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Seismic Performance of RC Framed Structures with Vertical Single Setback Irregularity

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Abstract: The presence of structural irregularities has been identified as one of the major factors contributing to the poor seismic performance of reinforced concrete (RC) framed buildings. Vertical setback irregularities, in particular, introduce abrupt discontinuities in stiffness and mass distribution, which amplify seismic demands and increase the risk of local and global failure modes. This paper investigates the seismic behaviour of RC framed buildings with a single vertical setback irregularity and compares their response with that of a regular frame of identical plan dimensions and height.

A six-storey RC frame is modelled and analysed using the Response Spectrum Method (RSM) in compliance with IS 1893:2016 (Part-1), with simulations performed in ETABS software. The study covers all seismic zones of India to capture the influence of varying seismic intensities on building response. Key seismic response parameters—lateral displacement, storey drift, and base shear—are extracted and compared between regular and irregular configurations.

The results reveal that vertical setback irregularity significantly modifies the seismic demand. While the regular frame exhibits uniform and predictable response patterns, the setback frame records increased lateral displacement and storey drift near the setback levels, with localized peaks that may approach or exceed codal drift limits. Base shear distribution is also found to be non-uniform, with the setback frame showing higher concentration at critical floors.

These findings highlight that even a single vertical setback can alter the seismic performance substantially, underlining the importance of considering such irregularities in design and codal provisions. The outcomes of this study provide valuable insights for structural engineers and policymakers to enhance the seismic safety of irregular RC buildings in India.

I. INTRODUCTION

A. Overview

The behaviour of structures is significantly influenced by structural irregularities, especially when subjected to seismic loads. Earthquakes impose dynamic forces whose effects are strongly dependent on the mass, stiffness, and overall geometry of the structure. In irregular buildings, discontinuities frequently arise in the geometric configuration or the lateral force-resisting system. Such irregularities may occur in the form of vertical irregularities (setbacks, soft storeys, floating columns), plan irregularities (re-entrant corners, torsional irregularities), or a combination of both, and they considerably alter the seismic response.

In recent decades, the study of structural performance under seismic loads has become increasingly important due to the recurring occurrence of moderate to severe earthquakes worldwide. Unlike static loads, seismic forces are reversal in nature, short in duration, and highly unpredictable, making irregular structures more vulnerable. Conventional buildings are generally designed for gravity and wind loads, but when subjected to earthquakes, irregularities lead to concentration of stresses, higher inter-storey drifts, torsional effects, and even partial collapse.

The devastating consequences of recent earthquakes highlight the necessity for adopting earthquake-resistant design principles as per codal provisions (e.g., IS 1893–2016 in India). This has encouraged engineers, architects, and urban planners to focus on creating structural systems that can safely dissipate seismic energy, control lateral displacements, and prevent catastrophic failures. Enhancing the resilience of irregular structures against seismic actions is therefore a critical concern in modern earthquake engineering practice.

B. Types Of Structural Irregularities

Building irregularities come in a variety of forms depending on where they exist and how they are constructed, but they can be broadly grouped into two categories.

1) Vertical Irregularities: These refers to an abrupt change in the properties of strength, stiffness, geometry, and mass that results in an uneven distribution of forces and deformation throughout the height of the building
2) Horizontal irregularities: These include large openings, re-entrant comer, abrupt changes in torsion, diaphragm deformations, and stress concentration, as well as asymmetrical plan forms or discontinuities in the horizontal resisting parts.

C. Plan Irregularities

It describes "asymmetrical plan forms or discontinuities in horizontal resisting parts, such as wide apertures, re-entrant corners, and abrupt changes that generate torsion, diaphragm deformations, and stress concentration."

Buildings with irregular plane geometries may behave structurally poorly as a result of the following factors: Examples of time-dependent deformation include temperature differences, creep and shrinkage, various settlements, and various reactions to dynamic forces. As a result, some load-bearing system components could experience excessive strains. Re-entry corners irregularity, dimensions ratio irregularity, non-parallel system irregularity, and out of plane offset in this subject, irregularity refers to geometrical irregularities in the plan that are physically distinct from one another in behavior and physics.

1) Torsional Irregularity

Torsion irregularity must be considered when floor diaphragms are stiff in their own plan in respect to the vertical structural elements that resist lateral stresses. When the greatest storey drift, calculated with design eccentricity, at one end of the structure transverse to an axis is larger than 1.2 times the average of the storey drifts at the two ends, torsional irregularity is said to exist.

Torsional irregularity is defined in the Indian Standards (IS 1893-Part-1-2016) Earthquake Code. A structure exhibits torsional irregular behaviour when: A floor's maximum horizontal displacement in the direction of lateral force is greater than 1.5 times greater than its minimum horizontal displacement in the same direction at the other end of the floor.

Every storey's maximum drift, including accidental torsion, at one end of the structure is limited to 20% of the average drift of the two ends of the building's storeys.

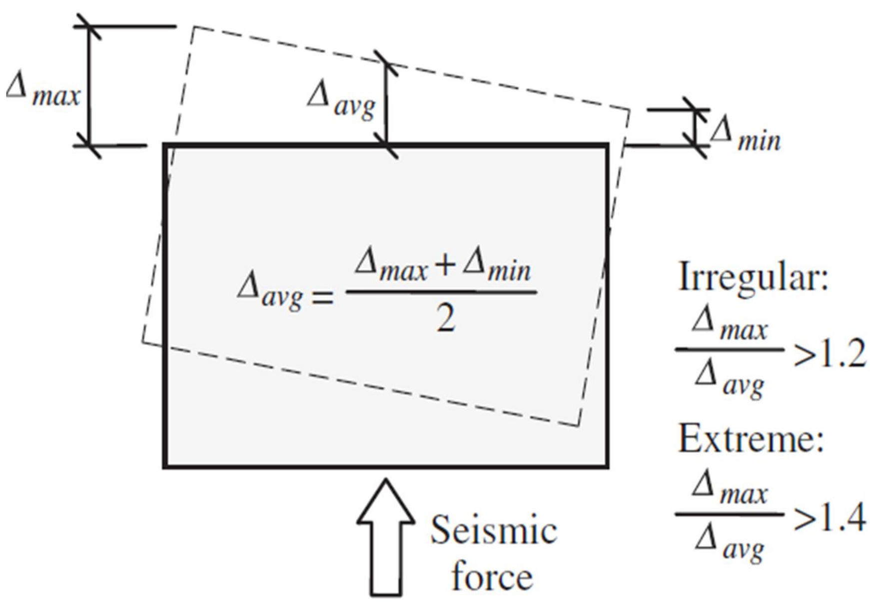

Fig. 1.1

2) Re-entrant Corners

Re-entrants, a loss of continuity, or inside corners are frequently found in overall building layouts with a plan that resembles an L, T, H, or +. The occurrence of these shapes, or combinations of these shapes, is caused by a lack of tensile capability and force concentration. Re-entrant corners are found in the plan configurations of a structure and its lateral force resisting system when both projections of the structure beyond the re-entrant comer are greater than 15% of the plan dimension of the structure in the given direction.

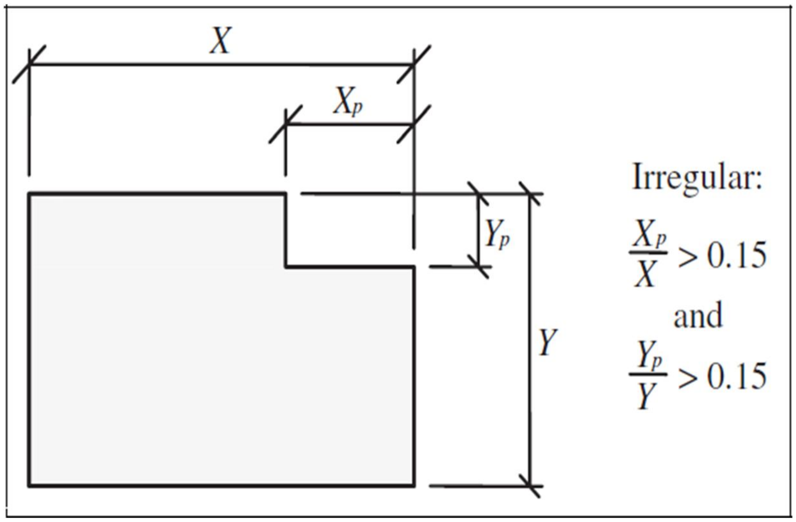

Fig. 1.2 Re-entrant irregularity

3) Diaphragm discontinuity

A horizontal resistance element called the diaphragm is responsible for transferring forces from vertical resistance elements to horizontal resistance elements. Diaphragms that abruptly discontinue or vary in stiffness, such as those that have cut-out or open portions that are more than 50% of the total area of the diaphragm or that change in effective stiffness by more than 50% from one storey to the next. The margins of the diaphragm serve as a horizontal beam and as It goes without saying that a beam's ability to carry loads will be greatly reduced if a hole is cut into its tension flange.

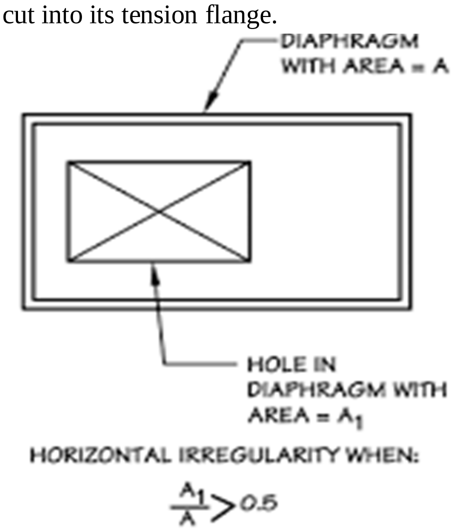

Fig. 1.3 Diaphragm Discontinuity

4) Out of Plane Offsets Irregularity

A lateral force resistance path that has discontinuities, such as offsets in the vertical elements A building's seismic safety is recognized to be compromised by out of plane offsets in vertical elements that are resisting lateral loads because they result in discontinuities of plane and detours in the load path. Out-of-plane offset in vertical elements is a term used to describe when structural walls or frames shift out of alignment in any level along a building's height.

The concept of a non-parallel system according to Indian Standards (IS 1893-Part-1-2016):

Discontinuities in a lateral force resistance route, such as out-of-plane offsets of vertical elements when structural walls or frames are moved out of plane in any Storey along the height of the building, are examples of irregularities.

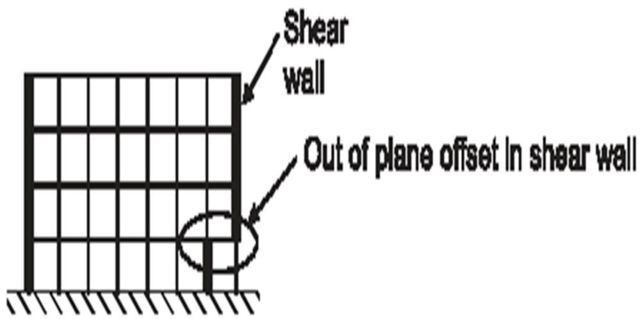

Fig. 1.4 Out of plane Offset Irregularity

5) Non Parallel Systems Irregularity

The vertical elements resisting the lateral force are not symmetric about or parallel to the principal orthogonal axes or the vertical elements. Situations like this are common for architects. The likelihood of torsional forces under ground motion is increased by the fact that the center of mass and the resistance do not coincide. This problem is often exacerbated in triangle- or wedge-shaped structures created by sharp roadway intersections. Torsion is more likely to occur since the building's narrower parts will be more flexible than its wider ones. The influence of torsion must be minimized or the torsional resistance of the narrow part of the building must be increased when designing these kinds of structures.

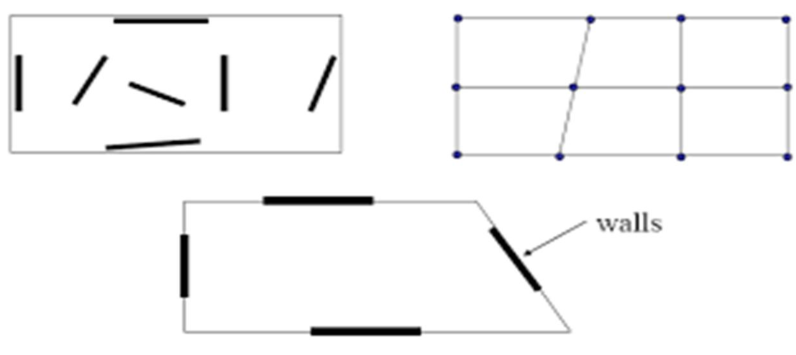

Fig. 1.5 Non-Parallel System Irregularity

D. Vertical Irregularities

The irregularities in the "load path or load transfer are one of the major contributors to structural damages in structures during strong earthquakes. The structure should contain a continuous load path for transfer of the seismic force, which develops due to acceleration of individual elements to the ground. Failure to provide adequate strength and toughness of individual elements in the system, or failure to connect individual elements, can result in distress or complete system collapse. As a result, all structural and non-structural elements must be sufficiently tied to the structural system, and the load path must be complete and sufficiently strong". The general load path is as follows; earthquake forces originate in all elements of building and are delivered through structural connections to horizontal diaphragms. The diaphragms distribute these forces to vertical resisting components such as columns, shear walls, frames, and other vertical elements in the structural system, which transfer the forces on the foundation

Vertical irregularities are described by vertical discontinuities in geometry, mass distribution, rigidity, and strength. Setback buildings are a subset of vertically irregular buildings that have geometric discontinuities. Geometric Irregularity, on the other hand, Introduces discontinuity in the vertical distribution of mass, stiffness, and strength.

Real structures are frequently irregular, as perfect regularity is an idealization that rarely occurs in practice. In the case of buildings, major seismic codes around the world distinguish between Irregularity in plan and Irregularity in elevation, but it must be understood that Irregularity in the structure is the result of a combination of both types. It can be seen that irregular structural configurations, either in plan or in elevation, were frequently identified as one of the major causes of collapse during previous earthquakes.

1) Stiffness Irregularity (Soft Storey)

The definition of earthquake in accordance with Indian Standards (IS 1893-Part-1-2016)

Stiffness irregularity: A "soft storey" is defined as "one in which the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average lateral stiffness of the three stories above."

A storeyis considered to be extreme soft if its lateral stiffness is less than 60% of the storey above it or less than 70% of the average stiffness of the three levels above. This category will include structures like those on stilts.

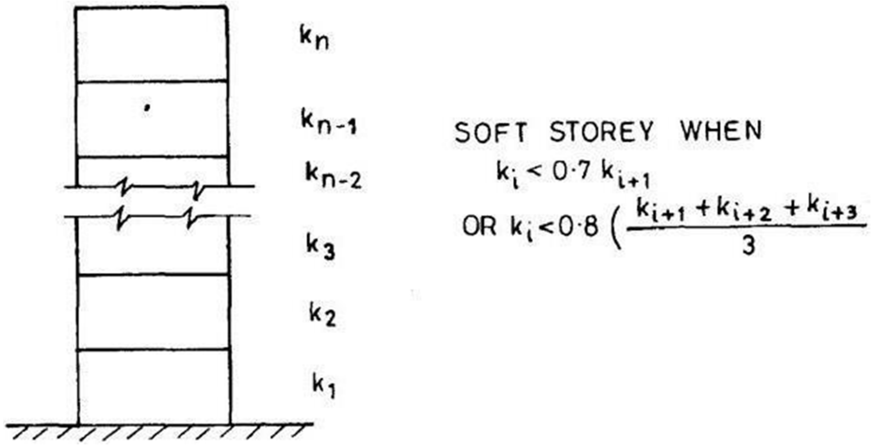

Fig. 1.6 Stiffness Irregularity

2) Mass Irregularity

When a storey's effective mass is more than a neighbouring storey's effective mass by more than 15%, there are mass irregularities. The real mass, which also includes the floor's dead weight and the actual weight of the equipment and the partition, is known as the effective mass. Overweight structures are more likely to collapse as a result of the P-effect, experience more lateral inertial forces, and have less ductility in their vertical load-resisting components.

There should be a minimum amount of effort put into avoiding massive plant rooms and enormous roofs. The use of dynamics analysis to examine the lateral force resisting elements in the presence of mass irregularities to provide a more accurate representation of the lateral load distribution of the base shear is beneficial.

The definition of the mass irregularity according to the Indian Standards (IS 1893-part-1-2016) earthquake code is: When a floor's seismic weight is greater than 150% of the floor below, mass irregularity is deemed to exist

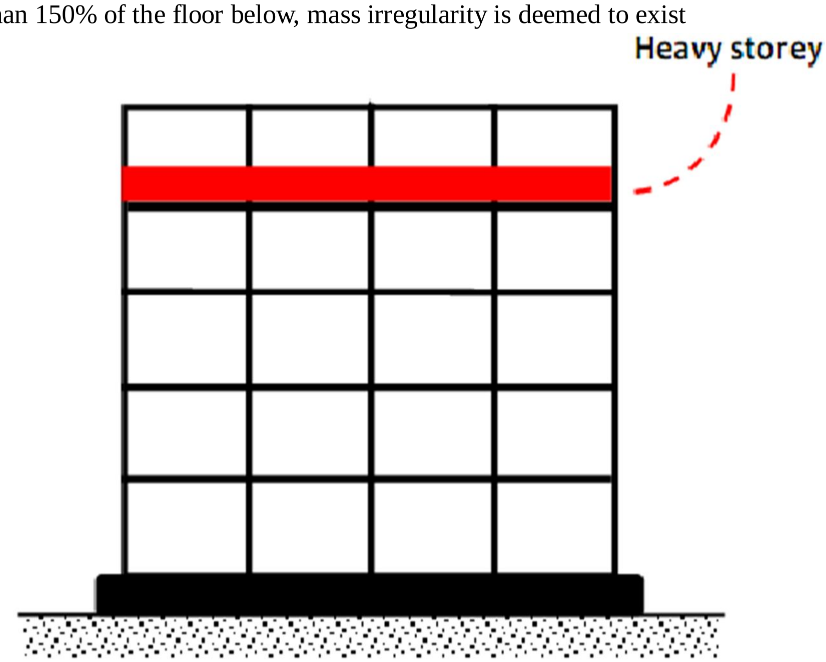

Fig. 1.7 Mass Irregularity

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3) Vertical Geometric Irregularity

A geometric irregularity known as a vertical set back that occurs in a vertical plane. When the horizontal dimension of the lateral force resisting system in any storey exceeds 125% of that of a neighbouring storey, it is taken into consideration. A vertical re-entrant corner can also serve as a representation of the setback. Total seismic separation in the plan through separation section is the general solution to the setback issue, allowing each component of the building to vibrate separately. Perform a dynamic study on the component that resists lateral forces when the building is not divided.

The definition of vertical geometric irregularity according to Indian Standards (IS 1893-part-1-2016) earth quake code is:

"Vertical Geometric Irregularity shall be considered to exist where the horizontal dimension of the lateral force resisting in any storey is more than 125percent of that in its adjacent storey."

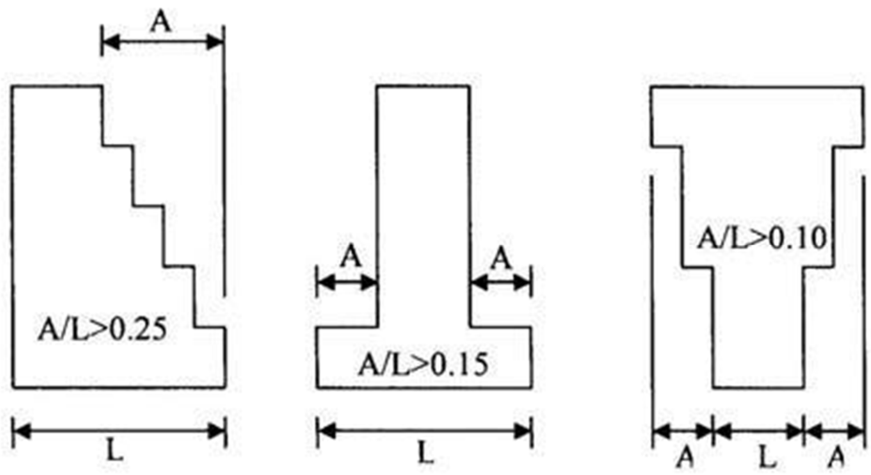

Fig. 1.8 Vertical Geometrical Irregularity

4) In-plane Discontinuity in Vertical lateral force Resisting Element

As per the Indian Standards (IS 1893-Part-1-2016) earth quake code the definition of In-Plane Discontinuity in vertical elements resting lateral elements Irregularity:

"In-plane discontinuity in vertical lateral force-resting elements shall be considered to exit, when in plane off set of the lateral force resting elements in greater than 20 percent of the plan length of those elements".

The internal force of vertical-force-resisting components (columns, seismic walls, and seismic bracing) is transmitted downward via horizontal transmission components (beam and truss)

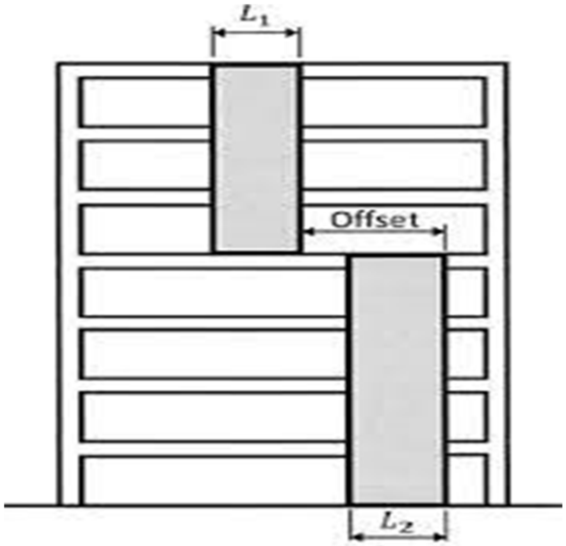

Fig. 1.9 In plane Discontinuity Irregularity

5) Discontinuity in Capacity (Weak Storey)

A weak storey is one whose lateral strength is less than 80% that of the level above. The strength of any seismic force-resisting element that shares the storey shear in the given direction makes up the storey lateral strength. The storey lateral strength is the sum of the strengths of all seismic force resting elements that share the lateral storey shear in the considered direction.

These are classified in to two types

1) Discontinuity in Lateral Strength-Weak Storey Irregularity

It exists when the lateral strength of the storey is less than 80% of the strength of the storey above. The storey lateral strength is the sum of the lateral strengths of all seismic-resisting elements that share the storey shear for the considered direction.

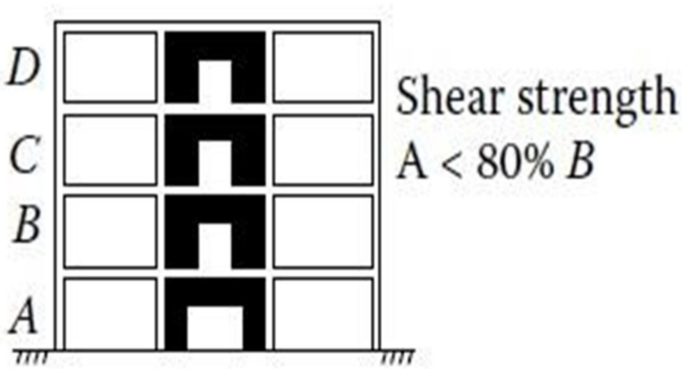

Fig.1.10 Discontinuity in Lateral Strength weak storey Irregularity

2) Discontinuity in Lateral Strength-Extreme Weak Storey Irregularity

Is defined to exist where "the storey lateral strength less than 65% of that in the storey above.

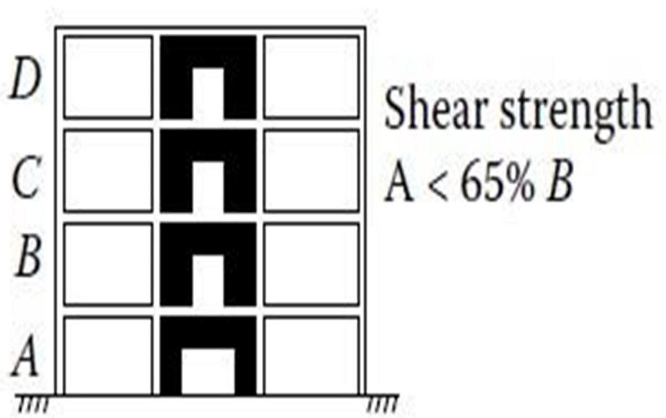

Fig. 1.11 Discontinuity in Lateral Strength Extreme weak storey Irregularity

E. Objectives Of The Study

Understanding the effect of structural irregularities on seismic performance is essential for ensuring the safety and stability of RC framed buildings. Vertical setbacks, in particular, introduce discontinuities that can significantly alter the seismic response when compared to regular frames. This study is therefore focused on evaluating and comparing the performance of regular and irregular buildings under different seismic zones of India by considering critical response parameters.

The following are the objectives of the study:

1) To analyze the seismic performance of RC framed buildings with a single vertical setback irregularity.
2) To compare the seismic response of the irregular building with a regular RC framed building of similar floor area and height.
3) To evaluate key seismic response parameters — lateral displacement, storey drift, and base shear — under different seismic zones of India.
4) To perform Response Spectrum Analysis (RSA) as per IS 1893:2016 (Part-1) using ETABS software.

F. *Scope Of The Study*

1) The study focuses on reinforced concrete (RC) framed buildings incorporating a single vertical setback irregularity in elevation.
2) Comparative analysis is carried out between the irregular building and a regular RC framed building with identical plan dimensions, height, and loading conditions.
3) The assessment is limited to dynamic analysis using Response Spectrum Analysis (RSA) as per IS 1893:2016 (Part-1).
4) Seismic performance is evaluated based on lateral displacement, storey drift, and base shear under seismic intensities corresponding to different seismic zones in India.

G. *Organization Of Dissertation*

The dissertation is organized into five chapters as outlined below:

1) Chapter 1: Provides an introduction to the study, highlighting different types of structural irregularities along with the objectives and scope of the present work.
2) Chapter 2: Reviews the relevant literature, summarizing the work of various researchers on the seismic and dynamic response of buildings.
3) Chapter 3: Explains the methodology adopted for the study, including modelling details, analysis procedures, and codal provisions followed.
4) Chapter 4: Presents the results of the analysis and discusses the seismic response of the considered building models, with comparisons across different cases.
5) Chapter 5: Summarizes the key findings of the study and provides the conclusions drawn, along with possible recommendations for future research.

II. LITERATURE REVIEW

A. *General*

The present chapter reviews the available literature related to the seismic performance of both regular and irregular structures. It summarizes the major findings of earlier works, identifies gaps in existing research, and establishes the rationale for focusing on the present study, which primarily deals with vertical setback buildings and other forms of irregularities.

B. *Chronologial Literature Survey*

Neha P. Modakwar et al. [1] studied the seismic behaviour of reinforced concrete buildings with both plan and vertical irregularities, focusing particularly on re-entrant corners and mass irregularity. The authors highlighted that such irregularities, though unavoidable in modern construction, play a critical role in amplifying seismic response. Using STAAD-Pro, they analyzed G+4 and G+14 storey L-shaped and cross-shaped buildings with 5m × 5m frames to evaluate the torsional effects and additional shear forces induced by irregular configurations. Their findings revealed that re-entrant corner columns are especially vulnerable, experiencing significant variation in shear forces and moments, particularly in directions perpendicular to the earthquake loading. Moreover, torsional effects were found to be more pronounced when diaphragms were removed, necessitating the strengthening of re-entrant columns at lower and top floor levels. While torsional behaviour remained consistent across seismic zones, variations in axial forces and moments were evident at higher floors. The study concluded that diaphragm irregularities should be avoided and that proper stiffening of re-entrant corner columns is essential to enhance the seismic resilience of irregular buildings

Hemant B. Khamkar, Ganesh V. Tapkire, and S. M. Dumne [2] investigated the effects of structural irregularities on the seismic response of multi-storey reinforced concrete buildings, with emphasis on both plan and vertical irregularities. The study categorized irregularities into five types: plan, vertical, stiffness, mass, and combined irregularities, and analyzed their contribution to structural vulnerability. Using modeling and seismic analysis approaches, the authors evaluated key response parameters such as storey drift, lateral displacement, base shear, and torsional irregularity. Their findings indicated that plan irregularities like re-entrant corners and unsymmetrical shapes amplified torsional effects, while vertical irregularities such as soft storey and mass irregularity increased lateral displacements and storey drifts. Buildings with combined irregularities were identified as the most critical, exhibiting maximum instability under earthquake loading. The authors concluded that irregularities significantly amplify seismic demands compared to regular structures, thereby reducing safety margins. They emphasized the importance of designing irregular buildings with enhanced ductility, strict adherence to codal provisions, and appropriate strengthening measures to mitigate seismic risks

M. T. Raagavi and S. Sidhardhan [3] conducted a detailed study on the seismic performance of various irregular structures, emphasizing the impact of plan, vertical, mass, stiffness, and combined irregularities on structural safety. The paper reviewed different modeling and analysis approaches, including response spectrum analysis (RSA) and time history analysis (THA), and examined critical response parameters such as displacement, base shear, storey drift, and stiffness. The study highlighted that torsional coupling caused by eccentricity between the center of mass and center of stiffness significantly amplifies seismic forces, leading to potential structural damage. It was observed that structures with setbacks, soft storeys, or re-entrant corners are particularly vulnerable during seismic events due to stress concentration and uneven force distribution. Additionally, buildings with heavy mass at the top exhibited maximum displacements, while plan irregularity consistently led to higher storey drift compared to regular buildings. The authors concluded that irregularities induce damaging effects by altering stiffness and ductility demands, making such buildings more prone to failure under seismic loading. They stressed that time history analysis is more precise and reliable than RSA for seismic design, and recommended that irregular configurations should be carefully treated with enhanced ductility and code-based provisions to mitigate risks

Aditya Tambare et al. [4] studied the seismic analysis of plan irregular structures using ETABS software, focusing on the effect of different unsymmetrical plan configurations on building performance under earthquake loading. The research involved the analysis of G+5 and G+10 RC framed structures with irregular plans such as L-shape, C-shape, and T-shape, and compared them with a regular configuration using linear static analysis, response spectrum method, and time history method. The findings revealed that plan irregular structures exhibited greater lateral displacements and base shear compared to regular structures, due to torsional rotation induced by the eccentricity between the centre of mass and centre of rigidity. Among the irregular shapes, the L-shaped models recorded the highest displacements, whereas the T-shaped models showed relatively lower displacements despite higher irregularity. The study concluded that plan irregularities significantly amplify seismic demands and, therefore, each irregular configuration must be studied separately rather than adopting generalized assumptions. The authors emphasized the need for careful modelling, code-based provisions, and ductility considerations to ensure safety in irregular buildings.

Sanjay Sabu and Sreerench Raghavu [5] analyzed the seismic performance of irregular reinforced concrete structures using ETABS software, with a particular focus on the effects of vertical irregularities and sloping ground conditions. The study emphasized that irregularities in mass, stiffness, and geometry significantly influence dynamic response, often leading to early failures during earthquakes. A G+15 multi-storey RC frame structure was modeled for both flat and sloping ground conditions, and evaluated using response spectrum analysis as per IS 1893 provisions. Parameters such as storey displacement, storey drift, base shear, storey stiffness, and overturning moment were compared. Results revealed that structures on sloping ground experienced higher storey shear and reduced stiffness, though with slightly lower displacements than flat-ground models. Soft storey and weak storey effects were particularly critical in vertical irregular configurations. The authors concluded that irregular structures demand special design considerations, as conventional methods may underestimate dynamic forces. They recommended that ductility-based design approaches and appropriate strengthening measures are essential to ensure safety in seismically active regions

Shantnoo S. Girme and Atul B. Pujari [6] presented a review on the progressive collapse analysis (PCA) of reinforced concrete flat slab structures considering the effects of geometrical irregularities in both horizontal and vertical directions. The study highlighted that flat slab buildings are more prone to progressive collapse due to the absence of beams, which otherwise help redistribute loads after column failure. Using guidelines from the GSA (2016) and DoD (2009), the review examined various analytical methods such as linear static analysis and dynamic PCA under scenarios of column removal at different locations. Key response parameters included demand-capacity ratio (DCR), chord rotation, and vertical joint displacement. The review showed that irregular flat slab buildings exhibited higher vulnerability to progressive collapse, especially under corner column removal, compared to regular structures. The incorporation of perimeter beams and strengthening of critical columns was found to significantly enhance progressive collapse resistance by providing alternate load paths. Additionally, the study emphasized that the severity of collapse depends on the type, location, and degree of irregularity, with combined vertical and stiffness irregularities showing the most critical effects. The authors concluded that incorporating redundancy, ductility, and continuity in design can help irregular flat slab buildings develop alternative load paths and prevent catastrophic collapse under extreme loading

Gangotri Kinagi and Lokesh J. K. [7] presented a study on the seismic performance of reinforced concrete buildings with structural irregularities using ETABS V19. The authors emphasized that irregularities in plan, elevation, stiffness, and mass distribution are among the major causes of structural damage and collapse during earthquakes. A G+6 storey RC building (CV Raman Block, NMAM Institute of Technology, Nitte) was modeled with different irregular configurations, and the seismic response was evaluated through time history analysis and pushover analysis. The results revealed that irregular structures exhibit higher displacements, storey drifts, and torsional responses compared to regular buildings. Soft storey and mass irregularities were found to be the most critical, often leading to instability at lower levels. Time history analysis confirmed that nonlinear dynamic analysis provides the most realistic predictions of seismic performance, highlighting the need for proper strengthening and code-based provisions in irregular structures. The study concluded that avoiding diaphragm discontinuities, ensuring balanced stiffness and mass distribution, and adopting ductility-based design approaches are essential for improving the seismic resilience of irregular structures.

Abhijeet Dhalwar and S. P. Tak [8] carried out a seismic analysis of vertical irregular steel structures with different seismic resilience techniques to evaluate their effectiveness in mitigating earthquake-induced responses. A G+15 setback steel building was modeled using SAP2000 v23, and nonlinear time history analysis was performed considering Zone V earthquake data (Bhuj earthquake). Four models were compared: (i) a basic irregular structure without resilience, (ii) a structure with fluid viscous dampers, (iii) a structure with inverted V-bracing, and (iv) a structure with elastomer bearing base isolation. The results showed that the basic irregular model experienced the highest base shear, displacements, and storey drifts. Among the resilience techniques, base isolation proved to be the most effective, significantly reducing base shear, lateral displacements, and storey drifts, while fluid viscous dampers enhanced ductility by effectively dissipating seismic energy. In contrast, inverted V-bracing reduced base shear but led to higher bending moments and storey drifts. The study concluded that base isolation systems provide the highest seismic efficiency for vertical irregular steel structures located in high seismic zones, while damping and bracing systems can serve as supplementary strengthening strategies.

Aleena Sam and Mathews M. Paul [9] presented a review on the performance evaluation of irregular structures under seismic response considering soil-structure interaction (SSI). The study highlighted that past earthquakes, including the 2015 Nepal, 2017 Mexico City, and 2023 Turkey–Syria events, demonstrated the extreme vulnerabilities of asymmetrical and irregular buildings, especially when constructed on soft or loose soils. The authors emphasized that while seismic codes such as IS 1893 (Part 1):2002 allow irregularities with specific penalties, they often neglect the role of SSI, which can significantly influence seismic response. The review categorized irregularities into plan, vertical, stiffness, mass, torsional, and combined irregularities, noting that most structures in reality exhibit multiple irregularities simultaneously. Case studies and numerical models showed that torsional effects, soft storeys, re-entrant corners, setbacks, and floating columns amplify seismic demands, often resulting in greater storey drift, lateral displacements, and torsional moments compared to regular buildings. Importantly, the paper stressed that SSI often worsens seismic performance, contrary to earlier assumptions of beneficial damping effects, especially in soft soil conditions where bearing capacity failure, liquefaction, and pounding between adjacent buildings are more pronounced. The authors concluded that future seismic design must integrate SSI explicitly, with performance-based design guidelines, refined numerical models, and combined geotechnical–structural approaches to capture realistic seismic demands in irregular buildings.

Dasa Bhagirath and Odedra Chirag [10] investigated the seismic performance of irregular steel buildings using response spectrum analysis in ETABS, following IS 1893:2016 and IS 875:2015 provisions. Four different structural configurations—square, L-shape, T-shape, and C-shape—were modeled for an 18-storey steel building with varying bay distributions. The study considered multiple load combinations (dead, live, wind, and seismic) and evaluated design forces in beams and columns, maximum storey displacement, and storey drift. Comparative analysis revealed that the square-shaped building showed superior performance in resisting beam and column forces, while C-shape and T-shape structures performed better under response spectrum analysis, particularly in terms of storey displacement and drift. The L-shape model exhibited average performance across most parameters, highlighting the influence of plan irregularities on structural response. The authors concluded that square configurations are structurally efficient under static forces but less favorable under dynamic seismic excitations, while irregular shapes demand special attention in design to ensure seismic resilience.

Abhijeet Patil and Rushikesh Sutar [11] carried out a seismic analysis of multi-storey irregular RCC buildings incorporating steel cross-bracing systems to enhance lateral resistance against seismic and wind forces. Using ETABS 20 and linear static seismic analysis, the study focused on G+11 storey structures with plan irregularities (L-shaped, T-shaped, and C-shaped configurations) under seismic Zone V conditions. The analysis compared the response of braced and unbraced structures in terms of base shear, axial forces, bending moments, storey drifts, and lateral displacements. The findings revealed that T-shaped buildings exhibited the maximum displacement, followed by L-shaped, while C-shaped buildings showed the least displacement. The introduction of cross-bracing significantly improved structural performance, reducing lateral displacements by 38% in L-shaped, 45% in T-shaped, and 30% in C-shaped buildings. The study further highlighted that bracing not only minimized displacements but also optimized column forces and bending moments, thereby improving overall seismic resilience. The authors concluded that steel bracing is a cost-effective and efficient method for strengthening irregular RCC buildings, with T-shaped structures benefiting most from bracing interventions

Anuradha R. Babar and S. N. Patil [12] presented a comprehensive review on the seismic performance of multi-storied irregular steel buildings, focusing particularly on the role of base isolation and damping systems as mitigation strategies. The authors examined various structural irregularities—including plan, vertical, mass, stiffness, and torsional irregularities—and discussed their impact on stress distribution, dynamic response, and overall structural vulnerability under earthquake loading. Through the analysis of experimental studies, nonlinear time history analysis, finite element simulations, and real-world case studies, the review highlighted that irregular buildings suffer from amplified vibrations, torsional effects, and stress concentrations compared to regular configurations. Base isolation systems, such as lead rubber bearings (LRB), high damping rubber bearings (HDRB), and friction pendulum systems (FPS), were found to significantly reduce seismic forces transmitted to the superstructure by decoupling it from ground motion. Similarly, damping devices—including viscous dampers, friction dampers, tuned mass dampers (TMDs), and viscoelastic dampers—effectively dissipated seismic energy and minimized inter-story drifts. The authors also noted the potential of AI-based adaptive control systems and hybrid seismic mitigation strategies that combine isolation and damping mechanisms for enhanced resilience. Despite these advancements, the review stressed challenges such as high implementation costs, maintenance requirements, and gaps in design codes for irregular steel buildings. The study concluded that interdisciplinary research, integration of emerging materials, and adaptive real-time control systems are essential for achieving safer and more sustainable seismic performance in irregular steel structures.

Sanskriti Nagar and Mahroof Ahmed [13] investigated the seismic performance of reinforced concrete buildings with vertical irregularities, such as stiffness irregularities (soft storey), vertical geometric irregularities (setbacks), mass irregularities, and combined irregularities. Using SAP2000, a total of 19 structural models—both with and without infill walls—were analyzed under seismic loading as per IS 1893 (Part 1):2002 and IS 456:2000. The study employed linear static analysis, nonlinear pushover analysis, and response spectrum analysis to evaluate the structural response. The results indicated that vertical irregularities significantly affect structural integrity, with soft storey and setback conditions being the most detrimental, leading to higher displacements, reduced ductility, and premature hinge formations. In contrast, the presence of infill walls enhanced overall performance by increasing stiffness, reducing displacements by 25–40%, and delaying hinge formation, thereby improving collapse resistance. However, non-uniform distribution of infill walls could itself introduce irregularities. The authors concluded that buildings with combined irregularities performed the worst under seismic loading, while regular structures demonstrated better resistance. The study strongly emphasized the need for special seismic provisions in design codes for irregular buildings.

C. Need For The Present Study

From the literature, it is clear that structural irregularities—both in plan and elevation—significantly increase seismic vulnerability of buildings. While plan irregularities such as L, T, and C-shaped buildings have been widely studied, vertical irregularities, particularly setback buildings, remain among the most critical due to abrupt changes in stiffness and mass, leading to high inter-storey drifts and stress concentration. Although IS 1893:2016 provides general provisions, specific guidelines for setback configurations are limited. Recent earthquake events have further highlighted their poor performance, demonstrating the urgent need for detailed investigation. Hence, the present study focuses on analysing the seismic response of vertical setback buildings, emphasizing parameters such as lateral displacement, storey drift, and base shear to develop a deeper understanding of their behaviour and to contribute towards safer seismic design practices.

III. METHODOLOGY

The methodology adopted in this study is designed to evaluate the seismic performance of reinforced concrete (RC) framed buildings with and without vertical setback irregularities. Vertical irregularities, particularly setbacks, alter the uniform distribution of stiffness and mass, thereby amplifying seismic demands. To capture these effects, a comparative analysis is carried out between a regular RC framed building and a setback frame.

The analysis follows the guidelines of IS 1893:2016 (Part 1), using Response Spectrum Analysis (RSA) as the primary dynamic analysis method. ETABS software is employed to model and simulate the structural response under varying seismic intensities corresponding to different Indian seismic zones.

The seismic performance of the frames is quantified through critical response parameters—lateral displacement, storey drift, and base shear—which collectively indicate the vulnerability of buildings to seismic actions. By adopting this methodology, the study provides a systematic framework to assess how vertical setbacks influence the dynamic behaviour and overall seismic safety of RC framed structures.

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A. *Flow Chart*

The overall methodology adopted in this study is summarized in the flow chart shown in Figure 3.1. The process begins with the modelling of a reinforced concrete (RC) space frame, which is considered in two configurations: a regular RC framed building (RF) and a vertical irregular RC framed building with a single setback (VSSF). Both building types are subjected to seismic analysis under different seismic zones (II, III, IV, and V) as per IS 1893:2016.

To capture the seismic behaviour, Response Spectrum Analysis (RSA) is performed using ETABS software. The structural responses, including lateral displacement, storey drift, and base shear, are then evaluated and compared between the regular and setback frames. This stepwise approach ensures a systematic assessment of how vertical setback irregularities influence the dynamic performance of RC framed buildings under varying seismic intensities.

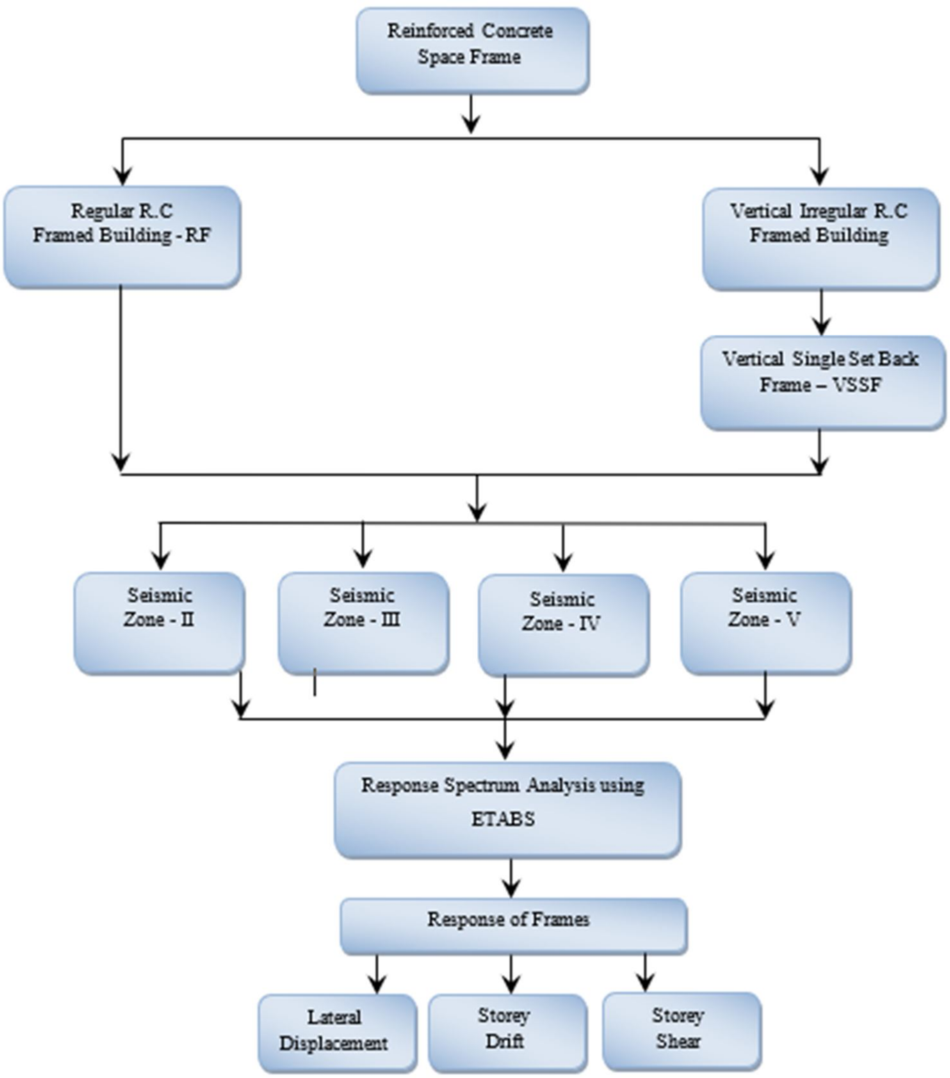
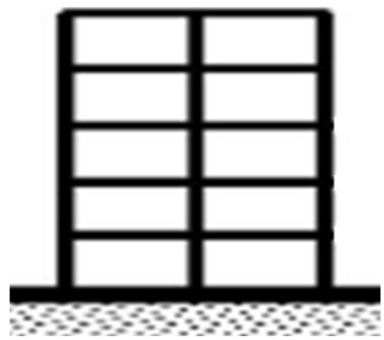
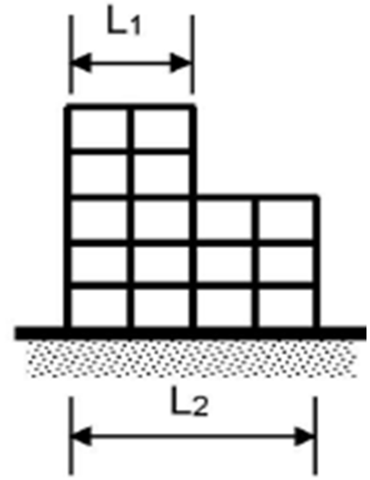


Fig. 3.1 Methodology Flow Chart

B. *Case Studies*

Table 3.1 summarizes the different case studies considered in this work for seismic analysis. Two categories of reinforced concrete space frames are analysed: a Regular Frame (RF) and a Vertical Single Setback Frame (VSSF). Each frame type is evaluated under different seismic intensities corresponding to Zones II, III, IV, and V as per IS 1893:2016.

Table 3.1 Details of Case Studies

Case No.	Frame Designation	Description of frame	Geometry of Frame
1	RF - ZII	Regular Space Frame – Seismic Zone II	
2	RF - ZIII	Regular Space Frame – Seismic Zone III	
3	RF - ZIV	Regular Space Frame – Seismic Zone IV	
4	RF - ZV	Regular Space Frame – Seismic Zone V	
5	VSSF – ZII	Vertical Single Setback Frame – Seismic Zone II	
6	VSSF – ZIII	Vertical Single Setback Frame – Seismic Zone III	
7	VSSF – ZIV	Vertical Single Setback Frame – Seismic Zone IV	
8	VSSF – ZV	Vertical Single Setback Frame – Seismic Zone V	

C. Geometric Details Of Models

The geometric details of the considered building model are presented in Table 3.2, while Figure 3.2 and 3.3 illustrates the plan, elevation, and isometric views of the selected case studies adopted for the present work. Furthermore, the cross-sectional properties of various structural components, including beams, columns, and slabs, are provided in Table 3.3. Together, these details establish the fundamental modelling parameters required for the seismic analysis.

Table 3.2 Geometric Details

S.No.	Parameter	Dimensions
1.	Typical Bay Dimensions	5 m × 5 m
2.	Typical Storey Height	3 m
3.	Super Structure Height	18m
4.	Depth of Foundation	1.8 m
5.	No. of Stories	6 No's

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Table 3.3 Section Properties

Structural Component	Dimensions			
	Zone - II	Zone - III	Zone - IV	Zone - V
Slab	150 mm	150 mm	150 mm	150 mm
Beams	300 mm × 450 mm	300 mm × 450 mm	300 mm × 450 mm	300 mm × 450 mm
Columns	375 mm × 375 mm	400 mm × 400 mm	425mm × 425 mm	450 mm × 450 mm

D. Material Properties

The material properties adopted for modelling the reinforced concrete building are listed in Table 3.4. The table specifies the grade, characteristic strength, and Young's modulus of the materials considered, namely M30 concrete and Fe550 reinforcing steel, in accordance with IS codes. These values form the essential input parameters for the seismic analysis and ensure realistic representation of structural behaviour.

Table 3.4 Material Properties

Material	Grade of Material	Characteristic Strength (MPa)	Young's Modulus (MPa)
Concrete	M30	30	27386.13
Steel-Rebar	Fe550	550	2×10^5

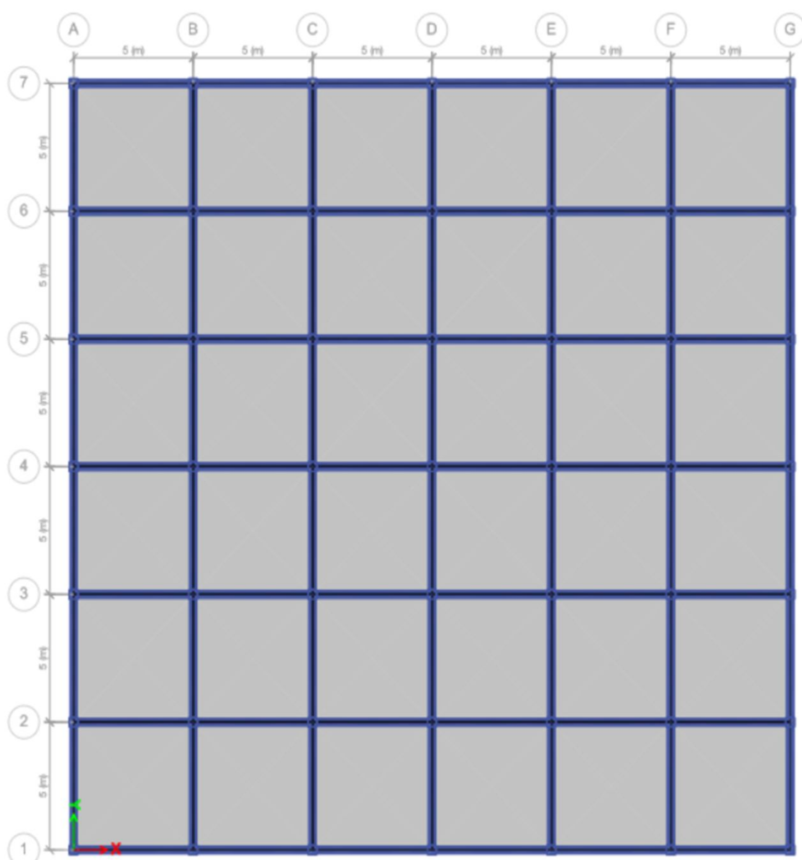

Fig. 3.2 (a) Plan of RF

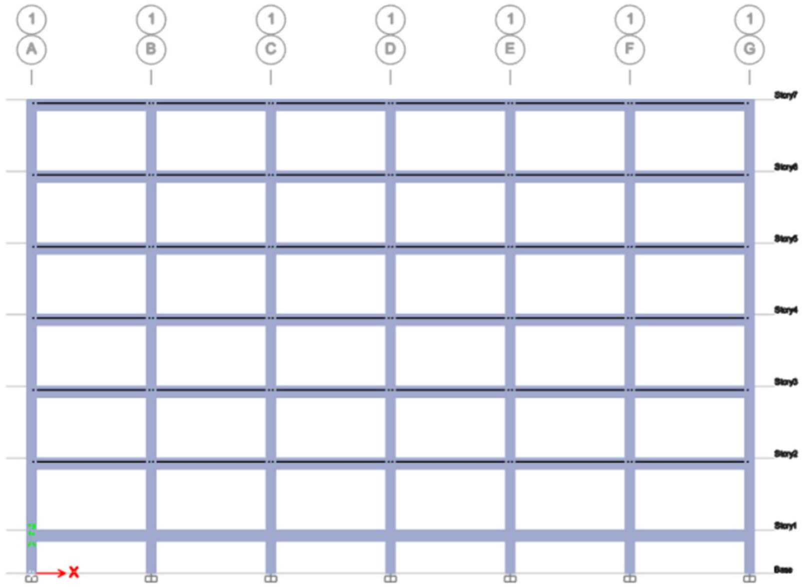

Fig. 3.2 (b) Elevation of RF

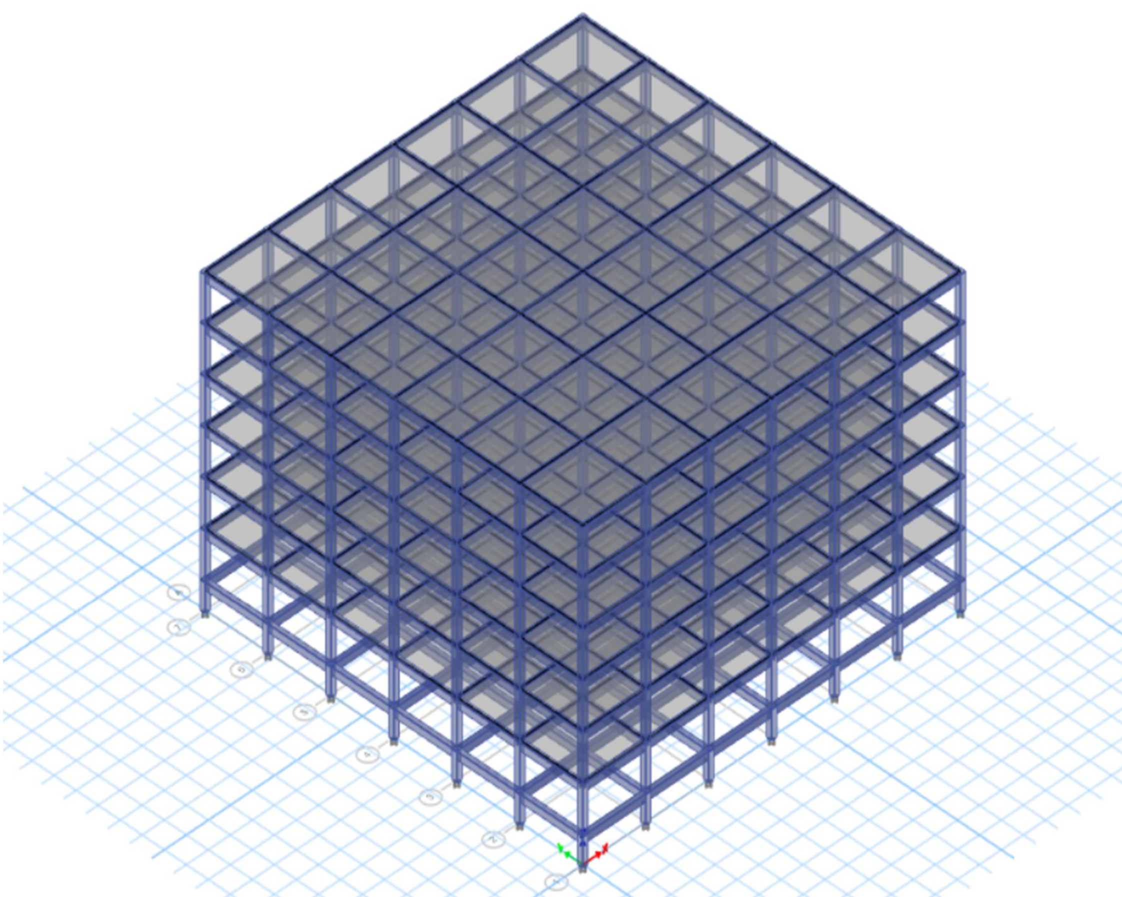

Fig. 3.2 (c) Isometric View of RF

Fig. 3.2 Geometric Views of Regular Frame – RF

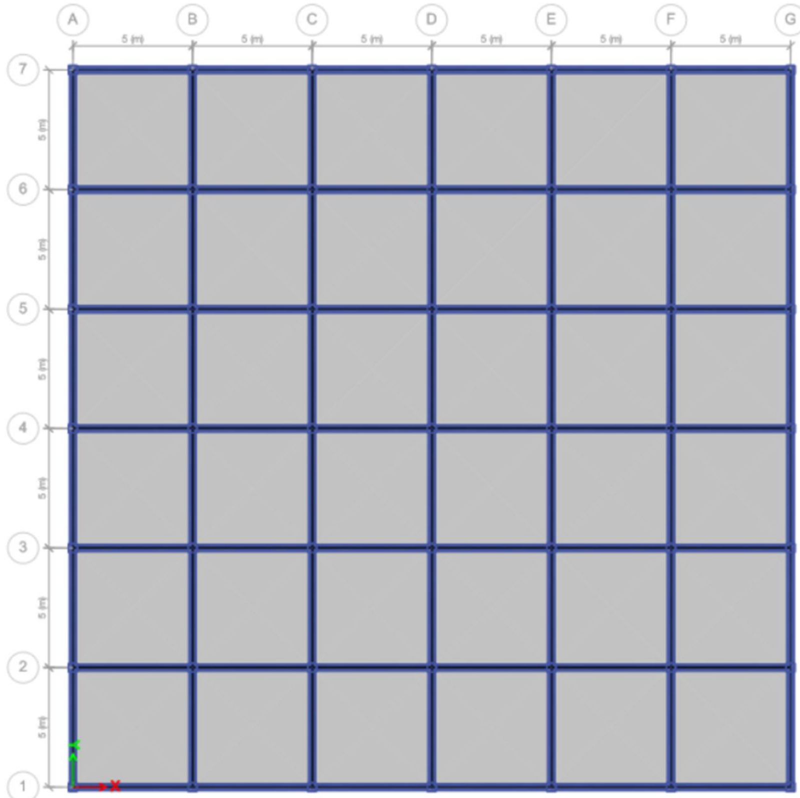

Fig. 3.3 (a) Plan of VSSF at Base Level

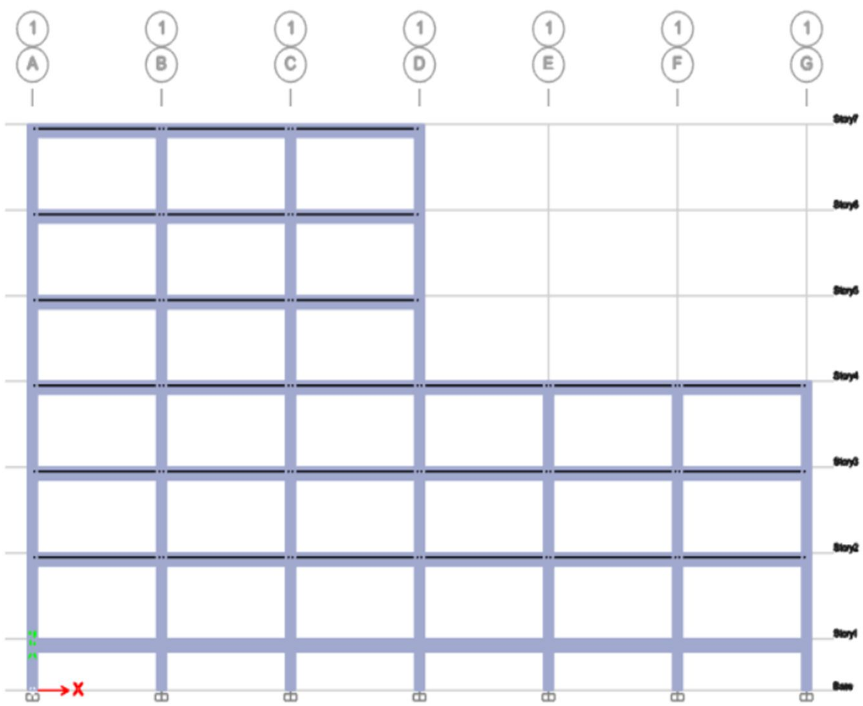

Fig. 3.3 (b) Elevation of VSSF

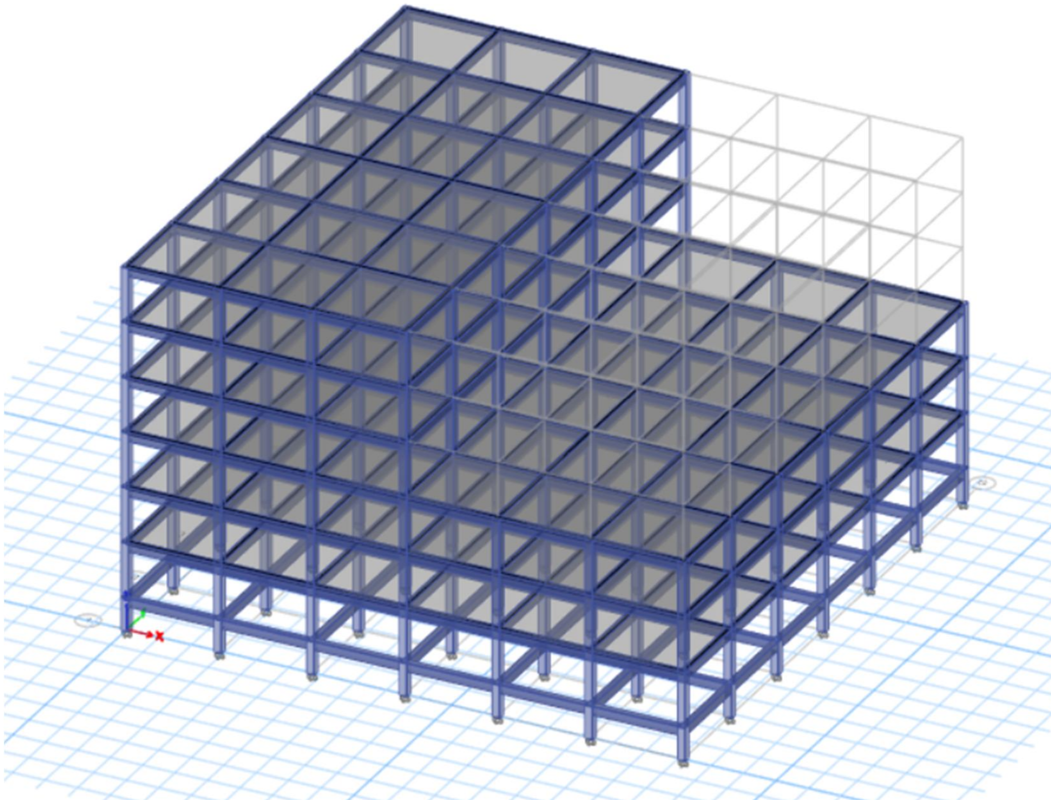

Fig. 3.3 (c) Isometric View of VSSF

Fig. 3.3 Geometric Views of Vertical Single Setback Frame – VSSF

E. Load Case Details

1) Dead and Live Loads

In structural analysis and design, dead loads represent the permanent, immovable weights such as walls, slabs, and finishes, while live loads account for variable or transient actions like occupancy, furniture, and environmental usage. Both categories of loads are crucial in evaluating the seismic performance of buildings, as they directly influence mass distribution and dynamic response.

In the present study, the intensity of dead and live loads is considered as per the provisions of IS 875 (Part 1 & Part 2), ensuring compliance with Indian codal standards. Table 3.5 summarizes the adopted values of wall load, parapet wall load, superimposed dead load on slabs, and live load, which serve as essential inputs for the seismic analysis of the building models.

Table 3.5 Intensity of Dead and Live Loads

S.No.	Type of Load	Intensity of Load
1.	Wall Load	12 kN/m
2.	Parapet Wall Load	3 kN/m
3.	Super Imposed Dead Load on Slab	2 kN/m^2
4.	Live Load	4 kN/m^2

2) Seismic Loads

Seismic loads are a key input in dynamic analysis, as they represent the lateral forces induced by earthquake ground motions. In this study, seismic forces are evaluated as per the provisions of IS 1893:2016 (Part 1). The analysis is performed for all four seismic zones of India, considering appropriate zone factors. The selected parameters include zone factor (Z), importance factor (I), response reduction factor (R), soil type, and the percentage of live load considered in seismic weight. These inputs are essential for accurately defining seismic demand on the structure. The adopted values are summarized in Table 3.6.

Table 3.6 Seismic Load Parameters

S.No.	Parameter	Value	Reference (IS 1893:2016)
1.	Zone Factor (Z)	0.10 (Zone II), 0.16 (Zone III), 0.24 (Zone IV), 0.36 (Zone V)	Table 3, Clause 6.4.2
2.	Importance Factor (I)	1.2	Clause 7.2.3
3.	Response Reduction Factor (R)	5 (SMRF)	Table 9, Clause 7.2.6
4.	Soil Type	Type II (Medium Soil)	Table 1, Clause 6.4.2
5.	Percentage of Live Load for Seismic Weight	50% (As imposed load > 3.0 kN/m²)	Clause 7.3.1

F. Dynamic Analysis

In the present study, the seismic behaviour of the building models is evaluated using Response Spectrum Analysis (RSA) as per the provisions of IS 1893:2016 (Part 1). RSA is a widely used linear dynamic analysis method that determines the peak structural response by utilizing a predefined design response spectrum rather than relying on a specific ground motion record. This approach effectively captures the influence of higher modes of vibration, making it more reliable than equivalent static methods for medium-to high-rise buildings.

The analysis is carried out using ETABS software, which is well-suited for modelling, analysing, and designing multi-storey RC frame structures. ETABS provides automated modal analysis, generates spectral ordinates, and combines modal responses using codal recommendations such as SRSS (Square Root of Sum of Squares) or CQC (Complete Quadratic Combination). This enables a realistic estimation of key seismic response parameters including lateral displacement, storey drift, and base shear, thereby facilitating a comparative assessment between regular frames (RF) and vertical setback frames (VSSF).

IV. RESULTS AND DISCUSSION

In this chapter, the seismic performance of a six-storey reinforced concrete (RC) Vertical Single Setback Frame (VSSF) building is evaluated and compared with that of a regular frame structure. The dynamic analysis is carried out using the Response Spectrum Method implemented in the ETABS software package.

The study considers all seismic zones of India as specified in IS 1893 (Part 1) - 2016, in order to capture the influence of varying seismic intensities on structural behaviour. Key seismic response parameters such as lateral displacement, storey drift, and storey shear are extracted from the analysis. The results are presented in the form of graphs for better visualization and interpretation.

The discussions following each set of results provide a comparative assessment between the Regular Frame (RF) and the Vertical Single Setback Frame (VSSF), highlighting the percentage variations observed across different seismic zones. This enables a clear understanding of the influence of vertical irregularities on the seismic performance of RC frames.

A. Seismic Response Of Regular Frame – RF

The seismic performance of the Regular Frame (RF) was studied under different seismic zones of India (Zone II, Zone III, Zone IV, and Zone V) in terms of lateral displacement, storey drift, and storey shear. The comparative results are discussed below.

1) Lateral Displacement: Figure 4.1 shows the variation of lateral displacement along the storey height. The displacement increases progressively with height and attains its maximum value at the roof level. In Zone II, the displacement remains minimal, while in Zone V it is almost 3 times higher than Zone II. Specifically, lateral displacement increases by approximately 40–50% from Zone II to Zone III, 70–80% from Zone III to Zone IV, and about 100–120% from Zone IV to Zone V. The smooth distribution confirms the regular frame behaviour without irregularities.
2) Storey Drift: The inter-storey drift profiles (Figure 4.2) show a non-linear distribution, with maximum drift observed around the mid-height to upper storeys. The drift values rise consistently with higher seismic intensity. Compared to Zone II, the storey drift in Zone V is nearly 2.5 to 3 times higher, with incremental increases of about 35–45% between successive zones. These results indicate that drift control becomes critical in higher seismic zones, as excessive inter-storey drifts can lead to non-structural damage and potential instability.

3) Storey Shear: Figure 4.3 illustrates the distribution of storey shear along the height of the RF. As expected, the maximum shear force occurs at the base and gradually reduces towards the upper storeys. The magnitude of base shear increases sharply with seismic zone intensity: Zone V registers nearly 2.5 to 3 times the base shear of Zone II. Between successive zones, the increase is approximately 40–50%, consistent with the seismic zone factor increments prescribed in IS 1893 (Part 1).
4) Overall Observations: The combined evaluation of lateral displacement, drift, and shear demonstrates a clear dependency of structural response on seismic zone intensity. While lateral displacement and drift control are more critical for serviceability and non-structural safety, the shear demand dictates the strength requirements of the frame members and foundations. The percentage increases across all three parameters highlight the vulnerability of frames in Zone IV and Zone V if not designed with adequate seismic provisions.

Hence, it is evident that:

- Lateral displacement in Zone V is nearly 200–220% higher than in Zone II.
- Storey drift in Zone V is nearly 150–200% higher than in Zone II.
- Base shear in Zone V is nearly 200–220% higher than in Zone II.

These results underline the necessity of incorporating ductile detailing, enhanced stiffness, and energy dissipation mechanisms to ensure the safety and performance of structures in higher seismic zones.

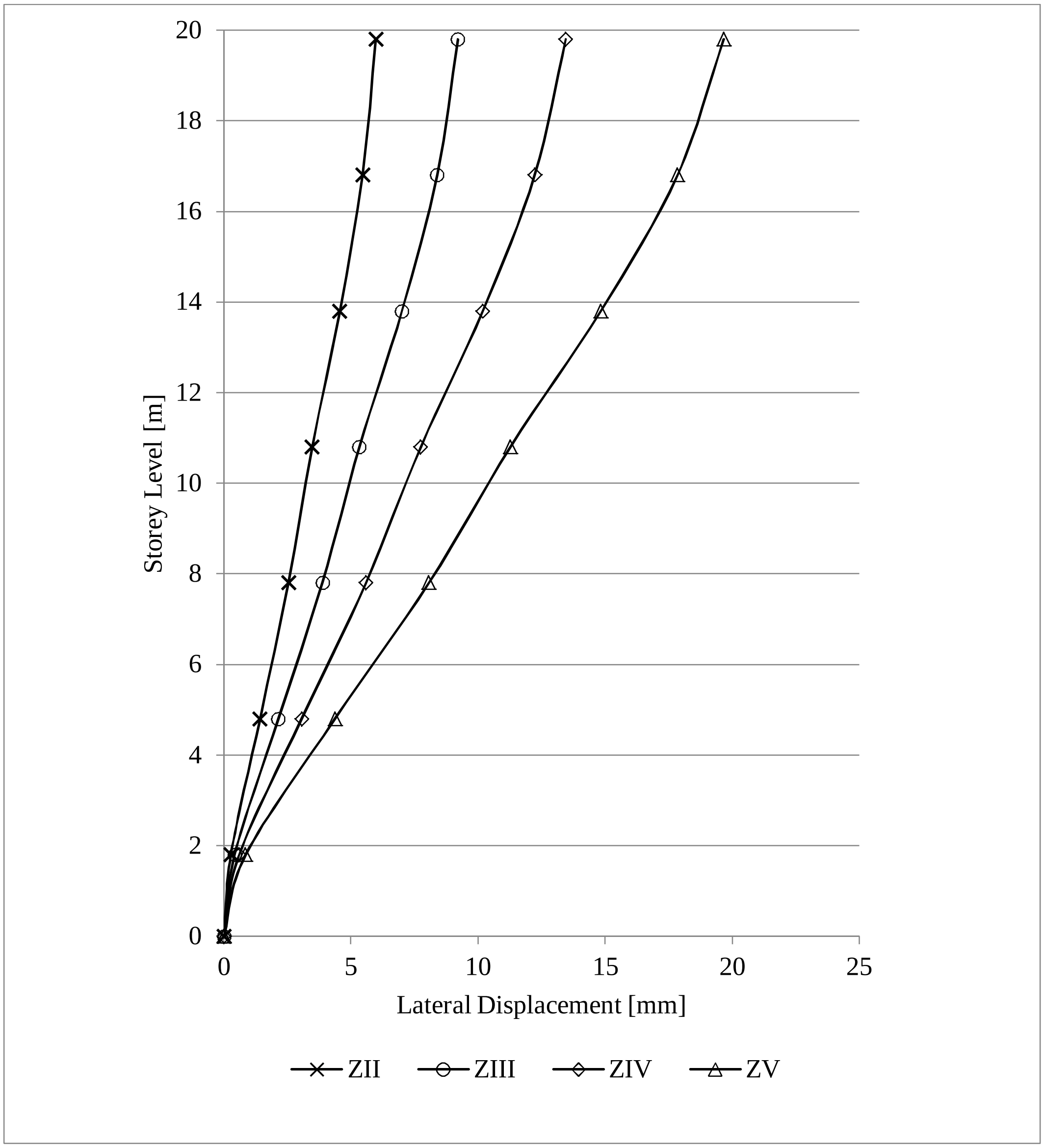

Fig. 4.1 Seismic Response (Lateral Displacement) of Regular Frame – RF at all Seismic Zones in India

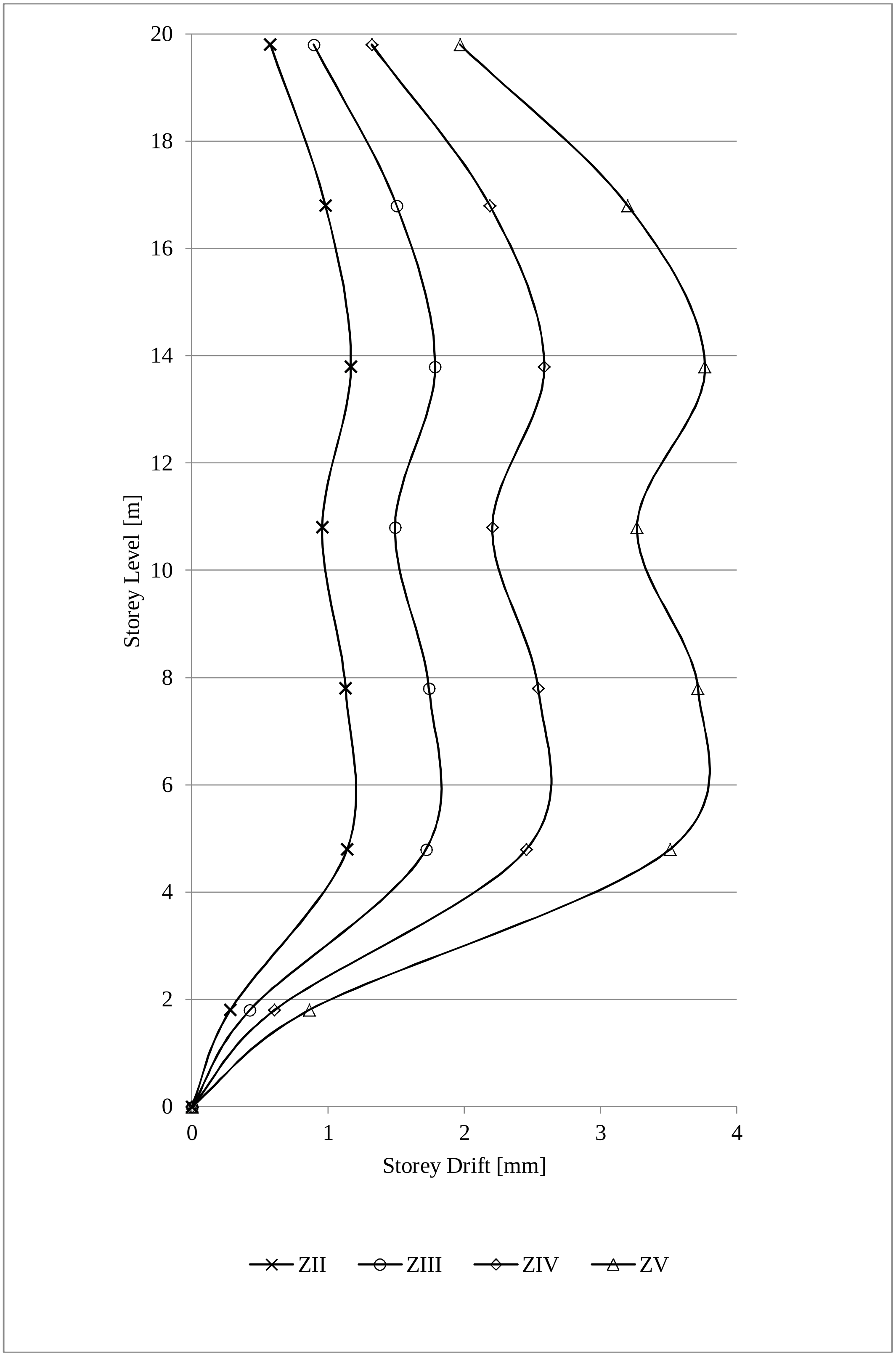

Fig. 4.2 Seismic Response (Storey Drift) of Regular Frame – RF at all Seismic Zones in India

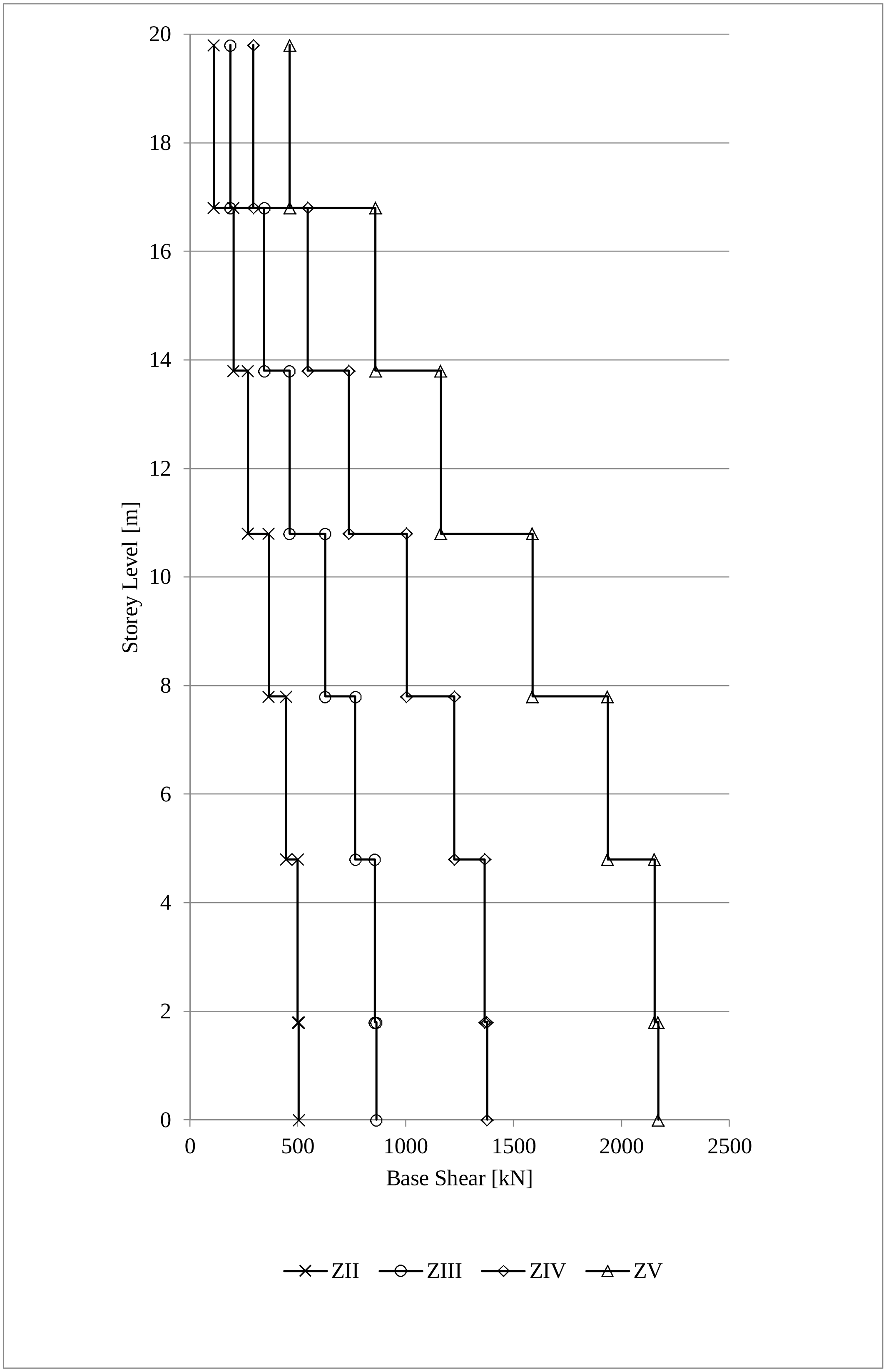

Fig. 4.3 Seismic Response (Storey Shear) of Regular Frame – RF at all Seismic Zones in India

B. Seismic Response Of Vertical Single Setback Frame – VSSF

The seismic performance of the Vertical Single Setback Frame (VSSF) under different seismic zones (II–V) has been evaluated in terms of lateral displacement, storey drift, and storey shear. The results are plotted in Figures 4.4 to 4.6 and discussed below.

1) Lateral Displacement: The displacement profiles indicate that lateral displacement increases progressively with storey height, reaching its maximum value at the top floor in all seismic zones. With the increase in seismic intensity, the displacement magnitudes rise considerably. Zone II records the least displacement, while Zone V shows the maximum, with nearly 2.5 to 3 times higher roof displacement than Zone II. Between successive zones, the displacement increases by about 40–50% from Zone II to III, 65–75% from Zone III to IV, and nearly 100% from Zone IV to V.
2) Storey Drift: The drift distribution for VSSF exhibits a non-uniform trend, with peak drift values concentrated around the setback level. This behaviour arises due to the abrupt change in stiffness introduced by the vertical setback. As seismic intensity increases, storey drift values also increase significantly. From Zone II to Zone V, the drift amplification is nearly 2.5 to 3 times, with average incremental increases of 30–40% between successive zones.
3) Storey Shear: The storey shear profiles show that maximum shear forces occur at the base and reduce gradually along the height. However, due to setback-induced stiffness irregularity, abrupt variations in shear distribution are visible at and above the setback level. The base shear demand in Zone V is nearly 2.8 to 3 times higher than that in Zone II, with a consistent increase of about 40–50% between successive zones.
4) Overall Observations: From the results, it is evident that the seismic response of VSSF is highly sensitive to seismic intensity. (a) Lateral displacement increases up to 3 times from Zone II to Zone V. **(b)** Storey drift increases by nearly 2.5 to 3 times, with concentration near the setback level. **(c)** Base shear demand increases by about 2.8 to 3 times between Zone II and Zone V.

These findings highlight that while VSSF frames can be designed for seismic safety, their irregular configuration leads to unfavourable response. Special seismic detailing and drift-control strategies are therefore necessary for such irregular frames in higher seismic zones.

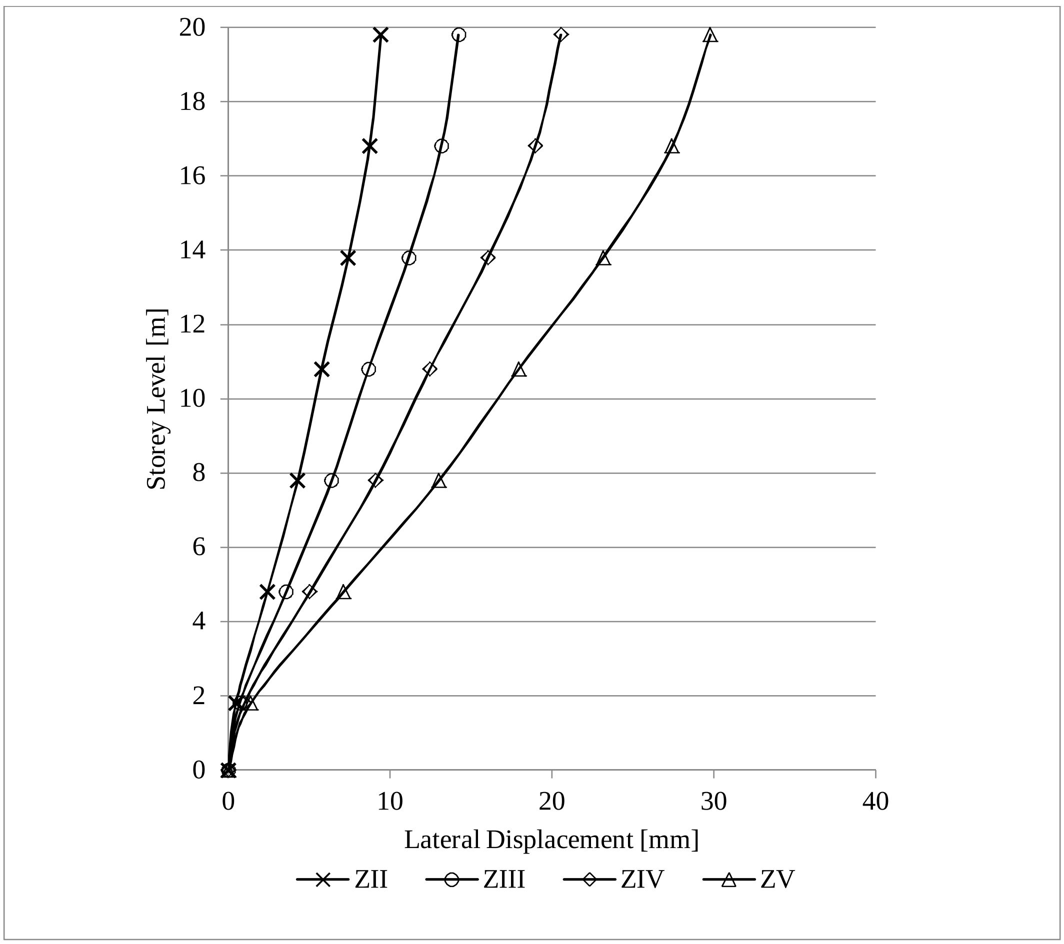

Fig. 4.4 Seismic Response (Lateral Displacement) of Vertical Single Setback Frame – VSSF at all Seismic Zones in India

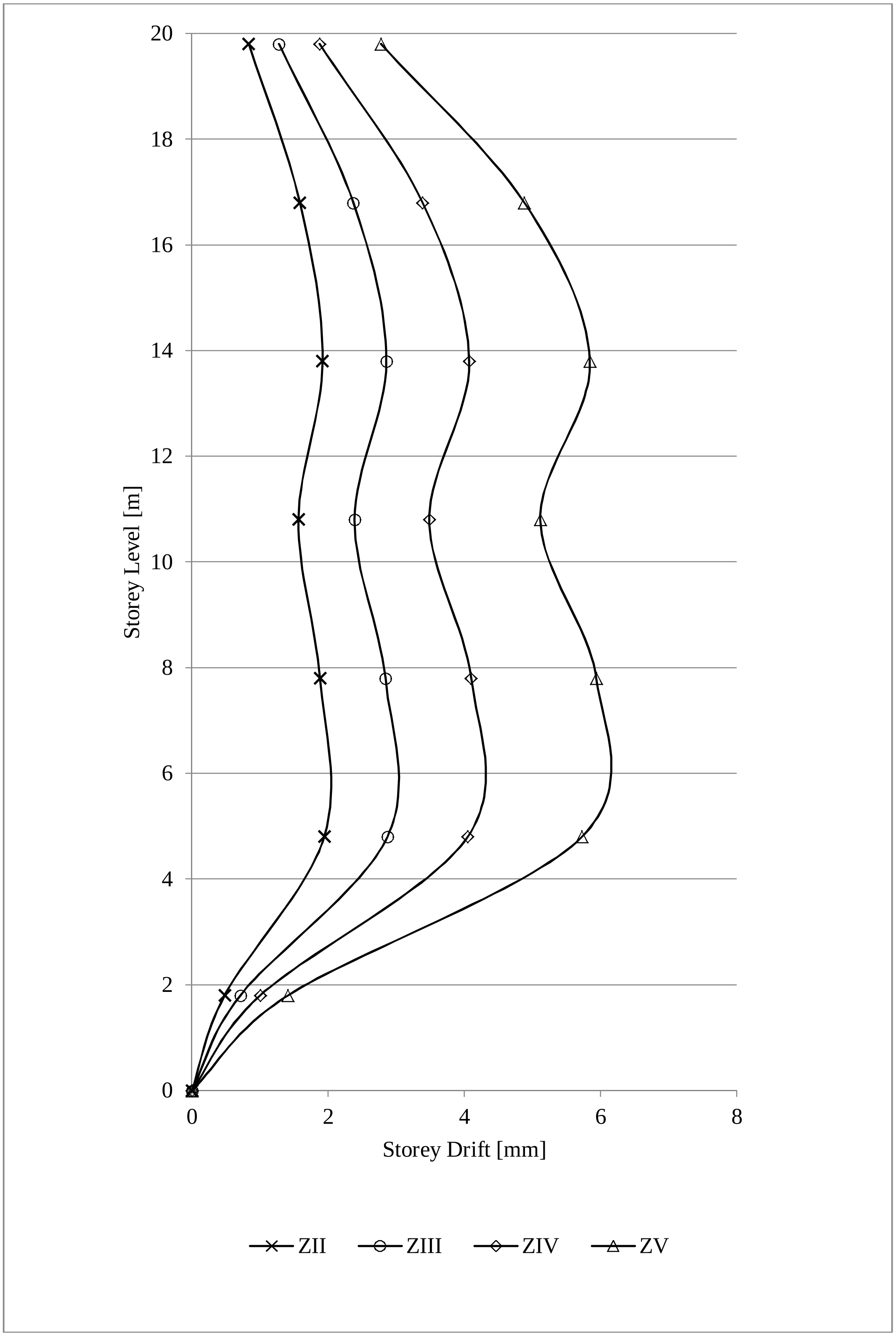

Fig. 4.5 Seismic Response (Storey Drift) of Vertical Single Setback Frame – VSSF at all Seismic Zones in India

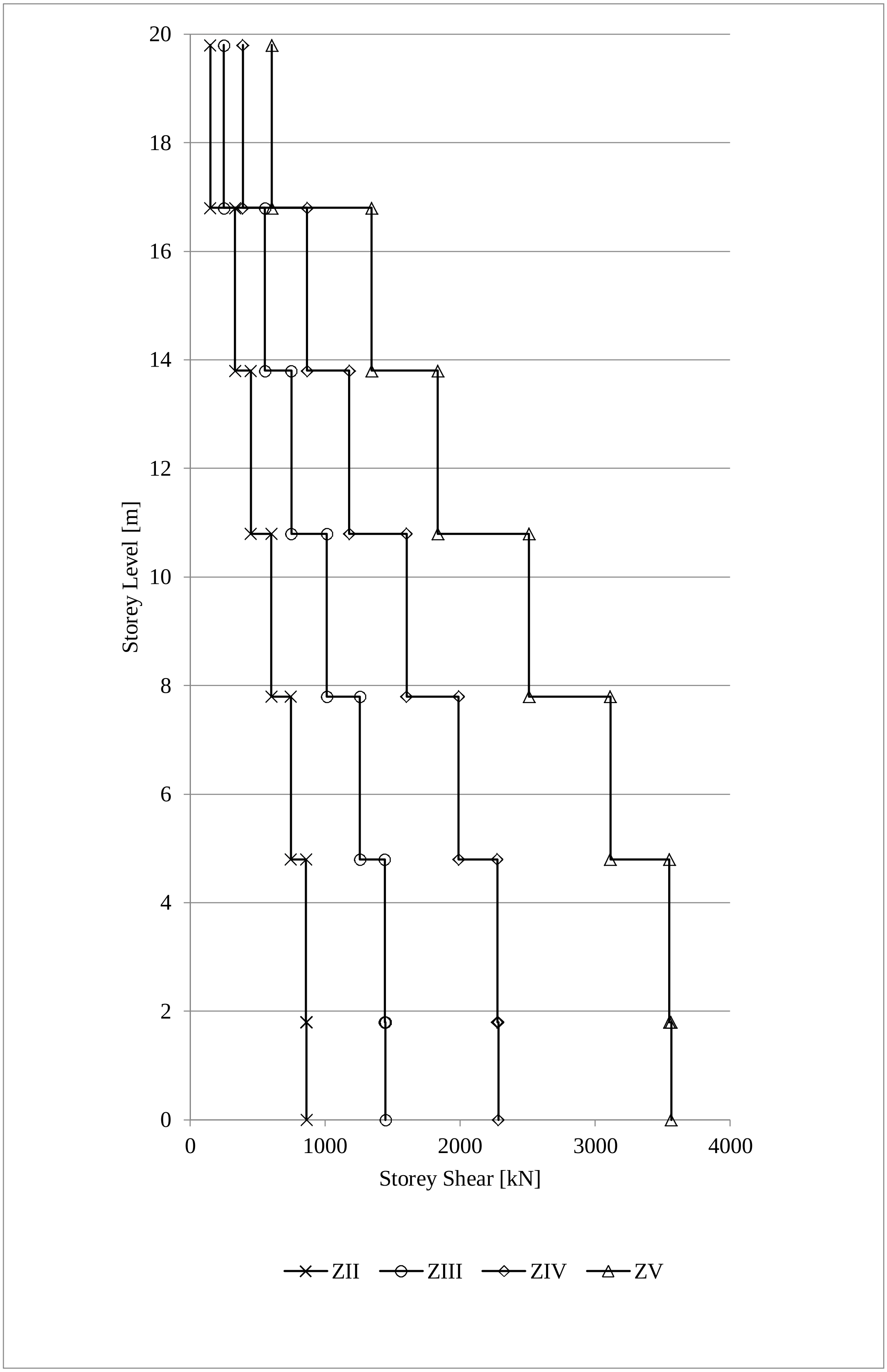

Fig. 4.6 Seismic Response (Storey Shear) of Vertical Single Setback Frame – VSSF at all Seismic Zones in India

C. Seismic Response Of Regular (Rf) And Vertical Single Setback (Vssf) Frames Under Seismic Loads

The seismic responses of Regular Frame (RF) and Vertical Single Setback Frame (VSSF) are evaluated and compared in terms of lateral displacement, storey drift, and storey shear across seismic Zones II, III, IV, and V. The results, presented in Figures 4.7–4.9, highlight the influence of vertical irregularity (setback) on the overall seismic performance.

1) Lateral Displacement: Both RF and VSSF show increasing lateral displacement with storey height, peaking at the roof. However, VSSF consistently experiences higher displacements, with roof displacement being 10–12% higher in Zone II and nearly 30–35% higher in Zone V. This occurs because the reduction in stiffness above the setback weakens the global resistance, allowing larger roof sway even though the total mass is slightly lower.
2) Storey Drift: RF records slightly higher inter-storey drift than VSSF across all seismic zones, with differences of about 5–10%. This trend is due to two factors: (i) stiffness concentration at the setback level in VSSF restricts relative inter-storey movement, and (ii) the reduced seismic mass of VSSF generates lower inertia forces compared to RF.
3) Storey Shear: Maximum storey shear occurs at the base in both frames, but RF consistently registers 8–12% higher base shear than VSSF. This is primarily because VSSF has a smaller seismic mass, leading to reduced inertial force demand, whereas RF, having larger mass and uniform stiffness, develops greater shear at the base.
4) Overall Observations: VSSF exhibits higher roof displacement due to stiffness irregularity at the setback. RF records higher drift and base shear, as its larger seismic mass and uniform flexibility produce greater inertial forces. Geometric differences (non-equivalent areas) between RF and VSSF models play a key role: the reduced mass in VSSF contributes to lower drift and shear, despite its larger overall sway.

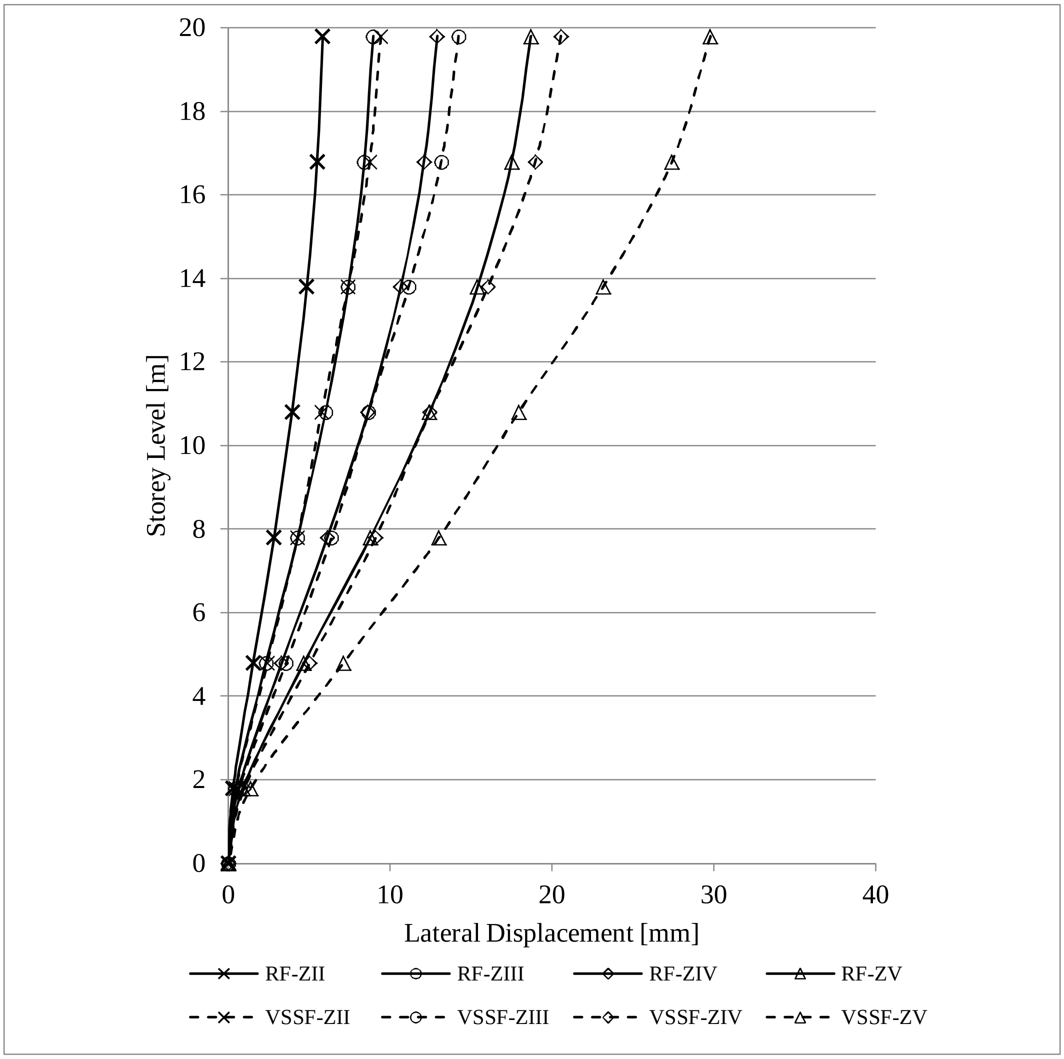

Fig. 4.7 Lateral Displacement Response of Regular (RF) and Vertical Single Setback (VSSF) frames under Seismic Loads

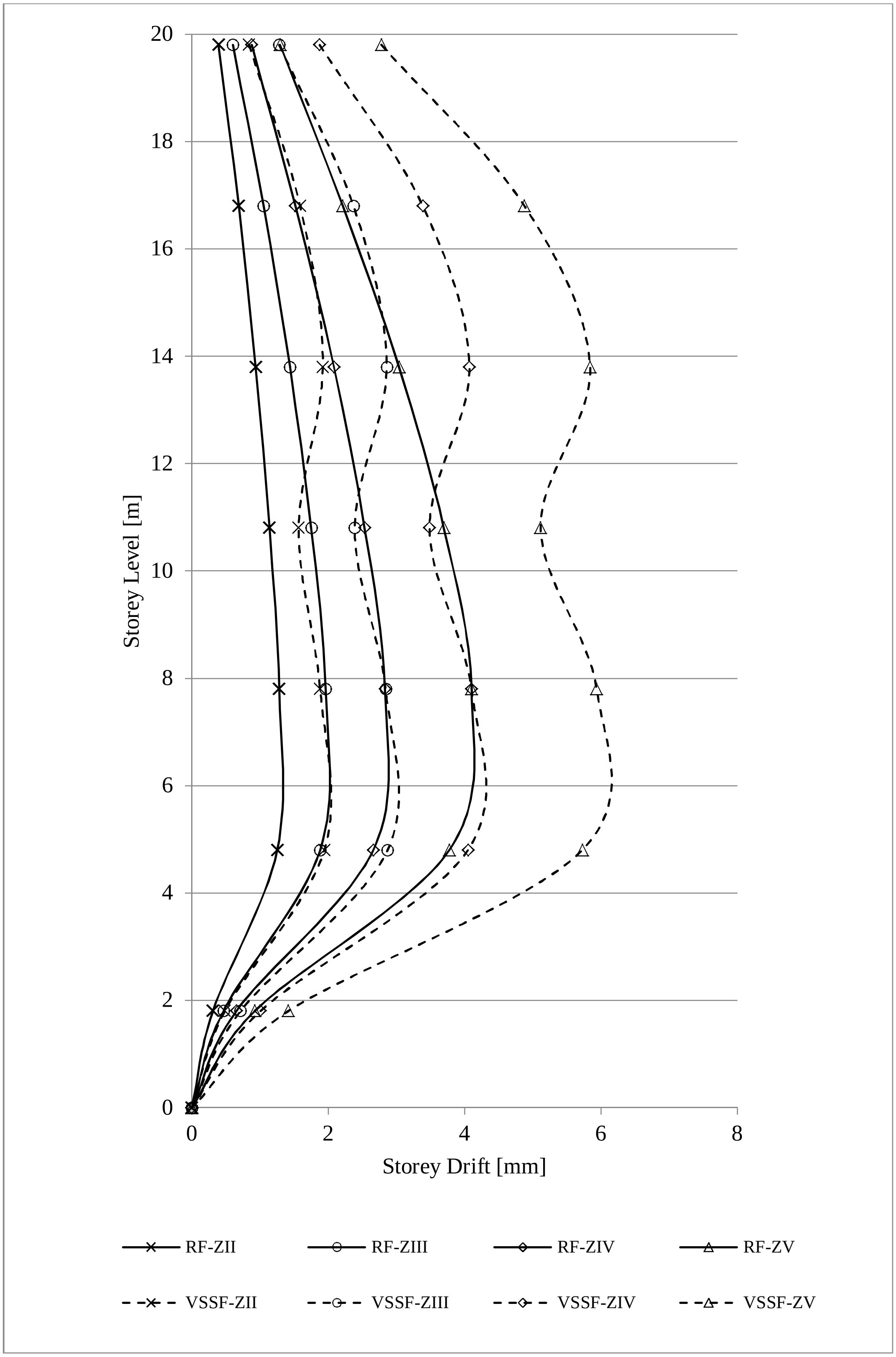

Fig. 4.8 Storey Drift Response of Regular (RF) and Vertical Single Setback (VSSF) frames under Seismic Loads

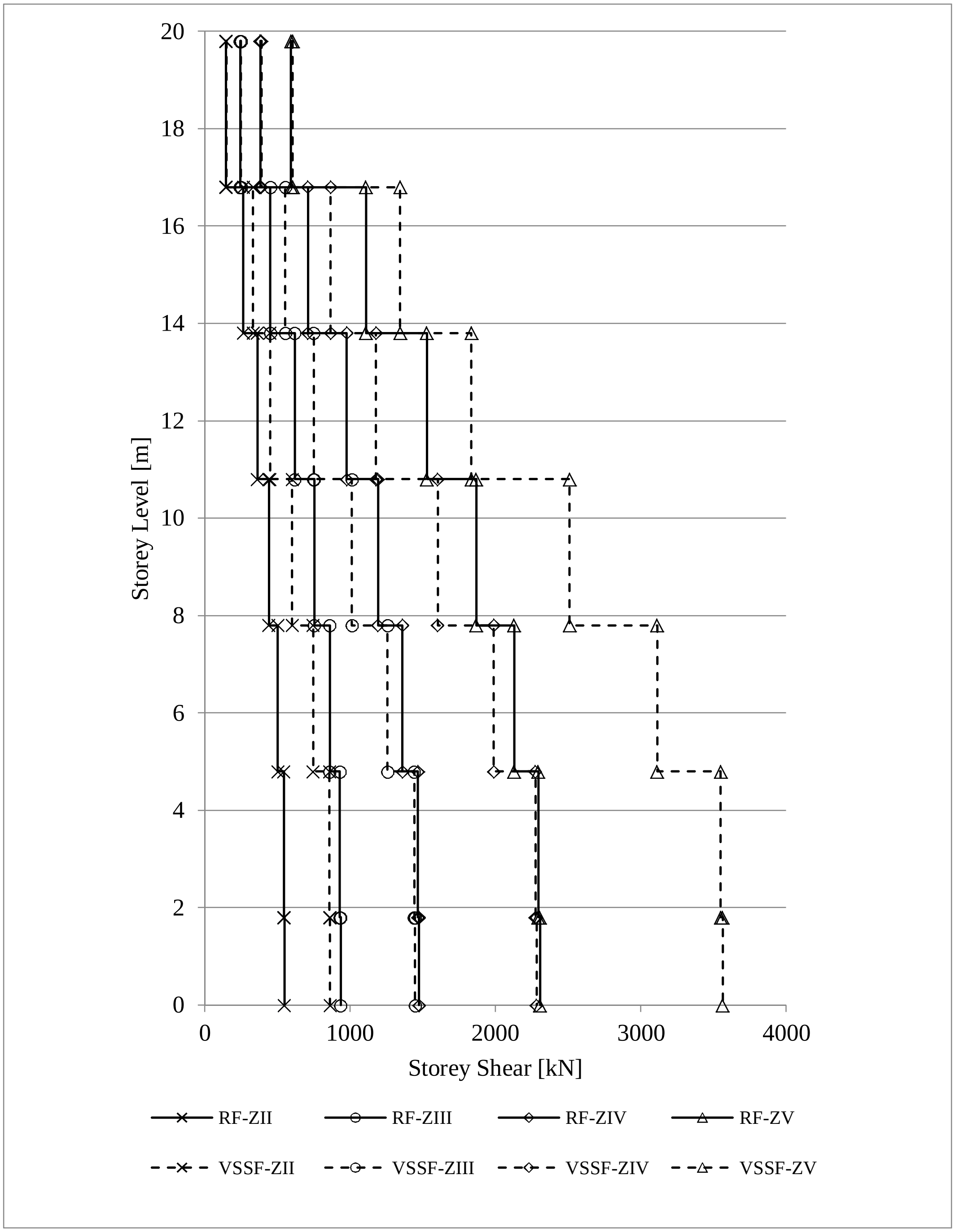

Fig. 4.9 Storey Shear Response of Regular (RF) and Vertical Single Setback (VSSF) frames under Seismic Loads

V. CONCLUSIONS

The seismic response of Regular Frame (RF) and Vertical Single Setback Frame (VSSF) buildings was studied using the Response Spectrum Method across all seismic zones of India. The major conclusions are:

1) Structural responses increase consistently with seismic zone severity; values in Zone V are approximately 2.5–3 times higher than in Zone II, confirming the significant influence of seismic zoning.
2) VSSF exhibits 30–35% higher roof displacement than RF in Zone V due to stiffness discontinuity above the setback, which reduces global resistance and amplifies sway.
3) RF records 5–10% higher storey drift compared to VSSF, as the uniform mass and flexibility of RF generate larger inter-storey deformations, whereas the reduced seismic mass of VSSF limits inertia forces despite its geometric irregularity.

4) Base shear is consistently higher in RF (by about 8–12%) compared to VSSF, primarily because the larger seismic mass in RF produces greater inertial forces, while VSSF, with reduced effective mass, transfers comparatively lower shear to the foundation.
5) VSSF is vulnerable to excessive roof displacements from stiffness irregularity, but its lower mass results in comparatively reduced drift and shear.
6) The non-equivalent areas and mass reduction in VSSF play a critical role in explaining these trends, and must be considered while interpreting the results.

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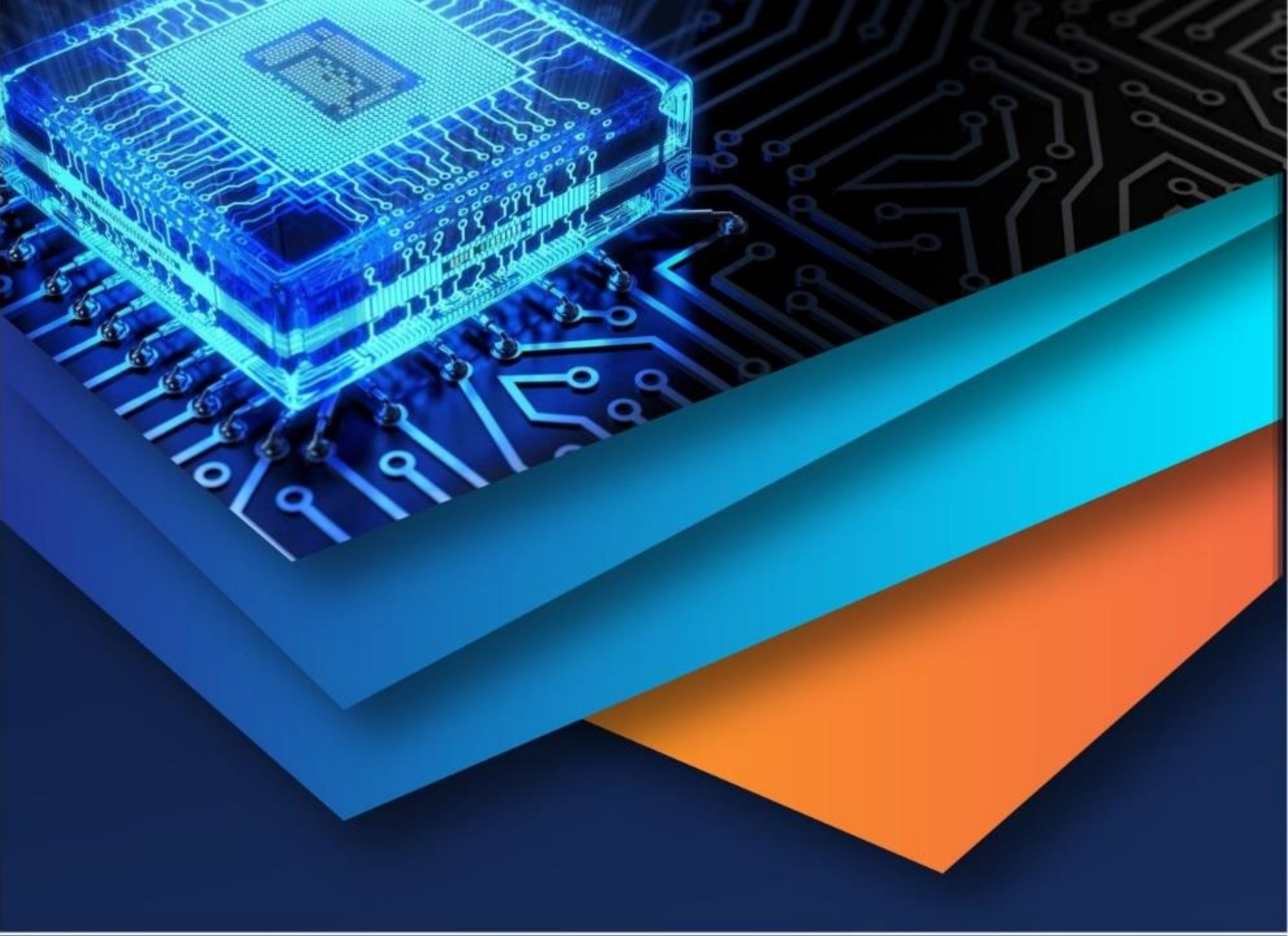

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