Journal of Structural Engineering & Applied Mechanics (2022) 5(4):264-276
DOI 10.31462/jseam.2022.04264276

RESEARCH ARTICLE

Finite element model updating of İskenderpaşa mosque and minaret based on experimental measurements

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Article History

Received 8 December 2022
Accepted 26 December 2022

Keywords

Historical masonry structures
Iskenderpaşa mosque
Minaret
Operational modal analysis
Model updating

Abstract

Historical masonry structures have an important place in cultural heritage. Therefore, maintenance of these structures should be made periodically to prevent natural and manmade hazards. The maintenance of these structures is divided into two parts, namely experimental and numerical applications. Experimental, especially non-destructive methods are crucial for increasing the knowledge level of historical structures. Also, experimental tests provide information data that is used in the modal updating process of numerical models. Thus, simulations that are impossible to make experimentally can be easily carried out with updated numerical models. In this paper, a historical masonry mosque called İskenderpaşa and its minaret is investigated by nondestructive experimental tests. Also, finite element models of both structures are created by ANSYS software. To obtain reliable numerical models, finite element model updating processes are made with the aid of experimental data. At the end of the study, the differences between natural frequencies are reduced from 18.6% to 4.9% for the mosque and from 15.2% to 4.8% for the minaret. According to the study, the modulus of elasticity is the most effective update parameter for both structures.

1. Introduction

Historical masonry structures have a big place in the cultural heritage of each civilization. These structures form the main part of tourism motivation. Although surviving at least a hundred years, these structures are vulnerable to some manmade actions and natural hazards, especially seismic hazards [1, 2]. Therefore conservation and periodic maintenance are required for these structures.

Researchers have developed different experimental and numerical methods, to evaluate the structural behavior of historical structures and so making the right and proper interventions in conservation and restoration processes. Thus, the level of knowledge of investigated historical structure is increased by these methods.

Minor destructive and nondestructive experimental tests have been suggested by researchers for historical structures. Many of these tests are concerned with the material properties of a local part of the structure. Also, some of the tests give information about the whole structure. The ambient vibration test is one of the non-destructive tests and obtains dynamic characteristics such as natural frequencies, mode shapes, and

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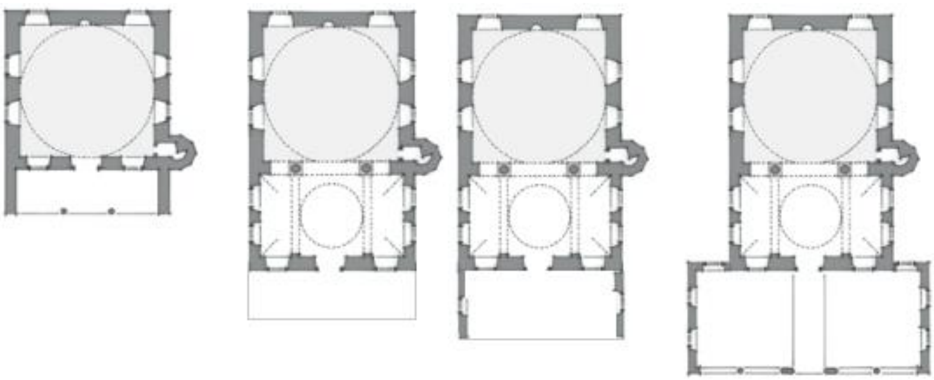
damping ratios which are related mass and stiffness of structures [3]. In addition, this method is very useful for updating numerical models of historical structures, to make reliable numerical analyses.

Ambient vibration tests have been widely used in the literature for all types of structures, especially historical masonry structures. The method was used for masonry towers [4-7], masonry minarets [8-10], masonry bridges [11-14], masonry buildings [15-17], masonry mosques [18-20], masonry churches [21, 22] and other historical masonry structures [23, 24]. It can be seen from the literature that ambient vibration tests have been commonly used for all types of historical masonry structures.

In this paper, a historical masonry mosque called Iskenderpaşa and its minaret is investigated. Ambient vibration tests of these structures were made and experimental dynamic characteristics were extracted using Enhanced Frequency Domain Decomposition (EFDD) technic. Also, a finite element model of the mosque and its minaret were created. Finally, the created numerical models are updated according to the experimental dynamic characteristics.

2. İskenderpaşa Mosque and its minaret

İskenderpaşa Mosque is located in Trabzon and Ortahisar districts. İskenderpaşa Mosque is one of the most important Ottoman masonry mosques in Trabzon. Existing documents in historical records show that the building was built in 1529 by İskender Pasha, one of the governors of Trabzon during the Kanuni period. During this period, some revisions had been made to the mosque at different times. Today, the mosque has a rectangular masjid (11.16 m×16.80 m) and a rectangular final masjid (16.67 m×7.67 m) horizontally adjacent to this space. The thickness of the masonry walls varies between 0.79m and 1.03 m. The mosque has a large dome with a diameter of 9.15 meters, a small dome with a diameter of 4.44 meters, and a minaret with a height of 23.23 meters. The minaret is adjacent to the western wall of the mosque, and the balcony of the minaret is gone up through a small door from the masjid. In addition, there are two half-domed vaults and two cylindrical columns in the place of worship [25]. The physical development stages of the mosque in time and some views of the mosque are presented in Fig. 1.



1529 1874 1882-1883 1897-2019

(a)

Fig. 1 (a) Physical development stages of the mosque in time [25], and (b) some views of Iskenderpaşa Mosque and its minaret

(b)

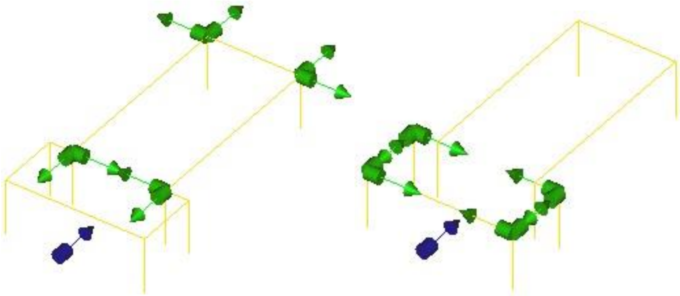
Fig. 1 Continued

2.1. Ambient vibration tests

Ambient vibration tests were carried out on both mosque and minaret to determine their dynamic characteristics such as natural frequencies, mode shapes, and damping ratios. In the tests, B&K 3560 data acquisition system with 17 channels and B&K 8340-type uni-axial accelerometers with 10V/g sensitivity, uni-axial signal cables, PULSE [26], and OMA [27] software were used as the test equipment. The frequency range was selected as 0-25Hz for each test. Nine accelerometers were used for the test of the mosque and eight accelerometers were used for the test of the minaret. The accelerometers were located at the upper part of the mosque in transverse and longitudinal directions. Also, the accelerometers were located at four points each with different heights of the minaret in transverse and longitudinal directions (Fig. 2). Detailed information about experimental measurements is presented in another study [28].

Measurements were carried out for 30 minutes and 10 minutes for the mosque and the minaret, respectively. The signals obtained from the accelerometers were accumulated to signal processing with the aid of PULSE and OMA software. Modal parameters were extracted using the EFDD technique. Singular values of the spectral density matrices (SVSDM) of the data set obtained by the EFDD technique for the mosque and minaret are given in Fig. 3. As shown, the natural frequencies were obtained between the 0 and 15 Hz frequency range for both structures. Model shapes of the mosque and minaret are given in Fig. 4. The first mode is the transverse mode, the second is the longitudinal mode, and the third is the torsional mode for the mosque. In addition, the modes of the minaret were obtained as 1st transverse mode, 1st longitudinal mode, 2nd transverse mode, and 2nd longitudinal mode respectively.

The experimental dynamic characteristics of the mosque and minaret, extracted with the EFDD method are presented in Table 1. The natural frequencies were calculated within 7.12 Hz-11.02 Hz and 1.04 Hz-7.15 Hz respectively for the mosque and minaret. In addition, the damping ratios were calculated within 0.26%-1.45% and 0.26-2.43% for mosque and minaret, respectively.



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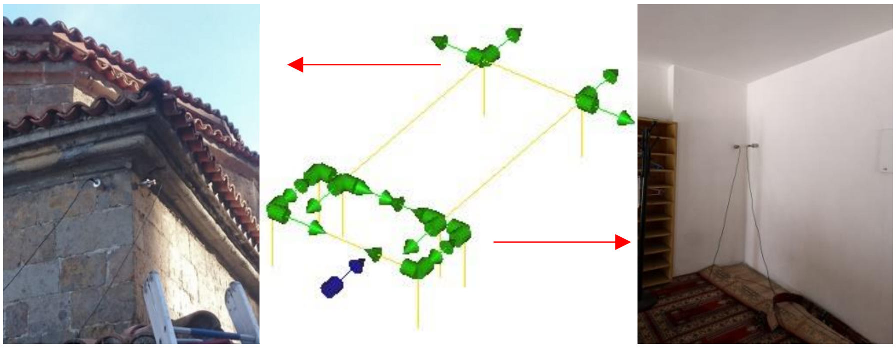
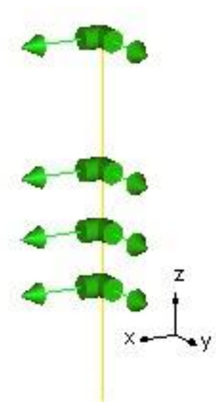
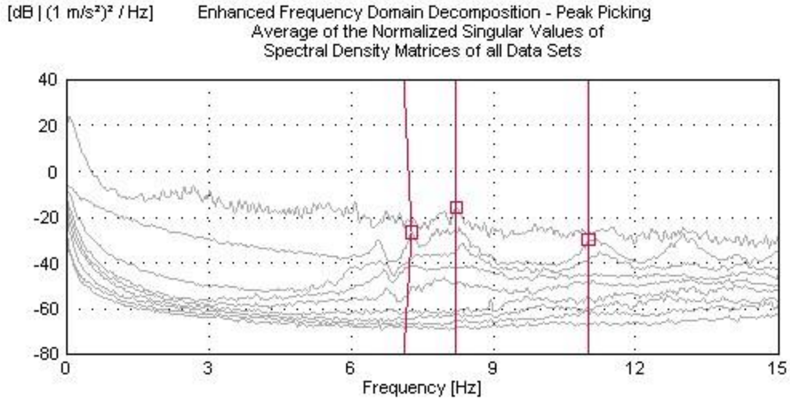


(a) Mosque

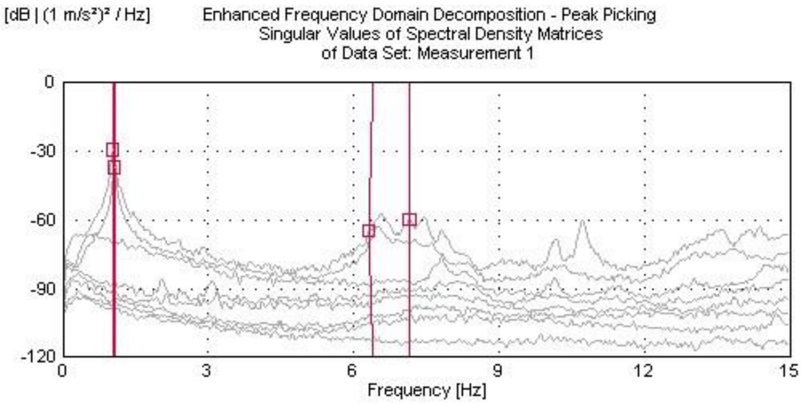


(b) Minaret

Fig. 2 The accelerometer layout and connections for the mosque and minaret

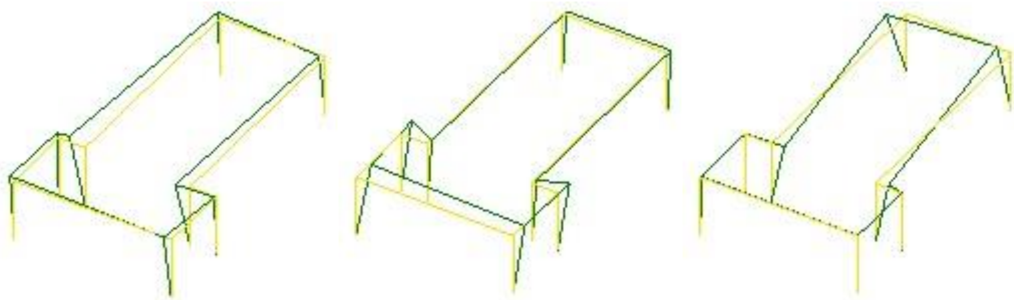


(a) Mosque



(b) Minaret

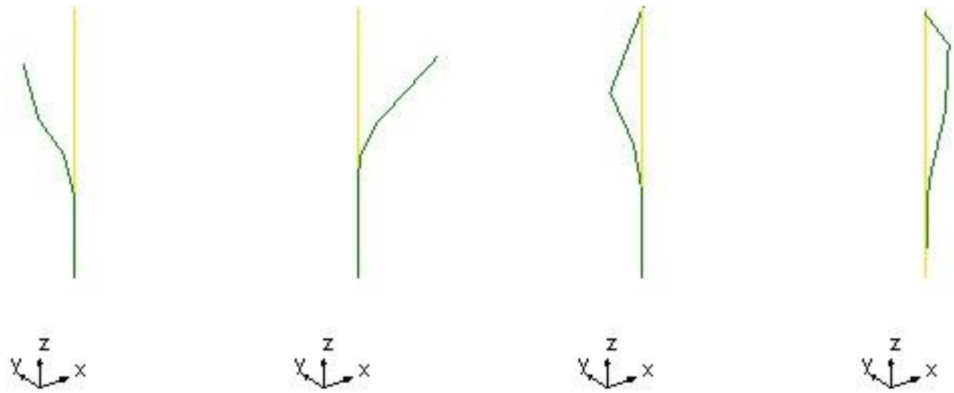
Fig. 3 Spectral density matrices of the data set of mosque and minaret



Transverse Longitudinal Torsion

(a) Mosque

Fig. 4 The experimental mode shapes of the mosque and minaret



1st transverse mode 1st longitudinal mode 2nd transverse mode 2nd longitudinal mode

(b) Minaret

Fig. 4 Continued

Table 1 Natural frequencies and damping ratios of the mosque and minaret

Mode	Mosque		Minaret	
	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
1	7.12	1.45	1.04	2.43
2	8.20	0.50	1.06	0.93
3	11.02	0.26	6.40	0.26
4	-	-	7.15	1.03

2.2. Finite element model

Finite element models of the mosque and minaret were constituted with ANSYS software [29]. In the finite element model of the mosque and minaret, SOLID186 solid element was used (Fig. 5). This element has 20 nodes and three degrees of freedom per node. The element has the capability of plasticity, elasticity, creep, stress stiffening, large deflection, and large strains. In addition, the element has tetrahedral, pyramid, or prism options for meshing, and these options provide easy meshing for models [29].

The supports at the foundations of the mosque and minaret were assumed as fixed in the model. Parts of the models were assumed as fully bonded in the FE model. Masonry elements were modeled with the macro modeling technic. The finite element model includes 185,652 nodes and 112,542 solid elements. The finite element models of the mosque and minaret are given in Fig. 6.

Seven different structural element components exist in the FE model of the mosque, namely main, middle and last part masonry walls, masonry arches, brick domes and vaults, and reinforced concrete (RC) elements (columns, beams, and floor). In addition, the minaret consists of five different element components as pulpit and transition segment, cylindrical body, stairs, minaret balcony and pot, and minaret cone. There has been no experimental study concerning the material properties. In the literature, different material properties are presented for masonry structures [30-35]. From the literature, it can be seen that the modulus of elasticity and material density change within 1.5E9-5.0E9 N/m^2 and 1600-2400 kg/m^3, respectively. The material properties are taken to be similar to the literature. Selected material properties are given in Table 2.

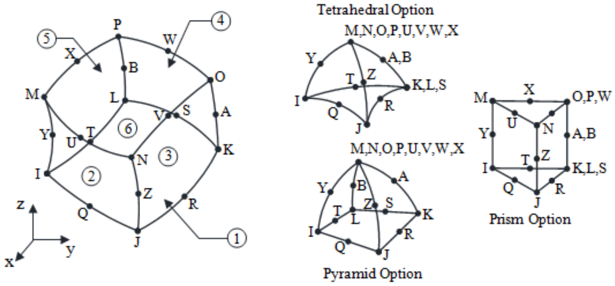


Fig. 5 SOLID186 element [29]

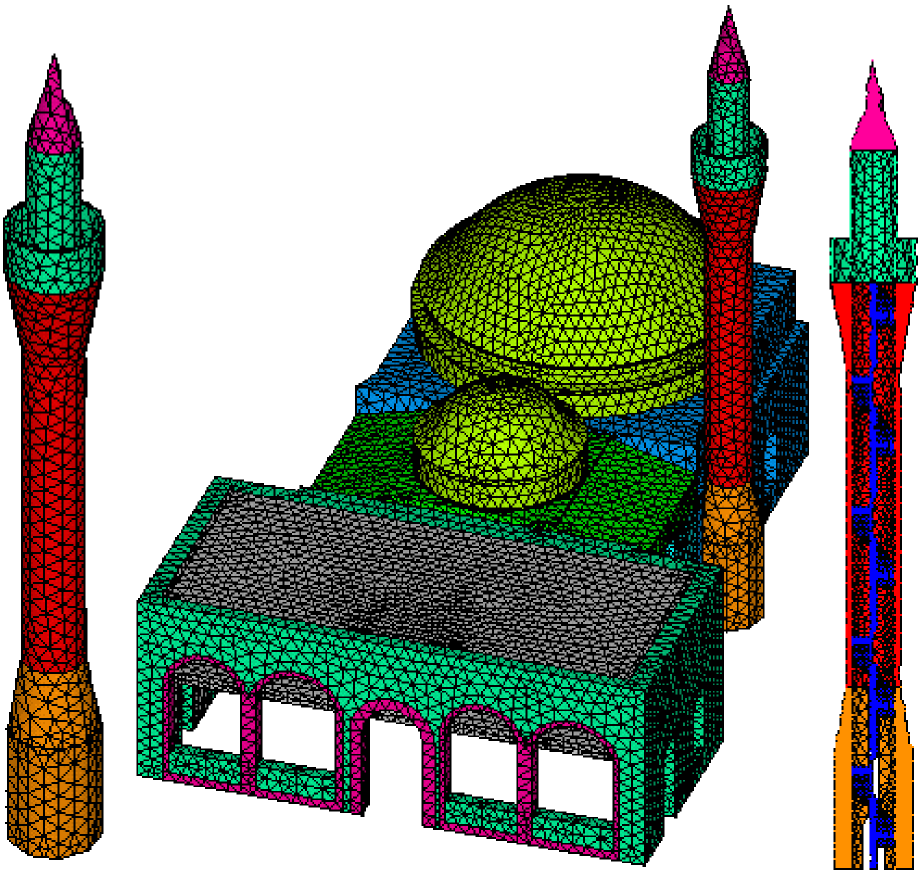


Fig. 6 Views and sections of the finite element model of the mosque and its minaret

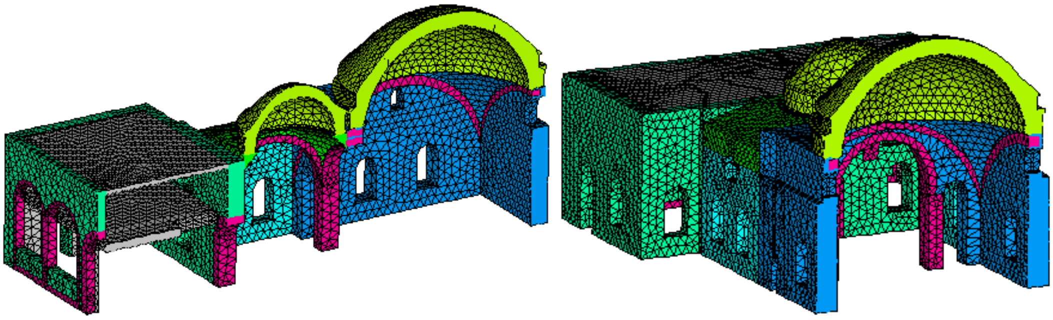
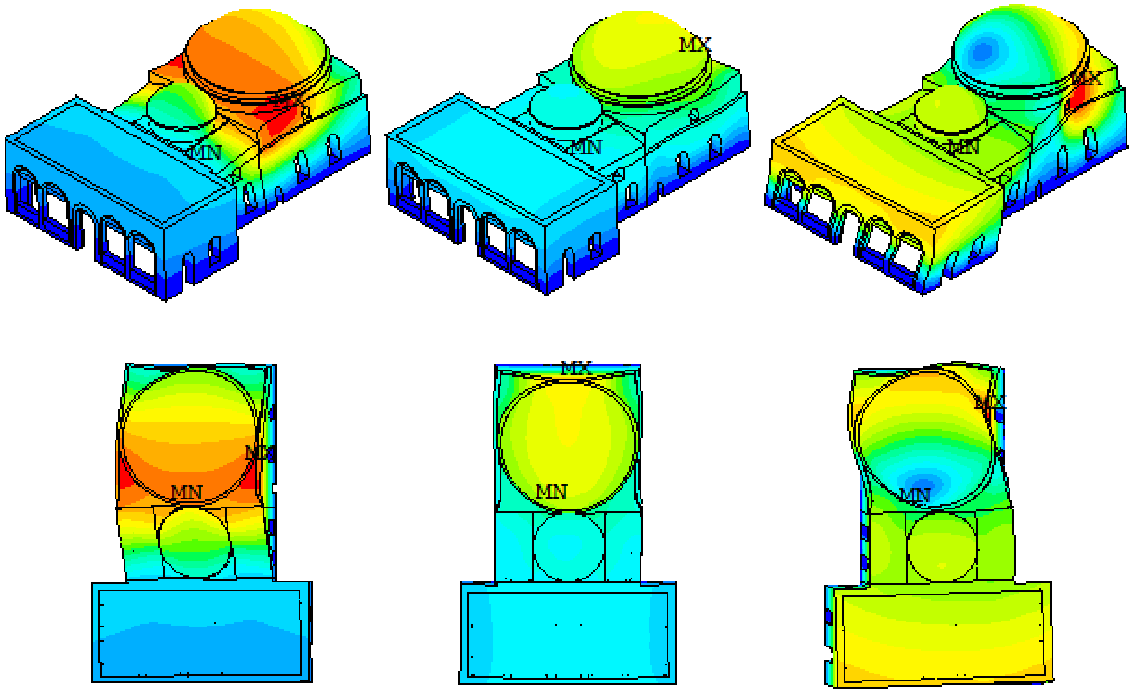


Fig. 6 Continued

Table 2 Linear material properties of the mosque and minaret

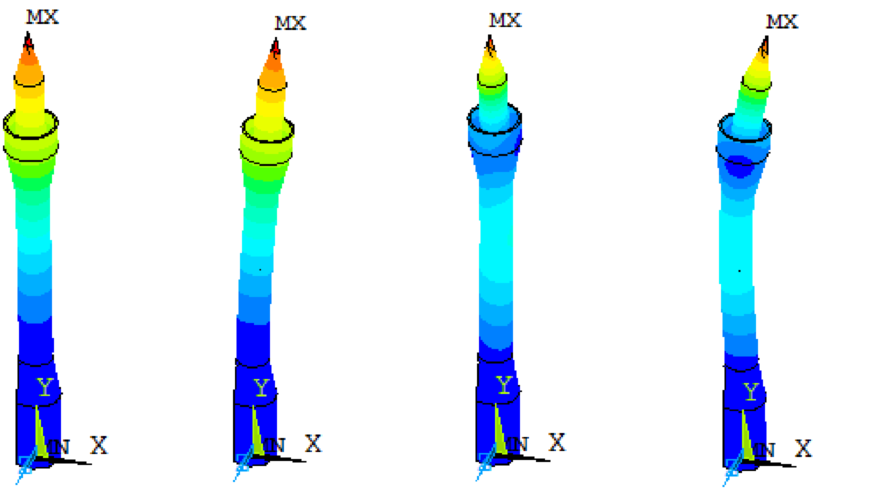
	Elements	Material Properties		
		Modulus of elasticity (N/m^2)	Poisson ratio	Mass density (kg/m^3)
Mosque	Main part walls	2.00E9	0.20	2000
	Middle part walls	2.00E9	0.20	2000
	Last part walls	2.00E9	0.20	2000
	Arches	3.00E9	0.20	2000
	Brick domes	2.00E9	0.20	1600
	Vaults	2.00E9	0.20	1600
	RC elements	2.00E10	0.20	2400
Minaret	Pulpit and transition segment	2.00E9	0.20	2000
	Cylindrical body	2.00E9	0.20	2000
	Stairs	2.00E9	0.20	2000
	Minaret Balcony	2.00E9	0.20	2000
	Minaret cone	1.00E9	0.20	500

The initial numerical dynamic characteristics of the mosque and minaret were obtained with the help of finite element modal analysis. The first three frequencies were obtained in the range of 0.94 Hz to 6.06 Hz for the mosque and the first four frequencies were obtained in the range of 7.79 Hz to 10.05 Hz for the minaret. The mode shapes of the mosque were obtained as transverse, longitudinal, and torsion modes, respectively. The mode shapes of the minaret were obtained as 1st transverse, 1st longitudinal, 2nd transverse, and 2nd longitudinal modes, respectively. The mode shapes of the mosque and minaret are presented in Figure 7. Experimental and numerical natural frequencies are given in Table 3. The maximum difference between the frequencies was obtained as 18.6% for the mosque and 15.2% for the minaret.



Transverse Longitudinal Torsion

(a) Mosque



1st transverse mode 1st longitudinal mode 2nd transverse mode 2nd longitudinal mode

(b) Minaret

Fig. 7 The numerical mode shapes of the mosque and minaret

Table 3 Comparisons of experimental and initial numerical natural frequencies

Mode	Mosque			Minaret		
	Experimental (Hz)	Diff. (%)	Initial Model (Hz)	Experimental (Hz)	Diff. (%)	Initial Model (Hz)
1	7.12	9.4	7.79	1.04	9.6	0.94
2	8.20	18.6	9.73	1.06	11.3	0.94
3	11.02	8.8	10.05	6.40	5.9	6.02
4	-	-	-	7.15	15.2	6.06

2.3. Finite element model updating

It can be seen from Table 3 that there are some differences between the results obtained from numerical and experimental tests. These differences are due to some uncertainties in material properties and boundary conditions. To eliminate these differences (differences≤5 or less) and obtain a more realistic numerical model, the finite element models need to be updated. The update was done manually by trial and error.

In the manual model update, the modulus of elasticity and density of the elements were chosen as the update parameters to minimize the errors between the experimental and numerical frequencies. Table 4 shows the changes in the update parameters before and after the model update. The final numerical frequencies for the manual model update are presented in Table 5. As seen in Table 5, the maximum differences between experimental and numerical frequencies were reduced from 18.6% to 4.9% for the mosque and from 15.2% to 4.8% for the minaret.

Table 4 Change in material properties for manual model update

	Elements	Material Properties					
		Modulus of elasticity (N/m^2)			Material density (kg/m^3)		
		Initial	Diff. (%)	Updated	Initial	Diff. (%)	Updated
Mosque	Main part walls	2.00E9	30.0	1.40E9	2000	10.0	2200
	Middle part walls	2.00E9	30.0	1.40E9	2000	10.0	2200
	Last part walls	2.00E9	75.0	3.50E9	2000	10.0	2200
	Arches	3.00E9	16,6	3.50E9	2000	10.0	2200
	Brick domes	2.00E9	25.0	1.50E9	1600	9.4	1750
	Vaults	2.00E9	25.0	1.50E9	1600	9.4	1750
	RC elements	2.00E10	50.0	3.00E10	2400	-	2400
Minaret	Pulpit and transition segment	2.00E9	50.0	3.00E9	2000	10.0	2200
	Cylindrical body	2.00E9	37.5	2.75E9	2000	-	2000
	Stairs	2.00E9	-	2.00E9	2000	10.0	2200
	Minaret balcony	2.00E9	37.5	2.75E9	2000	-	2000
	Minaret cone	1.00E9	-	1.00E9	500	-	500

Table 5 Comparisons of experimental and updated numerical natural frequencies

Mode	Mosque			Minaret		
	Experimental (Hz)	Diff. (%)	Initial Model (Hz)	Experimental (Hz)	Diff. (%)	Initial Model (Hz)
1	7.12	4.9	7.47	1.04	4.8	1.09
2	8.20	4.9	8.60	1.06	2.8	1.09
3	11.02	2.4	10.75	6.40	4.8	6.71
4	-	-	-	7.15	2.2	6.99

When the update parameters are compared, it has been observed that the modulus of elasticity is more effective. The masonry walls in the mosque structure, which were built at different times, have different material characteristics. The most recently built masonry wall material properties were higher after the update. After the update, the density of the stone walls was obtained as 2200 kg/m^3, the density of the brick vault and the dome was 1750 kg/m^3, and the density of the stone-brick wall in the minaret was 2000 kg/m^3. In such structures, soil conditions can also be used as an update parameter. However, the fact that the historical mosque is 500 years old and there are no cracks in the walls indicates that the mosque was built on very hard soil. Therefore, there is no need to use soil properties to be updated parameters.

3. Conclusions

In this study, a historical masonry mosque and its minaret were investigated. Ambient vibration tests were carried out and experimental dynamic characteristics of the structures were extracted by EFDD method. Also, finite element models of the structures were created. To obtain reliable numerical models, finite element modal updating processes were carried out with the aid of experimental dynamic characteristics.

The following conclusions can be drawn from the study:

1. The experimental natural frequencies were calculated within 7.12 Hz-11.02 Hz and 1.04 Hz-7.15 Hz respectively for the mosque and minaret. In addition, the damping ratios were calculated within 0.26%-1.45% and 0.26-2.43% for mosque and minaret, respectively.
2. Experimental mode shapes of the mosque were obtained as transverse mode, longitudinal mode, and torsional mode. In addition, the modes of the minaret are obtained as 1st transverse mode, 1st longitudinal mode, 2nd transverse mode, and 2nd longitudinal mode, respectively.
3. The initial numerical dynamic characteristics of the mosque and minaret were obtained with the help of finite element modal analysis. The first three frequencies were obtained in the range of 0.94 Hz to 6.06 Hz for the mosque and the first four frequencies were obtained in the range of 7.79 Hz to 10.05 Hz for the minaret.
4. The numerical mode shapes of the mosque were obtained as transverse, longitudinal, and torsion modes, respectively. The numerical mode shapes of the minaret were obtained as 1st transverse, 1st longitudinal, 2nd transverse, and 2nd longitudinal modes, respectively.
5. The maximum difference between experimental and numerical natural frequencies was obtained as 18.6% for the mosque and 15.2% for the minaret.
6. With the aid of making a manual model updating procedure, the differences between experimental and numerical frequencies were reduced from 18.6% to 4.9% for the mosque and from 15.2% to 4.8% for the minaret.
7. Modulus of elasticity and density were selected as update parameters. According to the study, the modulus of elasticity is the most effective update parameter for both structures.

8. After the update, the density of the stone walls was obtained as 2200 kg/m^3, the density of the brick vault and the dome was 1750 kg/m^3, and the density of the stone-brick wall in the minaret was 2000 kg/m^3.
9. In such structures, soil conditions can also be used as an update parameter. However, the fact that the historical mosque is 500 years old and there are no cracks in the walls indicates that the mosque was built on very hard soil. Therefore, the soil properties were not used to be updated parameters.

Finally, historical masonry structures are special structures that need more attention for conservation. Therefore, both nondestructive experimental tests and numerical analysis should be used together to estimate real behavior. Thus, proper interventions would be made for conservation and restoration processes.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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