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THE BEHAVIOUR OF TWISTED TALL BUILDING STRUCTURES UNDER LATERAL LOADS

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Anahtar Kelimeler

Twisted tall building, seismic performance, wind loads, composite shear wall, case study

Öz

Twisted tall building structures have recently been used as an architectural and structural form. On the other hand, there are very few studies on the behavior of twisted tall buildings under seismic and wind lateral loads. In this study, the behavior of twisted tall buildings under seismic and wind-induced loads is investigated and compared with their prismatic counterpart. As a case study, a twisted building in Miami, Florida, is modified by twisting all floor levels with an angle of 3 degrees. Lateral forces (wind and seismic) are considered for this location and using ASCE 7-16. The 3-dimensional models are created by using ETABS for analysis. The structural system of the building consists of a composite core system. The floor system consists of a post-tensioned concrete slab and the surrounding twisted columns are reinforced concrete. For the analysis of twisted tall building structures under lateral loads such as wind loads and seismic loads, the application of provisions and the behavior of prismatic and twisted tall building structures are discussed. In the study, it was found that the lateral stiffness of the twisted tall building under seismic loads is lower than that of the prismatic tall building.

BURGULU YÜKSEK YAPILARIN YANAL YÜKLER ALTINDA DAVRANIŞI

Keywords

Burgulu yüksek yapılar, deprem performansı, rüzgar yükleri, kompozit perde duvar, vaka analizi

Abstract

Burgulu yüksek bina yapıları son dönemlerde mimari ve yapısal bir form olarak kullanılmaktadır. Öte yandan, burgulu yüksek yapıların, deprem ve rüzgar yükleri altında yanal yükler olarak davranışına ilişkin çok az çalışma bulunmaktadır. Bu çalışmada, burgulu yüksek katlı yapıların deprem ve rüzgar yükleri altındaki davranışı incelenmiş ve emsali olan prizmatik yapı ile karşılaştırılmıştır. Bir vaka analizi olarak, Miami, Florida'da bulunan burgulu bir yüksek bina, tüm katları 3 derecelik bir açıyla döndürülerek düzenlenmiştir. Binanın bulunduğu konumdaki yanal kuvvetler (rüzgar ve sismik) dikkate alınmış ve ASCE 7-16 yönetmeliği kullanılmıştır. ETABS kullanılarak analiz için 3 boyutlu modeller oluşturulmuştur. Bina taşıyıcı sistemi, betonarme kolonlu kompozit bir çekirdekten oluşmaktadır. Döşeme sistemi ardgermeli betonarme döşemeye sahiptir ve burgulu kolonlar betonarmedir. Rüzgar yükleri ve sismik yükler gibi yanal yükler altında burgulu yüksek bina yapılarının analizi için, yönetmelik hükümlerinin uygulanması ve prizmatik, burgulu yüksek bina yapılarının davranışı kıyaslamalı olarak tartışılmıştır. Çalışmada, deprem yükleri altında burgulu yüksek binanın yanal rijitliğinin prizmatik yüksek binaya göre daha düşük olduğu tespit edilmiştir.

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1. Introduction

Interest in tall buildings has continued from the past to the present. The construction of tall buildings has accelerated for reasons such as population growth, the increased value of land in cities, prestige, and competition between countries. There are many building forms used to construct tall buildings, and one of these building forms is twisted tall buildings. Twisted tall buildings are defined by the Council on Tall

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Buildings and Urban Habitat (CTBUH) as the gradual rotation of the floor or facade toward the upper floors of the building. The popularity of twisted tall building structures is increasing day by day because twisted tall buildings have better aerodynamic performance under wind loads than prismatic structures (Günel and Ilgın, 2014). The first example of a twisted tall building is the 190-meter Turning Torso in Malmoe, Sweden, which was completed in 2005. The twisted 632-meter Shanghai Tower is currently the world's second tallest building.

Some researchers have published on the topic of twisted tall building structures. In (Moon, 2012, 2015), maximum displacement and lateral stiffness by modeling the twisted structure at different angles and heights and found that the lateral stiffness decreases with increasing rotation in twisted structures. It was stated that the twisted tall building structures are not very beneficial to the structural system. In (Kim and Hong, 2011), the tilted structure with a braced core and the twisted structure with a reinforced concrete core with the prismatic structure compared and evaluated the capacities of progressive collapse resistance with dynamic analysis. It was observed that the potential progressive collapse of the twisted structure did not change significantly compared to the prismatic structure. In (Lee, Kim, Kang and Kim, 2014), seismic behavior of a 60-story twisted tall building with an outrigger system at different angles and locations was investigated. It was found that the angle of rotation affects the relationship between bearing capacity and story displacements for twisted tall buildings. In (Kwon and Kim, 2014), resistance to earthquake loads by removing columns in twisted structures with different angles was investigated. Several researchers have conducted experimental studies on twisted tall buildings with wind tunnel tests (Tanaka et. al., 2013 and Bilgen, 2019). In these studies, twisted tall building structures were found to perform well in terms of aerodynamic shape. In (Shabab, Irtaza and Agarwal, 2021), the aerodynamic coefficients of prismatic and twisted tall buildings with different cross-sections were compared using the computational fluid dynamics method. It was found that wind aerodynamic load is lower in twisted tall buildings than in prismatic tall buildings.

Some researchers have made some classifications of twisted tall buildings (Vollers, 2015 and Taşkın, 2019). In this study, twisted tall building structures are divided into two types in terms of structural engineering. The first type (Type-1) is twisted structures in which the center of the structural system is fixed in the core and the facades or floors rotate. The second type (Type-2) is twisted structures in which the outer structural system rotates while the inner core is fixed. Examples of Type-1 and Type-2 are shown in Fig.1 and Fig.2.

(a) **(b)**

Figure 1. Examples of Type-1 Model of Twisted Tall Building Structures: (a) Evolution Tower, Russia (b) Shanghai Tower, China

(a) **(b)**

Figure 2. Examples of Type-2 Model of Twisted Tall Building Structures: (a) Cayan Tower, United Arab Emirates ; (b) Al Bidda Tower, Qatar

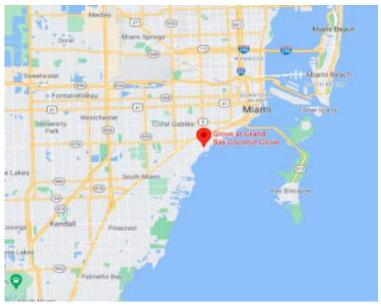


Figure 3. Location of Investigated Twisted Tall Building Structures

Figure 4. Grove at Grand Bay Towers a. Grove at Grand Bay North Tower b. Grove at Grand Bay South Tower

Grove at Grand Bays is the first twisted tall building in the United States of America. Grove at Grand Bays consists of two buildings, North and South, and they have high ceilings and large terraces. In this study, Grove at Grand Bay South Tower (Miami, USA) was selected as a case study (Fig. 3). It has 21 floors and a height of 93.8 meters, as shown in Fig. 4b. Analyses were performed by using ETABS (CSI, 2020). The buildings were modeled by using the existing structural and architectural information. The behavior of the structure was investigated under wind and seismic loads.

2. 3-D Finite Element Modelling of Twisted Tall Building Structures

2.1. Structural System of Grove at Grand Bay South Tower

The height of each floor is 13.33 feet (4.064 m) of the building, except for the top floor and podium floor. The angle of rotation on each floor is approximately 3 degrees up to the 15th floor, and the building rotates approximately 39 degrees counterclockwise overall. The Grove at Grand Bay South Tower has 30-inch (762 mm) thick reinforced concrete shear wall with internal steel plate at the core of the building. Steel plates up to 3.75-inches (95.25 mm) thick are placed in the inner part of the shear wall. Rolled steels are used in the boundary zone. The steel plates in the shear wall extend to the 15th floor (Fig. 5). Diameter of a column in a story is 30-inches(762 mm). The concrete strength of the walls and columns in the building is 12,000 psi (82.74 MPa), 10,000 psi (68.95 MPa), and 8,000 psi (55.16 MPa). The longitudinal rebars are B500C-Φ36 in the building, and S355 steel is used in the steel plate. The floor system consists of a post-tensioned flat plate slab. The thickness of the slab varies from 10 inches (254 mm) to 12 inches (304.8 mm), and the concrete strength of the slab does not exceed 12 ksi (82.74 MPa). The torsion of the building is reduced by using a roof truss system at the top of the building. Tower floor plates are cambered by up to a half-inch(12.7 mm) rotationally. The typical architectural plan of 20th floor is shown in Fig. 6.

Figure 5. Steel Plates Inside the Composite Shear Wall (DeSimone, Ramirez and Mohammad, 2015)

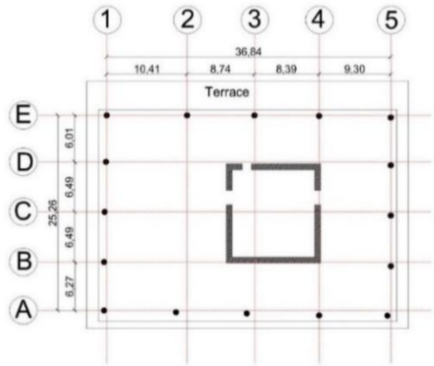
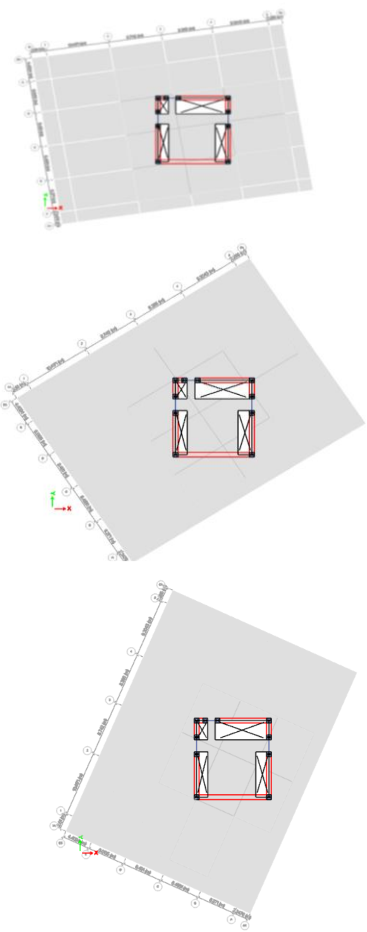


Figure 6. Architectural Plan of the 20th Floor (units are in m)

2.2. Finite Element Modelling and Assumptions

The selected twisted tall building was modified at an angle of three degrees from the first floor to the last floor. The floor plans of the building are shown in Fig.7. 3D finite element models of the prismatic and twisted tall building structures are shown in Fig. 8. The concrete classes are C80/95, C70/85, and C55/67 on the 1-11 level, 12-17 level, and 18-23 level, respectively. The diameter of the circular reinforced concrete columns and the thickness of the composite shear walls are 762 mm. The #11 rebar used in the columns and shear walls is Ø36 in the metric system. The Grade 75 rebar class used in the selected building is modeled as B500C rebar in the metric system. The composite shear wall was modeled from bottom to top because all floors rotate at an angle. The grade 50 steel class in the internal steel plate was modeled as S355. The I-shaped steel sections in the shear walls were modeled as frame columns and connected to the multi-layer composite shear wall with rigid links. The slabs were modeled as reinforced concrete using C80/95 concrete in the modeling by assigning a rigid diaphragm, and the thickness of the slabs was 11 inches (279.4 mm). The I-shaped steel in the composite columns at the corner points of the shear wall was W 310 x 310 x 283, and the connecting beams between the shear walls were modeled as composite. The hat truss at the top of the structure was ignored in the models. The cambered floors were not considered in the models. All floors were considered the same height (4.064 m). The bottom ends of columns and shear walls were attached to the ground with fixed supports. The soil class was taken from the site class map according to the location of the building (Rong and Thomson, 2012).



(a)

(b)

(c)

Figure 7. Plans of The Twisted Tall Building: (a) 3rd floor (9-degree rotation); (b) 11th floor (33-degree rotation); (c) 22nd floor (66-degree rotation)

Table 1. Wind Load Parameters for Prismatic Tall Building

Parameter	Value
Wind Speed	76 m/s
Exposure Type	B
Gust Factor (X-Direction)	1.14
Gust Factor (Y-Direction)	1.12

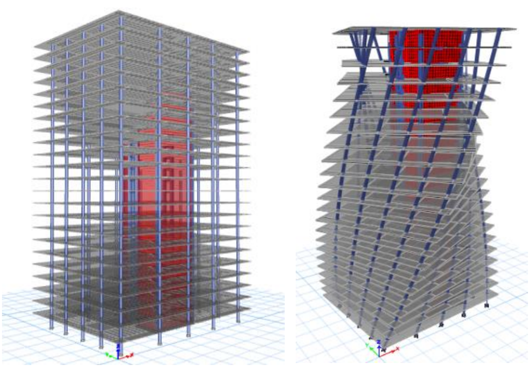


Figure 8. 3-D Finite Element Model of the Prismatic and Twisted Tall Building Structures

Table 2. Assigned Load and Seismic Load Parameters

Parameter	Value
Super Dead Load	76 m/s
Live Load	B
S_s	0,04
S_1	0,02
Site Class	D
Response Modification (R)	6.5
System Overstrength (Ω)	2.5
Deflection Amplification (C_d)	5.5
Occupancy Importance (I)	1

Super dead load was included in the total weight in the analysis. For seismic loading, the additional %5 accidental eccentricities were included. Figure 9 shows the horizontal elastic design spectrum derived from the following equation 1(ASCE 2017). Because the selected building is flexible, the gust factors are calculated in the x and y direction according to ASCE 7-16(Section 26.11.5). For wind force calculations, the gust factor effect depends on the natural frequency of the building and the building plan dimensions. The gust factor effect (G_f) was calculated 1.14 in the x direction and 1.12 in the y direction. Table 1 and Table 2 show the load parameters in the analysis. The percentage of modal participation was over 90% for the prismatic and twisted tall buildings.

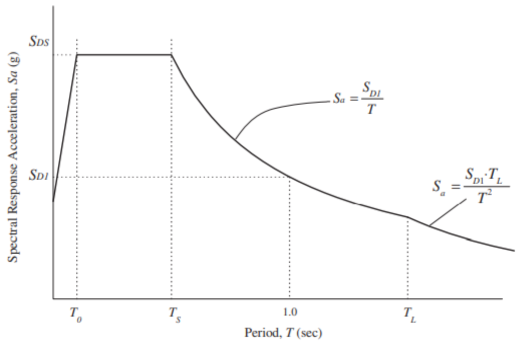


Figure 9. Design Response Spectrum (ASCE 7-16)

$$S_a = S_{DS}(0{,}4 + 0{,}6\frac{T}{T_0}) \qquad T \le T_0$$

$$S_a = \frac{S_{D1}}{T} \qquad T_0 \le S_a \le T_s$$

$$S_a = \frac{S_{D1}\, T_L}{T^2} \qquad T_L \le S_a \quad (1)$$

$$G_f = 0.925\left(\frac{1 + 1.7I_{\bar{z}}\sqrt{g_Q{}^2Q^2 + g_R{}^2R^2}}{1 + 1.7g_v I_{\bar{z}}}\right) \quad (2)$$

The composite shear walls in the selected building consist of steel plates and reinforced concrete (Figure 10). The composite shear wall was modeled in ETABS as a shell with a multi-layer shell element (Figure 11). The composite behavior was accounted for by modeling the I-steel-shaped composite corner regions as frames and connecting them to the multilayer shell model with rigid links. The composite shear walls were connected by composite link beams via rigid links.

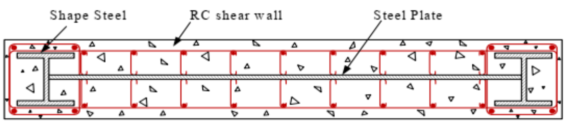


Figure 10. Steel Plate Reinforced Concrete Composite Shear Wall (SPRC) (Xiao et. al., 2012)

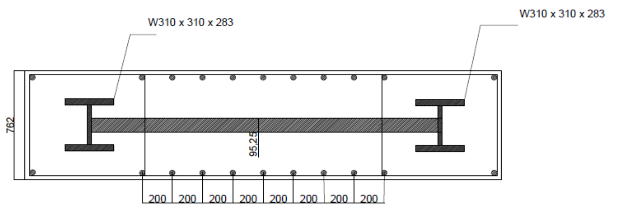


Figure 11. Cross Section Of Composite Shear Wall In Modeling (units are in mm)

3. Results and Discussions

3.1. Base Shear Forces of Models

The base shear in the prismatic tall building is 4263 kN under the seismic load cases in X and Y directions under seismic load. The value of base shear is 14497 kN in the X direction and 19597 kN in the Y direction. The base shears of models are shown in Table 3. Under seismic load cases in X and Y directions, the value of base shear is 4245 kN in twisted tall building. Base shear is 12323 kN in the X direction and 16658 kN in the Y direction of wind load in twisted tall building.

Table 3. Base Shear Forces

Load Type	Prismatic Tall Building	Twisted Tall Building
Seismic Load	X: 4263 kN	X: 4245 kN
	Y: 4263 kN	Y: 4245 kN
Wind Load	X: 14497 kN	X: 12323 kN
	Y: 19597 kN	Y: 16658 kN

3.2. Seismic Behaviour of Prismatic Tall Building Structures

The response spectrum analysis was performed for the seismic analysis. The seismic load was applied in both X and Y directions for the model, separately in each case.

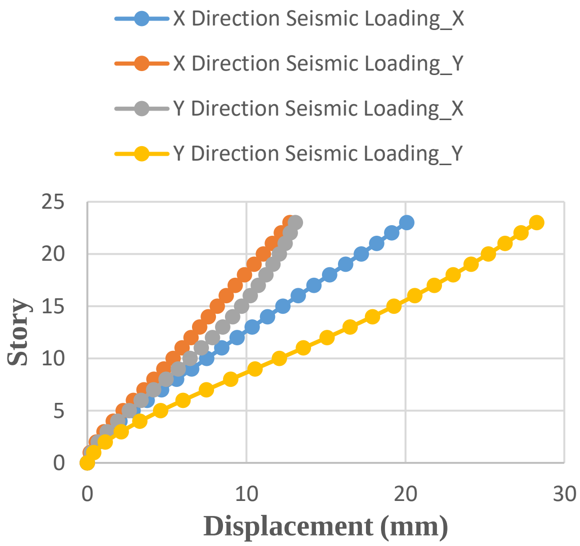


Figure 12. Top Story Displacements Under Seismic Load Case

The maximum top deflection is 2.0 cm under seismic loading in the X direction and 2.8 cm under seismic loading in the Y direction (Figure 12). The story drift values of the model are shown in Figure 13. The maximum drift is 6.3 mm for seismic loading in the X direction and 8.6 mm for seismic loading in the Y direction. The maximum overturning moments in the X-direction and Y-direction are found 1.69×10^5 kN.m and 2.46×10^5 kN.m, respectively, in Figure 14.

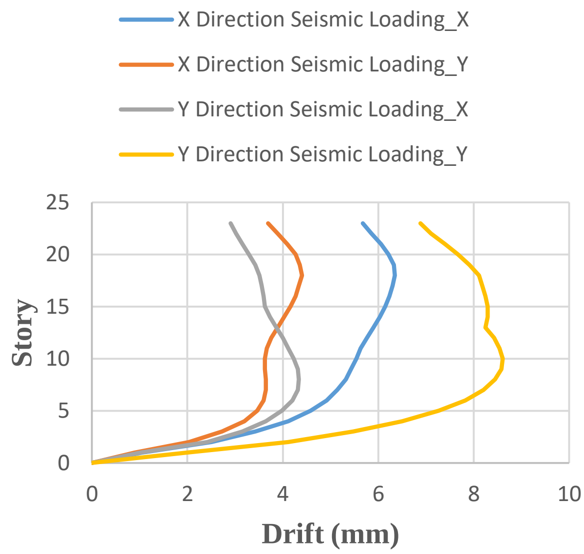


Figure 13. Story Drifts Of The Model Structure Subjected To The Seismic Load

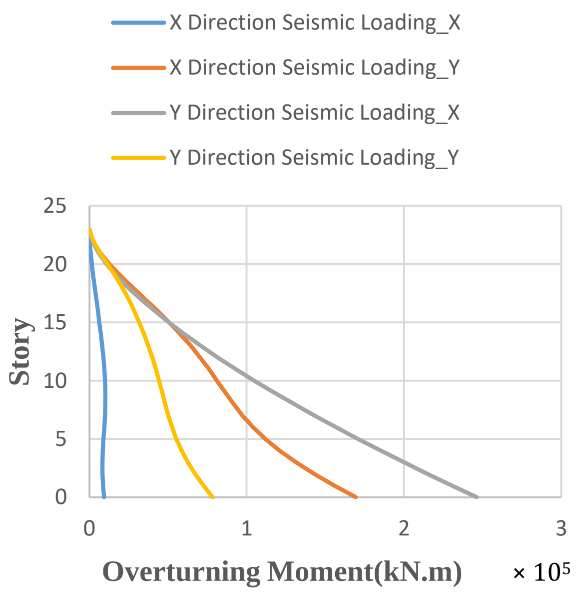


Figure 14. Overturning Moment Under Seismic Load Case

3.3. Wind Load Case and Behaviour of Prismatic Tall Building Structures

The code-based wind loading was used in the wind analysis. The wind load was applied in both X and Y directions, separately. The maximum displacement of the top story under wind load in X and Y directions is shown in Fig. 15 for each floor of the prismatic tall building. The maximum displacement of the top floor is 6.9 cm in the X-direction and 11.1 cm in the Y-direction under wind load. According to the literature, the maximum lateral displacement of tall buildings should not exceed the ratio H/500 (Serviceability criteria).

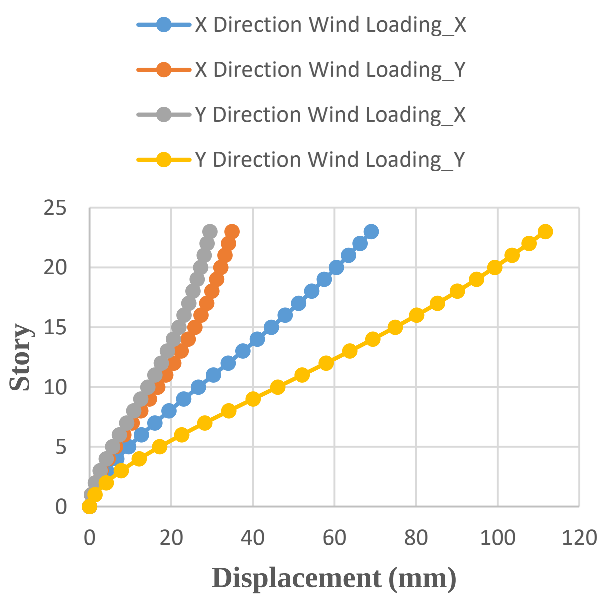


Figure 15. Top Story Displacements Under Wind Load

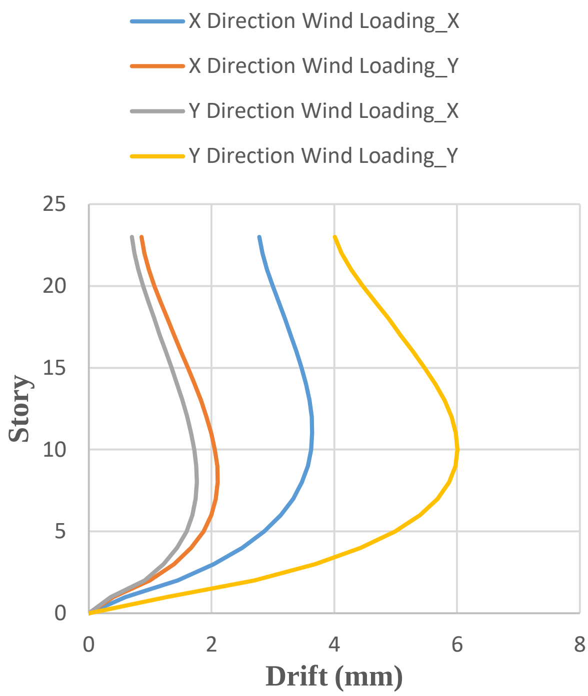


Figure 16. Story Drifts Of The Model Structure Subjected To The Wind Load

Top deflections under wind load are below the serviceability criteria, which is 18.7 cm. The maximum drift is 3.64 mm under wind loading in the X direction and 6 mm under wind loading in the Y direction (Figure 16). The maximum overturning moment values for wind loading in the X direction and wind loading in the Y direction are found 7.36×10^5 kN.m and 9.92×10^5 kN.m, respectively (Figure 17).

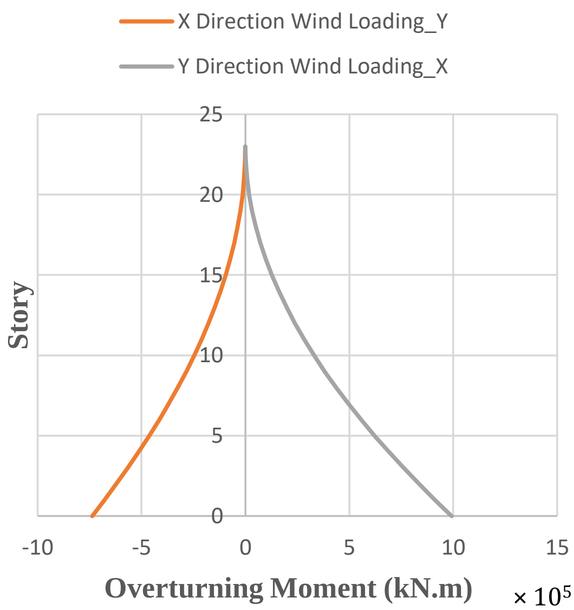


Figure 17. Overturning Moment Under Wind Load Case

3.4. Seismic Behaviour of Twisted Tall Building Structures

The seismic analysis in twisted tall building, response spectrum analysis was carried out. In each case, the seismic load was applied in both the X and Y directions separately. Under seismic loading, the maximum upper deflection is 2.6 cm in the X direction and 2.9 cm in the Y direction (Figure 18). Figure 19 shows the results of the drift of the model relative to the floors. The maximum drift for seismic load in the X direction is 8.36 mm, while the maximum drift for seismic load in the Y direction is 8.8 mm. It is observed that there are increases in story drifts between 16-23. level. The maximum relative displacement value for the earthquake force is calculated 81.28 mm under ASCE 7-16 standard. Figure 20 shows the maximum overturning moment values in the X and Y directions 1.71×10^5 kN.m and 2.42×10^5 kN.m, respectively. Maximum overturning moment of X axis in X direction is found 0.0636×10^5 kN.m. Maximum overturning moment of Y axis in Y direction is found 0.75×10^5 kN.m.

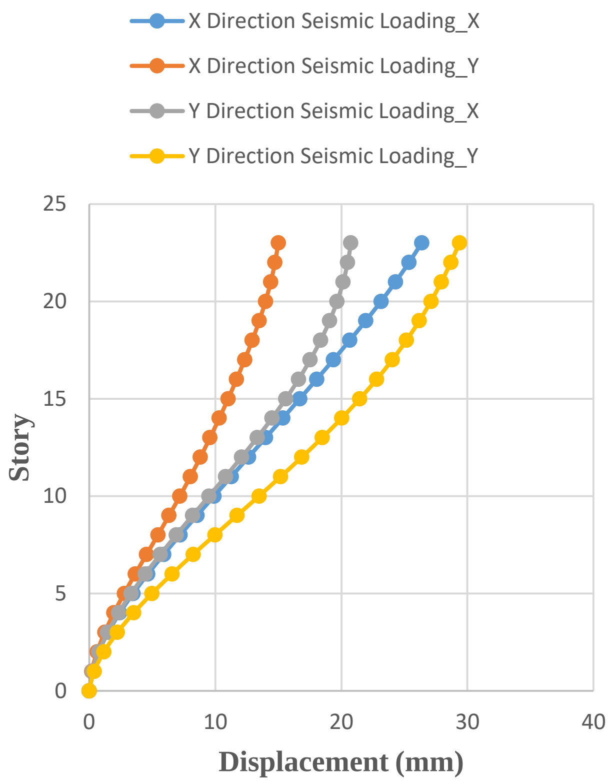


Figure 18. Top Story Displacements Under Seismic Load Case

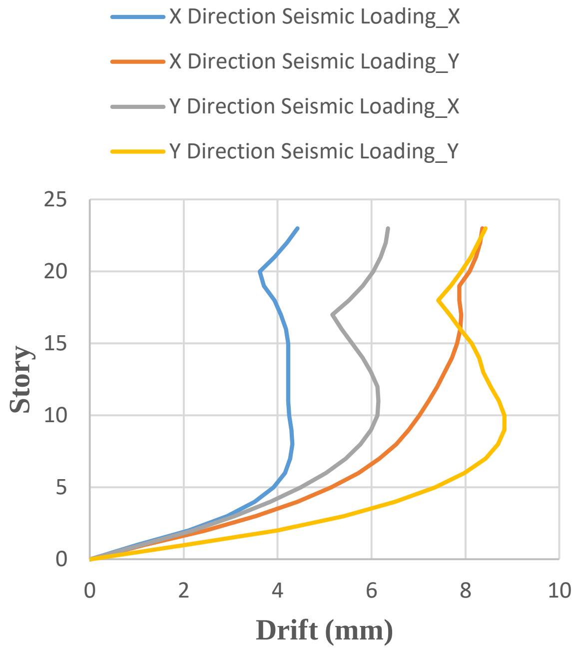


Figure 19. Story Drifts Of The Model Structure Subjected To The Seismic Load

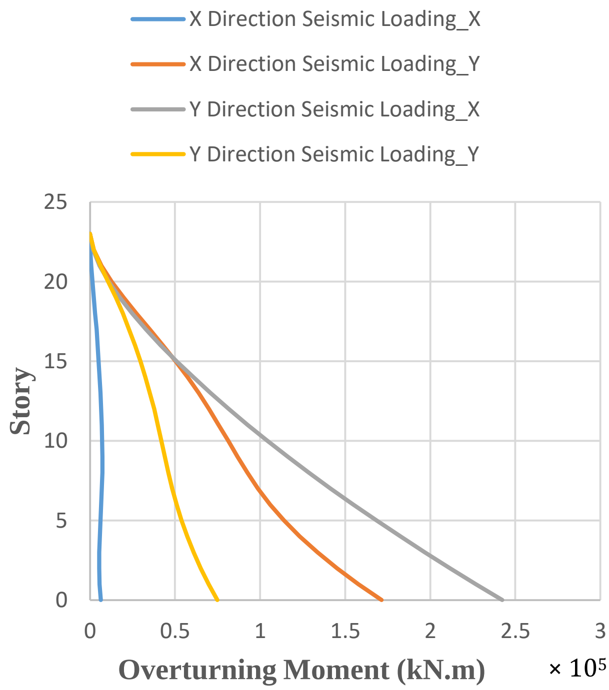


Figure 20. Overturning Moment Under Seismic Load Case

3.5. Wind Load Case and Behaviour of Twisted Tall Building Structures

In the literature, it is known that twisted tall building structures play an active role in reducing wind loads (Bilgen, 2019). In this study, the wind forces occurring in the prismatic structure were applied by reducing 15% in the twisted tall building structure (Niğdelioğlu, 2022). The wind load was applied in both the X and Y directions. The maximum displacement of the top floor under wind load in X and Y directions is shown in Fig. 21 for each floor of the twisted tall building. The maximum displacement of the top floor under wind load is 6.8 cm in the X direction and 9.6 cm in the Y direction. In the literature, the maximum lateral value of the structures is generally given as the H/500 ratio. The upper deflections under wind load are lower than the serviceability criterion, which is 18.7 cm. Under wind load, the maximum drift is 3.55 mm in the X direction and 5.129 mm in the Y direction. (Figure 22). Figure 23 shows the maximum overturning moment values for the wind load in the X-direction and the wind load in the Y-direction, which are 6.25×10^5 kN.m and 8.43×10^5 kN.m, respectively.

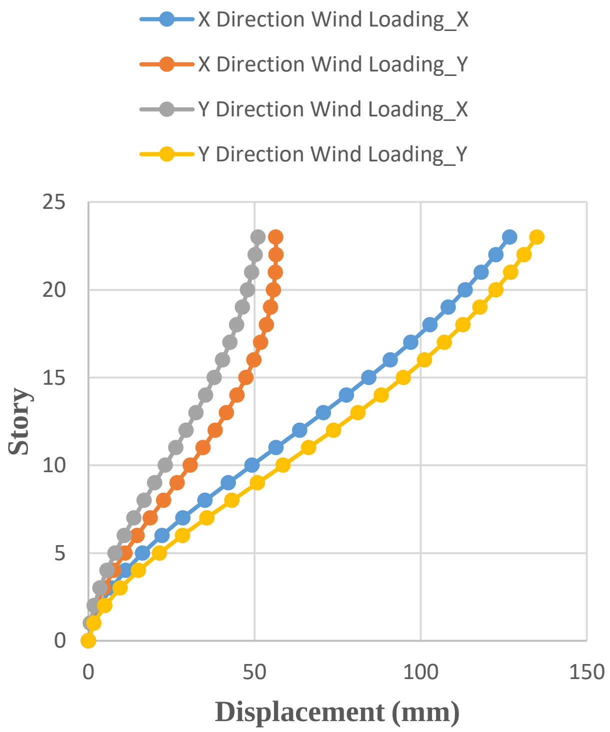


Figure 21. Top Story Displacements Under Wind Load Case

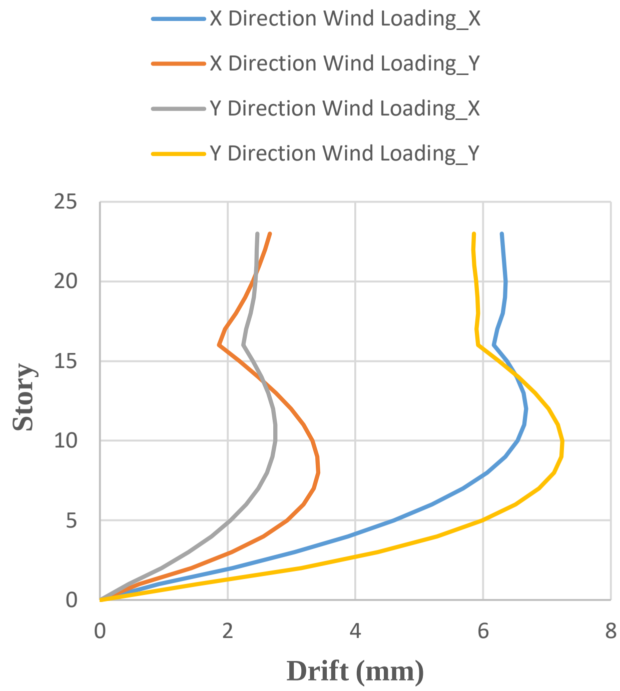


Figure 22. Story Drifts Of The Model Structure Subjected To The Wind Load

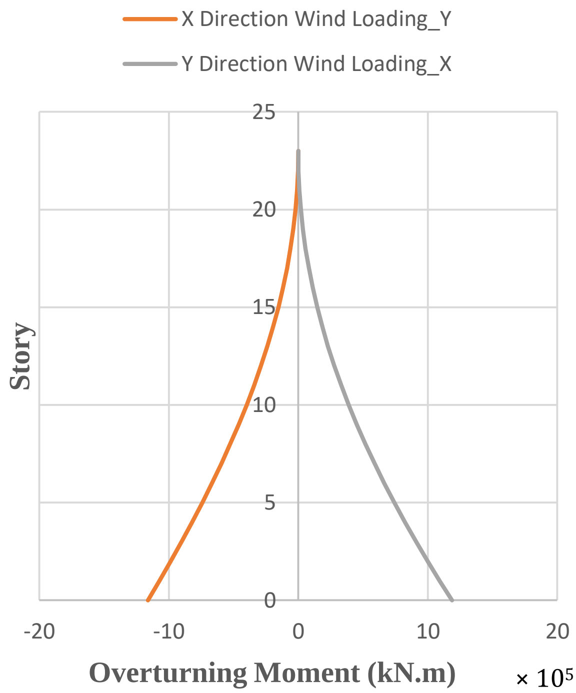


Figure 23. Overturning Moment Under Wind Load Case

4. Conclusion

This paper presents a finite element model for the analysis of twisted tall building structures under lateral loads and a corresponding prismatic tall building. The Grove at Grand Bay South Tower was used as a case study and the behaviour of the building under lateral loads was investigated and compared. Results include maximum story displacements, maximum inter-story drifts, base shear, and overturning moments. The maximum story displacement values under wind and seismic loading for prismatic and twisted tall buildings are less than H/500 of the building height. The twisted building is within the allowable deflection criteria. The drift values under wind and earthquake loading are within the criteria of ASCE 7-16. Since the twisted structure has an irregular form, the percentage of modes exceeds 90% when 17 modes are considered in the analysis. With 11 modes in the prismatic structure, the mod participation rate value of 90% exceeds. The maximum story displacements under seismic load are lower than under wind load, because wind load is more critical than seismic load. The base shear values under wind loads are higher than under seismic loads because the location of the building isn't an earthquake-prone region. The twisted tall building has maximum relative displacement of 8.36 mm in the x-direction, whereas the prismatic tall building has a maximum relative displacement of 6.3 mm. It is also found that the overturning moment values are higher under wind loads. It is observed that the relative displacements increased on the 16-23rd floors of the twisted tall building compared to the prismatic structure. The increase in relative displacement on these floors can be considered as the reason that the existing building is not rotated on these floors. In the study, the lateral stiffness of the twisted tall building under earthquake loading is lower than the prismatic tall building. The twisted form of the building has contributed to the decline in wind force compared to the prismatic form of the building. In addition, the wind load in Y direction is bigger than X direction in both building forms. In order to better analyze the wind force distribution in twisted tall buildings, it is recommended to apply the wind to the facade of the building via wind tunnel tests and computational fluid dynamics studies in next future studies.

Author Contributions

In this paper; Abdullah Niğdelioğlu, modelling of the buildings, writing, literature survey; Uğur Albayrak, conceptualized the paper, supervision; Can Balkaya conceptualized the paper, supervision and reviewed the manuscript.

Conflict of Interest

No conflict of interest was declared by the authors.

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