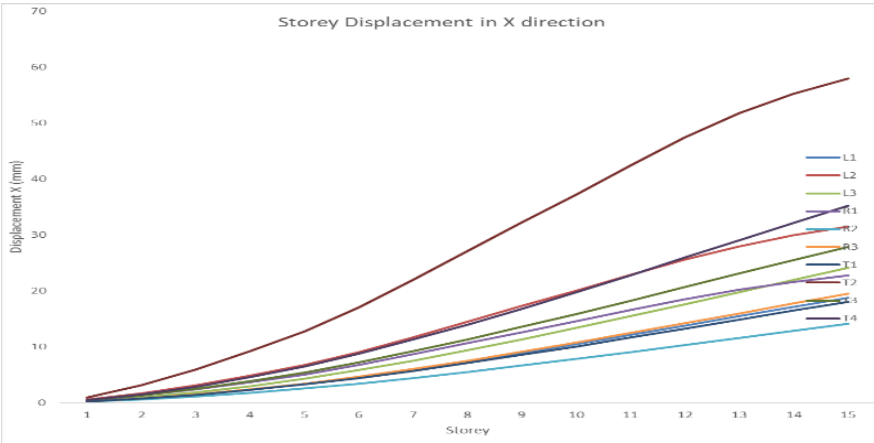

Figure 11: Graph showing comparison of displacement x - models with shear wall for a 15-story building

Conversely, models like L4 and L3 have relatively reduced movement, indicating enhanced lateral resistance and structural integrity. Figure 11 shows how different shear wall layouts can significantly affect the building's response to loading.

6.2. Displacement in the Y Direction

- Shear walls contribute less to controlling vertical deflections at floors due to seismic loading in the +/-Y direction.
- Vertical deflections of models with a shear wall at the periphery/corners are even higher than those without a shear wall.
- However, the shear wall at the building's central core helps reduce vertical deflection, thereby demonstrating its effectiveness in reducing floor vibrations caused by the up-and-down motion of seismic waves.

6.3. Base Shear and Base Shear / Seismic Weight Ratio

- Base Shear values or ratios of models with shear walls are high compared to the same models without shear walls.

- Base Shear values of models with a shear wall at the periphery are found to be more than those with a shear wall at the centre.
- Base shear values of L-Shaped buildings are found to be more than those of T-Shaped buildings. This can be attributed to the predominantly higher torsion in L-shaped buildings.
- For T-Shaped Buildings, providing a shear wall at the web portion (T4) is found to experience less base shear than providing a shear wall in the flanged portion (T3).
- The base shear-to-seismic weight ratio decreases as the building height increases (Figure 12).

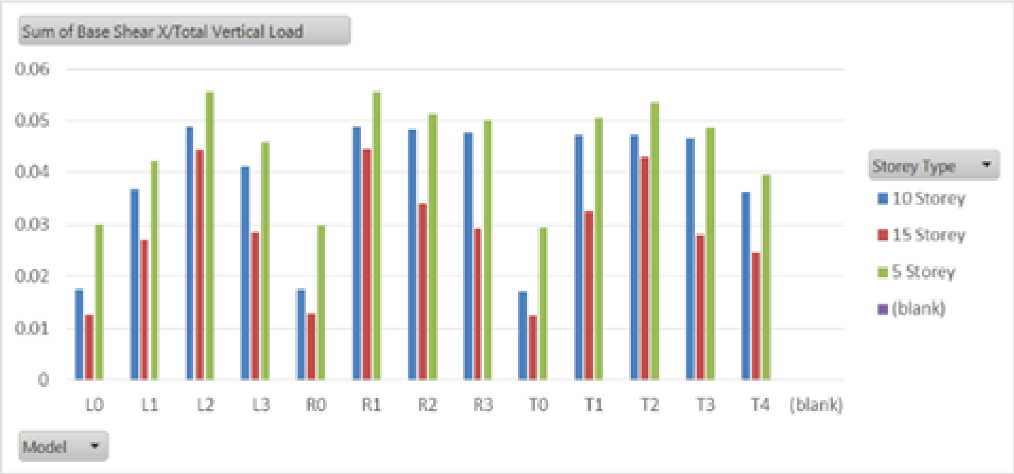

Figure 12: Graph showing comparison of base shear to seismic weight ratio for various models with shear wall

6.4. Storey Shear

- For T-Shaped buildings with 10 storeys, it is observed that the storey shears are almost equal for shapes T1, T2, and T3. However, the storey shear is comparatively lower for model T4.
- However, when the building height increases to 15 Storeys, Model T1 becomes more effective than T2 and T4.
- On observation of a 5-storey building, it is observed that, though base shear is high for L-Shaped Buildings, the storey shear reduces as the height of the building increases, and the storey shear of the topmost storey is almost less than that of regular rectangular buildings.
- For 5 Storey buildings, the storey shear for L – Shaped and Rectangular buildings is almost equal. However, for a 15-storey building, there is a significant difference in the storey shear, indicating that plan irregularity in storey shear increases with height (Figure 13).

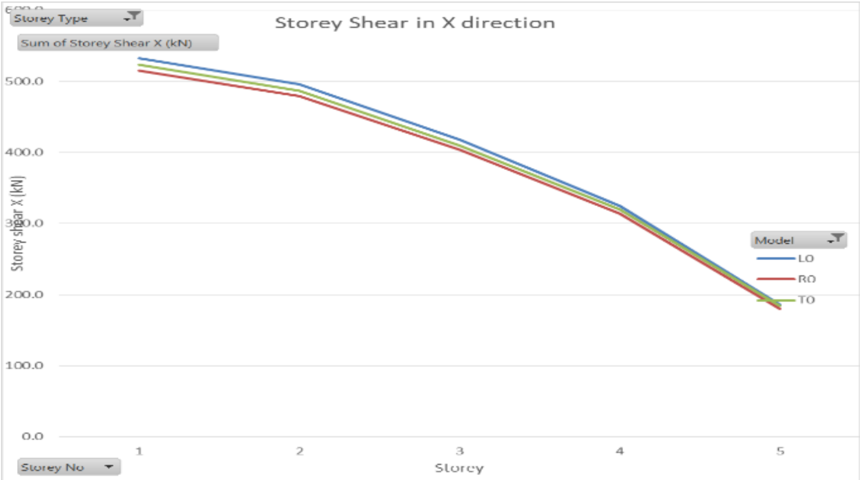

Figure 13: Graph showing comparison of storey shear for various models without a shear wall of a 5-storey building

Figure 14 shows how storey shear changes in the X direction for different structural models over five storeys. The storey number is on the X-axis, while the total storey shear in kilonewtons (kN) is on the Y-axis. The graph compares several models, including L1, L2, L3, R1, R2, R3, T1, T2, T3, and T4. For all types, the storey shear is highest on the first storey and gets lower as you go up to the subsequent storeys.

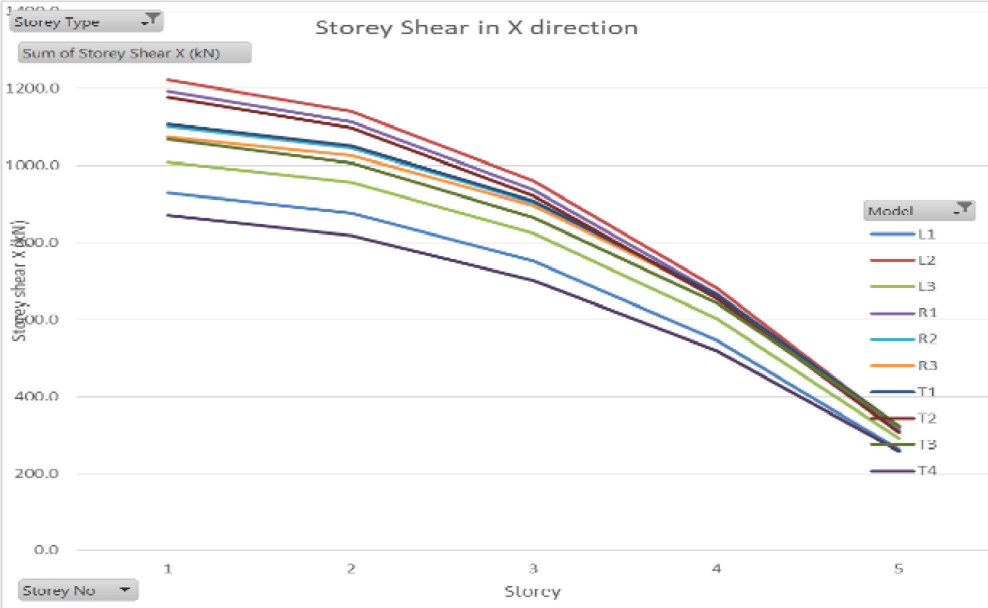

Figure 14: Graph showing comparison of storey shear for various models with a shear wall of a 5 Storey building

Models L2 and L3 have larger shear values at the lower floors, while model T4 has lower shear values throughout the height. The models show different levels of storey shear, but all curves follow a similar pattern of decreasing from the base to the top storey. This shows how a multi-story building typically responds to lateral forces.

6.5. Additional Torsion Per Storey

The additional torsion per storey for a 15-storey building across all model types has been analysed (Figure 15).

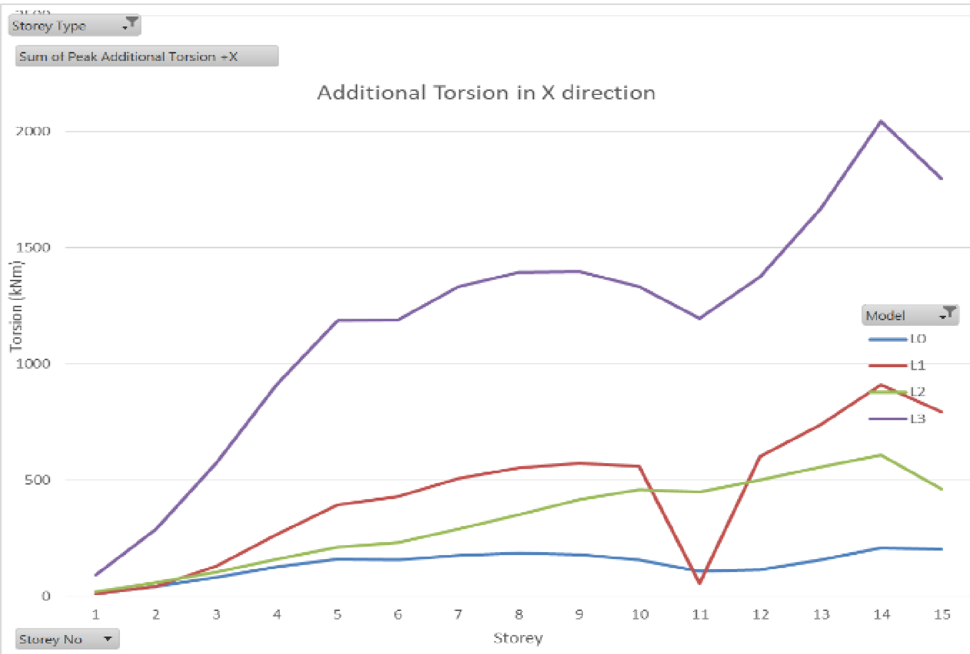

Figure 15: Graph showing comparison of additional torsion X for an L-shaped building

These additional torsions were then compared with the respective eccentricities between the centre of mass and the centre of rigidity in the specific directions (Figure 16).

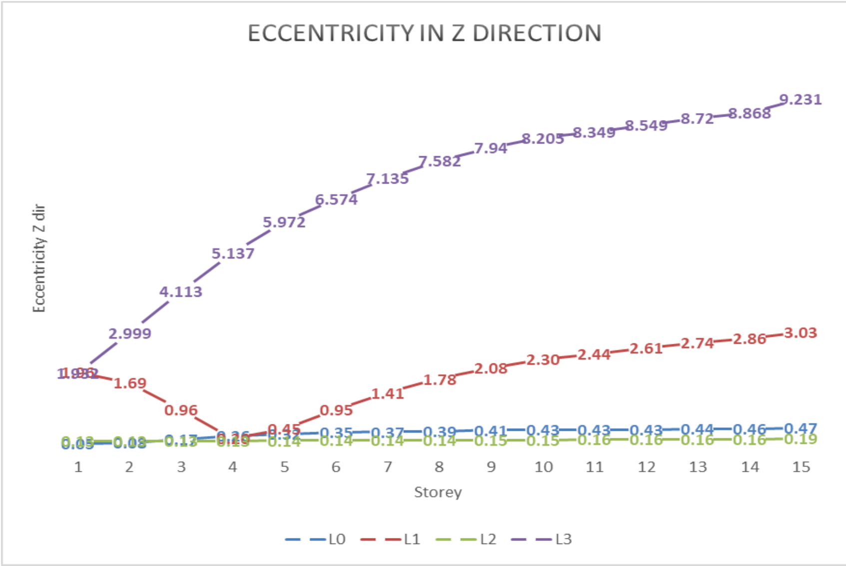

Figure 16: Graph showing variation of eccentricity (Z dir) for an L-shaped building

- It is observed that lower eccentricities at lower floors generally result in lower torsion at higher floors.
- It is observed that the torsion of models without shear walls is generally lower than that with shear walls.
- It is observed that, though the eccentricities are lower for model L2 than for the other models, the torsion in the Z direction is significantly higher. This can be attributed to higher eccentricities at lower floors. In addition, model L2 lacks parallel shear walls, which can provide effective torsional restraint, thereby reducing additional torsion on the buildings.
- T3 and T4 have the same eccentricity in the X direction. However, the torsion of T4 is lower due to effective restraint from the slender web portion.

7. Conclusion

The following major points have been found through excessive analysis of results:

- The ratio of base shear to the building's overall seismic weight tends to decrease as the number of floors increases. This means taller buildings respond to earthquake forces differently from shorter ones. The building's dynamic properties, such as its natural period and flexibility, also improve as it grows taller. Because of this extra flexibility, the building tends to absorb and release some of the seismic energy by changing shape rather than sending all the force directly to the base. Because of this, taller structures have a smaller percentage of their structural mass that adds to base shear.
- In structural models like Model L3, where shear walls are put at the corners, these walls are less effective in controlling lateral deflection as the structure gets taller. Corner shear walls work well to keep low- and medium-rise buildings from moving sideways, but they don't work as well in taller buildings. This happens because the greater height makes the structure more flexible and causes greater lateral drift, making it harder for corner shear walls to keep the whole structure stiff.
- It has been observed that increasing the distance between the center of mass and the center of stiffness in the lower floors reduces the extra twisting effects in the higher floors. This regulated eccentricity helps move the lateral forces around the structure more evenly. By addressing this structural imbalance at lower levels, the torsional reaction on the top floors can be reduced. This makes the building more stable and better able to handle ground motion.
- Placing peripheral edge shear walls along the buildings' outside borders is a great way to control lateral drift and lower base shear. Placing them on the outside of the structure increases its overall moment of inertia, making it stronger against lateral forces such as earthquakes and wind loads. On the other hand, shear walls in the central core primarily help stabilize the building vertically. They work especially well to stop vertical movement induced by seismic ground motion and make the building's core, which commonly has elevators and staircases, stiffer. Using both peripheral and core shear walls together can greatly improve a multi-story building's earthquake resistance.

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Conflicts of Interest Statement: The authors declare no conflicts of interest and affirm that the study was conducted with complete academic independence and integrity.

Ethics and Consent Statement: The study complied with relevant ethical standards, and informed consent was obtained from all participants prior to their involvement.

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