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Response evaluation of historical crooked minaret under wind and earthquake loadings

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Abstract. Turkey has been hosted various civilizations throughout centuries and it has become one of the oldest settlements all over the world due to the geographical location. Therefore, it has accommodated innumerable historical structures remain from the past civilizations. Protection and conservation of these historical constructions should be the major points for continuity of history. Crooked minaret is one of between these historical invaluable structures. It is located at the city of Aksaray and it dates back approximately 800 years. The minaret has lost its vertical position in time and bends on the North-West direction. In this study, general information is given about minarets and some restoration recommendations are given for crooked minaret based on performed some finite element structural analyses. These analyses are considered into three cases; 1-Dead loading, 2- Wind loading, and 3-Earthquake loadings. Results from the analyses are discussed detailed and some useful recommendations are given in the end of the study.

Keywords: crooked minaret; Aksaray; finite element method; LUSAS; restoration; wind

1. Introduction

Conservation and restoration of historical structures should require a careful systematic study in order to achieve high quality results. A conservation study should also require a multidisciplinary work including history, architecture and engineering as the basic sciences. In order to attain a real success, a continuously well-communicated team should be created and a control mechanism should be formed to manage the works and to balance the relationship between different disciplines.

Anatolia is a peninsula that has been home to various civilizations throughout the centuries. For this reason, thousands of historical buildings on this peninsula are still available. Mesopotamian and Hittite remains are still visible in the eastern part of Turkey while Hellenistic and Greco-Roman structures are frequently encountered on the western areas (Sevgili *et al.* 2005). As known, Turkey is on the most active faults in the world. Therefore, most of the studies on historical structures were about seismic responses, and different types of strengthening techniques of these heritages. Some scientific studies on these historical structures have been carried out by

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many researchers. Koçak *et al.* (2010) examined the church of St.Sergius and Bacchus, built during 527-536 AD in times of Justinian Regina. After determining the material parameters by experimental procedures, linear and nonlinear analyses of the structure for different loading conditions were performed. Similar studies were performed on the behavior of masonry buildings and minarets against some occurred earthquakes such as Adanur (2010) and Beyen (2008). Additionally, a few studies were performed on masonry minarets. Syrmakezis (2006) emphasized the effectiveness of structural control techniques for the rehabilitation of historical structures. Altunisik (2011) aimed to determine the dynamic response of masonry minarets before/after FRP composite strengthening. El-Attar *et al.* (2005) investigated the seismic vulnerability of a representative Mamluk-style minaret and proposed some seismic protection techniques. El-Attar *et al*. (2008) investigated the seismic performance of two historical Islamic minarets with wire dampers. Bayraktar *et al.* (2008) described the finite element modeling, modal testing and finite element model calibration of a historical masonry minaret. Shrestha *et al.* (2011) investigated the applicability of newly developed Cu-Al-Mn shape memory alloy bars to retrofitting of historical masonry constructions. Sezen *et al.* (2008) and Dogangun *et al.* (2008) were studied dynamic behaviors of reinforced concrete and masonry minarets. Dogangun and Sezen (2012) investigated on five historical mosques and their minarets which damaged during 1999 Turkey earthquakes.

Hagia Sophia, begun in 532 as the principal church of the Byzantine Empire, investigated dynamic behavior and earthquake response by Çakmak *et al.* (1995) and Swan *et al.* (1993). Similarly, Turk and Celebi (2006) have made some suggestions about St. Baniya Church at the city of Isparta. The Baniya church is one of the most important structures of the historically, archaeologically and culturally valuable items that make up the historical fabric of Isparta, Turkey.

A non-destructive study was conducted by Tavukçuoğlu *et al.* (2005) on the 13th century caravanserai of Ağzıkarahan in Aksaray. This building suffered from problems of seasonal rising damp in its lower parts. Historical Zazadin Caravansary (Khan) on Silk Road around Aksaray was evaluated and documented by digital close range photogrammetry by Yilmaz *et al.* (2008).

There are great deficiencies in the civil engineering field on restoration of historical structures in Turkey. Construction engineers are generally interested in reinforced concrete buildings. Architects involved in the restoration of historical structures. Not only architects but also civil engineers are important for the restoration of an historical structure. Namely, the stability of the historical structure (before and after restoration) is very important. The structure may be again damaged after restoration if the stability ignored. Besides, stability analyses should be performed by civil engineers. For this reason, a multidisciplinary study is extremely important.

General information about the historical structure and the region should be obtained before starting the restoration. First, the structure should be investigated by an art-historian. Construction date, construction technique, materials used in the past repairs, old photographs, should be investigated. Then explore the region's geological structure. This ground survey informs us about the soil under the historical structure. The information should be collected about the region's climatic conditions such as rainfall, humidity, temperature data, and etc.

After gathering the above information, the current state of the structure should be obtained using photogrammetric methods. In the light of the obtained data stress-strain analyses, failure analyses, and nonlinear analyses should be performed using structural analysis software. Afterwards, the restoration strategy should be defined under these circumstances.

2. Parts of minarets

In different regions of the world, minarets were built with different features depending on the material availability in the region, on time technology, art and culture backgrounds. The material used and selected geometry plays an important role in determining the load carrying system of a minaret.

(a) Sultanahmed Mosque in Istanbul (URL-1)

(b) Selimiye Mosque in Edirne (URL-2)

Fig. 1 Minaret applications at classical ottoman period

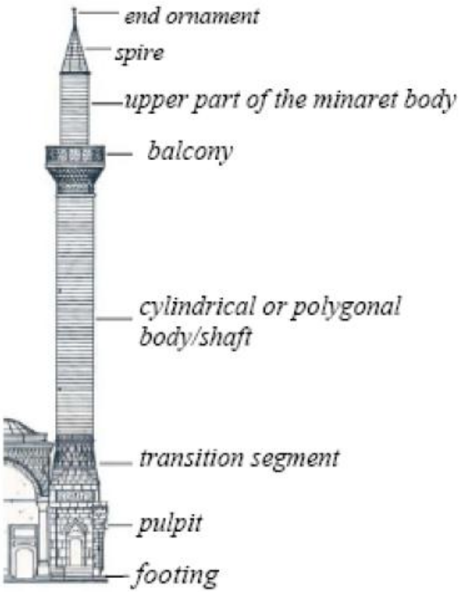
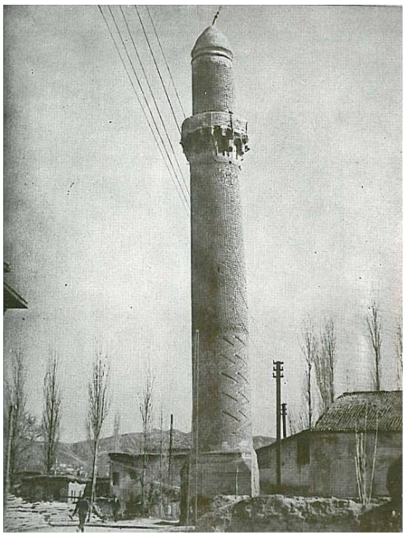
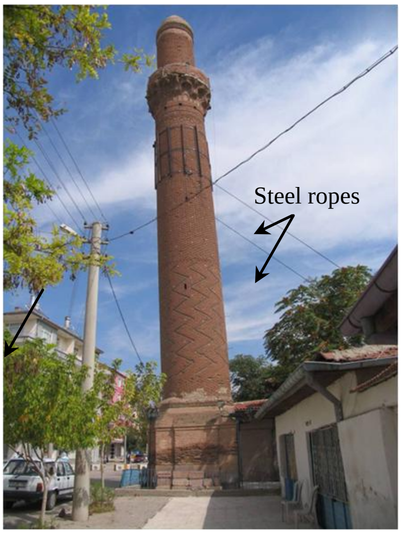


Fig. 2. Typical Classical Ottoman Period minaret parts. (Altunisik 2011)

Minaret can be defined as a high tower that adjacent to the mosque or in a separate, which prayer read and to spread the sound around from one or several balcony. Balconies create mass concentrations along the minaret's height and affect its dynamic structural response. Minarets have found their most mature form during classical Ottoman Mosques (Fig. 1). Stone, brick or wood materials are generally used for the minarets, while cubic, cylindrical or polygonal shapes are selected as the cross section. A classical period of the Ottoman minarets consists of from bottom to up; footing, pulpit, transition segment, cylindrical body, balcony and spire. The base or boot is usually square or polygonal, and is sometimes called the pulpit by architects (Fig. 2). The minaret contains interior spiral stairs running all the way up to the highest balcony level which are not externally visible.



(a) At 1931 from Albert Gabriel (1962)



(b) Today view

Fig. 3 Historic and current views of the minaret

3. Crooked minaret of Aksaray

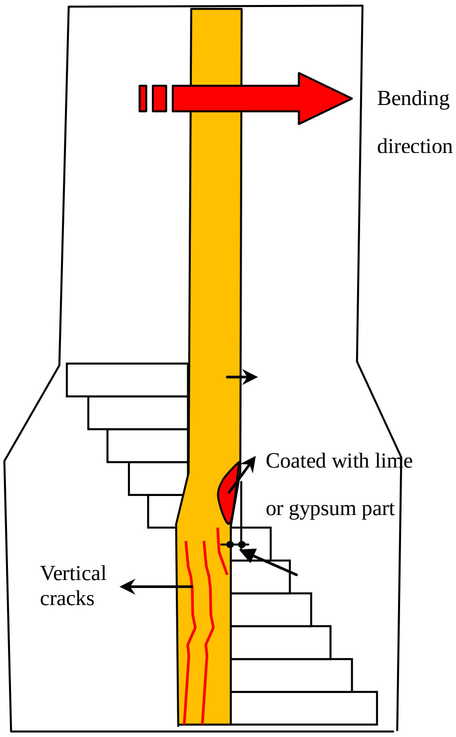
Aksaray is a city in the Central Anatolia of Turkey. This region was an important stopover along the Silk Road that crossed through Anatolia for centuries, thus it has a long history. The Roman town Garsaura was named Archelaïs by Archelaus of Cappadocia, the last Cappadocian king. The region came under the control of the Seljuk Turks after the Battle of Malazgirt and the Anatolian Seljuk Sultanate they founded left important landmarks in and around Aksaray. The Arab traveler Ibn Battuta who was in the region in the 14th century was impressed by the class of Muslim traders that had emerged in Aksaray and noted the urban center as a beautiful city, surrounded by waterways and gardens, with a water supply coming right to the houses of the city.(URL-3 2010)

The Crooked Minaret, one of the typical Seljuk minarets, located within the boundaries of Aksaray in Central Anatolia (250 km. south of capital). It was built between 1221 and 1236 by Sultan 1 Keyhusrev (Seljuk Sultan). Crooked minaret is similar with pizza tower in Italy in terms of curvature. For this reason, every year thousands of domestic and foreign tourists come to Aksaray.

The minaret has a history of about 800 years. It is lost vertical position with time and bending on the North-West direction. The minaret bound with steel ropes to the ground by the General Directorate of Foundations in order to prevent the destruction in 1995. In 1931 and as of today in view of the minaret can be seen from Fig. 3. Translation at the top of the structure increases in time, and has exceeded 1100 mm.

Crooked Minaret is a separate structure next to the mosque. It is resting on a four corners pedestal, cylindrical body, a single balcony and spire. It was built with masonry construction technique and it has a total height of 30.06 m. The pedestal of the minaret, and boot, also called the upper part of the pedestal, including the transition segment were built with masonry brick material. Masonry bricks were also used at cylindrical body, balcony, upper part of the minaret body and spire. Khorasan mortar was used between these bricks. Load-bearing stairs on the inside of the minaret, which is part of the system, was designed as brick stairs as seen from Fig. 4(a). Besides, significant degree cracks and deformations can also be seen from Fig. 4(b).

(a) View from inner part of the minaret



(b) Schematic view of the damage parts

Fig. 4 Entrance of the minaret

Some observations were performed on the site. According to these observations and survey projects, plan and section views of the pulpit of the minaret can be seen from Fig. 5. A bulge was constructing about 40 cm in width to fit the pulpit on the northern façade of the minaret. It is estimated that, under the first round stairs in the pulpit part filled with bricks or different materials about 300 cm heights. The thickness of this filled part starting from approximately 200 cm to 300 cm, then falls to 88 cm from bottom. However, the pulpit wall of the minaret has approximately 88 cm thickness on the north side. This situation is caused by the difference of rigidity in the horizontal direction. It can be seen this situation from I-I section from Fig. 5. Especially, thickness decreased to 50 cm at the transition segment and marked as Area-B in Fig. 5. Area-A is the weakest section of the minaret. The direction of the weak section from the core and direction of the movement at +15.20 m level can be seen from the same figure.

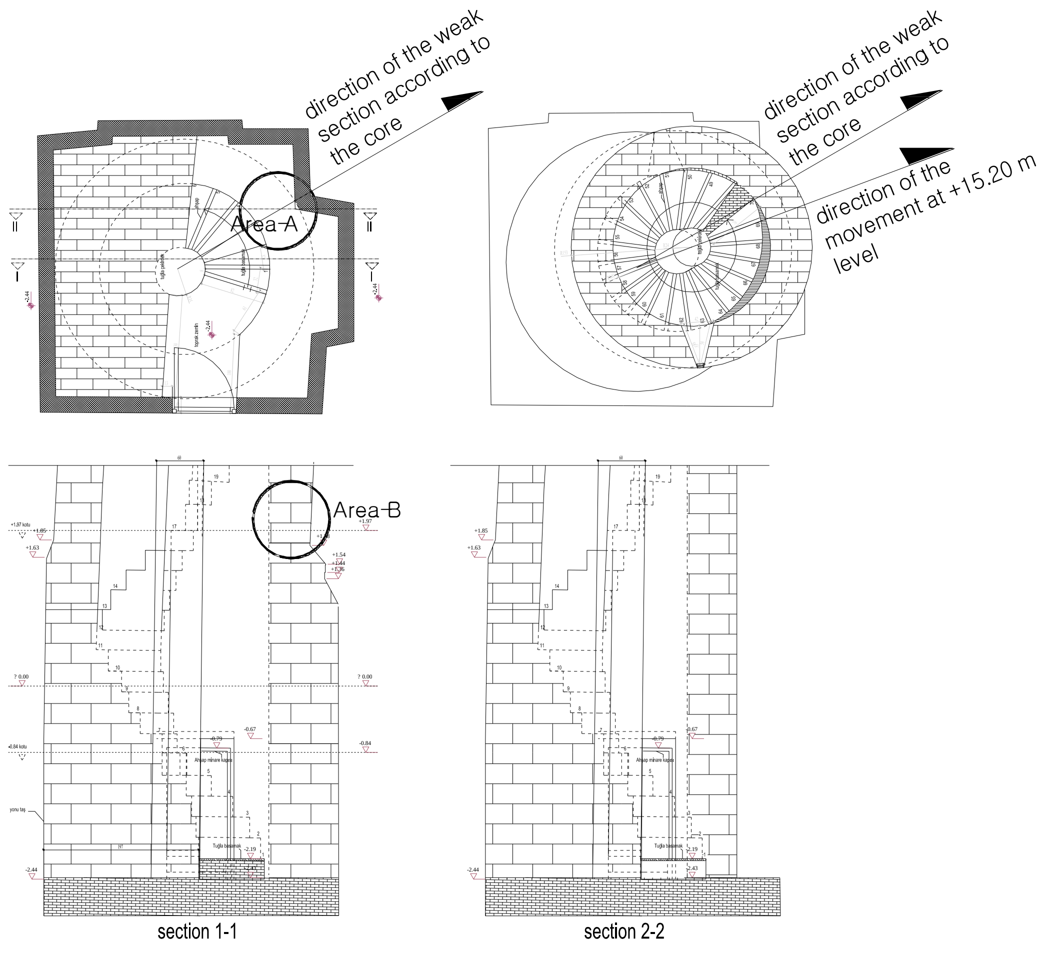


Fig. 5 Cross-section and longitudinal sections of the boot

Upper part of the boot has brick damages as shown in Figs. 6 and 7. Other than that no damage was found at the bottom of the boot part of the minaret. Therefore, the pedestal has undergone significant loss of cross-section due to deteriorating and diminishing of bricks. Also in this section there are vertical cracks in the bricks besides separation and degradation.

Fig. 6 Some damages on boot segment of Crooked Minaret

Fig. 7 North façade of the boot and transition segment

4. Structural analyses and results evaluation of crooked minaret

In this study, the current state of the minaret is investigated against the effects of the curve, earthquake, and also wind loadings. The minaret is modeled by finite element method. LUSAS (2012) structural analyses program is used for this aim. Three-dimensional solid elements are used.

These elements have 8 nodes and each node has three displacement degrees of freedom. 2694 elements and 4282 nodes are defined for the finite element model of the minaret. The minaret is modeled under macro modelling assumptions. Therefore masonry units and mortar are assumed as homogenized solid elements. Experimentally obtained elastic material properties such as Young's Modulus, Poisson's Ratio, and Compressive Strength are taken into account as 1000 MPa, 0.2 and 5.52 MPa respectively in average.

The linear elastic analyses are carried out subjected to the crooked minaret. The analyses performed in this context have the following titles:

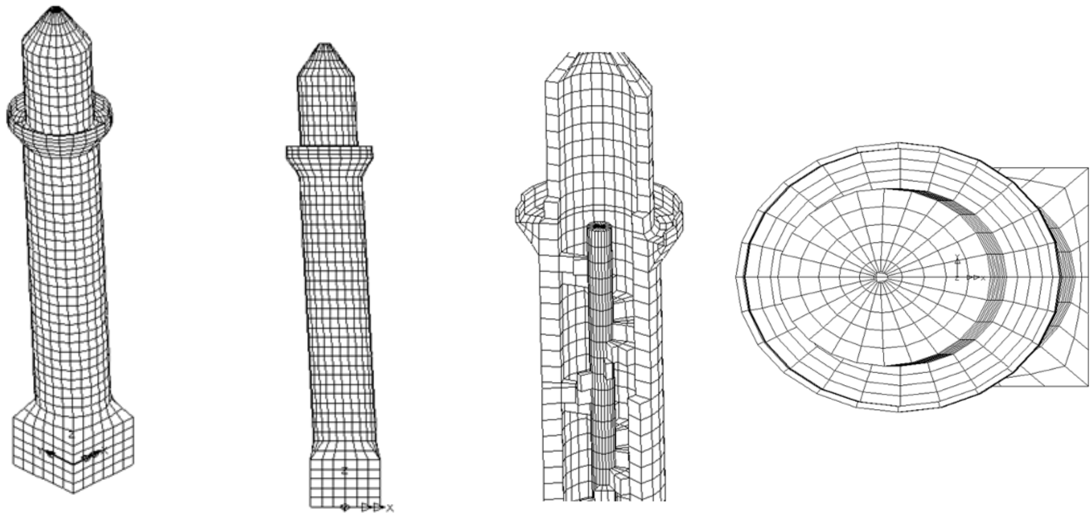
1. ***Dead Load Analysis:*** In this analysis, the current state of the minaret is taking into account and the behavior is determined under its own weight.

2. ***Wind Load Analysis:*** In this analysis, the current state of the minaret is taking into account and the behavior is determined against the effects of wind.

3. ***Earthquake Analysis:*** In this analysis, the current state of the minaret is taking into account

and the behavior against the effects of an earthquake is determined.

The finite element model is given in the following Fig. 8.

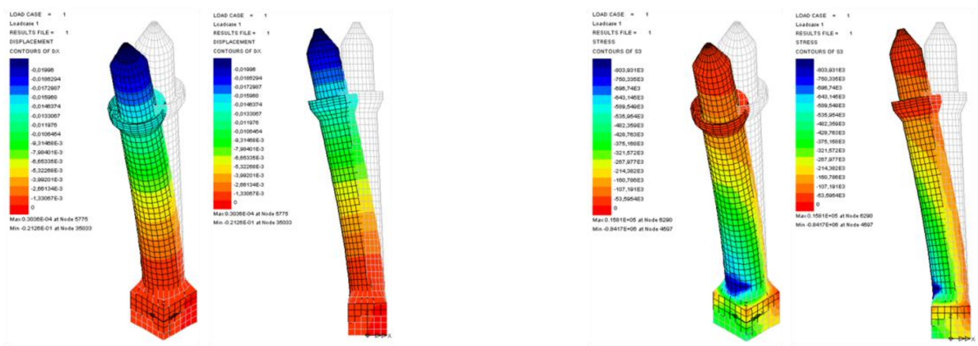


(a) perspective (b) *xz* plane view (c)view of stairs (d)*xy* plane view

Fig. 8 Finite element model of the structure

4.1 Dead load analysis

The linear analysis was performed under its own weight. Performed the first set of the analysis and resulting displacements and compressive stresses are shown in Fig. 9, on the deformed model of the minaret.



(a) Displacement contours of self-weight analysis (d_{max}=21.2 dnfldmmm) (b) Compressive stress contours of self-weight analysis (S3=0,85 MPa)

Fig. 9 Results from dead load analysis

Regions have shown in blue shows parts of the largest displacements (Fig. 9). From displacement contours occurred under its own weight, the maximum displacement in the horizontal direction, as has occurred 21.2 mm from the compressive stress contours, the maximum stress has occurred at the bottom of the cylindrical body as 0.85 MPa.

4.2 Wind load analysis

Geometric properties of the minaret, which is the subject of our analysis, should examine the effect of wind. Wind load calculation depends on the geometry of the structure. The effects of pressure, absorption and friction combination of the wind should be calculated. Overall size of the resultant wind load of a structure is expressed in the following equation (TS 498, 1997).

$$W = C_f .q.A \text{ (kN)} \tag{1}$$

Where; C_f is the aerodynamic load coefficient, q is the absorption (kN/m^2), and A is the affected surface. Distributed wind loads calculated according to the Turkish Specification (TS-498 1997) are given below in Fig. 10.

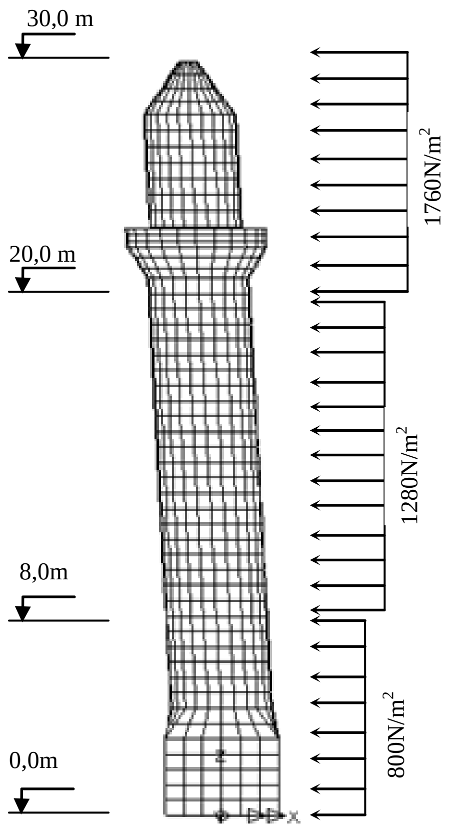
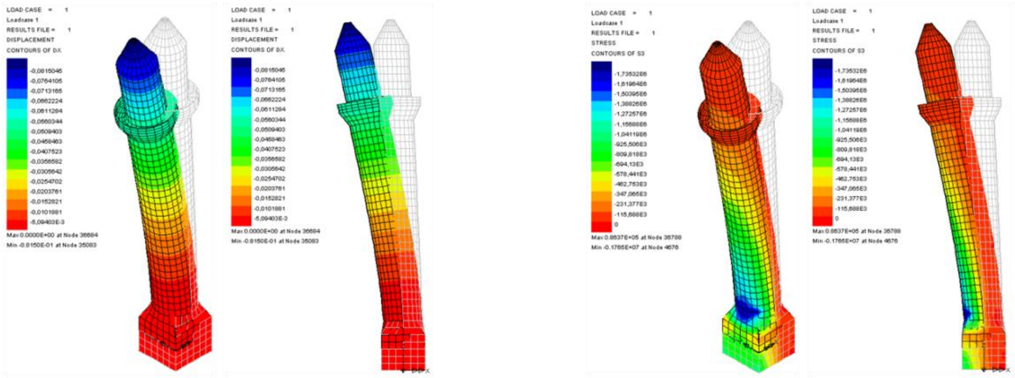


Fig. 10 Wind loading schema on undeformed mesh of the structure

Performed a second set of analysis and resulting displacements are shown in Fig. 11(a) on the deformed model. Parts of the regions, shown in blue in the figure, show the largest horizontal displacements. When displacement contours occur under the influence of wind loading, the maximum displacement of 81.5 mm in the horizontal direction has occurred. Compressive stresses occurring in the minaret are also given in Fig. 11(b).



(a) Displacement contours of self-weight analysis (d_{max}=81.5 mm) (b) Compressive stress contours of self-weight analysis (S3=1,77 MPa)

Fig. 11 Results from wind loading analysis

4.3 Earthquake analysis

The city center of Aksaray is in the 4th degree earthquake zone. The meaning of the 4th degree earthquake zone, earthquakes occur in this region are expected to peak ground acceleration between 0.1 g and 0.2 g.

The first 20 mode of the structure is considered on the basis of earthquake analysis. Approximately 90% of total mass is activated by the first 20 modes of vibration. Period and frequency of these modes are presented in Table 1.

Table 1 First 20 mode, frequency and period values of the structure

Mode	Frequency	Period (sec)	Mode	Frequency	Period (sec)
1	0.936804	1.067	11	21.1316	0.047
2	0.938141	1.066	12	28.6993	0.035
3	5.05261	0.198	13	28.7498	0.035
4	5.05716	0.198	14	31.1377	0.032
5	6.8991	0.145	15	33.2425	0.030
6	10.6263	0.094	16	34.2542	0.029
7	11.7642	0.085	17	34.3501	0.029
8	11.7771	0.085	18	37.8159	0.026
9	19.6212	0.051	19	37.9064	0.026
10	19.6478	0.051	20	42.5284	0.024

The first and second period values were determined as 1.067 seconds. The first five mode shapes of the minaret are given in Fig. 12.

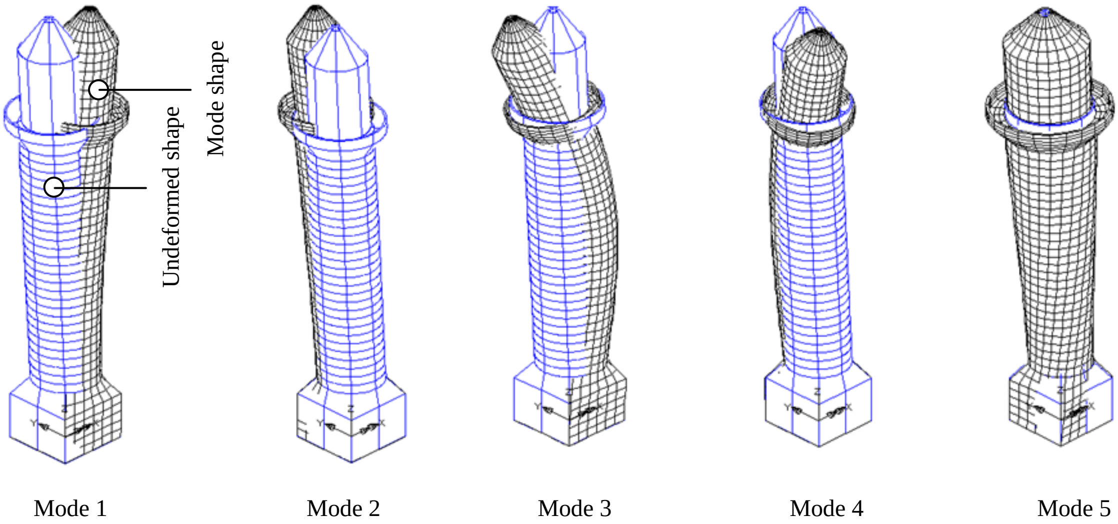


Fig. 12 Mode shapes for first five modes of the structure

4th degree earthquake zone as defined in the Turkish Earthquake Code (TEC, 2007), design spectra considering the seismic analysis was carried out according to the method of combining modes (CQC method). Displacements obtained from the analysis were determined and shown in Fig. 13 on the deformed mesh of the minaret.

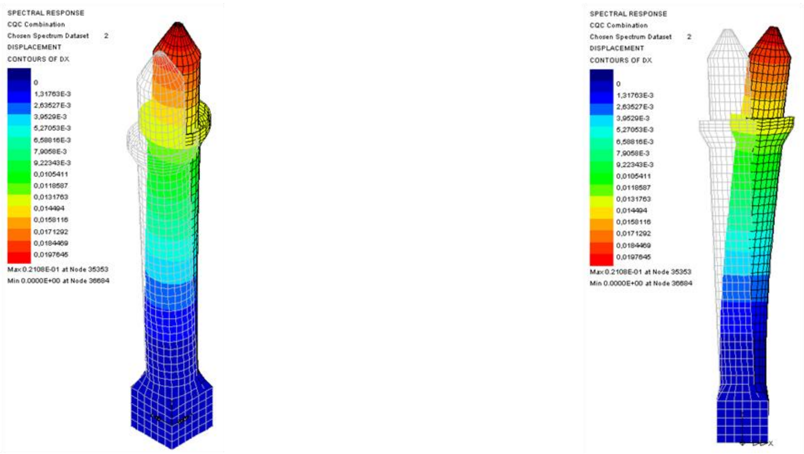


Fig. 13 Displacement contours of seismic analysis(d_{max}=21 mm)

4.4 Evaluation of analyses results

Three analyses were performed for the minaret such as own weight, wind and earthquake analysis. The results are obtained and evaluation, guidance is given in Table 2 below.

Table 2 Collective results from performed analyses

	Dead load analysis	Wind load analysis	Earthquake analysis
Displacements, mm	2.12	8.15	2.1
Tension stress, MPa	0.28	0.81	0.38
Compression Stress, MPa	0.85	1.77	0.021
Shear Stress, MPa	0.053	0.069	0.052
Tension Strain	0.000139	0.000403	0.000188
Compression Strain	0.00041	0.00087	0.000014

As shown in the Table 2, under its own weight 1MPa compression stress, while under the influence of wind is approaching the values of 2 MPa. These values can be considered as high values for degraded and decomposed masonry brick. On the other hand, the tensile strength of 0.81 MPa of the wind analysis, the value is extremely dangerous. Because tensile stress should not be occur on masonry structures such as slender minarets.

5. Conclusions

As a result of investigations carried out on the Crooked Minaret and the structural analysis reached the following conclusions:

- Exposure all the effects of about 800 years and has made in the horizontal displacement of 1130 mm, although the building is still standing, and reached today, this masterpiece by the load-bearing system designer deliberately chosen and carefully constructed.
- As of today, spoilage and cross-section of up to extreme loss threaten the load-bearing system of this still standing magnificent minaret. It should be eliminated these negative effects on load-bearing capacity of the minaret.
- According to the results of the analyses, the minaret has the problem of excessive stability due to curvature. For this reason, an effect that may occur such as earthquake, hurricane or any vehicle crash cause total collapse of the minaret. The most urgent protections should be taken here.
- There are three options for the restoration of the minaret can be considered. The first option is collapsing and rebuilding the minaret according to the original state. In the implementation of this option, the minaret will become much more secure. However, it will be no longer called crooked minaret, it will be only a normal minaret. The second option is lifting upper part of the body and reconstructing pedestal and the transition part and re-seating the minaret. This option is very specialized teams to take part in this regard and handle about 250 tons of a minaret and can hold this way for a long period of time the equipment to be provided. If this option is preferred, a

circular body and a balcony supported by parts of the circular plate and a steel conveyor belts may be suspended within the system. Lifted parts of the minaret mounted on the transition element with the help of anchors. However, it will be also no longer called crooked minaret, only pedestal and transition part will be renovated and called perpendicular minaret. On the other hand is a distortion that may occur during operations, instruments, or continuous operation may cause breakage or fracture in the body of the minaret. For this option should keep in mind the risk in question. The third option is a support system can be applied to protect the existing state of the minaret. With this option, a new load-bearing system will be added to the minaret. This system will contribute the safety to the load-bearing system of minaret. Support system can be applied as an abstract design without disturbing the historic fabric and cultural value of the structure. If this option is preferred structure is still called as crooked minaret. Therefore, it will not lose anything about originality. After supporting the system, the restoration project of the minaret and the necessary repairs can be continued.

- According to the authors' opinion, the third option would be better to protection of both the state of the minaret and the region's tourism potential. An abstract design for the support system can be applied obscuring the glory of the minaret, and the minaret may also be specified in a monumental value.

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