Effect of Overcrowding on Seismic Performance of Elevation Irregular Medium Height Structures

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Abstract

Buildings are typically designed to resist prescribed dead, live, wind, and seismic loads. However, overloading—due to material misplacement or long-term use—can exceed design thresholds, especially in elevation-irregular structures. This study investigates the compounded seismic vulnerability caused by such overloading through three-dimensional nonlinear pushover analysis in ETABS. Two reinforced concrete frame types—regular and elevation-irregular—are analyzed with live loads ranging from 5 to 40 kN/m^2. The results indicate that live load increases amplify roof displacement and vulnerability indices, with irregular frames exhibiting significantly greater sensitivity. The study underscores the importance of occupancy control in seismically active regions.

Keywords: Elevation irregularity, Seismic performance, Overloading, Pushover analysis, Increased live load.

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1 Introduction

Earthquakes are inherently unpredictable and capable of causing severe structural damage. Failures during seismic events typically originate at weak points, often due to discontinuities in mass, stiffness, or geometry—features that define elevation irregularities [1,2]. These irregularities alter the dynamic behavior of buildings and increase their susceptibility to seismic damage. Structures are generally designed to resist dead, live, wind, and seismic loads. However, overloading—caused by unplanned storage, misplacement of construction materials, or overcrowding during events—can exceed design thresholds [3,4]. Such excess loading increases stress on structural elements and the foundation, further exacerbating the risk of collapse [5]. Vertical irregularities, such as soft storeys, abrupt stiffness changes, or asymmetrical profiles, disrupt uniform force distribution during ground motion. Their presence, coupled with overloading, significantly elevates the seismic vulnerability of buildings and the associated risk to occupants. This study employs nonlinear static pushover analysis to assess the combined impact of elevation irregularity and increased live load on reinforced concrete frames. Regular and elevation-irregular configurations are analyzed under live loads varying from 5 kN/m^2 to 40 kN/m^2. Key parameters such as base shear, roof displacement, and vulnerability index are evaluated to highlight the heightened seismic risk caused by structural irregularity and overcrowding.

2 Pushover Analysis

Pushover analysis is a nonlinear static procedure used to estimate a structure's lateral load capacity under seismic excitation. The method involves modelling all load-resisting components—such as dead and live loads, and their force–deformation behavior—and applying incrementally increasing lateral forces to simulate ground motion [6, 7]. The resulting pushover curve represents base shear versus roof displacement, reflecting the structure's capacity to absorb and dissipate energy [8]. This approach is widely used to assess seismic performance, particularly for existing structures or performance-based design applications. The demand curve, derived from the response spectrum of the relevant seismic zone, soil type, and damping, is superimposed onto the capacity curve. Their intersection defines the performance point—an indicator of the expected structural response during an earthquake [9]. Figure 1 illustrates a typical pushover capacity curve and corresponding damage thresholds.

Damage is assessed across distinct states—slight, moderate, severe, or collapse-level—and separately for structural and non-structural components. The vulnerability index is computed by weighting the probability of each damage state (from fragility curves) with its associated cost fraction [9].

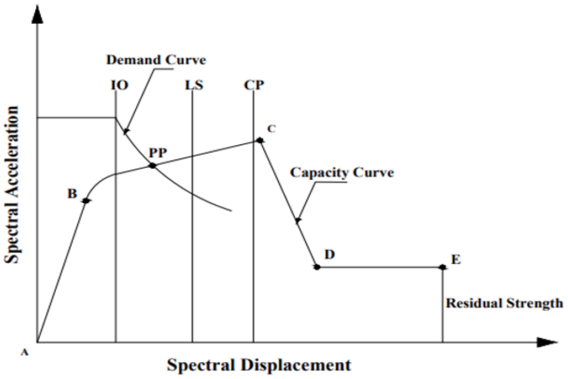

Figure 1 Capacity and demand curves showing damage state thresholds [9].

3 Characterization of the Structures

Structural irregularities arise from discontinuities in mass, stiffness, or geometry, which disrupt the uniform distribution of seismic forces and increase vulnerability. According to IS 1893:2016, vertical irregularities include abrupt changes in stiffness or mass over the height of a building, as illustrated in Figure 2 [2].

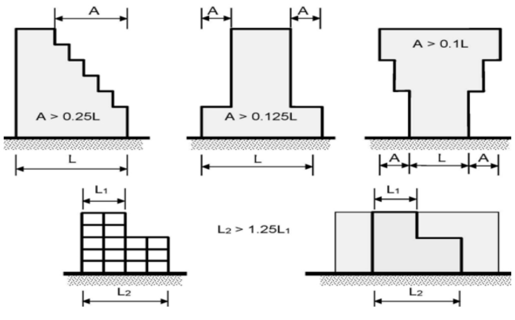

Figure 2 Elevation irregularities in structural configuration [2, 10].

This study analyzes three-storey reinforced concrete (RC) moment-resisting frames, both regular and elevation-irregular, using ETABS. Both configurations were modeled with identical material properties, story heights, bay widths, and cross-sectional dimensions. Special RC moment-resisting frames (SMRFs) were adopted as per IS 1893 and FEMA 440 guidelines [10, 11]. The geometric configuration and 3D views of both frames are illustrated in Figure 3. Table 1 presents the modeling parameters.

Table 1 Design details for frame configurations

Parameter	**Value**
Structure type	Special RC Moment Resisting Frame
Materials	M20 (Concrete), Fe415 (Steel)
Beam section	230 mm × 300 mm
Column section	300 mm × 300 mm
Slab thickness	150 mm
Storey height	3.0 m
Bay width	3.0 m
Plan size	9.0 m × 9.0 m
Seismic zone	Zone III
Soil type	Medium
Floor finish	1 kN/m^2
Live load	5–40 kN/m^2

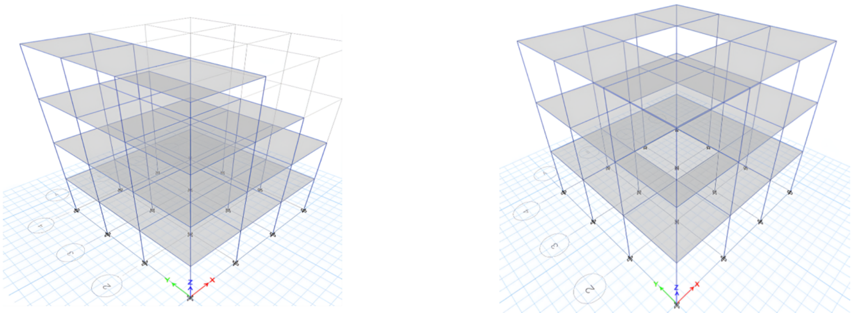

Figure 3 3D models of irregular (left) and regular (right) RC frames.

3.1 Structural Outline

The frames are designed for gravity loads as per IS 875, including slab self-weight (3.75 kN/m^2), wall loads (16.5 kN/m), finishes (1.0 kN/m^2), and live loads ranging from 5 to 40 kN/m^2 [10]. Pushover analysis is carried out using a displacement-based approach in accordance with FEMA 440 [11]. The seismic demand is defined using IS 1893 parameters with soil type II, an importance factor of 1.0, and a response reduction factor of 3.0.

3.2 Seismic Vulnerability Assessment

Seismic vulnerability refers to a structure's susceptibility to damage under a given intensity of shaking. It is commonly assessed using fragility functions that express the probability of exceeding specific damage states [12, 13]. These functions are critical for estimating potential risk and informing design or retrofitting strategies.

3.3 Vulnerability Index Calculation

The vulnerability index aggregates expected damage by combining the probability of exceeding a damage state with its cost fraction [4, 5]. Figure 4 outlines the damage probability matrix formulation.

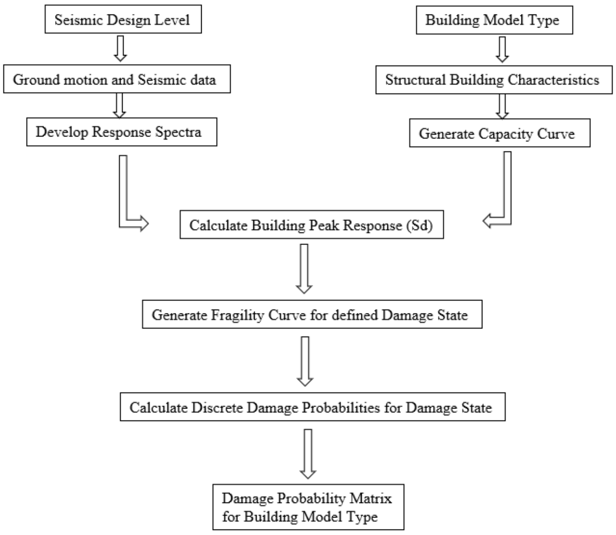

Figure 4 Flowchart for developing the damage probability matrix [14].

4 Results and Discussion

This section presents the seismic performance outcomes from nonlinear pushover analysis of regular and irregular RC frames subjected to increasing live loads. The response was evaluated based on four key metrics: base shear capacity, roof displacement, performance point shift, and vulnerability index. As shown in Figure 5, base shear increased with live load up to 35%, after which it declined. Regular frames exhibited higher lateral strength than irregular ones throughout the load range, highlighting the stabilizing effect of elevation uniformity. Figure 6 illustrates roof displacement behavior. Displacement increased with higher loads, and irregular frames showed nearly double the displacement of regular frames under the same conditions, indicating reduced lateral stiffness. Performance points, derived from the intersection of capacity and demand curves, are shown in Figure 7. As live load increased, the performance point shifted rightward—from elastic range toward collapse prevention—suggesting reduced ductility and increased vulnerability under overloading. The vulnerability index (Figure 8) rose steadily with live load increments from 5 kN/m^2 to 40 kN/m^2. Irregular frames consistently showed higher indices, reinforcing the compounded seismic risk due to elevation irregularity and overcrowding.

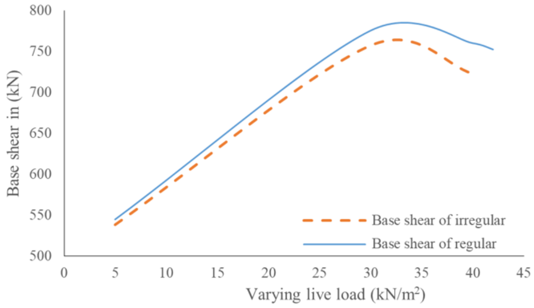

Figure 5 Base shear capacity of regular and irregular frames under increasing live loads.

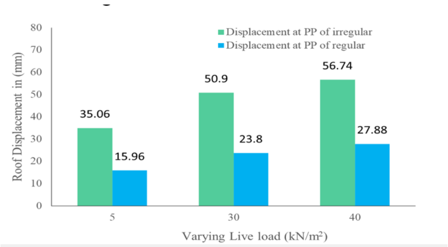

Figure 6 Roof displacement in regular and irregular frames for varying live loads.

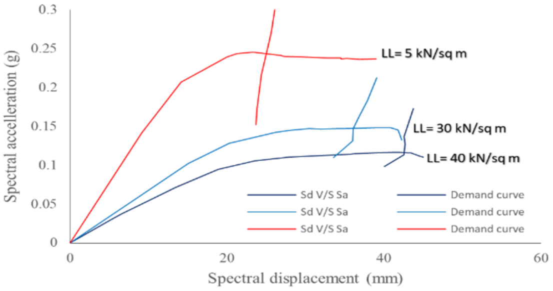

Figure 7 Pushover curves and performance points under different live loads.

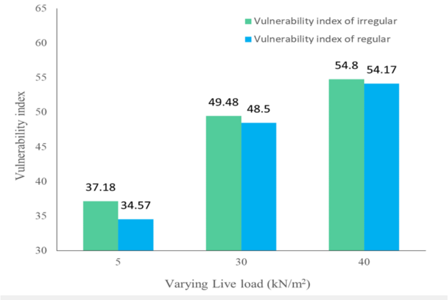

Figure 8 Vulnerability index of regular and irregular frames under varying live loads.

5 Conclusions

This study used nonlinear pushover analysis to evaluate the seismic behavior of reinforced concrete frames with regular and elevation-irregular configurations subjected to varying live loads. The results show that increased live loads significantly affect seismic performance by reducing overall stiffness and pushing the structure toward inelastic behavior. Base shear capacity increased up to a 35% rise in live load but declined beyond that point, indicating a loss of strength. Roof displacement and vulnerability indices rose steadily with live load, with irregular frames showing nearly twice the displacement and consistently higher vulnerability. The performance point shifted from elastic to near-collapse range under excessive loads, particularly in irregular frames. These findings confirm that elevation irregularities substantially increase seismic risk when combined with overloading due to overcrowding or mismanaged occupancy. Adherence to load design specifications and minimization of vertical irregularity are thus essential in buildings located in seismic zones.

References

[1] S. Prasad. Seismic performance study on RC wall buildings from pushover analysis. *IJRET: International Journal of Research in Engineering and Technology, pages 2321–7308, 2014.*

[2] Bureau of Indian Standards. IS 1893 (Part 1): Criteria for earthquake resistant design of structures – General provisions and buildings. New Delhi, 2016.

[3] C. Bedon, F. Stochino, and D. Honfi. Buildings and structures under extreme loads. *Applied Sciences, 10(16):5676, 2020.*

[4] S. Prasad and A. Krishnaiah. Effect of poor soil condition on seismic vulnerability of overcrowded building, 2022.

[5] R. F. Warner. Overload behavior of concrete structures: Design considerations. Australian Journal of Structural Engineering, 5(2):139–144, 2004.

[6] C. Bhatt and R. Bento. Comparison of nonlinear static methods for the seismic assessment of plan irregular frame buildings with non-seismic details. *Journal of Earthquake Engineering, 16(1):15–39, 2011.*

[7] S. Fotopoulou, S. Karafagka, C. Petridis, M. Manakou, E. Riga, and K. Pitilakis. Vulnerability assessment of school buildings: Generic versus building-specific fragility curves. Journal of Earthquake Engineering, pages 1–30, 2022.

[8] S. Antoniou and R. Pinho. Development and verification of a displacement-based adaptive pushover procedure. *Journal of Earthquake Engineering, 8(5):643–661, 2004.*

[9] Applied Technology Council. Seismic evaluation and retrofit of concrete buildings, ATC-40, vols. 1 and 2. Redwood City, CA, 1996.

[10] R. Peres, R. Bento, and J. M. Castro. Nonlinear static seismic performance assessment of plan-irregular steel structures. *Journal of Earthquake Engineering, 24(2):226–253, 2018.*

[11] Federal Emergency Management Agency. FEMA 440: Improvement of nonlinear static seismic analysis procedures. Washington, D.C., 2005.

[12] N. S. Roy and S. Choudhury. Seismic vulnerability assessment methods: A review. *Structural Integrity, pages 282–300, 2022.*

[13] D. Felsenstein, E. Elbaum, T. Levi, and R. Calvo. Post-processing HAZUS earthquake damage and loss assessments for individual buildings. Natural Hazards, 105(1):21–45, 2020.

[14] M. Biradar and S. Prasad. Influence of soil stiffness on seismic vulnerability of irregular buildings. Unpublished manuscript.

Biography

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