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# Performance-Based Seismic Design of Tall Reinforced Concrete Buildings for Disaster Resilience in High-Risk Urban Zones

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**Abstract:** Tall buildings are crucial in the modern urban era, providing a solution to accommodating the rising population density and addressing the land scarcity problem. Despite mitigating population density, constructing tall buildings is complex, as their structural safety under seismic loading remains a significant challenge, particularly in a seismically active region such as Nepal. Performance-Based Design (PBD) is an advanced structural engineering approach that prioritises the design of buildings based on their expected performance under various seismic loading scenarios. This study focuses on the seismic-resistant design of a 16-storey Reinforced Concrete (RC) shear-wall-framed tall building using a Performance-Based Design approach. The structure was modelled and analysed using ETABS software, in accordance with NBC 105:2020. Linear static and response spectrum analyses were performed, followed by a non-linear static pushover analysis for performance evaluation using FEMA 440 equivalent linearization. The results confirmed that all structural components met strength and serviceability criteria. The pushover analysis revealed that plastic hinges formed primarily in beams, indicating a ductile failure mode. The capacity curve and performance point were obtained, indicating that the overall performance level met the Life Safety criteria for the Design Basis Earthquake. The study concludes that the PBD approach effectively ensures seismic resilience and recommends its expanded use for essential structures in high-risk zones.

***Keywords:*** *Performance-based design, Seismic resistant design, RC tall building, Pushover Analysis, Nepal*

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## 1. Introduction

Tall buildings are a crucial component of the modern urban era, providing a means of accommodating rising population density and addressing land scarcity (Al-Kodmany, 2018). A building taller than 50 meters is referred to as a tall building. Despite mitigating population density, the construction of tall buildings remains a complex undertaking, as their structural safety under seismic loading remains a significant challenge, particularly in seismically active zones (Al-Kodmany and Ali, 2025).

Although the increasing demand for tall buildings worldwide is driven by rising population density, conventional seismic design relies primarily on force-based methods. The force-based design ensures life safety but fails to accurately depict or guarantee the building's performance during and after an earthquake (Chandler and Lam, 2001). Consequently, there is a growing demand for advanced technologies that can accurately represent or provide improved insight into the performance of buildings under various seismic scenarios.

Performance-Based Design (PBD) is an advanced structural engineering approach that prioritises the design of buildings based on their expected performance under different seismic loading scenarios (Choudhury, 2024). It has emerged as an innovative approach that enables engineers to assess and control the seismic behaviour of structures more effectively. Unlike conventional code-based designs, which rely on prescriptive methods, PBD enables the design of buildings to meet specific performance objectives, thereby improving resilience and functionality after an earthquake (Martínez-Paneda, 2023).

Nepal is one of the nations identified as having a high seismic hazard, lying in the central segment of the Himalayan collision zone. Throughout its history, Nepal has experienced six large, damaging earthquakes (in 1255, 1408, 1505, 1833, 1934, and 2015) with magnitudes equal to or greater than 7.6, as well as several strong earthquakes since 1255 (Rastogi, 2024). These earthquakes have caused serious disasters, resulting in huge human casualties and substantial monetary losses. The latest and most destructive earthquake (Mw=7.8, 25 April 2015, Gorkha earthquake) and its accompanying aftershocks resulted in a high toll of casualties.

Nepal, especially in cities like Kathmandu, is experiencing rapid urbanisation and population growth. Therefore, tall buildings are designed to accommodate more people and businesses in a smaller footprint compared to low-rise buildings, making efficient use of limited urban land. Hence, there is a need to build a structure that can resist seismic forces with minimal or no damage.

Several studies have investigated the application of advanced analysis methods for assessing seismic performance. By considering the diaphragm discontinuity, Nagpure and Sanghai (2018) investigated the impact of diaphragm adaptability on the seismic response of R.C.C. framed buildings. Pujari and Khamlar (2022) investigated performance-based seismic diaphragm design for tall buildings. Singh and Raju (2017) investigated performance-based design for residential buildings. Furthermore, Thomas and Chandran (2016) conducted a performance analysis of RC-framed buildings using nonlinear analysis. However, a discernible research gap exists in the context-specific application of a comprehensive Performance-Based Design methodology to tall RC shear wall buildings situated in high-seismic risk regions, such as Nepal, which are characterised by unique seismological conditions and a rapid, pressing need for urban vertical expansion. Many existing studies either focus on generic frames, different structural systems, or regions with well-established seismic design practices, leaving the efficacy of PBD for ensuring the disaster resilience of essential tall structures in the Nepalese context insufficiently explored.

This study aims to apply a Performance-Based Design approach to a tall RC building in a high-seismic region. The specific objectives are:

a. To carry out finite element linear and non-linear modelling of the tall building in ETABS software.
b. To carry out code-based seismic analysis and design of tall buildings as per NBC 105:2020.
c. To understand the behaviour of the structure and response to seismic loading in various seismic zones and soil types.
d. To carry out a non-linear static pushover analysis for the performance evaluation of a tall building.

# 2. Materials and methods

The methodology for this study followed a structured process for the seismic-resistant design of the tall RC building using a Performance-Based Design approach. The first stage of the project was Data collection, which included information such as the type of building, the size of the building, the soil condition of the site, the design of the building, the plan and elevation of the design, all required drawings, and the identification of the seismic zone for the seismic analysis. The primary objective of this step was to gather sufficient information required for the project analysis. Before proceeding with load calculation, the Preliminary size of slabs, beams, and columns, as well as the type of material used, is decided. Preliminary Design of structural members was based on the IS Code provisions for slab, beam, column, wall, staircase and footing of serviceability criteria for deflection control and failure criteria in critical stresses arising in the sections at the ultimate limit state, i.e. Axial loa

Modelling of the structure is the process that typically involves creating a digital or mathematical representation of the structure to assess the loads and forces on it and to analyse the structure. The modelling involves two types of models: linear models (based on Hooke's Law) and non-linear models (based on the non-linearity of material and geometry). Different types of software are used for modelling the structure. Software such as ETABS and SAP2000 was used to model the structures. Analysis of a building can be done by various processes. The Response Spectrum method is suitable for more complex and taller structures, as well as for higher mode effects. In this method, mode superposition is used to calculate the peak response. Pushover analysis is a method where structural components are modelled with nonlinear behaviour; a capacity curve is used to assess performance. This method determines the plastic hinge formation and failure mechanism, and evaluates the structure's capacity to resist lateral loads

The loads considered in the analysis were Gravity Load, which is the self-weight of the structural members and is analogous to dead load, comprising the loads due to the materials used in the construction of parts or components in a building, including the loads due to structural elements like beams, columns, slab, walls, finishing, etc. The lateral loads acting on the building are earthquake loads and wind loads. However, in the case of Nepal, wind loads are not severe, so only earthquake load analysis is carried out. Wind pressure occurs on all exposed surfaces and acts normally to the surface on which it acts. Live load, also known as imposed load on structures, encompasses the weight of stored materials and liquids, as well as the load imposed by vehicles and moving equipment. The Load Combinations were taken from NBC 105:2020. For Response Spectrum Analysis, the Earthquake load case can be replaced by the Response Spectrum case.

The response spectrum method was used for the model analysis. A response spectrum is a plot or graph that shows the peak response (displacement, velocity, or acceleration) of an SDOF system for a range of natural periods (or frequencies), subjected to a particular ground motion (earthquake). This method simplifies the complex dynamic analysis, especially for an MDOF system. The Response spectrum curve was used from the NBC 105:2020 code. The base shear of the structure was calculated using this method for dynamic analysis. Several checks for structural irregularity were performed. Structures with simple and regular configurations suffer much less damage during a large earthquake; therefore, efforts were made to make the structure as regular as possible. The building was checked for vertical irregularity, including Weak Story, Soft Story, and Mass Irregularity, as well as Plan Irregularity, including Torsion Irregularity. Checks were also performed for Drifts and Displacement at the Ultimate Limit State and S

The design and ductile detailing followed the Limit State Design Method IS 456:2000 for the design of reinforced concrete members. Ductile detailing of the reinforced concrete structure was performed in accordance with IS 13920:2002 to ensure compliance with the earthquake-resistant design philosophy. Special consideration was taken in detailing linear frame elements (beams and columns) to achieve ductility in the concrete, localising the formation of plastic hinges in beams and not columns, to ensure the capacity theory of Strong Column | Weak Beams. To check the performance of the structure, a Pushover analysis was used. Push-over analysis is a type of nonlinear static structural analysis used primarily in earthquake engineering to evaluate the performance of buildings. It guides the way a structure behaves under incremental lateral loads, like those during an earthquake. It was used to assess the performance of the building beyond the elastic range and to identify weak points or failure mechanisms of the structure. The output of the analysis provides the capacity curve, the plastic hinge formation sequence, the target displacement, and the performance level of the building. The steps involved in Pushover Analysis are: a) Model of the structure, b) Apply gravity load, c) Add lateral loads, d) Increase the applied load, e) Observe structural response, f) Plot a capacity curve, g) Check performance. The assumptions for the pushover analysis were that plastic hinges were assigned to all member ends and the maximum target displacement of the structure was kept at 4.0% of the building's height. The seismic performance of a building is evaluated in terms of pushover curve, performance point and plastic hinge formation.

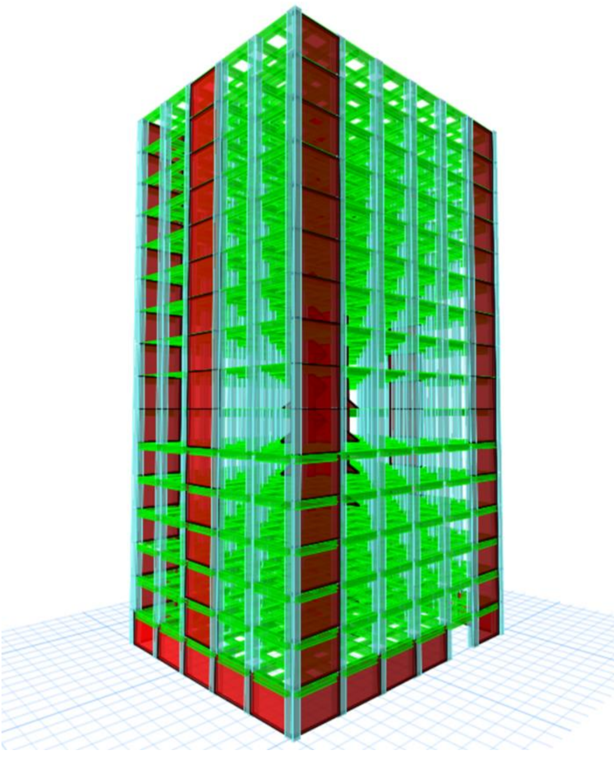

**Figure 1**: 3D-Model of the structure

# 3. Results and discussion

## 3.1. Modal Analysis

The dynamic characteristics of the structure were determined through modal analysis. The fundamental natural periods of the building were found to be 1.199 seconds in the first mode (translation in Y-direction), 1.147 seconds in the second mode (translation in X-direction), and 0.950 seconds in the third mode (torsion). The modal participating mass ratios confirmed that a sufficient number of modes were considered, with the cumulative mass participation exceeding 90% in both translational directions by the 12th mode, as detailed in Tables 1 and 2.

**Table 1:** Modal Periods and Frequencies

| Case | Mode | Period (sec) | Frequency (cyc/sec) | CircFreq (rad/sec) | Eigenvalue (rad2/sec2) |
|---|---|---|---|---|---|
| Modal | 1 | 1.199 | 0.834 | 5.240 | 27.455 |
| Modal | 2 | 1.147 | 0.872 | 5.480 | 30.025 |
| Modal | 3 | 0.950 | 1.052 | 6.613 | 43.729 |
| ... | ... | ... | ... | ... | ... |

**Table 2:** Modal Participating Mass Ratios

| Case | Mode | Period (sec) | Frequency (cyc/sec) | CircFreq (rad/sec) | Eigenvalue (rad2/sec2) |
|---|---|---|---|---|---|
| Modal | 1 | 1.199 | 0.000 | 0.703 | 0.000 |
| Modal | 2 | 1.147 | 0.695 | 0.000 | 0.000 |
| Modal | 3 | 0.950 | 0.000 | 0.000 | 0.684 |
| ... | ... | ... | ... | ... | ... |

**Horizontal Base Shear Coefficient**

As per NBC 105:2020, the horizontal base shear coefficients for the structure were calculated. The elastic site spectra for horizontal loading, $C(T_1)$, were found to be 0.788. The Horizontal Base Shear Coefficient for the Ultimate Limit State (ULS), $Cd(T_1)$, was 0.161, and for the Serviceability Limit State (SLS), $Cd(T_1)$ was 0.131. The exponent related to the structural period (k) was 1.373.

**System Verification and Irregularity Checks**

The structural system was verified to function as a dual system in accordance with NBC 105:2020. The moment-resisting frames were designed to resist independently at least 25% of the design base shear. The analysis confirmed that the frame resisted 37.73% of the total base shear in the X-direction and 96.75% in the Y-direction, both values exceeding the required 25% (OK).

Comprehensive checks for all structural irregularities were performed:

- The lateral strength of every story was found to be greater than 80% of the story above. All stories were verified as OK.
- The lateral stiffness of every story was greater than 70% of the story above and 80% of the average stiffness of the three stories above or below. All stories were verified as OK.
- The difference between the effective masses of two consecutive stories was less than 50%. No mass irregularity was found.
- The maximum horizontal displacement at any floor was less than 1.5 times the minimum displacement at the same floor. The structure was found to be torsionally regular.

**Drift and Displacement**

The inter-story drift and lateral displacement were within the permissible limits stipulated by NBC 105:2020. The ratio of the inter-story deflection to the corresponding story height did not exceed 0.025 at the ultimate limit state and 0.006 at the serviceability limit state. The maximum roof displacement was also found to be within the allowable limits for both ULS and SLS.

**Pushover Analysis and Performance Evaluation**

he nonlinear static (pushover) analysis played a pivotal role in evaluating the seismic performance. The capacity curve depicts the relationship between base shear and monitored displacement. The performance point, which is the intersection of the capacity spectrum and the demand spectrum (as per FEMA 440 Equivalent Linearization), was found to lie at a base shear of 63,748.63 kN and a monitored displacement of 432.31 mm (Step 18).

**Table 3:** Base Shear vs. Monitored Displacement (Pushover Curve)

| Step | Monitored Displacement (mm) | Base Force (kN) | A-IO | IO-LS | LS-CP | >CP | Total Hinges |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0.000 | 3839 | 0 | 0 | 0 | 3839 |
| 1 | 23.613 | 7806.331 | 3839 | 0 | 0 | 0 | 3839 |
| ... | ... | ... | ... | ... | ... | ... | ... |
| 18 | 432.306 | 63748.627 | 3729 | 108 | 2 | 0 | 3839 |

... ... ... ... ... ... ... ...

The most critical finding was the state of the plastic hinges at the performance point. A total 3729 hinges were in the Immediate Occupancy (IO) range, 108 hinges were in the Life Safety (LS) range, and only 2 hinges had reached the Collapse Prevention (CP) range. No hinges were in the beyond-CP or collapse state. This confirms that the overall performance level of the building for the Design Basis Earthquake (DBE) is Life Safety (LS), successfully meeting the predefined performance objective.

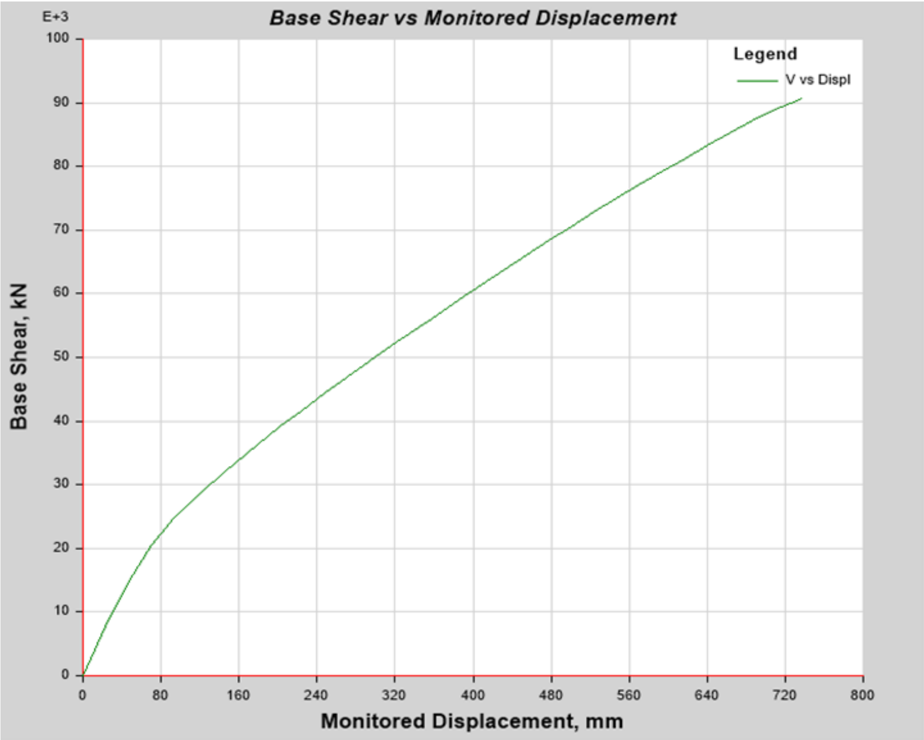


**Figure 2:** Pushover Curve – Base Shear vs. Monitored Displacement

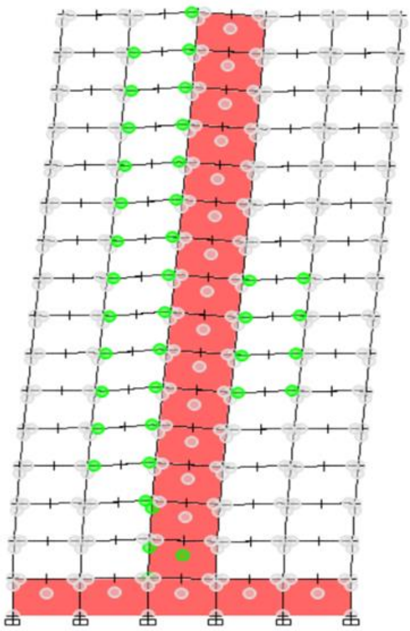

**Figure 3:** Hinge Formation at Performance Point

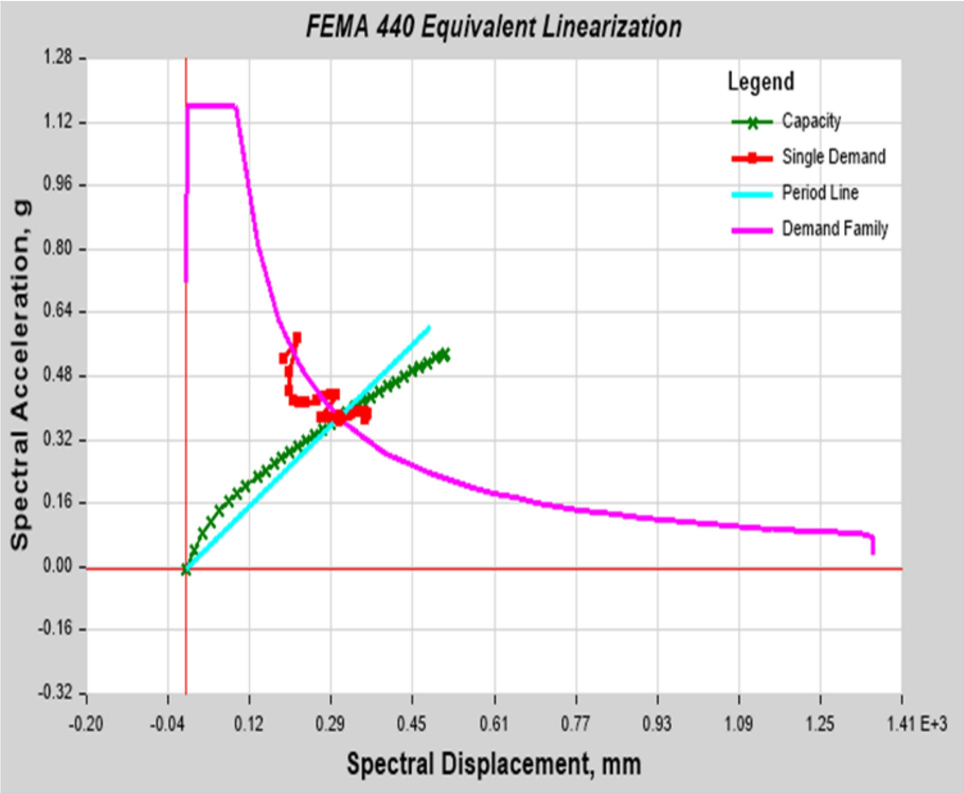


**Figure 4:** Pushover Curve – Base Shear vs. Monitored Displacement

**Design Outputs**

The detailed design of all structural elements was completed successfully based on the forces from the analysis. The final designed sizes and reinforcements are as follows:

- Slab: Typical floor slab thickness = 150 mm. Reinforcement: T8 bars @150 mm c/c.
- Beam: Typical main beam size = 500 mm x 700 mm. Reinforcement: Provided 6-25mm dia top bars and 4-20mm dia bottom bars at supports with 2L-8mm dia stirrups @100mm c/c.
- Column: Critical column size = 750 mm x 750 mm. Reinforcement: Provided 12-24mm dia bars with 8mm lateral ties @300mm c/c and special confining ties @75mm c/c at joint regions.
- Shear Wall: Thickness = 300 mm. Reinforcement: Provided 37-T25 mm dia vertical bars @150 mm c/c on each face. Boundary elements were designed with 9-T20 mm dia bars @125 mm c/c.
- Staircase: Waist slab thickness = 230 mm. Reinforcement: T12 bars @120 mm c/c and T10 distribution bars @300 mm c/c.
- Foundation: A mat foundation of depth 2500 mm was designed. Reinforcement: T28 bars @150 mm c/c in both directions. The maximum soil pressure was 171.354 kN/m², which is less than the allowable bearing capacity of 322.5 kN/m². All checks for punching shear and settlement were satisfactory..

## 3.2. Discussion

The Performance-Based Design approach provides a deeper understanding of how the tall building would behave under different seismic intensity levels. The analysis and design results confirm that the structure meets the required seismic performance objectives, achieving Life Safety under design-level earthquakes (Padalu and Surana, 2024).

The calculated base shear values and the confirmed absence of structural irregularities have profound implications for the design's efficiency and reliability. The horizontal base shear coefficient for the Ultimate Limit State ($Cd(T_1) = 0.161$) provided a realistic and code-compliant estimate of the total seismic force demand. This value, derived from the site-specific response spectrum, ensures that the design is neither overly conservative nor dangerously optimistic, striking a balance between safety and economy. More importantly, the system verification confirmed the successful functioning of the intended dual system, with the moment-resisting frames independently resisting a significant portion (37.73% in X and 96.75% in Y) of the design base shear. The integration of shear walls significantly enhanced lateral stiffness and overall performance. This was validated through the system verification check, which confirmed the structural system is considered to be a Dual-System as per NBC 105:2020. The moment-resisting frames were designed to resist independently at least 25% of the design base shear. The analysis confirmed that the frame resisted 37.73% of the total base shear in the X-direction and 96.75% in the Y-direction. This dual s

The pushover analysis provided valuable insights into the inelastic behaviour and potential failure mechanisms. The capacity curve and performance point were successfully obtained. The most critical finding was the state of the plastic hinges at the performance point, with plastic hinges primarily forming in beams, indicating a desirable ductile failure mode. The fact that 3729 hinges were in the Immediate Occupancy (IO) range, 108 hinges were in the Life Safety (LS) range, and only 2 hinges had reached the Collapse Prevention (CP) range confirms that the overall performance level of the building for the Design Basis Earthquake (DBE) is Life Safety (LS). Since no hinge is within the collapse prevention range, the designed building is safe for the design basis earthquake, and the life safety performance level is achieved (Ye, Lu, and Li, 2010). The achievement of the LS performance level under the DBE has significant practical implications for building resilience, occupancy, and post-earthquake recovery. Structurally, this performance level indicates that the building, while sustaining repairable damage such as widespread cracking and the formation of plastic hinges primarily in beams, retains its overall structural integrity and vertical load-carrying capacity. From a functional and economic perspective, an LS performance implies that the building, though not immediately operational after a major seismic event, can be repaired. While this repair may be extensive and costly, it is economically preferable to a total loss or demolition. This outcome enhances the building's long-term investment value and reduces the potential for economic disruption to owners and tenants.

The results align with findings from previous literature. The study concludes that a performance-based design approach captures the most genuine behaviour, which is consistent with the work of Khamlar and Pujari (2022). Furthermore, the finding that performance-based design results in a more economical design than the force-based design, as noted by Singh and Raju (2017), is supported by the efficient sizing of members achieved through this detailed analysis, even though the size of structural members may be large and uneconomical and actual construction practices may not achieve the detailing assumed in design.

The checks for all structural irregularities, including weak storey, soft storey, mass, and torsion, showed that the structure is regular. Structures with simple and regular configurations suffer significantly less damage during a large earthquake, and efforts have been made to make the structure as regular as possible (Abbas et al., 2021). This regularity contributed to predictable and favourable seismic performance, as evidenced by the controlled inter-story drifts and lateral displacements (Guler and Guler, 2024), which were within the permissible limits stipulated by NBC 105:2020.

Despite these positive outcomes, it is important to acknowledge the limitations of this study. The assumptions made in the model might not be validated with physical test data. Furthermore, pushover assumes a fixed load pattern and may not fully capture the dynamic response for taller buildings. This suggests that while the nonlinear static procedure is effective, incorporating nonlinear time-history analysis with multiple ground motion records would provide a more comprehensive assessment of dynamic response for future refinement (O'Donnell et al., 2017).

# 4. Conclusion

The performance-based design approach applied to the 16-story RC framed building demonstrated that the structure meets the required seismic performance objectives, achieving Life Safety under design-level earthquakes and Collapse Prevention under maximum considered earthquakes. The use of nonlinear static pushover analysis provided valuable insights into the inelastic behavior and potential failure mechanisms, with plastic hinges primarily forming in beams, indicating a desirable ductile failure mode. The integration of shear walls significantly enhanced lateral stiffness and overall performance.

Despite these positive outcomes, further refinement of the analysis is recommended. Incorporating nonlinear time-history analysis with multiple ground motion records would provide a more comprehensive assessment of dynamic response. Additionally, advanced modeling techniques, consideration of soil-structure interaction, and referencing international performance-based design standards such as ASCE 41 could improve accuracy and reliability. Expanding the use of PBD in seismic design practices, particularly for essential and tall structures in high-risk zones, is strongly encouraged to enhance structural resilience and life safety.

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