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Research Article

Damaged and Partially Collapsed: Pre- and Post-Earthquake Modeling of the Gaziantep Huseyin Pasha Mosque Minaret and Repair with Internal Steel Reinforcement

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Keywords

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Abstract

Historical structures occupy an important place among the cultural heritages of nations. The historical and cultural immovable properties destroyed in natural disasters such as earthquakes are values lost from our national heritage. Preserving these values and transmitting them to the future is of paramount importance. In this study, the pre- and post-earthquake conditions of the Hüseyin Pasha Mosque minaret located in Gaziantep—which suffered a 9-m collapse following the destructive earthquakes that occurred in Kahramanmaraş on February 6, 2023—were examined. An internal steel reinforcement method was proposed to restore the minaret to a usable condition, and the analytical results of this method were presented. The proposed method was evaluated from a static perspective and is intended to serve as the basis for restoration work aimed at reviving the structure's pre-collapse state. The pre-earthquake condition of the minaret was analyzed, and it was found that the collapse occurred because the adjacent mosque inhibited the displacements in the minaret at the level of the pulpit during the earthquake, which caused increased displacements in the upper part of the minaret and resulted in the collapse. The proposed steel reinforcement method increased the minaret's resistance against future earthquakes and ensured that, within the original-like cladding planned for the restoration works of the collapsed 9-m upper section, a load-bearing system is provided.

1. Introduction

The destructive and damaging effects of earthquakes, as with other structures, also have severe impacts on historical and cultural structures. These structures, which have served people since the time of their construction and remained standing for years—sometimes centuries—have been damaged or collapsed in recent earthquakes. The restoration, strengthening, and revitalization of these structures as cultural heritage is of great importance for humanity. In this study, a pre- and post-earthquake condition assessment was carried out for the Hüseyin Pasha Mosque minaret located in the Şahinbey district of Gaziantep province, following the earthquakes on February 6, 2023. The aim was to restore the collapsed sections of the minaret and to revitalize it with an internal steel load-bearing system.

To better assess the structural characteristics of historical structures, non-destructive field tests and numerical simulations are utilized. In addition, laboratory experiments are employed. In the literature, numerical analyses are commonly preferred to develop simulation models, particularly in cases where historical masonry structures have exhibited low performance during earthquakes. These simulations enable the identification of the weak points of the structures, thereby allowing the recommendation of strengthening measures tailored to the behavior of each individual structure [1].

The Darendeli Hüseyin Pasha Mosque was commissioned by Hüseyin Pasha, the trustee of Urfa Governor Ali Pasha, between 1718 and 1719. The minaret was constructed as a single-balcony structure at that time. The oldest available photograph of the mosque dates back to 1890 (Figure 1). During the Antep Defense (1920–1921), the mosque's minaret and some of its domes were destroyed by cannonballs. The collapse of the minaret up to the base of the pulpit is shown in Figure 2. In 1953, it was rebuilt as a single-balcony structure (Figure 3). Later, a new addition was made and a second balcony was added. However, it is not exactly known when this balcony was added. In its current state, it is used as a double-balcony structure. As shown in Figure 4, the motifs and craftsmanship of each balcony differ [2].

The mosques in Gaziantep province are constructed from finely cut stones, commonly known as Antep stone, which is widely preferred in the region. These stones are clayey limestones with a yellowish-cream color [3].

Figure 1. View of the original state of the minaret in 1890

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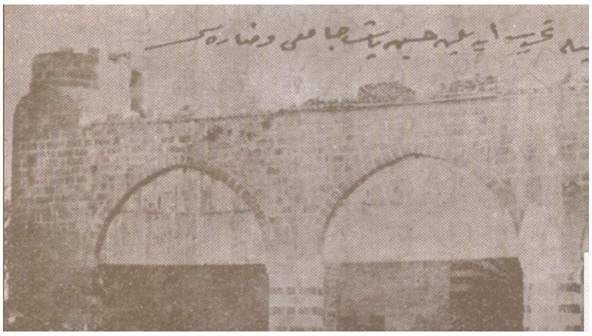


Figure 2. View of the dome and minaret destroyed by the French in 1920

Figure 3. View of the reconstructed minaret with a single balcony

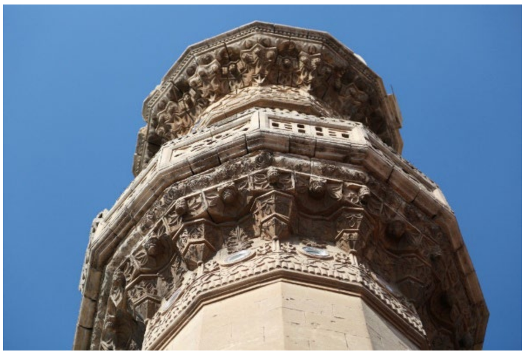


Figure 4. Balcony motifs constructed at different times

Locally, they are referred to as "keymık stone." The quarries in Gaziantep province are no longer in use today. The technique known as " impermeable stone joint" (akçe geçmez taş derzi) is employed in the region for the masonry of these stones [4]. This term is used for joints where the stones are laid so tightly that even a thin coin cannot pass through. The filling material used in these joints is known as " Khorasan Mortar," which has a characteristic of not bearing tensile loads [5].

- **Condition of the Mosque Before the Kahramanmaraş Earthquake**

The minaret, originally constructed with a single balcony, has undergone significant changes over time. During the occupation period, the minaret was demolished up to the pulpit level by the French, and later, it was reconstructed with two balconies at a greater height without any intervention in its foundation and base. During the reconstruction process, the interior of the pulpit was filled with irregular fill material. The fill inside the borehole drilled in the pulpit area to identify the quality of this irregular fill is shown in Figure 5. Observations made in the inspection hole revealed that the rubble from the 1920 demolition was used as irregular fill. According to the mosque's plan, the minaret, located at the northeast corner of the mosque, was built leaning against the mosque without any expansion joint (Figures 5 and 7). The door openings providing access to the balconies are located in the northeast direction, opposite this leaning area.

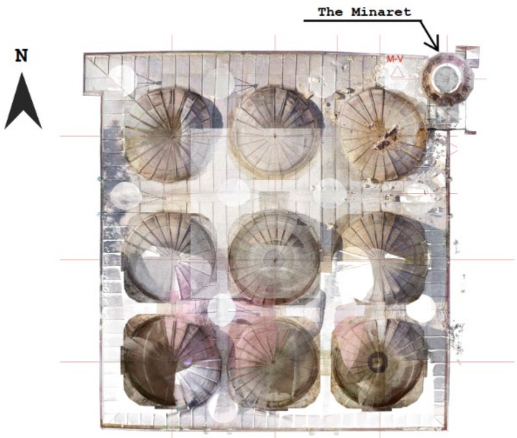


Figure 5. Plan view of the mosque and minaret

Figure 6. View of the irregular rubble fill inside the pulpit

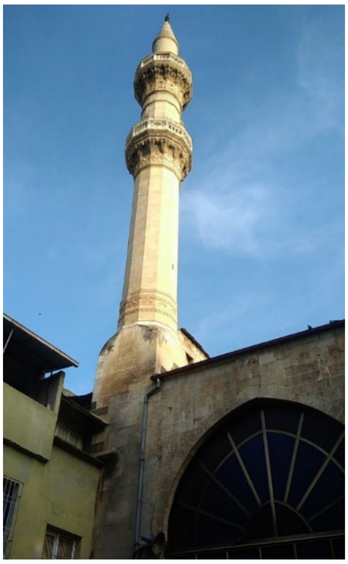


Figure 7. View of the minaret from the front courtyard in 2016 [6]

- **Condition of the Mosque After the Kahramanmaraş Earthquake**

Gaziantep province is a critical region in terms of earthquake risk due to its proximity to active fault lines. Historical earthquakes indicate that one of the most significant seismic events affecting the region was the large earthquake that occurred on the Türkoğlu-Antakya segment in 1822, with an estimated magnitude of Mw 7.5. [7]. However, it is estimated that the minaret did not sustain damage during this earthquake, based on the 1890 photograph in Figure 1 and the records of the affiliated foundation. In more recent history, earthquakes with magnitudes of Mw 5.5, 5.8, and 4.6 occurred in June, July, and August of 1971, respectively, causing severe damage to some buildings in the city. Additionally, earthquakes with magnitudes of Mw 4.4 in 1978 and Mw 5.0 in 1986 caused severe damage to some buildings [8]. However, the minaret and the adjacent mosque were not damaged by these earthquakes. A damage assessment of the minaret was conducted, and its survey was obtained using point cloud data. These damage conditions were also compared with previous studies [9].

During the earthquakes with epicenters in Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) districts of Kahramanmaraş province on February 6, 2023, the mosque and minaret were also affected. The upper part of the minaret above the second balcony, with a height of 905 cm, collapsed during the earthquake (Figure 8). Additionally, due to the minaret being adjacent to the mosque, crushing in the pedestal and body stones, as well as joint separations, were observed, as seen in Figure 9.

Figure 1. General view of the collapsed minaret from the rear courtyard after the earthquake

Figure 2. Crushing in the minaret pedestal and body stones, joint separations

- **Properties of Minaret Stones**

Before the February 6, 2023 earthquake, stone block samples were taken from the minaret's body walls to determine the compressive strength of the cut stones used in the structure. From these stones, 6 core samples with a diameter of 53 mm, 8 core samples with a height of 53 mm, and 3 core samples with a diameter of 26 mm were obtained, as shown in Figure 10. Uniaxial compressive strength and splitting tensile strength tests were performed on these samples.

Figure 10. Samples obtained from the minaret body wall stone

The values obtained from the core samples are provided in Table 1 and Table 2. According to the test results, the average uniaxial compressive strength of the wall samples was found to be 8.62 MPa, and the average splitting tensile strength was 2.39 MPa.

Table 1. Uniaxial Compressive Strengths

Sample No	L (Length)	P (Load)	Uniaxial Compressive Strength
1	53 mm.	15,3 kN	6,94 *MPa*
2	53 mm.	29,4 kN	13,33 *MPa*
3	53 mm.	23,8 kN	10,79 *MPa*
4	53 mm.	24,6 kN	11,15 *MPa*
5	53 mm.	25,6 kN	11,60 *MPa*
6	53 mm.	23,2 kN	10,52 *MPa*
AVG=			10,72 *MPa*
Standard deviation =			2,10
Strength =			8,62 *MPa*

Table 2. Splitting Tensile Test Strengths

Sample No	L (Length)	P (Load)	Splitting Tensile Strength
1	26 mm.	10,8 kN	4,99 *MPa*
2	26 mm.	8,3 kN	3,83 *MPa*
3	26 mm.	8,3 kN	3,83 *MPa*
4	53 mm.	13,9 kN	3,15 *MPa*
5	53 mm.	10,4 kN	2,36 *MPa*
6	53 mm.	10,2 kN	2,31 *MPa*
AVG=			3,41 *MPa*
Standard deviation =			1,02 *MPa*
Strength =			2,39 MPa

2. Material and Method

As seen in Figure 7, the minaret located at the northeast corner of the mosque was constructed leaning against the mosque without any expansion joint. The door openings providing access to the balconies are located directly opposite this leaning area.

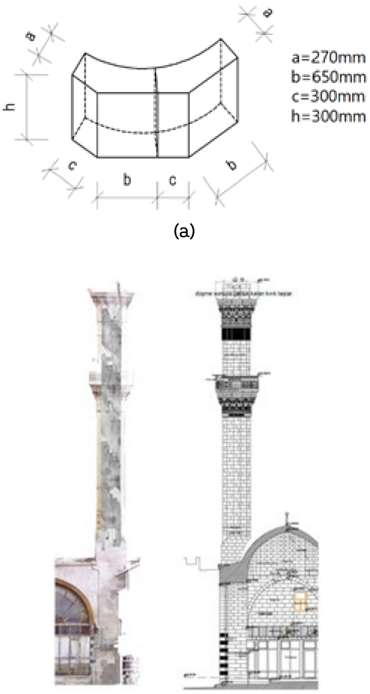
The pre-earthquake analysis of the minaret was conducted using a finite element software tool while preserving the geometry without any collapse. The experienced earthquake acted as a natural experimental setup for the minaret. The results obtained through the finite element method help in understanding the minaret's behavior during the earthquake and provide insights into the collapse process.

In light of this information, examining the collapse behavior of the minaret will assist in developing reinforcement and restoration strategies for its current state.

To determine the geometric condition of the structure after the earthquake, data were collected using the point cloud method. The point cloud consists of a dense set of points with three-dimensional coordinates obtained through laser scanners during field measurements. The point cloud method allows for highly accurate surveying of the structure's existing condition, enabling detailed modeling and damage assessment of the minaret.

Voxel modeling technique was used to create the structure's model based on the point cloud data. A voxel is the three-dimensional counterpart of a pixel. While a pixel defines a point in two-dimensional space, a voxel represents graphical information of a point in three-dimensional space. Voxel modeling is based on slicing the obtained point cloud set at specific intervals and superimposing the plans or sectional planes obtained from these slices. This method allows for a detailed three-dimensional representation of the structure model [10, 11].

The uniform shape and size of the stones used in the minaret body also facilitated the modeling process. The dimensions of these stones are provided in Figure 11, and this stone size was used in the voxel model.



(a)

(b)

Figure 3. (a) Typical cross-section of the minaret cut stone (b) Current minaret point cloud readings and survey obtained from the point cloud

The external view of the point cloud model of the mosque and minaret obtained after the earthquake is provided in Figure 12.

Figure 4. External view of the mosque and minaret point cloud model after the earthquake and Pazarcık earthquake east direction

For the Kahramanmaraş earthquake records, measurement data from the TK.2703 station, located approximately 3.50 km away and closest to the mosque, were used. The direction of the Pazarcık earthquake's impact on the mosque and minaret is shown in Figure 13 based on these data. The satellite image showing the locations of the TK.2703 station and the minaret is provided in Figure 13, and the information of the station is presented in Table 3.

Figure 5. Satellite image showing the locations of tk.2703 station and the minaret

Table 3. Measurement data of TK.2703 station

Recording Station	AI_274_GZT
Station Coordinates	37.05885 N, 37.35073 E Datum:WGS84
Elevation	851m
Location	Meteorology Directorate
Station Address	Gaziantep
Seismic Survey Date	October 13, 2008
Structure Type	Container

At 04:17 on February 6, 2023, a magnitude 7.7 earthquake occurred in Pazarcık, Kahramanmaraş. Many buildings collapsed, and 9 hours and 7 minutes later, at 13:24, another earthquake with a magnitude of 7.6 occurred in Elbistan. The initial Pazarcık earthquake had a significant impact on the structure due to both its intensity and proximity, which is also evident from the data obtained from the TK.2703 station. Eyewitnesses also stated that the collapse occurred during the first earthquake [12].

The acceleration-time graphs in E (east-west), N (north-south), and U (vertical) directions obtained from the TK.2703 station for the Pazarcık earthquake is provided in Figures 14, 15, and 16 below.

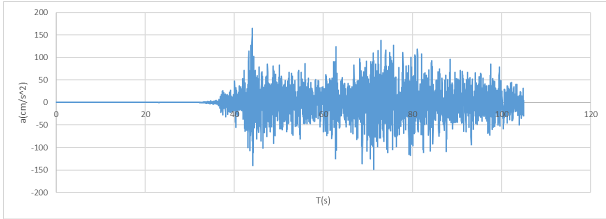


Figure 6. Acceleration-time graph of Pazarcık earthquake E direction from TK.2703 station

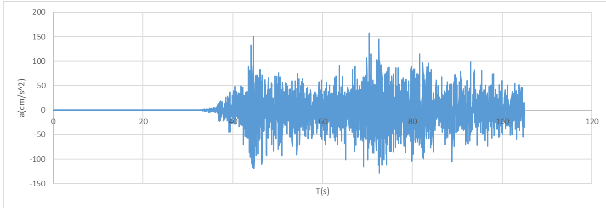


Figure 15. Acceleration-time graph of Pazarcık earthquake N direction from TK.2703 station

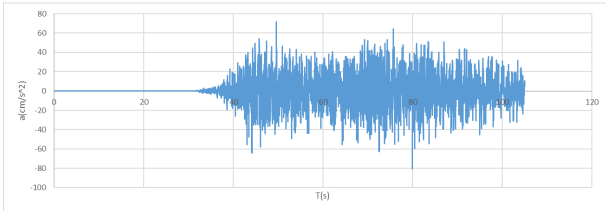


Figure 7. Acceleration-time graph of Pazarcık earthquake U direction from TK.2703 station

The filling mortar known as "Khorasan Mortar" used in the joints of the minaret stones has a characteristic of not partially resisting tensile loads. Therefore, the displacement and moments occurring in the minaret during the earthquake would result in collapse once the neutral axis distance of the minaret cross-section is exceeded.

The minaret's balcony access doors negatively affected its behavior as they reduced the cross-section's strength and the neutral axis distance in that area. The effective earthquake load acting on the minaret occurred in the east-west direction, as shown in Figure 13.

The construction of the mosque and minaret separately without any expansion joints is another significant factor influencing the behavior. The minaret leaning against the mosque restricted its displacement towards the mosque, while it could freely displace along its entire height away from the mosque. However, towards the mosque, the displacement was limited to the shaft and balcony region as the base was leaning against the mosque, which led to the collapse at the weakest section, the balcony door region. The collapse of the minaret sections onto the mosque roof supports this observation.

The minaret's cross-sectional properties (Figure 17) include a cross-sectional area of A=28400 cm2 and a moment of resistance at the weakest section (balcony door) of W=1514300 cm3. The neutral axis distance K was calculated as approximately 53.3 cm from the minaret's center.

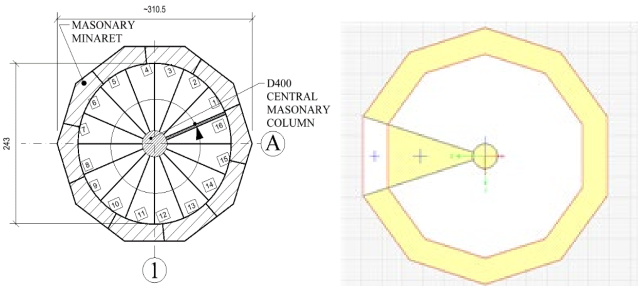


Figure 8. Typical cross-section and model cross-section of the minaret

The analytical model developed to examine the minaret's seismic behavior provided displacement results by modes, shown in Table 4 and Figure 18. Axial stresses S33 obtained from the analytical solution were as follows, for G+Ex Envelope Max min -0,783 MPa, max 1,103 MPa, for G+Ex Envelope Min min -2,985 MPa, max 0,164 MPa, for G+Ey Envelope Max min -0,907 MPa, max 0,533 MPa, for G+Ey Envelope Min min -2,52 MPa, max 0,182 MPa.

At the collapse elevation of +30 m, the maximum moment M=1241,29 ton.cm and axial load P=20,5 ton resulted in an eccentricity (e) 60,4cm, which exceeded the neutral axis distance K, confirming that the analytical model aligned with the observed collapse.

Table 4. Minaret modes and total displacements

Mode	Period(s)	Total Displacement(mm.)
1	2,16509	18,88
2	1,74003	20,67
3	0,46093	20,33

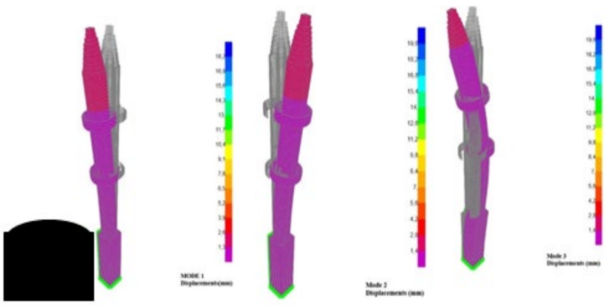


Figure 18. Minaret modes and total displacements

The creation of an internal load-bearing system has been planned to avoid visual deterioration on the exterior of the minaret. Carbon fiber meshes were deemed unsuitable due to their effective behavior only under axial tensile forces. Horizontal and vertical sections, along with the 3D model of the reconstruction work for the existing and collapsed part of the minaret, are shown in Figure 19. Since the minaret stairs are designed to make a full turn every 16 steps, 4 HE120A reinforcement columns have been deemed suitable, minimizing damage to the stair steps. Instead, 4 steel HE120A profile columns have been used, bonded with epoxy within the minaret body along the staircase gaps through a perforated spiral continuous plate with 4 mm thickness and 8 mm diameter holes. For the collapsed 9.0 m section, using stone slabs instead of full-length stone blocks has been considered suitable due to reducing the load on the minaret. Figure 20 shows the stone slab detail for the collapsed section.

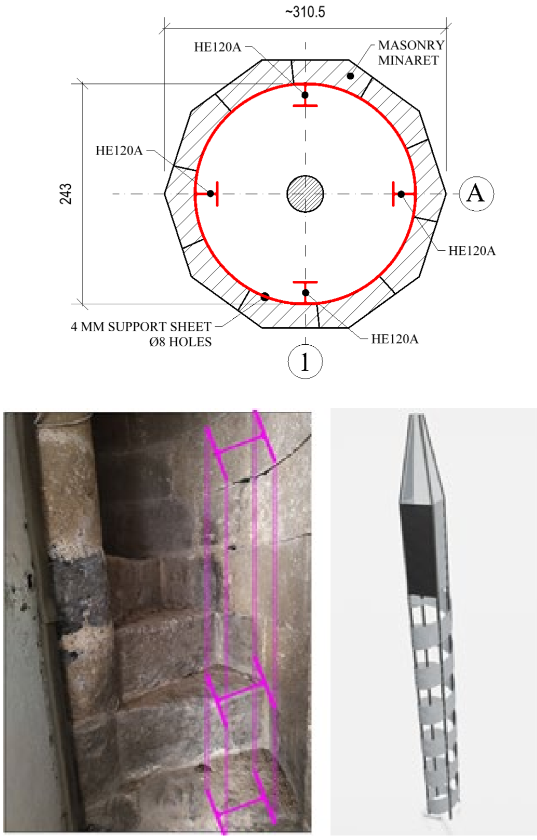


Figure 19. Placement of steel columns, their location inside the minaret, and 3D model of the steel reinforcement

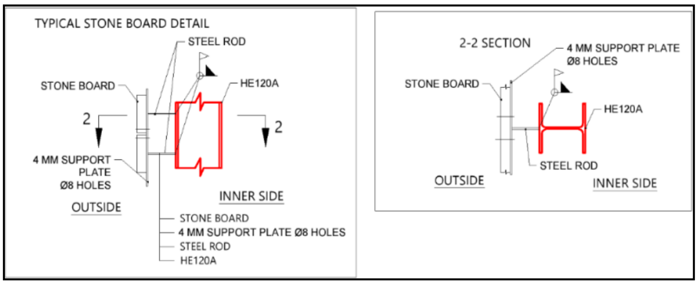


Figure 20. Stone slab detail for the collapsed section

For restoration purposes, it has been desired that the upper part of the collapsed second balcony be reconstructed in its original appearance. Thus, in the new construction for the restoration, the visual integrity will be completed by attaching thinner stone slabs to a steel sheet skeleton instead of stone walls. The outermost stone slabs will be connected to perforated sheets, which will then be welded to steel rods attached to the steel columns (Figure 21). The restoration will be carried out in accordance with the original form of the minaret, ensuring visual integrity.

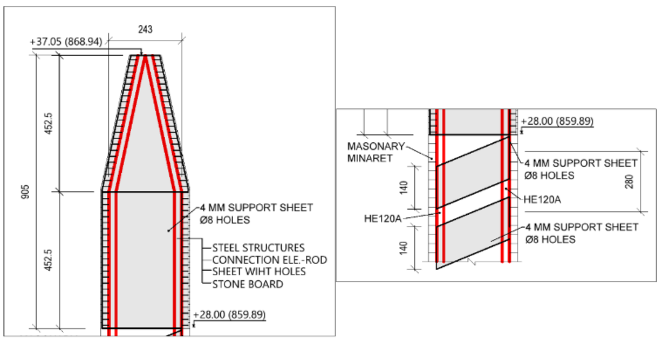


Figure 21. Spiral perforated steel plate and minaret section

The analytical model results after the repair and reconstruction of the upper part above the collapsed second balcony are presented in Table 5 and Figure 22. After the reinforcements, reductions in the minaret's period and displacements were observed. At the collapse level of +30 m, the moment value read from the analytical model was M=297.7 ton.cm and the axial load was P=5.65 tons, resulting in an eccentricity (e) of 52.7 cm. In this case, the eccentricity (e) was found to be smaller than the core distance (k), indicating that the tensile zone in the cross-section of the structure was reduced.

Table 5. Minaret modes and displacements after strengthening

Mode	Period(s)	Total Displacement(mm.)
1	1,55277	14,52
2	1,06749	15,78
3	0,33213	10,38

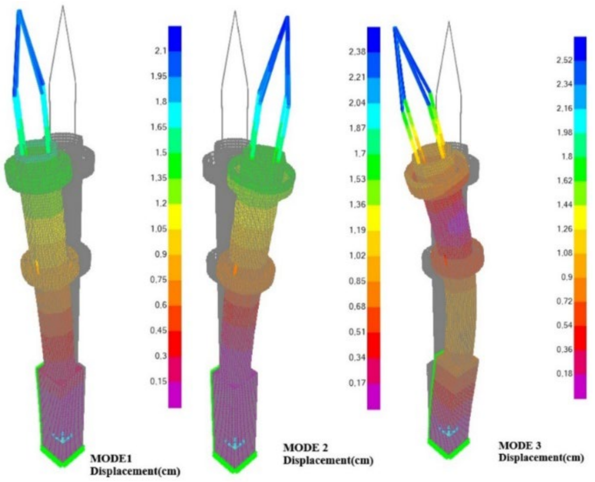


Figure 22. Minaret modes and total displacements

The axial stresses S33 obtained from the analytical model after the repair and reconstruction of the upper balcony are shown in Figure 23. The values are as follows: G+Ex Envelope Max: min -1.275 MPa, max 0.831 MPa; G+Ex Envelope Min: min -4.01 MPa, max 0.205 MPa; G+Ey Envelope Max: min -1.367 MPa, max 0.901 MPa; G+Ey Envelope Min: min -3.467 MPa, max 0.22 MPa.

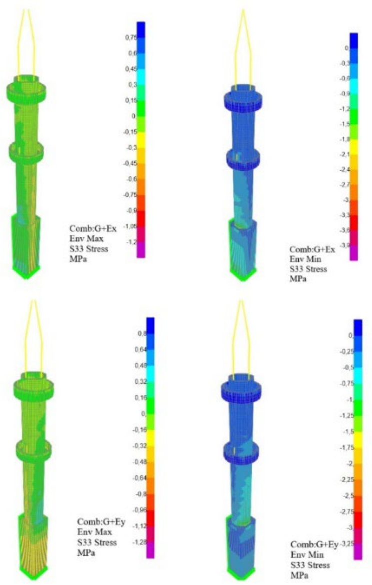


Figure 23. S33 stresses of the minaret after strengthening, MPa

According to the analytical model results for the steel columns, the design axial compressive strength was calculated as 366 kN, and the axial compressive strength acting on the profile according to the ASD (Allowable Stress Design) principle was 221 kN. The axial compressive loads acting on the steel columns were found not to exceed the column compressive capacity.

The axial stresses S22 obtained from the analytical model for the steel plate, which will be spirally wrapped around the steel columns along the minaret, are shown in Figure 25. The values are: G+Ex Envelope Max: min -22.7 MPa, max 13.8 MPa; G+Ex Envelope Min: min -47.4 MPa, max 2.2 MPa; G+Ey Envelope Max: min -16.9 MPa, max 12.1 MPa; G+Ey Envelope Min: min -59.1 MPa, max 0.5 MPa. The stress results are shown in Figures 24.

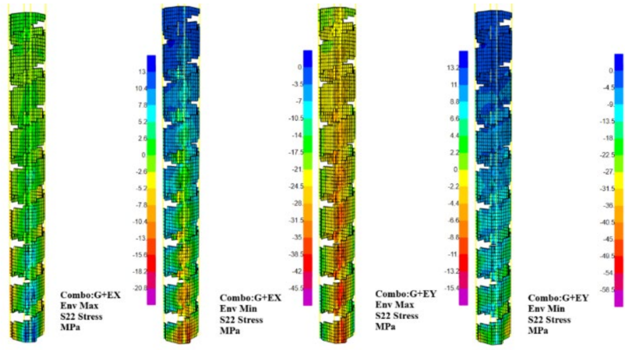


Figure 24. S22 stresses of the steel plate after repair, MPa

3. Conclusion

The seismic behavior of the minaret under the TK.2703 station acceleration data was analyzed using SAP2000 software. The material properties defined in the analytical model for the minaret section were adjusted according to the results of samples taken from the site. The minaret was modeled using solid elements similar to the ashlar masonry bricks with which it was constructed, to achieve a realistic approximation of its behavior. A total of approximately 54,000 elements were modeled, including the podium, balconies, body, stairs, central column, and spire.

A suitable modeling approach was achieved after comparing the analysis data with the actual seismic behavior of the existing minaret. The earthquake served as a natural experiment for observing the behavior. The TK.2703 station, located approximately 3.5 km from the minaret, provided actual three-directional acceleration-time graphs affecting the minaret.

Modeling the minaret alone did not yield realistic behavior. Therefore, the absence of an expansion joints between the mosque and the minaret, modeled as a cold joint, allowed for understanding the cause and direction of the collapse. The minaret was built without an expansion joint in such a way that its movement in the west direction during the earthquake was restricted by the mosque wall, while its movement in the east direction was permitted.

Using the same modeling approach, the proposed repair and reconstruction method was analyzed to achieve more realistic results.

In the analytical model prepared for the pre-collapse condition of the minaret, it was found that the cause of the partial collapse in the 9-meter section above the second balcony was displacement rather than stresses in the ashlar masonry.

It was observed that the earthquake, which can be considered a natural experiment, and the analytical model data coincided at this point. In the pre-earthquake condition of the minaret, the moment at the point of collapse under seismic loads was found to be 1241.3 ton.cm with an axial compressive load of 20.5 tons, and the resulting eccentricity was calculated as 60.4 cm. The calculated eccentricity value was found to be greater than the core distance of 53.3 cm.

For the minaret, a comparison between its pre-earthquake state and post-repair and reconstruction state showed a reduction of 28%, 39%, and 28% in the first three modal periods, respectively. Similarly, the modal displacements decreased by 23%, 24%, and 49% for the first three modes. This indicates that, after the repair and reconstruction, the minaret would have withstood the February 6, 2023, Pazarcık earthquake of magnitude 7.7, which occurred approximately 3.5 km from the TK.2073 station, without sustaining damage.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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