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Investigation of seismic safety of a masonry minaret using its dynamic characteristics

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Abstract. Besides their spiritual significance, minarets are humanity's cultural heritage to the future generations due to their historical and architectural attraction. Currently, many historical masonry minarets are damaged and destroyed due to several reasons such as earthquakes and wind. Therefore, safety of these religiously significant buildings needs to be thoroughly investigated. The utmost care must be taken into account while investigating these structures. Our study investigated earthquake behavior of historical masonry minaret of Hacı Mahmut Mosque. Destructive and non-destructive tests were carried out to determine earthquake safety of this structure. Brick-stone masonry material properties of structure were determined by accomplishing ultrasonic wave velocity, Schmidt Hammer, uniaxial compression (UAC) and indirect tension (Brazilian) tests. Determined material properties were used in the finite element analysis of the structure. To validate the numerical analysis, Operational Modal Analysis was applied to the structure and dynamic characteristics of the structure were determined. To this end, accelerometers were placed on the structure and vibrations due to environmental effects were followed. Finite element model of the minaret was updated using dynamic characteristics of the structure and the realistic numerical model of the structure was obtained. This numerical model was solved by using earthquake records of Turkey with time history analysis (THA) and the realistic earthquake behavior of the structure was introduced.

Keywords: historical masonry minaret; dynamic characteristics; operational modal analysis; model calibration; seismic safety

1. Introduction

Minarets are tower-type structures built as part of the mosques which are the places of worship for Muslims. The very first minaret was built in AD 678 by Maslama bin Mahled, Governor of Egypt. Having become an important component in religious architecture, minarets are built in different styles by the architectural character of each nation. Mainly, they were built to provide a point from which the call for prayer might be made. Over time, minarets were added with galleries in the form of balconies. While a single minaret was involved at the outset, a new architectural

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composition was later created with minarets placed on both sides of the courtyard. Erzurum Double Minaret Madrasa and Sivas Madrasa built in the 13th century during the Seljuk period are both very first examples thereof. This number rose to six or even seven afterwards. Even if they display non-uniformity among themselves, they have designing characteristics similar to other tower-type structures as they are high-rise structures that are usually taller than their width. Despite this, they may display some differences due to their specific structural components and techniques. Even though building materials and techniques used in the Muslim countries all over the world including our country in recent years display differences, older architectural traditions are maintained (Bloom 1989).

Minarets consist of three parts referred to as base, shaft and comb. Base is comprised of the footing built on firm ground, pulpit and transition segment which provides transition from the pulpit to the shaft. Shaft is the slender cylindrical body which supports the stairs of and provides the minaret with the necessary structural support. Balcony encircling the body is the place where muezzins chant adhan (call for prayer) and is located between the shaft and the comb. Part of the shaft above the balcony is called a comb. Above the comb is situated the spire covering the comb and adorned with decorative bricks, painted tiles, cornices, arches and inscriptions. Finally, there is the finial on the tip of the spire. Fig. 1 shows the parts available on a typical minaret.

Besides their historical and spiritual significance, minarets become part of the riches of the cities and countries in which they are located and bear great importance due to their architectural attraction. Almost all of the historical mosque minarets in our country are typical masonry Ottoman or Seljuk minarets. Although many of these structures are located in active seismic zones, unfortunately sufficient studies are not conducted for their dynamic behaviors, seismic safety,

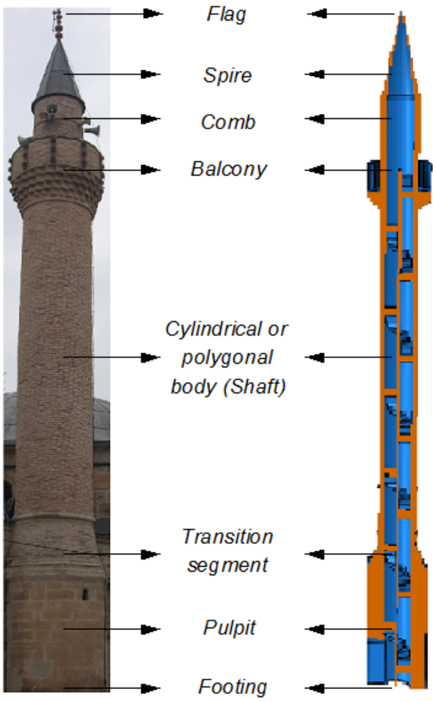


Fig. 1 Typical cross-section and parts of a minaret

restoration and reinforcement. These important structures which have survived for many years must be protected against earthquakes so that they may be safely handed down the next generations. And to do this, it is required to determine their behaviors at the time of an earthquake in a thorough and detailed manner. In literature, finite elements model of numerous structures were prepared and seismic behaviors were studied. (Koçak 1999, Lourenço 2002, Ayala *et al.* 2003, Apostolopoulos and Sotiropoulos 2008, Betti and Vignoli 2008, Júlio *et al.* 2008, Bayraktar *et al.* 2010a, Gonen *et al.* 2013, Foraboschi 2013).

Load bearing system of the minarets is similar with R/C and masonry structures. Due to its geometrical properties (slenderness and spiral stairs), seismic behavior of the minarets are quite different compared with other structural buildings and they are studied under tower type structures (Başturk *et al.* 2013). In theory, it is a rather difficult work to identify the dynamic characteristics of historical structures in an accurate manner. The basic reason for this is that the characteristics of the bearing system materials are not realistically known. Further, behaviors of structures under the effect of dynamic loads contain many uncertainties. However, the uncertainties in the parameters affecting the dynamic behavior also make it difficult to determine the dynamic behavior of the structure in a realistic manner. Capability to identify the natural frequency, mode shapes and damping ratio referred to as dynamic characteristics by experimental methods to reflect the existing features of the structure allows for more realistic attainment of the dynamic behavior of the structure (Bayraktar 2010b). Dynamic characteristics of the structure are used in the control of the accuracy of the created analytical models and the more realistic calculation of the seismic forces that will affect the structure. For these reasons, it is quite important to realistically determine the dynamic characteristics of structures by performing vibration tests.

Currently, Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA) are used to determine the dynamic characteristics of structures or objects in an experimental way in the analysis of engineering problems. In the EMA method, vibration must be applied externally in order to be able to receive accelerations. This is very difficult in case of large and historical structures. Therefore, most researchers have usually focused on the OMA method. In the OMA method, vibrations consisting of environmental impacts are recorded by accelerometers, and results analyzed and modal parameters revealed (Aras *et al.* 2011, Bayraktar *et al.* 2009, Foti *et al.* 2012, Osmancılı *et al.* 2012, Bartoli *et al.* 2013, Gentile and Saisi 2013).

Our study investigated earthquake safety of historical masonry Hacı Mahmut mosque's minaret. To accomplish this, first, stones and bricks forming the masonry system of the structure were examined using ultrasonic wave velocity, Schmidt Hammer, uniaxial compression (UAC) and Indirect tension (Brazilian) tests. Since mortar samples were very small, axial strength was determined using the point load test. The elastic modulus of mortar was taken from literature (Ercan and Nuhoglu 2014).

By the use of the homogenization approach, the behavior of mortar and stone/brick were assumed to act together; thus, the overall behavior of the composite media has been taken into account. While determining the elastic parameters of the masonry minaret, the homogenization equations depending on the strength parameters of constituents were used. The minaret has two types of masonry; stone masonry (SM) and brick masonry (BM). Numerical solution of the structure was established from the obtained values and numerical dynamic characteristics were determined. To validate results of the numerical model, the operational Modal Analysis (OMA) method was used. To do this, accelerometers were placed on the various points of the structure, structural vibrations due to environmental effects were determined. Using the results, numerical model was updated and the real numerical model was obtained. THA was done on the updated

Fig. 2 Inner and outer view from the minaret of hacı mahmut mosque

model by using Düzce/375-E component of Düzce earthquake (year=1999) and safety of the structure was established.

2. Description of the minaret of Hacı Mahmut Mosque

The minaret under study is located in the town of Bolvadin of the province of Afyon in Turkey. Hacı Mahmut ordered Pilavoğlu Avadik Avidisian Efendi, an Armenian architect, to build the mosque and the minaret in 1906. The octagonal base of the independent minaret located on the north-east corner of the mosque has a height close to the outer wall of the mosque. Transition is provided from the octagonal pulpit to the shaft by means of moldings with circular surfaces. Circular shaft extends up to the balcony. The base of the balcony is made of moldings with circular surfaces. Balcony is made in the form of a parapet. The cylindrical comb with a diameter smaller than the shaft terminates in a metallic spire. The minaret built as a brick and stone masonry structure using 76 concrete boarding steps at center. Height of the minaret is 24.5 m high (Fig. 2).

2.1 Material tests on constituents of the minaret

In order to determine the parameters needed for finite element modeling, nondestructive and destructive tests were carried out on the constituents of the masonry. Stones and bricks from the structure were taken and destructive tests were carried out. The sizes of the samples prepared were 54 and in diameter for the concrete, stones and clay bricks respectively. Uniaxial compression tests (UAC) and Indirect tension tests (Brazilian test) were conducted as discussed (TS-699, Ulusay *et al.* 2001) (Fig. 3). The average results are shown in Table 1.

Before the samples were taken to the laboratory to conduct nondestructive tests, L and LB type Proceq Schmidt Hammers were used to find the surface hardness values (rebound value) of the stone and clay brick samples, respectively. The Schmidt Hammer test was also applied to the stones and clay bricks of the intact minaret (Fig. 4). The compressive strength was calculated from the “rebound (R) value-compressive strength scheme” of Ulusay (Ulusay *et al.* 2001). In the laboratory, before indirect and uniaxial compression tests were applied to the stone and clay brick samples, ultrasonic wave velocity tests had been conducted using Pundit type equipment (Fig. 4). The modulus of elasticity values of the stone samples were also determined by Eq. (1) given in ASTM (1969)

$$\mathrm{E} = V^2 \rho (1 + \mathrm{m}) \frac{(1 - 2\mathrm{m})}{(1 - \mathrm{m})} \tag{1}$$

where V, ρ, and m were ultrasonic pulse velocity, density and poisson's ratio, respectively. The poisson's ratio was taken to be 0.21 for the andesite stone. The estimated modulus of elasticity values from ultra-velocity tests are higher than the values obtained through destructive tests (Table 1).

Fig. 3 Drilling out core samples, prepared samples with straingages, Brazilian test and uniaxial compression

Fig. 4 Ultrasonic wave velocity test and Schmidt test on stone and brick

Table 1 Test results of stone and bricks

Sample	Number of Samples	Density ρ (g/cm^3)	Rebound Value, R	Compressive Strength from R (Mpa)	Compressive Strength from UAC (Mpa)	E from UAC (Gpa)	Tensile Strength from Brazilian test (Mpa)	Ultra Vel. (m/sec)	E from U. V. (Gpa)
Stone (Stan.Deviation)	18	2.38 (0.81)	49 (2.93)	65	58.28 (3.4)	11.59 (0.4)	6.09 (1.81)	4030 (220)	16.24
Inner Brick (Stan.Deviation)	10	1.78 (0.12)	30.801 (2.8)	27	13.09 (2.4)	0.81 (0.06)	1.43 (0.08)	2170 (180)	-
Outer Brick (Stan.Deviation)	10	1.82 (0.13)	41.915 (1.71)	32	18.08 (2.2)	0.81 (0.06)	1.43 (0.08)	2304 (180)	-
Concrete boarding steps	3	2.0	50	12	7.56	2428	0.75	-	-

Table 2 Material parameters of masonry for FE model

Material Parameter	Stone Masonry	Inner Brick Masonry	Outer Brick Masonry	Concrete Spiral Staircase
Compressive Strength (MPa)	10.86	6.55	7.31	7.56
Tensile Strength (MPa)	1.05	0.656	0.73	0.75
Modulus of Elasticity (MPa)	2591	123	132	2428
Shear Modulus	1036.4	49.2	52.8	971.2
Density (kg/m^3)	2100	1750	1780	2400
Poisson Ratio	0.17	0.17	0.17	0.17

The mortar samples were too small and weak for drilling so only point load tests could be applied on arbitrary shaped samples. Using the point load index, the uniaxial compressive strengths of mortars were estimated. The average estimated uniaxial strength of mortars was calculated to be 5.75 MPa from point load tests. Tensile strength and modulus of elasticity of mortar was also estimated from the literature with the aid of point load test results. The tensile strength and modulus of elasticity σt 0.8 MPa and E, 140 MPa were taken, respectively. The density of the mortar was calculated to be 1.72 g/cm^3.

2.2 Determination of material parameters for initial analytical model

Masonry is a composite and this composite material consists of two or more different constituent materials. By the help of the homogenization technique, the mortar and stone/brick were assumed to act together so the overall behavior of the composite media has been taken into account. While determining the elastic parameters of the masonry minaret, the homogenization equations depending on the strength parameters of the constituents were used. The minaret has two types of masonry; stone masonry (MS) and brick masonry (MB).

2.2.1 Determination of material parameters of MS and MB from destructive test results

The compressive strength of masonry is determined by Eq. (2) as described by Eurocode 6, (1996)

$$f_k = \mathrm{K}\, f_b^{0.65}\, f_m^{0.25} \tag{2}$$

Where K is a constant, f_b is the compressive strength of stone or brick and f_m compressive strength of mortar. K is in the range of 0.4 to 0.6 and depends on the morphology of the masonry as described by Eurocode 6 (1996). K was taken to be 0.5 in this study. The modulus of elasticity of masonry was determined by the use of Eq. (3) as described by Lourenco (Lourenco 1996, Lourenco 2001)

$$\mathrm{E} = \frac{\mathrm{t_m} + \mathrm{t_u}}{\dfrac{\mathrm{t_m}}{\mathrm{E_m}} + \dfrac{\mathrm{t_u}}{\mathrm{E_u}}}\rho \tag{3}$$

where t_m, t_u, E_m, E_u are the thickness of mortar and height of the unit (stone or clay brick), the coefficient ρ varies with the bond between mortar and unit and was taken to be 0.6 for this study as described by Lourenco (1996, 2001). The shear modulus can be taken to be 40% of the modulus of elasticity as described by Eurocode 6 (1996). The tensile strength of masonry can be taken to be 10% of compressive strength as described by Kocak (Kocak 1999). The density of MB_i, MB_o and MS were calculated to be 1750 kg/m^3, 1780 kg/m^3 and 2100 kg/m^3, respectively. The poisson ratio was taken to be 0.17 for masonry as described by Kocak (Kocak 1999). The elastic material parameters of MS and $MB_{i,o}$ for the finite element model are shown in Table 2.

3. Numerical and experimental modal analysis

The natural frequencies and mode shapes in the analytical modal analysis are determined by using the free vibration equation of motion below

$$[\mathrm{M}]\{\ddot{\mathrm{X}}(\mathrm{t})\}+[\mathrm{K}]\{\mathrm{X}(\mathrm{t})\}=0 \tag{4}$$

where [M] and [K] represent the mass and rigidity matrices and $\ddot{X}(t)$ and X(t) are vectors of time varying acceleration and displacement, respectively. Natural angular frequencies (ω_1, ω_2, ω_3,…, ω_n) without damping are obtained from the solution of Eq. (4). The system's deformed shapes, which are a reaction to each natural frequency, are described as mode shapes. The smallest frequency is called the fundamental frequency and the corresponding mode shape is the first mode shape (Bayraktar *et al.* 2009).

Experimental modal analysis methods may be defined as the measurement of reactions consisting of vibrations on structures and the determination of the dynamic parameters of structures from measurement data. In these methods, structures are vibrated by a known force or environmental vibrations are considered while measurements are taken. If the structure is vibrated by a known force in the analyses conducted, the method is called the experimental modal analysis (EMA) and, if otherwise, it is called operational modal analysis (OMA). It is not possible to use the EMA method for such large structures as buildings, bridges, houses of worship. In practice, OMA is usually focused upon. OMA is the modal analysis method conducted by gathering the data of a structure in real time. In this method, natural vibrations of the structure are recorded under environmental factors by accelerometers. Records are analyzed by using intermediate programs

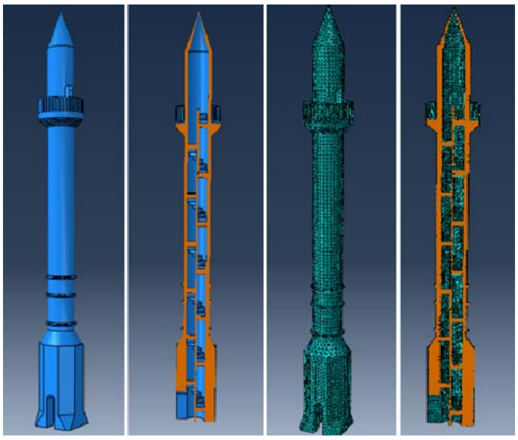


Fig. 5 Three-dimensional finite elements model of the minaret and meshed state thereof

and dynamic modal parameters of the structure found. As environmental impacts are not precisely known, modal parameters are revealed by algorithms different from the experimental modal analysis. The “Stochastic Subspace Identification (SSI) Technique” frequently encountered in literature is used in our study. The reason why the SSI method is preferred is that this method does not require any conversion in the process steps as it operates with time data.

3.1 Numerical modeling of the minaret of Hacı Mahmut Mosque

First of all, the survey of the minaret was issued and a finite element model of the structure was created and analyzed via the ABAQUS structural analysis program in Celal Bayar University’s server computer which are used for FE analyses. Solid element was used in the creation of the finite element model. Linear Perturbation-Frequency module which allows for the performance of

Table 3 Frequency values, element numbers and convergence graph by seed sizes

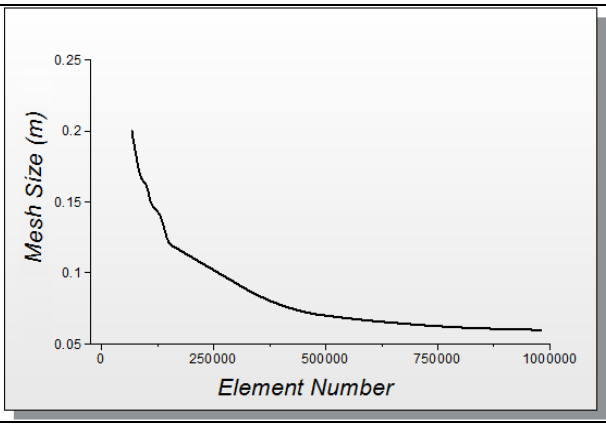
Mesh Size (m)	1.Mod Frequencies (Hz.)	Element Number	Convergence graph
0.20	1.231	67206	
0.18	1.227	78176	
0.17	1.226	84841	
0.16	1.222	101424	
0.15	1.220	109260	
0.14	1.221	134869	
0.13	1.218	162470	
0.12	1.219	153031	
0.10	1.217	260785	
0.09	1.215	314878	
0.06	1.210	972851	

Table 4 Frequency values obtained as a result of numerical analyses

Mod	Frequencies (Hz)
1	1.210
2	1.220
3	6.891
4	6.972
5	11.958

eigenvalue eigenvector analysis was used in the numerical analysis. 972851 tetrahedral (C3D4) solid elements with four nodal points were used in the finite elements analysis of the minaret. It was fixed at the base in the analyses that the structure had been supported in a built-in manner at the base. The three-dimensional finite elements model of the structure and the meshed state thereof are shown in Fig. 5.

Convergence analysis was conducted in order to determine the most proper seed size to be used in the model. In the convergence analysis, frequency analysis was conducted for each seed sizes from 0.2 m to 0.06 m on the model and the frequency values obtained are given in Table 3.

It was determined as a result of the convergence analysis that the most proper seed size was 0.06 m and the frequencies of the initial five modes of the structure obtained in the frequency analysis conducted are given in Table 4.

3.2 Experimental results

Experimental measurements of the minaret of historical Hacı Mahmut Mosque were carried out by using the OMA method. A SENSEBOX-7021 low noise accelerometer and a 24 bits simultaneous TESTBOX-6501 data collection unit were used in the experimental study. Data obtained were transferred to computer via the TESTBOX software and dynamic characteristics were obtained via the Artemis Modal Pro (AMP) software. Measurements were carried out at a time during the same day. Two measurements were taken against potential errors. Twelve single-axis accelerometers were connected to the potential points of motion of the structure obtained via the analysis of the numerical model thereof in the measurement. Three data collection units were used to gather the signals from the accelerometers. Points to which the accelerometers were connected are shown in Fig. 6.

Dynamic modal characteristics of the minaret were experimentally obtained in the ARTEMIS Modal Pro (AMP) program. Operational Modal Analysis is a technique of estimating modal parameters like modal frequency, modal damping, and mode shape based on the knowledge of output responses only. The frequency can be estimated relatively easily, the damping is not as simple at all. It has been observed that damping estimates made through OMA are not accurate and often the errors are significant (Avitable 2006).

Mode values, damping ratios are shown in Table 5. As shown in table 5 the damping ratios found varied for each method (The Curve-fit Frequency Domain Decomposition (CFDD), Enhanced Frequency Domain Decomposition (EFDD), Stochastic Subspace Identification (SSI), Unweighted Principal Component (UPC), Principal Component (PC), Canonical Variate Analysis (CVA)).

The stabilization diagram presents the natural frequencies of all the estimated eigenvalues as

Fig. 6 Points and directions at which accelerometers are installed on the structure

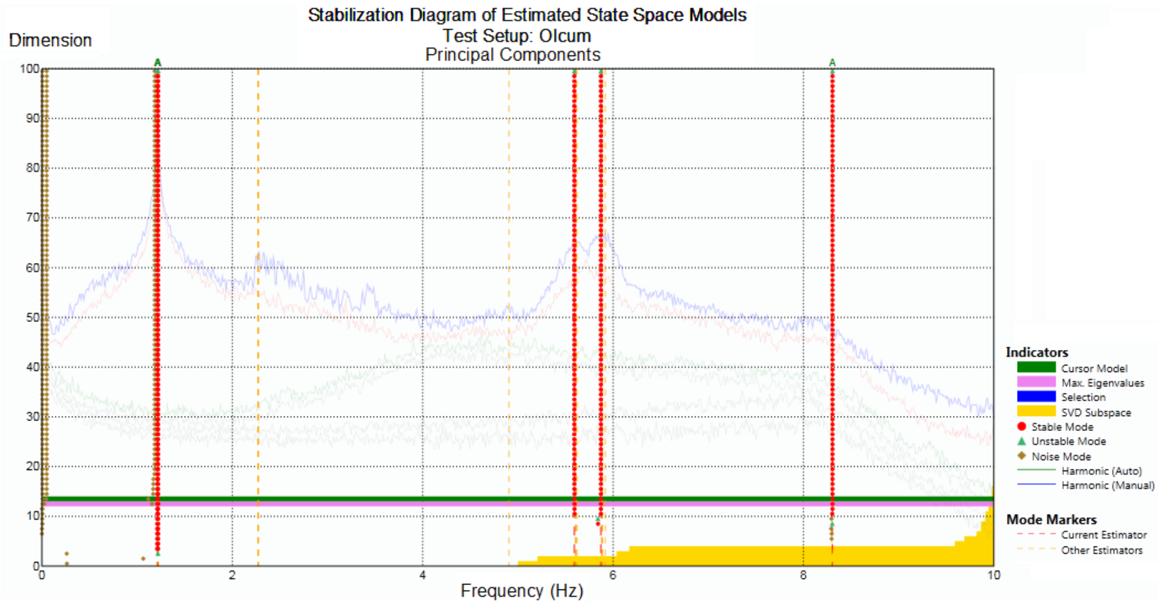


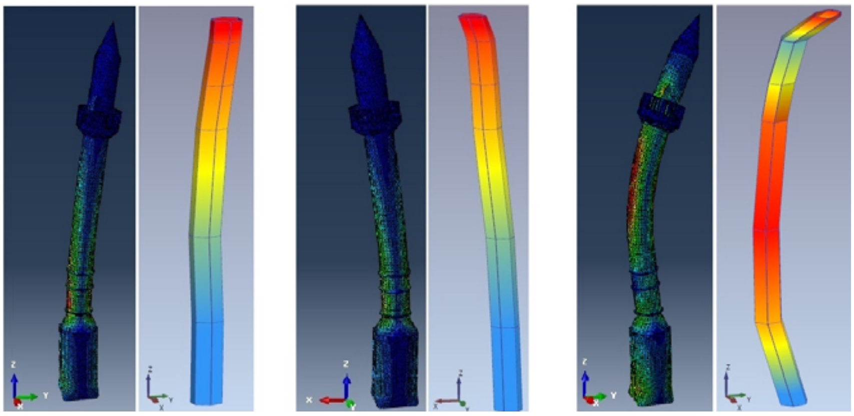
Fig. 7 Stabilization diagram of the structure

Table 5 Experimental dynamic modal parameters of the structure

Frequency (H)	Damping %				
	EFDD Method	CFDD Method	SSI-UPC Method	SSI-PC Method	SSI-CVA Method
1.211	1.033	0.542	1.108	0.863	0.861
1.221	1.042	0.523	0.700	0.611	0.635
5.593	0.954	0.533	1.799	1.591	1.777
5.872	1.048	0.712	1.452	1.509	1.589
8.305	1.063	0.625	1.127	4.909	3.454

Table 6 Numerical and experimental dynamic characteristics

Mod	Uncalibrated frequencies with FEM (Hz.)	Calibrated frequencies with FEM (Hz.)	Frequencies with SSI	
			Frequencies (Hz.)	Difference %
1	1.16	1.21	1.211	0.211
2	1.17	1.22	1.221	0.221
3	6.605	6.891	5.593	4.593
4	6.681	6.972	5.872	4.872
5	11.463	11.958	8.305	7.305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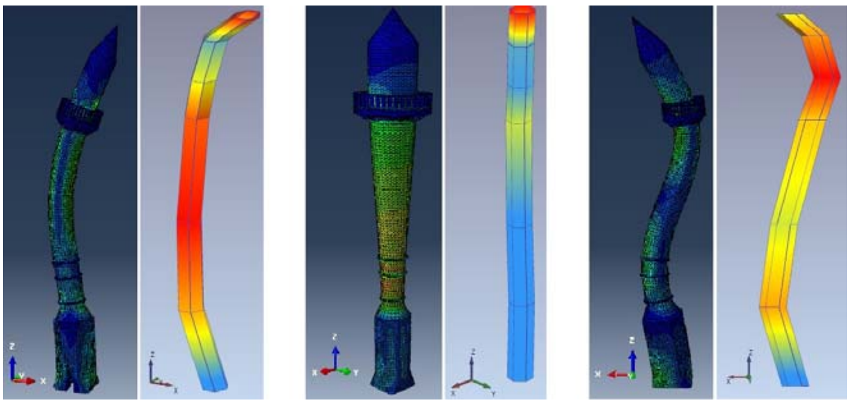
4. Mod 5. Mod 6.Mod

Fig. 8 Experimental and numerical mode shapes

well as a background wall-paper of the Singular Value Decomposition of the spectral density matrices of the currently selected test setup. This wall-paper has nothing directly to do with the estimation. However, it is a valuable help in the search of structural modes since these will be located at the spectral density peaks. The horizontal axis is a frequency axis ranging from zero to the Nyquist frequency (Artemis PRO). The vertical axis lists the dimensions of the available state space models. Stabilization diagram obtained are shown in Fig. 7.

3.3 Calibration of numerical model

To approximate experimental results with numerical ones, elastic modulus of walls was determine with calibration. Frequencies, experimental frequencies found by the SSI method and damping ratios of the calibrated model are presented in Table 6. The calibrated numerical frequencies converge to the experimental results to a great extent (Table 6). An average difference of 3.44% occurred between the experimentally obtained frequencies and the numerical frequencies.

Experimental and calibrated numerical mode shapes are given in Fig. 8. The mode shapes obtained by both methods displayed a good compatibility. Determined both experimentally and theoretically, the mode 1 of the structure was in *Y* direction; mode 2 in *X* direction, mode 3 in *Y* direction, mode 4 in *X* direction, mode 5 in torsion direction and mode 6 in *X* direction.

4. Determination of seismic safety

Seismic analysis of the minaret was conducted using the Düzce/375-E directional component of the Düzce earthquake, which took place in 1999 (Fig. 9). Earthquake was applied in the direction of the initial mode of the historical structure. Damping ratios obtained from the experimental measurements were used for each mode in the seismic analyses of the historical structure.

Changes along the height of the displacements of the minaret obtained as a result of the seismic analysis and the counter view at the time when the maximum displacement occurred are shown in Fig. 10.

As shown in Fig. 10, displacements increase along the height. Maximum displacement was found to be 171 mm at the very top of the spire of the minaret at the 13.7th second of the seismic ground recording. Time-dependent change in the maximum and minimum principal stress of the minaret as a result of seismic analysis is given in Fig. 11.

Fig. 11 reveals that principal stress formation in time scale is symmetrical. Stress diagram of the system where the principal stress is maximum and minimum are given in Fig. 12. Maximum principal stresses caused a pressure of 7 MPa and a tensile stress of 5.2 MPa when the earthquake acceleration record was at 8.8 s. There was a shift from MS to MB and ultimate tensile strength of the masonry exceeded and the ultimate pressure was at its maximum (Table 2). Therefore, the structure was prone to break down from this region due to tensile damage and collapse of the structure was expected.

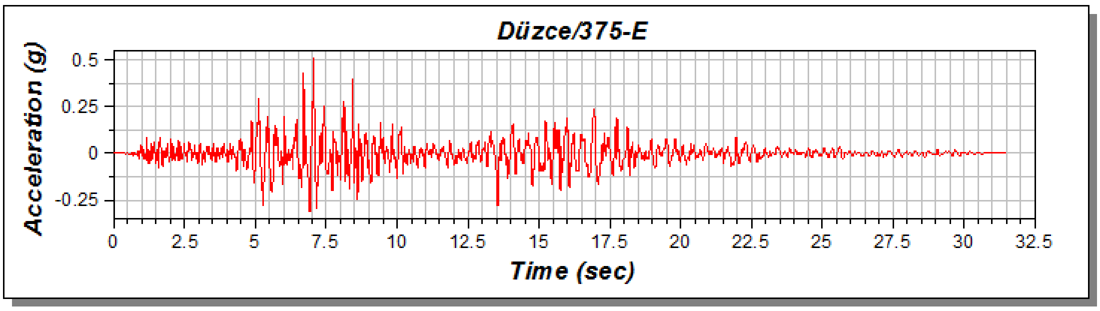

Fig. 9 Acceleration ground recording of the 375-E component of Düzce Earthquake (1999)

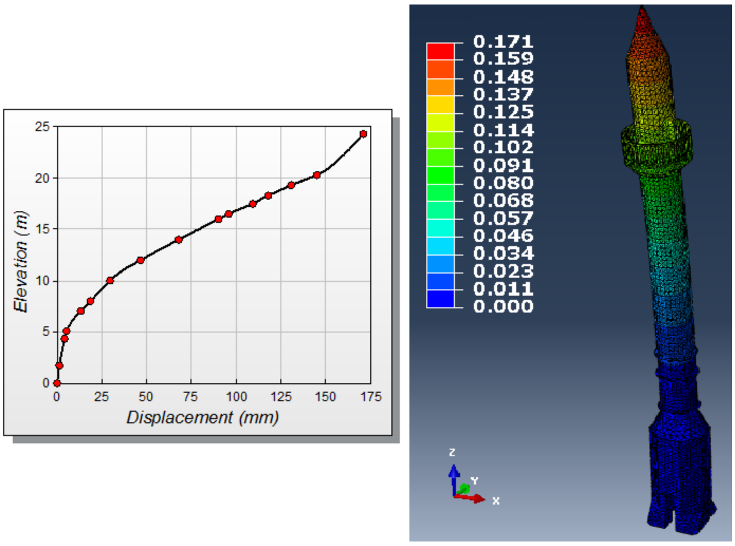

Fig. 10 Displacements along the height and displacement counter distribution

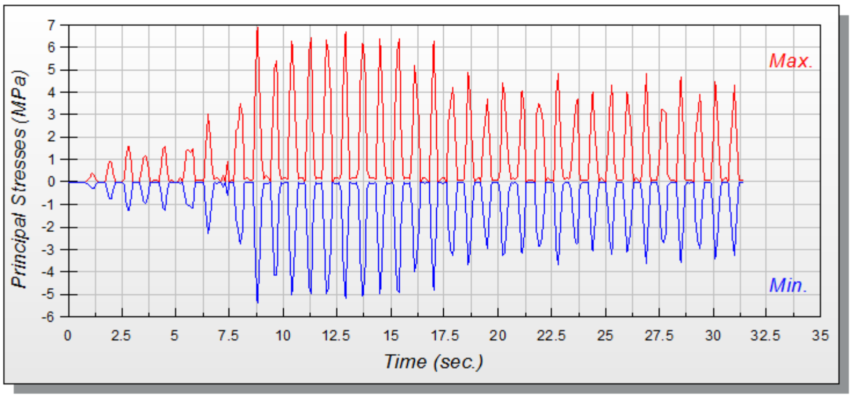

Fig. 11 Time-dependent change in the maximum and minimum principal stresses

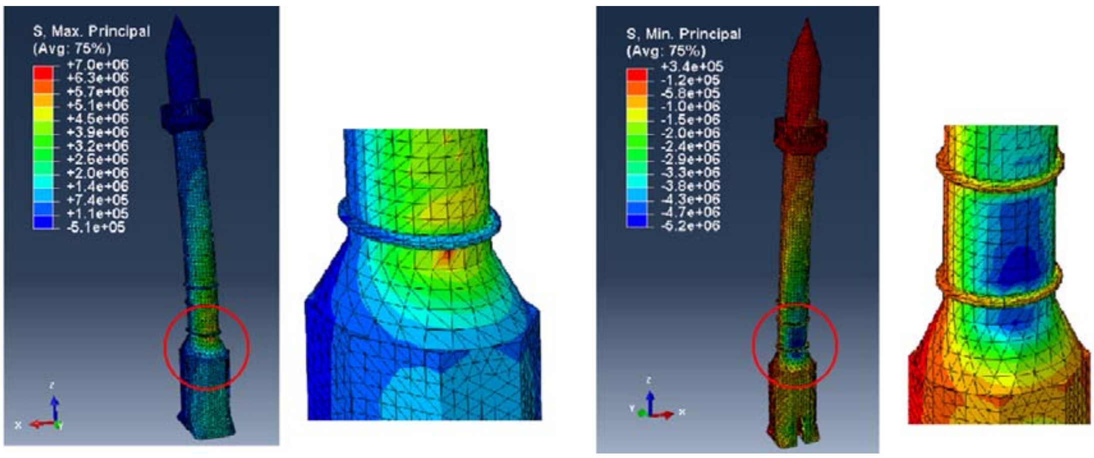

Fig. 12 Distribution and values of stress occurring in the minaret as a result of analyses

5. Discussion

The first five frequency values of the structure determined experimentally by the OMA method were between 1.211 and 8.305 Hz. The numerical model of the minaret was improved by taking changes in material properties into account. Using the improved numerical model, the first five frequency values were determined to range from 1.21 to 11.958 Hz. The mean difference in frequencies obtained by the two methods was about 3.5%.

Applying the improved numerical model by affecting E-S component of 1999 Düzce earthquake, dynamic solution of the structure was obtained. The displacement of minaret increased with its height and the maximum value was found to be 171 mm on the spire part of the minaret. The maximum and minimum principal stresses were 7 MPa and - 5.2 MPa, respectively and occurred in the transition region from pulpit to shaft. These values have the ability to inflict damages in the structure. Thus, should the minaret be exposed to earthquake loads, it may start inflicting damages and may result in the collapse of structure. Therefore, to prevent any damages, which are likely to occur in the stressed regions of the structure, stressed regions need to be strengthened.

Engineering structures strengthened with FRP composites are gaining popularity because of its easiness and low cost. Altunısık (2011) has strengthed a minaret using FRP composites and increase the strength of minaret in his study. He also explains that FRP composite strengthening is very effective in the dynamic response of the historical minarets. To determine the static, dynamic, linear and nonlinear structural behavior of the historical masonry structures such as bridges, minarets, bell towers, dams, buildings, which are our cultural values that left behind by thousands of years' cultural accumulation, FRP composite strengthening should be considered and the responses should be compared before the FRP composite strengthening.

6. Conclusions

Our study investigated the earthquake safety of historical masonry Hacı Mahmut Mosque. Destructive and non-destructive tests were done on the materials forming the structure and parameters required for the numerical model were obtained. Using these parameters, numerical analysis was established and calibrated with the OMA method and the final finite element model simulating the real time behavior of structure was obtained. This finite element model was used to determine earthquake safety of the structure by carrying out Time History Analysis (THA). Applying the ABAQUS program, the mesh size was assessed as 0.06 m. Solid elements were used in the development of the finite element method and dynamic characteristics were determined using the model. To validate the finite element model, non-destructive OMA method was used to determine dynamic characteristics such as frequency, damping ratios and modal shapes of the masonry minaret. Elastic modulus values were changed step by step until the frequencies obtained by the numerical and OMA methods became equal.

When modal shapes were closely investigated, numerical solutions and experimental values were observed to fit very well proving that numerical model and boundary conditions of the structure were properly formed. With the updated numerical model, the difference in frequency values between experimental and numerical values shrank to 3.44%.

For the first five frequency values were found to fit well with OMA and Numerical solution. Earthquake analysis done with the calibrated material properties of the minaret yielded reliable results. To sum up, our study conclusively demonstrated which parts of the minaret needed to be improved and what kind of strengthening methods were required in order for the structure to be handed down the next generations.

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