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Impact of wind loads on the structural integrity of reinforced concrete (RC) minarets

Rüzgar yüklerinin betonarme minarelerin yapısal bütünlüğüne etkisi

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Abstract

The rapid climatic shifts caused by global warming represent a growing and serious threat that demands immediate global attention and preparation. The collapse of minarets in Mersin, İzmir, Ankara and Kahramanmaraş due to strong winds has served as the inspiration for this research article. These incidents highlight the lack of sufficient investigation into the wind effects on minarets in Turkey and underscore the presence of minaret structures that may pose significant risks. In the conducted study, the Çamlıca Mosque minarets, the tallest minarets in Turkey, were used as a reference. Finite element analyses were performed using the ANSYS program for three distinct height scenarios: a high height of 107 meters, a medium height of 57 meters, and a low height of 27 meters. The dimensions of the base, pulpit, transition segment and spire parts of the minarets are the same, only the body lengths have been changed. Wind speeds were calculated according to the height of the minarets and the relevant regulation TS498 data was considered. The research concluded that the minaret with a body height of 20 meters, considered the lowest, was the safest under the influence of strong winds, experiencing a displacement of approximately 9.1 mm at the top. However, it was observed that the displacement values for the medium-height (57 m) and tall (107 m) minarets would increase significantly, with a high risk of structural collapse occurring at the transition segments. In the study, where principal tensile and compressive stress were also calculated and presented, it was found that the tensile stress in the lowest minaret was around 1.5 MPa. However, this value increased significantly in the medium and tallest minarets, rising to approximately 6.5 times and 25 times higher, respectively.

Keywords: Compressive stress, Displacement, Pulpit section, Transition segment, Tensile stress, Wind effect on minaret

Öz

Küresel ısınmanın neden olduğu hızlı iklim değişiklikleri, acil küresel önlem ve hazırlık gerektiren büyüyen ve ciddi bir tehdit oluşturmaktadır. Mersin, İzmir, Ankara and Kahramanmaraş'taki minarelerin şiddetli rüzgarlar nedeniyle çökmesi bu araştırma makalesinin ilham kaynağı olmuştur. Kuvvetli rüzgarlar yüzünden minarelerin devrilmesi, Türkiye'de minareler üzerindeki rüzgar etkilerinin yeterli düzeyde araştırılmadığını ve önemli riskler oluşturabilecek minare yapılarının sayısını vurgulamaktadır. Yapılan çalışmada, Türkiye'nin en yüksek minareleri olan Çamlıca Camii minareleri referans olarak kullanılmıştır. Sonlu elemanlar minare model analizleri, 100 metre yüksek, 50 metre orta ve 20 metre düşük olmak üzere üç farklı yükseklik senaryosu için ANSYS programı kullanılarak gerçekleştirilmiştir. Minarelerin kaide, minber, geçiş parçası ve sivri uç kısımlarının boyutları aynı olup, ana gövde uzunlukları değiştirilmiştir. Rüzgar hızları minarelerin yüksekliklerine göre hesaplanmış ve ilgili yönetmelik TS498 verileri dikkate alınmıştır. Araştırmada, gövde yüksekliği en alçak olarak kabul edilen 27 metre olan minarenin, en üst noktasında yaklaşık 9,1 mm'lik bir yer değiştirme meydana gelmiş, kuvvetli rüzgar etkisi altında en güvenli olduğu sonucuna varılmıştır. Ancak orta yükseklikteki (57 m) ve yüksek (107 m) minareler için yer değiştirme değerlerinin önemli ölçüde arttığı, geçiş segmentlerinde yapısal çökme riskinin yüksek olduğu görülmüştür. Asal çekme ve basınç gerilmelerinin de hesaplanıp sunulduğu çalışmada, en alçak minaredeki asal çekme gerilmesinin 1,5 MPa civarında olduğu bulunmuştur. Ancak bu değer orta ve yüksek minarelerde önemli ölçüde artarak sırasıyla yaklaşık 6.5 kat ve 25 kata kadar artabileceği hesaplanmıştır.

Anahtar kelimeler: *Basınç gerilmesi, Yerdeğiştirme, Minare kaide kısmı, Geçiş kısmı, Çekme gerilmesi, Minareye rüzgar etkisi*

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1. Introduction

Global warming has the potential to trigger extreme events such as fires, floods, storms, and severe winds on an unprecedented scale, necessitating changes in structure design standards to better withstand these new challenges, as already evident in the increasing frequency and severity of natural disasters today. In this study, the risk status of strong winds according to minaret heights was examined parametrically. Minarets are among the most slender, delicate and tallest structures, but when considered in terms of the number of minarets, it is predicted that there are many more than other skyscrapers and tall tower structures. In countries with a dense Muslim population, such as Turkey, it is possible to see a few minarets on almost every street.

Minarets, the slender and tall structures, are more vulnerable to lateral loads such as earthquakes and wind. According to the TS-498/97 regulation, in wind load calculations, parameters such as the building surface exposed to the wind, the aerodynamic load coefficient (Cf) depending on the type of building, the wind speed depending on the height of the building from the ground, and the roof slope are the effects taken into account (Küçük, 2009; TS 498, 2003). Minaret damage and destruction caused by strong winds in Turkey was investigated (Türkeli, 2014). The stress distribution contours reveal critical areas, such as where the cross section narrows above 10 m and around openings (doors or control openings). These "mortal places" are vulnerable and require extra care to ensure the structure retains sufficient ductility and can withstand stress without failing. Determination and comparison of wind loads for industrial reinforced concrete chimneys that are geometrically similar to minarets were investigated (Karaca & Erdem, 2012). ACI 307/98, CICIND 2001, DIN 1056, Eurocode 1 and TS 498 standards were compared and evaluated. As a result of the analysis, the most comprehensive and largest wind load values were obtained from Eurocode1. Existing RC minarets in Northern Cyprus were studied in terms of earthquake and wind effects (Reşatoğlu et al., 2018). The study particularly emphasized the increase in the number of RC minarets in Northern Cyprus in recent years. The research was carried out with SAP2000 finite element program and static wind analysis and dynamic earthquake response spectrum analyses were performed. The shear force values coming to the base were determined to be greater in TS498 than in ACI307-98. However, a more consistent graph was obtained in the inclination angle of the wind load intensity in ACI307-98. The performance of masonry minarets in Turkey against earthquakes and winds was studied, focusing on the causes of minaret topples (Doğangün et al., 2006). When the codes of practice and research articles for earthquake and wind resistant design of minarets were investigated, unfortunately it was seen that there was no Turkish standard and specification directly related to the analysis and design of minarets. The damage photographs of the minarets caused by earthquake and strong winds are presented, and secondly, the local stress concentrations and displacement behaviors obtained from seismic analyses are briefly discussed and demonstrated. The use of TS498 and TS-EN-1991-1-4 in wind load calculation of reinforced concrete minarets considering the soil-structure ınteraction has been compared (Türkeli, 2019). The results indicate that soil-structure interaction negatively affects wind loads by increasing them, and this interaction should be considered in wind load calculations. Determination of natural foundation period of minarets and evaluation of the effect of different materials on their seismic sensitivity by using artificial neural network were investigated (Işık et al., 2023). When the actual periods from experimental analysis were compared with values estimated by the ANN using fewer parameters, the results showed a 99% accuracy. Evaluation of masonry minarets collapsing due to strong winds under uncertainty was investigated numerically and experimentally (Ural & Firat, 2015).

In Turkey, wind effects, similar to earthquakes, have caused damage to minarets. (Doğangün et al., 2006) On February 27, 2002, a storm with a velocity of 96 km/h struck Mersin-Erdemli, leading to the collapse of minarets at five mosques and damage to those at four others (Figure 1a). Nearly a year later, on February 9, 2003, a windstorm with a velocity of 100 km/h caused another minaret failure in the same city (Figure 1b). Most recently, on July 24, 2005, two masonry minarets in the city center of Kahramanmaraş-Afşin failed due to strong winds at 60 km/h (Figure 1c). (Erdoğan, 2024) On November 24, 2024, the minaret of a mosque in the Tarsus district of Mersin collapsed due to strong winds (Figure 1d). (Konuralp, 2024) On November 23, 2024, a strong wind collapsed the cone of a mosque minaret in Izmir (Figure 1e). (Diri, 2023) On May 17, 2023, the minarets of two mosques collapsed in a storm in Ankara (Figure 1f). Due to winds reaching speeds of 45 kilometers per hour, many trees fell and roofs were blown away. In the resulting wind, the minaret of the İmik Dede Mosque in the Çankaya district collapsed and stones falling from the minaret fell into the courtyard of the mosque. Similarly, in the Etimesgut district, a roof that flew off a building due to the wind fell on the minaret of the Etimesgut Central Mosque, causing it to collapse (Figure 1g). (Yiyen, 2024) On November 24, 2024, the minaret of the Fatih Mosque in the Osmangazi Neighborhood of the Onikişubat district collapsed in the strong winds in Kahramanmaraş (Figure 1h). (NTV, 2020) On January 6, 2020, the minaret of a mosque in Edirne, where an orange warning was issued due to strong winds, collapsed due to the wind (Figure 1k). The Figure 1 below illustrates examples of minarets that have collapsed due to the impact of strong winds in Turkey. Upon examining the minaret collapses presented in Figure 1, it is observed that the minarets typically collapse by detaching from the transition zone at the base. This zone, characterized by a significant loss of the transition section, experiences higher shear forces and moment values, which contribute to the structural failure.

Figure 1. Examples of minarets that have collapsed due to the impact of strong winds in Turkey

The effect of strong winds on reinforced concrete minarets has been studied quite limitedly compared to the seismic effect. In recent years, it has been observed that the minarets made of masonry stone have been replaced by reinforced concrete minarets that can be built taller due to developing technology and material quality. This study contributes to the research gap in the literature by examining the displacement, principal tensile and compressive stresses that occur as a result of the effects of strong wind loads, especially on tall minarets. In this context, the height of the Çamlıca Mosque minaret, which is the highest minaret in Turkey, is 107 meters and was examined as a reference example in terms of its height. Additionally, a study was conducted on minarets with total heights of 27 meters and 57 meters, both having the same cross-sectional features, to examine the impact of height on displacement and stress.

2. Finite element methods and materials

This study was carried out by applying static wind loads on the finite element models of the minarets. Minarets are designed in 5 parts: foundation, pulpit, transition segment, main body and spire. The stairs, balconies, doors and windows of the 3D modeled minarets are not included in the scope of this study. Numerical analyses of three-dimensional minaret finite element models under static wind loads were carried out in the ANSYS program. Figure 2 shows the entire 27-meter-high minaret and the details of the upper and lower parts. All sections of the other two minarets have the same dimensions, except that the heights of the main body are 50 m and 100 m instead of 20 m.

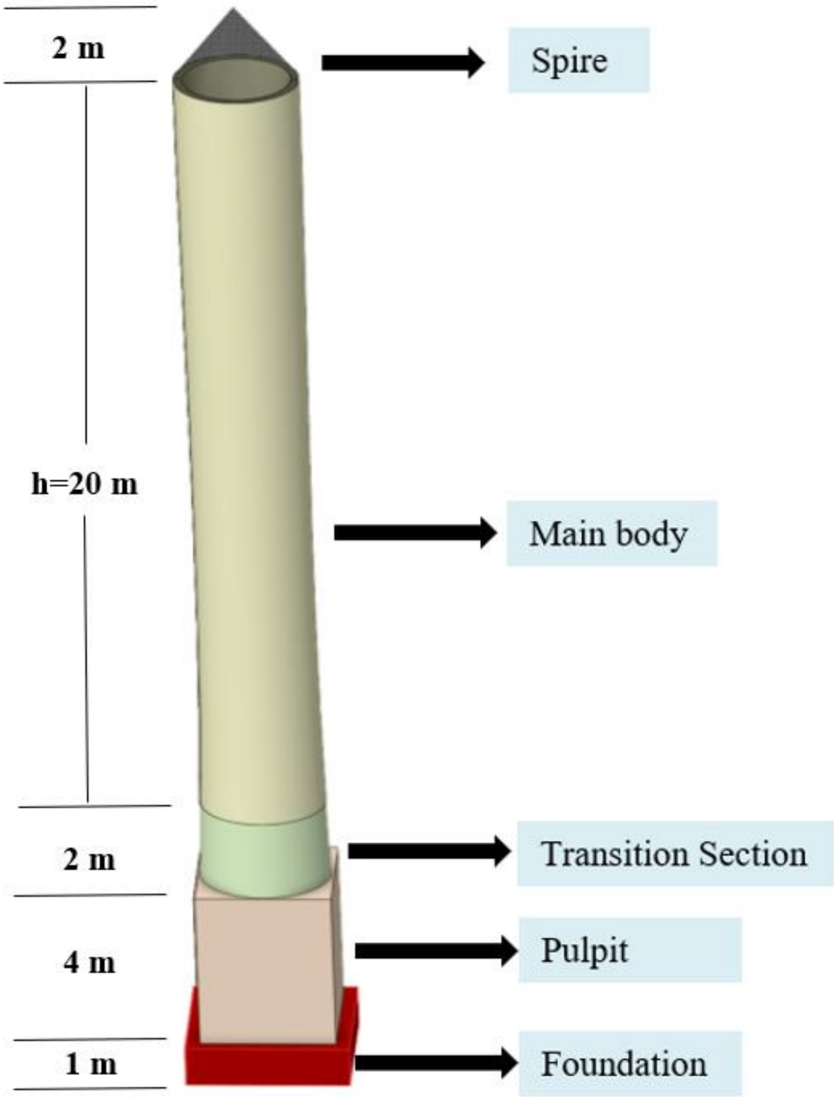

Figure 2. Low height 27-meter-high minaret and the details of the upper and lower parts.

Figure 3 presents the details of the cross-sectional areas of the foundation, pulpit, transition section and main body of the minarets. The foundation section has a square base measuring 3 meters by 3 meters, with a height of 1 meter. The pulpit section has a square section of 2.5 m x 2.5 m from outside to outside and a cylindrical space of 2 m diameter inside and its height is 4 meters. The transition part has the shape of a cylindrical cone that narrows from 2.4 meters to 2.3 meters on the outside, and the inside has a cylindrical volume of 2 meters in diameter and 2 meters in height. The main body section has a constant thickness wall with a 30 cm section.

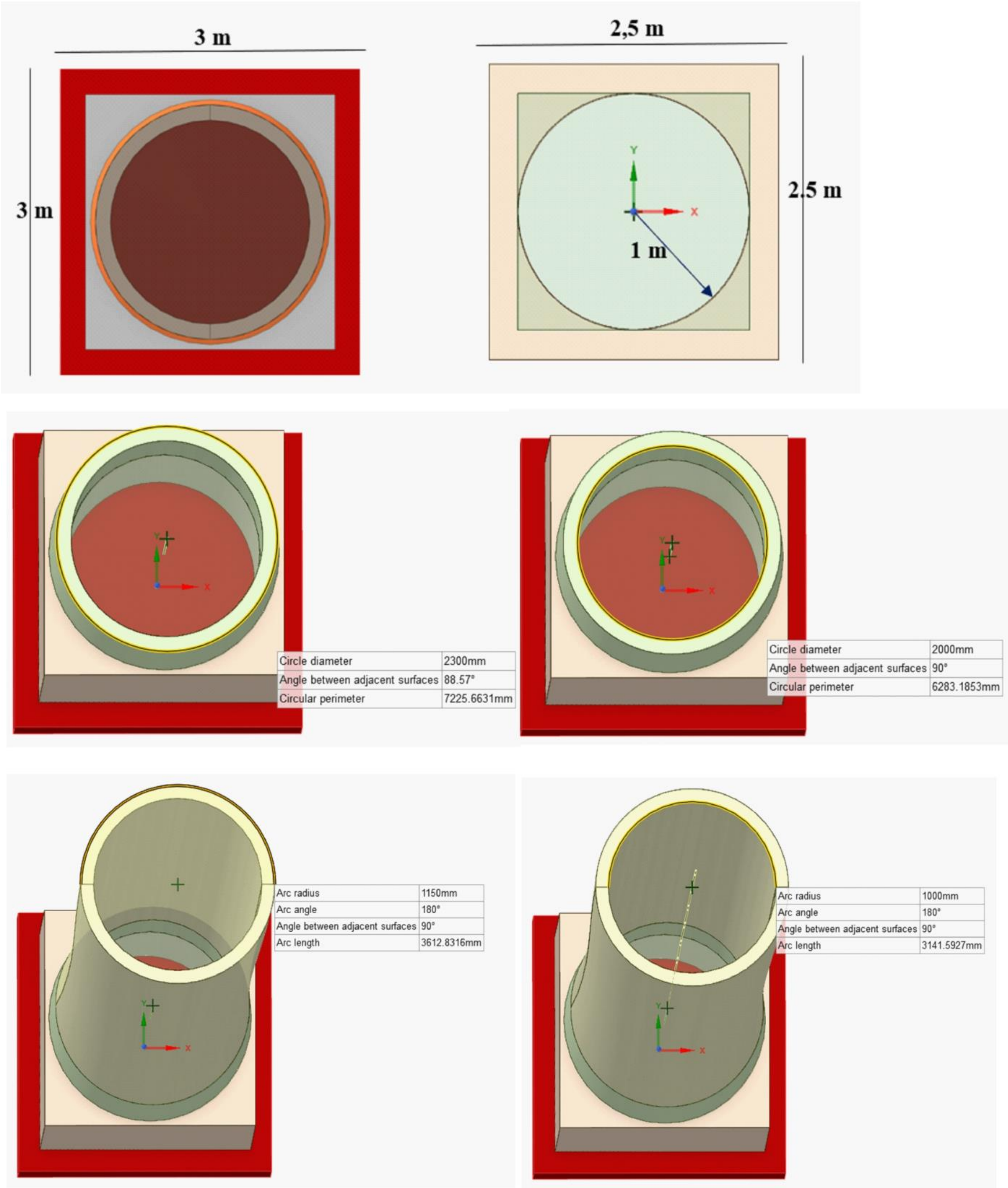

Figure 3. Low height 27-meter-high minaret and the details of the upper and lower parts.

Figure 4 shows finite element minaret models of low (27 m), moderate (57 m) and high (107 m) minarets, varying according to their heights.

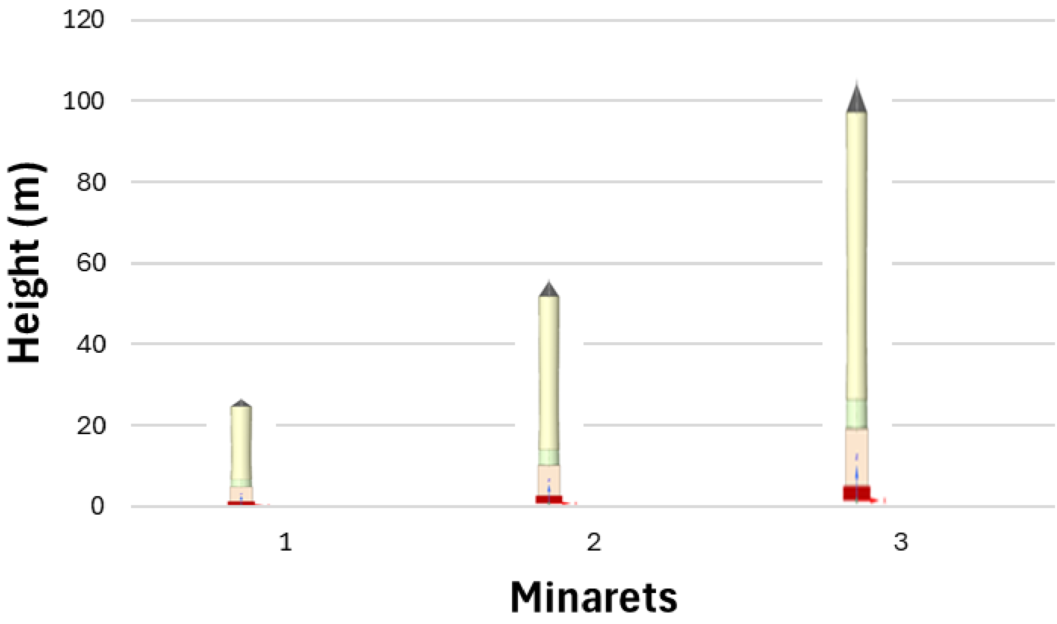

Figure 4. Low height 27-meter-high minaret and the details of the upper and lower parts.

Figure 5 shows wind load pressure and finite element models of minarets with heights of 27m, 57m and 107m, respectively. The 27-meter-high minaret is composed of 1,474 elements and 9,858 nodes. The 57-meter-high minaret features 2,641 elements and 18,981 nodes, while the 107-meter-high minaret contains 4,806 elements and 34,284 nodes.

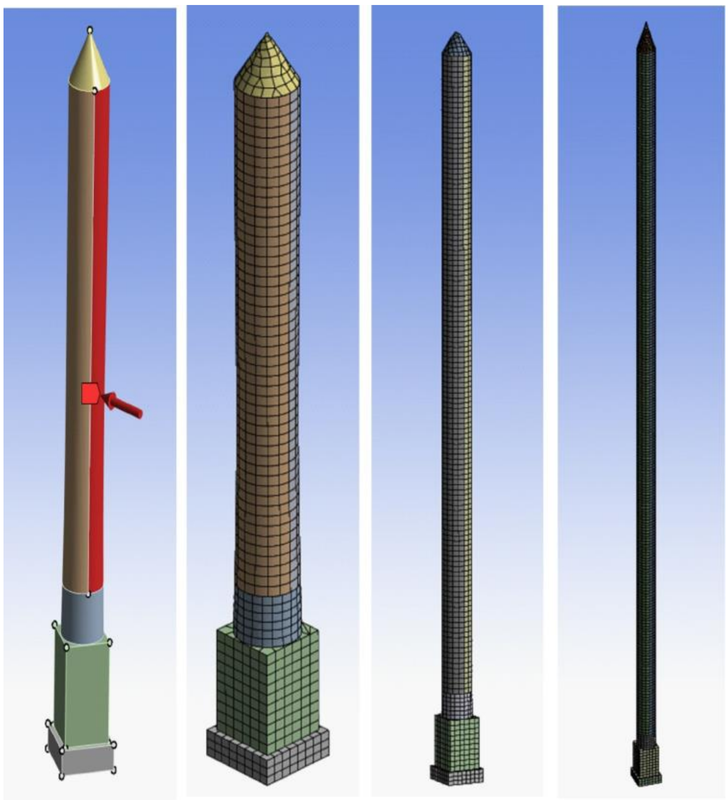

Figure 5. Wind load pressure and finite element models of 27m, 57m and 107m minarets respectively

Concrete and steel material information used in the finite element models is presented in Table 1.

Table 1. Material properties

Materials	Elastic Modulus (MPa)	Poisson Ratio ν
Concrete	30000	0.2
Steel	200000	0.3

3. Wind load calculations method

In the strong wind load (W) calculations to be made in this section, the TS498 Turkish Standard on 'Calculation Values of Loads to Be Taken In Dimensioning of Building Elements' was taken into consideration. The wind load should be taken into account in every direction, acting at its maximum value (TS 498, 2003). The wind load calculation depends on the geometry of the structure. Pressure, suction and friction effects are combined and taken into account. The magnitude of the wind load on a structure as a whole is calculated by equation (1);

$$W = Cf\ q\ A\ (kN) \tag{1}$$

Notations;
Cf= Aerodynamic load coefficient
q = Suction (speed pressure) kN/m^2
A = Affected surface area, m^2

The determination of the load coefficient (Cf) depends on the geometry of the structure and the wind direction. This coefficient is obtained from the wind channel test. Equation (2) calculates the suction value of the wind.

Suction (Speed pressure)(q):

$$q=\rho v^2/2g\ (kN/m^2) \tag{2}$$

If we take the unit volume weight of air as $\rho = 1.25\ kg/m^3$ as a very approximate value, the speed (v) is substituted in m/s. Equation (3) calculates the approximate suction value depending on the wind speed.

$$q=v^2/1600\ (kN/m^2) \tag{3}$$

Table 2 presents the wind speed and suction values depending on the altitude according to TS498.

Table 2. Wind speed and suction values depending on the structure height

Height from Ground (m)	**Wind speed v (m/s)**	**Suction q (kN/m^2)**
0-8	28	0.5
9-20	36	0.8
21-100	42	1.1
>100	46	1.3

4. Results and discussions

In this section, the results of the static wind load finite element analysis conducted for the minarets are presented. First, the minarets were analyzed under a strong wind load of 1.28 kN/m^2 to understand the effect of the minaret body height on displacement and stresses.As a result of the analyses conducted on the three different main body heights, considering the effects of strong wind pressure, the total displacement at the top points of the minarets, as well as the maximum principal tensile and compressive stresses, are presented. Figures 6, 7 and 8 present the displacement, principal tension and compressive stress results of minarets with heights of 27 meters, 57 meters and 107 meters, respectively. As a result of the static wind finite element analysis, a displacement of approximately 9.11 mm was obtained at the top of the 27-meter minaret. It is observed that the maximum principal tensile stress of 1.57 MPa and the maximum principal compressive stress of 1.53 MPa occur in the transition section of the minaret. This situation is in accordance with the studies in the literature and the cases of minaret collapse due to wind effect.

This proves that the finite element minaret model performs correctly. A displacement of 165.56 mm was obtained at the top of the 57-meter-high minaret, and it is seen that the spire part of the minaret is separated from the minaret. The maximum principal tensile stress was approximately 9.71MPa and the maximum principal compressive stress was approximately 9.74 MPa in the transition section.

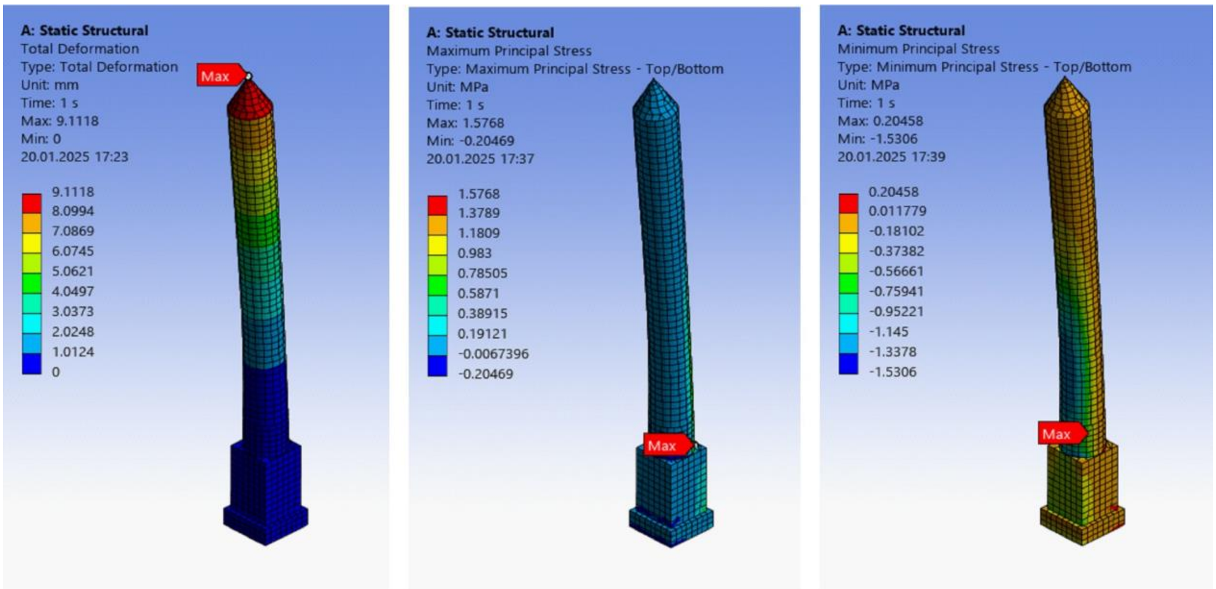

Figure 6. Finite element analysis results of the 27-meter-high minaret

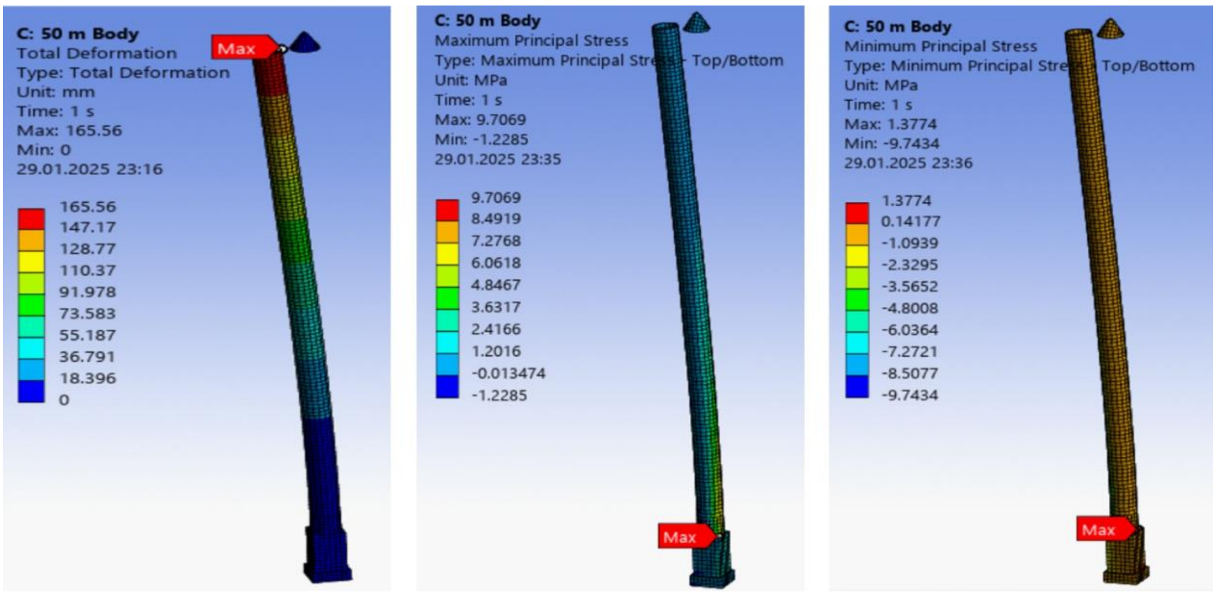

Figure 7. Finite element analysis results of the 57-meter-high minaret

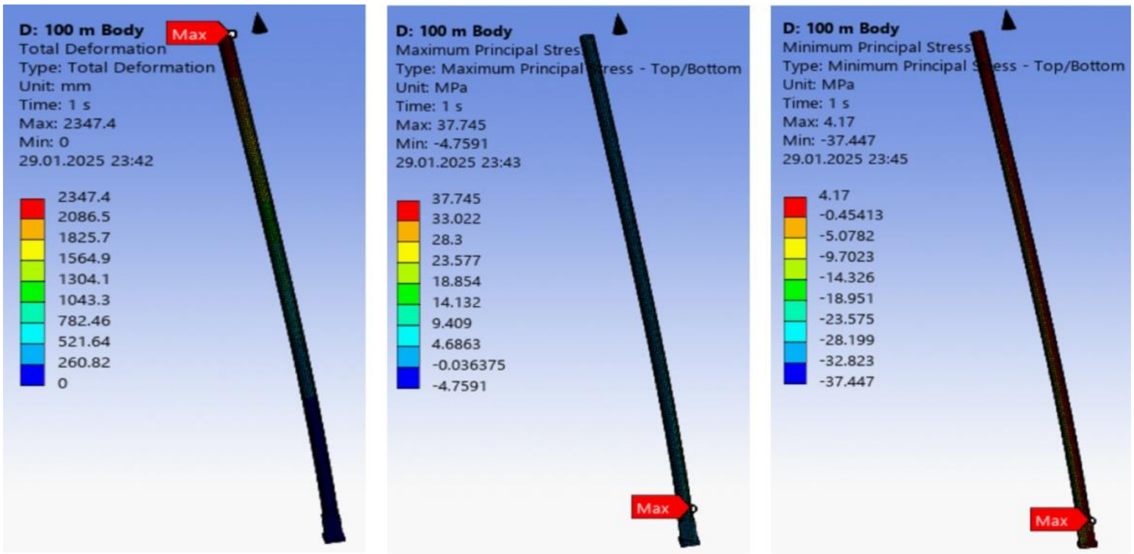

Figure 8. Finite element analysis results of the 107-meter-high minaret

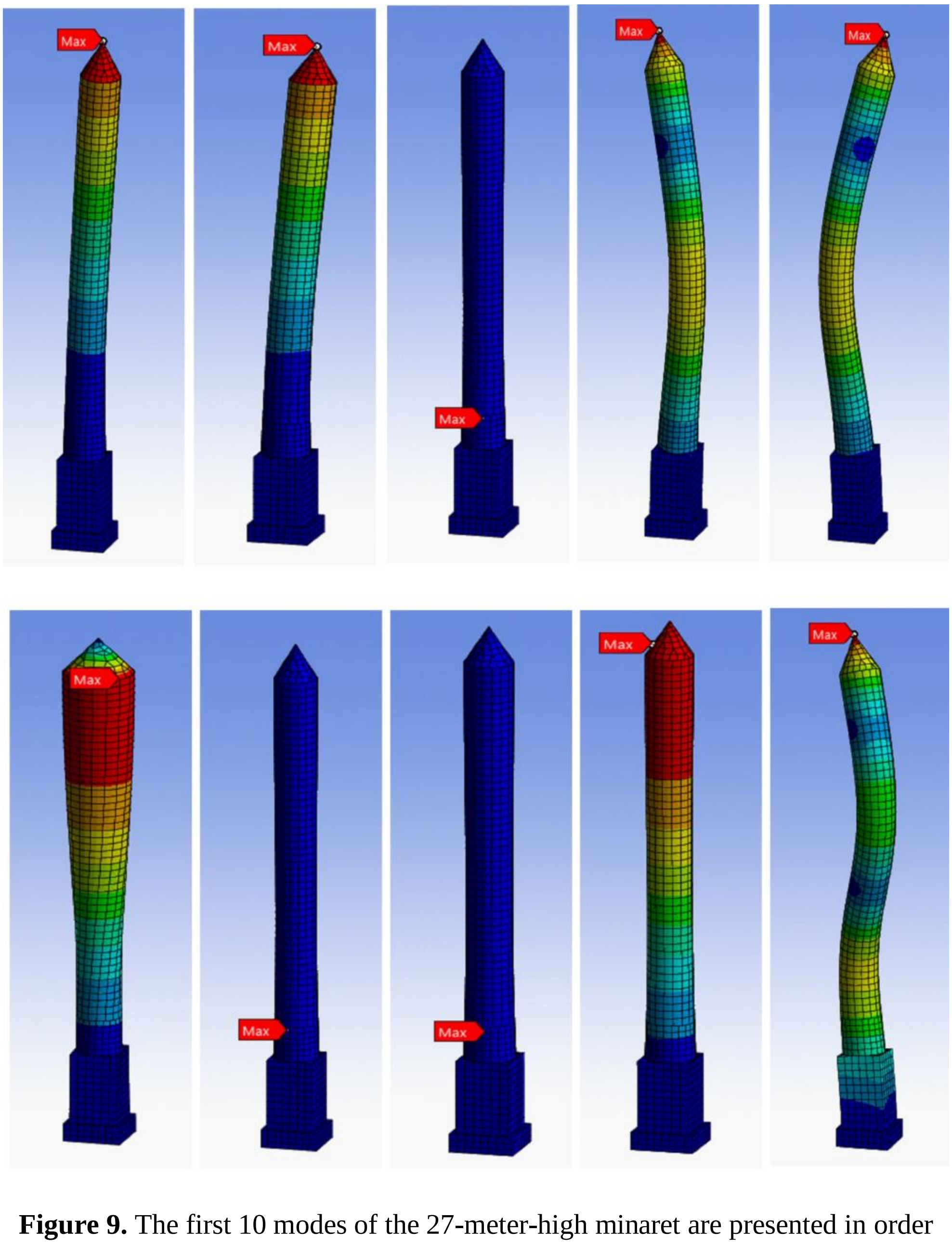

Figure 9. The first 10 modes of the 27-meter-high minaret are presented in order

When the finite element results of the 107-meter-high minaret were examined, it was found that the top point was separated from the cone part and the minaret collapsed by making a horizontal movement of approximately 234 cm. It was found that the principal tensile and compressive stresses in the 107-meter minaret were 24.67 and 24.5 times higher than the 27-meter minaret selected as reference, respectively. According to the analysis results, it was determined that the safest minaret was the 27-meter-high minaret with the lowest minaret body height and was selected as the reference minaret in the subsequent analyses of the study.

Figure 9 presents the modal shapes of the first 10 modes of the 27-meter-high minaret, which is the most suitable height according to the results of this study and the available cross-sectional areas. As seen in the figure, the first and second modes are formed in the x-direction in the axisymmetric plan geometry of the cylindrical shape of the minaret, and the fourth and fifth modes are formed in the y-direction. Torsional mode occurs in the 6th mode. In the 10th mode, buckling mode occurred. The third, seventh, eighth and ninth modes are interpreted to occur on the vertical axis.

Table 3 presents the frequency values of the first 10 modes of the 27-meter-high minaret. The mode frequency values of the 27-meter-high minaret vary between approximately 2.58 Hz and 36.32 Hz.

Table 3. Frequency values of the first 10 modes of the 27-meter-high minaret

Mode Shape No	Frequency (Hz)
1	2.5755
2	2.5766
3	13.356
4	15.703
5	15.709
6	23.432
7	30.495
8	32.05
9	36.021
10	36.318

Table 4 presents the wind loads used according to the height of the minarets. Behavior of the 27-meter-high minaret in extremely strong wind conditions. In order to investigate the behavior of the 27-meter-high minaret in possible extremely strong wind or storm conditions, the displacement, principal tensile and compressive stresses under the loads of the 2nd and 3rd cases presented in Table 4 are given in Figure 10-11.

Table 4. Wind loads

Case No	**Aerodynamic load coefficient (Cf)**	**Suction wind speed pressuse (q) (kN/m^2)**	**Wind Load (W) (kN/m^2)**
1	1.6	0.8	1.28
2	1.6	1.1	1.76
3	1.6	1.3	2.08

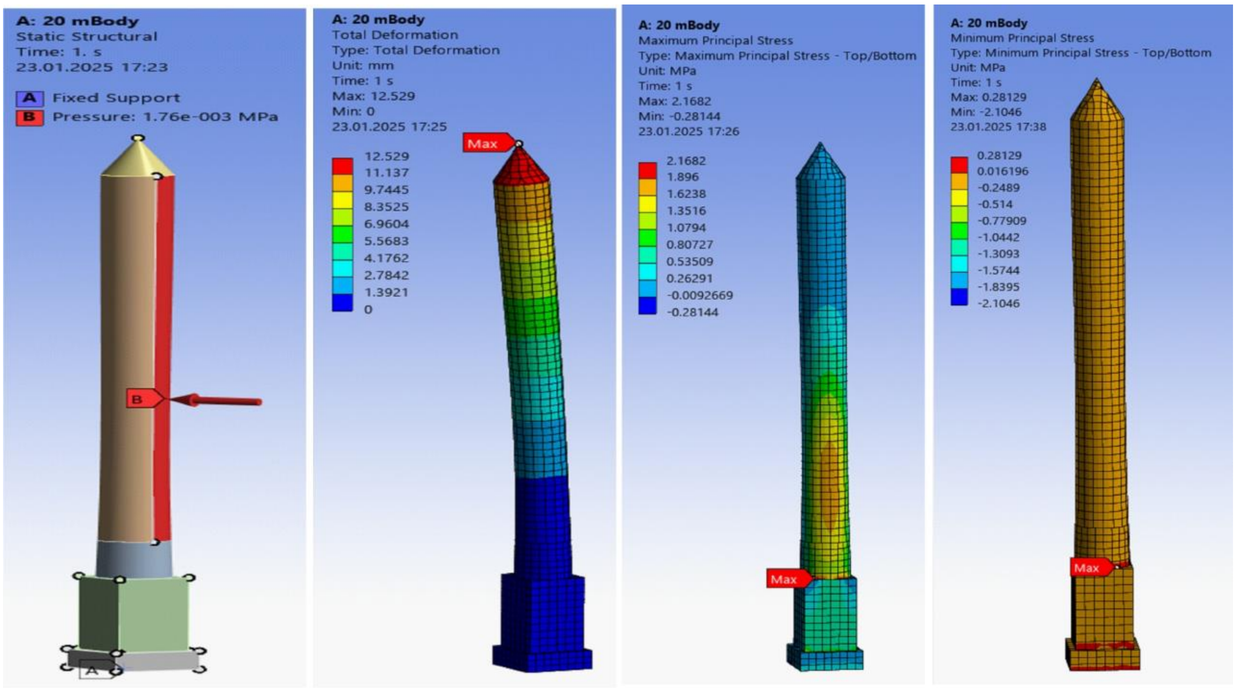

Figure 10. Analysis results of the 27-meter-high minaret under 1.76 kN/m^2 wind load

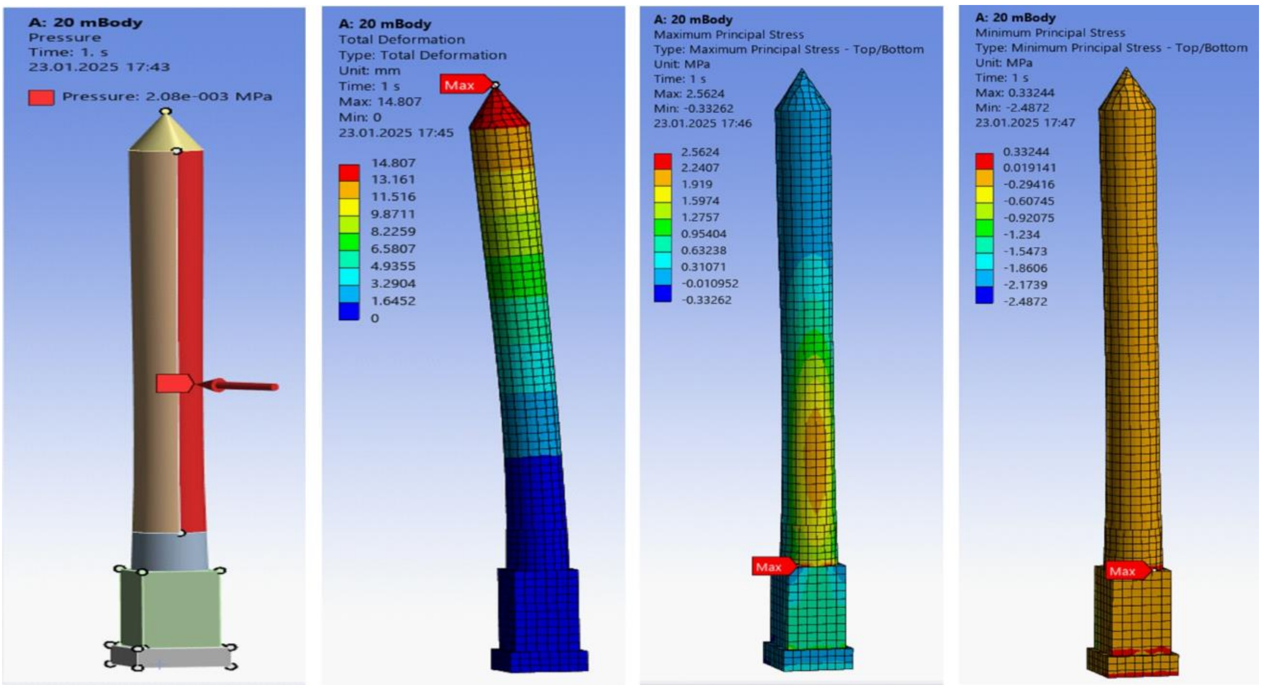

Figure 11. Analysis results of the 27-meter-high minaret under 2.08 kN/m^2 wind load

The results of Figures 6, 10 and 11 are presented comparatively in Table 5.

Table 5. Proposed minaret analysis results after extreme wind load

Case No	Wind Load W (kN/m^2)	Total Displacement (mm)	Max Principal Tensile Stress (MPa)	Max Principal Compression Stress (MPa)
Case 1	1.28	9.11	1.57	1.53
Case 2	1.76	12.53	2.17	2.10
Case 3	2.08	14.81	2.56	2.49

3 strong wind loads were applied to the 27-meter minaret and the results are given comparatively in Table 5. In the second and third cases, where the wind load increased by 37.5% and 62.5%, the total displacement values increased by 3.4 mm and 5.7 mm, respectively. The principal tensile stress values in cases 2 and 3 increased to 2.17 and 2.56 MPa, respectively. The principal compressive stress values in cases 2 and 3 increased to 2.10 and 2.49 MPa, respectively. This situation showed that the height of the minaret is a much more important and effective parameter than the wind intensity in terms of minaret safety.

5. Conclusion

In this study, the collapse of minarets due to strong winds, which has increased in number especially in recent years in Turkey, was taken into consideration. As a result of this research, in which the main body height of the minarets was evaluated in terms of minaret behavior and stresses, the following general outcomes and key findings were obtained.

When the situation depending on the minaret body height was examined in terms of safety, a non-linear increase in displacements and stresses was determined depending on the height as the minaret height increased.

The main body height of the minaret has increased only 2.5 times compared to the low minaret with a main body height of 20 m, but the total displacement value at the top of the minaret has increased approximately 18.4 times.

At a height of 57 meters, the principal tensile stress and principal compressive stress increased by 6.18 and 6.36 times, respectively, compared to that at a height of 27 meters.

Although the height of the main body of the 107-meter minaret has increased 5 times, the stresses have increased approximately 25 times, clearly revealing the structural risk factor that the height of the minaret carries.

It is recommended that high-minaret structures should be designed by taking into account the effects of strong winds along with earthquakes and storm situations where wind forces may reach extreme levels, and that the cross-sectional thickness of the minaret main body should be determined adequately.

In the study conducted according to the height of the main body of the minarets, a minaret height of 27 meters was recommended as the most suitable and safe minaret.

This parametric research study has shown that minaret slenderness is a more effective parameter in minaret structural safety analyses compared to wind load.

While evaluating minaret safety, material strength values are also suggested as a separate study subject.

The importance of minaret geometry in terms of minaret safety under wind loads is a separate issue that needs to be considered and studied in future studies.

Minarets that collapse due to wind effects typically fail by splitting at the transition area. This is primarily because the transition region experiences the highest principal tensile and compressive stresses under the applied wind loads, as revealed by studies. The moment effect also peaks in this area, contributing significantly to the failure. Additionally, the sudden reduction in cross-sectional area at this point causes a sharp increase in stresses, further exacerbating the structural vulnerability.

It should also be kept in mind that the higher the minarets are built, the higher the risk of them collapse over under lateral loads.

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Author contribution

The research, literature, finite element modeling, analysis and evaluation parts of the study were carried out by Muhammet Karabulut.

Conflicts of interest

The authors declare that there is no conflict of interest.

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