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Assessment Of Plan Irregularity Factor For A Trapezoidal Structure

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Abstract: Seismic analysis of irregular buildings is crucial due to the non-uniform distribution of seismic loads, which can enhance seismic forces. Advanced analysis tools like modal, response spectrum, and pushover analysis are essential for assessing seismic performance. A trapezium-shaped structure is needed when the available plan is not symmetric along any axes. This case study examines the G+20 building's seismic performance in seismic zone 4, where the left and right sides of a standard rectangular building are changed to create a trapezium. Dynamic analysis is performed on the regular and irregular structures, observing maximum storey drift, storey displacements, and stiffness which are essential for strengthening seismic resistance and structural integrity in earthquake-prone regions. This research focuses on evaluating the plan irregularity factor for trapezoidal buildings, characterized by their non-orthogonal geometry. The study employs advanced seismic analysis techniques using ETABS software to simulate and analyse the impact of varying degrees of plan irregularity on the structural behaviour of trapezoidal buildings. The findings underscore the importance of incorporating plan irregularity considerations into design and analysis processes to enhance seismic resilience of trapezoidal structures.

Index Terms – Trapezoidal building, Plan irregularity, displacements, storey drift, seismic analysis, seismic loads G+20 Building, combination, response etc.

I. Introduction

The behaviour of a building is influenced by its structural arrangement, which includes size, shape, and geometry. Inertia forces are generated and concentrated near the centre of mass when subjected to dynamic loads, with vertical elements like columns and shear walls resisting horizontal inertia forces. These forces are concentrated at the centre of stiffness. Eccentricity occurs when the centre of mass and stiffness are not the same, leading to torsional coupling and structural damage. Regular structures have no notable plan or vertical configuration discontinuities, but irregular structures under lateral loads are impacted by specific physical discontinuities in their elevation, plan, or both. Vertical irregularities distribute mass, stiffness, and geometry throughout a building's height, while horizontal irregularities are caused by discontinuities in the plan. Seismic response of a structure is influenced by various structural imperfections, which are chosen carefully during the design process. When sides of a regular rectangular building are adjusted to angles, it transforms into a more complex trapezoidal shape, increasing torsion or twisting forces.

1.1.IRREGULARITY IN BUILDING

Structural irregularities in buildings refer to deviations from a symmetrical and uniform distribution of mass, stiffness, and strength, which are crucial for the stability and performance of a structure, especially under dynamic loads like earthquakes. There are two main categories of structural irregularities: vertical and horizontal. Vertical irregularities occur when there are significant variations in the properties of the structure along its height. Examples of this include soft stories, where one floor is significantly less rigid than the others, or mass irregularities, where one floor is considerably heavier than the rest. These irregularities can create points of weakness, making the building more susceptible to collapse or significant damage during seismic events. Horizontal irregularities, on the other hand, happen when there is an uneven distribution of mass or stiffness across the building's floor plan. This can lead to torsional effects, where parts of the building twist excessively during an earthquake, increasing the likelihood of structural failure.

1.2.TRAPEZOIDAL BUILDINGS

Trapezoidal buildings, characterized by varying heights and widths, are crucial for seismic safety due to their importance in the design process. When the sides of a regular rectangular building are adjusted to angles such as 5, 10, 15, or 20 degrees, the structure is transformed from a simple rectangular to a more complex trapezoidal shape. This geometric modification introduces a degree of irregularity into the building's design, which subsequently increases torsion, or twisting forces, within the structure. The resulting trapezoidal buildings are characterized by varying heights and widths, which makes them vital in the context of seismic safety.

OBJECTIVES

[1] Investigate the discrepancy in seismic analysis literature for G+20 trapezoidal structures and compare their seismic performance with regular rectangular buildings.
[2] Perform a seismic analysis of rectangular buildings at 0 degrees and trapezoidal buildings with angles of 5 to 20 degrees.
[3] Evaluate key seismic performance parameters such as maximum storey displacements, drifts, and stiffness, providing insights into the structural behaviour of these buildings under seismic loads to enhance understanding of their performance.

2.METHODOLOGY AND MODELLING

In this research understanding how the building responds to seismic forces and determining ways to strengthen it against earthquakes are the main goals of this chapter, which covers the modelling and methodology for the seismic analysis of a G+20 building. It covers static, response spectrum, approaches at angles of 0, 5, 10, 15, and 20 degrees. Various loads, such as response spectrum functions, adhering to specific standards, and performing pushover analysis, are applied to see how the building holds up under severe conditions. By systematically analyzing the building's seismic response in various scenarios, the foundation for understanding its response is laid.

2.1. Modelling

A typical rectangular building with a 0-degree angle to 20-degree angle and 20 stories (G+20 Stories) is depicted in Model 1 to Model 5 plan are shown in Figure 1. Each storey of the building is three meters high, for a total height of 57 meters. With a slightly higher height of 3.3 meters, the base storey may be intended for utilities or other uses. The structural analysis and design process is optimized by the regular rectangular configuration, which facilitates efficient load transfer and uniform force distribution. The following are the types of models:
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1. Regular rectangular building with G+20 floors and a 0-degree angle.
2. G+20 trapezoidal structure with a 5-degree angle.
3. G+20 trapezoidal building with a 10-degree angle.
4. G+20 trapezoidal structure with a 15-degree angle.
5. G+20 trapezoidal building with a 20-degree angle.
6. G+20 trapezoidal structure with a 5-degree angle on one side.
7. G+20 trapezoidal building with a 10-degree angle on one side.
8. G+20 trapezoidal structure with a 15-degree angle on one side.
9. G+20 trapezoidal building with a 20-degree angle on one side.

2.2.Plans Views of Trapezoidal Symmetric at Both Sides

This study explores the structural design and analysis of five building models, each varying in shape and angle. Figure 1 is Model 1(0 degree) represents a typical rectangular building with 20 stories (G+20) and a height of 57 meters, offering an efficient design for load transfer and force distribution. Models 2 to 5 introduce trapezoidal buildings with increasing angles of 5, 10, 15, and 20 degrees, respectively, while maintaining the same total height and number of stories as Model 1(0degree). These trapezoidal forms add complexity to the structural design, requiring customized methods for load distribution, lateral stability, and structural reinforcements. Additionally, the unique shapes of these models present challenges in seismic and wind reactions, demanding creative technical solutions to ensure their safety and durability in various environmental conditions. Figures 1 to 5 below illustrate the variations in building shapes for each angle.

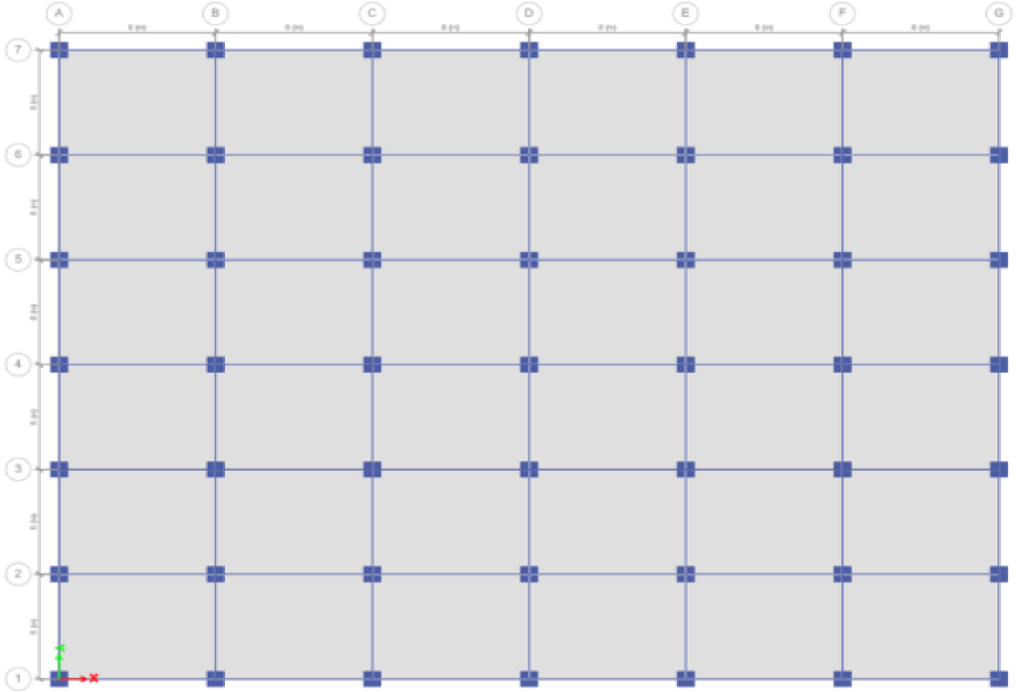


Fig.1 Regular Rectangular Building with 0 degree

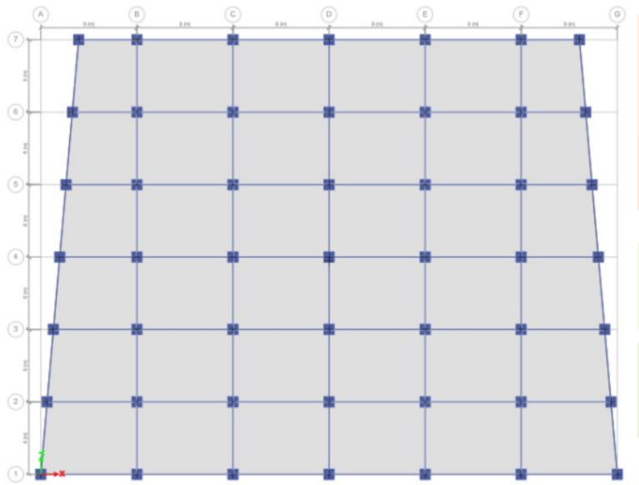


Fig.2: Trapezoidal Structure with a 5-degree angle

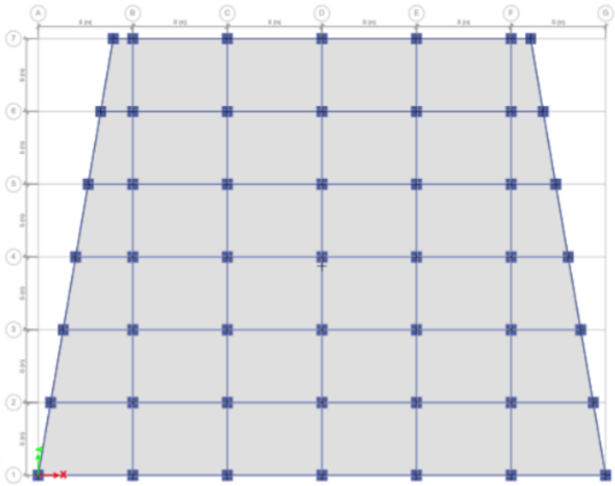


Fig.3: Trapezoidal Structure with a 10-degree angle

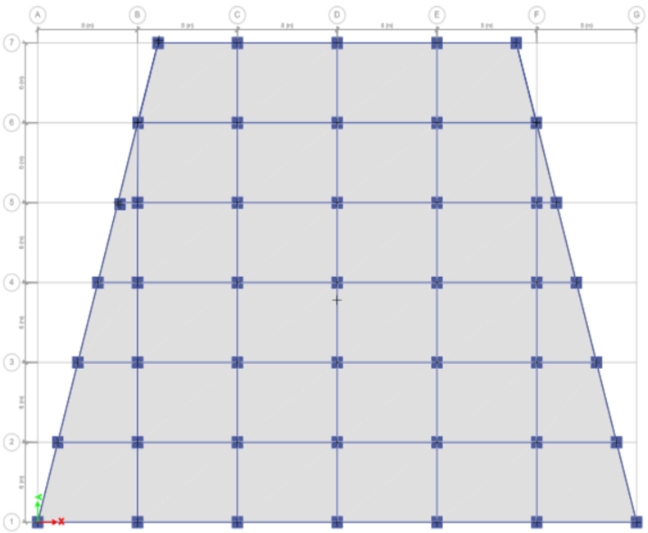


Fig.4: Trapezoidal Structure with a 15-degree angle

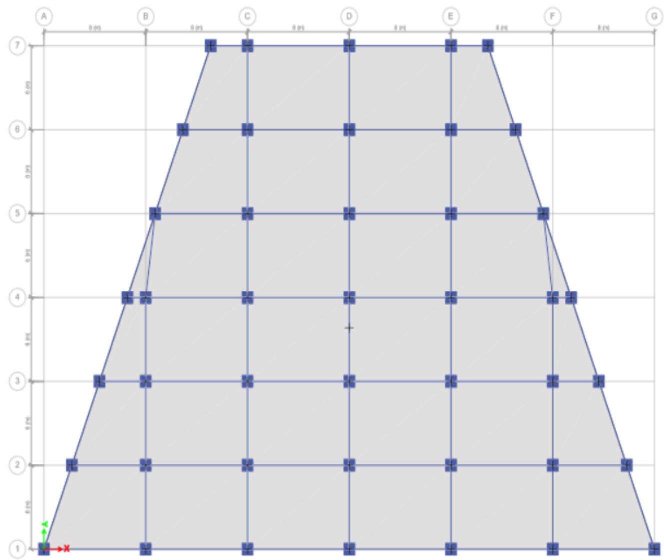
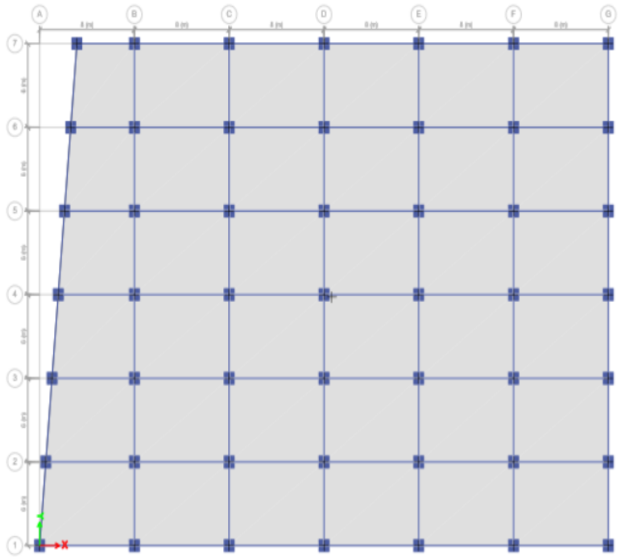


Fig.5: Trapezoidal Structure with a 20-degree angle

2.3.Plans Of Trapezoidal Asymmetric at One Side

This study also investigates the structural design and analysis of five building models, each with varying shapes and one-sided angles. Model 1 (0 degrees) represents a typical rectangular building with 20 stories (G+20) and a height of 57 meters, ensuring efficient load transfer and force distribution. Models 2 to 5 introduce trapezoidal buildings with one-sided angles of 5, 10, 15, and 20 degrees, respectively, while maintaining the same height and number of stories as Model 1. These trapezoidal forms add complexity to the structural design, requiring customized methods for load distribution, lateral stability, and reinforcements. The unique shapes of these models also present challenges related to seismic and wind reactions, requiring innovative technical solutions to ensure their safety and durability across various environmental conditions. Figures 6 to 9 below showcase the differing shapes of the buildings corresponding to each angle.



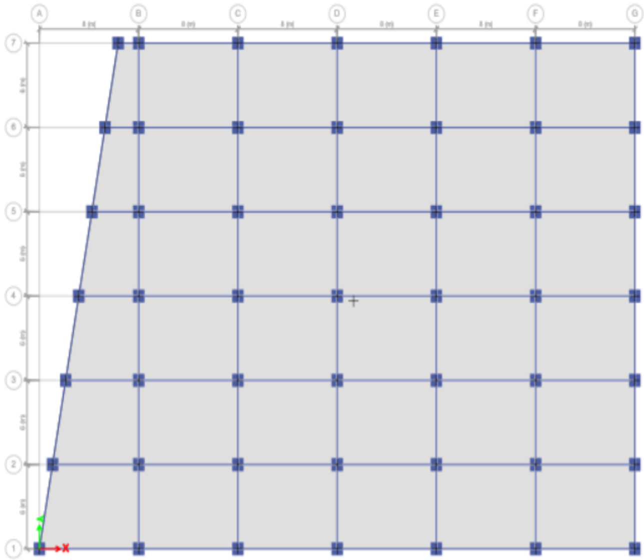
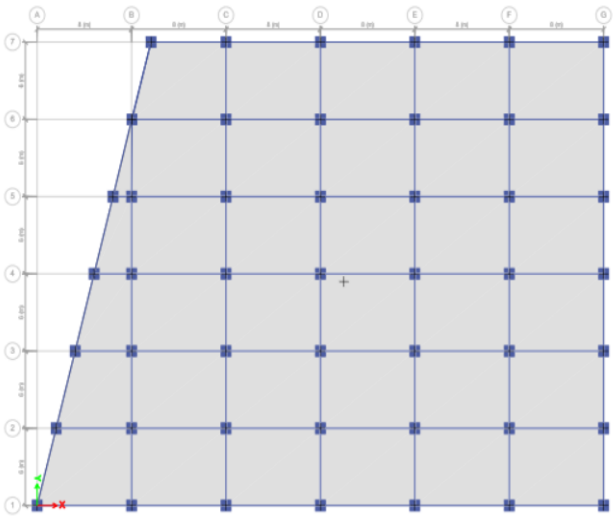


Fig.6: Trapezoidal Structure with a 5-degree angle on one side. **Fig.7** Trapezoidal Structure with a 10-degree angle on one side.



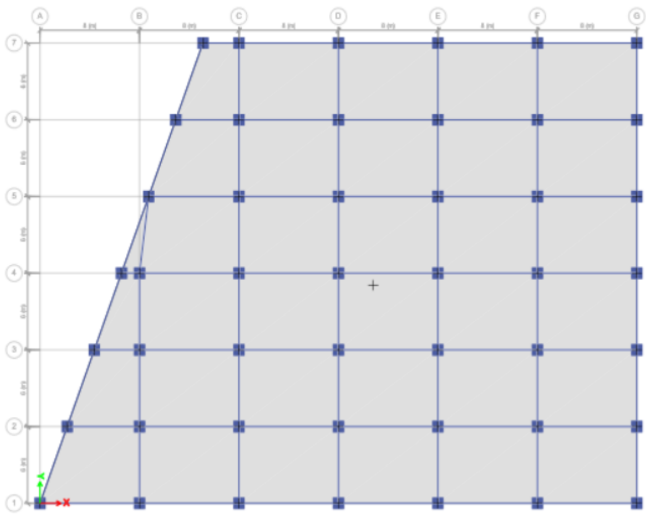


Fig.8: Trapezoidal Structure with a 15-degree angle on one side. **Fig.9**: Trapezoidal Structure with a 20-degree angle on one side.

3. ANALYSIS RESULTS

3.1. Displacements

3.1.1. Displacements In EQ-X Direction

In Graph (Figures 10), the displacements in the X-direction are shown at different angles (5°, 10°, 15°, and 20°). The data indicates that the displacement values increase as the storey height rises. For example, at 5°, Storey 20 has a displacement of 27.703 mm. At 10°, the displacement increases to 28.158 mm at the same storey level. As the angle increases, the displacement continues to grow, showing a consistent increase at each floor. This pattern is evident across all stories, with the higher stories experiencing larger movements. The results show that with higher degrees of lateral movement, the building experiences more displacement, especially at the top floors. This trend indicates that with the increase in lateral forces, the top stories of the building will experience higher displacement values. This data highlights the importance of designing the building structure to handle larger forces at higher levels to ensure stability and safety during seismic events.

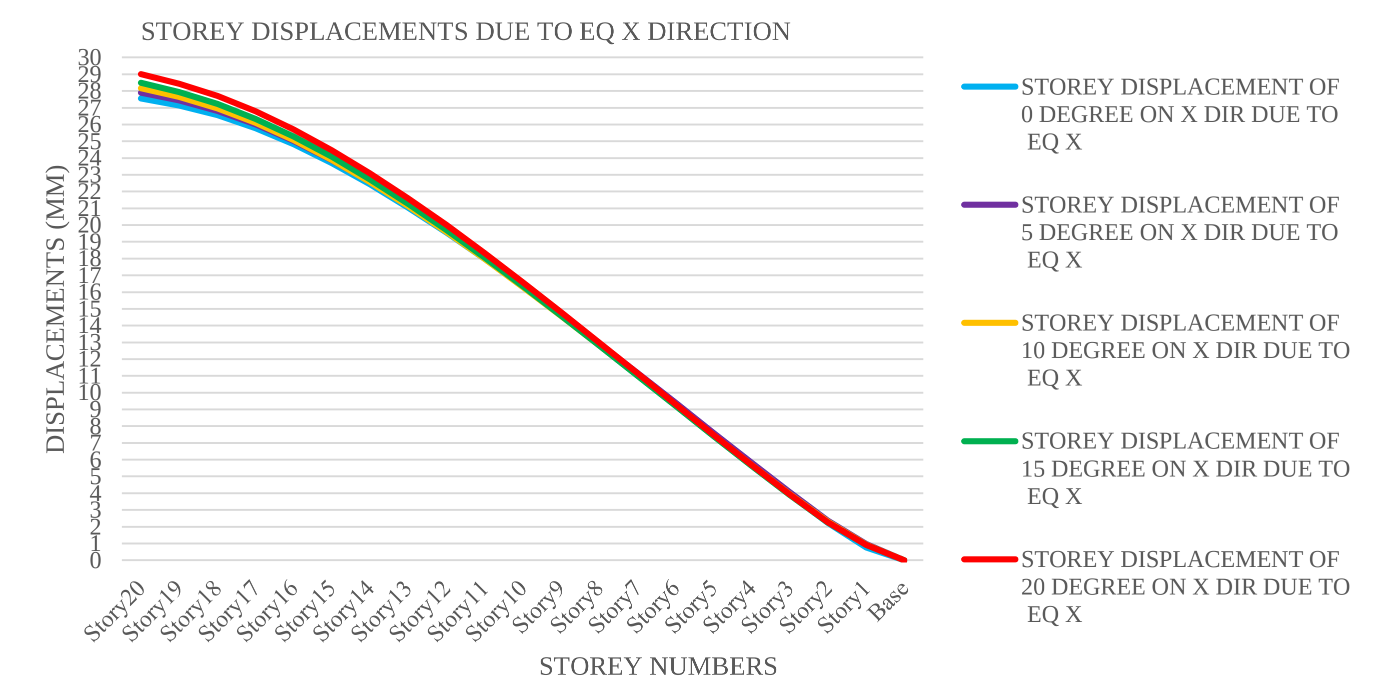


Figure 10: Storey displacements due to EQX for symmetric angles models

In Graph (Figures 11) also show the displacements in the X-direction at various angles (5°, 10°, 15°, and 20°) when lateral forces are applied from one side. At Storey 20, for instance, the displacement at 5° is 27.857 mm, and at 10°, it is 28.158 mm. As the degree of lateral movement increases, displacement values rise, especially in the higher stories. The data shows that the displacements increase with storey height, similar to the normal angle case. For example, at Storey 1, the displacement at 5° is 0.909 mm, which increases to 0.965 mm at 20°. In the lower stories, the movement is smaller, but it becomes more noticeable in the upper stories. As the lateral force increases, the displacement continues to grow, particularly at the higher stories. These results emphasize the need for structural reinforcement at the top stories to prevent excessive movement and ensure the building's stability during seismic events.

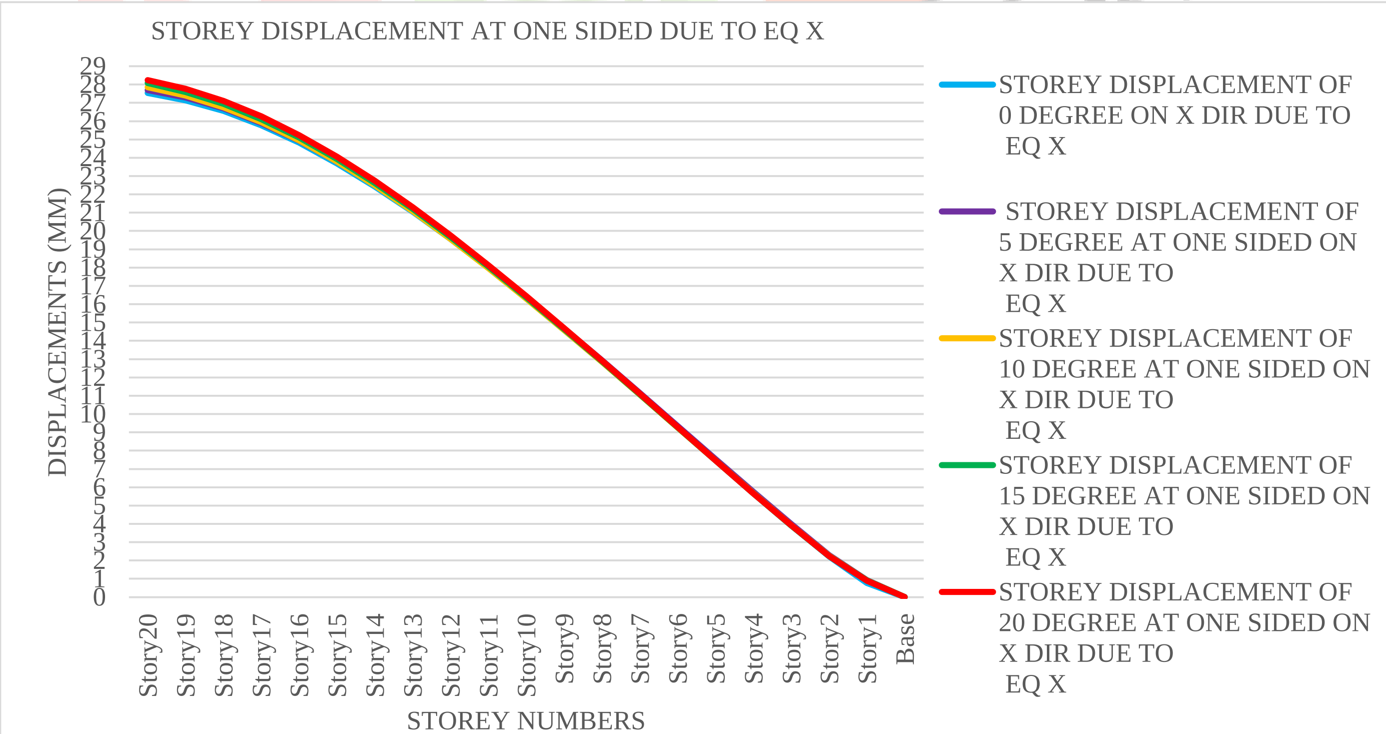


Figure 11: Storey displacements at one sided angles model due to EQX

3.1.2. Displacements In EQ-Y Direction

As shown in Graph (Figures 12), the displacements in the Y-direction increase with the height of the building. For instance, at a 5° angle, Storey 20 experiences a displacement of 25.005 mm, and at 10°, it moves to 24.469 mm. As the degree of lateral movement increases, the displacement continues to rise at the higher floors. For example, at 15° and 20°, the displacement continues to increase for Storey 20 and other higher stories. The lower floors, such as Storey 1, show smaller displacements, but as you go higher, the displacement values grow. This shows that when lateral forces are applied, the top floors experience more movement compared to the lower floors. The increase in displacement with the rise in degree indicates that higher lateral forces result in larger movements at the upper stories of the building, making them more susceptible to structural issues.

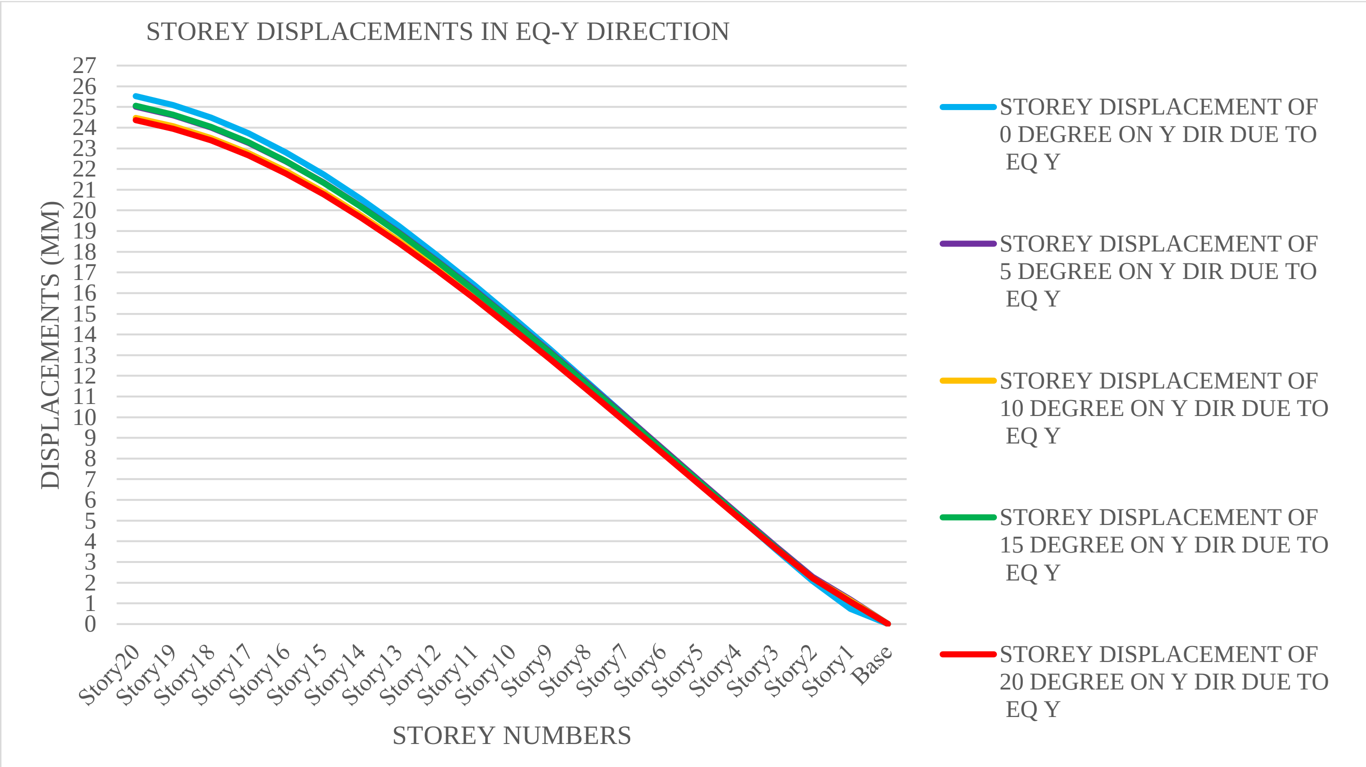


Figure 12: Storey displacements due to EQY for symmetric angles models

Graph (Figures 13) also display the displacements in the Y-direction when lateral forces are applied from one side. At 5°, Storey 20 shows a displacement of 25.627 mm, which is slightly higher than the displacement at the normal angle (25.005 mm). At 10°, the displacement at the one-sided angle is 25.829 mm, compared to 24.469 mm at the normal angle. The pattern of higher displacement values at the one-sided angle holds across all stories and for higher degrees of lateral movement. As the degree of lateral movement increases, the displacement at the upper stories continues to grow. This suggests that lateral forces acting from one side cause slightly more movement compared to forces applied evenly, which can affect the building's stability. The higher displacement values at the upper stories highlight the need for stronger support at these levels to maintain stability during seismic events.

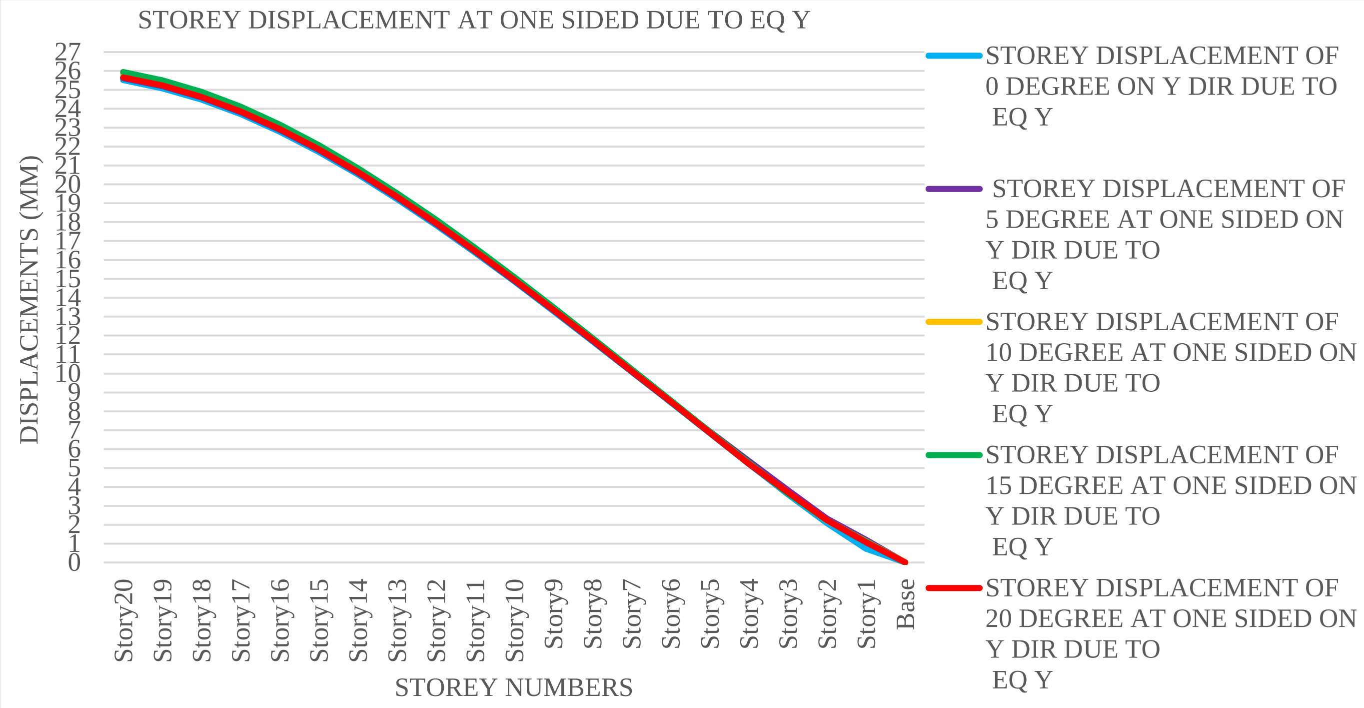


Figure 13: Storey displacements at one sided angles model due to EQY

3.2.Storey Drift

3.2.1. Drifts In EQ-X Direction

When lateral forces are applied at normal angles (0°, 5°, 10°, 15°, and 20°), the storey drift generally increases with both the height of the building and the displacement angle. As shown in Figure 14, at each angle, the drift is higher in the lower and intermediate stories compared to the higher stories. For instance, at 5°, Storey 20 shows a drift of 0.000144, and at 10°, it increases to 0.000179. As the displacement angle increases, the drift continues to rise across most stories. This indicates that the building's lower and intermediate levels are more affected by seismic forces than the higher levels. The highest drift value observed at the normal angle is 0.000599, occurring at Storey 7 with 0° of lateral movement, as seen in Figure 3.5. This suggests that intermediate stories experience the largest drift due to their position in the structure, being more susceptible to lateral displacement compared to the lower and upper stories. Therefore, the normal angle of force application causes more noticeable displacement, especially at these intermediate levels.

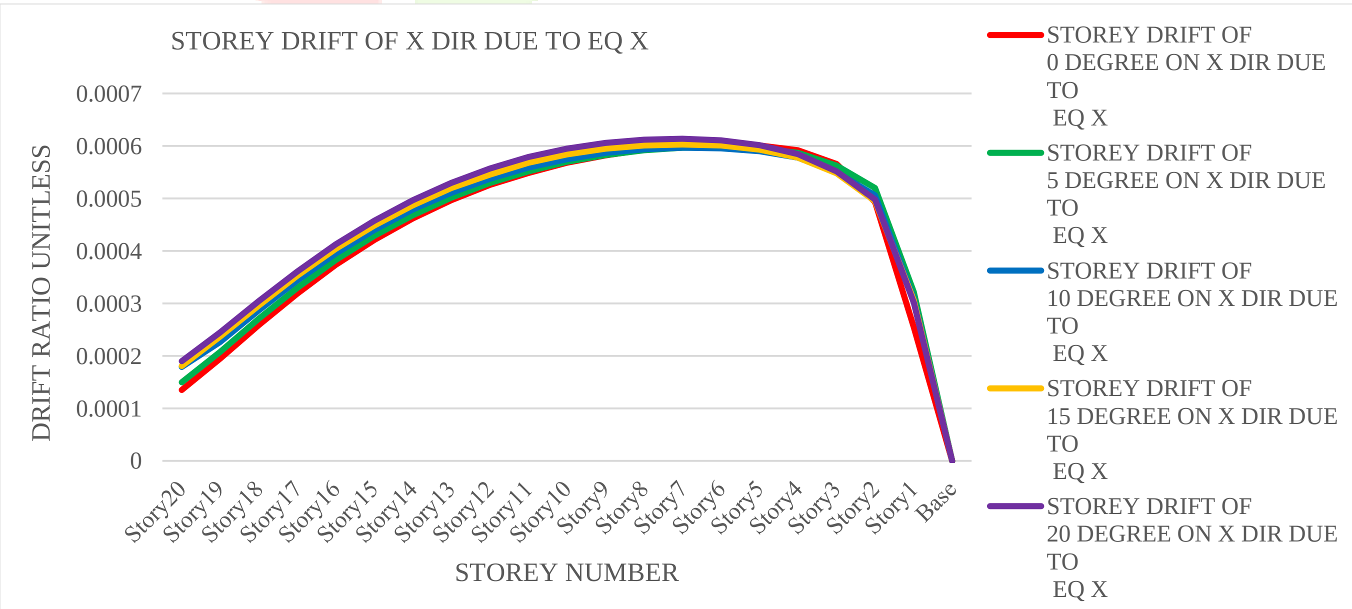


Figure 14: Storey drift ratio due to EQX for symmetric angle models

When the lateral forces are applied at one-sided angles, the storey drift is generally slightly lower than at normal angles for most stories. As shown in Figure 15, for example, at 5°, Storey 20 shows a drift of 0.000159 at the one-sided angle, which is slightly higher than the drift at the normal angle (0.000144). However, at 10°, the drift at the one-sided angle decreases to 0.000159, compared to 0.000179 at the normal angle. This trend of slightly smaller drift values at the one-sided angle continues as the displacement angle increases. The application of lateral forces on one side of the building results in less displacement compared to when forces are applied across both sides of the structure. As shown in Figure 3.6, this indicates that the one-sided angle causes reduced drift across most stories, suggesting that lateral forces from one side produce less movement within the building structure. As a result, the one-sided application leads to a more stable response in comparison to the normal angle across most of the stories.

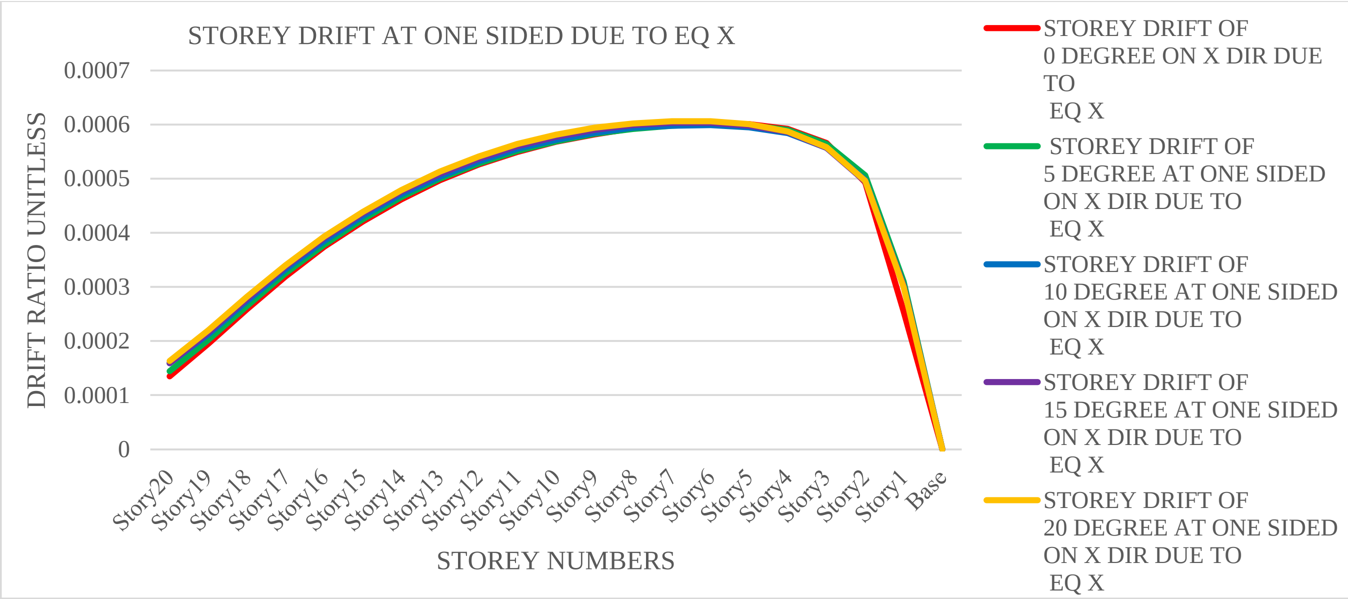


Figure 15: Storey drift ratio at one sided angle models due to EQX

3.2.2. Drifts In EQ-Y Direction

When lateral forces are applied in the Y-direction at normal angles (0°, 5°, 10°, 15°, and 20°), the storey drifts show minimal variation across different stories. As shown in Figure 16, at 5°, Storey 20 experiences a drift of 0.000144, and at 10°, the drift slightly decreases to 0.000136. This suggests that the lateral forces at normal angles affect the building almost uniformly, with only small changes between displacement angles. The highest drift value is observed at the lower stories, particularly at Storey 6, where the drift reaches 0.000606 at 20°. This indicates that the lower stories experience more significant drift compared to the higher stories. Overall, the drifts at normal angles are close to each other across different displacement angles, with the maximum drift occurring at lower levels of the building.

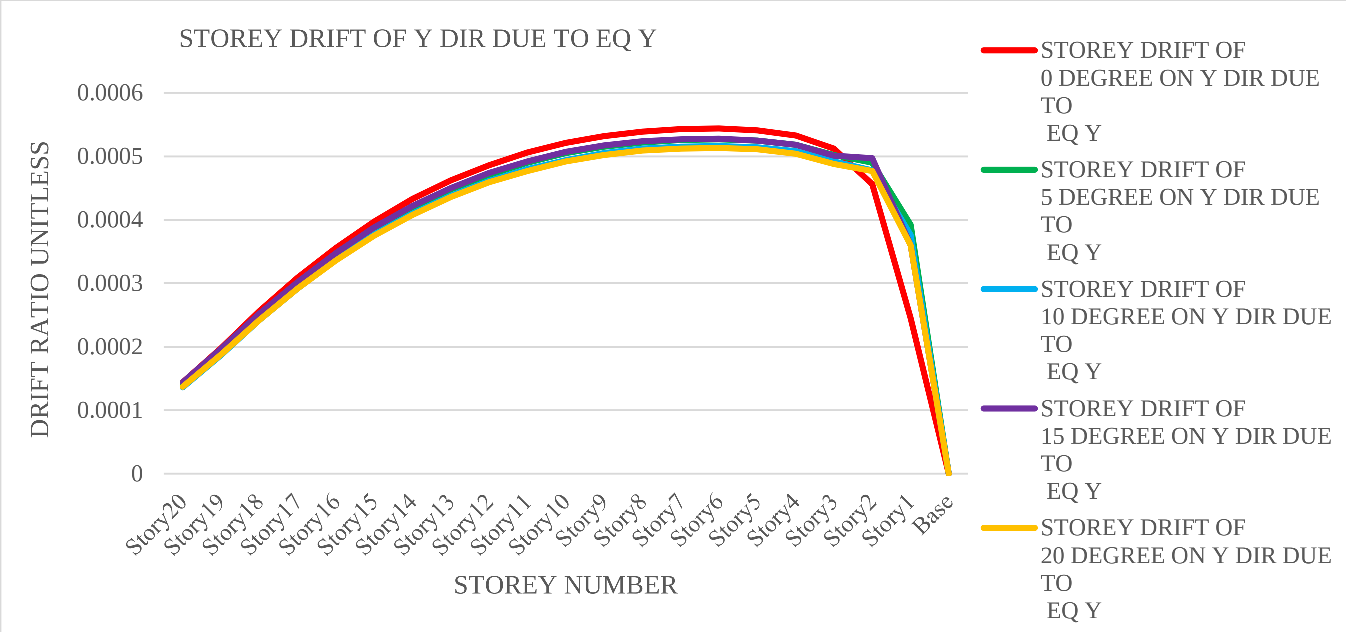


Figure 16: Storey drift ratio due to EQY for symmetric angle models

When lateral forces are applied at one-sided angles in the Y-direction, the storey drifts are generally very similar to those observed at normal angles. As seen in Figure 17, at 5°, Storey 20 shows a drift of 0.000145, which is almost identical to the normal angle value of 0.000144. Similarly, at 10°, the drift at the one-sided angle increases slightly to 0.000145, compared to 0.000136 at the normal angle. The difference between the drifts at normal and one-sided angles is minimal across all stories. The highest drift is again observed at the lower stories, with Storey 6 experiencing a drift of 0.000606 at 20°. This indicates that the one-sided force application also causes significant drift in the lower stories, similar to the normal angle case, with minimal difference in the overall response.

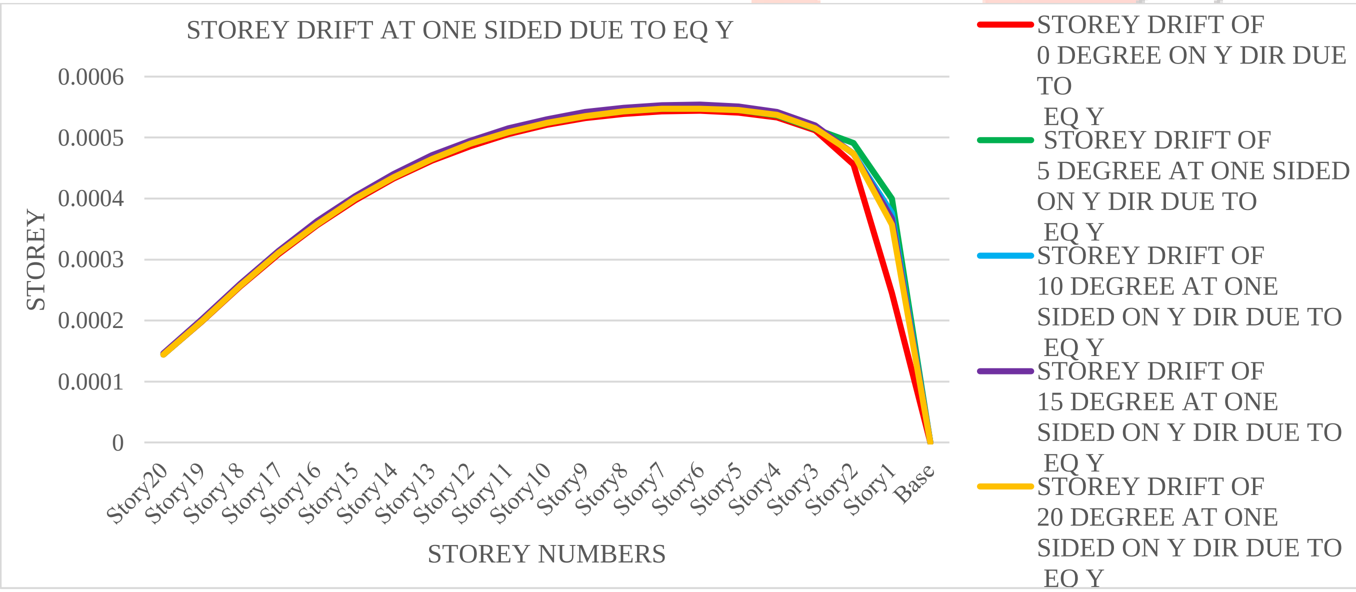


Figure 17: Storey drift ratio at one sided angle models due to EQY

3.3. TIME PERIOD

In seismic analysis, a building's time period is a crucial measure that indicates the duration of one natural vibration cycle. It is influenced by the structure's height, stiffness, and mass distribution. When the natural time period of a building coincides with the primary frequency of ground motion during an earthquake, resonance can occur, making the time period an important factor in assessing the building's dynamic response to seismic forces. For a symmetric structure, the time period decreases slightly across modes. In Mode 1, it drops from 1.862 seconds at 0 degrees to 1.799 seconds at 20 degrees. Mode 2 decreases from 1.705 seconds at 0 degrees to 1.696 seconds at 20 degrees. Mode 3 shows a minimal change, from 1.553 to 1.563 seconds, while Mode 4 experiences a more noticeable reduction, from 0.608 seconds at 0 degrees to 0.578 seconds at

20 degrees, likely due to increased oscillation mass. As shown in the graphs (Figures 18 and 19), below, these variations are clearly illustrated across the different modes and angles.

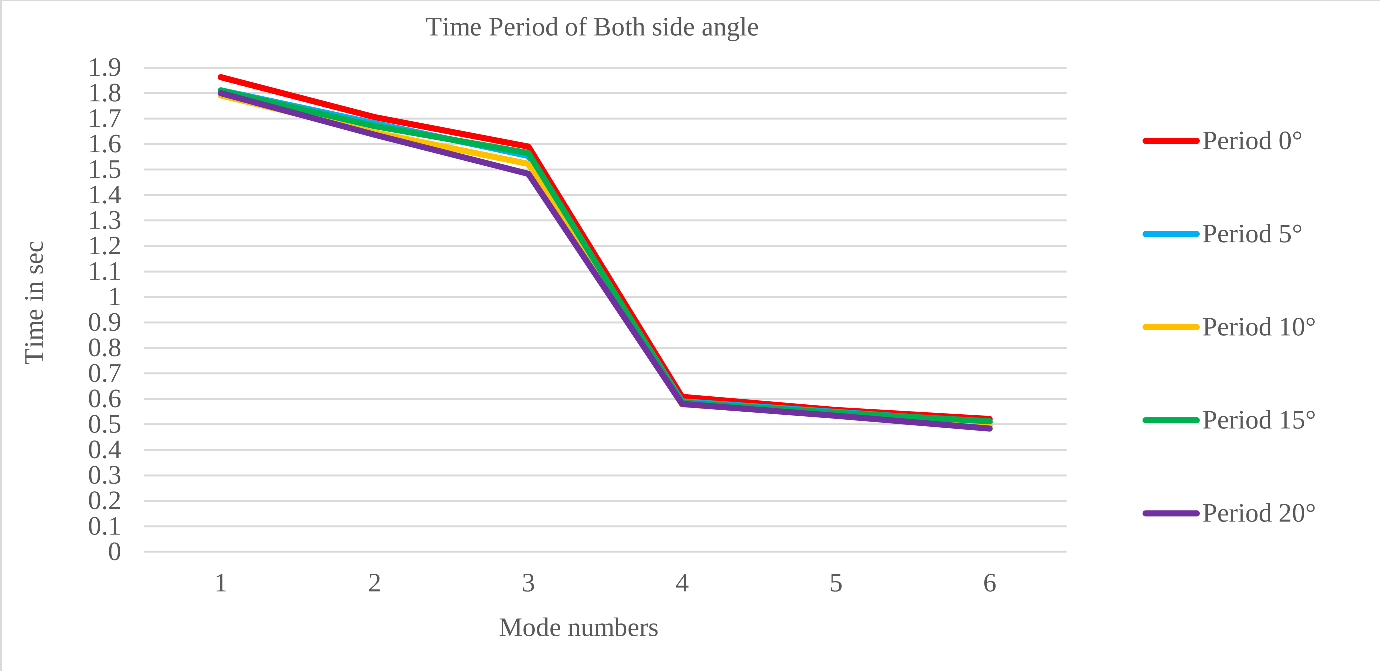


Figure 18: Time period for models of regular angle building

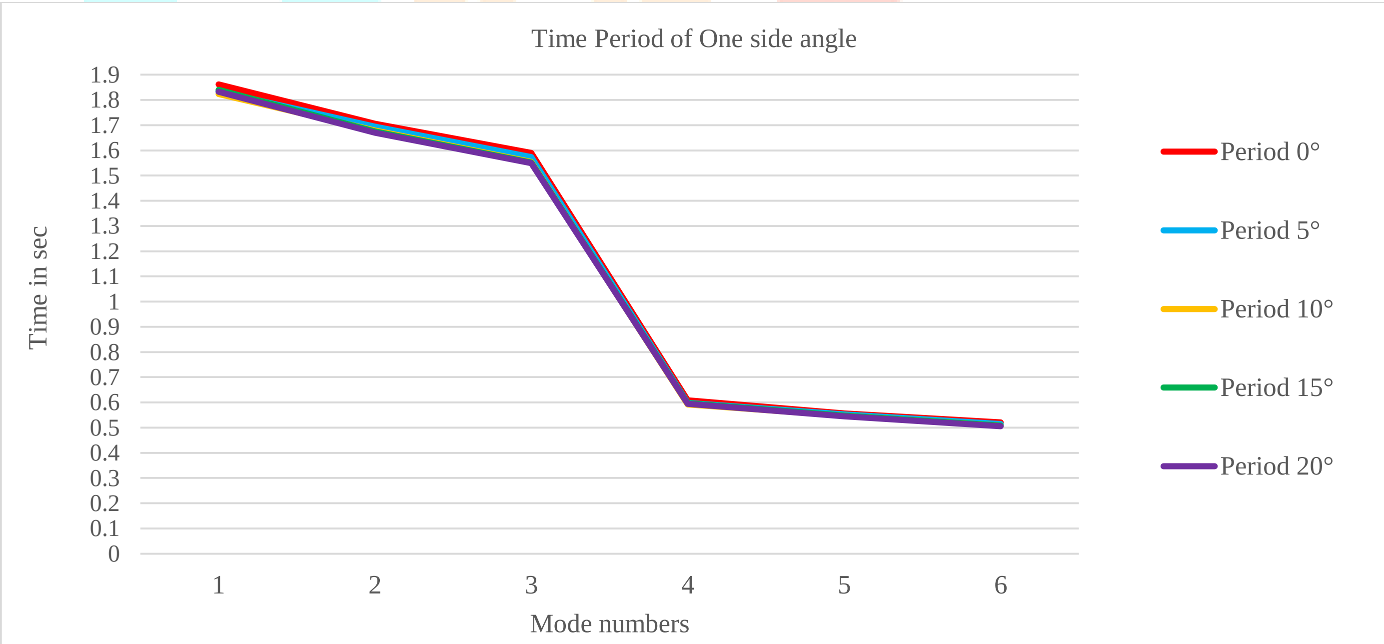


Figure 19: Time period for models of one side angle building

4. CONCLUSIONS

- The displacement values across stories decrease as the angle increases for both the symmetric and one-sided structures, indicating reduced movement in higher-angle scenarios.
- The drift values across stories also show a general decrease as the angle increases. Drifts represent the relative displacement between floors and reduce as the structure stiffens.
- Both the symmetric and one-sided structures show a decreasing trend in time periods across all modes as the angle increases. This suggests that with increasing angle, the structure becomes stiffer, leading to faster oscillation.
- The building behaves as an irregular trapezoidal structure when torsion exceeds 10%, with RZ values of the 20-degree building being 81% and 72% higher than those of the 0-degree building for both and one side angles, respectively.

- 0-degree angle buildings exhibit 10% lower storey displacements and 7% lower storey drifts compared to 10-degree angle buildings.
- At 10% torsion, the building shows significant irregularity, indicating a substantial impact of torsional effects on structural behavior at larger angles.
- Both side angle buildings have 12% higher storey displacements than one side angle buildings.

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