ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Comparison of structural responses for tall buildings with varying twisting rates and core wall configurations

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Received: 03.02.24; **Accepted:** 19.08.24; **Published:** 30.12.25

Citation: Omar, A. H., Alhalil, I. and Gullu, M. F. (2025). Comparison of structural responses for tall buildings with varying twisting rates and core wall configurations. Revista de la Construcción. Journal of Construction, 24(3), 533-550. https://doi.org/10.7764/RDLC.24.3.533

Highlights:

- Comparison of twisted tall buildings with different core wall layouts.
- Study of wind and seismic responses for varying twisting angles.
- Identification of optimal core layout and twisting angle for TB design.
- Use of multiple-criteria decision-making for model optimization.
- Analysis of structural performance, including natural periods and drift ratios.

Abstract: This study aims to compare the structural responses of tall buildings (TBs) with different twisting rates and core wall configurations to investigate their effect under various loading conditions. The study examines three groups of TBs with varying core wall layouts: hexagonal shape for group A, circular shape for group B, and square shape for group C. Three models were constructed for each group, with twisting angles of 0°, 90°, and 180°. The study initially compares the nine different models' natural periods of vibration and modal mass participation ratios. The towers' wind and seismic responses for each model under wind, response spectrum (RS), and nonlinear time history (NTH) analysis are also presented. The wind, RS, and NTH analysis outcomes regarding the structural system (natural periods, drift ratios, story shear forces, and overturning moments) and members (shear forces and bending moments on columns and walls) have been compared. Finally, a multiple-criteria decision-making algorithm was used to determine the optimum model based on the investigated responses. The findings indicate that the core wall layout has a more significant influence on the response of TBs than the twisting rate. Specifically, a building with a hexagonal core wall system and 0-degree twist is identified as the optimal configuration. Although its effects are less significant than seismic forces, wind analysis reveals that twisting in buildings slightly reduces the natural period and drift ratios. This study emphasizes the impact of TBs configurations and twisting rates on both wind and seismic responses.

Keywords: Tall building, twisting rate, wind load, seismic performance, optimization.

Abbreviation:

TBs: Tall buildings

RS: Response spectrum

NTH: Nonlinear time history

MCDM: Multiple-criteria decision-making

CRITIC: Criteria importance through intercriteria correlation

mTopsis: Modified technique for order preference by similarity to ideal solution

1. Introduction

In the current era of architecture, engineers face numerous challenges posed by unconventional design systems. Architectural designs regularly confront structural philosophies and try to explore innovative materials and creative systems. This is driven by the ever-increasing demand for amenities and stunning buildings due to human needs and desires (Xia et al., 2010). Over the past two decades, many twisting skyscrapers have been constructed and are still considered wonders of the 21st century (Baker et al., 2008), as shown in Figure 1. Despite being economically unprofitable and presenting challenges during design and construction, metropolises continue to pursue these buildings as a part of urban planning. They lead to additional construction expenses and increase computational effort while they possess aesthetic and impressive qualities. Twisting is incorporated into the architectural design for its unique visual attraction; however, it has a detrimental impact on the overall stiffness of structures (Erkoç and Torunbalcı, 2024; Ali and Moon, 2007). From a structural perspective, twisting a building modifies its parameters and adds complexity to the system (Vollers, 2001). The twisting angle that governs the tower's twisting rate is the most influential parameter when designing twisted tall buildings (TBs). Choosing a structural system (e.g., twisted diagrids, braced tubes, and outriggers) is also crucial in the design of TBs.

The results of various studies on the obstacles associated with the structural behavior of twisted-form buildings have been summarized herein. DeSimone et al. (2015) found out that due to twisting in buildings, the inclination is inevitable on some columns, leading to additional horizontal forces on each joint caused by gravitational forces. Navya et al. (2021) studied twisted towers with frames as a lateral load-resisting system and compared the natural periods of vibration and base reactions. They concluded that conventional structures perform better than twisted structures under seismic action. Moon (2012) compared the dynamic response of TB systems to vortex shedding in windward and crosswind directions. It has been observed that diagrids and braced tube systems are very efficient for the conventional shapes of TBs. However, when comparing the two systems, the braced tube system was more sensitive to the twisting rate. Lee et al. (2021) conducted a study to compare different models under linear dynamic analysis. The study revealed that increasing the twisting rate causes an increase in the inter-story displacement and acceleration.

Szolomicki and Golasz-szolomicka (2017) focused on the implementation of the diagrid system within a significant number of twisted towers and provided detailed technical insights, while Başarir and Sev (2011) reviewed most of the constructed twisted towers and explained the morphological scheme and geometrical properties of twisting forms in a systematic approach. Besides, they addressed the complexities associated with designing and building such structures, including decisions related to the choice of supporting structures and detailing facade systems. Orbay et al. (2017) tested the wind tunnel approach to investigate the aerodynamic properties of the prismatic and twisted models. Based on the findings, they determined that the effects of windward and crosswind directions on the twisted models are more noticeable in the tower's lower levels than in the prismatic model. Zhaoa et al. (2011), as part of the design team for the Shanghai Tower, studied one of the most challenging events for the tower's design: typhoon. After experimental and analytical studies for such types of wind, they proposed that those kinds of towers should have a twisting rate to overcome the hazards of the wind load since it is dominant in that area. Shahab et al. (2021) conducted a comparative study of several models of twisted forms to show the best twisting rate regarding aerodynamics using the computational fluid dynamics (CFD) modeling approach. They concluded that each set of models' best twisting rate differs by analyzing a bunch of squares, pentagonal, and hexagonal twisted models. For the square models, it has seen that a model with 180 degrees of total rotation is the best for resisting aerodynamic loads. Moon (2014) emphasizes the importance of selecting an appropriate structural system for TBs and determining its geometric configuration. The study highlighted that the efficiency of the chosen structural system is significantly influenced by its configuration, particularly in terms of carrying lateral shear forces and overturning moments due to wind loads. Paknahad et al. (2019) presented the applications of different configurations of core systems in TBs to mitigate the effects of seismic vibrations. They modeled nine different shapes of core walls in a 25-story building and evaluated their effectiveness in reducing seismic effects. The study emphasized the feasibility and cost-effectiveness of the core system and suggested that improvements in data processing using updated information, standards, and software could lead to more accurate results and better evaluation of core systems. Moon (2011) modeled twisted diagrids, braced tubes, and outrigger systems and found that all systems become less efficient as the twisting rate increases. He also found that the braced tube system is more sensitive to twisting rate than the diagrid system. Moreover, among all systems, it has been recommended to use straight mega columns in the non-twisting zone of the tower with a combination of other methods, such as diagrids, braced tubes, and outriggers.

The engineering challenges associated with the structural behavior of twisted form buildings have been extensively studied in recent years, with various approaches used to analyze and compare different systems and models. These studies provide valuable insights into the design and construction of TBs with a twisting form; however, they investigated the effects of twisting rate and structural systems' configurations (e.g., shape of the core wall cross-section) separately. The current study extensively scrutinizes the impact of both twisting rate and structural system configurations on the seismic response of TBs, with recommendations for the optimum twisting angle and structural wall layout. The first aim of the current study is to investigate the natural period of vibrations and modal mass participation ratios for a total of nine models. The study then examines the outcomes of wind, response spectrum (RS), and nonlinear time history (NTH) analyses on the entire structural system, including drift ratios, story shear forces, and overturning moments. The results of the shear forces and bending moments on structural walls and columns are also presented. Finally, a multiple-criteria decision-making algorithm will determine the optimal twisting angle and structural wall configuration based on the results of the wind, RS, and NTH analysis on TBs. It is important to note that this research does not focus on conducting a sensitivity analysis of parameters or modeling assumptions. Instead, its primary aim is to evaluate the behavior of case study buildings with varying configurations under different analysis types. Parameters and assumptions used in this research are mentioned as limitations in the relevant sections.

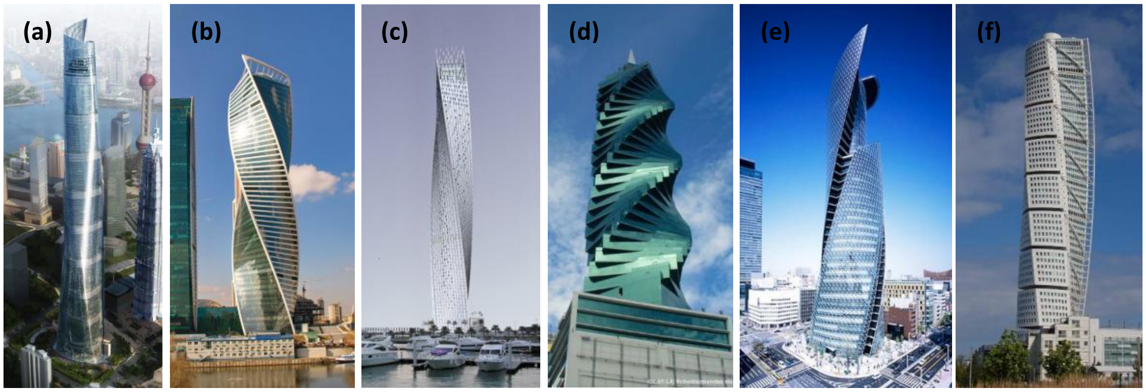


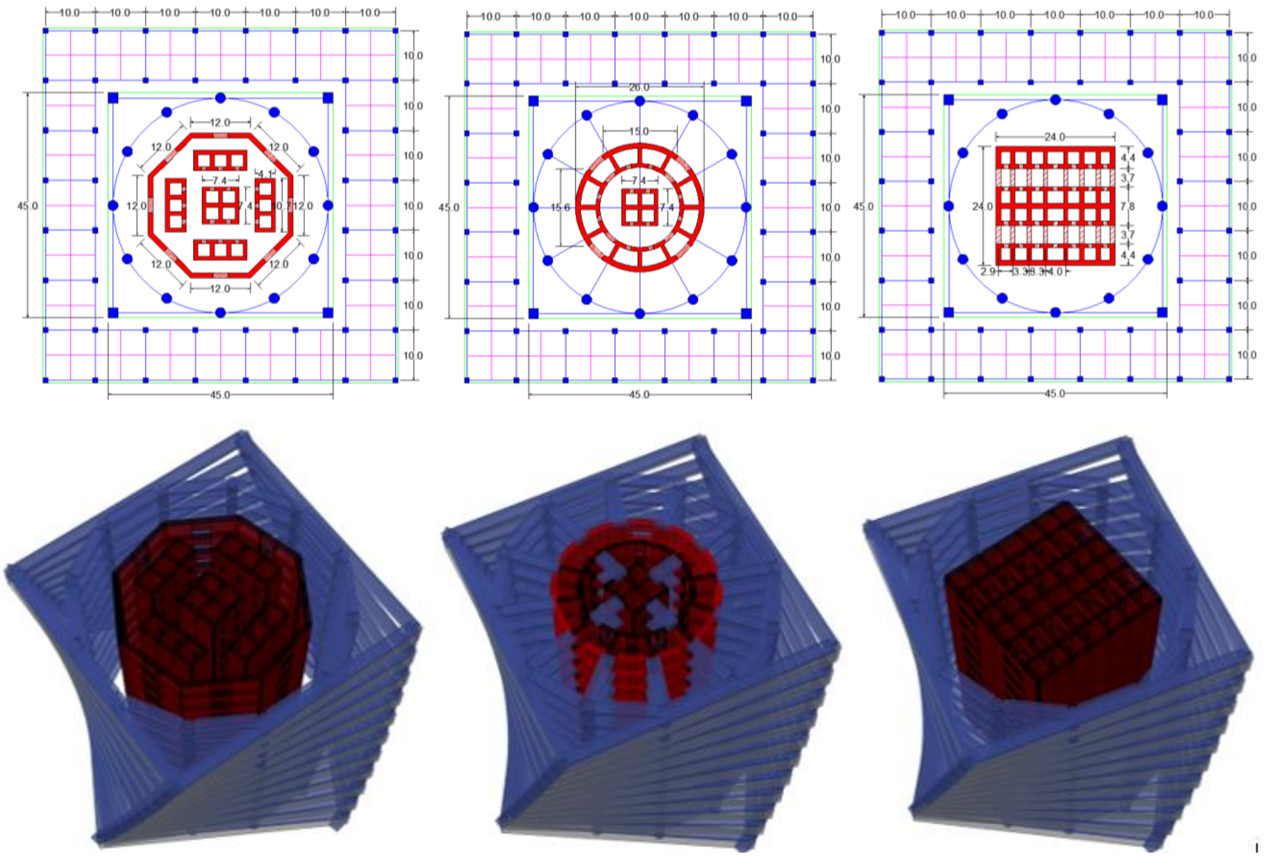
Figure 1. Examples of twisted TBs in the world; (a) Shanghai tower, (b) evolution tower, (c) infinity tower, (d) F&F tower, (e) Mode Gakuen spiral tower, and (f) Turning torso building.

2. Research methodology

The present research focuses on analyzing tower models characterized by a square cross-section in plan, possessing a length of 45 meters and a height of 260 meters, spanning 65 stories. The towers incorporate a five-story podium featuring seven bays spaced at 10-meter intervals in both directions. The columns within the podium have square cross-sections, measuring 1 meter in depth and width, and are interconnected with primary beams of identical dimensions. Each bay within the podium contains secondary beams with a width of 0.8 meters and a depth of 1 meter, positioned at the midpoint. From the sixth story onward, the towers introduce twisting with corner columns having a square cross-section measuring 2 meters in depth and width. These corner columns are connected to perimeter beams with a width of 2 meters and a depth of 1 meter. In the podium stories, the straight mega columns exhibit a circular cross-section with a diameter of 2.5 meters, while in the tower, they have a diameter of 2.0 meters. All columns are linked to beams with a width of 2 meters and a depth of 1 meter. Both the tower and its podium feature a slab thickness of 300 mm, and the core walls possess a thickness of 1 meter, while the other structural walls maintain a consistent thickness of 0.8 meters across all models. The models were allowed to twist up to different twisted angles, including 0, 90, and 180 degrees. In total, nine models were generated and divided into three groups: group A comprises three hexagonal core wall models, group B consists of three circular core wall models, and group C includes three square core wall models. The three groups in this study offer a broad range of structural characteristics for comparison and analysis. The details of each model are presented in Table 1, and their cross-section details are illustrated in Figure 2.

The buildings under this study have been designed for office use with Risk Category I and an importance factor (I) of 1. The Mander model (Mander et al., 1988) was employed to generate the stress-strain curve of confined and unconfined concrete material with a compressive strength of 65 MPa, and the Takeda model (Takeda et al., 1970) was utilized to account for hysteresis behavior. The reinforcing steel rebar exhibits a tensile strength of 420 MPa, and effective stiffness modifiers, according to (ASCE 7-16, 2016), have been utilized to consider the concrete cracked section in the analysis. Long-term effects such as creep and shrinkage are not considered. Lumped and distributed plasticity approaches have been used to define the nonlinear behavior of the frame and wall members. The rigid diaphragm assumption has been considered for all story levels. This study does not consider soil structure interaction, as all models have been assumed to be fixed support in their base levels. Elasticity modules are 37892 MPa and 200000 MPa, and density is 24 kN/m^3 and 76.97 kN/m^3 for concrete and steel, respectively. The Poisson ratio is 0.2 and 0.3 for concrete and steel, respectively. The gravity loads considered for the building include the self-weight of the structure, an added dead load of 2.5 kN/m^2, and a live load of 3 kN/m^2 applied uniformly across all floors. In calculating the building's mass, we have incorporated 25% of the live load and 100% of both the dead load and the superimposed dead load. It is worth mentioning that no load combinations were considered in the analysis phase of this study, as the objective is to assess the responses to wind and earthquake actions separately.

All buildings have been analyzed in the ETABS package program (ETABS, 2021). Modal analysis has been performed for all models to evaluate the fundamental period of vibration and mass participation in all directions. Additionally, a wind analysis is conducted to assess the impact of wind on twisted TBs. For wind analysis, the wind load was determined by (TS-498, 1987) utilizing the directional procedure with a wind speed of 30 m/s for design purposes. Although this wind speed appears relatively low, it is suitable for evaluating the structural response in the specific area under consideration, consistent with the region analyzed for seismic effects. Wind exposure parameters, including a windward coefficient of 0.8 and a leeward coefficient of 0.5, were factored into the analysis. These parameters were applied in the software to account for wind load effects, and the wind loads were assigned to all stories above the ground level. Furthermore, an RS analysis was conducted to assess its reliability in TB assessment compared to NTH analysis. Since the NTH method is widely recognized as the most accurate approach for assessing the seismic response of reinforced concrete structures (Salmassi et al., 2024; Alhalil & Gullu, 2023; Afsari et al., 2024), it has been chosen as a reliable method for analyzing the seismic performance of the towers considered in this study. For RS analysis, the target response spectrum was defined as per (TSC, 2018) utilizing Ss values of 0.6 and S1 values of 0.2, and a site class of ZC was adopted. In this study, NTH analysis is regarded as the primary reference for seismic analysis results of the towers. Time history data from (PEER, 2023) was employed, specifically selecting records of the Hollister earthquake with a moment Magnitude (M_w) of 5.14 for the NTH analysis, as shown in Figure 3. Subsequently, a time history function was developed through scaling and spectral matching in the time domain to align with the related target response spectrum stated before. It is essential to recognize that validating the findings of the current research through seismic tests on actual buildings is impractical due to the limited number of experimental studies, which are generally confined to structures of modest height. Conversely, the use of software simulations to assess the impact of wind on structures is gaining traction for its cost-effectiveness and versatility (Mehta et al., 2024). Consequently, the results derived from these simulations are deemed sufficiently reliable to support this research.



(a) **(b)** **(c)**

Figure 2. Building's layout and structural systems; (a) hexagonal core wall for group A, (b) Circular core wall for group B, and (c) Square core wall for group C.

Table 1. Details of models for each group.

Group name	Model tag	Each story rotating angle	Cumulative twisting angle
Group A – hexagonal core wall	G1-M1	0.0 degree	0°
	G1-M2	1.5 degree	90°
	G1-M3	3.0 degree	180°
Group B – circular core wall	G2-M1	0.0 degree	0°
	G2-M2	1.5 degree	90°
	G2-M3	3.0 degree	180°
Group C – square core wall	G3-M1	0.0 degree	0°
	G3-M2	1.5 degree	90°
	G3-M3	3.0 degree	180°

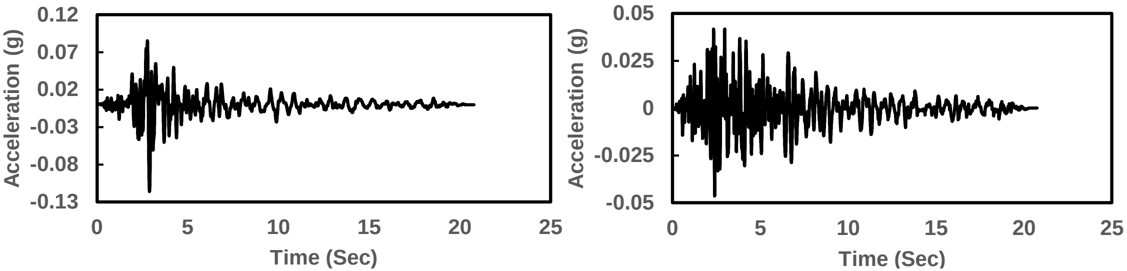
3. Results and discussion

The results of this study are presented in the following sections, covering both local and global responses. The global responses include the fundamental period, story drift, story shear forces and overturning moments. The local responses include shear forces in columns and bending moments in walls. Finally, the optimal model will be selected based on these results using an advanced criteria-based algorithm.

3.1. Global response

3.1.1. Fundamental period

The fundamental period of vibration is one of the most influential parameters in the dynamic response evaluation of TBs. This study performed a modal analysis for all the 3D building models to understand their overall characteristics. The fundamental periods of vibration for each group are compared for the first three vibration modes, as shown in Table 2, with group B having the highest values for all three modes, followed by group A and then group C. Although the differences between the values are relatively small, it can be concluded that group C models with square core walls have lower fundamental periods than other groups. In brief, the twisting rate and core wall shape do not significantly affect TBs in terms of the fundamental period vibrations.



(a) (b)

Figure 3. Hollister earthquake's time history records in the directions of a) X and b) Y.

Additionally, the study examined the modal mass participation ratios for each of the three vibration modes, as shown in Table 3. The modal analysis also revealed that the first and second mode shapes are translational modes in X and Y directions, while the third mode is rotational-dominant. The results indicate that group A, with a hexagonal core wall, has modal mass participation ratios slightly smaller than other groups. The modal mass participation ratios in the rotation about the Z axis slightly increase when the twisting rates increase.

Table 2. Fundamental periods for the first three modes of all models.

Groups	Model tag	Fundamental period of vibration (s)		
		Mode 1	Mode 2	Mode 3
Group A - hexagonal core wall	G1-M1	5.63	5.62	1.70
	G1-M2	5.58	5.58	1.69
	G1-M3	5.86	5.86	1.76
Group B – circular core wall	G2-M1	6.02	6.00	1.91
	G2-M2	5.92	5.90	1.90
	G2-M3	5.90	5.88	1.83
Group C - square core wall	G3-M1	5.43	5.37	1.90
	G3-M2	5.40	5.34	1.89
	G3-M3	5.33	5.26	1.83

3.1.2. Drift ratios

The comparison of the towers' drift ratios is shown in Figure 4 for the three types of analysis. Drift ratios are determined as the relative displacement of a story divided by the story height. Due to symmetry in configurations and applied loads, the models exhibit equal drift responses in X and Y directions for both the wind and RS analyses. However, during the NTH analysis, distinct acceleration components were utilized for X and Y directions to show the effect of combinations of the orthogonal directions, as the analyses were conducted simultaneously in both the X and Y directions. For the wind loading case, the magnitudes of drift ratios are smaller than those observed in seismic analysis. Group C buildings have the smallest drift ratios along height compared to others. Notably, the model with 0-degree rotating and square core wall (G3-M1) showed superior performance with limited drift demand.

Table 3. Modal mass participation ratios for the first three modes of all models.

Groups	Model tag	Modal mass participation ratio		
		Mode 1 (U_x)	Mode 2 (U_y)	Mode 3 (R_z)
Group A - hexagonal core wall	G1-M1	59.52%	59.52%	64.94%
	G1-M2	59.77%	59.77%	65.33%
	G1-M3	59.62%	59.63%	65.81%
Group B - circular core wall	G2-M1	57.85%	57.95%	67.13%
	G2-M2	58.18%	58.27%	67.54%
	G2-M3	58.52%	58.62%	68.13%
Group C - square core wall	G3-M1	58.59%	58.83%	64.94%
	G3-M2	58.27%	58.51%	65.36%
	G3-M3	58.16%	58.41%	66.00%

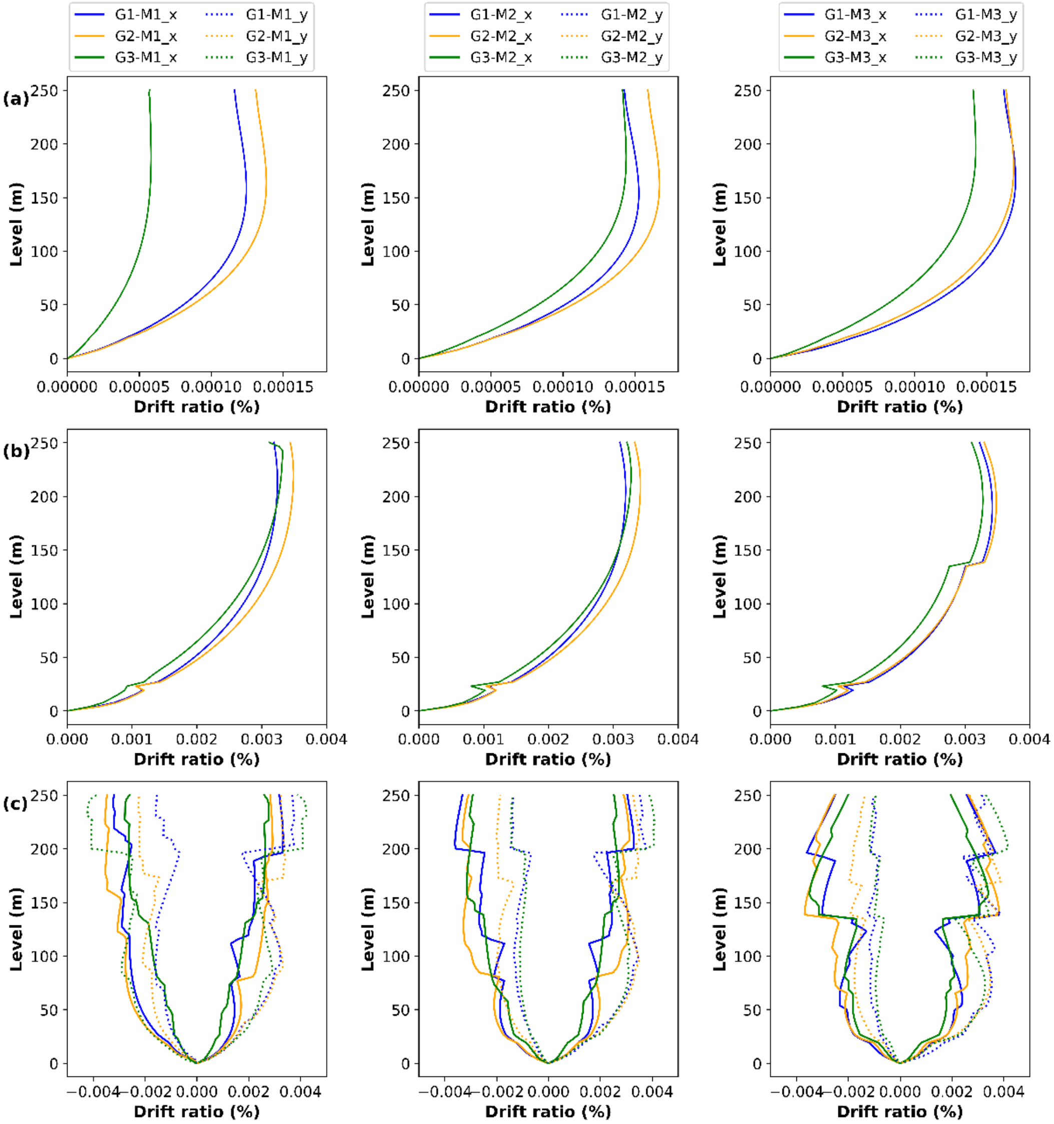


Figure 4. Story drift results for (a) wind, (b) RS, and (c) NTH.

For RS analysis, it can be asserted that there is no significant difference in the models' response concerning drift demand. A distinct sudden change in the response is consistently observed in all models' lower parts of the tower. This change is attributed to the abrupt transition of the building from the podium to the tower. A sudden change occurs in models with a 180-degree twisting angle in the tower's middle. This is due to the slab twisting and returning to its original position, meaning that one of the middle floors has a zero inter-story twisting angle for shaping the tower. Results indicate that models with a square core wall configuration exhibit, to some extent, the best performance, as evidenced by the lowest drift ratios.

For NTH analysis, results among models with a 0-degree twist (G1-M1, G2-M1, and G3-M1) confirmed that the model with a circular core wall (G2-M1) has the maximum story drift ratio in X direction and the model with a square core wall (G3-M1) has the maximum value in Y direction. This makes the model with a hexagonal core wall (G1-M1) outperform the others in terms of drift ratio for models without twist. For models with a 90-degree twisting rate (G1-M2, G2-M2, and G3-M2), it was observed that models with a hexagonal core wall (G1-M2) exhibit the maximum story drift value in X direction, while the model with a square core wall (G3-M2) displays the maximum value in Y direction. For models with a 180-degree twist (G1-M3, G2-M3, and G3-M3), the model with a circular core wall (G2-M3) shows the maximum story drift ratio in the

X direction, while the model with a square core wall (G3-M3) exhibits the maximum in the Y direction. On the other hand, when comparing models with a hexagonal core wall (G1-M1, G1-M2, and G1-M3), it was found that the model with a 0-degree twist (G1-M1) shows the minimum story drift value. The same trend was seen for models with a circular and square core wall (i.e., models with 0-degree have the minimum drift value). In NTH analysis, due to nonlinearity, the behavior exhibits a complex nature represented by variations along the building height. Ultimately, a model with a square core wall and 0-degree twist (G3-M1) has shown the minimum values of story drift along the height compared to other models in all analysis scenarios. The RS analysis results have demonstrated consistency with the NTH analysis regarding story drift results.

3.1.3. Story shear forces

Figure 5 graphically represents the distribution of story shear forces along the tower's height, capturing the outcomes of all analyses. In the context of wind analysis, all models exhibit similar results with consistently decreasing linear relationships along building height. Models with 0-degree twist (G1-M1, G2-M1, and G3-M1) have the minimum story shear forces, while the other groups show the maximum. Notably, the wind has no significant effects on the models considered in this study regarding story shear forces. For RS analysis, a notable finding was that story shear forces for models with square core walls display the highest values, particularly models with 0-degree (G3-M1) twist, which shows the maximum values among all models. The other models present very close results when considering variations in twisting rate and core wall configurations.

For NTH analysis, a comparative evaluation among models with a 0-degree twist (G1-M1, G2-M1, and G3-M1) revealed that the model with the hexagonal core wall (G1-M1) demonstrates the lowest shear forces for both X and Y directions. When considering models with a 90-degree twist (G1-M2, G2-M2, and G3-M2), a model with a circular core wall (G2-M2) exhibits the highest shear force values in the X direction, whereas the model with a square core wall (G3-M2) displays the highest in Y direction. In models with a 180-degree twist (G1-M3, G2-M3, and G3-M3), a model with a circular core wall (G2-M3) demonstrates the highest shear force values in X direction, while the model with a hexagonal core wall (G1-M3) has the highest values in Y direction. On the other hand, among the models with square core walls (G3-M1, G3-M2, and G3-M3), a model with 0-degree twist (G3-M1) shows the highest shear values in both X and Y directions. The results exhibit close similarities with no distinct trends for hexagonal and circular core wall models.

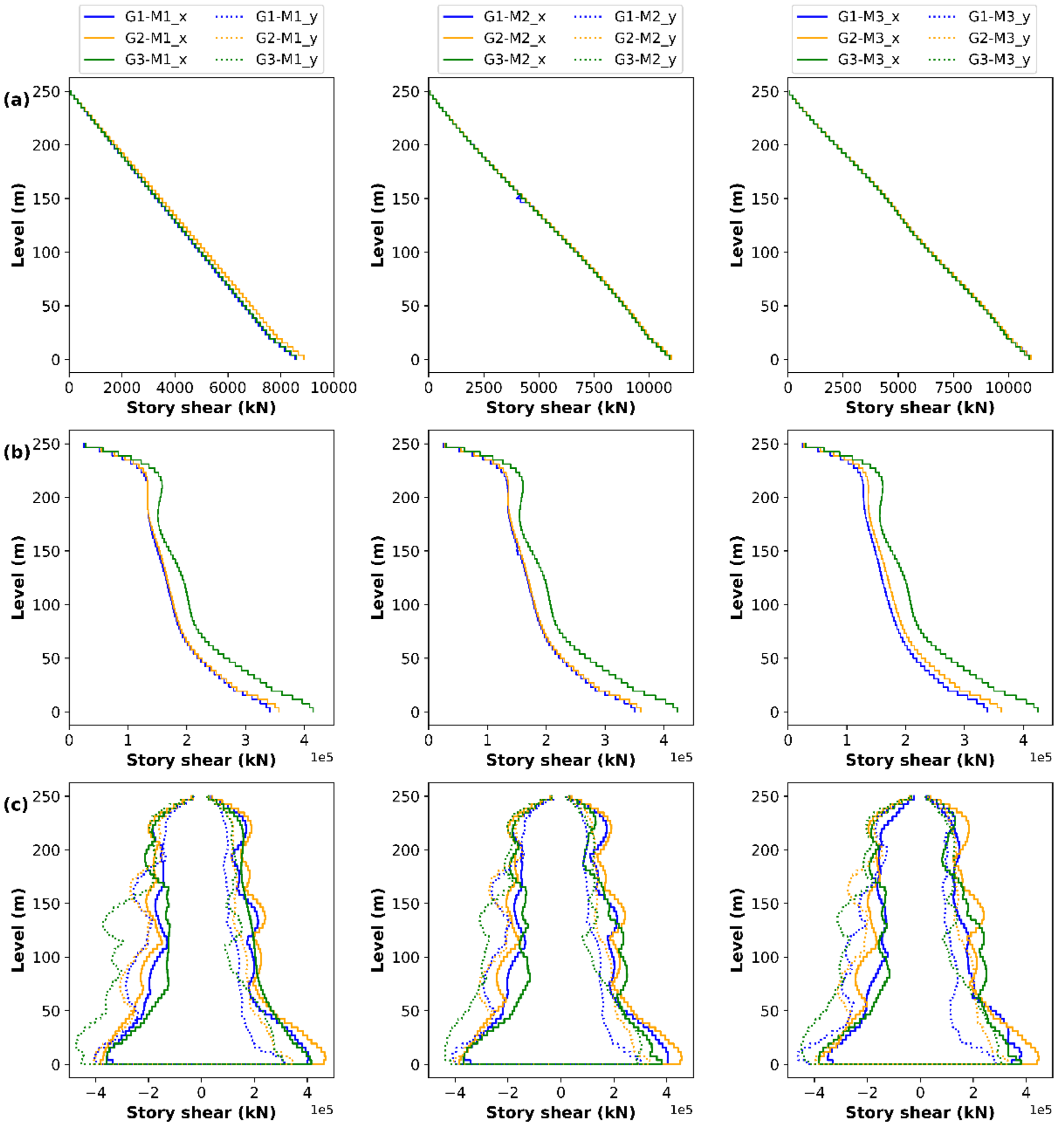


Figure 5. Story shear forces for (a) wind, (b) RS, and (c) NTH.

3.1.4. Overturning moments

The comparative analysis of overturning moments along the tower's height for the various loading scenarios is illustrated in Figure 6. All models show similar results for wind analysis with consistently decreasing relationships along building height. Models with 0-degree twist (G1-M1, G2-M1, and G3-M1) have the minimum overturning moment values compared to the other groups. Notably, there are no significant effects of wind on the models considered in this study regarding over-turning moments. For RS analysis, the models show very close results concerning variations in twisting rate and core wall configurations. In general, models with square core walls (G3-M1, G3-M2, and G3-M3) present the highest overturning moment values among other models.

In the case of NTH analysis, the trends of overturning moment results are similar to those of story shear results. Specifically, results among models with a 0-degree twist (G1-M1, G2-M1, and G3-M1) revealed that the model with square core walls (G3-M1) exhibits the highest overturning moment values, while the other models (G1-M1 and G2-M1) demonstrate similar lower values for both X and Y directions. When considering models with a 90-degree twist (G1-M2, G2-M2, and G3-

M2), a model with a square core wall (G3-M2) exhibits the highest overturning moment values in X direction, whereas the model with a circular core wall (G2-M2) displays the highest values in Y direction. In models with a 180-degree twist (G1-M3, G2-M3, and G3-M3), a model with a square core wall (G3-M3) demonstrates the highest overturning moment in X direction, while the model with a circular core wall (G2-M3) has the highest values in Y direction. This concludes that models with square core walls have the maximum overturning moments among all models.

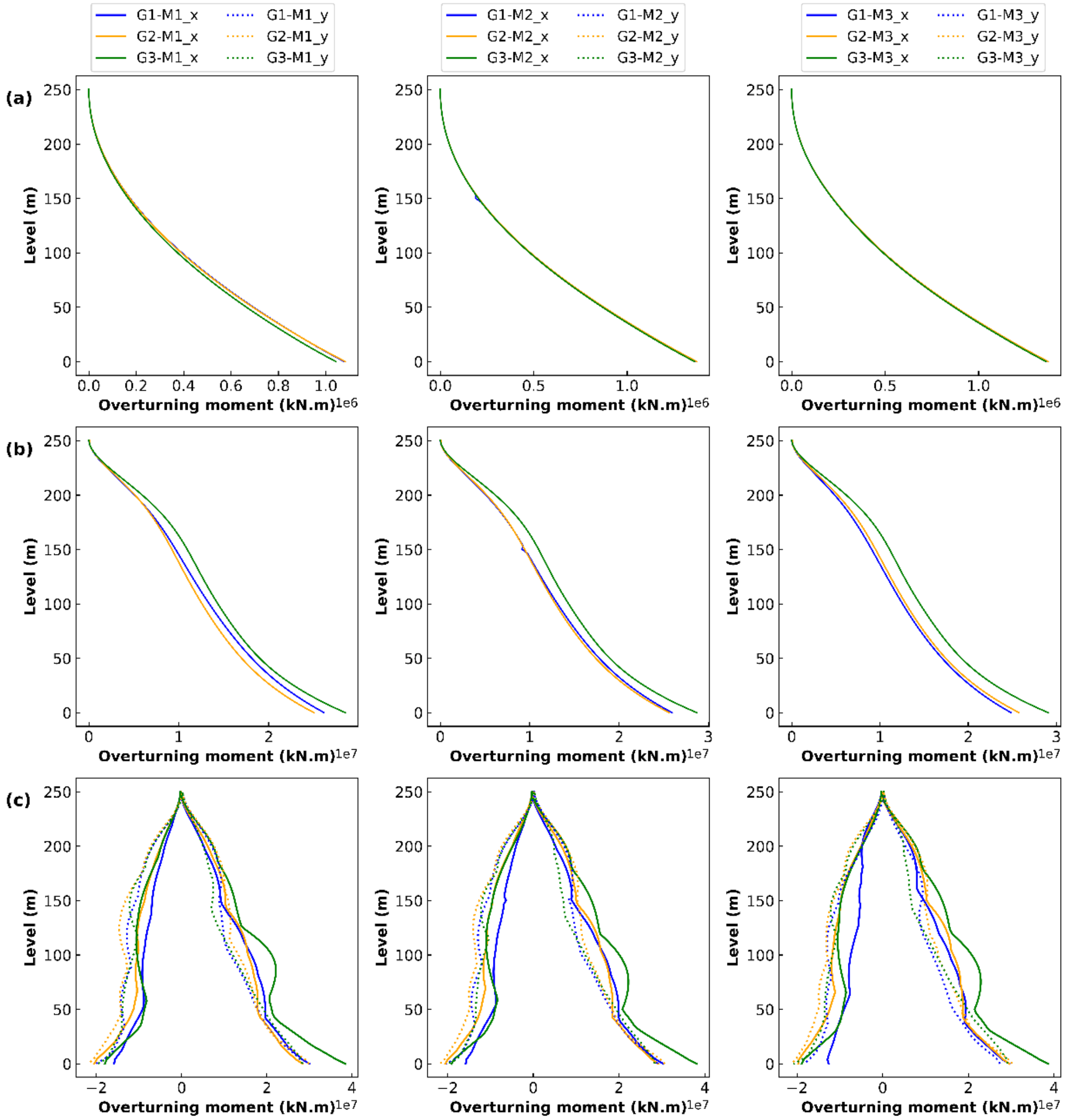


Figure 6. Overturning moment results for (a) wind, (b) RS, and (c) NTH.

3.1.5. Summary of the global responses'

Figure 7 presents the summarized results from Figure 4, Figure 5, and Figure 6, illustrating the maximum response for each quantity. The wind results are plotted against different y-axes presented on the right for better visualization and comparison since they are small compared to seismic results. The behavior of buildings subjected to wind loading fundamentally differs from that under seismic loading due to the distinct characteristics of these forces (Saini et al., 2024). Wind loading is generally steady or fluctuating, characterized by lower frequencies and longer durations, which induce a primarily lateral and aerodynamic response in structures. In contrast, seismic loading is dynamic, involving high frequencies and short durations that generate both lateral and vertical vibrations along with significant inertial effects. These differences result in variations in structural responses, as illustrated in Figures 4, 5, 6, and 7. Specifically, these figures depict the drift ratios, story shear forces, and overturning moments under both wind and seismic conditions, highlighting how each type of loading uniquely influences structural performance.

The drift ratios, story shear forces, and overturning moments resulting from the seismic analysis were significantly affected by the core walls' shape and the twisting rate; however, this effect becomes minimal in the case of wind analysis. G3-M1 is the optimal model for the drift ratio resulting from the NTH analysis. A model with a circular core wall and 0-degree twist (G2-M1) has presented the maximum values of story shear forces and overturning moment compared to other models. RS analysis results consistently align with NTH analysis regarding all the quantities, indicating that RS analysis is suitable for assessing seismic response in twisted TBs. Wind loading results have shown that models with 0-degree twists (G1-M1, G2-M1, and G3-M1) have minimum story shear forces and overturning moments compared to other models.

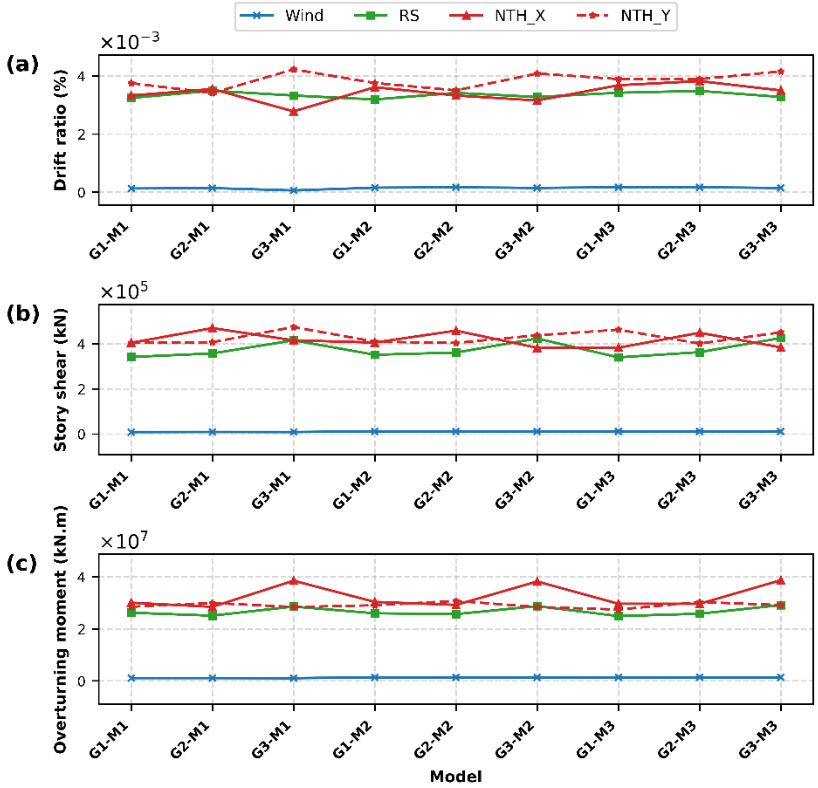


Figure 7. The maximum response of (a) drift ratio, (b) story shear, and (c) overturning moment.

3.2. Local responses

It has been decided to present the local responses of the tower components by distributed shear forces and bending moments on columns and structural walls. Note that the outcomes exclusively pertain to the X direction across all loading scenarios, as the results in the Y direction exhibit similarity except for NTH analysis, where results in the X and Y directions are presented.

The data from the local response is summarized in Figure 8, showcasing the values of total shear forces and total bending moments on both columns and walls. These quantities vary across different models and loading scenarios. NTH and RS results closely align, except for shear forces on walls, where significant differences exist for the 0-degree and 90-degree models. The 180-degree models demonstrate lower shear and moment values on columns while presenting maximum values for a moment on walls across all three loading scenarios. Wind results are plotted on a different scale within the same graph, with the y-axis presented on the right for better comparison. Although the wind results are much smaller than those of the seismic analysis, they exhibit similar trends.

After conducting wind, RSA, and NTH analyses on nine models distributed across the three groups, a comparison was made within each group. The aim was to identify the optimal twisting rate associated with superior performance metrics based on the smallest response for parameters like fundamental period, drift ratio, shear, and moments in global and local responses. The results shown in Figure 7 and Figure 8 and the fundamental periods will be used as criteria to govern the optimal model.

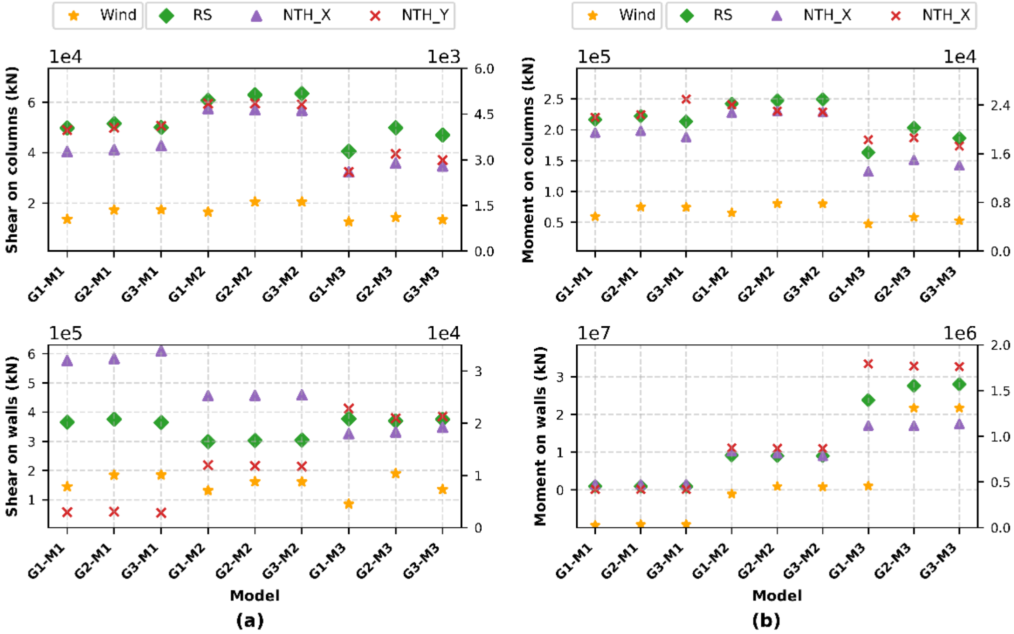
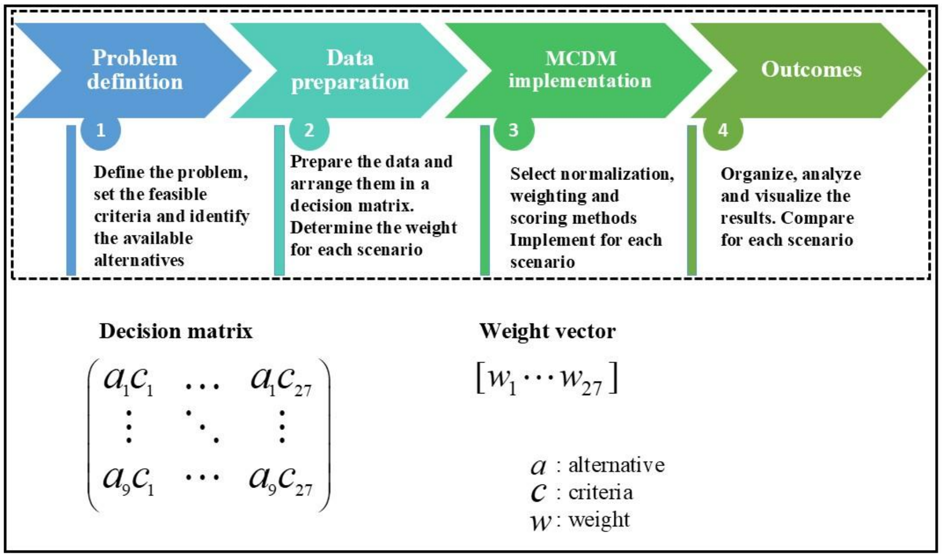


Figure 8. The maximum response of (a) shear forces on columns and walls, and (b) bending moments on columns and walls.

3.3. Optimum twisting rates for building models

Determining the optimal model for complex problems is intricate, as some results are closely matched while others intersect. Additionally, the data is complicated, and the scales for each quantity vary. Numerous Multiple-Criteria Decision-Making (MCDM) algorithms have been recently developed to assist in deciding the optimal solution or giving the best rank among multiple alternatives for a given problem. To assess the ranking of each alternative in such a problem, we employed the MCDM method via the “mcdm” package available in Python. The MCDM method provides multiple algorithms for normalization, weighting, correlating, and scoring alternatives, aiding in decision-making for determining the optimal options based on information derived from a user-provided decision matrix. A decision matrix is a data structure where rows represent alternatives for a given problem, such as the nine structural models in our case. The columns of the matrix define the criteria governing the optimal solution, including one period, four drift ratios, four story shear values, four overturning moment values, three total shear values on columns, four total shear values, and bending moments on walls, as well as four bending moment values on columns. The decision matrix of the current problem takes the shape of (9x27), with nine rows and twenty-seven columns, providing information to the algorithm for decision-making regarding the optimal model. The implementation of MCDM has demonstrated its accuracy in addressing various complex problems across different fields (Sahoo and Goswami, 2023). The MCDM process involves four main phases, as illustrated in Figure 9.



$$\begin{pmatrix} a_1c_1 & \cdots & a_1c_{27} \\ \vdots & \ddots & \vdots \\ a_9c_1 & \cdots & a_9c_{27} \end{pmatrix} \qquad [w_1 \cdots w_{27}]$$

Figure 9. MCDM implementation procedures.

The rank function was implemented in the MCDM method with four different scenarios, each employing a distinct weight vector. In the first scenario, we utilized a built-in weighting method called the criteria importance through intercriteria correlation (CRITIC) method (Diakoulaki et al, 1995). A manually defined weight vector was employed for the second scenario, assigning equal weight values to each quantity. In the third scenario, the weight of the story shear and overturning moment values was increased by 50%, and the weight of drift ratio quantities was increased by 100%. The weights of other quantities (period, shear forces, and bending moments on columns and walls) remained unchanged. For the fourth scenario, the NTH results of all quantities were amplified by 2, resulting in a 100% increase in weight. This approach was adopted to ensure fairness and account for any potential bias. In all scenarios, we used the "Linearization3" method (Shih et al., 2007) for normalization and the "mTopsis" method (Deng et al., 2000) for scoring. These scenarios comprehensively explore different weighting strategies to assess the optimal alternative rank based on the decision matrix.

The results of the four scenarios, depicted in the bar plots in Figure 10, reveal consistent trends with minor variations in magnitude. The average values across all groups for the four scenarios are emphasized at the top of each group, facilitating a comparative analysis. The G1-M1 model consistently achieves the lowest rank, emerging as the optimal model among the alternatives, followed by G1-M2 and G3-M1. Notably, models with a 0-degree twist demonstrate superior performance compared to those with a twist. Furthermore, the investigation indicates that the core wall configuration type does not significantly influence the optimal model compared to the deference concerning variation in twisting rate. Nevertheless, hexagonal configurations (group A) are optimal when considering models with the same twist angle, followed by circular models (group B). In light of these findings, the study advises designing TBs using a hexagonal-shaped core wall without rotation angles to minimize deformation and force demand.

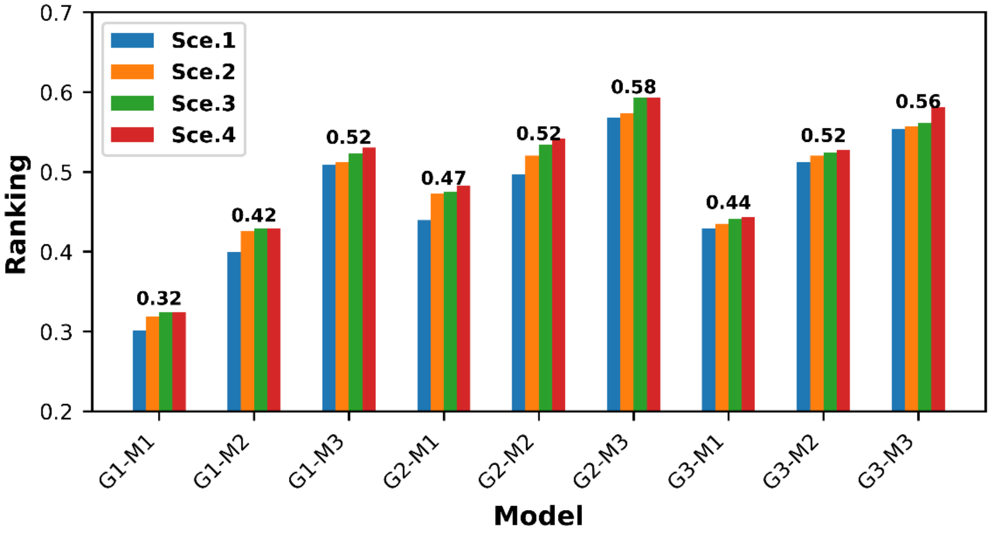


Figure 10. Results of different scenarios.

4. Summary and conclusion

This study presents a comparative analysis of the structural response of TBs with varying twisting rates and core wall configurations along the height of the structures. The building model considered in this analysis has a height of 260 meters (65 stories), with a square cross-section and a side length of 45 meters. Three different core wall layouts are analyzed in this study: group A, featuring a hexagonal core layout; group B, with a circular core layout; and group C, consisting of a square core layout. Each group includes three models, each subjected to different twisting angles of 0°, 90°, and 180°. Wind, RS and NTH analysis have been performed to assess the response of the models to seismic and wind loading. Findings of the current research have been written in the following paragraphs.

The tower global response study has yielded critical insights through the behavior of TBs, particularly those with different core wall shapes: hexagonal, circular, and square. These findings encompass various aspects of structural performance, including natural periods, story shear, overturning moments, and tower drift, and carry significant implications for the design of TBs. This study also identified some considerations related to natural periods. Notably, group B, characterized by circular core walls, demonstrated the highest mean fundamental period of vibration in all modes, followed by group A (hexagonal core walls) and group C (square core walls). A common thread across all groups is the consensus that fundamental period values slightly decrease when the twisting rate increases. Story shear values revealed that these values vary between the different core wall configurations irrespective of twisting angles. Hexagonal core wall models (group A) exhibited lower story shear values than their counterparts in group B and group C. Group C models exhibited the highest story shear values in the RS case, while group C attained the maximum values in the NTH analysis case.

Regarding overturning moment results, group C models exhibited the highest story shear values in both RS and NTH analysis cases. Additionally, the study addressed the towers' drift ratios, revealing that the drift ratio increases with higher twisting rates across all groups. The results of the local responses of the towers offered crucial insights into the distribution of shear forces and bending moments within the structural components, revealing notable variations dependent on the core wall shape and the chosen analysis method. An increase in twisting rate exposed a significant increase in bending moments and a slight reduction in shear forces on walls. Furthermore, the RS analysis method is consistent with the NTH results for most quantities investigated in this study.

Given the complexity of the results and the difficulty in determining the optimal model, the paper utilized Multiple Criteria Decision Making (MCDM) methods to analyze and identify the optimal models among all groups. Generally, models without twisting performed better than those with twisting for global and local response. However, models with 90-degree twisting rates are optimal for twisted models. Considering four weighting scenarios, the investigation into optimal structural models consistently identified G1-M1 as the optimal model among all other alternatives, emphasizing the effectiveness of hexagonal-shaped core walls without rotation angles in minimizing deformation and force demands in TB design.

The results of this study have considerable practical implications for the design of twisted tall buildings in industry. This study found that the core wall configuration plays a crucial role in mitigating lateral and torsional displacements. Specifically, hexagonal core walls provide superior resistance to shear forces and torsional effects, making them an efficient choice for resisting lateral loads and enhancing the overall stability of the building. The study also highlighted the importance of selecting appropriate twisting rates, as moderate twisting rates (e.g., 90°) provide the best structural performance without significantly increasing deformation. In contrast, higher twisting rates (e.g., 180°) lead to larger lateral displacements and increased bending moments, which could affect occupant comfort and structural efficiency. The study found that wind loads resulted in much smaller responses compared to seismic loads, but similar trends in shear and bending moments were observed. The seismic analysis highlighted the impact of twisting rates on torsional amplification, which can be critical for ensuring the structural stability of the building during earthquakes. Therefore, careful consideration of twisting rates and core wall layouts is necessary to optimize performance under both seismic and wind loading conditions. Additionally, the findings of this study suggest that hexagonal core layouts without twisting are the most efficient in terms of minimizing deformation and force demands. Therefore, designers may prioritize this configuration to enhance structural efficiency without compromising safety and stability.

The limitations of this study stem from the limited variation in parameters considered, such as material properties and load conditions, as well as the exclusion of soil-structure interaction. To optimize the design of TBs, future studies are recommended to incorporate soil-structure interaction for a more accurate simulation of TBs behavior. Additionally, exploring different configurations of core wall types, building layouts, heights of TBs, twisting rates, and variations in material properties is suggested as a direction for future research.

Author contributions: All authors contributed equally to the manuscript.

Funding: There is no funding provided for this study.

Conflicts of interest: We confirm that there is no conflict of interest.

References

Afsari, L., Gökdemir, H., and Günaydın, A. (2024). Seismic analysis of RC buildings using X-braced and inverted V-braced friction dampers. Journal of Vibration Engineering & Technologies, 12(2), 1673-1686.

Alhalil, I., and Gullu, M. F. (2023). Investigating Infill Wall Configurations on 3-D Structural Systems with a Generalized Modeling Approach. Arabian Journal for Science and Engineering, 48(10), 13523-13551.

Ali, M.M. and Moon, K.S., (2007). Structural developments in tall buildings: current trends and future prospects. Architectural science review, 50(3), pp.205-223.

ASCE 7-16, (2016). American Society of Civil Engineers. Minimum Design Loads and Associated Criteria for Buildings and Other Structures. ASCE/SEI 7, Reston, VA.

Baker, W.F., Korista, D.S. and Novak, L.C., (2008), March. Engineering the world’s tallest–Burj Dubai. In Proceedings of CTBUH 8th world congress “Tall and green: typology for a sustainable urban future”, Dubai (pp. 3-5).

Başarir, B. and Sev, A., (2011). A Recent Trend in Tall Building Design: Twisted Forms. Engineering Sciences, 6(4), pp.1603-1619.

Deng, H., Yeh, C. H., and Willis, R. J. (2000). Inter-company comparison using modified TOPSIS with objective weights. Computers & Operations Research, 27(10), 963-973.

DeSimone, V., Ramirez, L. and Mohammad, A., (2015). Structural challenges of twisting towers. Global interchanges: resurgence of the skyscraper city.

Diakoulaki, D., Mavrotas, G., and Papayannakis, L. (1995). Determining objective weights in multiple criteria problems: The critic method. Computers & Operations Research, 22(7), 763-770.

Erkoç, Y., and Torunbalcı, N. (2024). Design of Twisted-Form Buildings: Correlation between Architecture and Structure. Journal of Architectural Engineering, 30(3), 03124004.

ETABS, (2021), "Integrated Software for Structural Analysis &Design Version 21.0.1", Computers and Structures Inc.

Gane, V., and Haymaker, J. (2007). Conceptual design of high-rises with parametric methods. In Predicting the Future, 25th eCAADe Conference Proceedings (pp. 293-301).

Lee, D.H., Kim, H.S. and Kang, J.W., (2021). Dynamic Response Analysis of Twisted High-Rise Structures by Plane Rotation Angle. Journal of Korean Association for Spatial Structures, 21(1), pp.105-112.

Mander, J.B., Priestley, M.J.N. and Park, R. (1988) 'Theoretical Stress-Strain model for confined concrete,' Journal of Structural Engineering-asce, 114(8), pp. 1804–1826.

Marmar, A., Zouia, S., Ismail, S. A., and Hallik, A. (2021). Twisted buildings: concepts and approaches. Architecture and Planning Journal, 27(2).

Mehta, C., Gondaliya, K., and Amin, J. (2024). Investigation of Wind Interference on Vertically Twisted Skyscrapers. In: Nehdi, M., Rahman, R.A., Davis, R.P., Antony, J., Kavitha, P.E., Jawahar Saud, S. (eds) Proceedings of SECON’24. SECON 2024.Lecture Notes in Civil Engineering, vol 607.

Moon, K., (2012). Structural design and construction of complex-shaped tall buildings. In Australasian Structural Engineering Conference 2012: The past, present and future of Structural Engineering (pp. 883-890). Barton, ACT: Engineers Australia.

Moon, K.S., (2011). Outrigger Structures for Twisted Tall Buildings. Advanced Materials Research, 255, pp.737-741.

Moon, K.S., (2012). Braced tube structures for complex-shaped tall buildings. Advanced Materials Research, 450, pp.1584-1587.

Moon, K.S., (2012). Diagrid structures for complex-shaped tall buildings. Advanced Materials Research, 450, pp.1489-1492.

Moon, K.S., (2012). Optimal configuration of structural systems for tall buildings. In 20th analysis and computation specialty conference (pp. 300-309).

Moon, K.S., (2014). Studies on various structural system design options for twisted tall buildings and their performances. The Structural Design of Tall and Special Buildings, 23(5), pp.319-333.

Navya, K.S., Vishal, B.V., Kavitha, S. and Mamatha, P.G., (2021). Seismic Behaviour of Twisted Tall Building with Different Angle of Rotation. In Advances in Mechanical Engineering: Select Proceedings of CAMSE 2020 (pp. 65-75). Springer Singapore.

Nikandrov, P., 2016. Upward spiral: the story of the evolution tower. CTBUH Journal, 3, pp.12-19.

Orbay, E., Bilgen, S., Sezer-Uzol, N., Ay, B.Ö. and Ostovan, Y., (2017). Numerical and experimental investigation of aerodynamic loads for tall buildings with prismatic and twisted forms. In the international conference on wind energy harvesting.

Paknahad, M., Hejazi, F., Al-Attar, A.A., Shahbazian, A. and Ostovar, N., (2019), Different configurations of cores and shear walls in tall buildings. In IOP Conference Series: Earth and Environmental Science (Vol. 357, No. 1, p. 012005). IOP Publishing.

PEER, Pacific Earthquake Engineering Research Centre, (2023), Peer Strong Ground Motion Database.

Sahoo, S. K., and Goswami, S. S. (2023). A comprehensive review of multiple criteria decision-making (MCDM) Methods: advancements, applications, and future directions. Decision Making Advances, 1(1), 25-48.

Saini, D., Dokhaei, B., Shafei, B., and Alipour, A. (2024). Performance evaluation of high-rise buildings using database-assisted design approach. Structural Safety, 109, 102447.

Salmassi, M. A., Kheyroddin, A., and Hemmati, A. (2024). Evaluating the nonlinear behavior of tall buildings with end shear walls through chaos theory. Innovative Infrastructure Solutions, 9(3), 78.

Shahab, K., Irtaza, H. and Agarwal, A., (2021). Comparative study of aerodynamic coefficients of prismatic and twisted tall buildings with various cross sections using CFD. Journal of The Institution of Engineers (India): Series C, 102(3), pp.635-650.

Shih, H. S., Shyur, H. J., and Lee, E. S. (2007). An extension of TOPSIS for group decision making. Mathematical and computer modelling, 45(7-8), 801-813.

Szolomicki, J. and Golasz-szolomicka, H., (2017). Application of the diagrid system in modern high-rise buildings. International Journal of Advances in Science Engineering and Technology, 5(3), pp.7-13.

Takeda, T., Sözen, M.A. and Nielsen, N.N. (1970) 'Reinforced concrete response to simulated earthquakes,' Journal of the Structural Division, 96(12), pp. 2557–2573.

TS-498, (1987). Design Loads for Buildings, Turkish Standard Institution, Ankara, Turkey.

TSC, (2018). Turkish Seismic Code. Specifications for Buildings to be Built in Seismic Areas. Ministry of Public Works and Settlement, Ankara (2018).

Vollers, K., (2001). Twist and build: creating non-orthogonal architecture. 010 Publishers.

Xia, J., Poon, D. and Mass, D., (2010). Case Study: Shanghai Tower. CTBUH J, 2010, pp.12-18, Alhazmi, T., & McCaffer, R. (2000). Project procurement system selection model. Journal of Construction Engineering and Management, 126(3), 176-184.

Zhaoa, X., Ding, J. and Suna, H.H. (2011). Structural design of Shanghai Tower for wind loads, Procedia Engineering, 14, pp. 1759–1767.