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Dynamic Performance of Stiffness Irregular RC Framed Structures against Seismic Loads

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Abstract: Stiffness irregularities are among the most critical factors affecting the seismic performance of reinforced concrete (RC) framed buildings. Abrupt reductions in stiffness—caused by weak storeys or sudden loss of lateral resistance—distort the uniform distribution of seismic forces along the building height. This results in concentration of stresses, localized deformations, and a significant increase in inter-storey drift, often leading to soft-storey failures. In contrast, regular buildings with uniform stiffness demonstrate more predictable dynamic behaviour.

The present study investigates the seismic response of RC framed buildings with stiffness irregularities and compares their performance with that of regular frames. A six-storey (G+5) RC frame is modelled and analysed using the Response Spectrum Method (RSM) in compliance with IS 1893 (Part 1): 2016, implemented through ETABS software. Key seismic response parameters—lateral displacement, storey drift, base shear, and fundamental time period—are evaluated across different seismic zones of India.

The results highlight that stiffness irregularities intensify inter-storey drift and shear concentration at specific levels, particularly in soft-storey and partially infilled configurations. These findings emphasize the necessity of accounting for stiffness discontinuities in seismic design to avoid premature failures and to ensure compliance with codal safety requirements.

I. INTRODUCTION

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.

A. Classification 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.
3)

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B. 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.

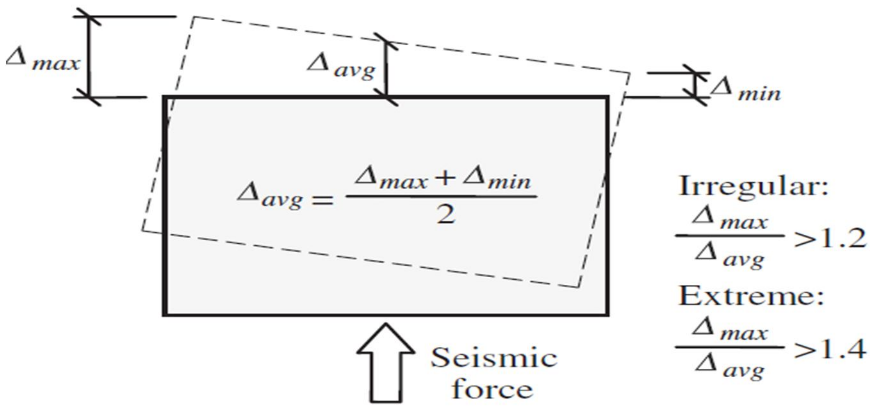

Fig. 1.1 Torsional irregularity

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.

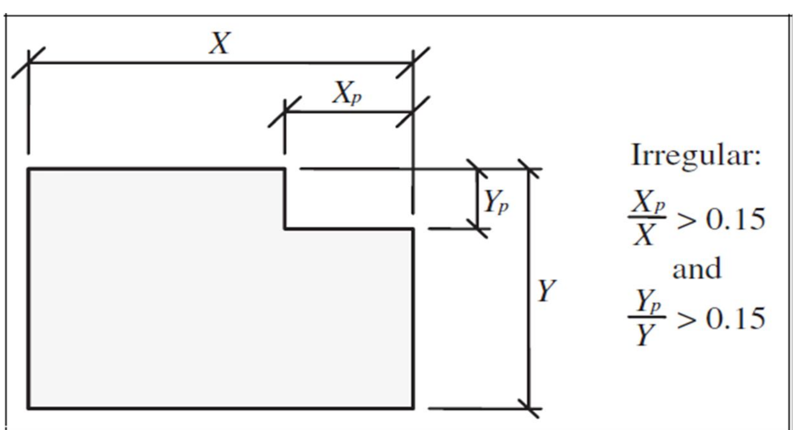

Fig. 1.2 Re-entrant irregularity

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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.

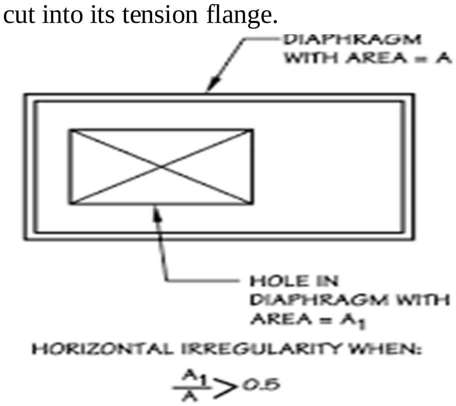

Fig. 1.3 Diaphragm Discontinuity

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.

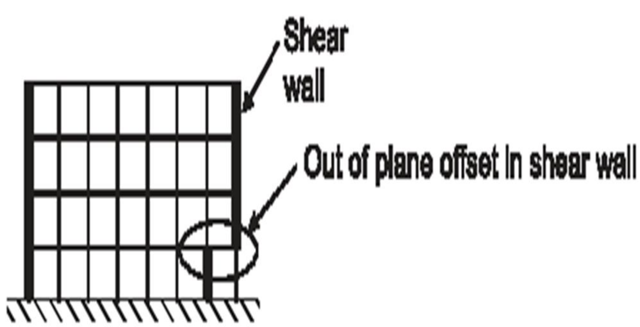

Fig. 1.4 Out of plane Offset Irregularity

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.

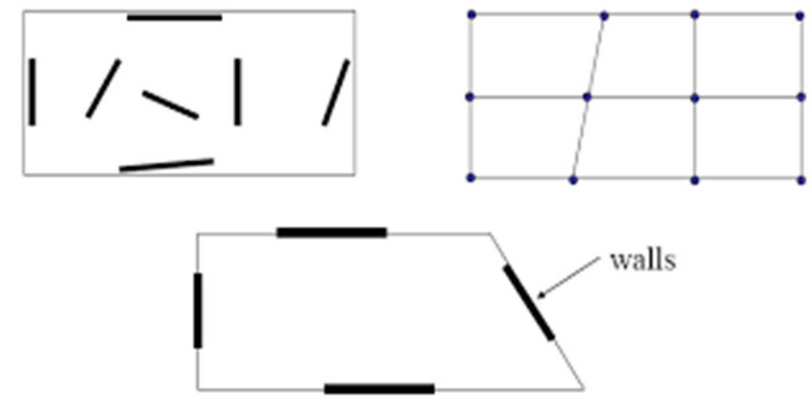

Fig. 1.5 Non-Parallel System Irregularity

C. 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.

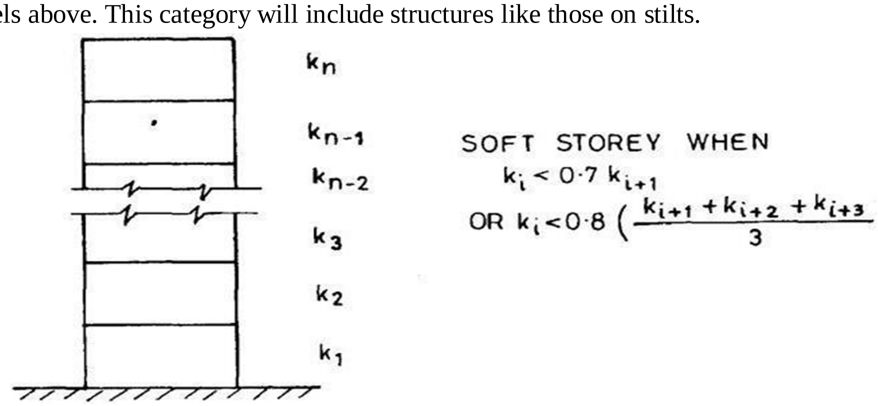

Fig. 1.6 Stiffness Irregularity

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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

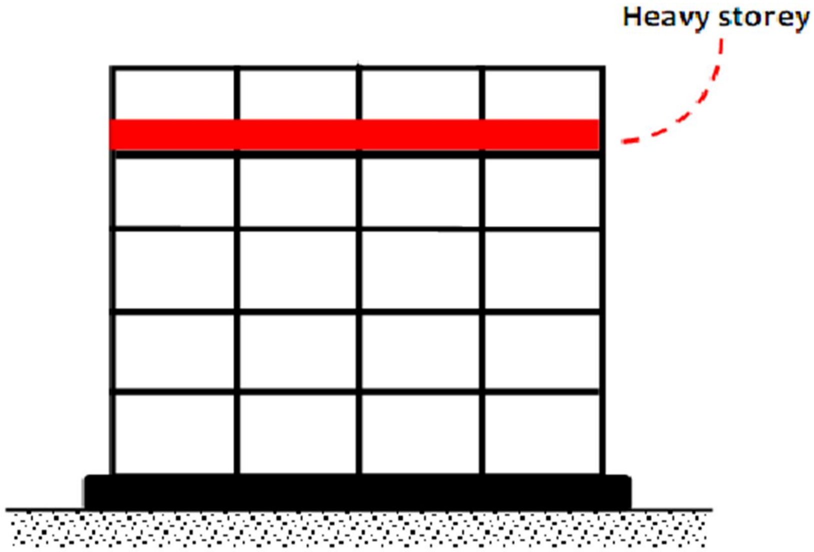

Fig. 1.7 Mass Irregularity

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."

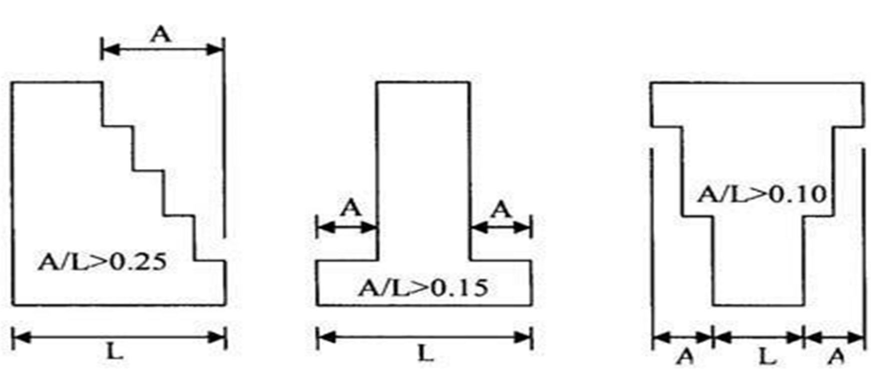

Fig. 1.8 Vertical Geometrical Irregularity

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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)

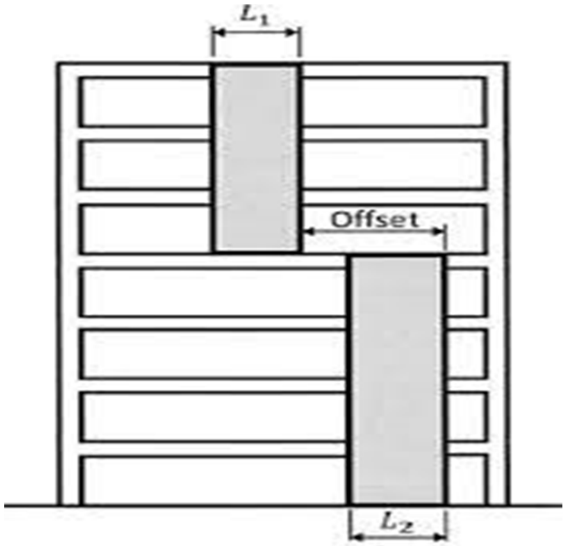

Fig. 1.9 In plane Discontinuity Irregularity

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

i) 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.

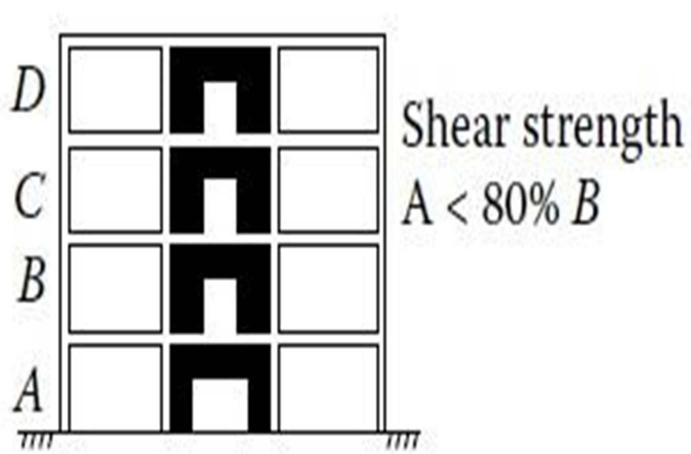

Fig.1.10 Discontinuity in Lateral Strength weak storey Irregularity

ii) 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.

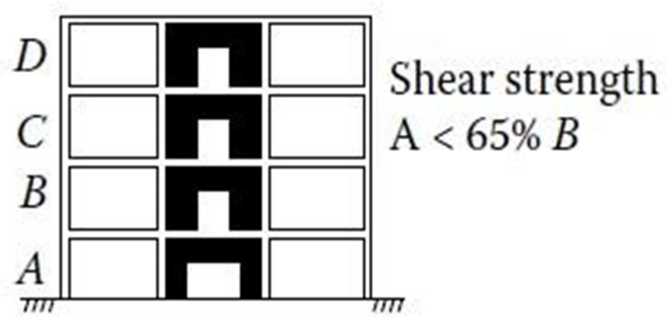

Fig. 1.11 Discontinuity in Lateral Strength Extreme weak storey Irregularity

D. *Objectives Of The Study*

Understanding the effect of stiffness irregularities on the seismic performance of RC framed buildings is essential for ensuring safety and stability. When abrupt changes in stiffness occur due to weak storeys, or sudden reductions in lateral resistance, the distribution of seismic forces across the height of the building becomes highly non-uniform. This leads to concentration of stresses and localized deformations, significantly altering the dynamic response compared to regular frames. In particular, stiffness irregularities intensify inter-storey drift, attract higher shear demands at critical levels, and increase the possibility of soft-storey failures.

Therefore, the present study is focused on evaluating and comparing the seismic performance of regular and stiffness-irregular buildings under various seismic zones of India, considering critical response parameters such as lateral displacement, storey drift, and base shear.

The following are the objectives of the study:

1) To model and analyze stiffness irregular RC framed buildings with varying stiffness configurations using ETABS software.
2) To evaluate seismic response parameters such as base shear, story displacement, story drift, and fundamental time period.
3) To compare the dynamic performance of stiffness irregular buildings with that of regular (uniform stiffness) buildings under similar loading conditions.

E. *Scope Of The Study*

1) The study is limited to G + 5 Storied RC framed buildings as per IS 1893 (Part 1): 2016 provisions.
2) Both regular and stiffness irregular building models will be considered for comparative analysis.
3) The seismic performance will be evaluated under linear dynamic analysis (Response Spectrum Method) using ETABS.
4) The study will focus on soft-story and partially infilled configurations to represent common real-world stiffness irregularities.

F. *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. Overview

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. Previous Studies

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 analysed 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

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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

Studies consistently show that stiffness irregularities, such as soft storey or weak storey effects, amplify seismic demands by increasing lateral displacement, storey drift, and torsional response. Despite recognition in IS 1893:2016, specific guidelines for quantifying and mitigating stiffness irregularities are limited. Since these irregularities are common in high-rise and open ground storey buildings, there is a strong need to analyse their seismic behaviour in detail. Therefore, the present study emphasizes the impact of stiffness irregularities on structural performance, focusing on response parameters like base shear, drift, and displacements to support safer design strategies.

III. METHODOLOGY

A. Introduction

The methodology adopted in this study is designed to evaluate the seismic performance of reinforced concrete (RC) framed buildings with and without stiffness irregularities. 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.

B. 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 stiffness irregular RC framed building (SIF). 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 stiffness irregularities influence the dynamic performance of RC framed buildings under varying seismic intensities.

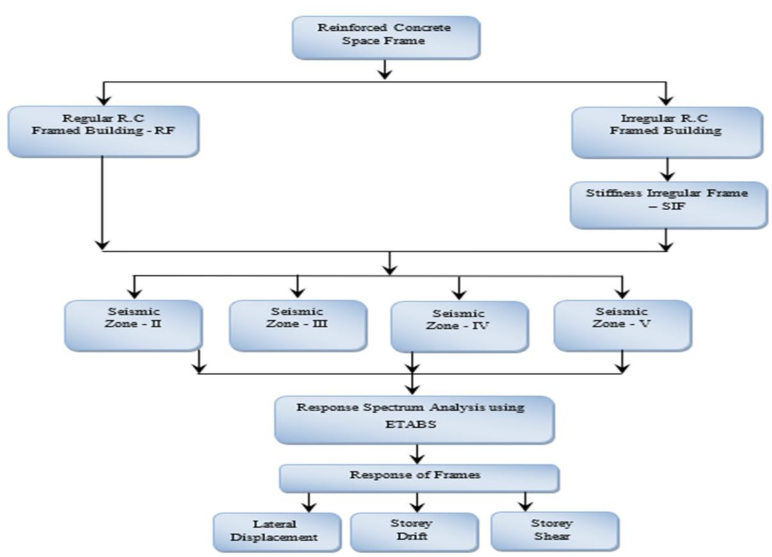

Fig. 3.1 Methodology Flow Chart

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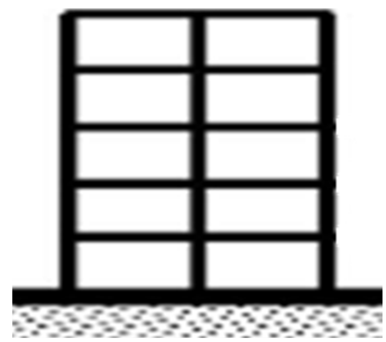
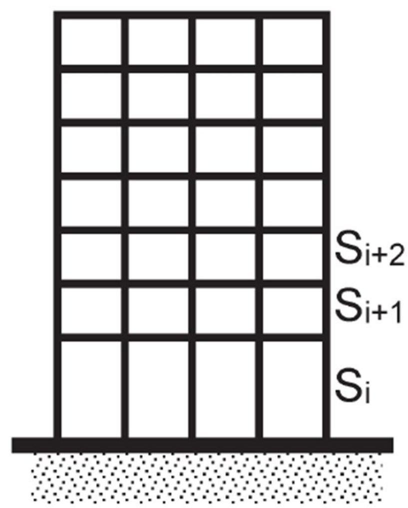
C. Case Studies

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 Stiffness Irregular Frame (SIF). 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	SIF – ZII	Stiffness Irregular Frame – Seismic Zone II	
6	SIF – ZIII	Stiffness Irregular Frame – Seismic Zone III	
7	SIF – ZIV	Stiffness Irregular Frame – Seismic Zone IV	
8	SIF – ZV	Stiffness Irregular Frame – Seismic Zone V	

D. 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.	Storey Height	4.4m – Stilt Floor 3.6m – Ground & 1st Floor 3.0m – 2nd,3rd & 4th Floor
3.	Super Structure Height	20.6 m
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

E. 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

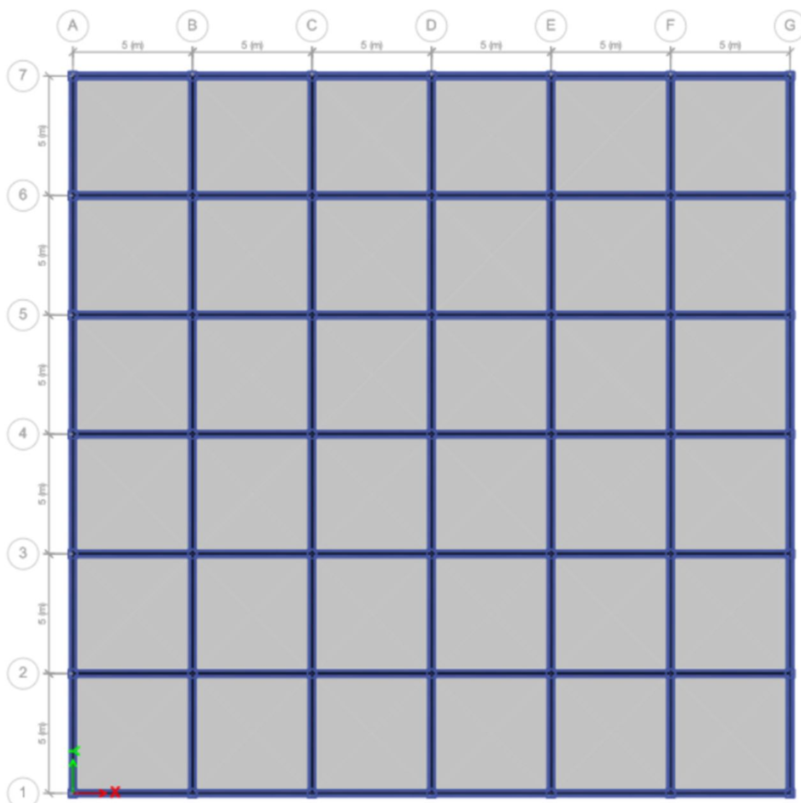

Fig. 3.2 (a) Plan of RF

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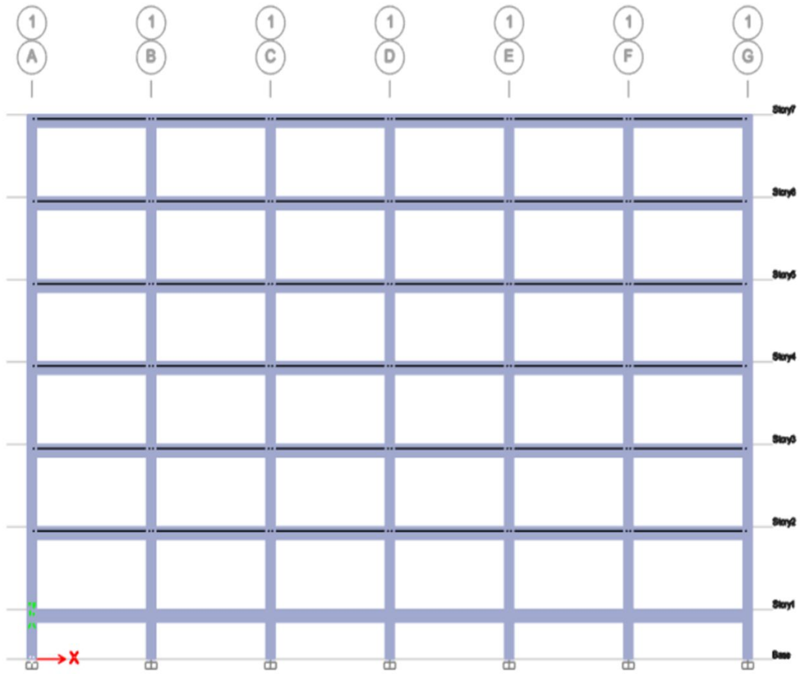

Fig. 3.2 (b) Elevation of RF

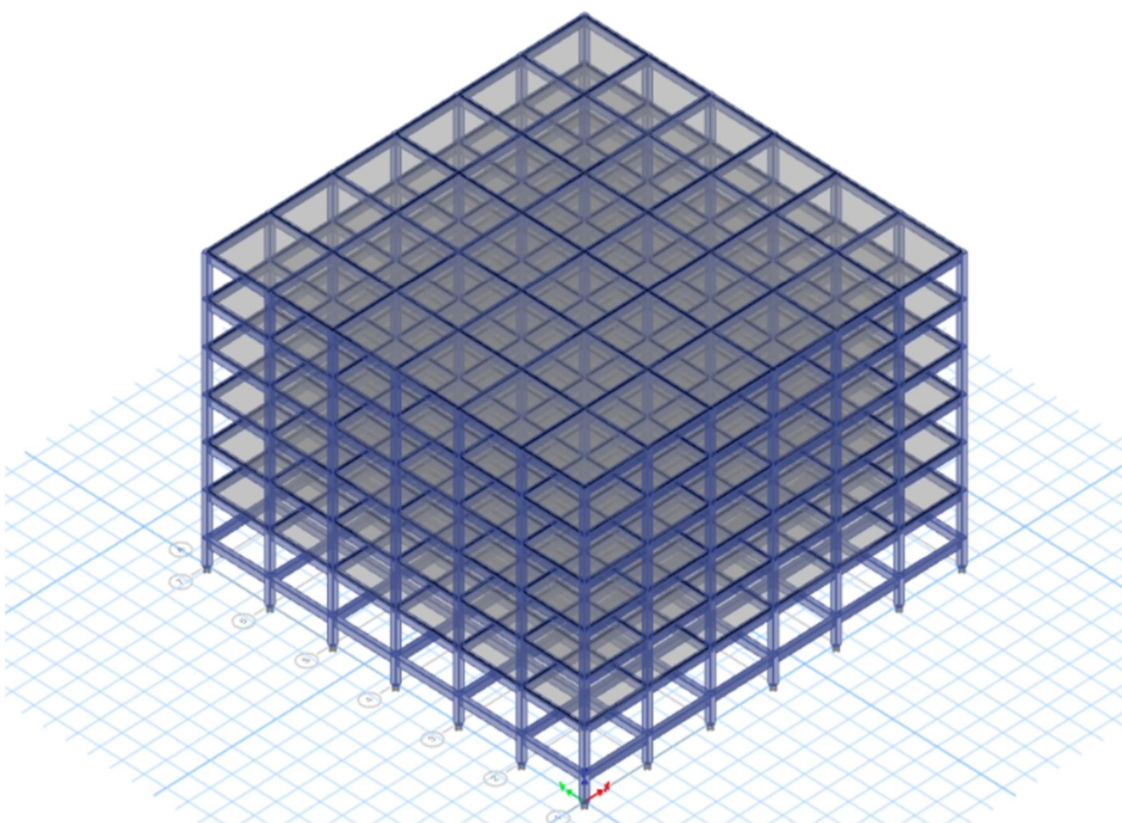

Fig. 3.2 (c) Isometric View of RF

Fig. 3.2 Geometric Views of Regular Frame - RF

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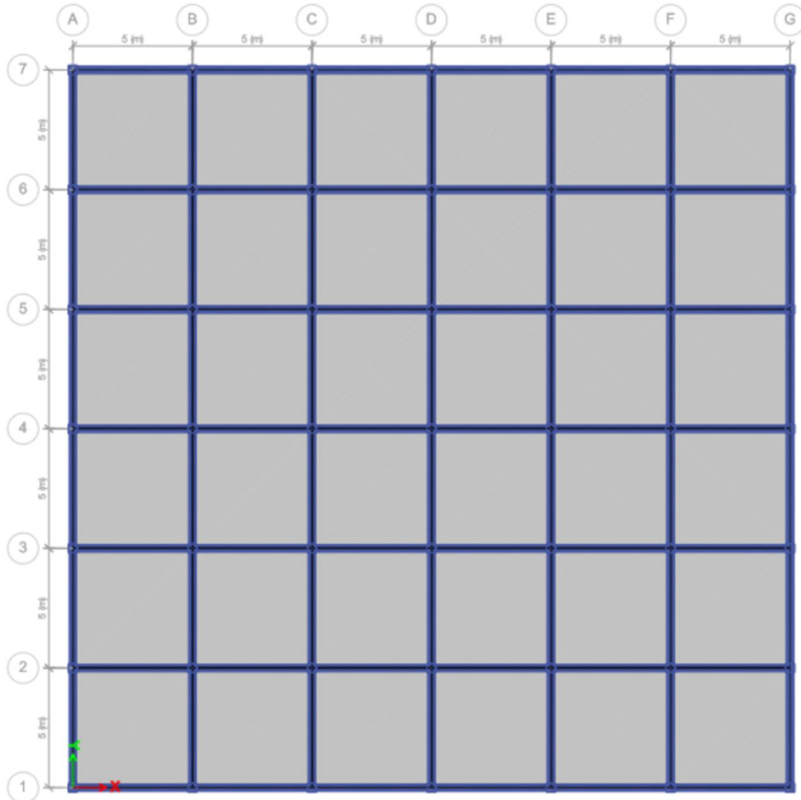

Fig. 3.3 (a) Plan of SIF

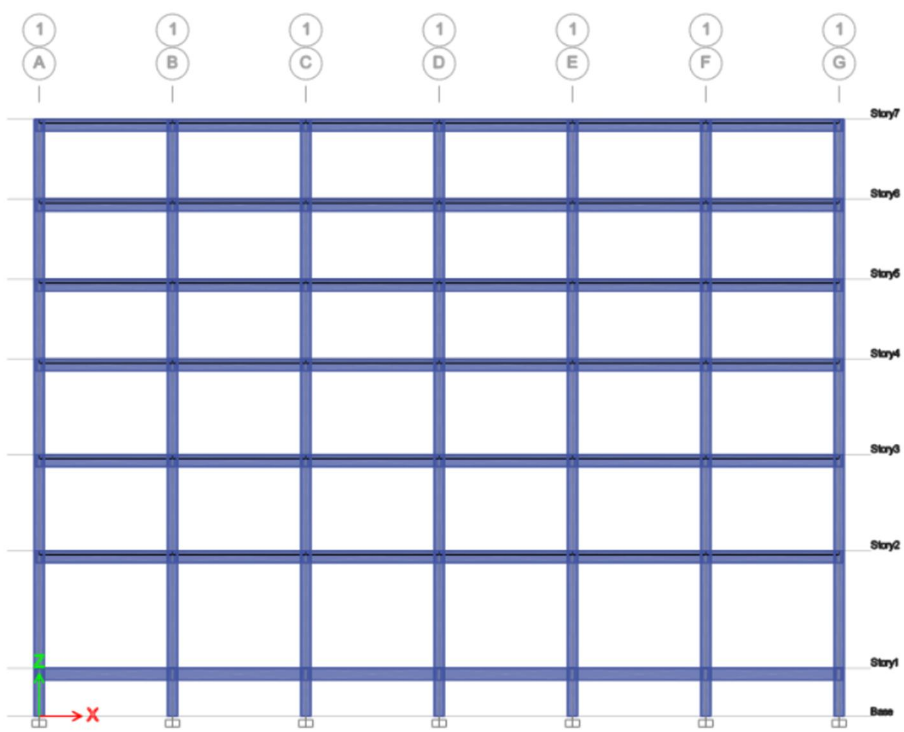

Fig. 3.3 (b) Elevation of SIF

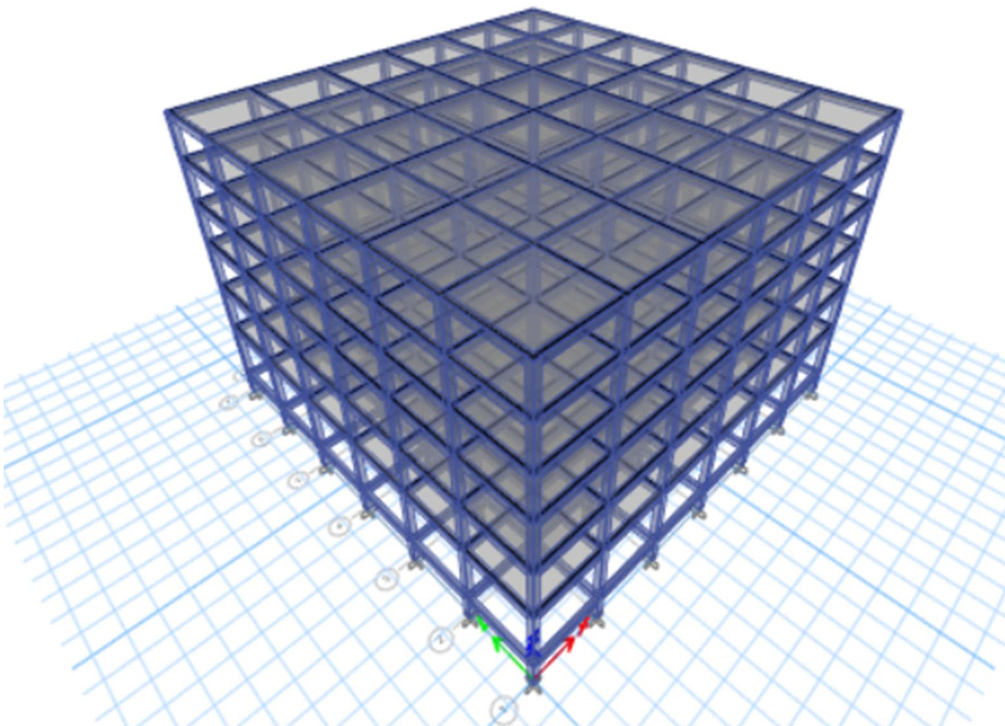

Fig. 3.3 (c) Isometric View of SIF

Fig. 3.3 Geometric Views of Stiffness Irregular Frame - SIF

F. 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

G. 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) Stiffness Irregular Frame (SIF) is evaluated and compared with a Regular Frame (RF). The stiffness irregularity in the considered model is introduced through variation in storey heights: the stilt floor is 4.4 m, the ground and first floors are 3.6 m each, while the remaining upper floors (2nd, 3rd, and 4th) are 3.0 m. This non-uniform storey height distribution creates stiffness discontinuities along the vertical direction, which disrupt the uniform transfer of seismic forces. The analysis is performed using the Response Spectrum Method (RSM) in ETABS, as per IS 1893 (Part 1) – 2016. Seismic Zones II to V are considered to capture the influence of increasing seismic intensity. The critical response parameters—lateral displacement, storey drift, and storey shear—are extracted and presented graphically for interpretation. The comparative study between RF and SIF reveals that the variation in storey stiffness leads to larger lateral displacements, sudden peaks in storey drift at transition floors, and irregular distribution of storey shear. These effects become more pronounced with higher seismic zone factors, underlining the importance of carefully addressing stiffness irregularities in design to ensure seismic safety.

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.

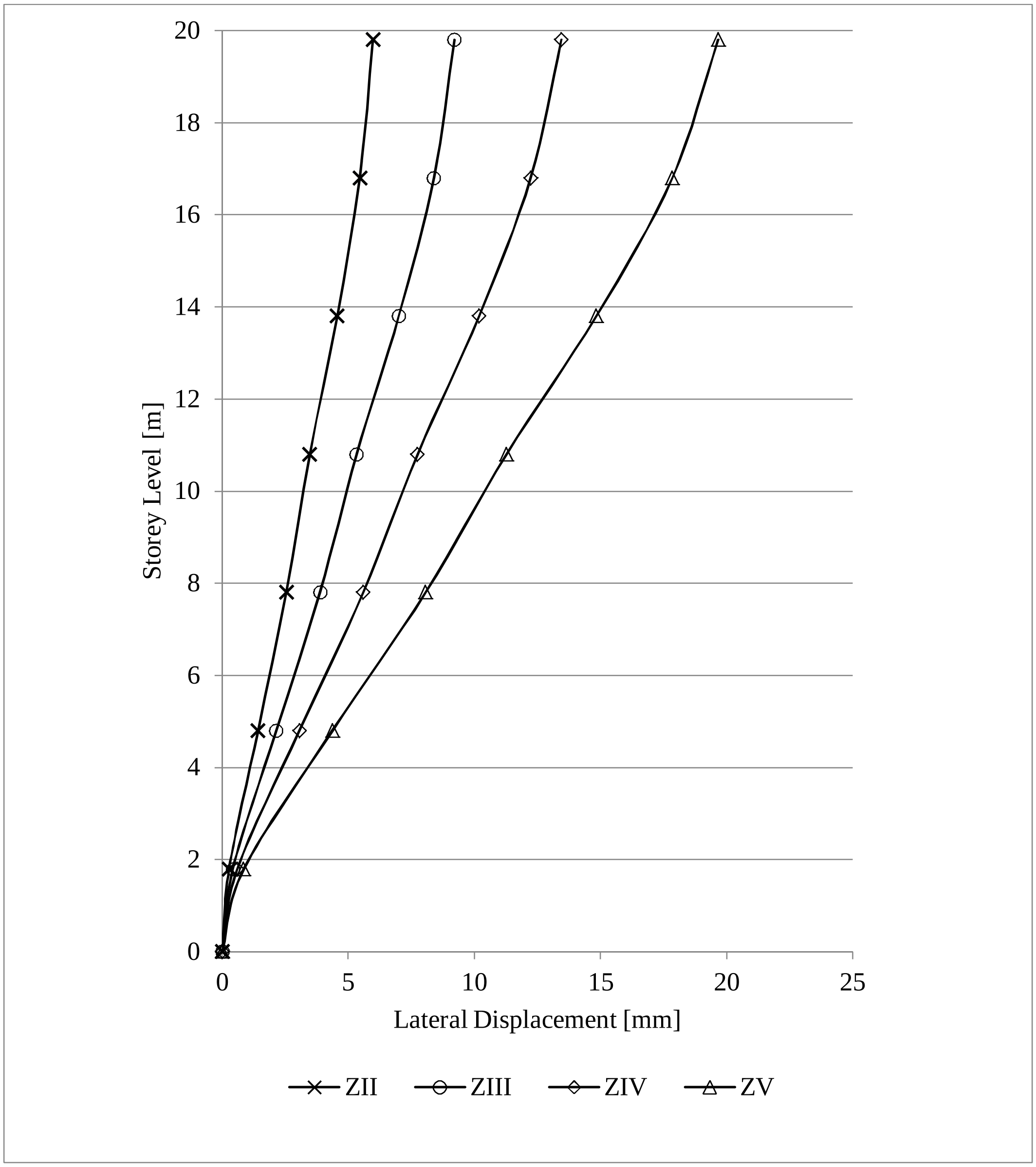

Fig. 4.1 Seismic Response (Lateral Displacement) of Regular Frame – RF at all Seismic Zones in India

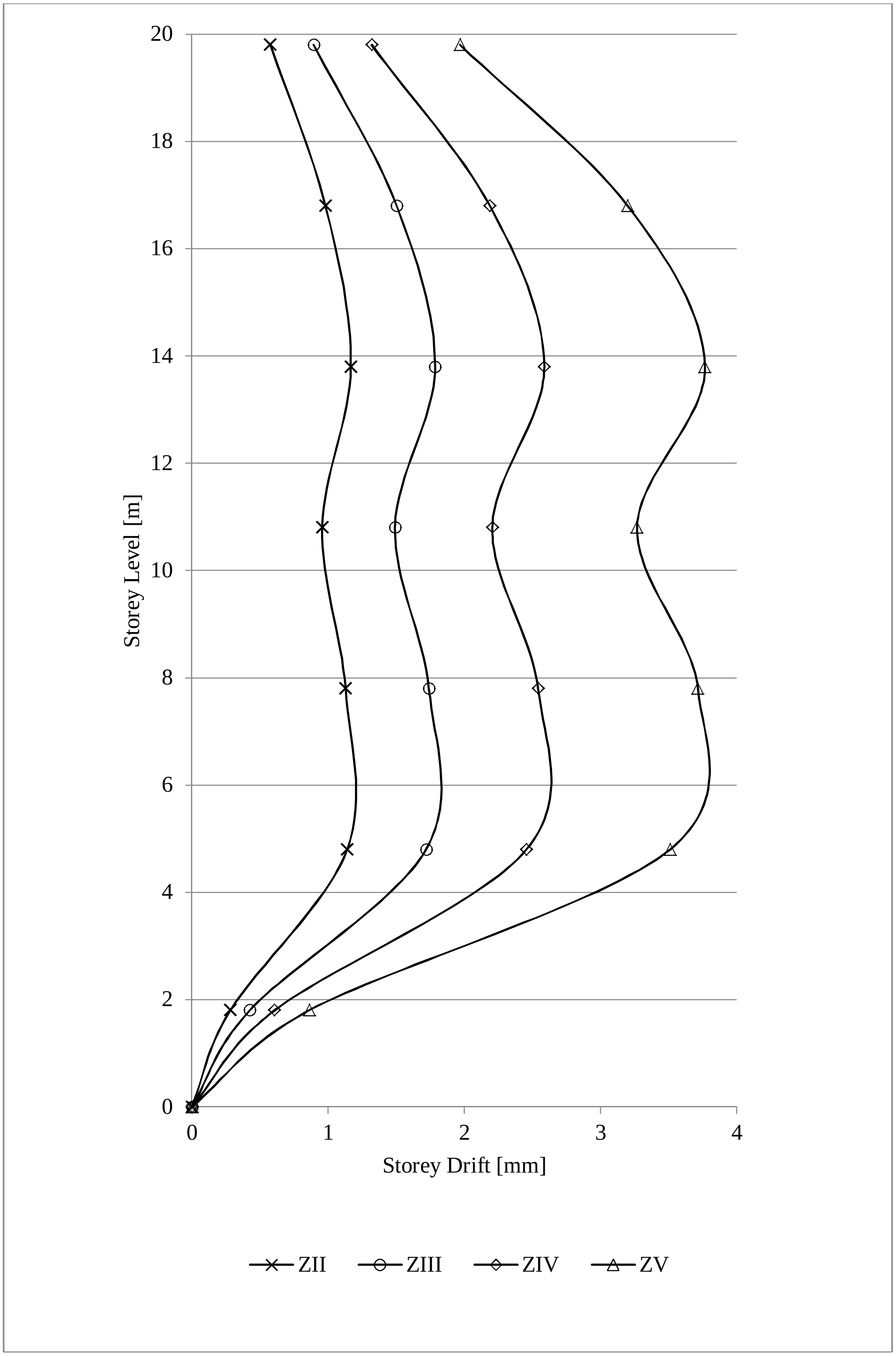

Fig. 4.2 Seismic Response (Storey Drift) of Regular Frame – RF at all Seismic Zones in India

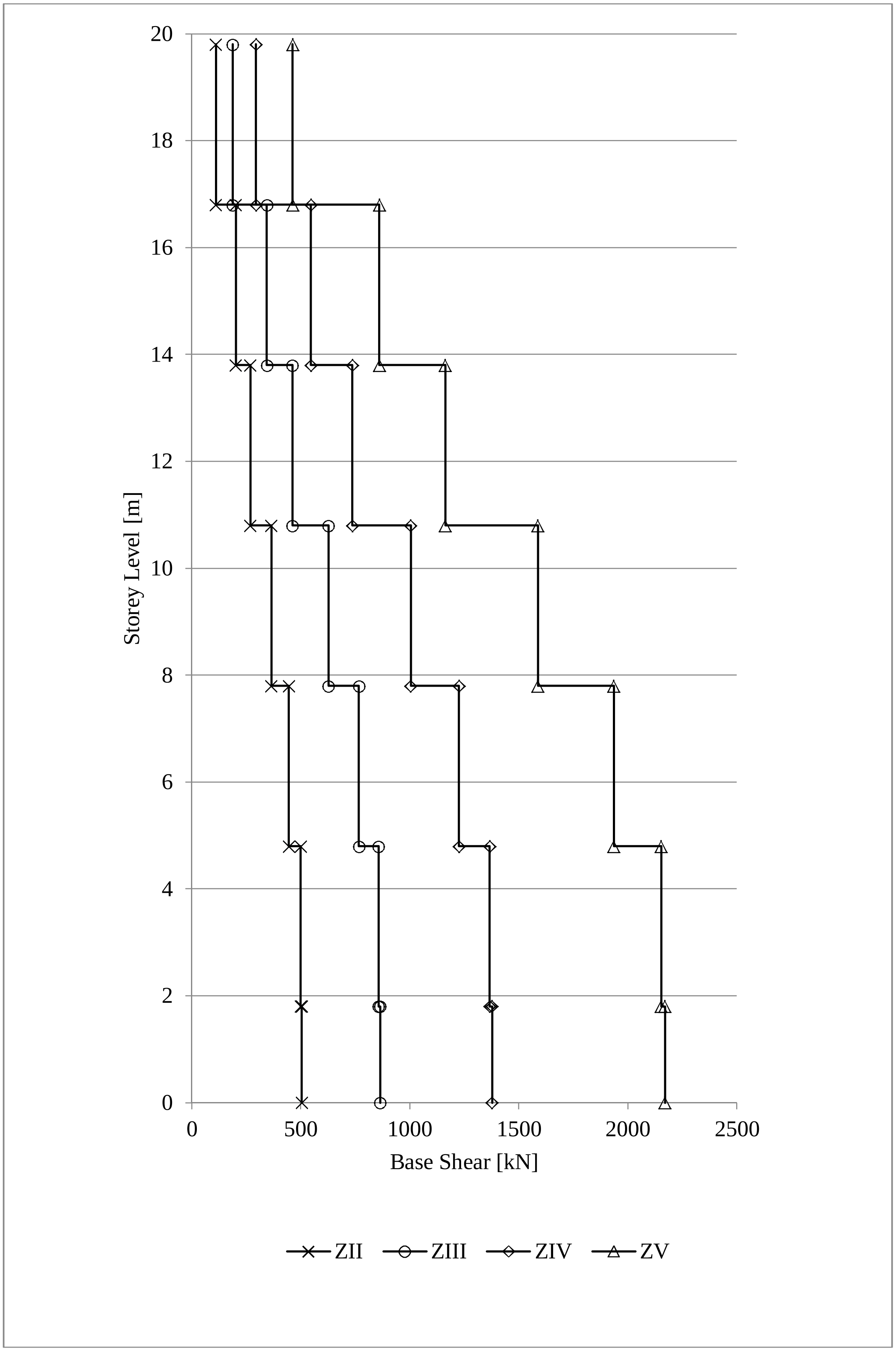

Fig. 4.3 Seismic Response (Storey Shear) of Regular Frame – RF at all Seismic Zones in India

B. Seismic Response Of Stiffness Irregular Frame– SIF

The seismic performance of the Stiffness Irregular Frame (SIF) has been evaluated for seismic Zones II–V. The analysis considers lateral displacement, storey drift, and storey shear, with results presented in Figures 4.4–4.6.

1) Lateral Displacement: The displacement profiles (Fig. 4.4) reveal that lateral displacement increases gradually with height, reaching a maximum at the roof in all seismic zones.
   - Zone II records the lowest displacement, while Zone V exhibits the highest, with roof displacement nearly 3 times that of Zone II.
   - The incremental increase is about 45–55% between Zone II and III, 60–70% from Zone III to IV, and nearly 90–100% from Zone IV to V.
   - Compared to RF, the discontinuity in stiffness makes the SIF more flexible above the irregularity, producing larger displacements in upper storeys.

2) Storey Drift: The drift profiles (Fig. 4.5) show a non-uniform distribution, with peaks concentrated near the stiffness discontinuity level.
   - Drift magnitudes increase significantly with seismic intensity, amplifying nearly 2.8–3.0 times between Zone II and Zone V.
   - Average successive increments are about 30–40%.
   - The presence of sudden stiffness change leads to sharp drift concentration at specific storeys, unlike the smoother profiles in RF. This highlights the vulnerability of SIF to localised damage.

3) Storey Shear: The storey shear profiles (Fig. 4.6) show maximum values at the base, reducing along the height. However, abrupt variations are observed at and above the stiffness irregularity level.
   - Base shear increases almost 3 times between Zone II and Zone V.
   - Successive increases are approximately 35–50% across seismic zones.
   - The shear distribution is irregular above the discontinuity, reflecting force redistribution caused by the stiffness imbalance.

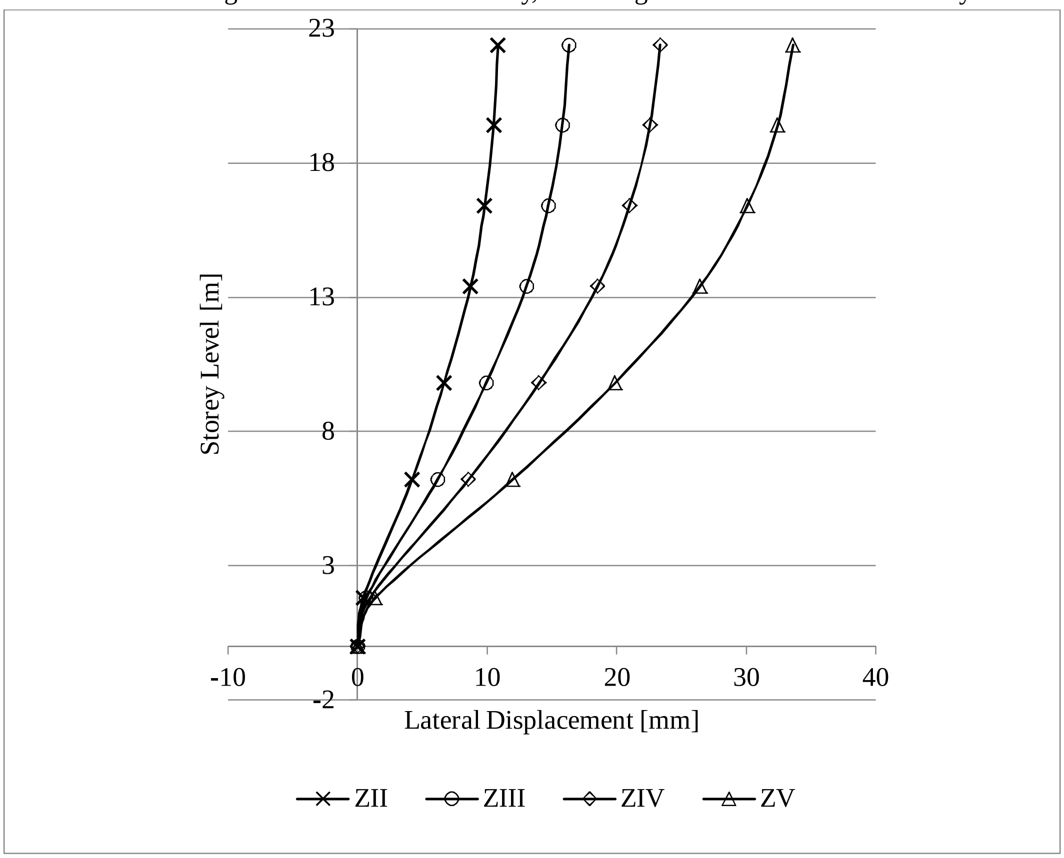

Fig. 4.4 Seismic Response (Lateral Displacement) of Stiffness Irregular Frame - SIF at all Seismic Zones in India

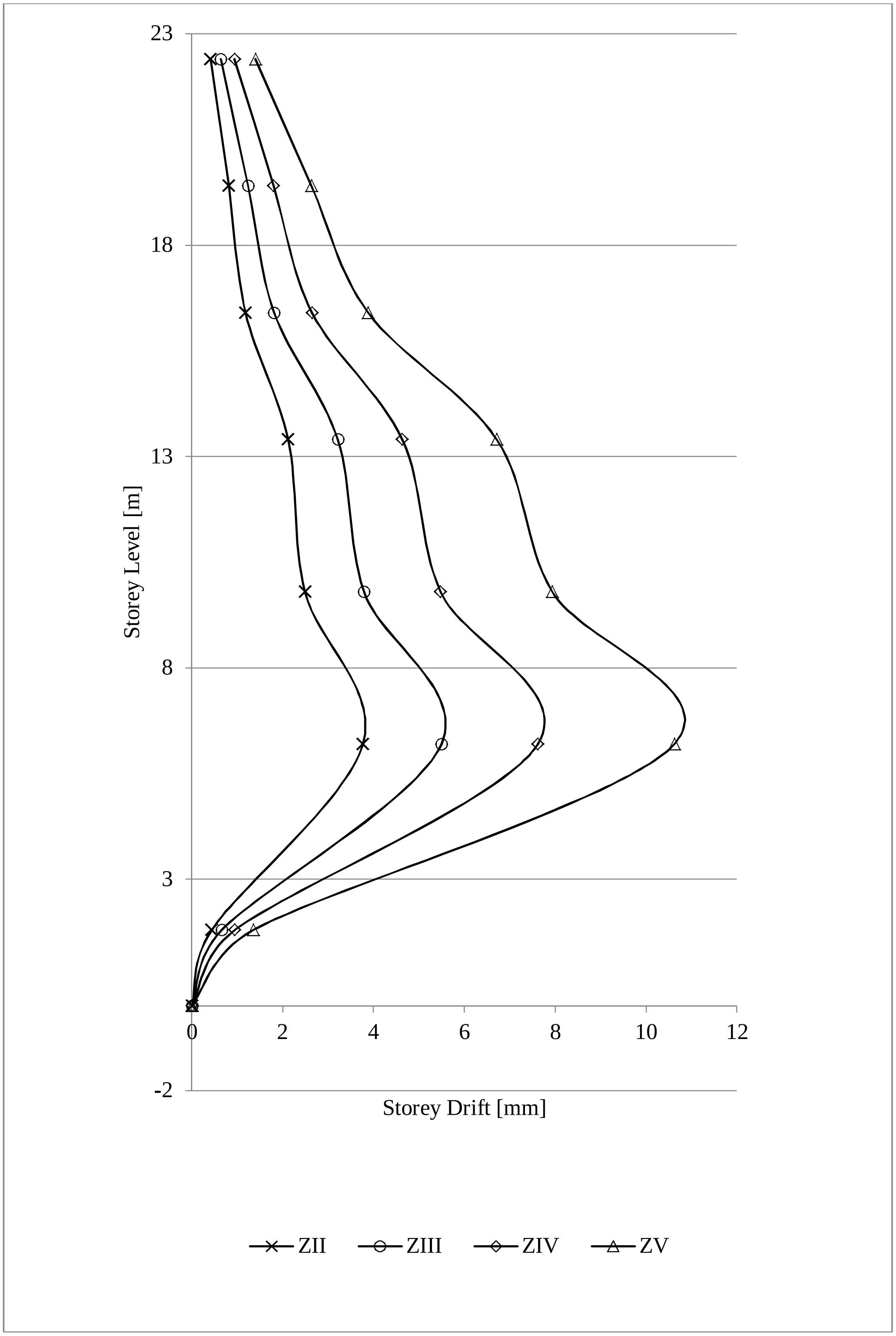

Fig. 4.5 Seismic Response (Storey Drift) of Stiffness Irregular Frame - SIF at all Seismic Zones in India

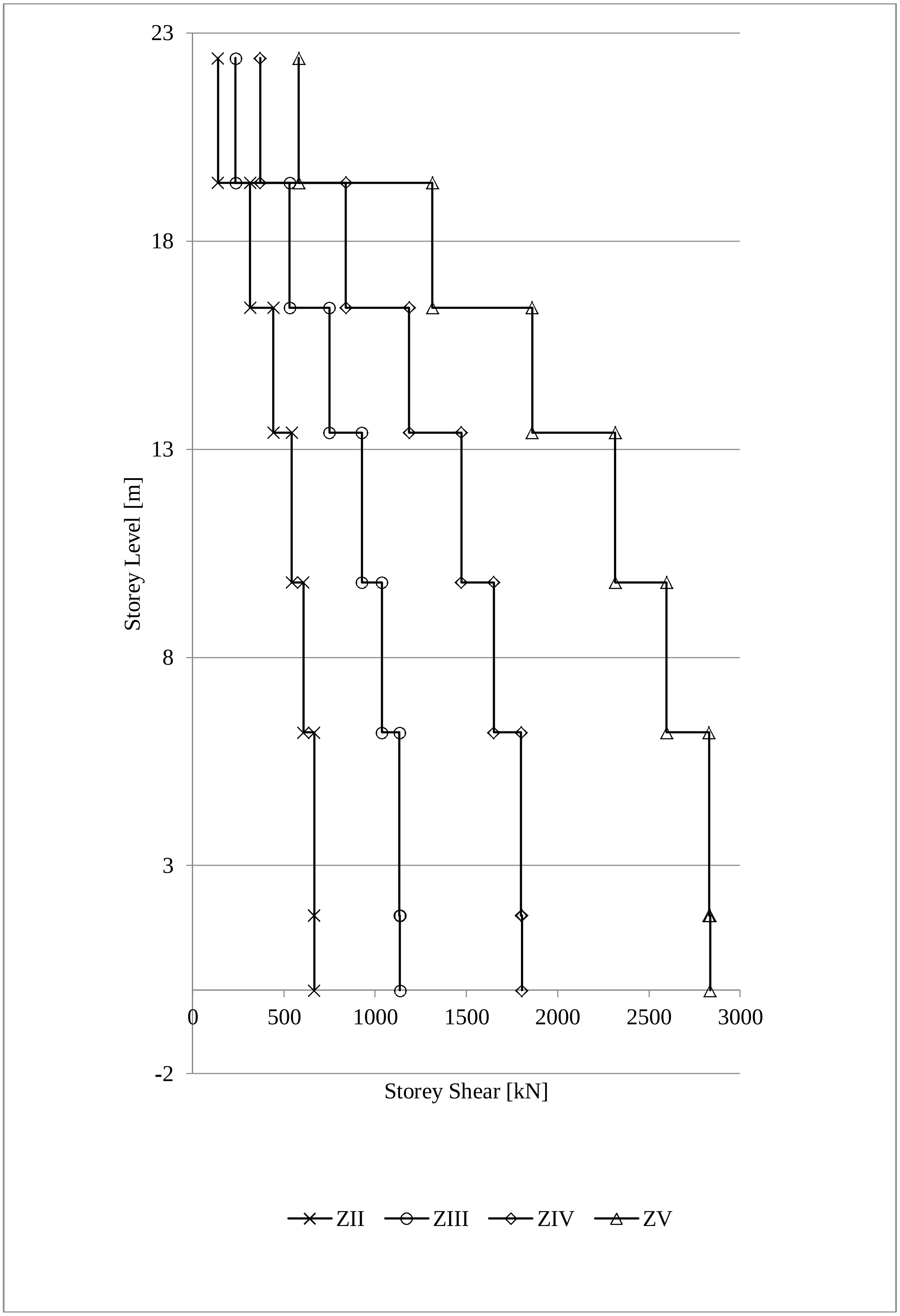

Fig. 4.6 Seismic Response (Storey Shear) of Stiffness Irregular Frame - SIF at all Seismic Zones in India

C. Seismic Response Of Regular (Rf) And Stiffness Irregular (Sif) Frames Under Seismic Loads

The seismic responses of the Regular Frame (RF) and the Stiffness Irregular Frame (SIF) are compared across seismic Zones II–V. The results are analyzed in terms of lateral displacement, storey drift, and storey shear, as illustrated in Figures 4.7–4.9.

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1) Lateral Displacement: Both RF and SIF show progressive increase in displacement with storey height, peaking at the roof. However, SIF exhibits considerably larger displacements than RF due to stiffness discontinuity.
   - In Zone II, the difference is small, but as the seismic intensity increases, the displacement gap widens significantly.
   - By Zone V, the roof displacement of SIF is nearly 30–35% higher than RF.
   - Incremental increases across successive zones are sharper in SIF, reflecting its greater sensitivity to seismic loading.
2) Storey Drift: The drift profiles highlight distinct differences between RF and SIF.
   - RF: Shows smooth drift variation with a single peak at the mid-to-upper storeys.
   - SIF: Displays sharp peaks near the stiffness discontinuity level, leading to localised drift concentrations.
   - Across zones, drift values in SIF are 35–40% higher than RF, with Zone V showing the most pronounced variation.
   - The irregularity in stiffness makes the SIF more vulnerable to excessive inter-storey deformation.
3) Storey Shear: Both RF and SIF show maximum shear at the base, reducing gradually along the height. However, in SIF, abrupt shear fluctuations occur at and above the discontinuity level.
   - In Zone V, the base shear in SIF is approximately 20–25% higher than RF.
   - Successive increases in base shear are larger in SIF, reflecting the additional force redistribution caused by stiffness irregularity.

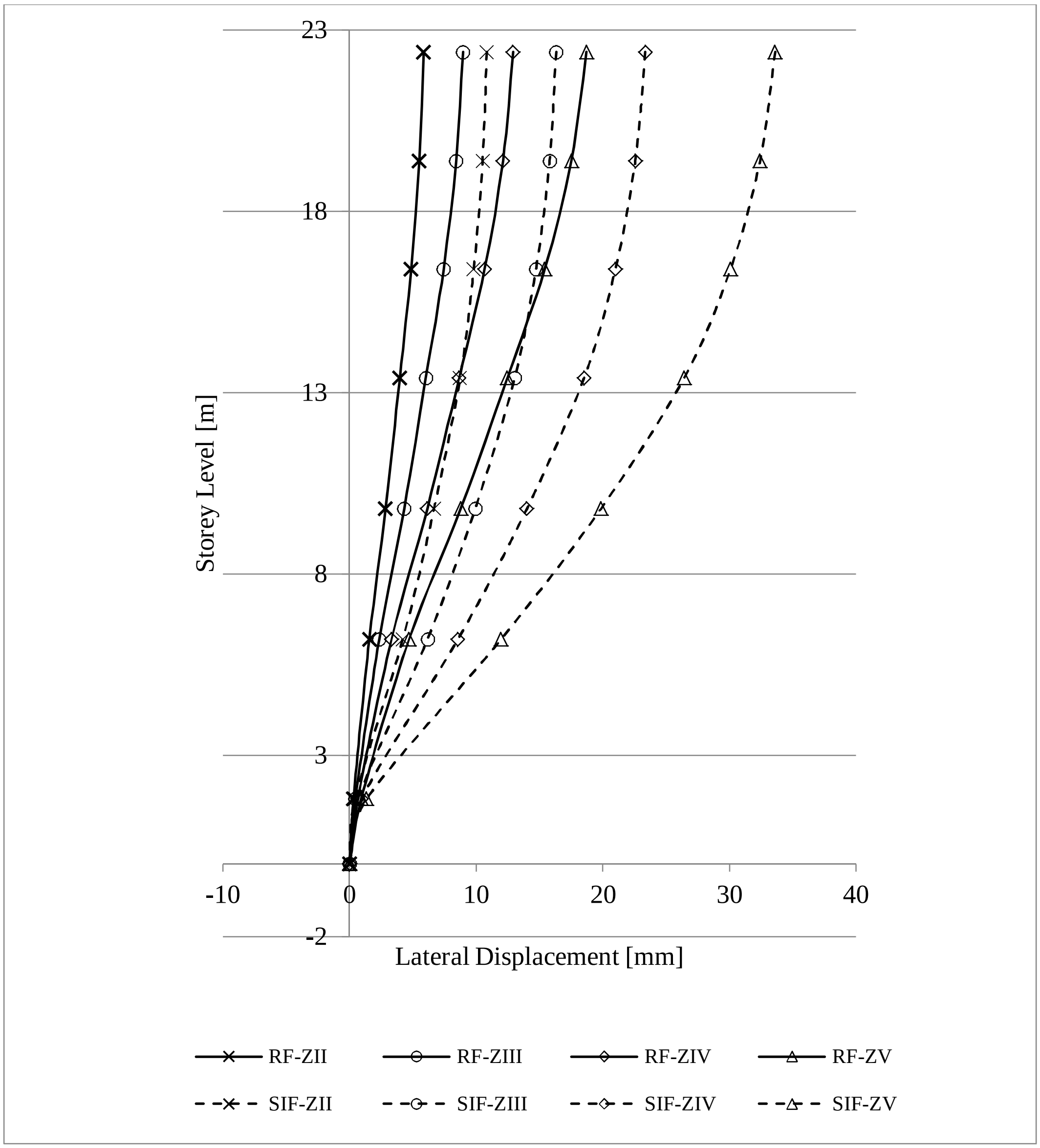

Fig. 4.7 Lateral Displacement Response of Regular (RF) and Stiffness Irregular (SIF) Frames under Seismic Loads

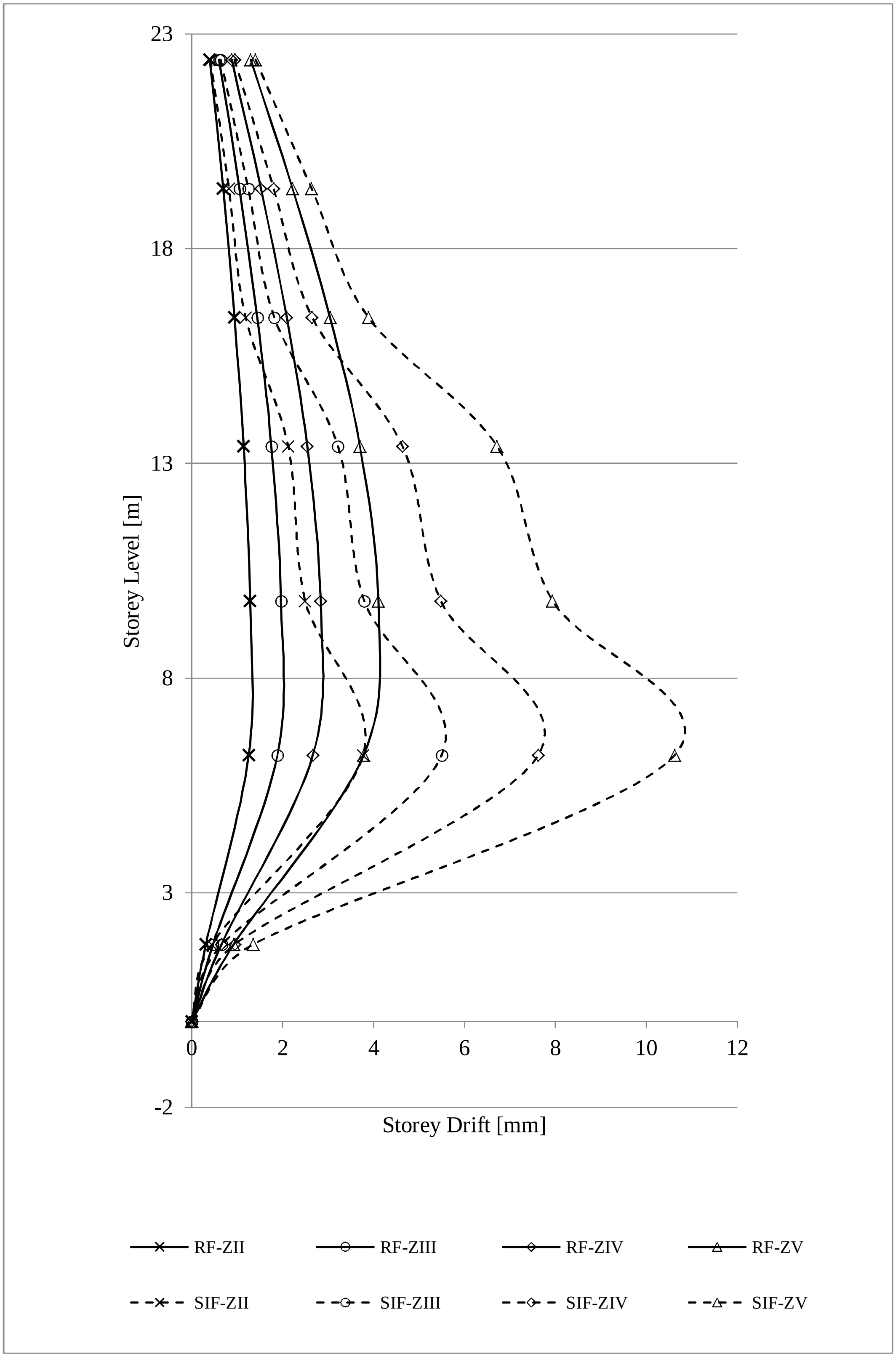

Fig. 4.8 Storey Drift Response of Regular (RF) and Stiffness Irregular (SIF) Frames under Seismic Loads

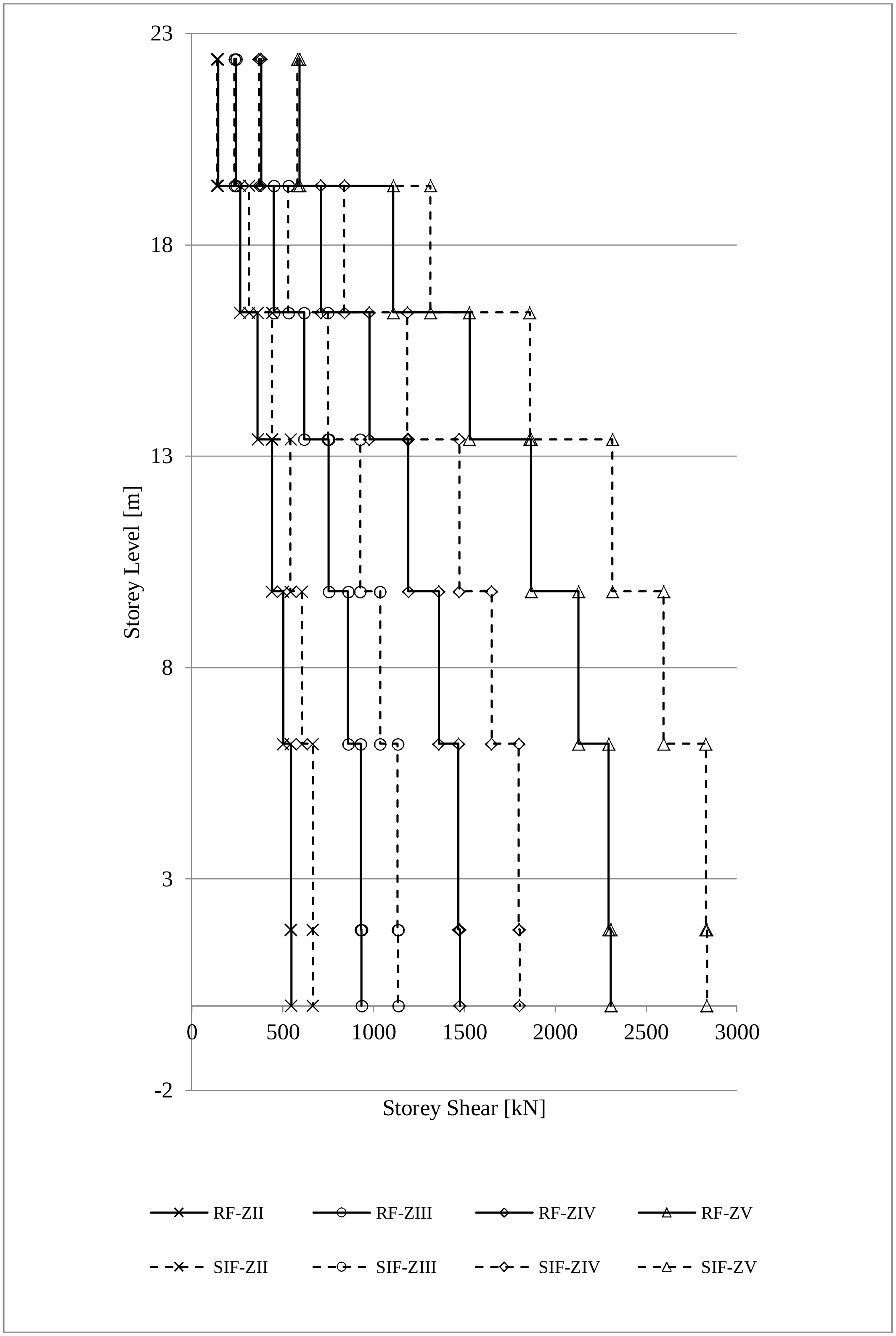

Fig. 4.9 Storey Shear Response of Regular (RF) and Stiffness Irregular (SIF) Frames under Seismic Loads

V. CONCLUSIONS

The seismic response of Regular Frame (RF) and Stiffness Irregular Frame (SIF) buildings was studied using the Response Spectrum Method across all seismic zones of India. The major conclusions are:

1) The SIF consistently exhibits larger lateral displacements than RF, with roof displacement being 30–35% higher in Zone V, reflecting increased global flexibility due to stiffness discontinuity.
2) The response amplification from Zone II to Zone V is sharper in SIF compared to RF, indicating that stiffness-irregular systems are more sensitive to seismic intensity escalation.
3) Unlike RF's smooth drift distribution, SIF develops sharp drift peaks at the irregularity level, which may lead to localized damage and cracking in critical storeys.
4) Peak drift values in SIF are 35–40% higher than RF in higher seismic zones, making drift control a key design requirement for stiffness-irregular frames.
5) The base shear demand in SIF is about 20–25% higher than RF, with abrupt shear variations above the discontinuity, indicating the need for stronger foundations and critical member detailing.
6) Overall, SIF frames are more vulnerable than RF, as stiffness discontinuity amplifies displacements, drifts, and shear irregularities. In high seismic zones, SIF requires careful stiffness balancing, ductile detailing, and drift-control measures to ensure codal compliance and safety.

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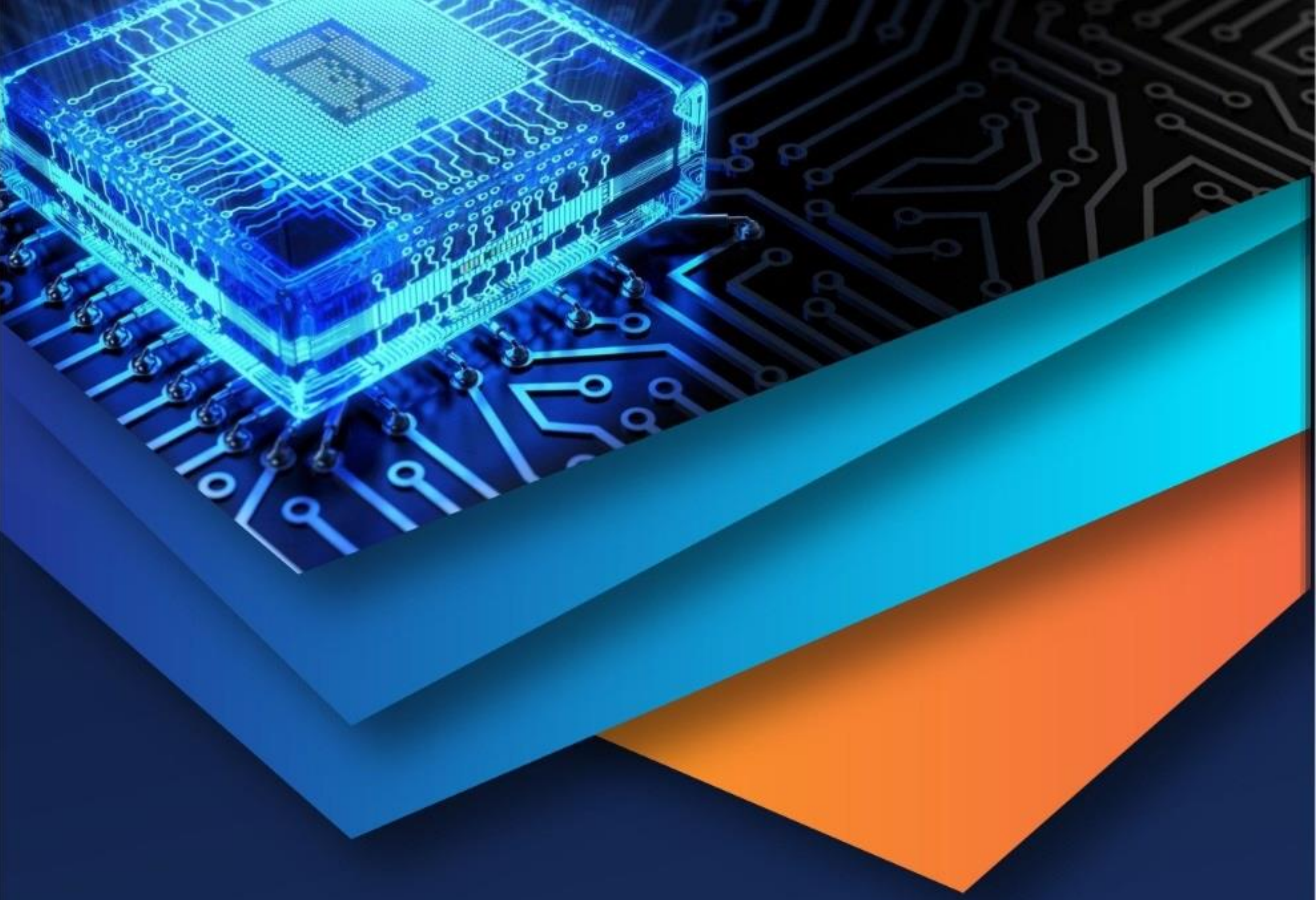

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