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Seismic Performance of Multi-Storeyed Buildings: A Comprehensive Review of Structural Irregularities, Analysis Methods and Emerging Trends

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Abstract - *With the rise of multi-storeyed buildings, seismic safety has become a crucial aspect in the design of the structures. Structural configuration, building height, mass and stiffness distribution, structural irregularities, soil conditions and lateral-load-resisting systems affect the seismic performance of these buildings. This paper provides a critical review of the existing literature on the seismic performance of multi-storeyed buildings from 2020 to 2026. The selected papers provide insight into plan and vertical irregularities, soft storeys, floating columns, shear walls, bracing and dual systems, diagrid structures, soil–structure interaction and various analysis methods in the field of seismic performance of buildings. In general, structural irregularities cause higher storey displacement, inter-story drift, torsional behavior and concentration of seismic demands; whereas properly designed shear walls, bracing and diagrid systems can positively affect the lateral stiffness and deformation performance of these buildings. Recent research shows more applications of the nonlinear time history analysis, pushover analysis, incremental dynamic analysis and seismic fragility analysis in assessing structural damage and vulnerabilities. Nevertheless, only a limited number of studies have investigated the combined effects of structural irregularities, building height, soil conditions and lateral-load-resisting systems within a unified framework.*

Keywords: - Seismic Performance; Multi-Storeyed Buildings; Structural Irregularity; Plan Irregularity; Vertical Irregularity; Soft Storey; Shear Wall; Diagrid Structure; Soil–Structure Interaction; Seismic Analysis; Seismic Fragility; Performance-Based Assessment

1. INTRODUCTION

Urbanization has led to a rise in construction of multi-storey and high-rise buildings because of lack of land space. High-rise buildings are prone to lateral loads during earthquake, and the response of structures is dependent upon the height of structure, distribution of mass and stiffness, structural system and soil condition. Seismic analysis of high-rise buildings is therefore necessary for safe operation of multi-storey buildings during ground motions.

Plan and vertical irregularity can affect the behaviour of buildings during earthquake. Torsion effects can be caused by plan irregularity whereas vertical irregularity like soft storey, setback, mass discontinuity and floating columns causes sudden change in stiffness and strength which leads to increased storey displacement and drift. Lateral load resisting system consisting of shear wall, bracing, dual systems and diagrid structure is of importance in controlling earthquake response. Several analytical methods like response spectrum, time history, pushover and fragility analysis have been employed for this purpose.

The review discusses the latest research findings related to seismic behavior of multi-storey buildings from 2020 to 2026. The areas covered in the review include structural irregularity, soft stories, shear walls, advanced structural system, soil influence and seismic analysis. Major conclusions from existing literature are critically analyzed for the identification of research gaps and new areas of research with special focus on seismic resistance of multi-storey buildings.

2. OBJECTIVES OF THE REVIEW

The main objectives of this review are:

- To study the effect of plan and vertical irregularities like torsion irregularities, soft story, setbacks and floating columns on the seismic behaviour.
- To study the behaviour of various structural systems, like moment resisting frames, shear walls, bracing, double systems and diagrid system.
- To compare the recent approaches of analysis in terms of seismic analysis like response spectrum, time history analysis, pushover analysis, incremental dynamic analysis and fragility analysis.
- To study the effect of soil properties, near fault motions and other seismic parameters on the seismic performance of multi-story buildings.
- To identify the research gaps and limitations of the existing literature and propose future research directions.

3. LITERATURE REVIEW

3.1 PLAN AND VERTICAL IRREGULARITY

Lin et al. [1] (2020) investigated the seismic response of vertically irregular buildings under near-fault ground motions. The study found that vertical irregularities significantly affect seismic demand, particularly under near-fault conditions.

The authors of [2] (2020) proposed a multidirectional pushover procedure for torsionally irregular RC buildings. The study showed that multidirectional loading provides a more representative assessment of deformation and strength demands than conventional unidirectional pushover analysis.

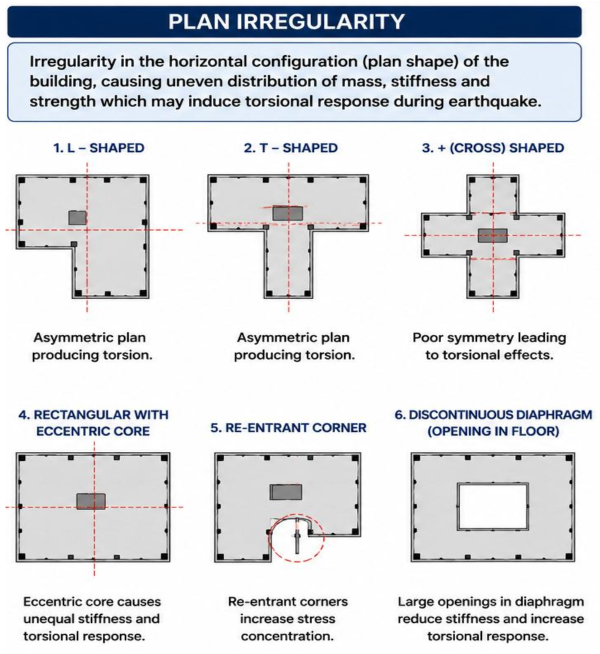

Fig. 2. Typical Forms of Plan Irregularity in Multi-Storeyed Buildings

Jia et al. [3] (2022) investigated the seismic behavior of irregular high-rise buildings using numerical simulation. The study found that structural irregularities increase uneven displacement, inter-storey drift, and internal forces, emphasizing the need to consider irregular configurations in seismic assessment.

Nady et al. [4] (2022) quantified vertical irregularities in earthquake-resistant RC buildings using quantitative measures for their identification and assessment. The study found that the severity of vertical irregularity significantly influences seismic response and can support consistent seismic evaluation and design.

Saif et al. [5] (2023) investigated the seismic behavior of RC buildings with different plan irregularities. The study found that irregular plans intensify torsional effects and produce non-uniform seismic demands, highlighting the importance of plan configuration in seismic performance.

Blasi et al. [6] (2024) investigated the seismic response of irregular RC buildings under gravity and seismic loads. The study found that irregular configurations experience greater deformation and localized seismic demands, emphasizing the need to consider actual structural configurations in seismic assessment

Prayuda et al. [7] (2025) investigated the seismic performance of multi-storey RC frames with horizontal and vertical irregularities. The study found that combined irregularities produce more complex seismic behavior than individual irregularities, highlighting the need for holistic assessment.

Tamizharasi et al. [8] (2025) compared code-based methods for assessing vertical stiffness discontinuity in RC frames. The study found that the method used to identify stiffness discontinuity can influence the classification of structural irregularity.

Raj et al. [9] (2025) investigated the effect of structural irregularity on the seismic fragility of RC structures using fragility-based analysis. The study found that irregularity increases seismic vulnerability and damage probability, demonstrating the usefulness of fragility analysis for assessing structural performance beyond conventional parameters.

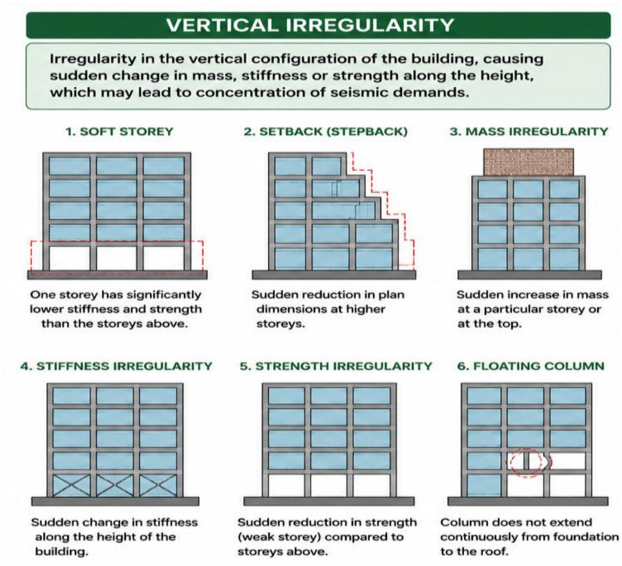

Fig. 3. Common Forms of Vertical Irregularity in Multi-Storeyed Buildings

Tajunnisa et al. [10] (2026) investigated the seismic behavior of horizontally irregular buildings using pushover analysis. The study found that horizontal irregularity affects deformation distribution and lateral capacity, demonstrating the usefulness of nonlinear static analysis for seismic assessment.

Santos et al. [11] (2026) numerically investigated the combined effects of corrosion and vertical irregularities on the seismic behavior of RC frames. The study found that corrosion-induced degradation further deteriorates the seismic response of vertically irregular structures.

3.2 SHEAR WALLS AND LATERAL LOAD-RESISTING SYSTEMS

Dalai and Parhi [12] (2021) investigated the seismic behavior of multi-storey RC buildings with and without shear walls. The study found that shear walls enhance structural stiffness and reduce deformation, confirming their effectiveness as a lateral load-resisting system.

Ahamad and Pratap [13] (2021) investigated the effect of shear wall position on the seismic performance of a G+20 RC building using ETABS. The study found that shear wall placement significantly influences displacement, storey drift, and overall seismic response.

Duduskar et al. [14] (2021) evaluated multi-storey structures with floating columns and shear walls under seismic loading. The study found that floating columns adversely affect seismic behavior due to discontinuities in stiffness and load paths, while shear walls improve lateral strength and reduce seismic deformation.

Nayak et al. [15] (2022) investigated the seismic performance of RC buildings with shear walls of different geometries. The study found that shear wall geometry and arrangement significantly affect lateral-load performance.

Behera and Parhi [16] (2023) compared high-rise buildings with diagrid and conventional RC frame systems. The diagrid system improved lateral stiffness and deformation control, demonstrating its potential as an alternative structural system.

Pranava et al. [17] (2025) studied torsionally irregular RC buildings with different shear wall arrangements. The results showed that optimized shear wall placement can significantly reduce torsion, displacement, drift, and base shear.

Sirsat and Pandit [18] (2026) evaluated irregular 25-storey RC buildings with and without shear walls considering the P–Δ effect. Shear walls improved lateral stiffness and reduced deformation, while the P–Δ effect was significant in tall, flexible structures.

3.3 SOFT STOREY AND FLOATING COLUMNS

Duduskar et al. [14] (2021) investigated tall structures with floating columns and shear walls under seismic loading. Floating columns cause discontinuities in load transfer and concentrated seismic demands, while shear walls improve lateral stiffness and reduce these effects.

Abd-Alghany et al. [19] (2021) studied multi-storey RC buildings with soft storeys. The study found that stiffness discontinuity at soft-storey levels increases deformation and seismic forces, thereby increasing vulnerability.

Eldar and Singh [20] (2022) examined irregular structures with floating columns under seismic loading. The study found that floating columns alter stiffness and internal-force distribution, increasing seismic demand and highlighting the importance of continuous load paths.

3.4 SOIL EFFECTS AND SITE CONDITIONS

Mouhine and Hilali [21] (2022) investigated the seismic vulnerability of irregular RC structures considering site effects. The study found that site conditions can modify ground-motion characteristics and significantly influence the seismic vulnerability of irregular buildings.

Kumar and Ghosh [22] (2025) evaluated the effect of soil amplification on irregular RC buildings of different heights. The results showed that soil amplification significantly affects seismic demand, particularly when building height and structural irregularity are considered together.

Jarapala and Menon [23] (2025) studied the seismic fragility of RC structures on sloping terrain. The study found that changes in geometry and stiffness create complex seismic behavior, and conventional irregularity measures may not accurately represent the fragility of buildings on slopes.

3.5 DIAGRID AND ADVANCED STRUCTURAL SYSTEMS

Behera and Parhi [16] (2023) compared diagrid and conventional RCC high-rise structures under seismic loading. The study found that diagrid systems improve load transfer and deformation control, enhancing seismic performance.

Magsi et al. [24] (2024) assessed the seismic capacity of a diagrid exoskeleton using probabilistic nonlinear dynamic analysis. The results indicated that the diagrid system provides adequate seismic capacity.

Liu et al. [25] (2024) investigated a diagrid core-tube structure with replaceable steel coupling beams. The study showed that replaceable components can improve seismic resilience and post-earthquake repairability.

3.6 NONLINEAR ANALYSIS, PUSHOVER AND FRAGILITY-BASED ASSESSMENT

The multidirectional pushover technique suggested by [2](2020) proved the significance of taking multidirectional earthquake effect into account while analyzing the behavior of torsionally irregular structures. It was proven that the conventional approach of using unidirectional pushover does not always give reliable results in case of lateral loads applied to a structure in multiple directions simultaneously.

Blasi et al. [6] **(2024)** investigated the seismic response of irregular reinforced concrete buildings under design conditions of gravity and earthquakes. The study highlighted the significance of analyzing the nonlinear response of the structures in order to understand their behavior.

Rathnasiri et al. [26] **(2024)** proposed a simplified method for evaluating the seismic vulnerability of plan-irregular reinforced concrete buildings using the degree of irregularity. The study demonstrated that a quantitative irregularity parameter can be useful for estimating vulnerability without requiring highly complex analysis for every structural configuration.

Smiroldo et al. [27] **(2024)** investigated non-regular reinforced concrete structures using fragility curves. The study demonstrated that fragility analysis can provide a probabilistic measure of structural vulnerability by relating earthquake intensity to different damage states. This approach provides more meaningful information about expected structural performance than a single deterministic response parameter.

Magsi et al. [24] **(2024)** further demonstrated the application of probabilistic nonlinear dynamic analysis to advanced structural systems. Such approaches are particularly useful when uncertainties in structural properties and ground motions need to be incorporated into seismic performance assessment.

Sharma et al. [28] **(2025)** performed a displacement-based seismic fragility assessment of a high-rise reinforced concrete building. The study used displacement-related response parameters to estimate the probability of different damage states. The results support the increasing use of displacement-based and probabilistic methods for assessing the seismic vulnerability of high-rise buildings.

Raj et al. [9] **(2025)** applied seismic fragility assessment to investigate the influence of structural irregularities on reinforced concrete buildings. The findings demonstrated that irregularity can influence both structural response and the probability of exceeding specific damage states. Fragility-based methods therefore provide an effective framework for comparing the seismic vulnerability of different structural configurations.

Oyguc et al. [29] **(2026)** investigated the fragility of irregular reinforced concrete buildings subjected to mainshock–aftershock sequences. The study extends conventional single-earthquake assessment by considering the cumulative effect of sequential ground motions. The findings highlight that damage caused by a mainshock can reduce the remaining capacity of a building and consequently increase its vulnerability during subsequent aftershocks.

Tajunnisa et al. [10] **(2026)** used pushover analysis to evaluate horizontally irregular concrete buildings. The study demonstrated that nonlinear static analysis can provide useful information about lateral strength, deformation capacity and performance of irregular structures. Such analysis is particularly useful for evaluating the progression of structural response beyond the elastic range.

3.7 SEISMIC CONTROL AND ENERGY DISSIPATION

Titirla and Larbi [30] **(2024)** comparatively investigated seismic performance enhancement in irregular reinforced concrete buildings using friction and viscous dampers. The study demonstrated that supplemental damping devices can reduce seismic response by dissipating a portion of the earthquake-induced energy. The results indicate that friction and viscous dampers can be effective for controlling displacement and structural demand in irregular buildings, providing an alternative to relying solely on increased structural stiffness.

3.8 RECENT DEVELOPMENTS IN SEISMIC PERFORMANCE ASSESSMENT

Recent research shows a gradual shift from conventional elastic seismic analysis toward nonlinear, probabilistic and performance-based assessment methods. Studies on fragility analysis [27], [28], [9], probabilistic nonlinear analysis [24], and mainshock–aftershock sequences [29] indicate increasing emphasis on evaluating the probability of damage rather than relying only on peak displacement or base shear.

The influence of site conditions has also received increasing attention. Studies by **Mouhine and Hilali** [21]**, Kumar and Ghosh** [22]**,** and **Jarapala and Menon** [23] demonstrate that soil characteristics, soil amplification and terrain conditions can significantly modify the seismic response of irregular buildings. These findings suggest that structural irregularity should not be evaluated independently of the surrounding geotechnical environment.

Similarly, recent studies have expanded the scope of seismic assessment by considering structural deterioration and second-order effects. **Sirsat and Pandit** [18] incorporated the P–Δ effect in the seismic evaluation of high-rise irregular buildings, while **Santos et al.** [11] considered the combined influence of corrosion and vertical irregularity. These studies demonstrate the need to move beyond idealized undamaged structural models when evaluating the seismic performance of existing buildings.

Overall, the literature from 2020 to 2026 demonstrates that the seismic performance of multi-storey buildings is governed by the interaction of **structural configuration, plan and vertical irregularity, stiffness distribution, lateral-load-resisting systems, building height, soil conditions, ground-motion characteristics and structural deterioration**. Conventional response-spectrum analysis remains widely used for comparative studies, while nonlinear pushover, nonlinear dynamic analysis, probabilistic assessment and fragility-based approaches are increasingly being adopted for more comprehensive evaluation. However, most existing studies continue to investigate individual parameters or specific structural configurations rather than evaluating their combined effects within a common analytical framework. This observation provides the basis for identifying the research gaps discussed in the following section.

4. COMPARATIVE DISCUSSION OF REVIEWED STUDIES

The literature examined within the years 2020 to 2026 confirms that the seismic behavior of multi-story buildings is highly influenced by structural shape, irregularity, stiffness distribution, height, and site conditions. Literature about plan irregularities revealed increased torsion effect, non-uniform displacement and greater earthquake forces for irregular buildings as compared to those having regular shapes. Literature about vertical irregularities, such as soft stories, stepbacks and floating columns, revealed increased storey drift and displacement due to sudden variations in stiffness, strength and loading transfer mechanism. It was observed from literature that a comparison of various types of lateral load resisting systems reveals that shear walls, bracing and dual systems offer better lateral displacement and storey drift control as compared to conventional moment-resisting frames. Recent studies about diagrid systems also reveal improved lateral stiffness and deformation control in tall buildings. However, the effectiveness of all these systems depends mostly on their configuration and placement. Optimum placement of shear walls has been found to play a significant role in torsional control of irregular buildings.

Seismic analysis methodologies are also noted to follow a certain progression in the reviewed literature. The Response Spectrum Analysis is still used in traditional comparative studies, especially in the case of ETABS-based research. However, non-linear pushover analysis, non-linear time history analysis, incremental dynamic analysis and fragility analysis are now providing more insights into the building's ability to withstand earthquakes. They are becoming more popular in recent studies, especially in the case of irregular structures.

Soil condition and ground motion properties also had a significant effect on the response of the structure to earthquakes. Buildings constructed in soft soils demonstrated higher displacement and seismic loads than the buildings built in stiff soils. It was also revealed that near fault ground motions lead to greater reactions than far field ground motions. Cumulative damage caused by main shock-aftershock sequences is also becoming an important factor in the recent research on irregular structures.

From the above comparison, it is evident that there is no sole factor or method that alone can be considered adequate to capture the earthquake performance of such structures. Most of the current works are mainly focused on individual factors like irregularity, shear walls, soil condition or structural systems. However, the works investigating the effects of the combination of these factors with the consideration of the height of structure, soil-structure interaction, nonlinearity and modern structural systems are relatively few.

5. RESEARCH GAPS

- Irregularities in structures: Most of the existing literature examines plan or vertical irregularities separately. Very few works examine the combined impact of plan, vertical, torsional, and stiffness irregularities on multi-storey buildings.

- The impact of building height and soil characteristics: The combined impact of building height, structural irregularities, and soil characteristics needs to be studied.
- Evaluation of structural systems: Shear wall system, bracing system, dual system, and diagrid structure have been analyzed in literature, but no comparative analysis has been performed for them.
- High-level Seismic Assessment: Most research works still depend on classical response spectrum analysis. It is essential to have a higher utilization of non-linear time history, push-over, Incremental Dynamic Analysis, and fragility analysis for evaluation of the damage and collapse of structures.
- Impact assessment and intelligence assessment: An intelligent assessment system should consider the structural irregularity, structure height, soil, ground motion, and lateral-load-resisting system. Another potential research area is the application of AI/ML techniques in seismic response and structure optimization.

6. FUTURE WORK SCOPE

- Future studies should investigate the **combined effect of plan, vertical and torsional irregularities** on multi-storeyed buildings with different heights.
- The influence of **soil conditions and soil–structure interaction** should be incorporated along with structural irregularities and different earthquake ground motions.
- A systematic comparison of **shear walls, bracing, dual systems and diagrid structures** should be carried out under similar building configurations and seismic conditions.
- More studies should adopt **nonlinear time-history analysis, pushover analysis, Incremental Dynamic Analysis and fragility assessment** to evaluate damage, collapse probability and seismic resilience.
- **AI/ML-based approaches** can be explored for predicting seismic response, identifying vulnerable structural configurations and optimizing the location and configuration of lateral-load-resisting systems.
- Future research should focus on developing an **integrated performance-based framework** that considers building configuration, structural system, soil condition and earthquake characteristics for improving the seismic safety and resilience of multi-storeyed buildings.

7. CONCLUSION

- The seismic behavior of multi-storeyed buildings depends greatly on building configuration, height, distribution of mass and stiffness, structural irregularities, soil conditions and lateral load resisting system.
- Plan and vertical irregularities including torsional irregularity, soft story, setback and floating columns normally lead to an increase in storey displacement, drift and concentration of seismic forces.
- Shear wall, bracing, dual and diagrid systems can be used to improve the lateral stiffness and minimize the seismic deformations effectively.
- Lately, there has been a trend in shifting from conventional response spectrum analysis to pushover analysis, nonlinear time history analysis, incremental dynamic analysis and fragility based analysis.
- Soil conditions, near-fault ground motion and mainshock-aftershock sequence have been seen to affect the seismic behavior of multi-storeyed buildings.
- Literature review shows that existing research has concentrated on the study of one factor at a time; hence, the combined effect of all these factors needs to be studied further.
- Generally, future seismic assessment will need to take an integrated and nonlinear approach.

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