Sustainable Seismic Performance Assessment of Asymmetrical High-Rise RC Buildings Using NonLinear Dynamic Analysis

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Abstract: Earthquakes pose a continuous threat to life and infrastructure, especially in regions of high seismicity, making accurate assessment of structural response critical for the safety and resilience of modern buildings. This study explores the seismic performance of asymmetrical high-rise reinforced concrete (RC) buildings—specifically L-, T-, U-, and E-shaped configurations—which inherently introduce plan irregularities due to uneven mass and stiffness distribution. These irregularities lead to complex dynamic behaviors such as torsional effects and stress concentrations that can significantly influence seismic response. Using ETABS 2021, 30-storey Special Moment Resisting Frame (SMRF) models were developed and analyzed with two advanced dynamic methods: Nonlinear Time History Analysis (NLTHA) and Response Spectrum Analysis (RSA), following the provisions of IS 1893:2016. The models incorporated geometric and material nonlinearity, P-delta effects, and Rayleigh damping, with seismic input based on the 2001 Bhuj earthquake (Zone V) to simulate realistic ground motion. Key parameters such as storey displacement, inter-storey drift, base shear, stiffness, and joint acceleration were evaluated across all configurations. The results demonstrated that the shape and plan irregularity of a building critically affect its seismic performance. The L-type configuration showed superior performance in controlling displacement and maintaining stiffness, while T- and E-types exhibited higher vulnerability to lateral forces. Moreover, NLTHA consistently predicted more realistic and severe responses compared to RSA, underscoring the necessity of nonlinear analysis for irregular structures. Supporting UN Sustainable Development Goal 11 (Sustainable Cities and Communities), this research advances the understanding of seismic design for irregular high-rise buildings, contributing to the development of disaster-resilient infrastructure.

Keywords: Seismicity, Dynamic Behaviour, Torsional effects, Damping

1. INTRODUCTION

A structure is classified as vertically irregular when it shows significant variation in mass, stiffness, or strength along its height. According to IS 1893:2016, mass irregularity exists when a floor has over 200% the mass of an adjacent floor. A weak storey has less than 60% the stiffness of the floor above, while a soft storey has stiffness below 70%. These irregularities often arise intentionally—such as when upper floors are designed with smaller columns or beams for utility spaces—or unintentionally, due to inconsistent construction practices or material use. These changes lead to non-uniform distribution of seismic forces, affecting structural performance during earthquakes. When irregularities occur in the plan layout, they are termed horizontal irregularities, commonly seen in asymmetrical designs. While structural codes provide guidelines to classify and limit irregularities, they often generalize severity without fully accounting for the complex dynamic effects introduced by irregular geometry.

A structure is said to be irregular, when certain structural parameters exceed the limits specified by standards. Table 2 shows the limits for mass (M), stiffness (S), vertical geometric (VG), re-entrant corner (REC) and torsional (T) irregularities prescribed by IS1893:2016 (Part I).

Table 2. Irregularity limits prescribed by IS 1893:2016 (Part I) (i = storey number, a = adjacent storey number, Δ_{max} = maximum deformation and Δ_{avg} = average deformation).

Type of irregularity	Classification	Limits
Mass (M)	Vertical irregularity	$M_i < 1.5M_a$
Stiffness (S)	Vertical irregularity	$S_i < S_{i+1}$
Vertical geometry (VG)	Vertical irregularity	$VG < 1.25\ VG_a$
Re-entrant Corner (R)	Horizontal irregularity	$R_i <= 15\%$
Torsion (T)	Horizontal irregularity	$\Delta_{max} <= 1.5\Delta_{avg}$

Table 1.1 Irregularity limits prescribed by IS 1893:2016 (Part I)

2. OBJECTIVES OF THE STUDY

1. To investigate critical seismic response parameters, including Maximum storey displacement, Inter-storey drift, Base shear, Storey stiffness, and Joint acceleration.
2. To study the influence of structural asymmetry on seismic behavior, particularly torsional effects and displacement irregularities.
3. To compare and interpret the results of NLTHA and RSA for each asymmetrical configuration in order to identify the most seismically efficient geometry.
4. To provide recommendations for improving seismic performance in irregular high-rise buildings based on the analysis outcomes.
5. To contribute to Sustainable Development Goal 11 (Sustainable Cities and Communities) by promoting resilient building design and enhancing urban safety in earthquake-prone regions.

3. SCOPE OF THE STUDY

- Development of analytical models of 30-storey RC buildings with four distinct asymmetrical configurations: L-shape, T-shape, U-shape, and E-shape.
- Application of Non-Linear Time History Analysis (NLTHA) and Response Spectrum Analysis (RSA) as per the seismic guidelines outlined in IS 1893:2016 (Part 1).
- Use of Bhuj 2001 ground motion data scaled appropriately for Zone V seismic intensity as per Indian standards.
- Evaluation of key seismic parameters such as maximum storey displacement, inter-storey drift, base shear, and stiffness degradation.
- Comparative performance assessment among the different building configurations to identify the impact of asymmetry on seismic vulnerability.

4. LITERATURE REVIEW

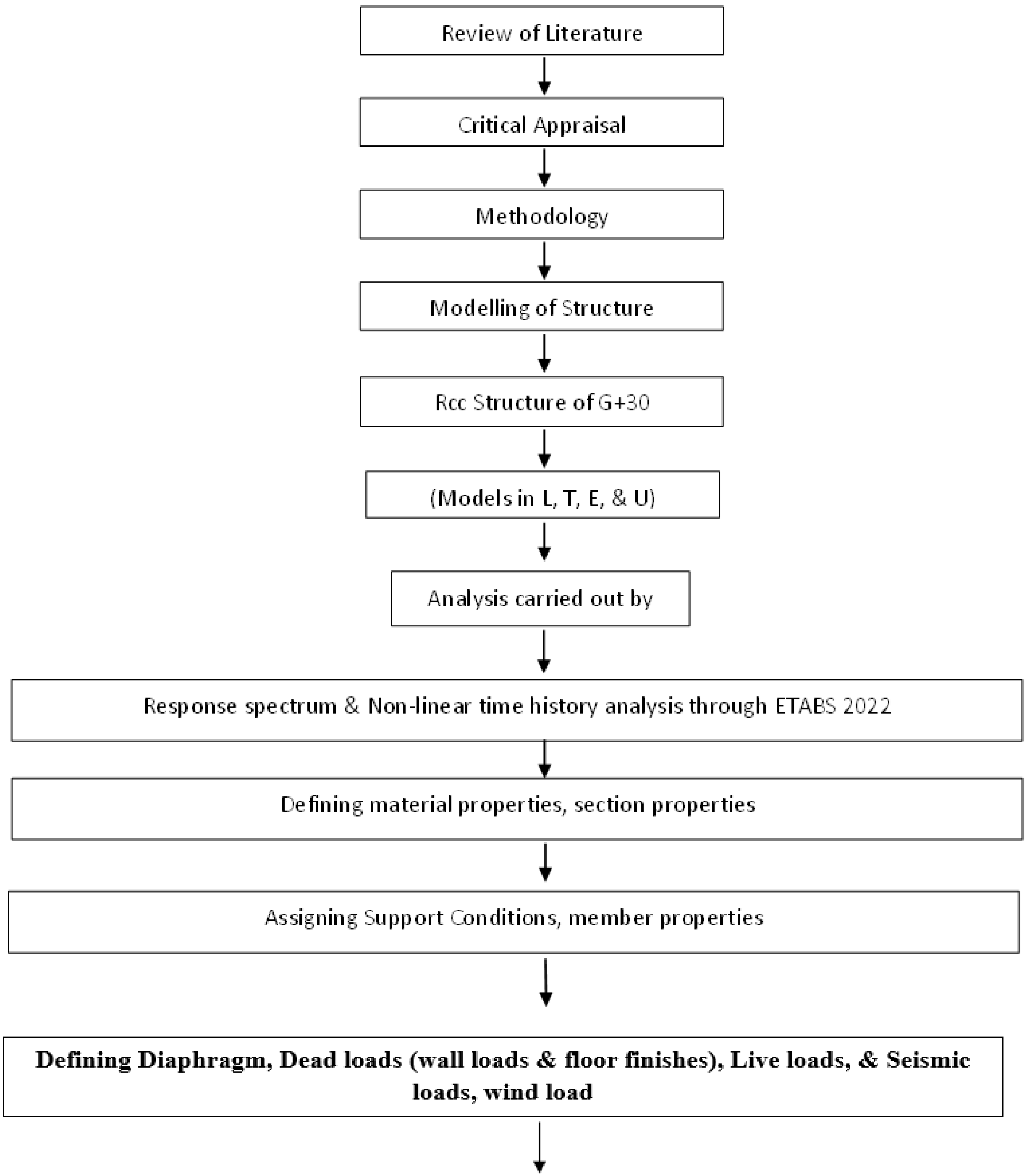
Siva Naveen E, Nimmy Mariam Abraham, Anitha Kumari S D [1] (2019) A study found stiffness irregularity heavily impacts seismic response; proper design must consider irregularity type, location, and degree for optimal performance.
Yogesh Ramesh Vanshe and Nagendra M. V [2] (2020) Symmetrical 20-story buildings in seismic zones perform better; rectangular shapes displace most. Stability requires sufficient columns, irrespective of shape.
Mohammed Zahid Rizwan and S.M. Hashmi [3] (2020) A study found steel bracing, especially X-bracing, significantly improves seismic performance in 10-story RC buildings by reducing displacement and increasing stiffness, proving cost-effective.

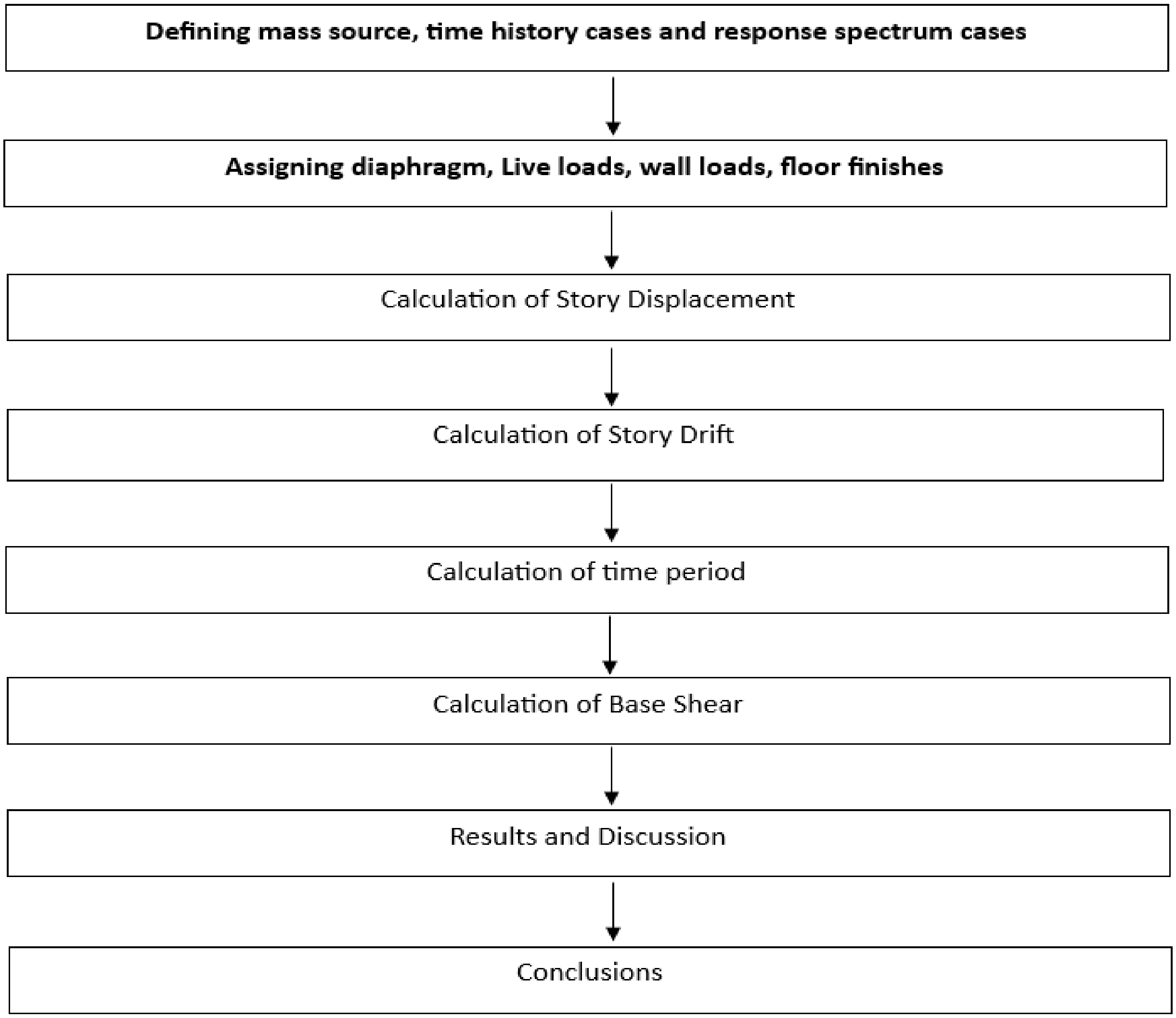
5. METHODOLOGY

5.1 General

Nonlinear Time History Analysis (NLTHA) is a powerful tool for assessing how structures perform during earthquakes. Unlike simpler methods, it uses dynamic inelastic analysis to estimate real strength and deformation demands, especially for buildings with base isolators. NLTHA examines critical factors like global drift and inelastic deformations, providing a nuanced picture of a building's behavior beyond elastic limits. This method accurately captures internal force redistribution and realistic structural responses during inelastic deformation. While complex and time-consuming with no universal codes, NLTHA is indispensable for critical projects needing a realistic understanding of seismic performance.

5.2 Methodology





5.3 Step by Step Process to Perform the Non-Linear Modal Time History Analysis

1. Define the ground acceleration $\ddot{u}_g$ numerically at every time step
2. Define the structural properties.

a. Determine the mass matrix m and lateral stiffness matrix k

b. Estimate the modal dumping ratios ζ_n

Determine the natural frequencies ω_n and natural modes of vibration

3. Determine the modal components s_n of the effective earthquake force distribution.
4. Compute the response contribution of the nth mode by the following steps, which are repeated for all modes.
5. Perform static analysis of the building subjected to lateral forces s_n to determine r_n^{st}, the modal static response for each desired response quantity r.
6. Determine the pseudo –acceleration response $A_n(t)$ of the nth mode SDOF system using numerical step methods.
7. Determine $r_n(t)$ using summation rule given in equation to get the final response.

6. STRUCTURAL MODELING AND ANALYSIS

6.1 Model Description for 30 Story Building

1. Model 1 – L-Type Building
2. Model 2 – T-Type Building
3. Model 3 – E-Type Building
4. Model 4 – U-Type Building

S.No	Variable	Data
1	Type of structure	Moment Resisting Frame
2	Number of Stories	30
3	Floor height	3m
4	Live Load	3.0 kN/m^2
5	Wall load	External wall =12 kN/m Internal wall = 6KN/m
6	Materials	Concrete (M30) and Reinforced with HYSD bars (Fe550)
7	Size of Columns (L,T,U&E)	600x600 mm
8	Size of Beams (L,T,U&E)	300x600 mm
9	Depth of slab (L,T,U&E)	150mm thick
10	Specific weight of RCC	25 kN/m^3
11	Zone	V (as per IS 1893:2016)
12	Importance Factor	1.2
13	Response Reduction Factor	5
14	Type of soil	Medium

Table 6.1 Assumed Preliminary data required for the analysis of the frame

Model 1 – L-Type Building

L-type model consist of 13 bays in x dir and 9 bays in y –dir each bay of 3m spacing each the total area is 513 sq.m.

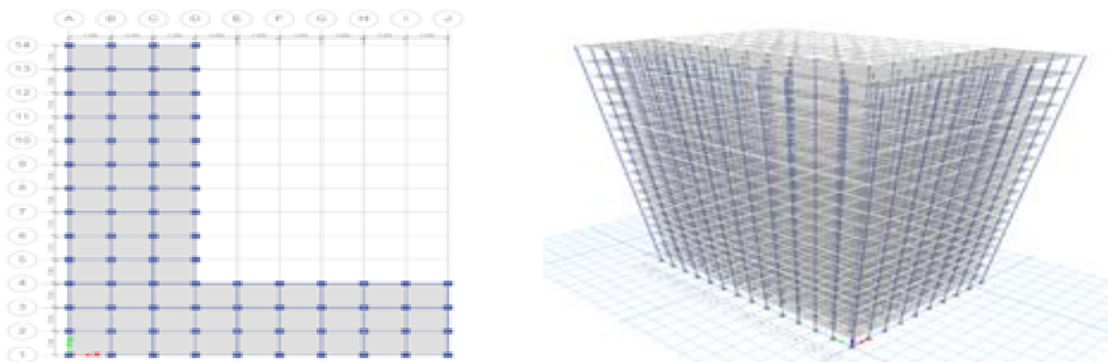


Figure 6.1: Plan & 3D isometric view of L-Type 30-storey RC building modelled in ETABS

Model 2 – T-Type Building

T-type model consists of 13 bays in x dir and 9 bays in y –dir each bay of 3m spacing each the total area is 513 sq.m

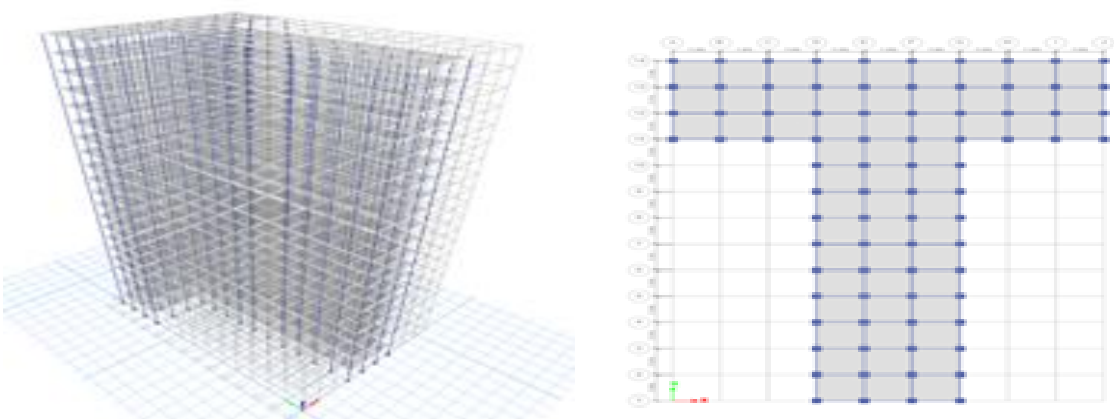
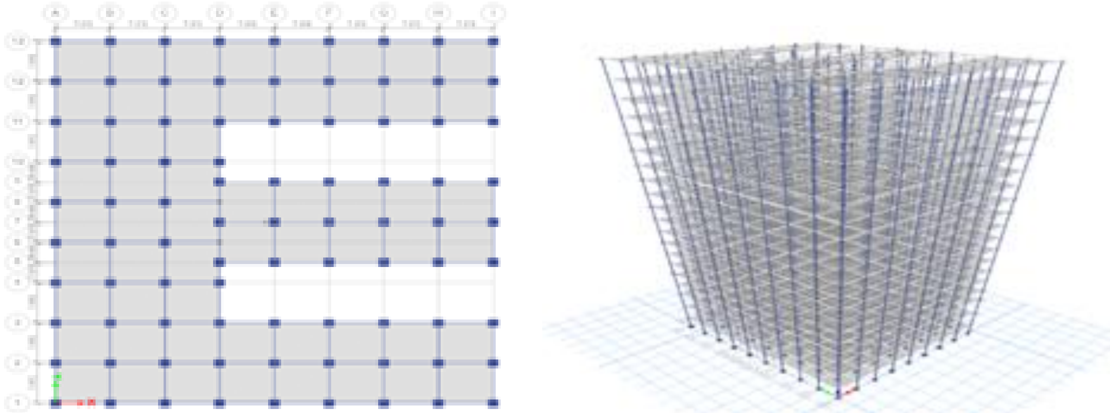


Figure 6.2: Plan & 3D isometric view of T-Type model 30-storey RC building modelled in ETABS

Model 3 – E-Type Building

E-type model consists of 9 bays in x dir and 8 bays in y –dir each bay of 3m spacing each the total area is 513 sq.m.

Figure 6.3: Plan & 3D isometric view of E-Type model 30-storey RC building modelled in ETABS



Model 4 – U-Type Building

U-type model consists of 13 bays in x dir and 8 bays in y –dir each bay of 3m spacing each the total area is 513 sq.m

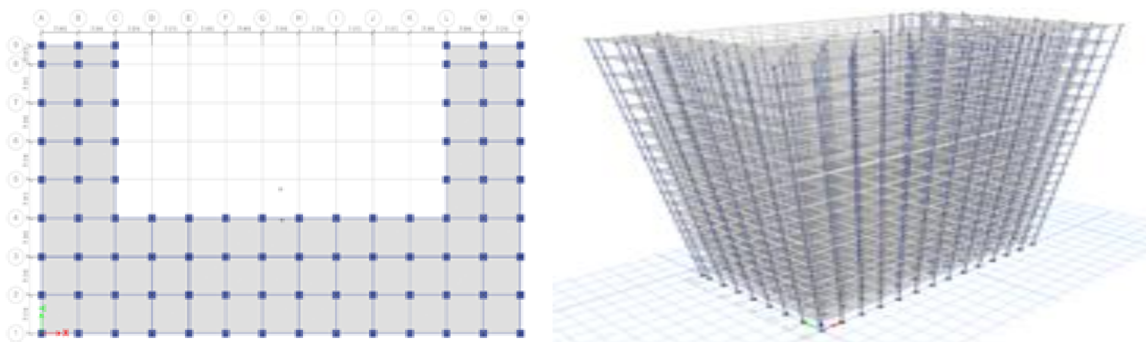
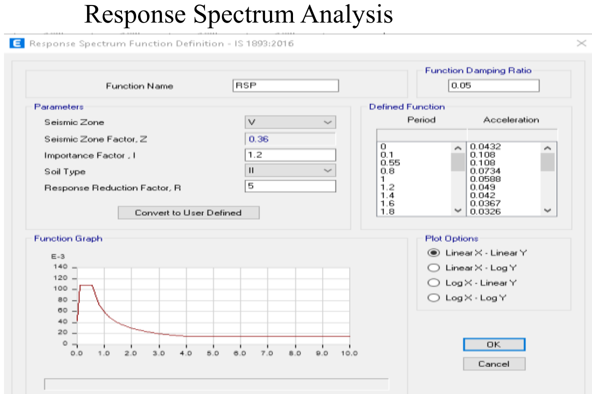


Figure 6.4: Plan view of U-Type model 30-storey RC building modelled in ETABS.

6.2 Analysis Methods

There are four types of analysis methods: linear static, linear dynamic, nonlinear static and nonlinear dynamic Structural loads will reach collapse loads, and material stresses will be above yield stresses during earthquake loads. Therefore, it is necessary to add material and geometric nonlinearity into the study to acquire better findings. Aside from the distribution of demands and strength, these approaches also provide information about the deformation and ductility of structures.

Response Spectrum Analysis



Nonlinear Time History Analysis

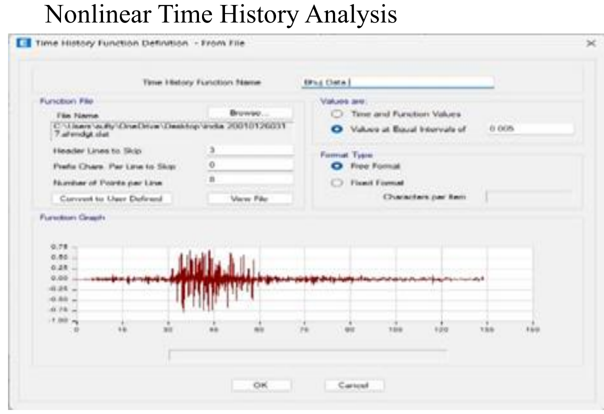


Figure 6.5: Response spectrum function definition in Etabs, BHUJ component earthquake ground acceleration record.

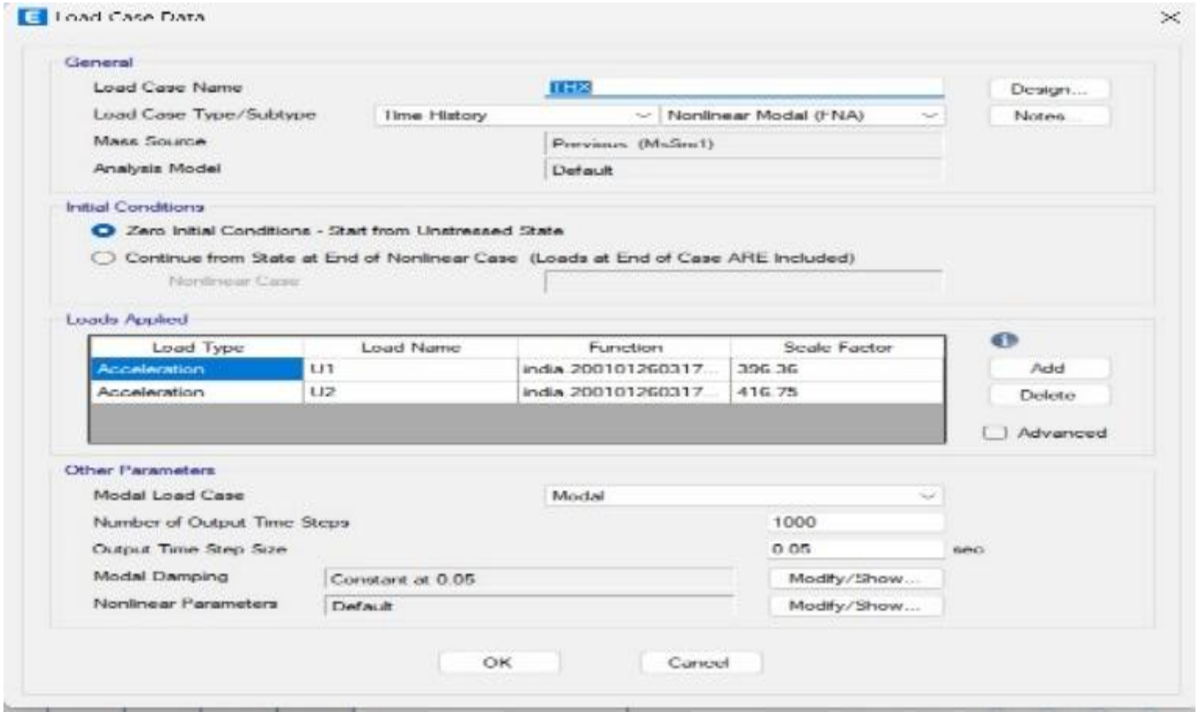


Figure 6.6: Illustrates the nonlinear direct integration time history (Th-x) load case using time history function.

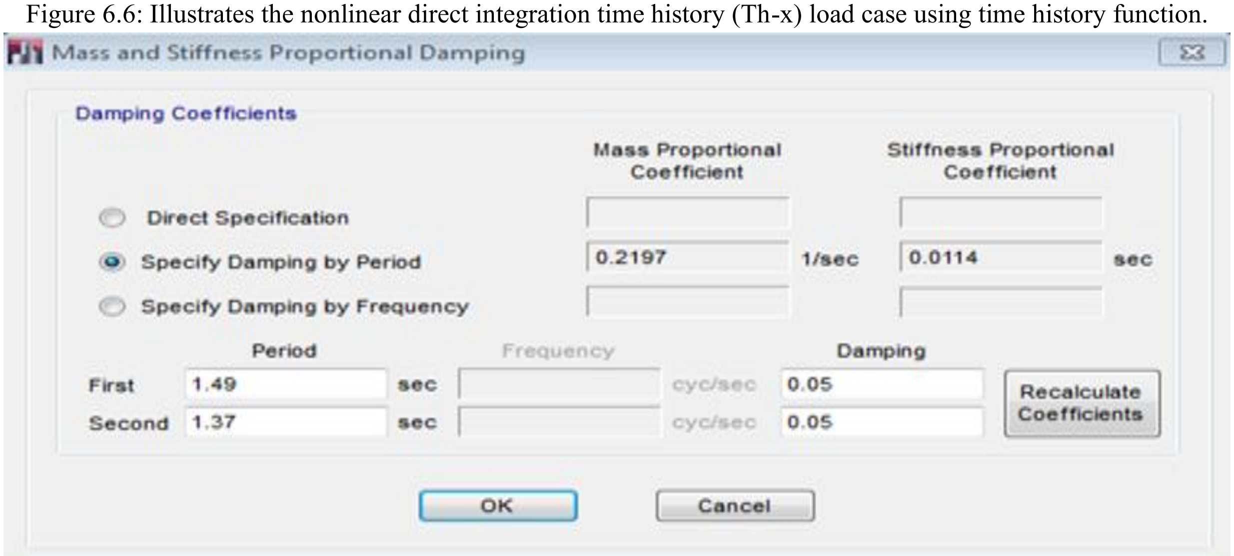


Figure 6.7: Illustrates the Rayleigh damping, which is also called mass and stiffness proportional damping.

7. RESULTS AND DISCUSSION

The results obtained are of different parameters such as story displacement, Storey drifts, story stiffness, base shear and base moment etc. The results obtained by carrying out by response spectrum and nonlinear time history Analysis for G+30 Storey Buildings.
Subsequent Discussions are made about the Results Obtained based on the story drifts, displacement etc. for Symmetric buildings individually and also considering the seismic zone effect of Symmetric buildings by comparing the responses of the structure for 30 story Buildings.

7.1 Discussion for Story Displacement

- Under Response Spectrum (RSP) loading, the T-TYPE structure experienced displacements of 99.021 mm in the X-direction and 60.415 mm in the Y-direction. The L-TYPE showed 96.344 mm (X) and

77.208 mm (Y), indicating slightly lower displacement in X but a notable increase in Y compared to T-TYPE. The E-TYPE exhibited 62.562 mm in X and 83.548 mm in Y, showing a significantly reduced displacement in X and a noticeable increase in Y. Meanwhile, the U-TYPE had 63.119 mm in X and 70.396 mm in Y, maintaining low displacements in both directions relative to T-TYPE and L-TYPE.

- Under Time History (THX) loading, the T-TYPE reached displacements of 180.852 mm in X and 120.867 mm in Y, much higher than under RSP. The L-TYPE recorded 138.978 mm in X and 163.9 mm in Y, showing a smaller X displacement but a larger Y displacement than T-TYPE. For the E-TYPE, THX displacements were 123.145 mm (X) and 138.356 mm (Y), remaining lower than L-TYPE in both directions. Finally, the U-TYPE had 115.579 mm in X and 156.147 mm in Y, which were moderate compared to the other types.

- In X-direction, T-TYPE consistently shows the highest displacement under both RSP and THX, indicating its higher flexibility or lower stiffness in that direction. E-TYPE and U-TYPE show better performance (lower displacements).
- In Y-direction, displacements are generally higher under THX. L-TYPE records the maximum Y displacement under THX, suggesting susceptibility to vertical motion, while T-TYPE remains the lowest in both cases.
- Overall, displacements under Time History loading are significantly higher than those under Response Spectrum for all types in both X and Y directions. T-TYPE is the most flexible in X, especially under THX, while L-TYPE tends to deform more in the Y-direction under dynamic conditions. E-TYPE and U-TYPE provide better control of displacement, suggesting improved structural stiffness or layout effectiveness in resisting lateral loads.

7.2 Story Drift Results & Discussion

Figure7.1: Story drift for all model with RSP & THX method in X & Y dir

- Under Response Spectrum (RSP) loading, the T-TYPE structure shows a Story drift t of 0.000899 mm in the X-direction and 0.000362 mm in the Y-direction, indicating relatively higher movement along the X-axis. The L-TYPE records 0.000867 mm in X and 0.000589 mm in Y, showing slightly lower Story drift in X but a higher value in Y compared to T-TYPE. The E-TYPE displays significantly reduced X-direction Story drift at 0.000405 mm, while Y-direction Story drift is 0.000736 mm, the highest among all types in RSP for Y. The U-TYPE presents moderate values with 0.000472 mm in X and 0.00049 mm in Y, performing better than T- and L-TYPEs in X and better than E-TYPE in Y.
- Under Time History (THX) loading, Story drift increase across all structure types. The T-TYPE shows 0.001736 mm in X and 0.000749 mm in Y, both significantly higher than its RSP values. The L-TYPE reports 0.001323 mm in X and 0.001068 mm in Y, with Y-direction Story drift higher than T-TYPE,

suggesting more lateral flexibility. The E-TYPE has 0.001001 mm in X and 0.001398 mm in Y, showing a consistent trend of lower X Story drift and high Y Story drift. The U-TYPE registers 0.000983 mm in X and 0.001366 mm in Y, similar to E-TYPE, with balanced performance in both directions.

- T-TYPE consistently shows the highest X-direction story drift in both RSP and THX, indicating more lateral flexibility or less stiffness along X.
- E-TYPE exhibits the highest Y-direction drift under both load cases, especially under THX (1.398 mm), suggesting susceptibility to lateral motion in that axis.
- U-TYPE maintains moderate and balanced drift in both X and Y directions, especially under RSP.
- Across all types, THX drifts are significantly higher than RSP values, reflecting the greater effect of time-dependent dynamic loading compared to spectrum-based response

7.3 Story Stiffness Results & Discussion

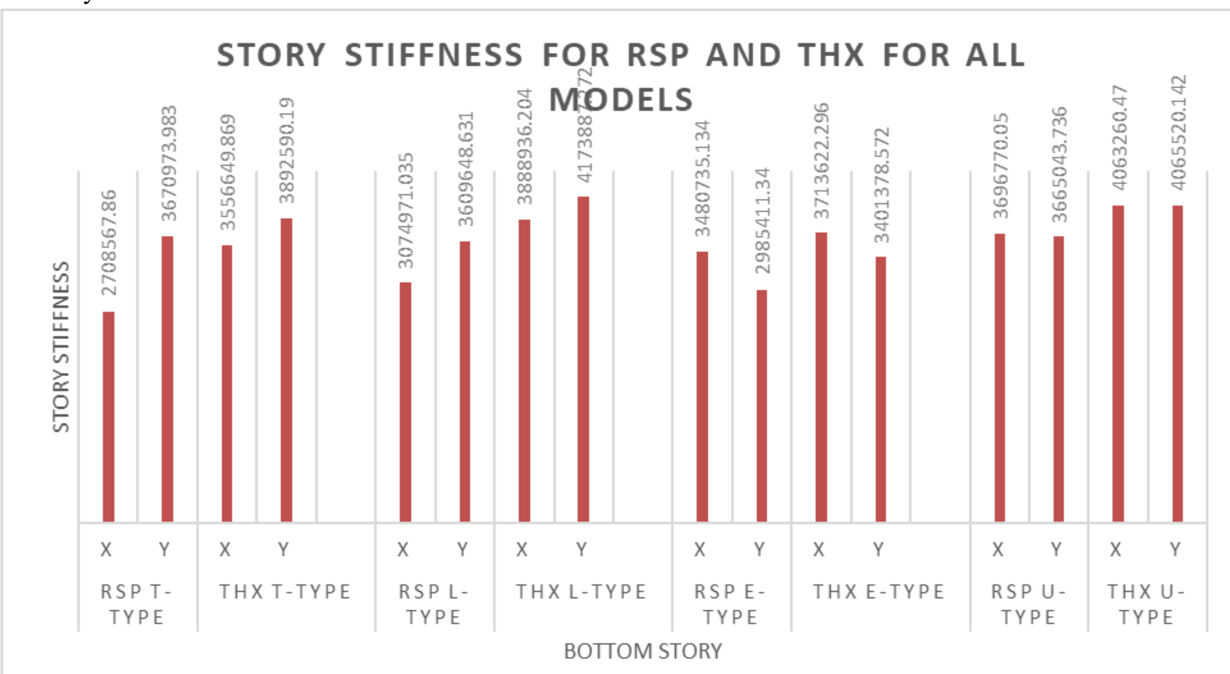


Figure7.2: Story stiffness for all model with RSP & THX method in X & Y dir

Response Spectrum (RSP) – Stiffness

- T-TYPE shows a stiffness of 2,708,567.86 kN/m in X-direction and 3,670,973.98 kN/m in Y-direction, indicating greater lateral rigidity in Y.
- L-TYPE has a higher stiffness in X compared to T-TYPE at 3,074,971.04 kN/m, but slightly lower in Y at 3,609,648.63 kN/m, showing balanced behavior in both axes.
- E-TYPE demonstrates even greater stiffness in X at 3,480,735.13 kN/m, though Y stiffness drops to 2,985,411.34 kN/m, suggesting stronger lateral stiffness along X.
- U-TYPE offers the highest stiffness in X under RSP, at 3,696,770.05 kN/m, and remains robust in Y as well at 3,665,043.74 kN/m, showing uniform strength in both axes.

Time History (THX) – Stiffness

- T-TYPE increases its stiffness in both directions: 3,556,649.87 kN/m (X) and 3,892,590.19 kN/m (Y).
- L-TYPE also increases in both: 3,888,936.20 kN/m (X) and 4,173,887.27 kN/m (Y), outperforming T-TYPE.

- E-TYPE shows 3,713,622.30 kN/m in X and 3,401,378.57 kN/m in Y, with balanced but slightly lower stiffness in Y compared to L and U types.
- U-TYPE continues to lead with 4,063,260.47 kN/m in X and 4,065,520.14 kN/m in Y, showing the highest and most consistent stiffness across both directions under THX loading.
- Under both RSP and THX conditions, U-TYPE consistently demonstrates the highest and most balanced story stiffness in both X and Y directions, making it the most structurally rigid of the four. T-TYPE shows the lowest stiffness in X under RSP and THX, indicating greater lateral flexibility. E-TYPE has high stiffness in X but lower values in Y, suggesting directional stiffness imbalance. L-TYPE performs well overall, but U-TYPE clearly stands out for providing the most robust and uniform lateral resistance under seismic and dynamic loading.

8. CONCLUSION AND FUTURE SCOPE

This study investigated the seismic performance of high-rise reinforced concrete (RC) buildings with asymmetrical plan configurations—specifically L-shaped, T-shaped, U-shaped, and E-shaped structures. The analysis was conducted using advanced nonlinear dynamic techniques, namely Non-Linear Time History Analysis (NLTHA) and Response Spectrum Analysis (RSA), following the provisions of IS 1893:2016. All models were developed and analysed using ETABS 2021, and ground motion data from the 2001 Bhuj earthquake (Zone V) was used for NLTHA.
Based on the results and comparative assessment of structural response parameters, the following conclusions are drawn:

1. Influence of Plan Irregularity

- Plan irregularity significantly affects the seismic response of high-rise buildings.
- Among all configurations, the E-type and U-type buildings exhibited the highest displacement and drift values, indicating higher seismic vulnerability.
- The L-type building consistently demonstrated better lateral performance, with lower storey displacement and drift ratios.

2. Displacement and Drift Performance

- Maximum storey displacement in all models remained within the permissible limit of H/250, as specified in IS 16700:2017.
- Inter-storey drift was also within acceptable limits (0.004) under both RSA and NLTHA for all cases, though values were significantly higher under NLTHA, especially for E- and T-type structures.
- NLTHA predicted larger and more realistic deformation behavior compared to RSA, particularly at higher floors.

3. Base Shear and Stiffness

- Models with higher plan eccentricity (T and U types) exhibited greater base shear demands.
- Lateral stiffness varied nonlinearly along the height; structures with more compact plans (like L-type) maintained higher stiffness, leading to reduced lateral displacement.

4. Analysis Method Effectiveness

- NLTHA provided more detailed and realistic structural responses than RSA, as it considers actual time-dependent ground motion and material nonlinearity.
- RSA remains a reliable and time-efficient tool for preliminary design, but for critical or irregular buildings, NLTHA is essential for safety and performance-based design.

Final Conclusion

Among the four irregular configurations studied, the L-type building offered the best seismic performance in terms of displacement control, stiffness, and base shear. In contrast, E-type and U-type buildings were more susceptible to torsional effects and non-uniform drift patterns. This study highlights the importance of plan symmetry and stiffness uniformity in the seismic design of high-rise buildings and underscores the need for nonlinear dynamic analysis in evaluating true performance under severe earthquake conditions. In alignment with Sustainable Development Goal 11 (Sustainable Cities and Communities), this study promotes disaster-resilient infrastructure and enhances scientific understanding for safer urban development in earthquake-prone regions.

Future Scope

1. Incorporation of Soil–Structure Interaction (SSI):

Future work could include SSI modeling to better represent real-world boundary conditions and evaluate the influence of varying soil types on asymmetrical configurations.

2. Multi-Earthquake Ground Motion Analysis:
Expanding the analysis to include a suite of ground motions from different seismic events and regions can enhance the robustness and generalizability of the findings.

3. Performance-Based Design and Fragility Assessment:
Adopting performance-based seismic design approaches and developing fragility curves for each shape could help assess damage probabilities and lifecycle performance under seismic loading.

4. Investigation of Retrofit Measures:
Future research can focus on retrofitting techniques—such as damping devices, bracing, or FRP wrapping—targeted at reducing the vulnerabilities caused by asymmetry in existing structures.

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