© November 2025 | IJIRT | Volume 12 Issue 6 | ISSN: 2349-6002

# A Literature Review on Seismic Performance of Buildings with Horizontal and Vertical Irregularities

Amol R Bendsure [1], Rahul S Patil [2]
[1]Post Graduate Student, Deogiri Institute of Engineering and Management Studies, Chhatrapati Sambhajinagar -431005, Maharashtra, India
[2]Assistant Professor, Department of Civil Engineering, Deogiri Institute of Engineering and Management Studies, Chhatrapati Sambhajinagar -431005, Maharashtra, India

*Abstract*—**This review paper examines the impact of horizontal and vertical irregularities on the seismic performance of reinforced concrete (RC) and steel buildings, with a focus on provisions outlined in IS 1893 (Part 1): 2016 for India's earthquake-prone regions (zones II-V). Horizontal irregularities (e.g., torsional, re-entrant corners, diaphragm discontinuities) and vertical irregularities (e.g., stiffness, mass, geometric) are defined and their effects on amplified seismic demands and collapse risks are analyzed. The paper synthesizes recent research, including novel seismic irregularity descriptors, base isolation for hillside structures, progressive collapse under column removal, and advanced seismic intensity measures for fragility assessment. Studies highlight the limitations of existing code provisions in addressing complex irregularities, particularly in high-rise and sloping-ground buildings, and propose solutions like tuned mass dampers, optimized design algorithms (e.g., ANN-PSO), and refined Rapid Visual Screening methods. Key findings emphasize the need for enhanced design guidelines to improve seismic resilience, integrating advanced computational and experimental approaches for accurate risk assessment and cost-effective structural designs in high-seismic regions.**

*Index Terms*—**Horizontal & Vertical Irregularity, Re-entrant corners, Diaphragm flexibility, Fragility assessment, Hillside buildings, Progressive collapse.**

## I. INTRODUCTION

The introduction to the review paper on horizontal and vertical irregularities, as per IS 1893 (Part 1): 2016, establishes a foundation for understanding their impact on seismic design in India's earthquake-prone regions (zones II-V). It covers the significance of seismic resilience, defines irregularities per IS 1893:2016, and classifies them into horizontal (torsional, re-entrant corners, diaphragm discontinuity, out-of-plane offsets, non-parallel systems) and vertical (stiffness, mass, geometric, in-plane discontinuity, strength).

The section addresses their effects on seismic performance, including amplified demands and collapse risks, and outlines IS 1893:2016 provisions, such as dynamic analysis and amplified design forces (1.5x for torsional, 2.5x for soft storeys). It concludes with the review's objectives, focusing on recent research, seismic response, and design implications aligned with IS 1893:2016 and global standards.

Rayudu Jarapala and Arun Menon [1] Proposes a novel seismic irregularity descriptor to quantify the seismic risk of reinforced concrete buildings on hill slopes with coupled plan and vertical irregularities as shown in figure -1. It evaluates common typologies (split-foundation, step-back, step-back setback, and flatland buildings) using 3D models, seismic fragilities, and mean annual exceedance probabilities, finding split-foundation configurations most vulnerable. Existing descriptors show weak correlation with seismic risk, while the new one—based on fundamental dynamic properties—demonstrates strong statistical correlation for improved risk assessment and design.

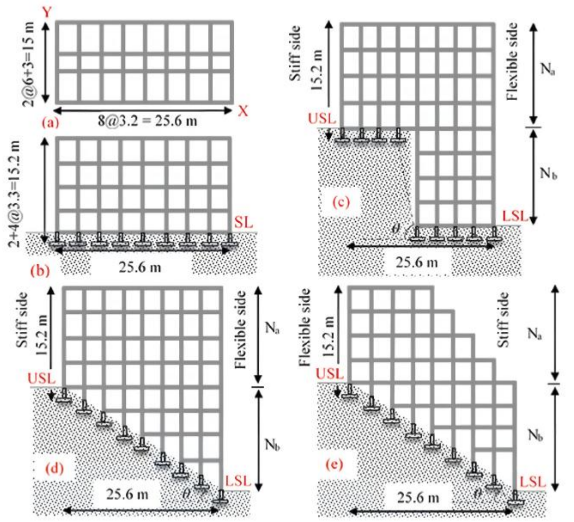


Figure 1: Geometries configurations of buildings on slopes [1].

Li Ruifeng et al. [2] introduces base isolation using bearings at the base of uneven stilted columns in hillside structures to reduce seismic response and mitigate stiffness irregularities as shown in figure 2. Shaking table tests on scaled base-isolated and fixed-base stilted frames confirm the approach's effectiveness in controlling damage. A direct displacement-based seismic design method is proposed and validated via time-history analyses of 7-storey and 3-storey examples, showing errors under 10% in shear, displacement, and bearing deformation, with shear differences among columns below 10%.

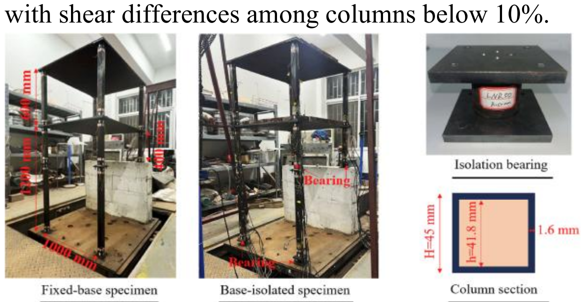


Figure 2: Test specimens [2].

Harpreet Singh and Aditya Kumar Tiwary [3] evaluates progressive collapse in 5-storey and 10-storey reinforced concrete structures with plan irregularities as shown in figure -3 (e.g., re-entrant corners, uneven bays) compared to regular ones, using nonlinear dynamic analysis under column removal scenarios (corner, edge, interior) via abrupt, 2-step, and 4-step methods. Key metrics include vertical displacement time history, chord rotation,

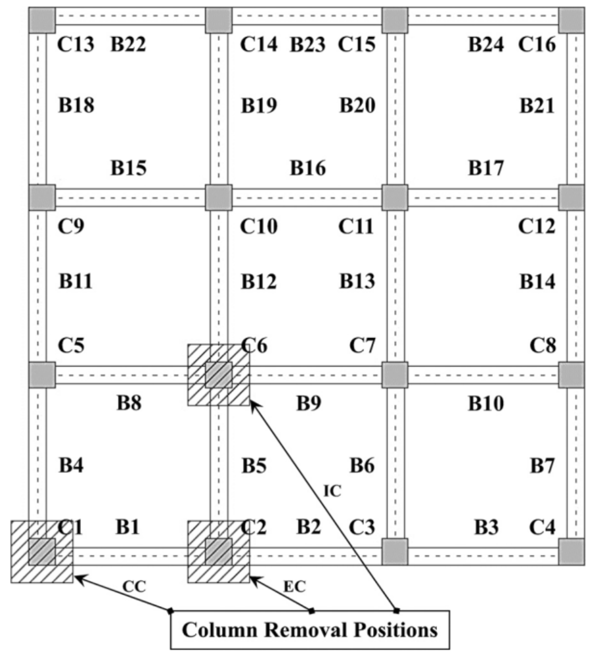


Figure 3: Typical plan view of model with column removal positioning [3].

Demand-Capacity Ratios (DCR) in beams/columns, and Axial Load Redistribution Ratio (ALRR). Results indicate corner removal yields the highest displacements (10-50% more than edge), but edge removal is most critical in highly irregular models under abrupt scenarios; progressive removals reduce DCR/ALRR by 5-10%, enhancing load redistribution and structural resilience, with implications for design guidelines in seismic-prone areas.

Rokalla Devi Santosh Kumar et al. [4] study develops structural scores and modifiers for Rapid Visual Screening (RVS) of irregular reinforced concrete buildings using the OSHPD HAZUS methodology, focusing on irregularities like overhangs, eccentric beams, floating columns, diaphragm discontinuities, and short columns at varying severity levels. Buildings are modeled in SAP2000 for pushover analysis to derive collapse probabilities, enabling a generalized, resource-efficient vulnerability assessment. Results are compared to existing RVS methods (e.g., FEMA P-155, Indian guidelines), showing improved accuracy in quantifying irregularity impacts for high-seismic regions like India, aiding retrofitting and risk mitigation.

Ananda Mitra and G. Tamizharasi [5] study investigates the impact of diaphragm flexibility on the seismic resilience of buildings with re-entrant corners as shown in figure-5, (e.g., rectangular, H-, T-, Z-shaped plans) under uni- and multi-directional earthquake shaking, considering projection ratios of 15% and 30%. Using elastic/inelastic analyses (nonlinear static and dynamic time history), it reveals heightened vulnerability at specific shaking angles (60° for rectangular, 135° for others), with plan geometry amplifying translational/rotational responses and diaphragm flexibility causing over 50% of elements to yield. Current code provisions for rigid diaphragms are inadequate for these buildings; to limit damage below 50%, normalized in-plane displacements should not exceed 1.2 (whole building) or 1.1 (wings).

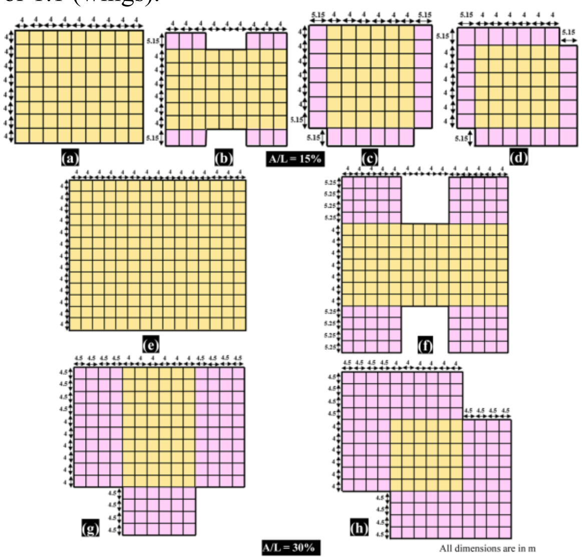


Figure 5: Plan configurations of buildings considered [5].

Dengjia Fang et al. [6] study proposes six novel seismic intensity measures (IMs) based on spectral acceleration and modal participation mass coefficients to evaluate fragility of hillside reinforced concrete frame buildings under pulse-like ground motions. Four typical models (HB-1 to HB-4) are analyzed, with IW1, IP, and IW2 emerging as superior IMs due to high performance in practicality, efficiency, proficiency, correlation (>0.9 with displacement/shear), and sufficiency. A Chinese code-based probabilistic seismic hazard analysis integrates with fragility assessment, showing under rare earthquakes: ~68% life safety probability, ~9% collapse prevention, and max 0.53% collapse risk (excluding HB-2). Greater irregularity amplifies damage, with short columns exhibiting heightened vulnerability.

Nadeem Hussain et al [7] study verifies seismic design coefficients (overstrength, deflection amplification Cd, and response modification R) from codes like ASCE 7 for regular and vertically irregular high-rise reinforced concrete shear wall buildings (40-60 stories refer figure 6), using 3D fiber-based models under bidirectional ground motions. Nine structures (bearing wall and dual systems) are designed and analyzed via inelastic pushover and incremental dynamic analyses with 26 earthquake records. Results show over strength factors of 2.62-2.98 (exceeding code's conservative 2.5), Cd with 14-25% safety margins, and R with 42-63% (bearing wall) or 7-21% (dual) margins, suggesting potential R increases for cost-effective designs while maintaining safety.

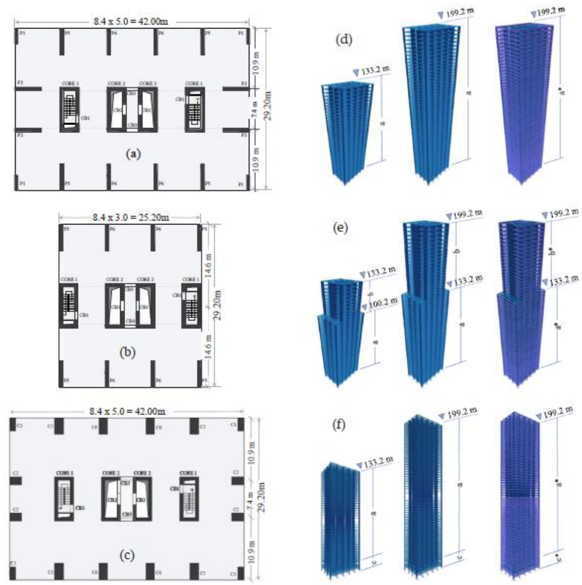


Figure 6: Description of 40 and 60-story benchmark structures showing floor footprints and 3D models [7].

Keyvan Saeedi et al. [8] This study examines post-earthquake progressive collapse in 5- and 10-story irregular steel moment-frame buildings with setback irregularities, using nonlinear dynamic analyses on over 60 models under 12 MCE-level earthquake records followed by column removal scenarios. Structures are grouped by vulnerability based on damage levels. Results show earthquakes heighten collapse risk; setback irregularities up to 13.33% enhance resistance (21% average response reduction vs. regular), but higher levels worsen it (82% increase). Recommendations include irregularity limits, adjusted minimum base shear, and maximum period to mitigate risks.

Xun Zhang [9] study optimizes the design of torsional irregularity in planar irregular reinforced concrete (RC) frames refer figure – 7, using a hybrid artificial neural network-particle swarm optimization (ANN-PSO) algorithm, applied to a 3D 6-story model analyzed via ETABS under static/dynamic loads.

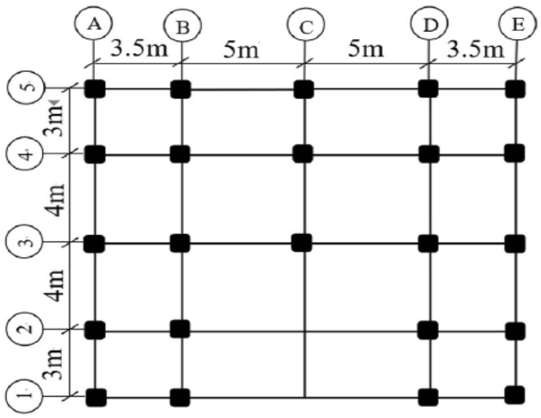


Figure 7: View of the frame model [9].

Design variables focus on column cross-sections per layer, constrained by torsional irregularity coefficients. Results show significant column size variations, minimized torsional coefficients (approaching limits), and elimination of Y-direction irregularities, offering an efficient ANN-PSO-FEM framework for economical, seismic-resilient RC structures in earthquake-prone regions.

Denise Penelope N. Kontoni and Ahmed Abdelraheem Farghaly [10] investigates seismic control of two irregular steel high-rise buildings (HRBs)—a vertically irregular step-pyramid-shaped refer figure-8, and a vertically/horizontally irregular L-shaped stadium design—using 3D models with soil-structure interaction (SSI) and tuned mass dampers (TMDs). Analysis under various earthquakes shows TMDs, optimally placed at building corners on the top and along the upper half-height, effectively mitigate seismic responses, enhancing safety and serviceability, with SSI providing a realistic behavior assessment.

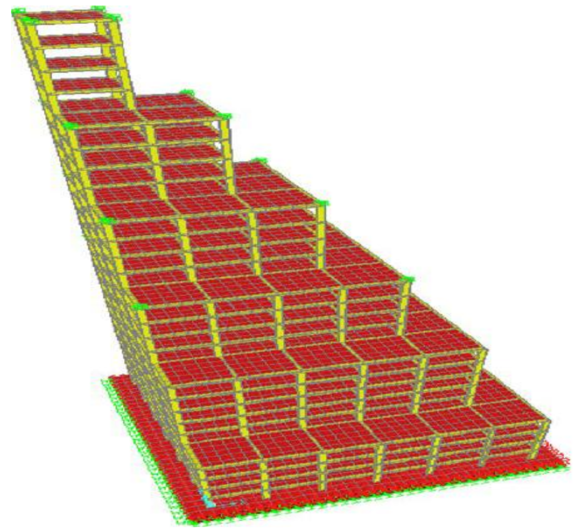

Figure 8: Vertical and Horizontal irregularity [10].

Md. Naimul Haque et al. [11] investigates the seismic responses of reinforced concrete (RC) buildings with planar irregularities (C-, L-, I-, and T-shaped plans shown in figure 9) using modal and time-history analyses under two ground excitations with varying dominant frequencies. Key responses analyzed include modal characteristics, base shear, roof displacement, acceleration, and story drift. Various irregularity parameters based on planar geometry are defined, with the overall aspect ratio (L/B) showing the strongest correlation to seismic responses. Findings indicate that responses vary significantly by earthquake type and irregularity, with I- and T-shaped buildings exhibiting the highest vulnerability, emphasizing the need for enhanced design considerations for irregular structures.

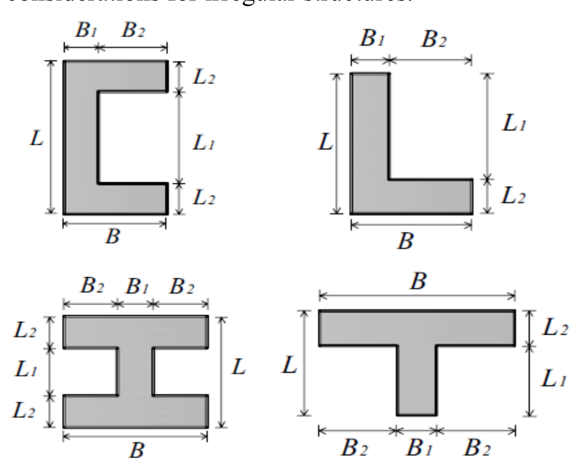


Figure 9: Considered geometry of the buildings with planar irregularity [11].

Rayudu Jarapala and Kishore Chandra Biswal [12] evaluates vertical irregularity levels in reinforced concrete step-back and step-back-setback buildings on sloping ground using regularity indices based on geometry, mode participation factors, and frequencies. Dynamic responses (inter-storey drift, top displacement) are analyzed under low-, intermediate-, and high-frequency earthquakes, revealing step-back frames vulnerable to low/medium frequencies and step-back-setback to medium/high. Seismic vulnerability indices show minimal correlation with regularity indices or earthquake frequency content, highlighting needs for improved code provisions.

M. V. Landge and R. K. Ingle [13] study compares elastic and inelastic floor response spectra (FRS) for regular and irregular low-rise reinforced concrete buildings (mass/stiffness irregularities at lower/higher stories, vertical geometric) under earthquake loading, focusing on acceleration amplification for non-structural component (NSC) design in critical industries. Using time-history analysis, it finds lower-story responses governed by input ground motion characteristics, distinct FRS peaks at modal periods due to dynamic filtering, and significant floor accelerogram amplification near building modal frequencies, emphasizing NSC vulnerability in irregular configurations.

Mahsa Amiri and Masood Yakhchalian [14] evaluates the torsional seismic response of vertically mass-irregular multi-storey RC framed buildings (up to 15 storeys) with varying aspect ratios, mass locations along height, and in-plan eccentricity using 3D finite element models under El-Centro ground motion via transient analysis shown in figure 10. Key metrics include base shear, fundamental period, roof deflection, and floor rotation. Findings show in-plan eccentricity has minimal impact when irregularities are in the lower half; proposes a parameter to quantify mass irregularity considering its location and eccentricity for improved seismic design.

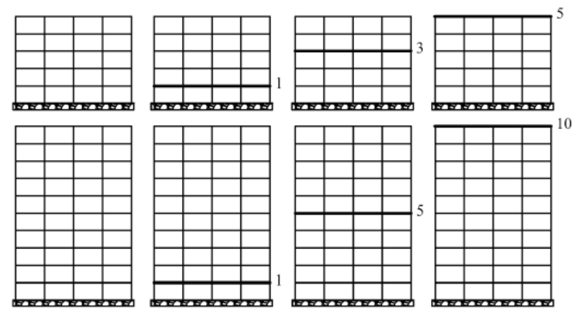

Figure. 10: Geometric representation of the regular and irregular structures [14].

Archana J. Satheesh et al. [15] investigates the impact of masonry infill walls on the seismic performance of reinforced concrete (RC) dual frames, using nonlinear dynamic analysis on an existing 7-story building damaged in the 2011 Van earthquake. Eighteen models with varying infill arrangements are analyzed under four ground motions via PERFORM 3D software. Results show infills increase stiffness but introduce irregularities, potentially altering damage states; neglecting them in design can lead to significant misunderstandings of seismic vulnerability.
H. Gokdemir et al. [16] examines torsional irregularity effects on seismic performance using SAP2000 models of buildings with varying floors, areas, and plans (e.g., L-shaped, rectangular). Torsion arises from eccentricity between mass and rigidity centers, leading to failures like "knife cut" column damage and pounding. Calculations show torsion increases with eccentricity; L-shaped plans experience more. Recommends symmetric designs, separating sections with adequate distances, and increasing weak-direction rigidity to mitigate risks. Compares torsional provisions in codes (e.g., Turkish Earthquake Code's $\eta_{bi} > 1.2$ threshold) and past earthquake observations (e.g., 1999 Izmit/Duzce).
Nabiollah Alirahimi Kashkooli and Mahmoud-Reza Banan [17] assesses the impact of setback irregularities on the accuracy of Modal Pushover Analysis (MPA) in predicting seismic demands (target displacement, story drifts, base shear) for 5-story steel moment-resisting frames, using 21 irregularity layouts designed for low/high response reduction factors (R). Nonlinear dynamic analyses under 14 ground motions are compared to MPA and FEMA440 results. MPA proves inconservative for irregular frames (error varying by R and response),

but shows good correlation with FEMA for displacements/drifts, highlighting limitations in irregular structures.

Gennaro Magliulo et al. [18] evaluates the seismic response of reinforced concrete frames with vertical overstrength discontinuities (strength irregularities in elevation), using regular frames designed per Eurocode 8 medium (DCM) and high (DCH) ductility classes as references. Nonlinear static (N2 method) and dynamic analyses with seven earthquakes show similar performance to regular frames, with all satisfying Ultimate Limit State despite irregularities. Concludes low sensitivity in EC8-designed frames, suggesting review of international code provisions on vertical strength regularity (e.g., Eurocode 8, Italian, US codes).

P. Rajeev and S. Tesfamariam [19] develops seismic fragility curves for pre-1970s gravity-load-designed reinforced concrete frames (3-, 5-, and 9-storey) considering soft storey (SS) and construction quality (CQ) irregularities, along with their interactions. Nonlinear finite element analyses generate probabilistic seismic demand models (PSDMs), with response surface methods predicting PSDM parameters as functions of SS and CQ. Results highlight sensitivity to these factors and interactions, showing increased vulnerability; fragility curves with confidence bounds are provided, suggesting enhancements to tools like HAZUS for risk-informed decisions.

Pradip Sarkar et al. [20] proposes a 'regularity index' to quantify vertical geometric irregularity in stepped reinforced concrete building frames, based on mass/stiffness distribution and dynamic properties (modal participation factors). It modifies code empirical formulas (e.g., IS 1893:2002, ASCE 7:2005) for fundamental period estimation, incorporating this index for improved accuracy in irregular frames. Free vibration analyses of 78 frames (varying heights/irregularities) validate the approach, showing better performance over existing irregularity measures for seismic design.

**CONCLUSION**

The literature underscores that plan and vertical irregularities significantly amplify seismic vulnerability in RC and steel buildings, particularly in high-seismic regions or on sloping grounds. Novel irregularity descriptors, advanced seismic intensity measures, and mitigation strategies like base isolation and TMDs provide robust tools for risk assessment and design optimization. However, current seismic codes often fall short in addressing complex irregularities, necessitating refined provisions and design guidelines. The integration of advanced computational methods (e.g., ANN-PSO, nonlinear analyses) and experimental validations (e.g., shaking table tests) enhances the accuracy of seismic performance evaluations, paving the way for safer, more resilient, and cost-effective structural designs in earthquake-prone areas.

REFERENCES


[1] Rayudu Jarapala and Arun Menon (2025) “A novel seismic irregularity descriptor for measuring seismic risk of buildings on slopes with coupled structural irregularities” J-Soil Dynamics and Earthquake Engineering, Volume No. 190, Page No. 01-17.

[2] Li Ruifeng et al. (2025), “Seismic response and design of base-isolated hillside stilted structures” J-Journal of Building Engineering, Volume No. 103, Page No. 01-18.

[3] Harpreet Singh and Aditya Kumar Tiwary (2025), “Evaluating progressive collapse performance of structures containing plan irregularities: A comparative analysis of column elimination scenarios” J-Journal of Structures, Volume No. 72, Page No. 01-33.

[4] Rokalla Devi Santosh Kumar et al. (2025) “Structural score and score modifiers to quantify seismic vulnerability of irregular buildings” J-Journal of Structures, Volume No. 72, Page No. 01-16.

[5] Ananda Mitra and G. Tamizharasi (2025) “Diaphragm flexibility and earthquake resilience of buildings with re-entrant corners under multi-directional shaking” J-Journal of Structures, Volume No. 75, Page No. 01-19.

[6] Dengjia Fang et al. (2025) “Comparative fragility assessment of hillside RC buildings under pulse-like ground motions with novel intensity measures” J- Journal of Structures, Volume No. 75, Page No. 01-18.

[7] Nadeem Hussain et al (2024), “Seismic design coefficients verification of regular and vertically irregular high-rise shear wall buildings using bidirectional horizontal ground motions and 3D

modeling", J-Journal of Structures, Volume No. 70, Page No. 01-20.

[8] Keyvan Saeedi et al. (2024) " Investigating post-earthquake progressive collapse resistance of irregular steel structures" J-Journal of Structures, Volume No. 67, Page No. 01-13.

[9] Xun Zhang (2024) "Design optimization of irregularity RC structure based on ANN-PSO" J-Heliyon, Volume No. 10, Page No. 01-16.

[10] Denise-Penelope N. Kontoni and Ahmed Abdelraheem Farghaly (2024) "Seismic control of vertically and horizontally irregular steel high-rise buildings by tuned mass dampers including SSI" J-Asian Journal of Civil Engineering, Volume No. 25, Page No. 1995-2014.

[11] Md. Naimul Haque et al. (2021) "Infuence of planar irregularities on seismic responses of RC building" J- Asian Journal of Civil Engineering, Volume No. 22, Page No. 995-1009.

[12] Rayudu Jarapala and Kishore Chandra Biswal (2020) "Dynamic behavior of vertically irregular sloping ground buildings" J- Asian Journal of Civil Engineering, Volume No. 22, Page No. 125-136.

[13] M. V. Landge and R. K. Ingle (2020) "Comparative study of foor response spectra for regular and irregular buildings subjected to earthquake" J- Asian Journal of Civil Engineering, Volume No. 22, Page No. 49-58.

[14] Archana J. Satheesh et al. (2019) "Effect of in-plan eccentricity in vertically mass irregular RC framed buildings under seismic loads" J- Asian Journal of Civil Engineering, Volume No. 20, Page No. 713-726.

[15] M. S. Razzaghi and M. Javidnia (2015) "Evaluation of the effect of infill walls on seismic performance of RC dual frames" J-International Journal of Advanced Structural Engineering, Volume No. 07, Page No. 49-54.

[16] H. Gokdemir et al. (2013) "Effects of torsional irregularity to structures during earthquakes" J-Engineering Failure Analysis, Volume No. 35, Page No. 713-717.

[17] Nabiollah Alirahimi Kashkooli and Mahmoud-Reza Banan (2013) "Effect of Frame Irregularity on Accuracy of Modal Equivalent Nonlinear Static Seismic Analysis" J- KSCE Journal of Civil Engineering, Volume No. 17, Page No. 1064-1072.

[18] Gennaro Magliulo et al. (2012) "Seismic performance of R/C frames with overstrength discontinuities in elevation" J- Bulletin of Earthquake Engineering, Volume No. 10, Page No. 679-694.

[19] P. Rajeev and S. Tesfamariam (2012) "Seismic fragilities for reinforced concrete buildings with consideration of irregularities" J- Structural Safety, Volume No. 39, Page No. 1-13.

[20] Pradip Sarkar et al. (2010) "Vertical geometric irregularity in stepped building frames" J-Structural Safety, Volume No. 32, Page No. 2175-2182.

[21] IS: 1893: 2016 (Part-I) "Criteria for Earthquake Resistant Design of Structures" Bureau of Indian standards, New Delhi, India.

[22] IS-875: 2008 "Code of Practice for Design Loads' Bureau of Indian standards" New Delhi, India.

[23] IS: 456: 2000 "Code of Practice for Plain and Reinforced Concrete" Bureaus of Indian Standards, New Delhi.