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Torsional Behavior of Reinforced Concrete High-Rise Structure with Diverse Shear Wall Resisting Systems under Seismic Loading

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Abstract Torsional effects, typically induced by asymmetrical mass and stiffness distribution, pose significant challenges to structural integrity during seismic events, leading to catastrophic failure. The present study presents a comprehensive evaluation of the torsional behavior of reinforced concrete (RC) high-rise structures subjected to seismic loading, with a focus on the influence of diverse shear wall resisting systems (Configurations 1 to 4). The study employs advanced finite element modeling to analyze four distinct shear wall configurations through inelastic static and nonlinear time history analyses. Both cracked and uncracked models are considered, incorporating stiffness modifiers as per IS 16700:2023 and P-Δ effects to simulate realistic seismic responses. Key performance indicators such as storey drift, storey displacement, modal behaviour, and torsional displacement are systematically assessed. Configuration 1, characterized by a symmetric and uniformly distributed shear wall layout, consistently demonstrates superior seismic performance. It exhibits reduced fundamental time periods, minimized storey drift and displacement, and a close alignment between the center of mass and center of rigidity, thereby mitigating torsional irregularities in accordance with IS 1893:2016 criteria. Furthermore, the shear wall area in Configuration 1 exceeds the codal minimum requirements, ensuring adequate lateral stiffness and stability. Comparative analysis reveals that configurations with asymmetrical shear wall placement are more susceptible to torsional amplification and dynamic instability. The findings underscore the critical role of strategic shear wall placement in enhancing seismic resilience and structural safety. Design recommendations are provided to optimize shear wall configurations for improved performance in earthquake-prone regions. Future research directions include the study of irregular geometries, nonlinear material behavior, higher mode effects, and soil-structure interaction to further refine seismic design methodologies.

Keywords Torsional Behavior, Seismic Loading, Lateral Load Resisting Systems, Finite Element Analysis

1. Introduction

In modern urban scenarios, the demand for robust seismic design has become increasingly critical due to the growing complexity in geometry and height of RC high-rise structures, resulting in disproportionate responses to seismic events. One of the key challenges in seismic design is addressing torsional irregularities, which often arise from the interaction between lateral seismic forces and the

structural geometry, leading to variations in stiffness distribution. These irregularities can intensify structural damage and, in severe cases, lead to catastrophic failure. Shear walls play a vital role in resisting lateral forces and significantly enhance the stiffness and stability of tall structures. Given the diversity in shear wall placement and design, a comprehensive study is necessary to investigate and evaluate the impact of various shear wall configurations on the torsional response of RC high-rise buildings. The present study establishes the concept of torsional restraint as the basis for classifying structural responses. A finite element method (FEM) based analysis was carried out on a three-dimensional RC frame building, focusing specifically on the structure's behavior under torsional loading conditions [1-4]. Earlier studies have demonstrated the significance of three-dimensional modeling and analysis of RC buildings with irregular plans for torsional response under seismic loads [5-7]. Many comparative studies have been conducted on different structural configurations with varying in-plane layouts and frame ductility design values, aiming to mitigate torsional effects [8-12]. The studies have evaluated the influence of torsion on the deformation and damage distribution in both plan and elevation, with particular attention to the increased shear demand on RC structural elements due to torsional amplification [13-15]. Results have revealed significant torsional rotation, especially in columns impacted by the top floor of adjacent structures, leading to elevated shear and ductility demands. Overlooking torsional irregularities caused by asymmetry can lead to unsafe designs [16]. An approach was proposed that offers benefits like seismic isolation and reduces inter-storey drifts. The effectiveness of a proposed method was assessed numerically on multistorey asymmetric buildings subjected to near-fault and long-period seismic events, showing a notable reduction in structural responses, including torsional effects. Applying this method to the base storey proved to be the most efficient strategy [17]. Additionally, a coefficient was proposed to quantify vertical stiffness irregularity in buildings, incorporating geometric dimensions, in-plane stiffness eccentricity, and the height-wise location of stiffness irregularity [18-24]. Similar analyses on systems with mass and stiffness eccentricities produced three-dimensional response curves, indicating that higher eccentricity expands the region affected by torsion in the second mode. Additionally, in systems with mass eccentricity, torsional effects appear in a limited area during the first mode of vibration [25-31]. From previous studies, a brittle collapse mechanism, characterized by the formation of shear hinges, was observed in the damaged column of an irregular building [32-38].

Traditional methods for identifying the optimum torsional axis involve applying static horizontal forces and torsional moments at each storey level. Mathematical formulations were proposed to allow the use of either static torsional moments or torsional ground motion excitation for locating the optimal torsion axis [39-44]. A comparative study of shear wall structures and bare frame buildings of asymmetrical ductile RC buildings with a soft first storey revealed that corner columns on a flexible side of such buildings should be conservatively designed for forces 1.5 times higher than those obtained from standard bare frame analysis [45]. The torsional effects reduce seismic performance due to the unfavorable redistribution of plastic deformations in vertical elements [46-50].

The present study evaluates the torsional behavior of RC high-rise structures with diverse shear wall resisting systems under seismic loading. RC buildings were modeled using ETABS 2021 finite element software. Two types of analyses were conducted: inelastic static analysis to evaluate structural capacity, and nonlinear time history analysis to assess drift behavior. The study examines the seismic behavior of asymmetric tall buildings by analyzing both cracked and uncracked models, using stiffness modifiers as specified in IS 16700:2023 [51] to closely reflect real-world conditions. The analysis also incorporates P-Δ (P-delta) effects, which account for additional moments and forces induced by displacement under load. A comparative evaluation of structural wall systems versus RC framed systems is carried out, with a particular focus on torsional performance. A comprehensive parametric study was carried out by varying key factors such as lateral force distribution, torsional resistance, and the stiffness of lateral load-resisting elements to evaluate the effectiveness of different lateral load-resisting systems in mitigating torsional effects. The present study aims to support the current design practices by contributing to the enhancement of seismic resilience of RC frame structures. The findings provide valuable insights for the informed and cautious design of buildings in earthquake-prone regions, ultimately improving structural safety and performance during seismic events.

The use of shear wall systems has become a widely accepted structural strategy, particularly in high-rise residential buildings. This is largely due to the nature of residential architecture, where the repetitive floor-to-floor layout enables the vertical continuity of these walls — a key requirement for their effective performance. Vertically continuous shear walls enhance the building's ability to resist lateral forces, such as those caused by wind and seismic activities. While shear walls do not need to be symmetrically arranged in the building plan, achieving symmetry is generally regarded as beneficial. Asymmetrical configurations can introduce torsional effects during lateral loading, potentially leading to uneven displacement and increased stress concentrations in certain parts of the structure. To mitigate such undesirable responses, designers often aim for a balanced and symmetric layout, both in-plane and out-of-plane, when configuring shear walls. This strategic arrangement helps to improve the overall seismic and wind performance of a building by distributing lateral forces more uniformly.

2. Materials and Methods

2.1. Material Properties

The material properties adopted for a multistorey structure considered in the present study were chosen to ensure both optimal performance and safety across all structural components, including beams, slabs, and walls. Beams were designed using high-strength concrete with a compressive strength of 30 MPa and reinforced with steel having a yield strength of 550 MPa, providing adequate resistance to bending and shear forces. Slabs, which are essential for load distribution and act as horizontal diaphragms, were also designed with concrete of 30 MPa compressive strength to maintain a balance between strength and weight. They were also reinforced with 550 MPa yield strength steel bars to effectively resist tensile stresses.

2.2. Seismic Analysis

In the present study, the response spectrum approach is utilized, as per IS 1893: 2016 [52] that illustrates the peak responses, such as maximum displacement, velocity, or acceleration, of a range of single-degree-of-freedom (SDOF) systems with varying natural frequencies under a given ground motion input. In the present study, the dead and live loads for high-rise residential structures are considered as per IS 875:1987 (Part 1) [53] and IS 875:1987 (Part 2) [54], respectively.

Seismic effects for the high-rise RC structure in Greater Noida, Uttar Pradesh, India, considered in the study were calculated in accordance with Indian Standard IS 1893-2016. Greater Noida is in Zone IV on medium-type soil. The effectiveness of the lateral load-resisting system depends on the type of structural system used, with the Response Reduction Factor (R) determined as per IS 1893-2016 (Part 1) guidelines. To ensure the structure's resilience to seismic forces, the dynamic base shear was scaled to be no less than 100% of the equivalent static base shear. The analysis utilized the response spectrum function in ETABS 2021, ensuring compliance with IS 1893-2016 standards.

2.3. Structure Configuration

The structure, utilizing shear wall systems, was modeled using finite element analysis software ETABS 2021. This sophisticated modeling enables an in-depth analysis of the structural system under seismic loading, incorporating a range of loading parameters as outlined in the applicable Indian codes and standards.

IS 16700:2023 provides comprehensive guidelines for the design and construction of buildings to ensure structural stability and safety, particularly in the context of seismic events. One of the critical requirements outlined in the standard pertains to the minimum percentage of wall area necessary to effectively resist seismic lateral loads.

This requirement ensures that buildings possess sufficient lateral stiffness and strength to withstand earthquake-induced forces, reducing the risk of excessive deformation, instability, or collapse. The minimum wall area, expressed as a percentage of the total floor area, is meant to ensure that the structural system includes enough shear-resisting elements, such as shear walls, to distribute and absorb seismic energy effectively.

Table 1 in the study presents the calculated percentage of shear wall area for the various shear wall configurations examined. These values are compared against the minimum thresholds set by IS 16700:2023, helping to assess the adequacy of each configuration in meeting seismic safety requirements.

Table 1. Percentage of Shear Walls for the various shear wall configurations examined in the study

Configuration No.	X	Y
1	1.35%	2.8%
2	1.10%	3.01%
3	1.41%	2.85%
4	2.69%	3.41%

The analysis assesses the structure's performance and behavior under various seismic scenarios, with a particular focus on key parameters such as storey displacement, storey drift, and storey stiffness. Structural details of different configurations considered in the study are tabulated in Table 2.

Four different shear wall configurations considered in the study are shown in Figure 1, Figure 2, Figure 3, and Figure 4. The strategic arrangement of the shear walls in these configurations is aimed at optimizing the structure’s ability to resist lateral forces, such as those induced by wind or seismic activity. By analyzing these different layouts, the study seeks to evaluate the effect of the positioning of shear walls on structural performance.

Table 2. Structural Details of Building for Different Shear Wall Configurations

Parameters	Configuration 1	Configuration 2	Configuration 3	Configuration 4
No. of storeys	2 Basement + Ground floor + 30 Storeys			
Total Length in X Direction (mm)	30560	34340	54040	44260
Total Length in Y Direction (mm)	27600	19975	24910	22086
Slab Thickness (mm)	150	150	150	150
Slab Element type	Shell Thin	Shell Thin	Shell Thin	Shell Thin
Diaphragm	Semi-Rigid	Semi-Rigid	Semi-Rigid	Semi-Rigid
Shear Wall Thickness (mm)	240	240	240	240
Basement to Ground Floor Height (mm)	5600	5600	5600	5600
Typical Floor to Floor Height (mm)	3100	3100	3100	3100
Height of Building (mm)	109750	109750	109750	109750

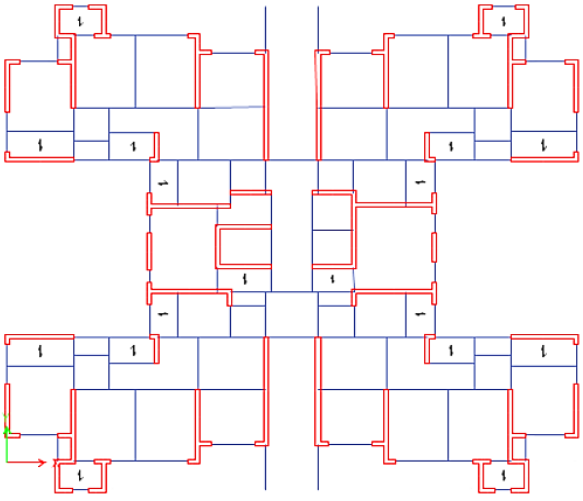

Figure 1. Configuration 1

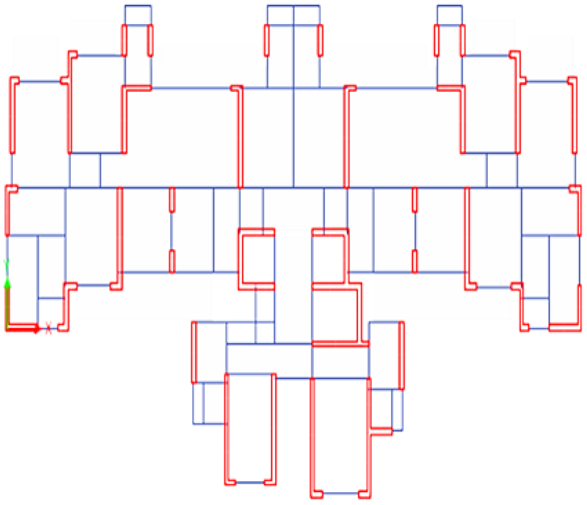

Figure 2. Configuration 2

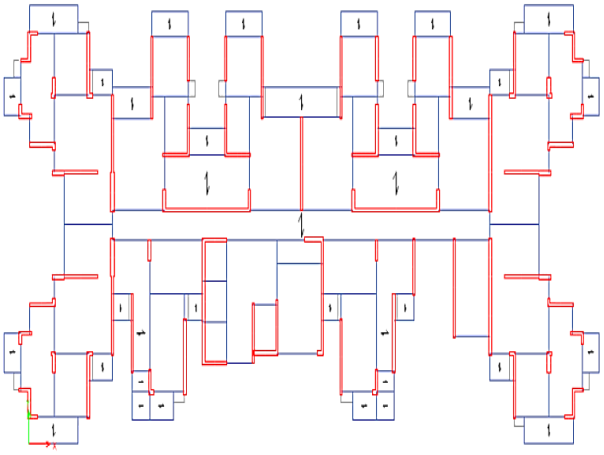

Figure 3. Configuration 3

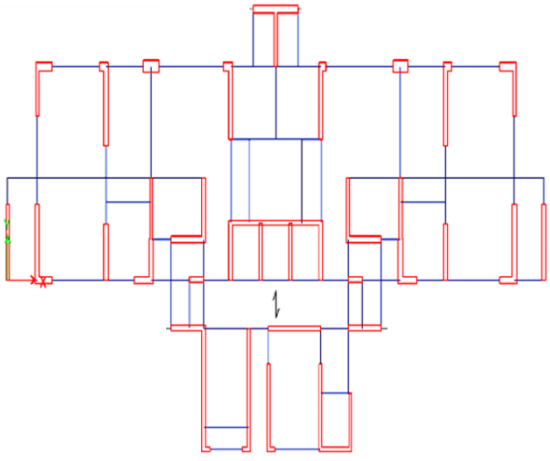

Figure 4. Configuration 4

3. Results and Discussions

3.1. Modal Analysis

In structural engineering, modal behavior refers to the dynamic response characteristics of a structure, specifically, how a structure vibrates in its various natural modes when subjected to dynamic forces such as earthquakes, wind, or mechanical vibrations. Each mode represents a unique deformation pattern, and understanding these modes is essential for evaluating seismic performance and ensuring structural safety.

In the present study, the time period associated with Configuration 1, as presented in Table 3, indicates that the configuration is likely to perform effectively under seismic loading. Time period typically reflects an optimal distribution of stiffness and mass, contributing to improved seismic resilience. Furthermore, the percentage variation between modes remains within acceptable engineering thresholds, reinforcing the structural adequacy and stability of this configuration.

Table 3. Modal Behavior for Shear Wall Configuration 1

Percentage Difference	Mode	Period (s)	UX (mm)	UY (mm)	RZ (degree)
-	1	3.992	0.7446	0.0009	0.004
9.594 %	2	3.609	0.0011	0.724	0.0001
14.214 %	3	3.096	0.0038	0.0002	0.7525

Table 4 highlights the higher time period observed in Configuration 2, which can be attributed to the increased mass in the X-direction. This added mass results in a longer duration to complete one full cycle of oscillation. In this configuration, the first mode is dominated by translational motion, while the second and third modes primarily exhibit rotational behavior.

Table 4. Modal Behavior for Shear Wall Configuration 2

Percentage Difference	Mode	Period (s)	UX (mm)	UY (mm)	RZ (degree)
-	1	6.168	0.7576	0.0001	0.0069
35.798 %	2	3.96	0.004	0.3891	0.3411
9.621 %	3	3.579	0.0031	0.3303	0.3994

Table 5 illustrates the higher time period observed in Configuration 3, which is primarily due to significant mass participation in the X-direction. As a result, the structure requires more time to complete one cycle of oscillation. Notably, the percentage difference between the first and second modes exceeds 10%, indicating distinct dynamic behavior between these modes. The first and third modes are predominantly translational, while the second mode is characterized by rotational motion.

Table 5. Modal Behavior for Shear Wall Configuration 3

Percentage Difference	Mode	Period (s)	UX (mm)	UY (mm)	RZ (degree)
-	1	7.41	0.6132	0.0004	0.0401
27.787 %	2	5.351	0.0419	0.0057	0.6085
6.765 %	3	4.989	0.0015	0.6323	0.0047

Table 6 highlights the higher time period observed in Configuration 4, which is attributed to partial mass participation in both translational directions. This indicates that the structure's response involves contributions from both X and Y directions during one cycle of oscillation. Additionally, the percentage difference between the first and second modes exceeds 10%, suggesting a significant variation in dynamic behavior between these modes.

Table 6. Modal Behavior for Shear Wall Configuration 4

Percentage Difference	Mode	Period (s)	UX (mm)	UY (mm)	RZ (degree)
-	1	5.832	0	0.4605	0.0534
22.702 %	2	4.508	0.4767	0.0009	0.0137
12.333 %	3	3.952	0.0402	0.0144	0.1318

3.2. Centre of Mass and Centre of Rigidity

The center of mass (CM) is a fundamental concept in structural dynamics, representing the point at which the entire mass of a building or structure can be considered to act. In practical terms, it is the average location of all the mass in the structure, considering the distribution of both structural elements (such as beams, columns, slabs, and walls) and non-structural components (such as finishes, partitions, equipment, and furniture).

In building design, accurately identifying the centre of mass is crucial for dynamic analysis, especially under seismic or wind loading. When external forces act on the structure, the position of the CM in relation to the center of rigidity (CR), which represents stiffness distribution, can significantly influence how the building responds. If there is a large offset between CM and CR, it can induce torsional effects, where the building not only translates but also twists, potentially increasing the risk of structural damage.

Table 7 presents the coordinates of CM and CR for various storeys in Building Configuration 1. The data indicate that there are slight variations in the positions of both CM and CR across different floors. These changes are relatively minor and remain within acceptable limits. This small variation suggests that the mass and stiffness distribution are uniform throughout the height of the structure, which is beneficial for seismic performance. A close alignment between CM and CR at each storey reduces the likelihood of significant torsional effects during lateral loading events, such as earthquakes. When these two

centers are well-aligned, the building tends to move more uniformly, primarily in translation, rather than exhibiting twisting or rotational behavior that could lead to stress concentrations and localized damage.

Table 7. Coordinates of Centre of Mass and Centre of Rigidity for Configuration 1

Storey No.	Centre of Mass		Centre of Rigidity	
	XCM (mm)	YCM (mm)	XCR (mm)	YCR (mm)
1	15.3112	12.2154	12.1185	15.2031
5	15.2933	12.108	15.1836	12.5833
10	15.2932	12.1102	15.1936	12.6969
15	15.2933	12.108	12.1188	15.2086
20	15.2933	12.108	15.2208	12.7264
25	15.2932	12.1102	15.2312	12.7093
30	15.3167	12.1475	15.2406	12.6933

Table 8 presents the coordinates of CM and CR for each storey in Building Configuration 2. The data reflect general stability in the center of mass, with only minor fluctuations across the height of the building, indicating a consistent mass distribution.

Table 8. Coordinates of Centre of Mass and Centre of Rigidity for Configuration 2

Storey No.	Centre of Mass		Centre of Rigidity	
	XCM (mm)	YCM (mm)	XCR (mm)	YCR (mm)
1	17.5179	4.9361	18.3872	3.0794
5	17.4639	5.0407	18.5313	3.0606
10	17.4639	5.0407	18.6011	2.9594
15	17.4639	5.0407	18.6188	2.8668
20	17.4639	5.0407	18.6138	2.7998
25	17.4639	5.0407	18.5991	2.758
30	17.4629	5.0409	18.5836	2.7745

However, a decreasing trend in the Y-coordinate of the center of rigidity is observed from lower to upper storeys. This shift implies that the stiffness distribution in the Y-direction is gradually altering, possibly due to changes in the arrangement or density of structural elements such as shear walls or columns.

The overall effect of this shift results in minimal horizontal offset between the CM and CR, which helps reduce torsional responses under lateral loading. However, the downward shift in rigidity may indicate that the upper stories are becoming relatively more flexible in the Y-direction compared to the lower storeys. This variation could influence the dynamic response, potentially affecting how seismic or wind loads are distributed and absorbed by the structure.

Table 9 presents the coordinates of the CM and CR across various stories for Building Configuration 3. The CM remains constant from the 5th to the 30th storey, indicating a stable mass distribution throughout the upper levels. In contrast, while CM remains unchanged, the CR gradually shifts downwards along the Y-direction, suggesting an increase in structural rigidity in this direction as the building height increases.

Table 9. Coordinates of Centre of Mass and Centre of Rigidity for Configuration 3

Storey No.	Centre of Mass		Centre of Rigidity	
	XCM (mm)	YCM (mm)	XCR (mm)	YCR (mm)
1	24.24	13.2218	24.264	12.32
5	24.2239	13.2122	24.1604	11.5262
10	24.2239	13.2122	24.1497	10.7109
15	24.2239	13.2122	24.1981	10.2083
20	24.2239	13.2122	24.2716	9.7313
25	24.2239	13.2122	24.3312	9.3554
30	24.2239	13.2122	24.3435	9.0709

Table 10 provides the corresponding data for Building Configuration 4. In this case, the X-coordinate of the CR shows a notable decrease with height, and the Y-coordinate also exhibits a downward trend. This consistent reduction in both coordinates indicates a progressive shift in rigidity distribution as the building rises.

Table 10. Coordinates of Centre of Mass and Centre of Rigidity for Configuration 4

Storey No.	Centre of Mass		Centre of Rigidity	
	XCM (mm)	YCM (mm)	XCR (mm)	YCR (mm)
1	31.7626	4.4818	28.5988	7.0454
5	21.4494	4.8634	24.2208	3.8693
10	21.4494	4.8634	22.6906	3.8133
15	21.4494	4.8634	22.0873	3.8497
20	21.4494	4.8634	21.6569	3.9144
25	21.4494	4.8634	21.3558	3.9593
30	21.4494	4.8634	21.2928	3.9551

3.3. Storey Drift

Storey drift, defined as the difference in lateral displacement between two consecutive floors, is a critical parameter in assessing seismic performance. Figure 5 illustrates the storey drift in X-direction under earthquake loading applied along the same axis. When compared to Configuration 3, the drifts in Configurations 1, 2, and 4 were significantly lower by 65.09%, 15.785%, and 62.22%, respectively. This demonstrates that Configuration 1 offers the most effective performance in reducing storey drift under seismic loads in X-direction, followed by Configurations 4 and 3. Overall, Configuration 1 emerged as the most advantageous in mitigating lateral displacement,

indicating that its implementation can substantially enhance the structural resilience of buildings during seismic events.

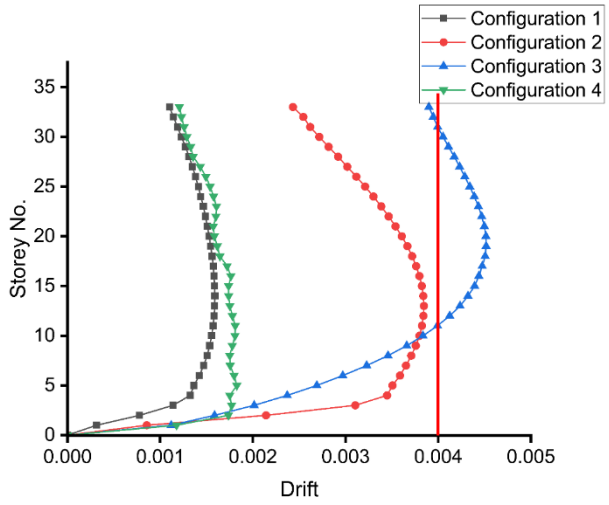

Figure 5. Storey Drift in X-direction

Figure 6 illustrates the storey drift in Y-direction under seismic loading applied along the same axis. Among the four shear wall configurations evaluated, Configuration 3 exhibited the highest storey drift. In contrast, Configurations 1, 2, and 4 showed significantly lower drift values—reduced by 55.54%, 43.60%, and 4.94%, respectively, compared to Configuration 3. These results indicate that Configuration 1 offers the best performance in minimizing storey drift in the Y-direction, followed by Configurations 2 and 4, highlighting its superior effectiveness in enhancing seismic resilience along this axis.

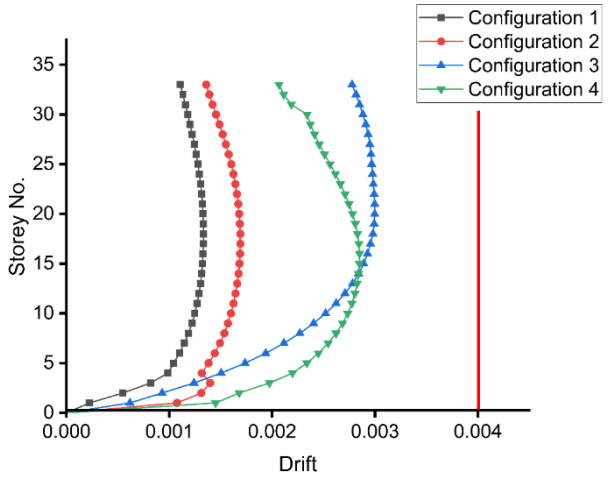

Figure 6. Storey Drift in Y-direction

3.4. Storey Displacement

Storey displacement is a key parameter in evaluating the performance and stability of buildings under lateral loads. It measures the relative movement between adjacent floors, providing insights into the building's structural integrity, stability, and occupant comfort. Excessive storey displacement may indicate issues such as excessive sway, structural deformation, or even potential failure. Therefore, careful analysis and control of displacements during the design process are essential to meet safety and performance standards.

Figure 7 illustrates storey displacement in the X-direction under seismic loading applied in the same direction. Among the four shear wall configurations analyzed, Configuration 3 exhibited the highest displacement. In contrast, Configurations 1, 2, and 4 demonstrated significantly lower displacements—reduced by 63.78%, 9.57%, and 52.07%, respectively—compared to Configuration 3. These results indicate that Configuration 1 provides the best displacement control under lateral loads in the X-direction.

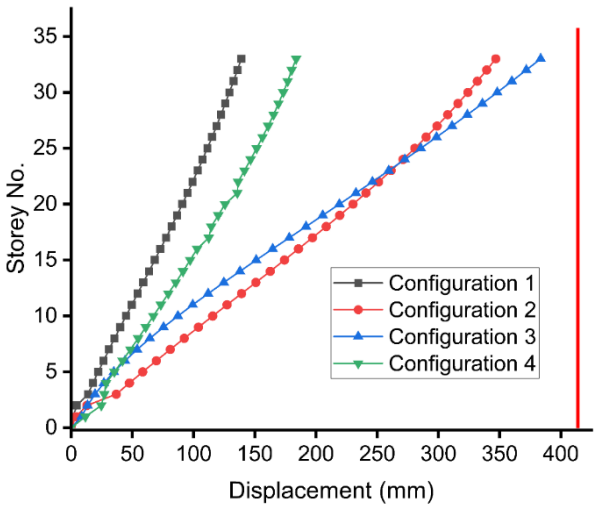

Figure 7. Storey Displacement in X-direction

Figure 8 presents the storey displacement in the Y-direction under an earthquake load applied in the same direction. Among the four shear wall configurations analyzed, Configuration 4 exhibited the highest storey displacement. In contrast, Configurations 1, 2, and 3 showed significantly lower displacements—reduced by 61.74%, 50.42%, and 19.85%, respectively—when compared to Configuration 4. These results indicate that Configuration 1 offers the most effective performance in minimizing storey displacement under seismic loads in the Y-direction, followed by Configurations 2 and 3.

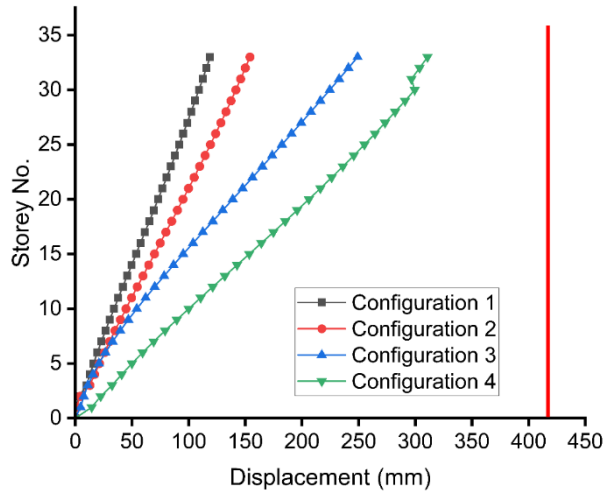

Figure 8. Storey Displacement in Y-direction

In summary, Configuration 1 consistently proved to be the most advantageous in reducing storey displacement due to seismic activity in the Y-direction. Its superior performance highlights its potential to enhance the structural resilience and overall seismic safety of buildings.

3.5. Torsional Irregularity in the Structure

According to IS 1893:2016, which governs earthquake-resistant design in India, the evaluation of torsional irregularities is essential for ensuring structural stability and minimizing the risk of damage during seismic events. Torsional irregularities occur when there is a significant offset between the center of mass and the center of rigidity, leading to uneven lateral displacement or rotation of the structure during seismic activity.

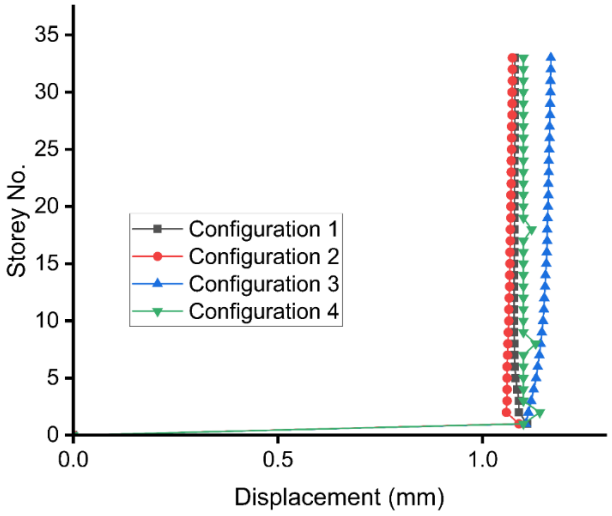

Figure 9. Torsional Displacement in X-direction

Figure 9 and Figure 10 illustrate the torsional behavior of the structure under seismic loading in X and Ydirections across four different shear wall configurations. This graphical representation helps in assessing the dynamic rotational response of each configuration. Configuration 1 displays a gradual increase in torsional response, followed by stabilization, suggesting a well-distributed stiffness and controlled rotational behavior. Configuration 2 also shows a minimal and consistent torsional response, indicating a symmetrical and stable layout with little risk of torsional irregularity. Configuration 3 exhibits a moderate response with some variation, which, while not excessive, indicates potential asymmetry that should be monitored. However, the behavior remains generally within acceptable limits.

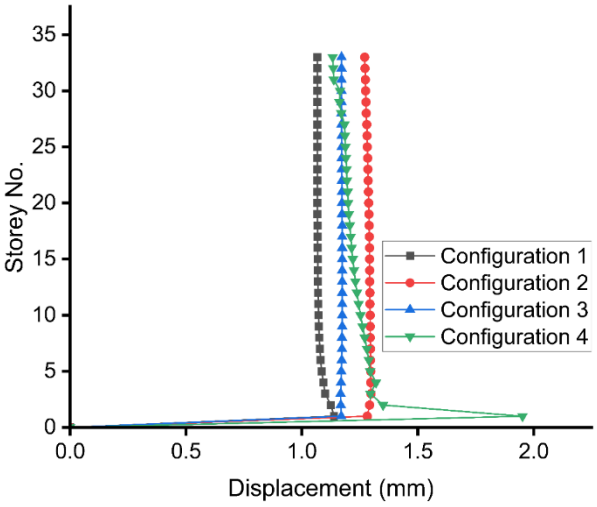

Figure 10. Torsional Displacement in Y-direction

Configuration 4 demonstrates a significant oscillatory torsional response, with noticeable peaks and fluctuations. This behavior suggests that the structural configuration has a less uniform distribution of stiffness or mass, making it more dynamically sensitive and potentially more vulnerable to torsional amplification during seismic activity.

These observations highlight the importance of shear wall placement and mass-stiffness balance in reducing torsional effects. Configurations 1 and 2, by showing stable torsional behavior, align more closely with IS 1893 recommendations, whereas Configuration 4 may require re-evaluation or redesign to improve its seismic performance.

4. Conclusions

This study presents a comparative evaluation of four shear wall configurations in high-rise reinforced concrete (RC) buildings subjected to seismic loading. Indian seismic design standards (IS 1893:2016 and IS 16700:2023) are integrated to assess torsional behavior and codal compliance. Advanced finite element modelling (FEM) in ETABS 2021 is employed, incorporating cracked and uncracked models, stiffness modifiers, and P-Δ effects for realistic simulation. A storey-wise assessment of the center

of mass (CM) and center of rigidity (CR) is carried out to examine torsional irregularities and their influence on dynamic response. The results highlight quantitative improvements in modal behavior, storey drift, and displacement, with Configuration 1 demonstrating superior seismic performance. Torsional irregularity criteria ($\Delta_{max} > 1.5 \times \Delta_{min}$), as specified in IS 1893:2016, are validated, confirming structural stability under seismic excitation. The findings further provide design recommendations for optimizing shear wall placement in configurations exhibiting higher torsional sensitivity. The conclusions drawn from the analysis highlight specific shear wall configurations that exhibit superior performance under seismic conditions, emphasizing efficient load distribution and enhanced resistance to earthquake-induced damage. Based on the analysis, the following key conclusions are drawn:

- The time period of the shear wall structural system in Configuration 1, which features well distributed shear walls throughout the plan, was 46.13% lower than that of Configuration 3, which had a relatively less scattered shear wall arrangement and exhibited the highest time period. This indicates that the shear wall system in Configuration 1 responds more quickly to lateral forces. The shorter time period aligns with the requirements outlined in Indian standards for designing structures to effectively withstand wind loads. Additionally, the modal behavior of Configuration 1, with the first and second modes in translation and the third mode in rotation, further enhances its suitability and makes it a preferred choice for seismic performance.
- The storey drift was reduced by more than 65% in X-direction and 55% in Y-direction for the shear wall system in Configuration 1. Additionally, the storey displacements for Configuration 1 were 64% and 62% lower compared to the other structural systems, demonstrating their superior performance in minimizing lateral displacements under seismic loading.
- The torsional behavior of Configuration 1 met the requirements outlined in the Indian Standard code, specifically the clause stating that Δ_{max} should be more than 1.5 times Δ_{min}. This demonstrates that Configuration 1 maintains stable torsional performance under seismic loads, ensuring compliance with the established guidelines for torsional irregularities.
- The percentage of shear walls provided in Configuration 1 exceeded the minimum requirements specified in the codal provisions for each principal plan direction. Specifically, the shear wall percentage was 1.35% in the X-direction and 2.80% in the Y-direction, ensuring that the structure meets or surpasses the necessary criteria for seismic load resistance as per Indian standards.

The shear wall configuration 1 outperforms as compared to other shear wall configurations, due to the symmetrical arrangement of the shear wall in the plan and uniform distribution in the elevation. However, the rearrangement of shear walls in configurations 2, 3, and 4 can be considered for improved lateral resistance.

5. Future Scope

The current study has provided a comparative evaluation of torsional behavior in reinforced concrete high-rise structures with varying shear wall configurations under seismic loading. To further advance this research, the following directions are proposed:

- Optimization of shear wall layouts
- Analysis of irregular and non-symmetrical structures
- Incorporation of nonlinear material behaviour
- Consideration of higher mode effects
- Performance-based seismic design
- Integration of supplemental damping systems
- Soil-structure interaction (SSI)

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