Seismic Response of Stiffness Irregularity at Ground Floor with and without Shear Walls

ABSTRACT

In today's scenario, one of the greatest challenges for structural engineers is designing and constructing seismic-resistant structures. Seismic activity, or earthquakes, poses a significant threat to civil engineering structures, and ensuring that buildings can withstand the forces generated during an earthquake is crucial for public safety and infrastructure resilience. Irregular configurations, whether in the building's floor plan or its elevation, are widely acknowledged as significant contributors to failure during seismic events. These irregularities can lead to uneven distribution of forces and stresses, compromising the building's ability to withstand the seismic forces and potentially resulting in structural failure. Soft storeys, typically located at ground levels for various functional purposes, pose challenges in seismic regions due to their lack of sufficient lateral load-resisting elements resulting in excessive lateral deformation and collapse during intensive earthquakes. Hence, the present study investigated the seismic response of irregular reinforced concrete structures possessing stiffness irregularity at ground floor with and without shear wall. A ten-storey regular frame is modified by incorporating vertical irregularity in elevation by increasing the height of the ground floor. The complete structural analysis and modeling are carried out by using the software ETABS 2020. The Time History method is applied, and the study is focused on seismic zones V in India. The performance of structures are compared based on criteria such as storey displacement, storey drift, storey shear and overturning moment. The results lead to the conclusion that a building structure exhibiting stiffness irregularity is prone to instability which is indicated by higher displacement and drift values. Structures incorporating shear walls have demonstrated greater stability compared to structures without shear wall as they exhibited higher base shear values and experienced a reduction in lateral displacement by more than 40%. The presence of shear walls also has enhanced the stability and strength of the structure, showing a linear response during critical earthquakes.

Keywords: Stiffness irregularity; earthquake; time history method; shear wall.

1. INTRODUCTION

Recent and historical earthquakes have demonstrated that inadequate construction and design practices, both in terms of quality and quantity, can result in significant losses and destruction of structures. In today's urban cities, it is not practical to construct structures with regular configurations in most cases due to factors such as irregular plot dimensions, aesthetic considerations, and functional requirements. However, structures with irregular configurations, whether horizontally or vertically, are more susceptible to the forces of earthquakes and wind, which can result in structural collapse, property damage, and casualties. Buildings with irregularities, particularly those constructed in seismically active areas, are not recommended due to their increased vulnerability to seismic events. Therefore, it is crucial to understand the seismic responses of such structures by conducting thorough seismic analysis. While building codes recommend regular configurations, real-world constraints often necessitate irregular structures, especially in earthquake-prone areas. There have been research efforts to understand the behavior of irregular configuration structures under earthquake forces, there is still a need for well-established guidelines specifically for multi-storey structures with irregular configurations.

Soft storeys are often incorporated at the ground level to provide ample space for parking, commercial activities, or other functional uses. While soft storeys offer benefits in terms of functionality, aesthetics, and construction economics, they can pose significant challenges in terms of structural integrity during seismic events. The lack of lateral load-resisting elements, such as shear walls or bracing, in a soft storey makes it susceptible to excessive lateral deformation and collapse during earthquakes. In regions prone to seismic activity, special attention must be given to designing soft storeys to ensure that they do not compromise the overall seismic performance and safety of the structure.

Studying the seismic behaviour of soft storeys facilitates the enhancement of structural design practices. Design improvements techniques, such as adding shear walls, bracing systems, or other lateral load-resisting elements, can help to enhance the seismic performance of soft storeys.

Shear walls, vertical elements added to structures, effectively resist lateral forces like wind, blasts, and earthquakes. Their inclusion provides a robust solution to prevent building collapse, making them excellent for enhancing earthquake resistance in multi-storey reinforced concrete buildings.

Poonam et al. (2012) studied the response of a 10 storeyed plane frame to lateral loads with mass and stiffness irregularities in the elevation. It was concluded that the less drift was for the regular frame configuration while the maximum drift was for the models with floating columns. Maximum shear was obtained for the frames carrying the heavier mass [1].

Patil et al. (2017) studied the dynamic response of multi-storey buildings with plan asymmetry. They have numerically analyzed multi-storeyed frames having different plan shapes. It was reported that the increase in height of T and L shaped buildings increased the displacement response and stress at the re-entrant corners [2].

Pujar et al. (2017) conducted a study on seismic analysis of plan irregular multi-storied buildings with and without shear walls. In this study, G+9 RCC buildings were modeled with horizontal geometric irregularities like I-Shape, L-Shape and C-Shape. It was concluded that by deploying shear walls the uprooting effect of the building was decreased by 50–70% [3].

Dubule et al. (2018) considered a residential building of G+ 13 storied structure for the seismic analysis which was located in zone III. Three types of irregularities namely mass irregularity, stiffness irregularity and combination of stiffness and mass irregularity were considered. It was concluded that the storey shear force was found to be maximum for the first storey and it decreased to minimum in the top storey in all cases. The stiffness irregular structure experienced lesser base shear and had larger inter-storey drifts [4].

Siva et al. (2019) studied a total of 54 irregular frames consisting of 34 configurationsthat have single irregularity and 20 have combinations of irregularities. It was concluded that the combination of stiffness and vertical geometric irregularities had shown maximum displacement response whereas the combination of re-entrant corner and vertical geometric irregularities had shown less displacement response. The structural response depended on the type, location and degree of irregularity [5].

Zabihullah et al. (2020) conducted a study on the effect of (vertical & horizontal) geometric irregularities on the seismic response of RC structures. It concluded that the vertical geometric irregularity model provided superior seismic performance whereas horizontal geometric irregularity model provided least seismic performance among the models compared [6]
Karra et al. (2021) conducted a study on a 40 storey high-rise building with mass and stiffness irregularity at different locations. It had been noted that the proposals of using the irregularities of mass and soft storey in the middle position of the 40 storey building was the best selection, if the regular building was not the choice for the architects of the project [7].

Zaid et al.(2021) observed the performance of simple G+10 Structure without and with shear wall and RCC X-bracing system and the effect of vertical irregularity (stiffness irregularity) was introduced at 3rd and 6th floors in high rise building (G+10). The results obtained from STAADPro concluded that a storey with increased storey height at lower storey's levels leads to more damage under seismic load. Shear wall model was the most effective structure and storey drift decreased to a minimum when irregular Structure was stiffened with the shear walls [8].

Neeraja et al. (2022) studied G+12 reinforced concrete framed structures, including both regular and various models with stiffness irregularities, to analyze the potential of progressive collapse in buildings. The failure of elements was more in stiffness of irregular models when compared to regular models. This showed that structures having irregularity in stiffness were more prone to progressive collapse [9].

Rachakonda et al. (2022) conducted a study on buildings with horizontal irregularity, vertical irregularity, stiffness irregularity and mass irregularity with and without shear wall and responses of the buildings were compared. It was concluded that vertical geometrical irregular buildings with shear walls had shown considerably better performance than other irregular buildings. By adding shear walls to irregular building models, the overall performance of the building was increased nearly 60-70% [10].

Intekhab et al. (2023) conducted a study on high rise buildings with different methods for analysis of seismic irregularities. It was concluded that the non-linear time history analysis, increment dynamic analysis, considered several intensity of ground vibrations to perform nonlinear analysis. Therefore, the method performed well against the other analytical techniques as all the scaled ground motions were recorded to predict the damage due to the earthquake [11].

Yaqubi et al. (2023) conducted a study on effects of irregularities and was compared with regular buildings of different stories in seismic zones II & IV. Irregular buildings with mass irregularity, stiffness irregularity, geometry vertical, and plan irregularity were considered. It was concluded that the storey displacement and storey drifts were maximum in the irregular building as compared to regular buildings and variation of storey displacement was observed lesser in G + 10 structures having irregular configuration with shear walls [12].

The goal of this research work is to contribute to the development of structures that are safer and more resilient to seismic forces by addressing stiffness irregularity and minimizing their adverse effects by incorporating lateral load-resisting elements.

According to IS 1893 (2016), a structure is considered to have stiffness irregularity if its lateral stiffness is less than the storey immediately above it [13]. Hence, this study investigated the seismic impact of the Nepal (Gorkha) Earthquake 2015 by using time history analysis. A ten-storey regular frame is modified to include stiffness irregularities in elevation by increasing the height of the ground floor with and without shear walls. The performance of structures is evaluated by comparing various criteria, such as storey displacement, storey drift, storey shear, and overturning moment.

2. METHODOLOGY

The present research focused on analyzing a (G + 9) multi-storied building with a built-up area of 30 m x 30 m. The column-to-column distance is maintained at 5 m in both X and Y directions. The study explored stiffness irregularity with and without shear walls using ETABS 2020 software. The structural analysis involved the application of time history methods, specifically considering seismic Zone V. The time history input function is shown by Fig. 1.

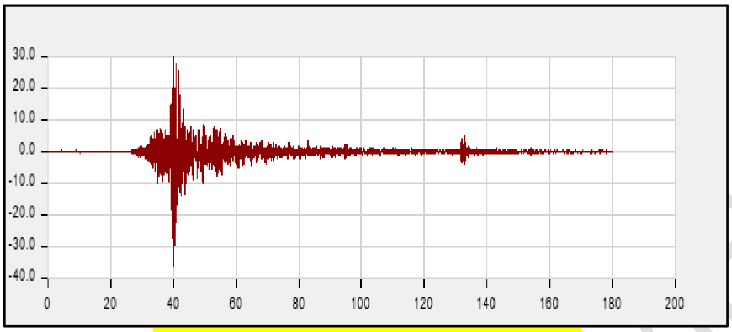

Fig. 1. Time history input function

Stiffness Irregularity without shear is addressed by adjusting the height of the ground floor to 4.5 m, while maintaining a height of 3 m for all other floors.

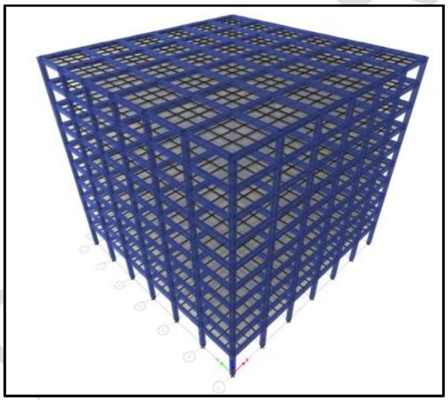

Fig. 2. Stiffness Irregularity without Shear Wall (SIWoSW)

Stiffness Irregularity with shear wall is addressed by adjusting the height of the ground floor to 4.5 m, while maintaining a height of 3 m for all other floors along with the addition of shear walls at 4 corners in L shape.

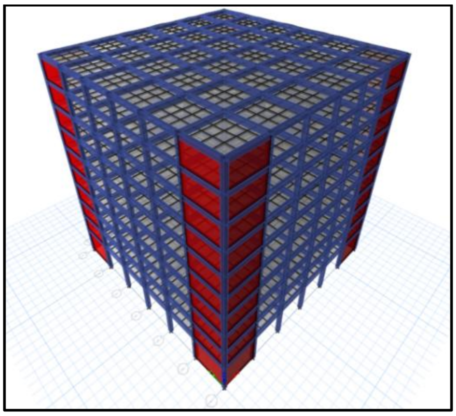

Fig. 3. Stiffness Irregularity with Shear Wall (SIWSW)

The analysis of the structure models incorporated the consideration of the limit state of collapse to ensure that a structure can withstand these forces without failure.

The essential parameters considered for the analysis are outlined below:
1. No of Stories: 10 (G+9)
2. Slab size: 0.150m
3. Column size: 450 mm x 450 mm
4. Beam size: 400 mm x 500 mm
5. Shear wall thickness: 0.150m
6. Live load (occupancy): 3.0 KN/m^2 and 1.5 KN/m^2 (roof) [14]
7. Dead load (floor finish): 1.5 KN/m^2 [15]
8. Density of concrete: 25 KN/m^3
9. Steel grade: Fe550
10. Importance factor: 1.5 [13]
11. Response reduction factor: 3 [13]
12. Damping Ratio: 5% [13]

The following data has been taken into account in this research work to conduct time history analysis:
1. Seismic event name: Nepal (Gorkha) Earthquake 2015
2. Date of occurrence of seismic event: 25th April 2015
3. Magnitude: 6.6
4. Station: KTP, Kirtipur Municipality Office, Kirtipur

3. RESULTS AND DISCUSSION

3.1 Storey Displacement

The storey displacement results obtained from time history X and Y direction are visually depicted in Fig. 4 and Fig. 5 respectively. Structure with shear walls has shown less displacement values at all the storeys as compared to structure without shear wall as the reduced lateral stiffness of a soft storey allows it to deform more easily, leading to increased lateral displacement. Among all the storeys, the maximum displacement is observed at the terrace. The addition of shear walls resulted in an average reduction of over 40% in overall displacement because the presence of shear walls in a structure reduces the lateral displacement or movement of the building when subjected to lateral loads.

Yaqubi et al. observed that the variation of storey displacement was observed lesser in G + 10 structures having irregular configuration with shear walls [12].

The findings of the storey displacement align with earlier research that used the response spectrum method, indicating a consistent pattern of reduced displacement in building storeys when shear walls were incorporated by Rachakonda et al. [10].

Sonawane et al. conducted a study on 12-storey buildings with different configurations and irregularities was analyzed using ETABS software in zone V. It was concluded that in buildings with soft stories, the stiffness decreased causing an increase in storey displacement [16].

Pardeshi et al. conducted experimental investigation on reducing the size of the member to make structure economical and efficient by locating shear walls at varying places in irregular shape building. It was concluded that the top deflection was reduced and reached within the permissible deflection after providing the shear wall in a shorter direction [17].

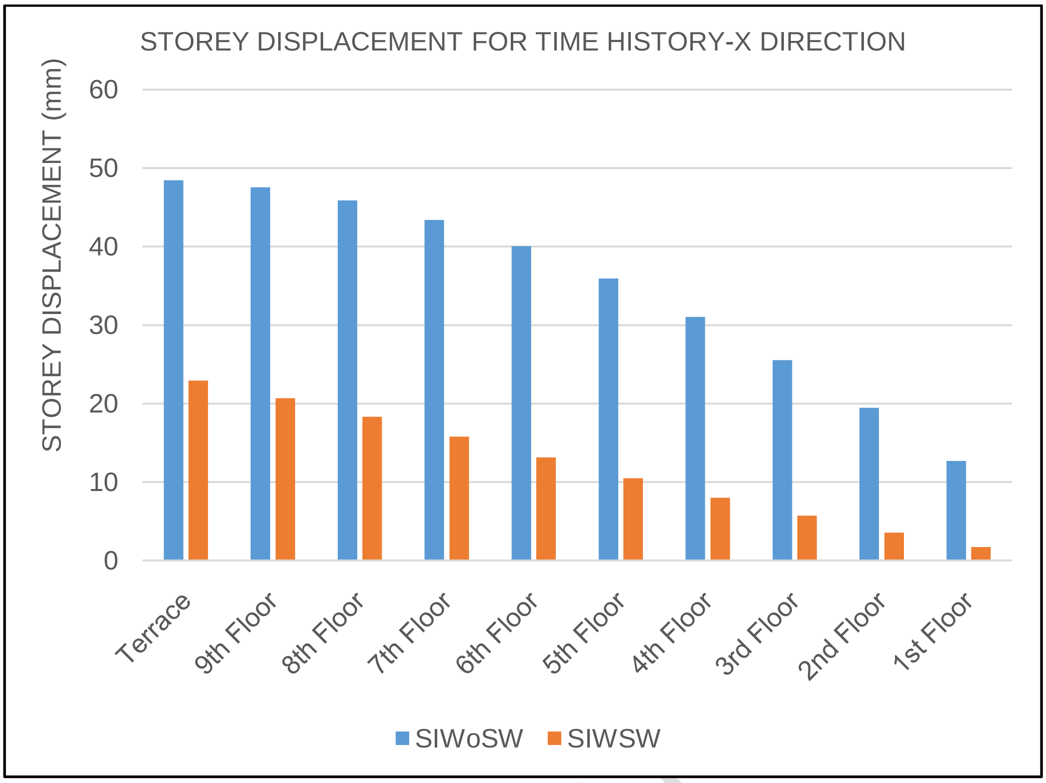

Fig. 4. Storey Displacement for Time History-X direction

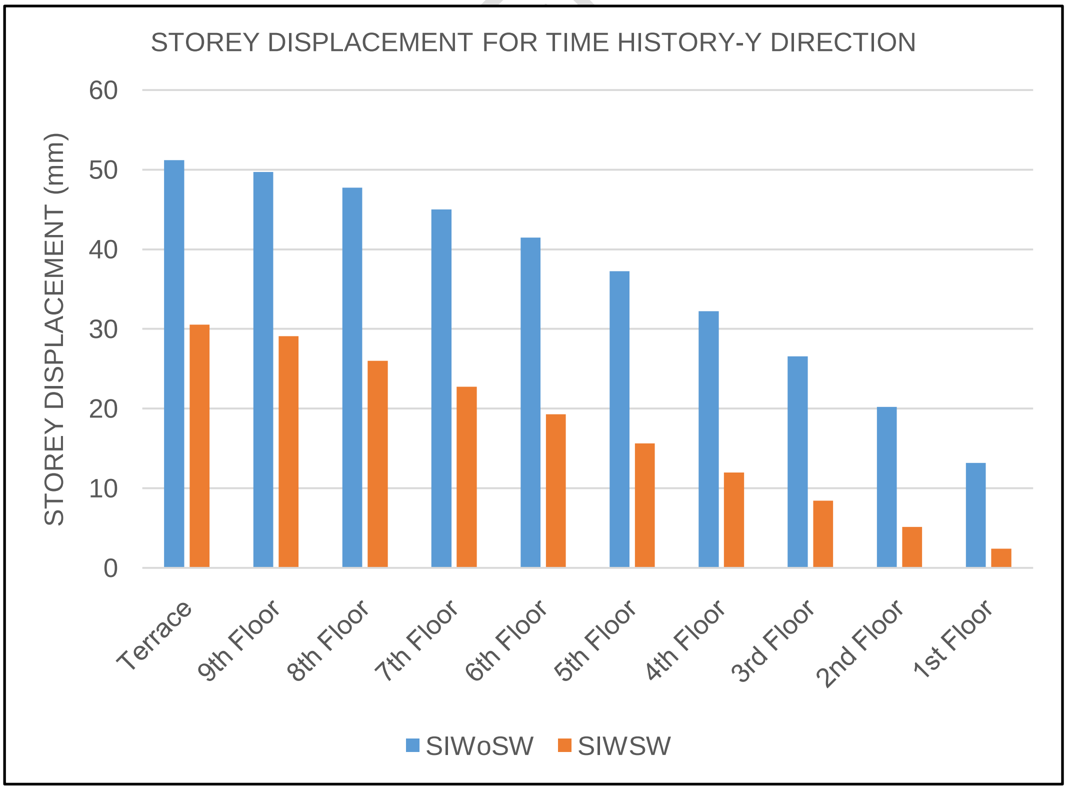

Fig. 5. Storey Displacement for Time History-Y direction

3.2 Storey Drift

Storey drift results in both X and Y direction are visually depicted in Fig. 6 and Fig. 7 respectively. Structure with shear walls has shown less drift values at all the storeys as compared to structure without shear wall because shear walls play a crucial role in reducing inter-storey drift by providing lateral support and limiting the relative movement between floors during seismic events.

Among all the stories, the first floor has experienced the maximum drift, primarily due to the increase in the height of the ground floor. Due to the inclusion of shear walls, the reduction is most significant at the first floor, amounting to more than 80% which is due to the role of shear walls in mitigating the lateral drift of the structure when subjected to lateral loads.

Ali et al. conducted a seismic analysis to assess the impact of soft storey configurations in G+6 building frames.The study concluded that buildings with a soft storey on any floor was susceptible to earthquake damage due to the reduced stiffness of the soft storey. The maximum drift was observed at the floor with the soft storey, surpassing the drift at adjacent floor levels [18].

The results regarding storey drift are consistent with previous research that employed the response spectrum method. This alignment suggests a recurring trend of decreased drift in building storeys when shear walls are added Rachakonda et al. [10].

Buildings characterized by a soft storey experienced an increase in lateral drift, as noted in the research conducted by Sonawane et al. [16].

Zaid et al. shear wall model was the most effective structure and storey drift decreased to a minimum when irregular structure was stiffened with the shear walls [8].

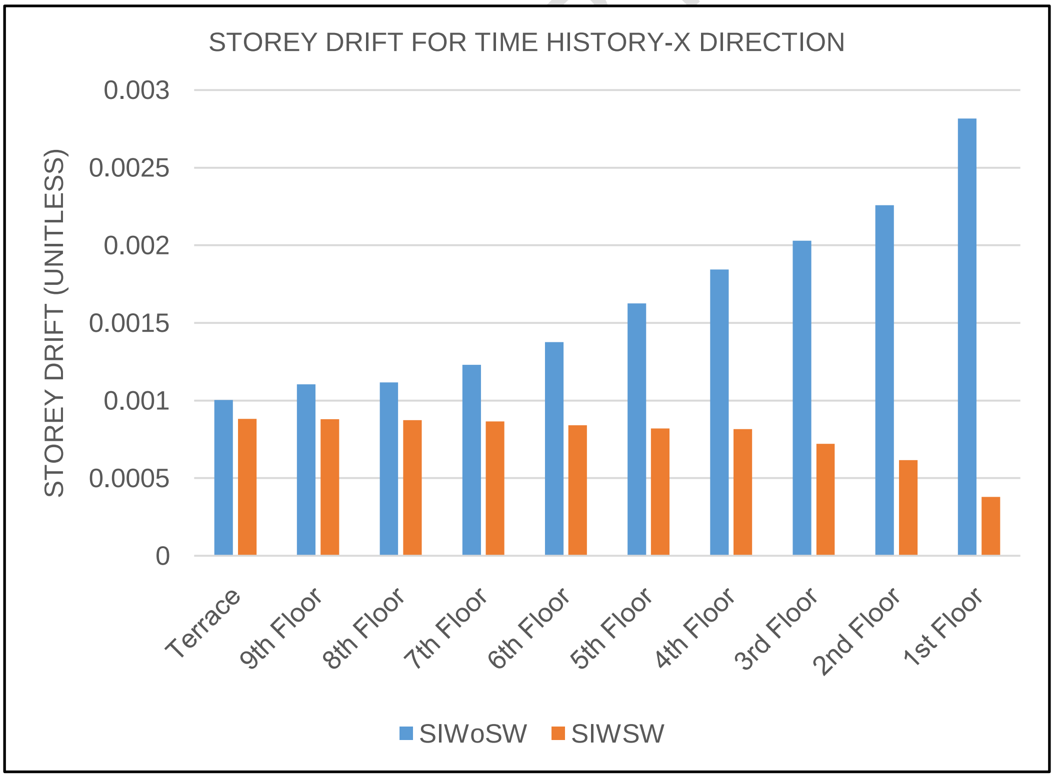

Fig. 6.Storey Drift for Time History-X direction

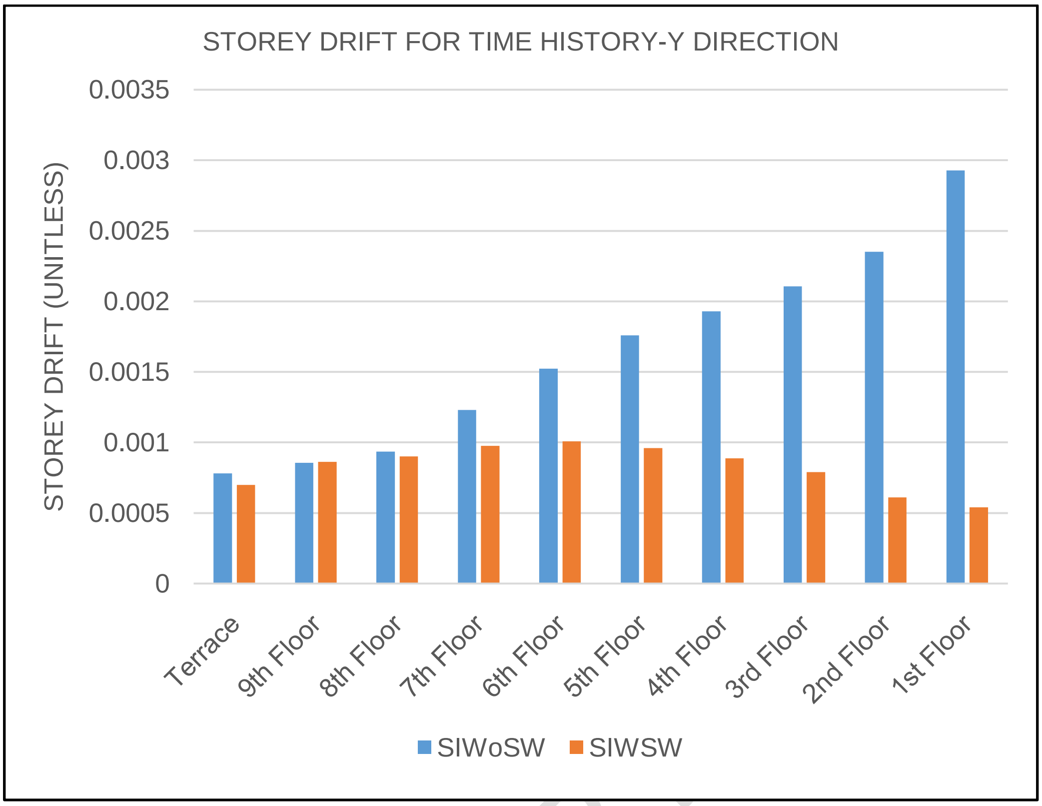

Fig. 7.Storey Drift for Time History-Y direction

3.3 Storey Shear

The results of storey shear in both the X and Y directions are visually presented in Fig. 8 and Fig. 9, respectively. In stiffness irregularity, there is a linear increase in storey shear from the terrace to the first floor. Dubule et al. concluded that the storey shear force was found to be maximum for the first storey and it decreased to minimum in the top storey in all cases [4].

The storey shear is more for the structure with shear walls as compared to without shear walls due to increase in seismic weight which increased the overall stability and seismic performance. The addition of shear walls led to an increase of more than 40% in storey shear because storey shear is influenced by the seismic weight of the structure, and thus, a structure with shear walls exhibited higher shear compared to a structure without shear walls.

Poonam et al. analyzed 10 storeyed plane frames to lateral loads with stiffness irregularities in the elevation and concluded that maximum shear was obtained for the frames carrying the heavier mass [1].

Chandrahas et al. study involved conducting pushover analysis on a G+9 multi storied building using SAP 2000 software to investigate the effects of a soft storey at various floor levels. It was observed that the presence of infill walls was noted to have a substantial impact on the stiffness and lateral resistance of a frame structure [19].

The analysis revealed that the storey shears were highest at the base of the structure and progressively decreased from the base to the top concluded by Mon et al. [20].

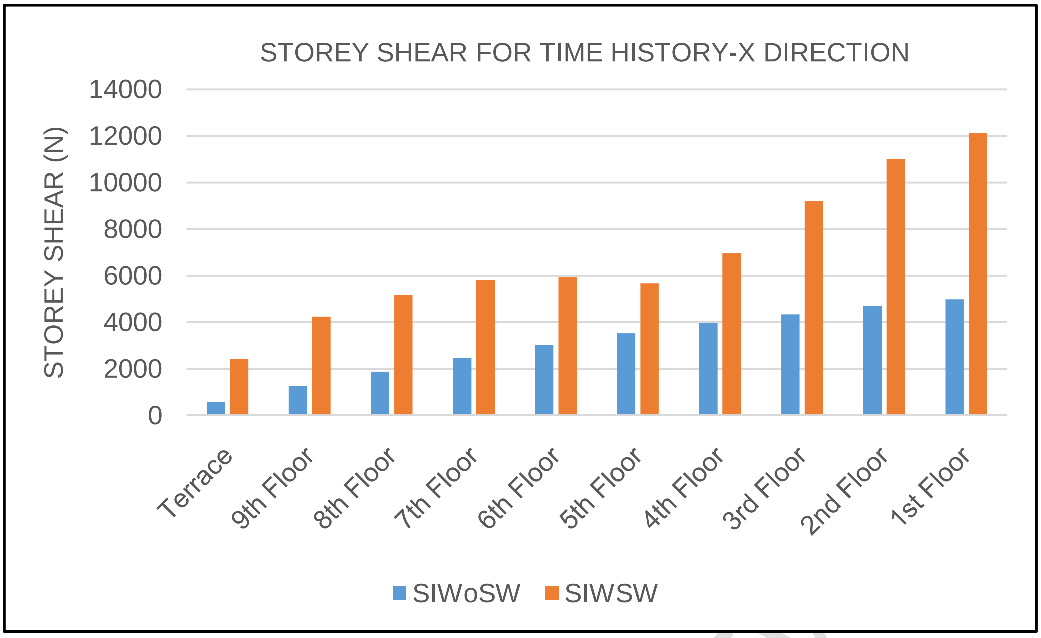

Fig. 8. Storey Shear for Time History-X direction

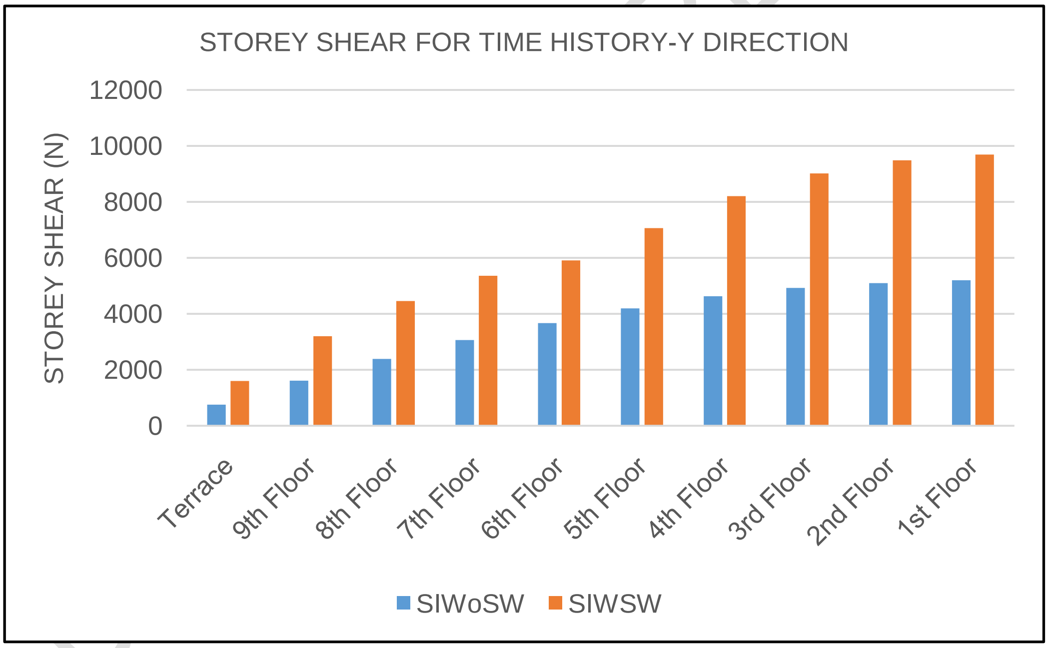

Fig. 9. Storey Shear for Time History-Y direction

3.4 Overturning Moment

The results of overturning moment in both the X and Y directions are visually presented in Fig. 10 and Fig. 11, respectively. In stiffness irregularity, there is a linear increase in overturning moment from the terrace to the first floor. The overturning moment is more for the structure with shear walls as compared to without shear walls. The addition of shear walls resulted in a significant increase of more than 40% in overturning moment as overturning moment is influenced by the seismic weight and height of the structure. This, in turn, contributed to a more stable response under lateral forces, reducing the risk of excessive overturning.

Pujar et al. reported that by deploying shear walls the uprooting effect of the building was decreased by 50–70% [3].
Mon et al. studied comparative analysis of high-rise reinforced concrete irregular buildings with shear walls. It was concluded that the storey moment was influenced by the seismic load, with the largest storey moment observed at the base [20].

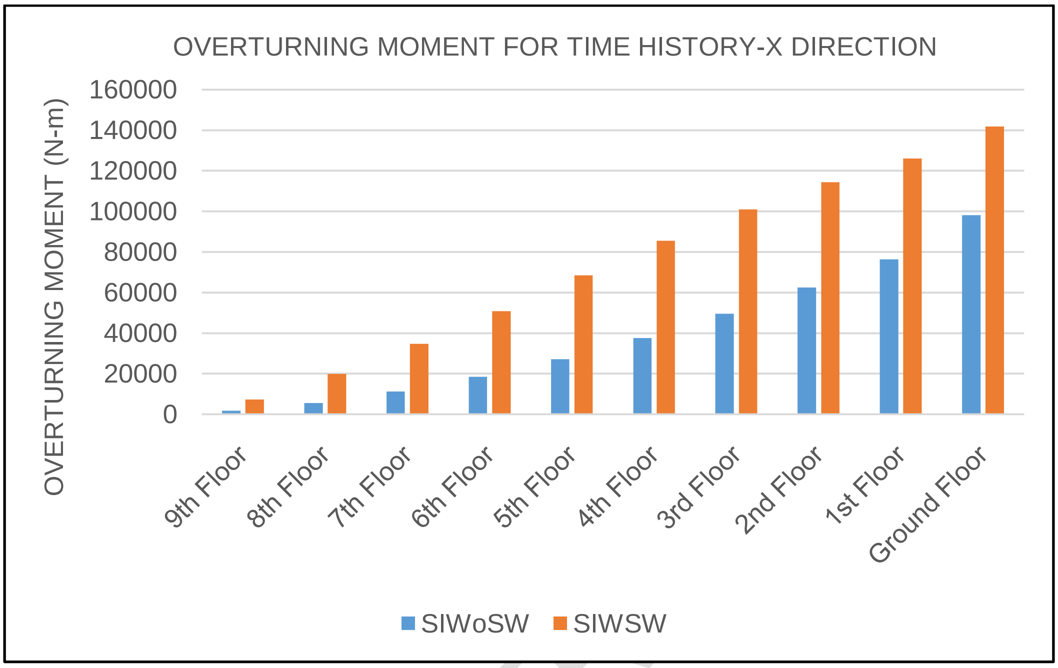

Fig. 10. Overturning Moment for Time History-X direction

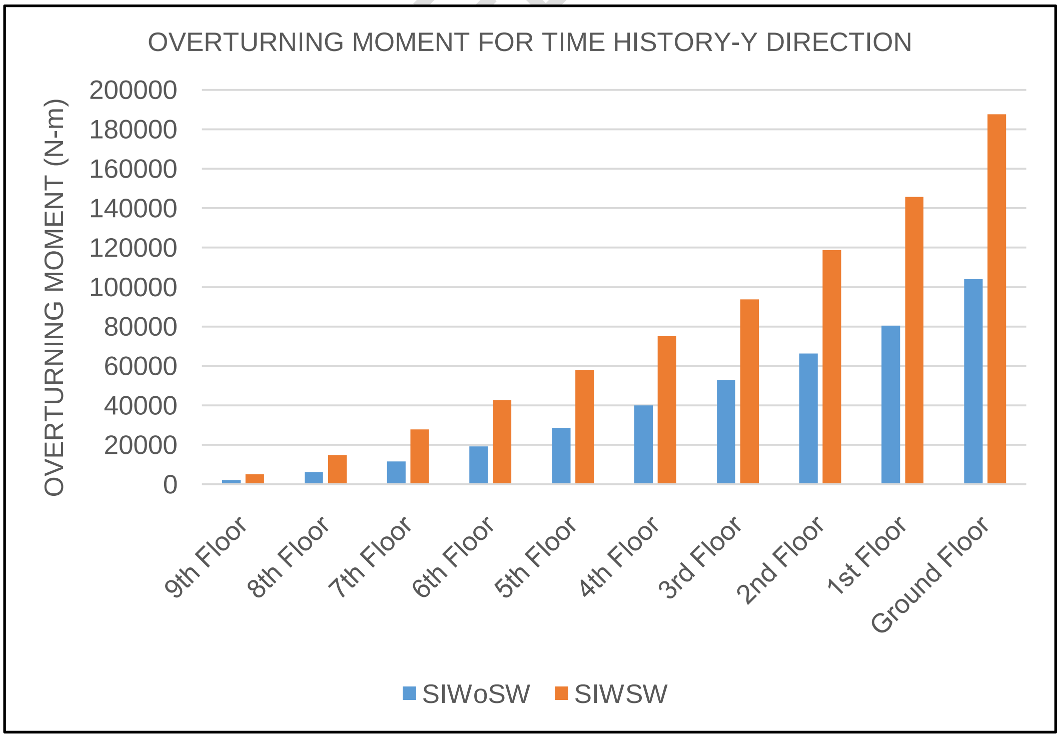

Fig. 11. Overturning Moment for Time History-Y direction

3.5 Deflected Shape

The visual representation in Fig. 12 illustrates the deflected shape of a structure with stiffness irregularity, both with and without shear walls, as analyzed in the Time History-X direction.

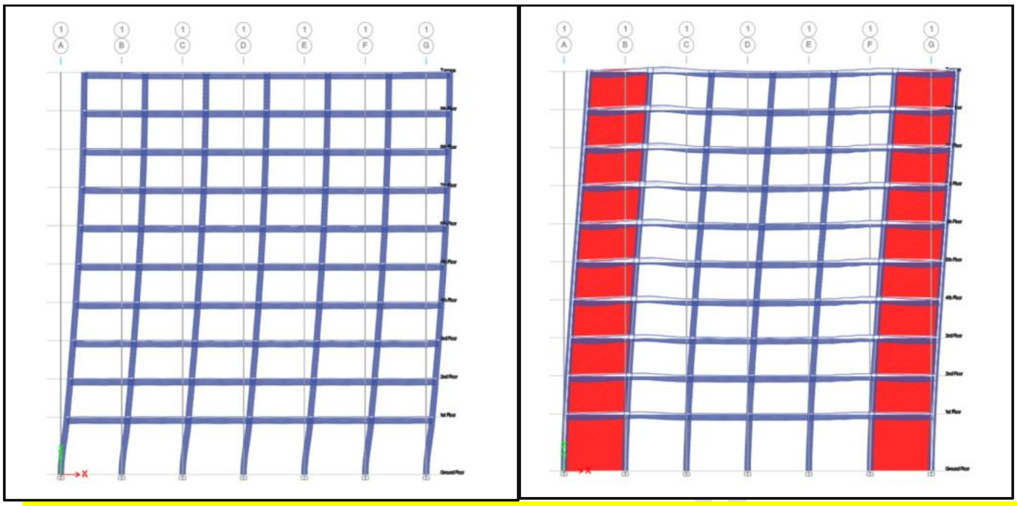

Fig. 12. Deflected shape of Stiffness Irregularity in Time History-X direction with and without shear wall respectively

The visual representation in Fig. 13 illustrates the deflected shape of a structure with stiffness irregularity, both with and without shear walls, as analyzed in the Time History-X direction.

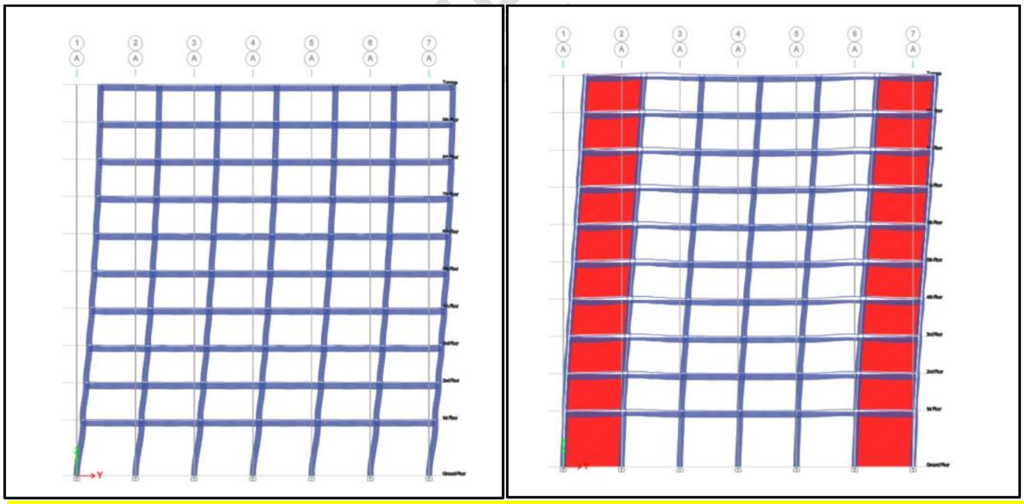

Fig. 13. Deflected shape of Stiffness Irregularity in Time History-Y direction with and without shear wall respectively

The deflected shape visualization revealed specific localized deformations, highlighting areas of concentrated forces or vulnerabilities. The presence of shear walls introduced additional lateral load-resisting elements. Shear walls contributed to the overall stiffness of the structure, helping control lateral deformations. As a result, the deflected shape with shear walls exhibited reduced lateral displacement, minimized inter-story drifts, and a more controlled response to seismic forces.

4. **CONCLUSION**

The goal of this research work is to understand, analyze, and address the impact of variations in stiffness within a building. This involves understanding how this irregularity affect the structure's response to ground motion and devising strategies to mitigate potential risks. The addition of shear walls to a soft story building significantly improved its ability to resist seismic forces.This approach aligns with best practices in seismic design and contributes to the safety and performance of the building in seismic events. The seismic performance of the structure is compared on the basis of parameters like displacement, drift, shear and overturning moment with and without shear wall.
The observations of the response during the significant earthquake provide the basis for the following conclusions:

1. The inclusion of shear walls in an irregular structure resulted in a significant improvement in the overall performance of the building under lateral forces, increasing it by approximately by more than 50%. This is because shear walls provide additional lateral stiffness to the structure. This increased stiffness helps in resisting lateral loads more effectively, reducing lateral deformations and improving the overall stability of the building.

2. The addition of shear walls led to a reduction of more than 40% in storey displacement values which signifies an increase in the stiffness of the structure, enabling it to better withstand lateral forces acting on the building.

3. The highest storey drift was observed at the first floor due to an increase in height at the ground floor. However, after the addition of shear walls, the storey drift decreased by more than 80% at the first floor, indicating a substantial improvement in the building's stability and resistance to lateral forces.

4. The base shear and overturning moment values are increased by more than 40% with addition of shear walls as shear walls play a crucial role in absorbing and dissipating lateral forces, transferring the loads to the foundation. This increased resistance to lateral loads is reflected in higher base shear values.

5. Structures with inclusion of shear walls demonstrated greater stability compared to structures without shear walls, as indicated by the higher levels of base shear and overturning moment associated with shear walls.

These conclusions collectively suggest that the shear wall makes the irregular structure perform better during an intensive earthquake.

5. FUTURE RECOMMENDATTIONS

The current research work involved several approximations and assumptions, suggesting potential areas for improvement through further research. The following future recommendations can be drawn:

1) Employing response spectrum, pushover analysis, and wind analysis to investigate other irregularities.
2) Comparing a specific irregularity at various locations within a structure.
3) Exploring combinations of horizontal and vertical irregularities using different software platforms.
4) Investigating load-bearing structures with various irregularities at different locations.
5) Assessing irregular structures with additional features like dampers, bracing, wall infills, and base isolation systems.
6) Conducting a comparative analysis of responses using different software platforms.

7) Performing seismic analysis considering recent earthquakes in various zones and site conditions.

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