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Structural Stability of Irregular Buildings: A Seismic Evaluation of Beam Configurations and Floor Variations

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Abstract: Structural irregularities—such as plan asymmetry, floor size variations, and non-uniform beam configurations—greatly influence seismic performance, especially in high-seismicity zones like Zone V. This study evaluates the seismic behavior of a nine-story reinforced concrete frame building with curved and straight beams, focusing on the 3rd, 6th, and 9th floors. Using STAAD Pro, the building was analyzed under earthquake loads using Response Spectrum and Time History Analysis as per IS 1893:2016.

Key parameters assessed include bending moment, shear force, and displacement. Results indicate that straight beams exhibited a maximum bending moment of 85.2 kNm on the 3rd floor, while curved beams recorded a lower value of 72.5 kNm at the same level. Similarly, displacement at the 9th floor was reduced from 7.6 mm in straight beams to 5.4 mm in curved beams, demonstrating improved lateral stability. Shear forces were also consistently lower in curved beams across all levels.

The study further incorporates soil-structure interaction (SSI), which revealed that foundation response and seismic energy dissipation vary with geometry. These findings suggest that curved beams enhance seismic resilience through better force redistribution and reduced stress concentration. The study recommends adopting optimized beam configurations and SSI-sensitive foundation design to improve the safety and performance of irregular structures in seismic zones.

Key words: Seismic stability, irregular buildings, plan asymmetry, curved beams, straight beams, structural dynamics, STAAD Pro Simulation.

1. Introduction

The stability of structures is a fundamental concern in structural engineering, ensuring both safety and functionality under various loading conditions such as gravity, wind, and seismic forces. While regular buildings with symmetrical layouts tend to have predictable and uniform structural responses, irregular buildings pose unique challenges due to non-uniform mass and stiffness distribution and discontinuities in their load paths. These irregularities significantly influence the dynamic behavior of structures, making them more susceptible to torsional effects, lateral displacements, stress concentrations, and ultimately, structural damage during seismic events.

In practical construction, irregularities are common and often unavoidable, arising from architectural requirements, functional needs, or aesthetic preferences. These may include plan irregularities—such as L-shaped, U-shaped, and T-shaped layouts or buildings with re-entrant corners—and vertical irregularities, including sudden changes in height, mass, or stiffness (e.g., soft stories, podium levels, and setbacks). These irregularities introduce complex load paths, alter force distribution, and reduce the efficiency of traditional seismic design assumptions.

Since the 1970s, both experimental and analytical research have highlighted the adverse effects of irregularities on the seismic performance of buildings. Key findings reveal that eccentricities in stiffness and strength result in increased vulnerability to damage, especially under earthquake-induced forces. Despite this, modeling and analyzing irregular buildings remains challenging due to their geometric complexity and the interaction of multiple variables. As a result, seismic design codes such as IS 1893:2016 provide only limited guidance, often recommending conservative limits or modifications to reduce irregularities instead of accommodating them through design innovations.

The variation in seismic code provisions across countries further complicates the issue, leading to inconsistencies in addressing torsional behavior and structural stability in irregular buildings. Torsional effects are influenced by several factors, including plan geometry, stiffness eccentricity, and dynamic interaction among structural elements. These factors demand a deeper analytical approach, especially in the context of Zone V seismic regions, where high-intensity ground motion is expected.

In modern high-rise construction, irregularities are frequently introduced for space utilization, aesthetic value, and functional zoning. However, the associated seismic performance implications necessitate advanced design and modeling techniques to ensure structural safety and serviceability. Therefore, this study aims to investigate the seismic stability of irregular buildings with a focus on plan irregularities and beam geometry, particularly analyzing the effect of curved and straight beams on key seismic response parameters such as bending moment, shear force, displacement, and torsional response. The outcomes will contribute to the development of design recommendations and mitigation strategies for enhancing the seismic resilience of irregular structures.

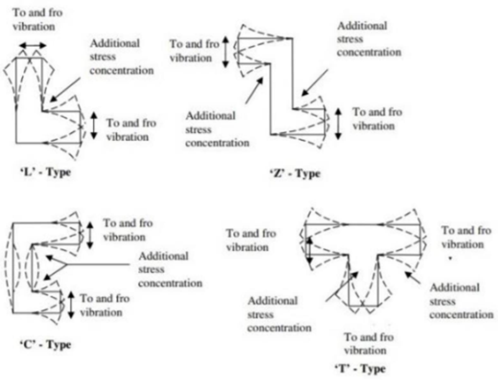


Figure 1 Cantilevered Tailed Vibration in Irregular Buildings

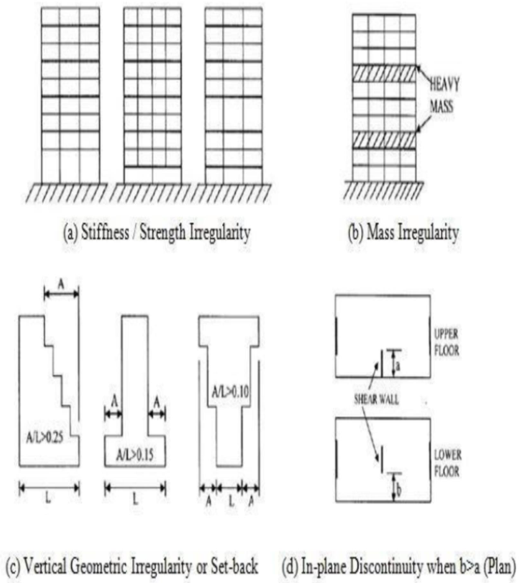


Figure 2Various Types of Irregularities in Elevation

Irregular reinforced concrete (RC) buildings are highly vulnerable to structural damage during seismic events, as demonstrated by numerous research studies. Therefore, assessing their seismic behavior and implementing measures to enhance their resilience against earthquakes is crucial. An extensive review by Anagnostopoulos et al. (2015) on the seismic performance of irregular buildings highlights that early research predominantly relied on simplified single-degree-of-freedom (SDOF) models subjected to unidirectional excitation. However, these models were insufficient in capturing the torsional response of RC structures, prompting researchers to develop more sophisticated three-dimensional (3D) mathematical models. Since then, significant research efforts have been directed towards understanding the seismic behavior of torsionally coupled RC buildings, as illustrated in Figure 3.

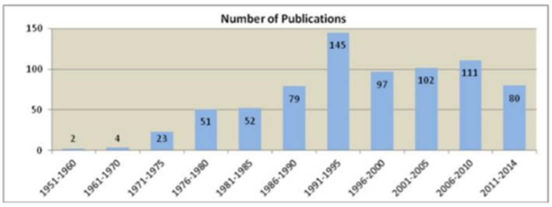


Figure 3Histogram of Publication on Building Torsion (Anagnostopoulos et al.,2015)

Studies have focused on various aspects of building irregularities, including asymmetry, vertical irregularity, plan irregularity, relevant seismic codes, and retrofitting strategies, as outlined in Figure 4 (Das et al., 2021). While extensive research has been conducted on asymmetry and vertical irregularities, comparatively fewer studies have addressed the seismic response of buildings with plan irregularities. Literature reports various types of structural damage experienced by irregular buildings due to seismic forces.

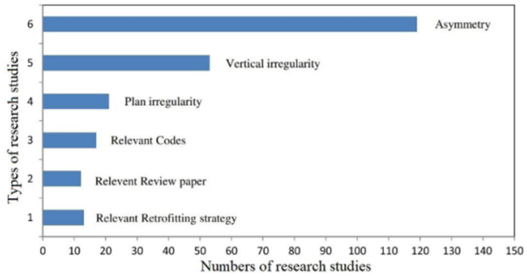


Figure 4Numbers of Research Work on Asymmetry/Irregularity (Das et al., 2021)

Table 1Previous Literature

Author(s) & Year	Key Focus	Findings
Putra et al. (2024)	Impact of geometric irregularities on seismic response	Eccentricities in mass and rigidity centers increase vulnerability
Blasi et al. (2024)	Effects of floor geometry variations on stability	Column cross-sectional reduction impacts floor displacements
Jambhulkar & Tenpe (2024)	Influence of mass distribution on seismic behavior	Uneven mass creates weak points, leading to higher damage risk
Kumawat et al. (2024)	Soft-story effects and structural collapse risks	Structures with weak lower levels exhibit excessive deformation
Pachla et al. (2024)	Nonlinear analysis of inter-story drifts and floor accelerations	Irregular buildings show increased damage index under prolonged shaking
Budthapa et al. (2024)	Mass irregularities leading to high lateral forces	Higher mass at upper stories amplifies seismic forces
Hentri et al. (2024)	Base shear and displacement variations due to mass irregularities	Base shear variations directly affect seismic resistance
Kumar & Samhitha (2024)	Impact of mass irregularities on seismic energy dissipation	Uneven mass distribution reduces structural resilience
Ghanem et al. (2024)	Live load distribution changes and their seismic implications	Usage changes complicate seismic response predictions
Wahane et al. (2024)	Plan irregularities, re-entrant corners, and torsional response	Torsional effects amplify stress concentrations
Flores & Zirakian (2024)	Discontinuities in diaphragms affecting lateral load transfer	Irregular diaphragms lead to localized stress concentrations
Patel & Khatri (2023)	Soft-story effects and stiffness irregularities	Soft-story effects worsen lateral deformation tendencies

Netke & Bhosale (2023)	Vertical setbacks and stress concentration analysis	Height discontinuities cause non-uniform stress distributions
Posudiievska (2022)	Vulnerability of vertically irregular structures	Buildings with vertical irregularities experience higher drift ratios
Esskely et al. (2023)	Compounding effects of plan and vertical irregularities	Combined irregularities increase complexity in seismic analysis
Alecci & Stefano (2018)	Challenges in balancing aesthetics and seismic safety	Architectural trends prioritize aesthetics over seismic regularity

Although significant research has been done on the seismic behavior of irregular buildings, key gaps remain. Most studies focus on either plan or vertical irregularities separately, with limited investigation into their combined effects. Experimental validation is also lacking, as most findings are based on numerical analysis. Additionally, current seismic codes like IS 1893:2016 follow prescriptive approaches and do not fully address performance-based design for buildings with multiple irregularities. Future research should focus on integrated analysis, experimental validation, and advanced design strategies to improve the seismic resilience of irregular structures.

The primary objectives of this study are:

- To analyze the effect of plan irregularities and beam configurations (curved vs. straight) on seismic response in Zone V.
- To study the influence of soil-structure interaction (SSI) on the stability of irregular buildings under seismic loading.
- To assess variations in base shear, lateral displacements, inter-story drift ratios, and torsional effects across different structural configurations.
- To develop design recommendations for optimizing geometry and improving load transfer and stress distribution in irregular structures.

This study aims to provide valuable insights into the seismic performance of irregular structures, contributing to improved design methodologies for resilient building systems in earthquake-prone regions.

Table 2 Structural and Seismic Details of the Multi-Story Frame Building

Category	**Details**
Building Type	Multi-story reinforced concrete frame structure with irregular geometry (curved and straight beams)
Analysis Type	Seismic analysis (Earthquake loading) at 3rd, 6th, and 9th floors
Design Codes Used	IS 456:2000 IS 1893:2016
Number of Stories	9 Stories
Building Plan Dimensions	16m × 27m
Total Height of Building	27m
Bay Spacing (X-direction)	3m
Bay Spacing (Y-direction)	3m
Seismic Load Consideration	Earthquake forces applied as per IS 1893:2016, considering Zone 5 seismic conditions
Foundation Type	Fixed support conditions
Column Size	300 mm × 300 mm
Beam Size	300 mm × 300 mm (including straight and curved beams)
Slab Thickness	150 mm
Concrete Grade	M30 (fck = 30 N/mm²)
Reinforcement Steel Grade	Fe500 (fy = 500 N/mm²)
Modulus of Elasticity of Concrete	21,718 N/mm²
Poisson's Ratio	0.17
Density of Concrete	2402.615 kg/m³

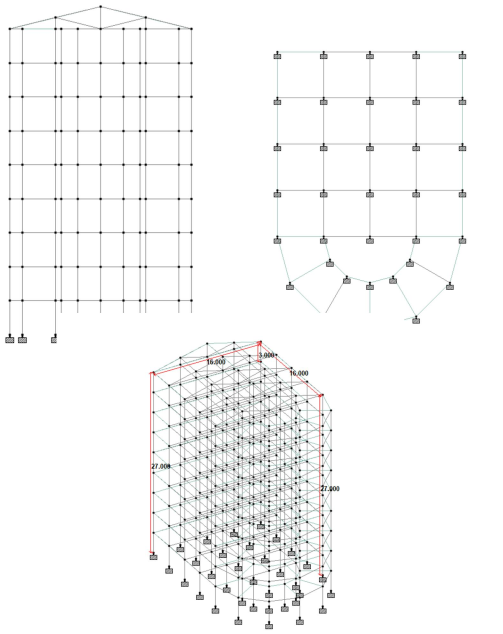
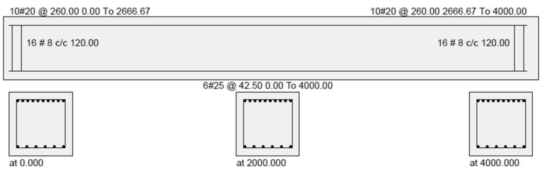


Figure 5(a) Front View, (b) Side View, and (c) Top View of structure



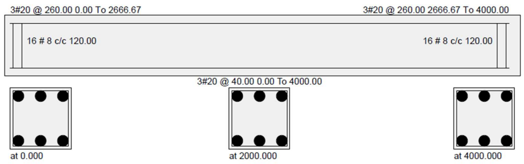


Figure 6Reinforcement detail of (a) curved beam and (b) straight beam

2. Output of analysis

This section presents a comparative analysis of the seismic response of curved and straight beams at different floors of the multi-story reinforced concrete structure under Zone 5 earthquake conditions. The key parameters examined include bending moments, shear forces, and displacements at the 3rd, 6th, and 9th floors for both curved and straight beams. The findings provide insights into the structural performance and the influence of beam geometry on the seismic stability of the building.

Table 5 Maximum outcomes for each condition

Floor	Beam	Bending Moment (kN-m)	Shear Force (kN)	Displacement (mm)
3rd	Straight	85.2	34.7	12.5
3rd	Curved	72.5	28.4	9.8
6th	Straight	78.9	30.2	10.3
6th	Curved	65.7	25.8	8.2
9th	Straight	62.3	22.9	7.6
9th	Curved	50.4	19.7	5.4

3. RESULTS AND DISCUSSION

The straight beam consistently shows higher bending moments across all floors, leading to greater stress concentrations.

The curved beam effectively redistributes seismic forces, reducing peak moment values and improving overall load-bearing efficiency.

Shear forces are higher in straight beams, particularly at support regions, increasing the risk of localized failure.

The curved beam maintains a more uniform shear force distribution, minimizing stress concentrations and improving seismic performance.

Displacements in straight beams are consistently higher, contributing to larger inter-story drift ratios.

The curved beam effectively reduces lateral deflections, enhancing the overall stability and resilience of the structure under seismic conditions.

Lower floors experience higher seismic forces, leading to greater bending moments and shear forces.

Curved beams show significant advantages in force distribution, particularly in lower and middle floors, where seismic loads are more critical.

At higher levels, the difference in behavior becomes more evident, with curved beams reducing inter-story drift and improving structural flexibility.

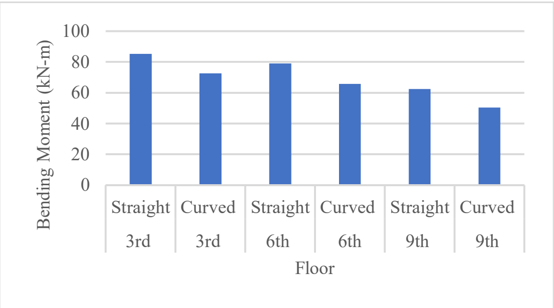


Figure 7Maximum Bending Moment of at each floor

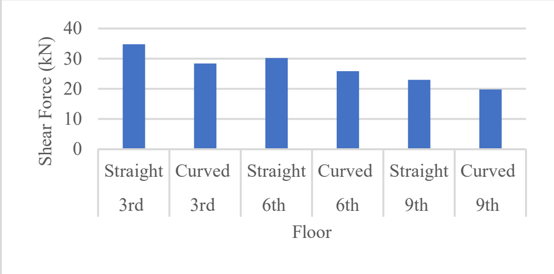


Figure 8Maximum Shear Force of at each floor

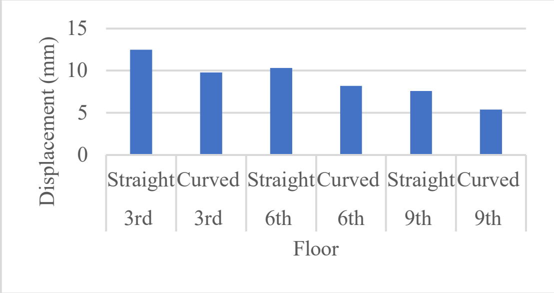


Figure 9Maximum Displacement of at each floor

Conclusion

This study demonstrates that curved beams offer significant advantages over straight beams in the seismic performance of multi-story reinforced concrete buildings located in Zone V. Through analysis conducted at the 3rd, 6th, and 9th floors, it was observed that curved beams consistently exhibit lower bending moments, reduced shear forces, and significantly lower displacement values. This indicates improved lateral stability and reduced inter-story drift, contributing to better energy dissipation during seismic events. At lower levels, straight beams were more prone to stress concentration and potential damage, while curved beams maintained more uniform stress distribution across all floors. These findings underline the importance of beam geometry in enhancing structural resilience and reducing vulnerability to seismic forces. The results suggest that curved beams can be effectively integrated into the design of earthquake-resistant buildings, especially in zones subjected to high lateral forces. Additionally, optimized reinforcement detailing in curved beams can further improve their performance, making them a reliable alternative in modern seismic design practices.

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