JAAFR INTERNATIONAL RESEARCH JOURNAL
JOURNAL OF ADVANCE AND FUTURE RESEARCH
JAAFR.ORG | ISSN : 2984-889X
An International Open Access, Peer-reviewed, Refereed Journal

Vertical Geometric Irregularity Effect on Performance-Based Seismic Design for Moderate Rise RC Moment Resisting Frame Buildings- A Review

Riddhi Verma[1] & Pushpendra Patel[2]

[1]PG Student, Department of Civil Engineering, Technocrats Institute of Technology - Computer Science and Engineering, India

[2] Professor, Department of Civil Engineering, Technocrats Institute of Technology Bhopal, India

Corresponding Author: riddhiv1999@gmail.com

Abstract : Vertical geometric irregularity is an important factor influencing the seismic behavior of reinforced concrete (RC) moment-resisting frame buildings. Setbacks, stepped configurations, and other abrupt changes in building geometry can modify the distribution of mass, stiffness, strength, and dynamic characteristics, potentially resulting in increased seismic demand and localized damage. This review paper critically examines the influence of vertical geometric irregularity on the performance-based seismic design of moderate-rise RC moment-resisting frame buildings. The review focuses on the effects of setback magnitude and location, dynamic characteristics, higher-mode effects, inter-storey drift, displacement response, nonlinear deformation, plastic hinge development, damage concentration, and seismic performance. Different analytical approaches, including nonlinear static analysis, nonlinear response-history analysis, displacement-based design, and performance-based seismic assessment, are examined to understand their applicability to vertically irregular structures. The reviewed literature indicates that the seismic response of vertically irregular buildings is strongly dependent on the configuration and location of geometric discontinuities and that conventional irregularity indices alone may not adequately represent actual structural performance. The review further highlights the importance of evaluating local deformation and damage concentration in addition to global response parameters. Significant research gaps remain in the integrated assessment of geometric irregularity, nonlinear response, higher-mode effects, and performance objectives for moderate-rise RC moment-resisting frames. The study emphasizes the need for an integrated performance-oriented framework capable of relating geometric irregularity to dynamic response, seismic demand, damage, and structural performance. Such an approach can contribute to safer and more reliable seismic design of vertically irregular RC buildings.

Keywords: Vertical geometric irregularity; Setback buildings; Reinforced concrete; Moment-resisting frames; Seismic performance; Performance-based seismic design; Nonlinear analysis; Inter-storey drift; Higher-mode effects; Damage assessment.

I. INTRODUCTION

1.1 Background of Seismic Design of Reinforced Concrete Buildings

Reinforced concrete (RC) moment-resisting frame buildings are widely used for residential, commercial, institutional, and mixed-use construction because of their structural efficiency, architectural flexibility, and ability to resist gravity and lateral loads through beam-column framing systems. In seismic regions, however, the performance of an RC building is governed not only by its strength but also by its stiffness distribution, ductility, energy dissipation capacity, and ability to develop a stable and desirable mechanism during strong ground motion. Earthquake-induced demands are inherently dynamic and may produce substantial variations in displacement, inter-storey drift, acceleration, and member forces over the height of a building. Consequently, the configuration and distribution of structural properties play a fundamental role in determining seismic performance.The seismic response of a building is strongly influenced by its geometry and the continuity of its lateral-force-resisting system. A building having approximately uniform mass, stiffness, strength, and geometry along its height generally exhibits a relatively predictable distribution of seismic demand. In contrast, abrupt changes in structural configuration can modify the dynamic characteristics and cause localized concentrations of deformation and force. Early investigations into the seismic response of buildings with vertical structural irregularities demonstrated that changes in structural properties along the height can significantly alter the response compared with regular frames [1]. Similar concerns have been reported for buildings incorporating setbacks, where reductions in floor dimensions produce discontinuities in the lateral-load-resisting system [2], [3].Conventional seismic design procedures have historically been based largely on equivalent lateral-force concepts, in which the expected inelastic behavior of a structure is incorporated through response modification or behavior factors. Although such procedures provide an efficient framework for practical design, their application to irregular structures can be challenging because the assumptions underlying simplified lateral-force distributions may not adequately represent the actual nonlinear response. Research on vertically irregular RC buildings has therefore emphasized the importance of considering the distribution of stiffness, strength, mass, and geometry when evaluating seismic response [4].

1.2 Structural Irregularity in Reinforced Concrete Buildings

Several studies have investigated the seismic behavior of RC frames with irregular profiles. Wood examined RC frames with irregular elevations and demonstrated that changes in structural profile can influence displacement, acceleration, and force response under earthquake excitation [3]. Das and Nau subsequently examined seismic design aspects associated with vertically irregular RC buildings and highlighted the importance of considering vertical discontinuities when establishing seismic design requirements [4]. A broader review by De Stefano and Pintucchi showed that vertical irregularity has remained a significant research topic because of its influence on dynamic response, nonlinear behavior, and seismic demand distribution [11].

An important limitation of classifying buildings simply as “regular” or “irregular” is that irregularity itself does not necessarily determine the magnitude of seismic vulnerability. The seismic response depends on the type, magnitude, location, and combination of irregularities, as well as on the structural period, ductility, strength hierarchy, ground-motion characteristics, and analysis method. Bhosale et al. investigated the relationship between vertical irregularity and seismic risk and demonstrated that commonly used regularity indicators may not always provide a direct measure of actual seismic risk [12]. This observation indicates that quantitative evaluation of irregularity should ideally be linked to actual structural response rather than relying exclusively on geometric thresholds.

1.3 Vertical Geometric Irregularity and Setback Configuration

A stepped building is a typical example of vertical geometric irregularity in which the building footprint progressively changes with elevation. Sarkar, Prasad, and Menon investigated stepped building frames and proposed a quantitative measure of vertical geometric irregularity based on dynamic characteristics. Their study emphasized that the seismic behavior of a stepped structure cannot be adequately characterized solely through conventional geometric measures because the dynamic properties of the structure also contribute significantly to its response [6].

Research on RC moment-resisting setback frames has demonstrated the importance of setback configuration in determining inelastic seismic demand. Varadharajan, Sehgal, and Saini investigated RC moment-resisting frames with setbacks and evaluated parameters associated with nonlinear seismic response [8]. Their subsequent investigation of multistorey RC frames with vertical setback irregularity further examined the influence of setback configurations on seismic behavior [9]. More recently, Mouhine and Hilali examined the effect of setback location on the performance of RC building frames and demonstrated that the location of the geometric discontinuity can significantly influence structural response under seismic excitation [15].Consequently, vertical geometric irregularity should not be considered solely as a geometric characteristic. It represents a change in the structural system that can affect mass distribution, lateral stiffness, strength distribution, modal participation, higher-mode response, deformation patterns, and damage concentration. These effects become particularly important when the building is expected to undergo significant inelastic response during severe earthquakes.

1.4 Seismic Response of Vertically Irregular RC Moment-Resisting Frames

The seismic response of a vertically irregular RC moment-resisting frame is influenced by the interaction between its geometric configuration and nonlinear structural behavior. In a regular frame, lateral deformation generally develops in a relatively continuous manner over the height. In contrast, a setback or other geometric discontinuity can cause changes in lateral stiffness and strength, resulting in non-uniform deformation demands.Important seismic response parameters include base shear, storey shear, roof displacement, inter-storey drift ratio, floor acceleration, member forces, plastic hinge rotations, and energy dissipation. Among these, inter-storey drift is particularly important because excessive drift may result in significant structural and nonstructural damage. Geometric discontinuities can cause drift concentrations near the setback level, potentially increasing local damage even when the overall roof displacement remains within an acceptable range.Athanassiadou investigated RC plane frames with elevation irregularities using nonlinear static and dynamic analysis and showed that irregularity can influence the distribution of seismic demand and the accuracy of simplified analysis procedures [5]. The importance of higher-mode effects is also

evident in vertically irregular structures. Chintanapakdee and Chopra compared response-history analysis with modal pushover approaches for vertically irregular frames and demonstrated that higher-mode contributions can be important when evaluating irregular structures [13].

The influence of vertical mass and stiffness irregularity has also been investigated in multistorey RC frames. Varadharajan et al. examined seismic response associated with mass and stiffness discontinuities and investigated parameters such as displacement and drift [10]. Mwafy and Khalifa further investigated the influence of vertical structural irregularity on seismic design and highlighted the importance of accurately representing irregular structural characteristics during seismic assessment [13].The formation and distribution of plastic hinges are particularly important for RC moment-resisting frames. A desirable seismic mechanism should promote controlled inelastic deformation in ductile structural members while avoiding premature brittle failure and excessive concentration of damage in a limited number of storeys. A geometric discontinuity may alter the sequence of yielding and cause localized plastic deformation. Maulana et al. therefore proposed a damage index ratio specifically for low- to mid-rise RC moment-resisting frames with setbacks subjected to earthquake loading [17]. Such approaches demonstrate the increasing importance of evaluating damage distribution, rather than relying exclusively on global force and displacement parameters.

1.5 Performance-Based Seismic Design

Men and Shi developed an Inter-Story Capacity Spectrum (ISCS) method for performance-based seismic design of vertically irregular RC frame structures [7]. Their approach emphasized inter-storey response and structural capacity, providing a methodology for evaluating the performance of vertically irregular structures beyond conventional global capacity measures. This is particularly relevant to setback structures because the critical performance condition may occur at or near the geometric discontinuity rather than at the building roof.

Performance-based optimization has also been investigated for RC structures. Fragiadakis and Papadrakakis proposed a performance-based optimum seismic design methodology that incorporates nonlinear structural response into the design process [20]. Similarly, Hajirasouliha et al. developed an efficient performance-based seismic design method for RC frames with the objective of achieving a more efficient distribution of strength and deformation capacity [21]. Although these studies are not limited exclusively to vertically irregular structures, they provide important methodological foundations for applying PBSD concepts to irregular RC moment-resisting frames.Displacement-based approaches provide another important framework for performance-oriented seismic design. Giannakouras and Zeris investigated the seismic performance of irregular RC frames designed using a direct displacement-based design approach [16]. Such studies demonstrate the potential for displacement-based methodologies to provide more direct control of seismic deformation than conventional force-based procedures.

2. Literature Review

2.1 Evolution of Research on Vertically Irregular RC Buildings

Research on the seismic behavior of vertically irregular buildings has developed progressively from early investigations of setback configurations and irregular structural profiles toward advanced nonlinear analysis and performance-based seismic design. The fundamental concern underlying these studies is that abrupt changes in

building geometry or structural properties along the height can modify the distribution of seismic demand and produce response characteristics that differ substantially from those of regular buildings.

One of the early investigations into this subject was conducted by Shahrooz and Moehle, who examined the seismic response and design implications of setback buildings [2]. Their work established the importance of considering changes in structural configuration along the height when evaluating earthquake response. Subsequently, Wood investigated the seismic response of reinforced concrete frames with irregular profiles and demonstrated that variations in the elevation configuration could significantly influence structural response under earthquake excitation [3]. These early studies provided an important foundation for understanding the relationship between building geometry and seismic behavior.

Valmundsson and Nau further examined the seismic response of building frames containing vertical structural irregularities and demonstrated that discontinuities in structural properties can alter the distribution of seismic demands over the building height [1]. Their findings highlighted the limitations of treating a vertically irregular structure as a simple extension of a regular frame. The research also established the importance of considering the interaction between structural configuration and dynamic response.

The development of research in this field was subsequently reviewed by De Stefano and Pintucchi, who examined the progress of investigations into irregular building structures and identified vertical irregularity as one of the major challenges in seismic design [11]. Their review demonstrated that the behavior of irregular buildings is governed by several interacting factors, including stiffness, strength, mass distribution, geometric configuration, higher-mode effects, and nonlinear structural behavior.

2.2 Classification and Characteristics of Vertical Irregularity

Vertical irregularity can occur because of abrupt variations in mass, stiffness, strength, geometry, or the continuity of the lateral-load-resisting system. The resulting structural discontinuities can influence the natural vibration characteristics and modify the distribution of earthquake-induced forces and deformations.

Das and Nau investigated the seismic design aspects of vertically irregular reinforced concrete buildings and highlighted the importance of accounting for changes in structural properties along the building height [4]. Their work demonstrated that the seismic response of irregular structures cannot always be adequately represented using assumptions developed for regular buildings.

Vertical irregularity is not necessarily restricted to one structural parameter. Mass irregularity may arise from sudden changes in floor mass, whereas stiffness irregularity can result from changes in member dimensions, storey height, infill conditions, or lateral-resisting elements. Strength irregularity may occur when the lateral resistance changes significantly between adjacent storeys. Geometric irregularity, in contrast, results from changes in the physical dimensions or configuration of the building itself.

Among these different forms, geometric irregularity is particularly relevant because it can simultaneously influence mass, stiffness, strength, and modal characteristics. This interaction makes it difficult to evaluate the effect of geometric irregularity using a single structural parameter.

Bhosale, Davis, and Sarkar investigated the relationship between vertical irregularity and seismic risk through the concept of a regularity index [12]. Their work demonstrated that a simple measure of geometric or structural irregularity does not necessarily correspond directly to seismic risk. Different irregularity types can produce different levels of vulnerability even when their nominal irregularity measures are comparable. This finding emphasizes the need to establish a stronger relationship between irregularity indices and actual seismic performance.

2.3 Vertical Geometric Irregularity and Setback Buildings

Shahrooz and Moehle provided early research on the seismic response and design of setback buildings [2]. Their work established the importance of considering the building profile in seismic design rather than treating the structure as a uniform frame. Wood subsequently investigated RC frames with irregular profiles and provided experimental evidence concerning the effect of irregular elevation configurations on seismic response [3].Sarkar, Prasad, and Menon specifically investigated **vertical geometric irregularity in stepped building frames** [6]. Rather than relying only on conventional geometric ratios, they proposed a regularity index based on the dynamic characteristics of the building. Their work showed that the seismic significance of a setback depends not only on the physical reduction in floor area but also on how the geometric change modifies the dynamic properties of the structure.

The importance of setback configuration was further investigated by Varadharajan, Sehgal, and Saini. Their research examined the inelastic seismic demands of RC moment-resisting setback frames [8]. The study considered nonlinear structural response and demonstrated that setback configurations can substantially influence inelastic deformation demands. Their subsequent investigation of multistorey RC frames with vertical setback irregularity further examined the influence of setback arrangements on seismic behavior [9].

2.4 Influence of Setback Location and Magnitude

The location of a geometric discontinuity along the building height is an important factor governing the seismic behavior of vertically irregular structures. A setback located at the lower portion of a building can affect the global lateral-load-resisting mechanism differently from a setback located near the upper storeys. Similarly, multiple smaller setbacks may produce a different response from a single large setback even when the total reduction in floor area is comparable.

Varadharajan et al. investigated vertical setback irregularity in multistorey RC frames and demonstrated that different setback configurations can result in different seismic response characteristics [9]. Their work emphasized the importance of considering the complete vertical distribution of the irregularity rather than describing the structure using only a single setback ratio.Mouhine and Hilali specifically examined the **effect of setback irregularity location** on the seismic performance of RC building frames [15]. Their results demonstrated that the location of the setback can significantly influence structural performance under seismic excitation. This observation is particularly important for performance-based design because the same nominal geometric irregularity may result in different deformation and damage demands depending on its position.

The relationship between geometric irregularity and dynamic characteristics has also been investigated in non-RC moment-resisting frames. Bohlouli and Poursha examined geometrically irregular steel moment-resisting frames with setbacks while considering their dynamic characteristics [14]. Although their study focused on steel frames, the

findings provide useful evidence that setback geometry can alter dynamic response characteristics and that seismic evaluation should account for the resulting modal behavior.Mwafy and Khalifa examined the effect of vertical structural irregularity on seismic design and demonstrated the importance of the vertical distribution of structural properties in determining seismic response [13]. Collectively, these studies indicate that both **magnitude and location** should be treated as important variables when evaluating vertical geometric irregularity.

2.5 Seismic Response of RC Moment-Resisting Frames with Vertical Irregularity

Athanassiadou investigated the seismic performance of RC plane frames irregular in elevation using nonlinear analytical approaches [5]. The study compared regular and irregular configurations and evaluated their response under seismic loading. The findings demonstrated that vertical irregularity can affect both global and local response parameters and that nonlinear dynamic analysis may be necessary for accurately evaluating certain irregular structures.Varadharajan et al. examined RC moment-resisting setback frames and evaluated their **inelastic seismic demands** [8]. Their work is particularly important because it moved the assessment beyond elastic response parameters and considered the actual deformation demands expected during strong earthquakes.

The seismic response associated with vertical mass and stiffness irregularity was investigated by Varadharajan et al. in another study [10]. Their work demonstrated that abrupt variations in structural properties can influence displacement and drift distributions. These effects are especially significant when stiffness and mass discontinuities occur simultaneously because their interaction can modify both the natural periods and mode shapes of the structure.More recent research has continued to investigate irregular RC structures under seismic loading. Blasi et al. examined the seismic response of irregular RC buildings designed for gravity and seismic loads [18]. Their work contributes to the recent understanding of how irregular configurations behave when subjected to realistic seismic demands and emphasizes the importance of considering the actual design condition of the structural system.

Prayuda et al. further investigated the seismic behavior of high-rise RC buildings affected by vertical irregularities [19]. Although high-rise buildings differ from moderate-rise structures in terms of modal characteristics and higher-mode participation, their findings provide useful evidence concerning the broader influence of vertical discontinuities on seismic response.

2.6 Dynamic Characteristics and Higher-Mode Effects

Sarkar et al. emphasized the importance of dynamic characteristics in defining vertical geometric irregularity [6]. Their regularity index approach demonstrated that a purely geometric description does not necessarily capture the dynamic consequences of a stepped configuration.Chintanapakdee and Chopra conducted an important investigation into the seismic response of vertically irregular frames using response-history analysis and modal pushover analysis [13]. Their study highlighted the role of higher modes in determining seismic demands in irregular frames. Conventional first-mode pushover analysis may not fully capture these effects because the assumed lateral-force distribution may differ substantially from the actual dynamic deformation pattern.

The implications are particularly important for moderate-rise RC buildings. While fundamental-mode response generally remains important, geometric discontinuities can increase the contribution of higher modes and modify the distribution of inter-storey drift and member forces. Consequently, a reliable performance-based assessment should

consider whether the selected analysis procedure adequately represents the dynamic behavior of the irregular configuration.

2.7 Irregularity Indices and Seismic Risk

Sarkar et al. proposed a vertical geometric irregularity index for stepped building frames based on dynamic characteristics [6]. This approach represented an important step toward establishing quantitative relationships between geometric configuration and structural response.Varadharajan et al. investigated irregularity indices in relation to seismic response and considered parameters such as fundamental period, roof displacement, and inter-storey drift [8], [10]. Their studies demonstrated that the magnitude and location of irregularity should both be considered when predicting seismic demand.

Bhosale et al. further investigated the relationship between regularity index and seismic risk [12]. Their results showed that the correlation between irregularity measures and seismic risk is not always straightforward. This suggests that future irregularity indices should ideally incorporate not only geometric characteristics but also structural capacity, dynamic properties, deformation demand, and damage potential.This issue is highly relevant to performance-based seismic design because PBSD requires a direct connection between structural configuration and measurable performance outcomes. An irregularity index that cannot predict or explain performance parameters such as drift, plastic rotation, or collapse probability has limited value for performance-oriented design.

2.8 Nonlinear Analysis and Seismic Performance Assessment

Athanassiadou used nonlinear static and dynamic analysis to evaluate irregular RC frames and demonstrated the importance of considering nonlinear response in irregular structures [5]. Varadharajan et al. similarly investigated inelastic seismic demands in setback RC frames using nonlinear analysis [8].The choice between nonlinear static and nonlinear dynamic analysis remains an important methodological issue. Pushover analysis provides a computationally efficient method for estimating capacity and deformation demand. However, the assumptions regarding the shape and distribution of lateral loading may become less reliable for structures with substantial vertical irregularity.

Chintanapakdee and Chopra demonstrated that modal pushover approaches can improve the representation of higher-mode effects in vertically irregular frames [13]. Their findings suggest that more advanced pushover procedures may be required when conventional first-mode assumptions are insufficient.Nonlinear response-history analysis provides a more detailed representation of structural response because it accounts directly for the time-dependent interaction between ground motion and structural behavior. However, it requires greater computational effort and careful selection of earthquake records. For performance-based assessment, the choice of analysis method should therefore depend on the level of accuracy required and the severity of irregularity.

2.9 Performance-Based Seismic Design of Vertically Irregular RC Frames

Men and Shi proposed an **Inter-Story Capacity Spectrum (ISCS)** method for performance-based seismic design of vertically irregular RC frame structures [7]. Their methodology focused on inter-storey response and provided a framework for evaluating the performance of structures with vertical irregularities. The study represents an important transition from conventional irregularity classification toward explicit performance evaluation.Fragiadakis and Papadrakakis investigated performance-based optimum seismic design of RC structures and demonstrated the

potential for integrating nonlinear structural analysis into an optimization-oriented design process [20]. Their research illustrates the broader development of performance-based methods in which structural design can be evaluated against specified performance requirements.

Giannakouras and Zeris examined the seismic performance of irregular RC frames designed according to the **Direct Displacement-Based Design (DDBD)** approach [16]. Their research is particularly relevant because displacement-based methods provide a direct connection between seismic performance objectives and deformation demand.

3. Research Gap

1. **Limited integration of vertical geometric irregularity with Performance-Based Seismic Design (PBSD)** of RC moment-resisting frames.
2. **Insufficient focus on moderate-rise RC buildings**, as many studies concentrate on general, low-rise, or high-rise structures.
3. **Limited systematic investigation of setback magnitude and location** and their combined influence on seismic performance.
4. **Existing irregularity indices do not always directly represent seismic risk or structural performance**.
5. **Limited assessment of damage concentration at setback levels**, particularly plastic hinge formation and inter-storey drift concentration.
6. **Higher-mode effects require further investigation** in vertically irregular moderate-rise RC frames.
7. **Limited comparison of nonlinear analysis methods**, including conventional pushover, modal pushover, and nonlinear response-history analysis.
8. **Insufficient comparison of force-based, displacement-based, and performance-based seismic design approaches** for vertically irregular RC frames.
9. **Limited application of damage-based performance indicators** for evaluating setback irregularity.
10. **Lack of consistent performance criteria** for comparing seismic behavior among different setback configurations.
11. **Limited synthesis of recent research** with the foundational studies on vertical irregularity and setback buildings.

4. Conclusion

The review demonstrates that vertical geometric irregularity has a significant influence on the seismic response and overall performance of reinforced concrete (RC) moment-resisting frame buildings. Changes in building geometry along the height, particularly setback configurations, can modify the distribution of mass, stiffness, strength, and dynamic characteristics, resulting in variations in seismic demand and deformation patterns. The magnitude and location of setbacks are important parameters governing inter-storey drift, roof displacement, storey shear, and nonlinear deformation demands. Geometric discontinuities may also lead to concentration of deformation and damage near setback levels, making these regions critical for seismic assessment and design.

The reviewed studies further indicate that conventional irregularity classification and geometric indices alone may not adequately represent the actual seismic performance of vertically irregular buildings. Higher-mode effects, nonlinear behavior, and changes in dynamic characteristics should be appropriately considered, particularly when evaluating

structures with significant vertical discontinuities. Nonlinear static and nonlinear response-history analyses can provide a more realistic understanding of structural behavior under strong earthquake loading.

Performance-Based Seismic Design provides a more effective framework for evaluating vertically irregular RC buildings because it focuses on actual structural performance rather than strength requirements alone. Performance objectives can be evaluated using parameters such as inter-storey drift, roof displacement, plastic deformation, damage concentration, and structural damage levels. However, existing research remains relatively fragmented, particularly regarding the combined influence of setback magnitude, setback location, higher-mode effects, nonlinear response, and performance objectives in moderate-rise RC moment-resisting frames.

Therefore, further research is required to develop an integrated performance-oriented framework that establishes a clear relationship between vertical geometric irregularity, dynamic characteristics, seismic demand, nonlinear deformation, damage concentration, and structural performance. Such an approach can support more reliable seismic assessment and contribute to the development of safer, more efficient, and performance-based design strategies for moderate-rise RC moment-resisting frame buildings with vertical geometric irregularities.

REFERENCES

[1] E. V. Valmundsson and J. M. Nau, "Seismic response of building frames with vertical structural irregularities," Journal of Structural Engineering, vol. 123, no. 1, pp. 30–41, 1997, doi: 10.1061/(ASCE)0733-9445(1997)123:1(30).

[2] B. M. Shahrooz and J. P. Moehle, "Seismic response and design of setback buildings," Journal of Structural Engineering, vol. 116, no. 5, pp. 1423–1439, 1990, doi: 10.1061/(ASCE)0733-9445(1990)116:5(1423).

[3] S. L. Wood, "Seismic response of R/C frames with irregular profiles," Journal of Structural Engineering, vol. 118, no. 2, pp. 545–566, 1992, doi: 10.1061/(ASCE)0733-9445(1992)118:2(545).

[4] S. Das and J. M. Nau, "Seismic design aspects of vertically irregular reinforced concrete buildings," Earthquake Spectra, vol. 19, no. 3, pp. 455–477, 2003, doi: 10.1193/1.1595650.

[5] C. J. Athanassiadou, "Seismic performance of R/C plane frames irregular in elevation," Engineering Structures, vol. 30, no. 5, pp. 1250–1261, 2008, doi: 10.1016/j.engstruct.2007.07.015.

[6] P. Sarkar, A. M. Prasad, and D. Menon, "Vertical geometric irregularity in stepped building frames," Engineering Structures, vol. 32, no. 8, pp. 2175–2182, 2010, doi: 10.1016/j.engstruct.2010.03.020.

[7] J. Men and Q. Shi, "ISCS method for the performance-based seismic design of vertically irregular reinforced concrete frame structures," The Structural Design of Tall and Special Buildings, vol. 22, no. 11, pp. 887–902, 2013, doi: 10.1002/tal.759.

[8] S. Varadharajan, V. K. Sehgal, and B. Saini, "Determination of inelastic seismic demands of RC moment resisting setback frames," Archives of Civil and Mechanical Engineering, vol. 13, no. 3, pp. 370–393, 2013, doi: 10.1016/j.acme.2013.02.006.

[9] S. Varadharajan, V. K. Sehgal, and B. Saini, "Seismic behavior of multistory RC building frames with vertical setback irregularity," The Structural Design of Tall and Special Buildings, vol. 23, no. 18, pp. 1345–1364, 2014, doi: 10.1002/tal.1147.

[10] S. Varadharajan, V. K. Sehgal, and B. Saini, "Seismic response of multistory reinforced concrete frame with vertical mass and stiffness irregularities," The Structural Design of Tall and Special Buildings, vol. 23, no. 5, pp. 362–389, 2014, doi: 10.1002/tal.1045.

[11] M. De Stefano and B. Pintucchi, "A review of research on seismic behaviour of irregular building structures since 2002," Bulletin of Earthquake Engineering, vol. 6, no. 2, pp. 285–308, 2008, doi: 10.1007/s10518-007-9052-3.

[12] A. S. Bhosale, R. Davis, and P. Sarkar, "Vertical irregularity of buildings: Regularity index versus seismic risk," ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, vol. 3, no. 3, 2017, doi: 10.1061/AJRUA6.0000900.

[13] A. Mwafy and S. Khalifa, "Effect of vertical structural irregularity on seismic design of tall buildings," The Structural Design of Tall and Special Buildings, vol. 26, no. 18, Art. no. e1399, 2017, doi: 10.1002/tal.1399.

[14] Z. Bohlouli and M. Poursha, "Seismic evaluation of geometrically irregular steel moment resisting frames with setbacks considering their dynamic characteristics," Bulletin of Earthquake Engineering, vol. 14, no. 10, pp. 2757–2777, 2016, doi: 10.1007/s10518-016-9910-y.

[15] M. Mouhine and E. Hilali, "Effect of setback irregularity location on the performance of RC building frames under seismic excitation," Archives of Civil Engineering, vol. 66, no. 4, pp. 399–412, 2020, doi: 10.24425/ace.2020.135228.

[16] P. Giannakouras and C. Zeris, "Seismic performance of irregular RC frames designed according to the DDBD approach," Engineering Structures, vol. 182, pp. 427–445, 2019, doi: 10.1016/j.engstruct.2018.12.058.

[17] T. I. Maulana, B. Enkhtengis, and T. Saito, "Proposal of damage index ratio for low- to mid-rise reinforced concrete moment-resisting frame with setback subjected to uniaxial seismic loading," Applied Sciences, vol. 11, no. 15, Art. no. 6754, 2021, doi: 10.3390/app11156754.

[18] G. Blasi, A. S. Scarlino, S. Chirivì, D. Perrone, and M. A. Aiello, "Seismic response of irregular RC buildings designed for gravity and seismic loads," Bulletin of Earthquake Engineering, vol. 22, pp. 5231–5257, 2024, doi: 10.1007/s10518-024-01971-4.

[19] H. Prayuda, O. Wilasamba, F. Saleh, T. I. Maulana, and F. Firdausa, "Evaluation of seismic behavior due to vertical irregularities in high rise reinforced concrete buildings," Media KomunikasiTeknikSipil, vol. 28, no. 2, pp. 178–191, 2022/2023, doi: 10.14710/mkts.v28i2.41765.

[20] M. Fragiadakis and M. Papadrakakis, "Performance-based optimum seismic design of reinforced concrete structures," Earthquake Engineering & Structural Dynamics, vol. 37, no. 6, pp. 825–844, 2008, doi: 10.1002/eqe.786.