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Impact of Shear Wall Placement on Seismic Performance of Vertically Irregular Structures

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ABSTRACT

This study investigates the dynamic behavior of buildings under various structural configurations, offering insights into optimizing design for seismic resilience and structural stability. Using the STAAD-PRO software, a comprehensive analysis of 96 distinct building models was conducted to explore load distribution, stress allocation, and overall structural integrity. The research focused on the impact of building height and shear wall placement on critical parameters, such as frequency, period, and story shear. The findings reveal that for buildings measuring 18 meters in height, the highest frequency is achieved when the shear wall is positioned exclusively at the front. Conversely, taller structures, such as those at 45 meters, exhibit prolonged oscillation cycles when shear walls are placed at the front, back, and both sides. Story shear analysis further highlights that the highest values occur with shear walls strategically placed at these same locations. Notably, the 18-meter structure demonstrates the highest sensitivity to lateral forces, with a clear trend of decreasing story shear as building height increases. The study also uncovers a strong correlation between building height and displacement. As height increases, so does structural displacement; however, configurations with shear walls at the front, back, and both sides effectively minimize this movement. In conclusion, this research underscores the complex interplay between shear wall placement, building height, and structural responses. These findings provide valuable guidance for enhancing earthquake resistance, optimizing structural designs, and informing engineering decisions in building design and construction.

Keywords: Structural analysis, STAAD-PRO software, Shear wall placement, Building height.

INTRODUCTION

Vertical Irregularity

According to Harirchian, Lahmer, Buddhiraju et al. (2020), vertical irregularities are those that are significantly large, tightly confined, or unevenly distributed along the vertical axis of the structure. Kostakis and Athanatopoulou (2020) emphasized that this imbalance can significantly alter a building's response to external forces, such as those generated by earthquakes or storms. Vertical abnormalities can compromise a building's stability and structural integrity, increasing its vulnerability to damage and failure (Yu et al., 2020; Dahiya et al., 2021).

To comprehend the seismic behavior of structures and vertical disturbances, a thorough analysis of relevant literature has been conducted. Researchers can identify suitable study topics and establish general design principles for these models through a comprehensive review of existing studies (Das et al., 2021). An overview of slip, ductility, and damage distribution in three dimensions, considering the effects of earthquake direction, provides warnings and recommendations based on undesirable outcomes. Studies indicated that seismic orientation, vertical distribution, relative plane orientation, and response can result in numerous variations (20%-60%) (Amarloo & Emami, 2019). A detailed review assessed the impact of the new Italian building code on the pushover analysis of buildings in a systematic manner. The effectiveness of development has been evaluated by comparing traditional and modern approaches and reviewing a survey of 3D RC models (Ruggieri & Uva, 2020). The significance of building design decisions in earthquake performance has been highlighted, with attention to the potential for planning and façade inconsistencies caused by architectural, functional, and distribution restrictions that lead to complex seismic responses in earthquake zones (Alecci & De Stefano, 2019).

Another study explored the seismic behavior of irregularly planned L-shaped building frames. It demonstrated the difference between critical moments derived through numerical methods and actual analysis, as well as the impact of seismic incident angles on necessary responses (Khanal & Chaulagain, 2020). A novel type-2 fuzzy-logic model-based approach has been proposed to evaluate building damage. This method considered several variables, including building characteristics, surface roughness, and ground motion, to assess earthquake-induced damage (Harirchian & Lahmer, 2020). The use of maximum-height shear walls to enhance lateral load resistance in multi-story buildings has been analyzed, with emphasis on prior research as a foundation for establishing further study goals (Patel & Jamle, 2019). Additionally, various pushover analysis techniques for unreinforced irregular masonry structures have been investigated. The effectiveness of these methods was compared, highlighting the importance of addressing structural irregularities to improve accuracy, particularly in the presence of torsion (Aşkolu et al., 2020).

Shear Walls

Shear walls are crucial for enhancing a building's seismic performance as well as its overall structural integrity (Madani & Dolatshahi, 2020; Yadav & Jamle, 2020). The external forces produced by earthquakes, wind loads, and other horizontal movements are intended to be withstood by these vertical components (Syed et al., 2021). The integration and location of shear walls can significantly influence how a structure behaves and reacts (Chen et al., 2020; Shakeel et al., 2019).

The cross-connection system for the automated design of curtain walls in residential buildings represents an innovative advancement in wall-design methodologies. A sophisticated and efficient approach is introduced, utilizing generative adversarial networks (GANs) to optimize the design process by leveraging existing wall-design data (Liao et al., 2021). This review examines precast reinforced-concrete walls, synthesizing findings from international studies on their external performance. Recent investigations into precast reinforced-concrete shear walls addressed critical aspects, including regulatory requirements, mounting techniques, experimental results, and deployment outcomes.

The application of shear-wall strips to enhance lateral load capacity in multi-story buildings is also reviewed, particularly the use of good-height shear walls to address vertical rise and horizontal irregularity issues in contemporary high-rise buildings. Adaptation studies emphasized how new systems meet seismic and wind-load requirements (Singhal et al., 2019). An in-depth analysis of equations, connectivity, and their impacts on ductility, axial resistance, and composite behavior highlighted the importance of considering inconsistencies in the design process, contributing to an understanding of effective design (Patel & Jamle, 2019).

A novel design strategy utilizing convolutional networks for curtain-wall building layouts has been introduced. This approach presents innovative procedures, including two separate estimations for the architectural design of wall and floor bounding-box dimensions (Mo et al., 2021). Research into seismic behavior demonstrated the role of shear walls in preventing structural deformation and damage during earthquakes, underscoring their importance in enhancing the safety of buildings against external loads (Pizarro et al., 2021). A 3D numerical study using ANSYS software evaluated dynamic responses of large height-width ratio liquid-storage structures with varying baffles and isolation. Results revealed increased wall tensile stresses with isolation and improved safety by adding horizontal baffles (Jing & Zhang, 2024). The study used Monte Carlo simulations to assess how uncertainties in soil properties, particularly shear modulus (G), influence the seismic response of structures. The findings highlighted the importance of considering stochastic variations in soil properties for more accurate and resilient seismic design (Merouane et al., 2024).

Innovative shear-wall systems for multi-story modular buildings constructed with precast concrete have also been examined. By investigating the effect of tall structures on seismic behavior, new architecture and construction methods have been highlighted. Research on cross-laminated timber (CLT) infilled shear walls explored their potential for seismic reinforcement in reinforced-concrete buildings, combining numerical evaluations and experiments to provide valuable insights for improving seismic performance (Wang et al., 2020; Stazi et al., 2019).

Machine learning's role in predicting the failure mode, strength, and deformation capacity of reinforced-concrete shear walls has been discussed, emphasizing the significance of various design parameters (Zhang et al., 2022). A dynamic analysis using ETABS evaluated the seismic performance of multi-story buildings with different shear-wall arrangements. By analyzing floor slide, foundation slip, motion, and torsional anomalies, this study contributes to the development of earthquake-resistant structures (Ahamad & Pratap, 2021).

Aim and Objectives

The primary aim of this study is to comprehensively investigate the effects of shear-wall placement and building height on the behavior and performance of RCC structures under various loading scenarios, with the goal of enhancing seismic resilience, load-bearing capacity, and structural design. To achieve this aim, the following objectives are pursued:

1. To simulate and evaluate the behavior of 96 distinct RC building models with varying shear-wall positions and building heights using STAAD-PRO software.
2. To analyze trends and correlations across different shear-wall configurations and building heights for key parameters, including displacement, frequency, time period, story shear, and participation percentage.
3. To identify the most effective shear-wall placements for minimizing displacement and enhancing structural stability.
4. To provide valuable insights into the interaction between shear-wall configuration, building height, and overall structural response, facilitating informed design decisions and practical application recommendations.

METHODOLOGY

This research effort contains a thorough investigation that includes the development and evaluation of 96 different structural models. These models incorporate changes in building height, seismic zones, and the positioning of shear walls in order to reflect various scenarios. STAAD-PRO is the main piece of software used for the analysis.

To elaborate, the study looks into the effects of various variables on the structural behavior of buildings made of reinforced concrete (RC). Three crucial parameters are specifically changed to investigate their effects:

1. Building Height: Several building heights are taken into account to evaluate how structural reactions vary when a building's height rises or falls. This variation sheds light on the performance of taller or shorter structures under various loading scenarios, such as earthquakes.
2. Seismic Zones: The study investigates various seismic zones, which stand for geographical areas with various levels of seismic activity. The goal of the study is to comprehend how structural behavior adjusts to different levels of ground shaking by looking at how the models react to seismic forces in various zones.
3. Shear-wall Position: The RC building's shear wall, a crucial structural component intended to withstand lateral stresses, is positioned in various places. Analyzing how changes in shear-wall placement influence the building's overall stability and

response provides valuable insights into optimal shear-wall positioning.

The researchers can test and evaluate the behavior of each of the 96 models thanks to the use of STAAD-PRO software. In order to investigate issues, like load distribution, stress distribution, and overall structural integrity, this program is frequently used for structural analysis and design. The goal of the research is to find patterns, trends, and correlations among the numerous parameters through this meticulous modeling and analysis approach. In the end, the discoveries will advance knowledge of the interactions among building height, seismic zones, and shear-wall placement that affect the structural performance of RC structures. The resilience and safety of structures in seismically vulnerable places could be improved by using this knowledge to inform more effective and efficient design approaches. The models were analyzed in accordance with IS 1893: Part 1: 2016, and all the building configurations were designed and evaluated in compliance with the relevant provisions of the Indian Standard Code. The models were analyzed using the Response Spectra Method of analysis, a widely recognized technique for evaluating the dynamic behavior of structures under seismic loading conditions. This method is particularly effective for determining the response of buildings to earthquake forces by utilizing a set of response spectra, which represent the maximum potential response of a structure at various frequencies.

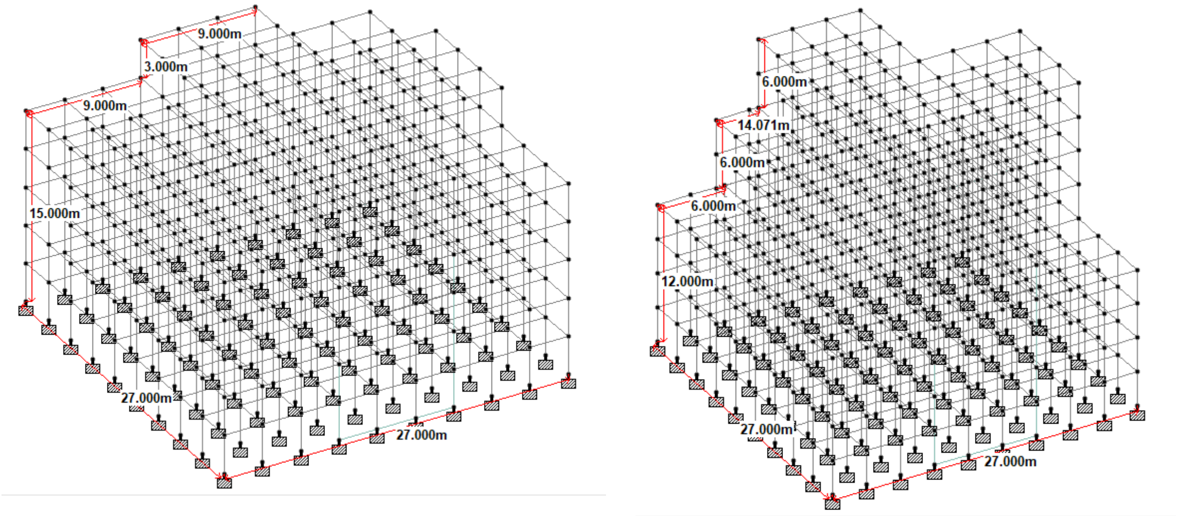
The following 96 models are analysed using STAAD-PRO software:

i. (18 m, 24 m, 33 m & 45 m) height building without shear wall (EQ Zone-II, III, IV & V).
ii. (18 m, 24 m, 33 m & 45 m) height building with shear wall at core location (EQ Zone-II, III, IV & V).
iii. (18 m, 24 m, 33 m & 45 m) height building with shear wall at front location (EQ Zone-II, III, IV & V).
iv. (18 m, 24 m, 33 m & 45 m) height building with shear wall at front & side locations (EQ Zone-II, III, IV & V).
v. (18 m, 24 m, 33 m & 45 m) height building with shear wall at front, side and back locations (EQ Zone-II, III, IV & V).
vi. (18 m, 24 m, 33 m & 45 m) height building with shear wall at front, side 1, back & side 2 locations (EQ Zone-II, III, IV & V).

Table 1 shows the different parameters considered for the modeling.

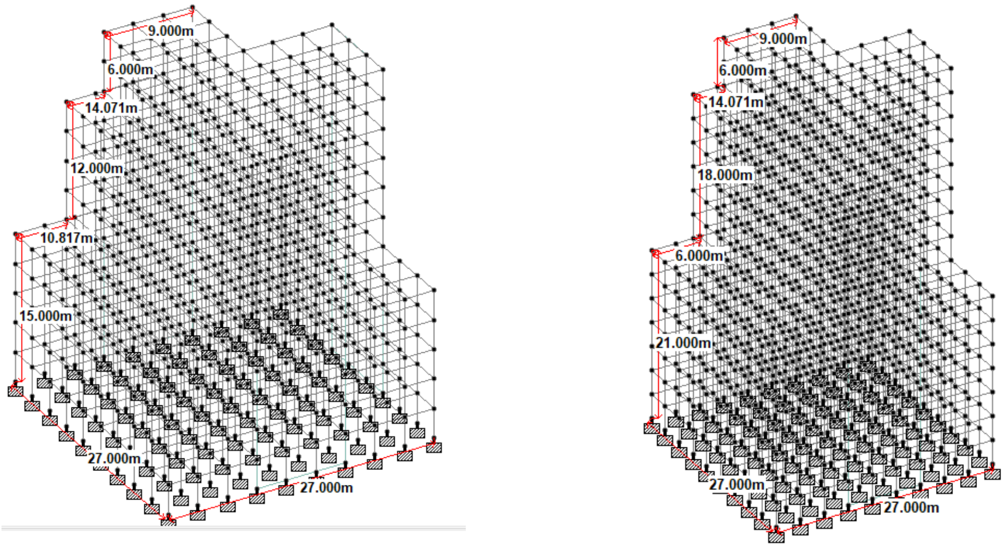
Table 1. Parameters for the analysis of RC building

Sr. No.	Parameter	Dimensions
1	Column size	500 x 500 mm
2	Beam size	230 x 500 mm
3	Support type (ST)	Fixed support
4	Response reduction factor (RRF)	5
5	Importance factor (IF)	1
6	Rock & site soil factor (RSSF)	2
7	Type of structure (TS)	1
8	Damping ratio (DR)	0.05
9	Thickness of shear wall	150 mm



(a) Geometry of the 18m model

(b) Geometry of the 24m model

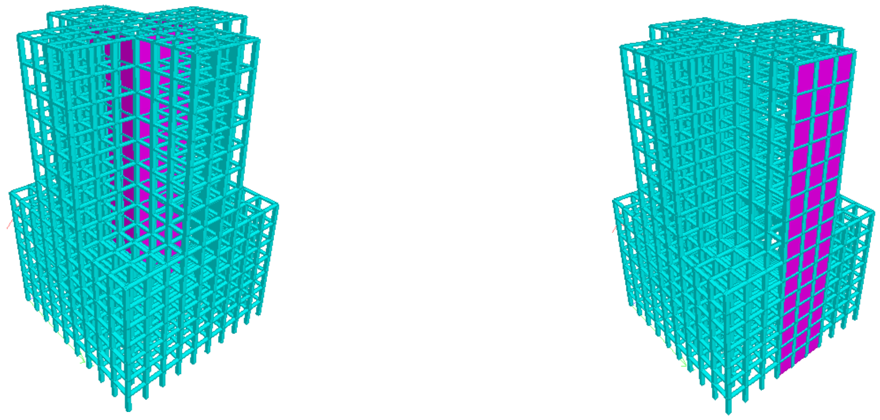


(c) Geometry of the 33m model

(d) Geometry of the 45m model

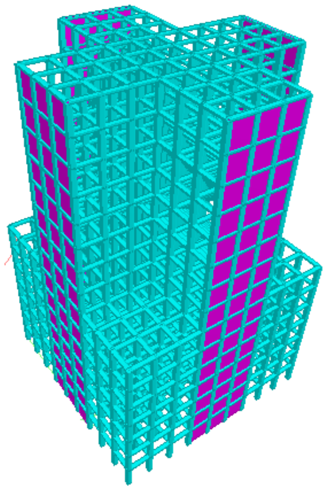
Figure (1): Geometry of the models

Figure (1) illustrates the geometric configurations of the models, featuring varying building heights of 18 m, 24 m, 33 m, and 45 m. The dimensions corresponding to these height variations are clearly indicated and labeled on the model's geometry.



(a) Shear wall at core location **(b) Shear wall at front location**

(c) Shear wall at front & side locations **(d) Shear wall at front, back & side locations**



(e) Shear wall at front, back & both side locations

Figure (2): 3D views of the different models used in this work

In Figure (2), various shear-wall placements—at the structure's front, core, both sides, and back—are shown from a three-dimensional perspective. The spatial organization and location of the shear walls within the structure are highlighted by this visual representation.

RESULTS AND DISCUSSION

An exhaustive analysis of the results from the laborious modeling and simulation efforts is presented in the Results and Discussions section. Building height, shear wall placement, and seismic zones are just a few of the study's many varied characteristics that are crucially interpreted in this part.

RC Building with 18m Height

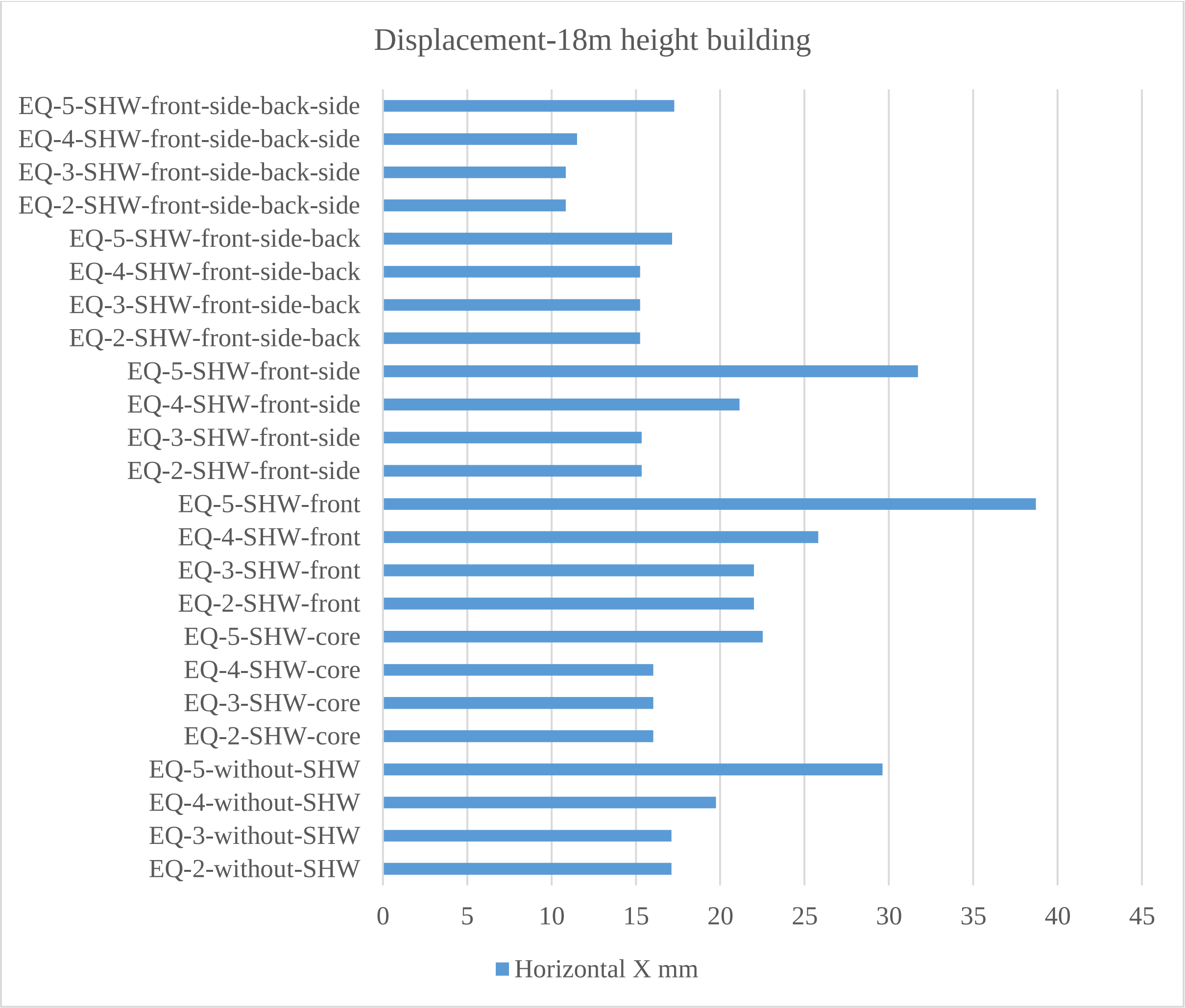


Figure (3): Displacement for 18m-height RC building

The bar chart in Figure (3) shows horizontal displacement (X-direction) at an 18-meter height for buildings under different seismic conditions. Buildings without shear walls (SHW) experience the highest displacement, with "EQ-5 without SHW" reaching around 40 mm, indicating greater vulnerability. In contrast, buildings with SHW show reduced displacement, such as 20 mm in "EQ-4 SHW-front-side" and 15 mm in "EQ-3 SHW-core," highlighting the effectiveness of shear walls in minimizing seismic impact.

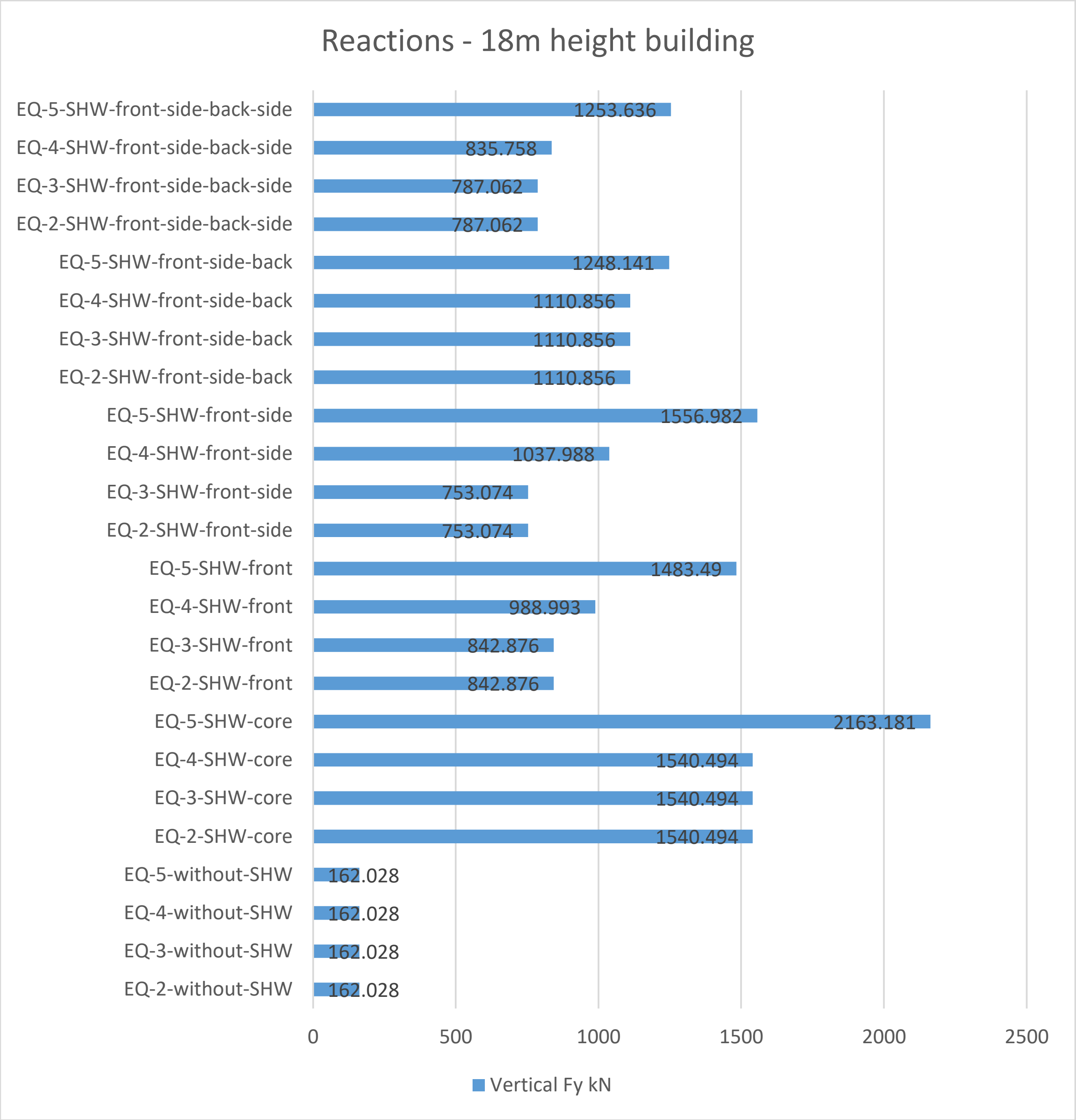
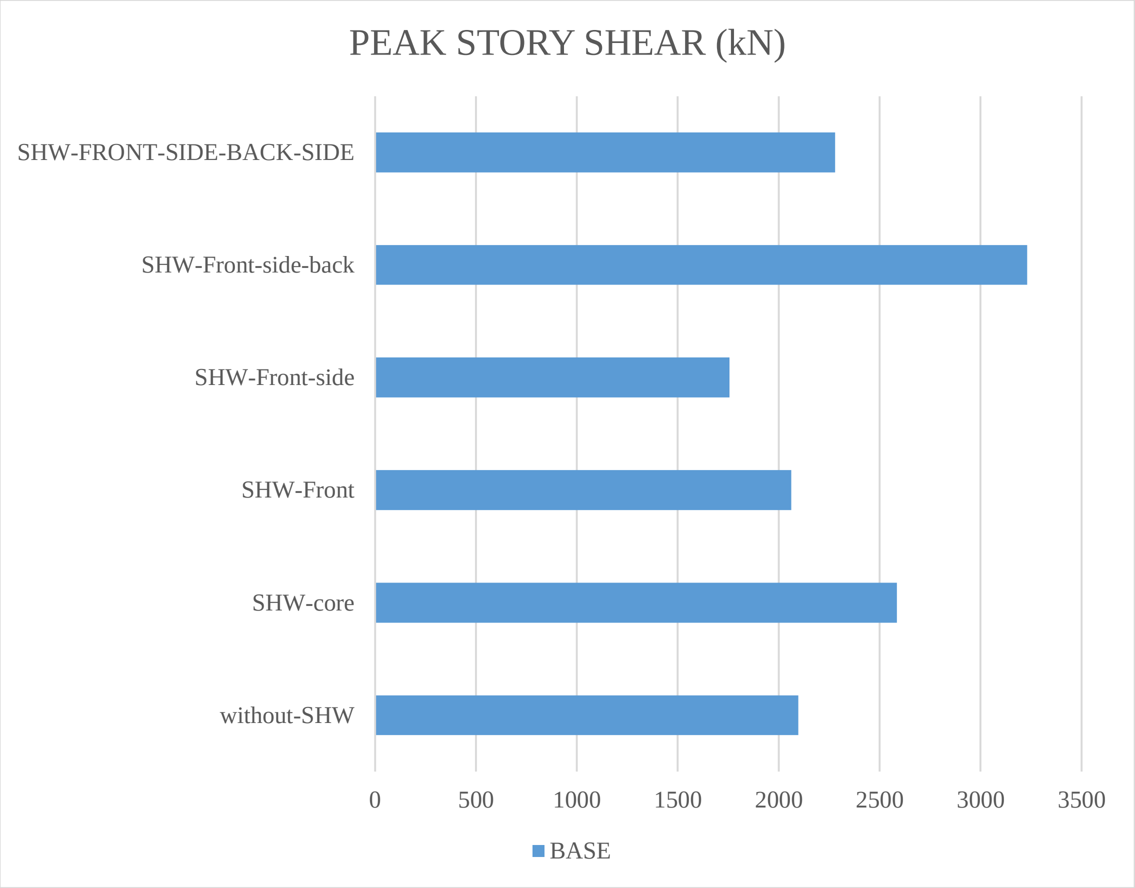
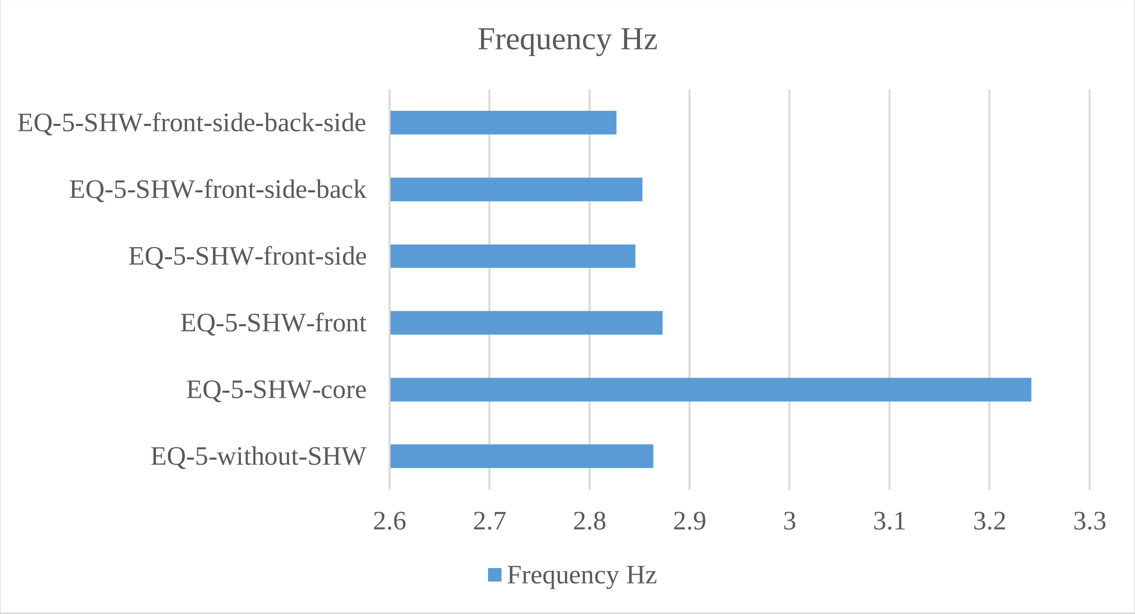


Figure (4): Vertical (F_y) reactions for 18m height RC building

The vertical responses (Fy) for an 18-m-tall reinforced concrete (RC) structure are shown in Figure (4). Notably, the least reactions are seen when there is no shear wall in the building. In contrast, when compared to alternative shear-wall placements and earthquake zone designs, the models with shear walls at the core site within Seismic Zone EQ Zone-V show the greatest reactivity. These results highlight how the distribution of vertical reactions inside the structure is significantly influenced by the positioning of shear walls and the seismic zone characteristics.



(a) Peak story shear for 18m height RC building



(b) Frequency for the 18 m height RC building

Figure (5): Peak story shear (a) and frequency (b) for 18m height RC building

The bar chart in Figure (5) illustrates the peak story shear (in kN) for buildings with different shear-wall (SHW) configurations. The "without-SHW" scenario shows the highest shear of approximately 3000 kN, indicating greater structural demand. Among SHW configurations, "SHW-core" and "SHW-front-side-back" achieve significant reductions, both near 2500 kN, while "SHW-front-side" shows the lowest shear around

1500 kN. This highlights the effectiveness of SHW in reducing story shear forces, with core configurations offering notable benefits.

The peak story shear values for an RC building are shown in the diagram across various floors. Notably, when compared to models with shear walls placed differently, those with shear walls at the front, side, and back locations have the highest story shear values. This finding emphasizes the important role that shear wall placement has in determining how shear stresses are distributed among the building's various levels.

RC Building with 24 m Height

When displacement, base responses, beam forces, story shear, and frequency are taken into account for an RC building with a height of 24 meters, different results are seen. These variations highlight the enormous influence that changing building height can have on structural behavior and response. The various reactions seen across these factors offer important insights into how height variations can affect the general effectiveness and stability of the building under various loading scenarios. This thorough research helps clarify how building attributes and structural behavior interact, allowing for more informed design choices and boosting the robustness of RC buildings.

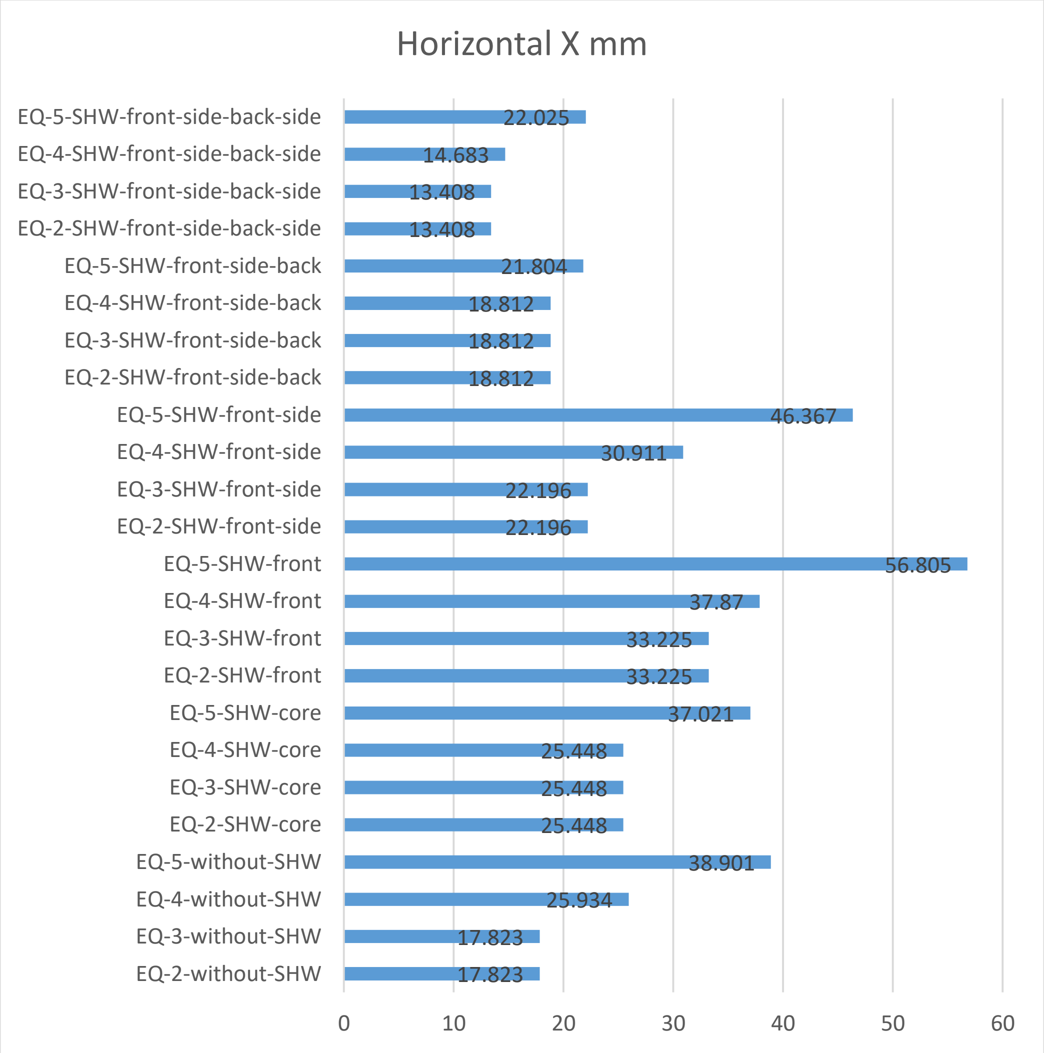


Figure (6): Horizontal displacement (X) for RC building with 24 m height

The RC building scenario with a front shear wall is where the maximum horizontal displacement (X-direction) is observed, as shown in Figure (6). In contrast, the building with shear walls at the front, back, and both side sites exhibits the lowest displacement. The significance of shear-wall placement in determining the lateral displacement behavior of the structure is highlighted by these findings. The observed discrepancies highlight the need for strategic shear-wall positioning for limiting and minimizing horizontal building movements under diverse loading scenarios.

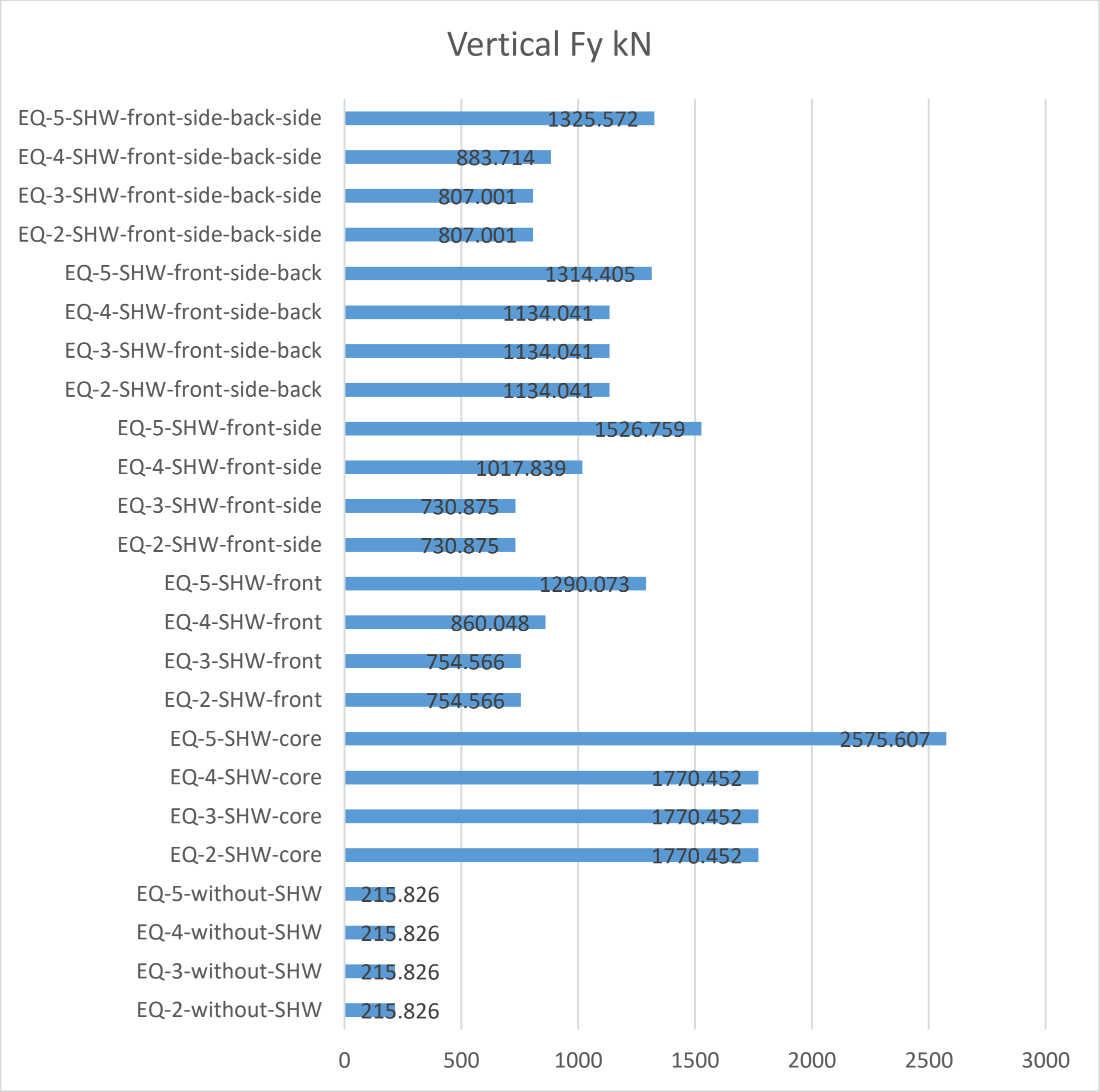
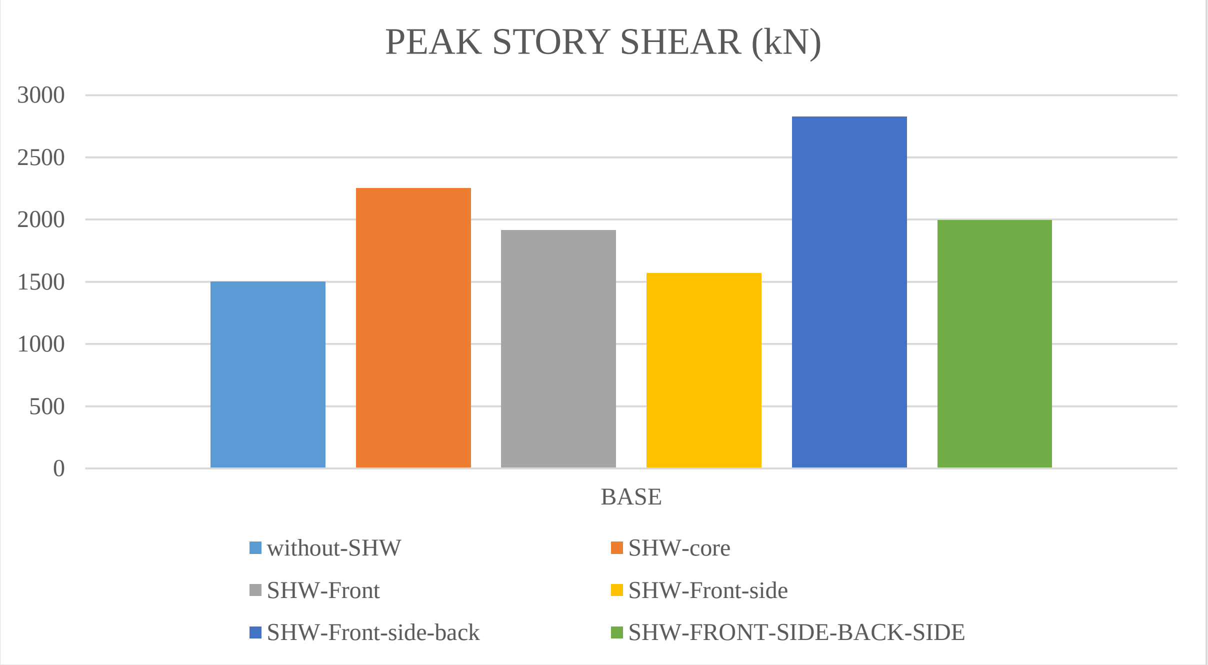
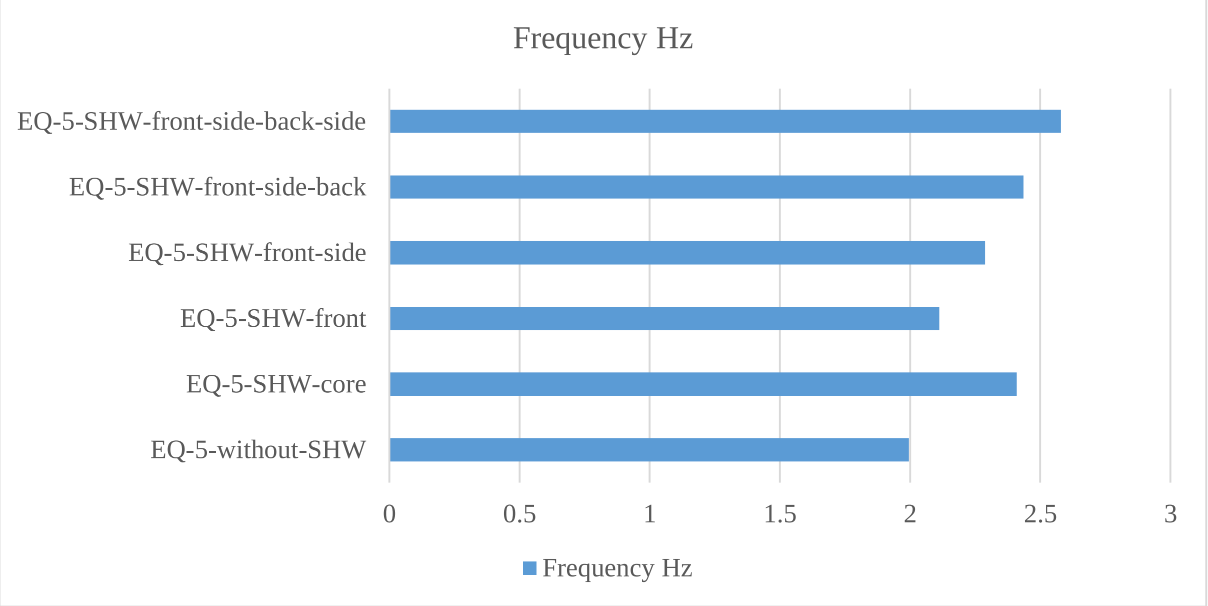


Figure (7): Vertical reaction for 24 m height RC building

In contrast to other model designs, the RC building in seismic zone-V with a shear wall at the core location exhibits the strongest vertical reaction, as observed in Figure (7). The lowest vertical reaction, on the other hand, occurs when the building's shear wall is absent. The vertical reactions were determined through the structural analysis of the building, specifically for the foundation story. These reactions represent the forces transmitted to the foundation, providing critical insights into the load distribution and structural behavior of the system under the applied loading conditions.



(a) Peak story shear for 24 m height RC building



(b) Frequency for 24 m height RC building

Figure (8): Peak story shear (a) and frequency (b) for 24 m height RC building

The bar chart in Figure (8) compares the peak story shear (in kN) for buildings with different shear-wall (SHW) configurations. The "without-SHW" scenario shows the highest shear at approximately 3000 kN, indicating maximum structural demand. Among SHW configurations, "SHW-core" has a shear of around 2500 kN, while "SHW-front-side" shows the lowest value near 1500 kN. The "SHW-FRONT-SIDE-BACK-SIDE" configuration achieves a moderate reduction, with shear around 2000 kN, emphasizing the effectiveness of shear walls in reducing structural forces. The buildings with shear walls at the front, back, and both side locations exhibit the highest frequency. The lowest frequency, on the other hand, is observed in structures lacking shear walls.

RC building with 33-m Hight

The results obtained for the 33-meter-tall RC structure take into account a number of different factors, including displacement, frequency, time period, participating percentage, and story shear. These findings illuminate the dynamic response characteristics of the building and offer a thorough understanding of its behavior under various loading scenarios. Informed design and engineering decisions are made possible by the analysis of these factors, providing information on the building's structural integrity, stability, and capacity to bear external forces.

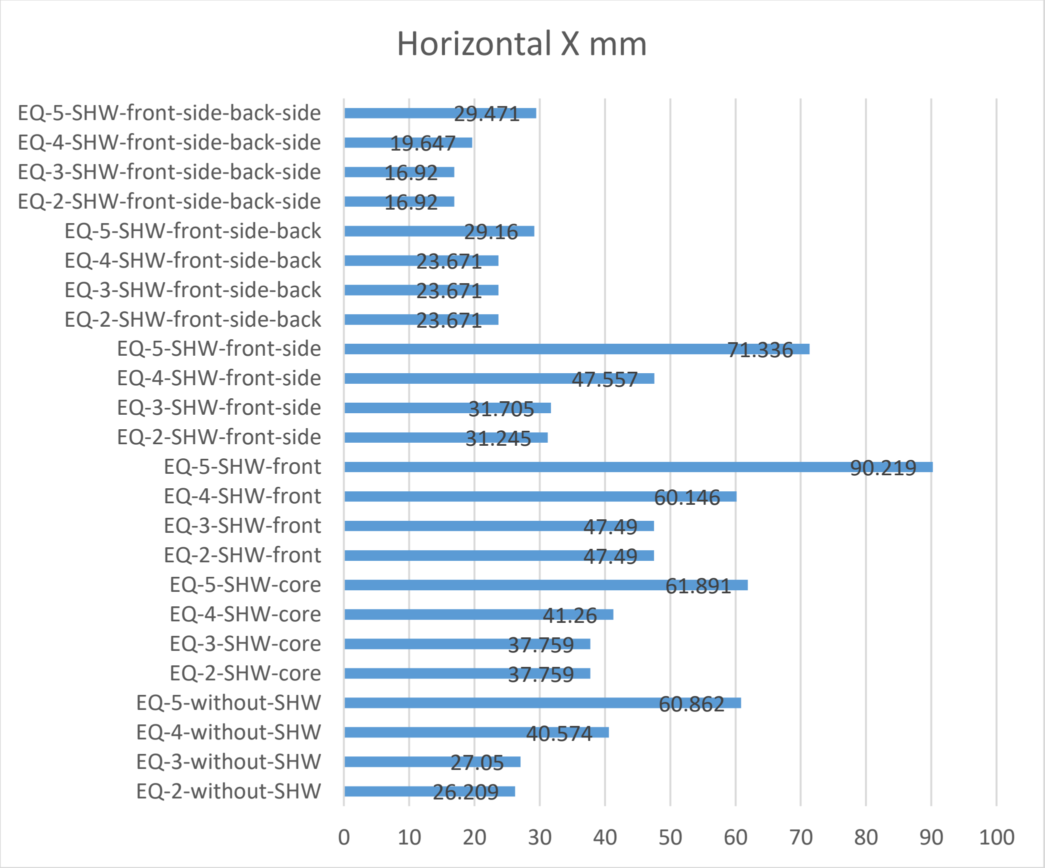
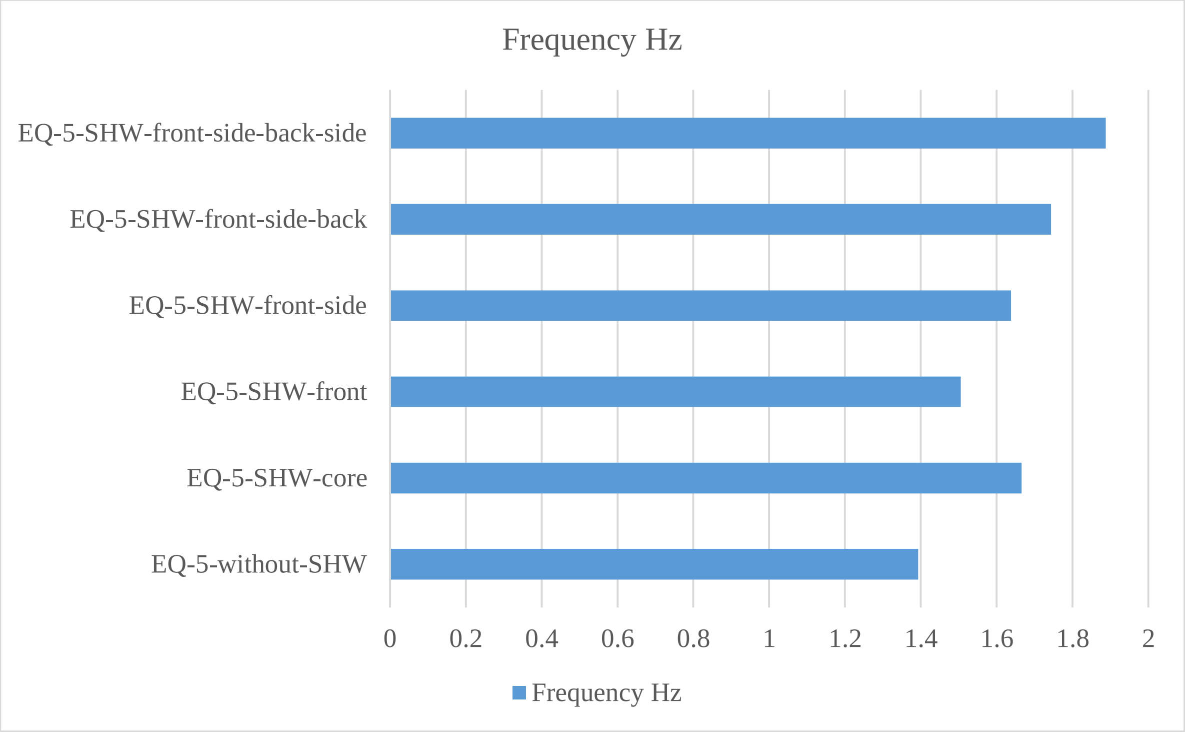
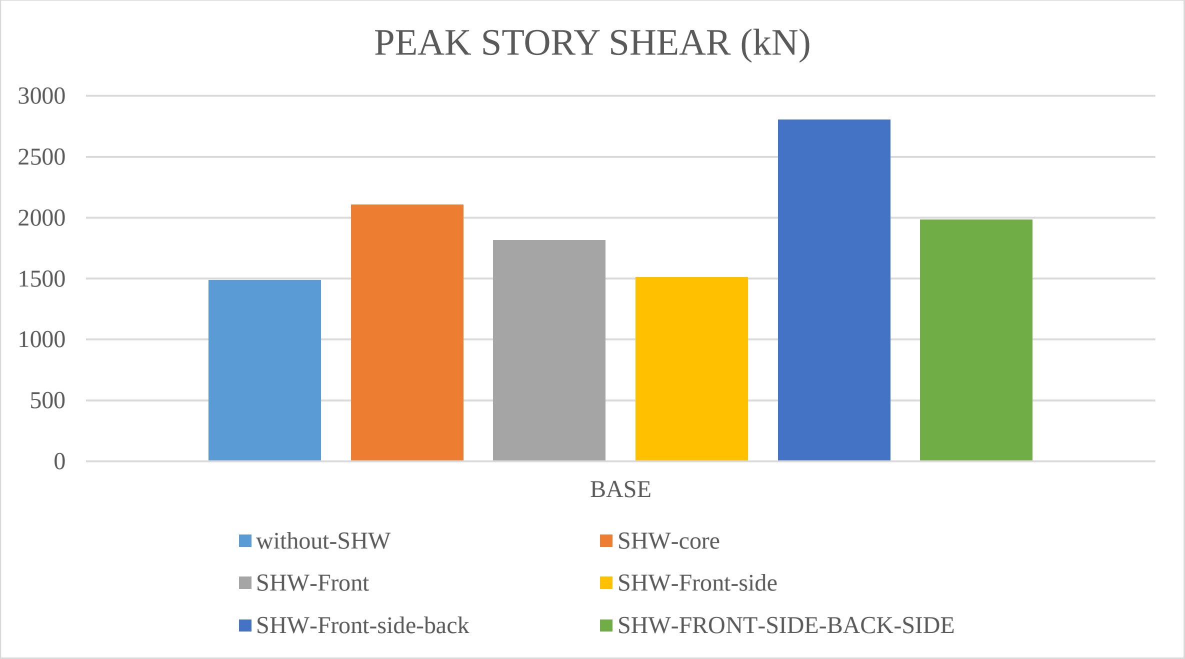


Figure (9): Horizontal displacement for the RC building with 33m height

Figure (9) show that the model with a shear wall at the front position exhibits the largest horizontal displacement, whereas the scenario with the building with shear walls at the front, back, and both side locations exhibits the shortest horizontal displacement.



(a) Frequency for the RC building with 33m height



(b) Peak story shear for the RC building with 33m height

Figure (10): Frequency (a) and peak story shear (b) for the RC building with 33m height

According to Figure (10), the RC building scenario with shear walls at the front, back, and both side locations records the highest frequency. In contrast, the absence of shear walls in a building results in the lowest frequency being recorded. The bar chart in Figure (10b) depicts the peak story shear (kN) for various structural configurations. The values show that the configuration without SHW has the lowest shear at around 1500 kN, while adding SHW elements increases the shear. The SHW-Core configuration reaches approximately 2500 kN, SHW-Front about 2000 kN, SHW-Front-Side around 1750 kN, and SHW-Front-Side-Back-Side achieves the highest shear at roughly 2750 kN, highlighting the effectiveness of incorporating SHW elements.

RC Building with 45m Height

The results for the RC building, which has a 45-meter height, are described in more depth below. The analysis takes into account variables including displacement, story shear, and time interval. These findings offer a thorough insight of the building's dynamic behaviour, as well as how it reacts to varied loading conditions.

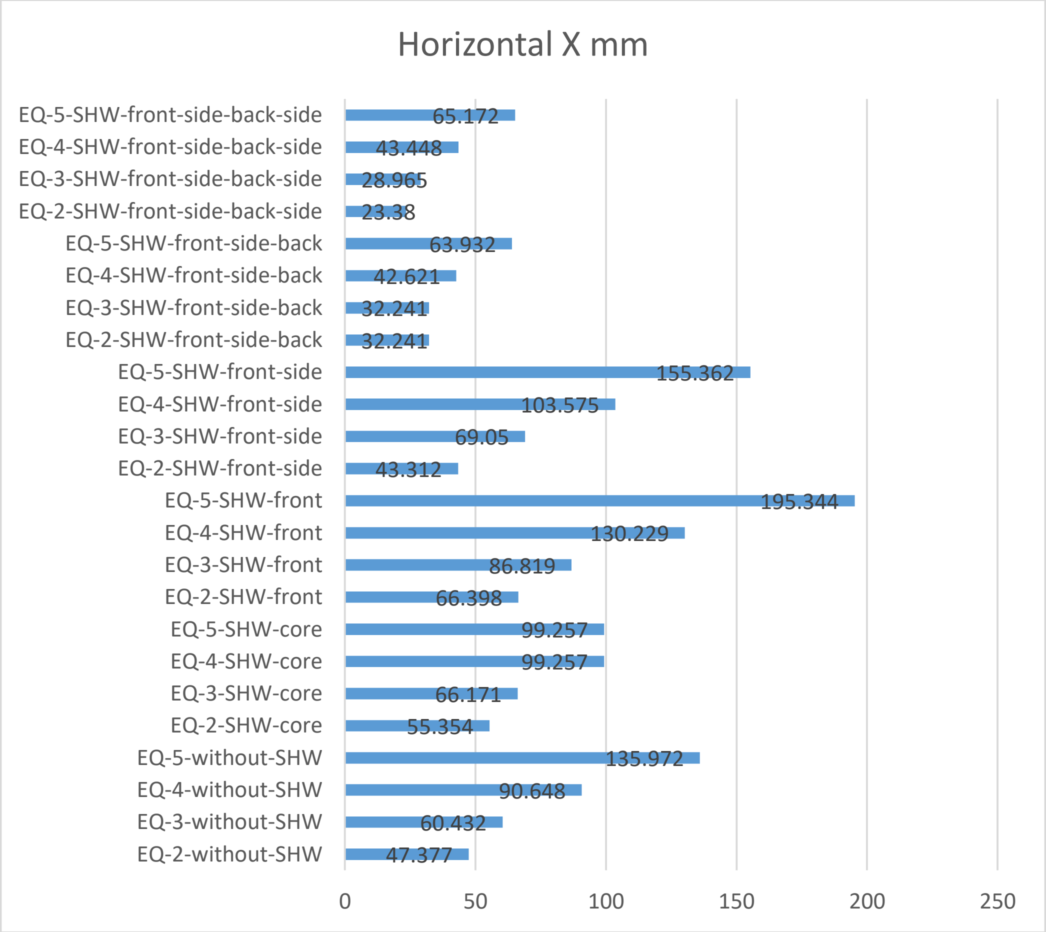
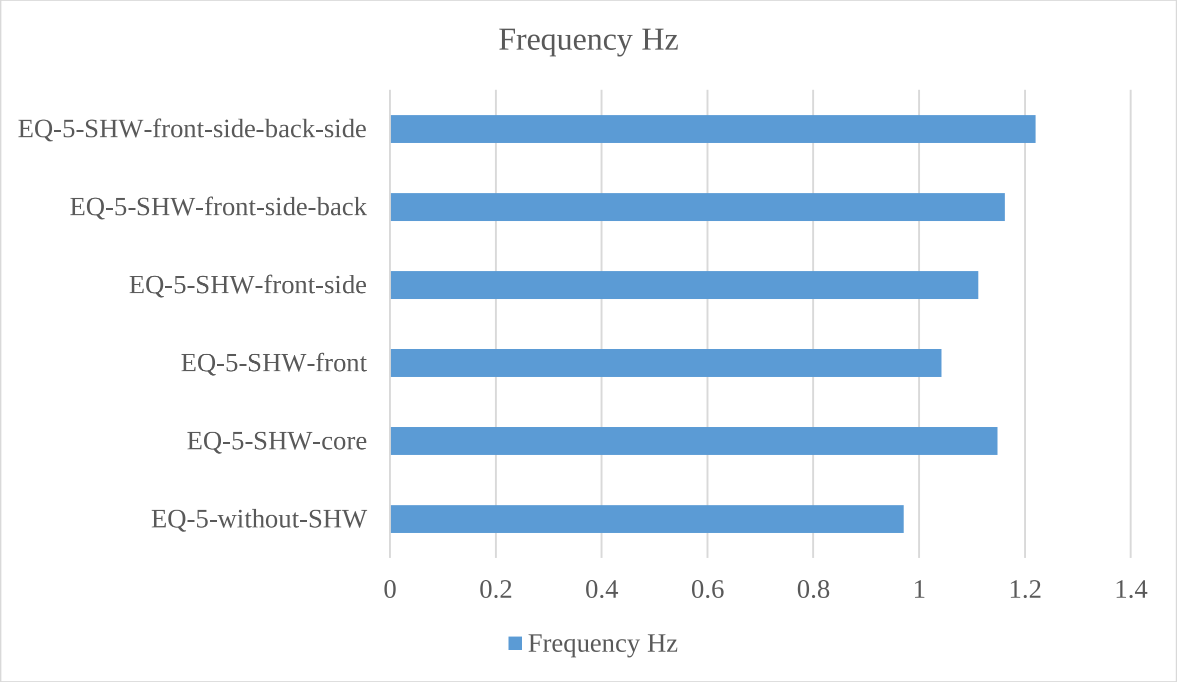
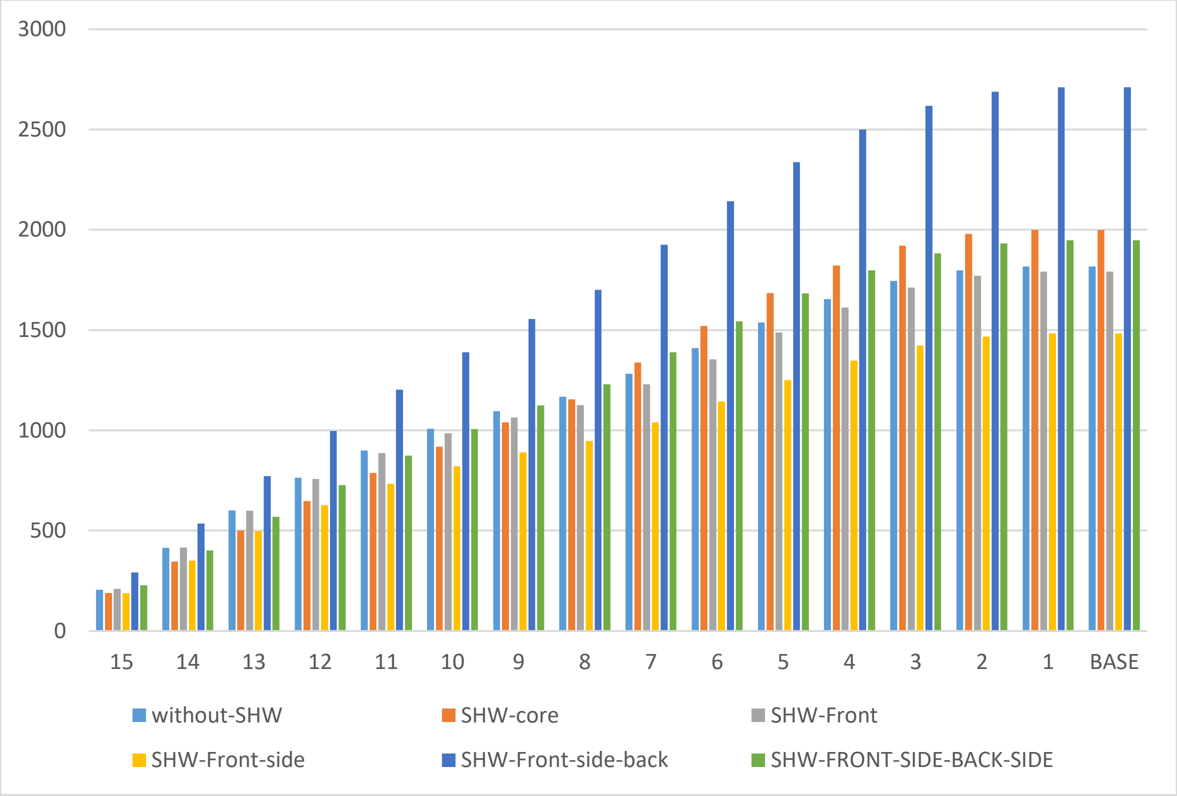


Figure (11): Horizontal displacement (X) for RC building with 45m height

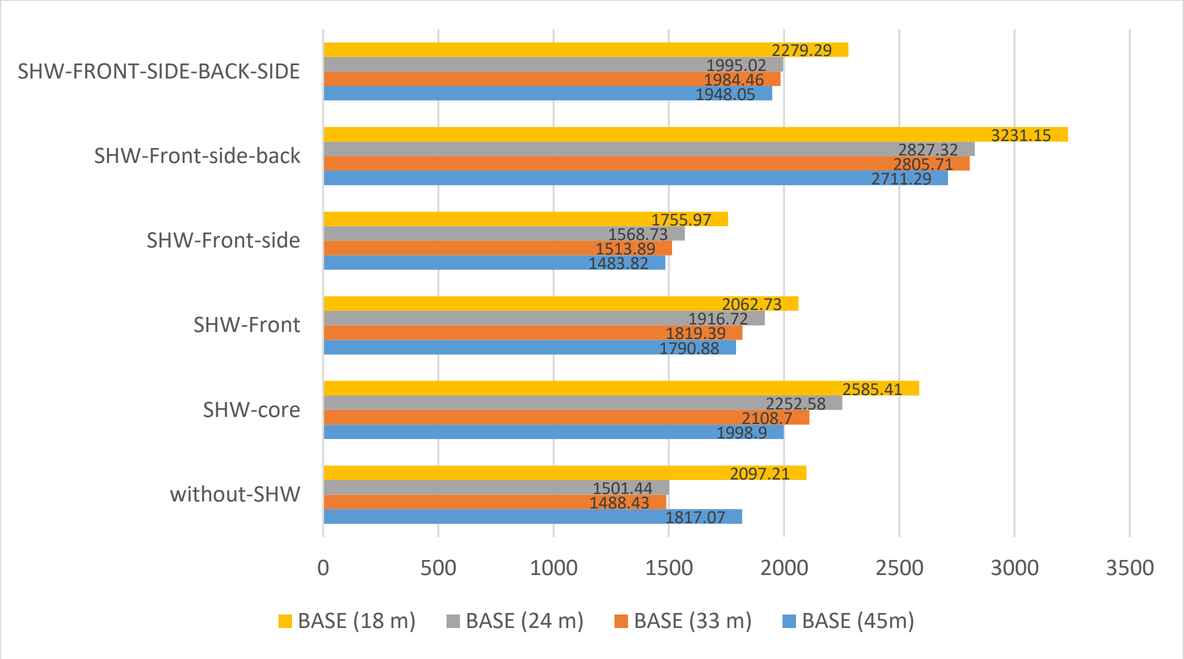
Figure (11) shows an RC structure with shear walls on the front side, notably in earthquake zone-V, causing the greatest displacement. In comparison, the model in seismic zone II with shear walls at the front, back, and both side locations exhibit the smallest displacement.



(a) Frequency for the RC building with 45m height



(b) Story shear for the RC building with 45m height



(c) Story shear for the combined models

Figure (12): Frequency (a), story shear (b) for the RC building with 45m height and story shear for the combined models (c)

The chart in Figure (12a) shows frequencies (Hz) for various structural configurations under EQ-5. Values range from 0.85 Hz for "without SHW" to 1.2 Hz for "SHW-Front-Side-Back-Side," indicating a steady increase in frequency with additional SHW elements. When shear walls are placed at the front, side, and back locations, the highest story shear is visible in the model. The building's base is particularly susceptible to this maximum shear value. On the other hand, the model with shear walls at the front and side locations has the lowest story shear.

Figure 12 (c) illustrates significant observations regarding story shear under various conditions. Notably, the story shear is maximized when shear walls are strategically positioned at the front, back, and both side locations of the building. Furthermore, a distinct pattern emerges concerning the relationship between story shear and building height. Specifically, the 18-meter-tall building exhibits the highest story shear compared to buildings with heights of 24 meters, 33 meters, and 45 meters. This observation indicates that shorter buildings demonstrate a more pronounced response to lateral loads, resulting in higher story shear values.

CONCLUSIONS

Thorough research of the behavior of 96 different models using the STAAD-PRO software has facilitated the simulation and evaluation of structural reactions. Due to the extensive structural analysis and design capabilities of this program, load distribution, stress patterns, and overall structural stability have been closely examined. The following conclusions are drawn:

1. Structural analysis: Structural reactions of 96 models were simulated and evaluated using STAAD PRO: analysis software.
2. Shear-wall placement: The highest frequency was observed when shear walls were at the front in an 18m building, while the longest period was seen in a 45m building with shear walls at the front, back, and sides.
3. Story shear: Maximum story shear occurred with shear walls at the front, back, and sides, especially in the 18m building, indicating a stronger response to lateral forces.
4. Displacement: Displacement increased with height; placing shear walls at the front, back, and sides minimized displacement.
5. Seismic behavior: Buildings with shear walls at the front, back, and sides had the highest frequency, while those without shear walls had the lowest frequency.
6. Structural forces: The highest story shear (~3000

kN) was observed without shear walls, while configurations with core and full perimeter shear walls reduced shear forces significantly.

7. Earthquake zones: Displacement was greatest in earthquake zone-V for a structure with a front shear wall, while the smallest displacement was recorded in zone-II with shear walls on all sides.
8. Key insights: Shear-wall configurations significantly affect structural performance, with core and perimeter placements enhancing stability and seismic resilience.

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