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In situ dynamic investigation on the historic "İskenderpaşa" masonry mosque with non-destructive testing

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Abstract. Turkey is a transcontinental country located partly in Asia and partly in Europe, and hosted by diverse civilizations including Hittite, Urartu, Lydia, Phrygia, Pontius, Byzantine, Seljuk's and Ottomans. At various times, these built many historic monuments representing the most significant characteristics of their civilizations. Today, these monuments contribute enormously to the esthetic beauty of environment and important to many cities of Turkey in attracting tourism. The survival of these monuments depends on the investigation of structural behavior and implementation of needed repairing and/or strengthening applications. Hence, many countries have made deeper investigations and regulations to assess their monuments' structural behavior. This paper presents the dynamic behavior investigation of a monumental masonry mosque, the "İskenderpaşa Mosque" in Trabzon (Turkey), by performing an experimental examination with non-destructive testing. The dynamic behavior investigation was carried out by determining the dynamic characteristic called as natural frequencies, mode shapes and damping ratios. The experimental dynamic characteristics were extracted by Operational Modal Analysis (OMA). In addition, Finite Element (FE) model of masonry mosque was constructed in ANSYS software and the numerical dynamic characteristics such as natural frequencies and mode shapes were also obtained and compared to experimental ones. The paper aims at presenting the non-destructive testing procedure of a masonry mosque as well as the comparison of experimental and numerical dynamic characteristics obtained from the mosque.

Keywords: ambient vibration testing; dynamics characteristics; historic masonry mosque; non-destructive testing; finite element model

1. Introduction

Historic monuments are the most visible aspects of the civilizations. In addition to their cultural value, historic monuments contribute significantly to esthetic beauty of environment and also important to stimulate the economic activity in regions. These monuments, however, are universally threatened by many deleterious effects such as vandalism, poor maintenance, weathering, soil settlements, man-made and natural phenomena. In some cases, applications intended to preserve, clean, or restore monuments may also cause deleterious effects. These factors, in particular natural phenomena such as earthquakes, are the source of demolishing and destroying of many historic monuments. Their preservation, together with monitoring at regular intervals and structural safety assessment against earthquakes, has become a high concern due to some dramatic events, such as in Italy the sudden collapse of the Civic Tower (Macchi 1993), the abrupt collapse (6 years after the earthquake) of the Dome of the Noto Cathedral (Binda *et al.* 2003, Bartoli *et al.* 2013), Estense Fortress, Cathedral of San Paolo and Modenesi Tower in Italy (Parisi and Augenti 2013), collapse of historic slender towers during 2011 Van earthquake in Turkey (Damcı *et al.* 2015) (Fig. 1).

The prediction of the structural behavior of historic monuments is a complex task (Lourenço 2002) and calls for more attention. This is because of the some properties of the historic structures. Usually, some of salient properties are (Lourenço 2002):

- geometric data and information about the inner core of the structural elements are missing;
- existing damage condition is unknown;
- historical structures have nonhomogeneous material form and there possess large variability of mechanical properties and characterization of the mechanical properties of the materials used is difficult and expensive;
- interventions on historic structures at different times are unknown;
- historic masonry structures are highly vulnerable to seismic actions. This is due to the structure of the masonry which has low tensile strength, and is primarily designed to resist compressive stresses. Hence, they can be easily damaged or even collapsed due to tensile stresses.

The above considerations emphasize the need of specific attention for each historic masonry monuments. Thus, before commencing any structural assessments on historic structures, detail investigation and structural examination should be performed on these structures, including field

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Fig. 1 Photographs of collapsed or heavily damaged historic masonry structures

surveys, in situ tests, experimental measurements and Finite Element (FE) analysis with appropriate model etc. Moreover, transferring existing technology and knowledge to preservation the historic monuments is an inevitable necessity because it is quite difficult to perform the accurate structural assessment (static and dynamic behavior) of the historic monuments due to the all above aspects.

Non-destructive testing methods such as OMA has been commonly used in the last ten years for all types structures, especially historic structures for which dynamic behavior is particularly difficult to understand globally. This method is a powerful tool that identifies the current dynamic behavior by extracting the dynamic characteristics (natural frequencies, mode shapes and damping ratios) from the vibration signals. This method, moreover, is used both continuous monitoring of structural health condition and calibrating of FE analysis results. FE method and OMA method have been widely used to assess the dynamic behavior of historic masonry structures. These were used for historic towers (Gentile and Saisi 2007, Bayraktar *et al.* 2009, D'Ambrisi *et al.* 2012, Bartoli *et al.* 2013, Pieraccini *et al.* 2014, Fragonara *et al.* 2017, Lorenzoni *et al.* 2018), for historic masonry bridges (Sevim *et al.* 2011, Türker 2014, Altunisik *et al.* 2015a, b, Bergamo *et al.* 2015, Rovithis and Pitilakis 2016, Russo 2016, Sayın 2016), and for other types of historic structures (Ramos *et al.* 2010, Atamturktur and Sevim 2011, Votsis *et al.* 2012, Ceroni *et al.* 2014, Altunişik *et al.* 2016a, b, 2017, Cakir *et al.* 2016, Demir *et al.* 2016, Kocatürk and Erdoğan 2016, Karaca *et al.* 2017, Nohutcu *et al.* 2017).

There exists countless historic monuments constructed by different civilizations at various times, can be observed in different regions in Turkey. The historic masonry mosques are distinctive class of masonry monuments and widely disseminated on the Turkey's territory. These structures having an aesthetic appearance and religious value are important for Muslims and used for worship, education and they had even been used as a treatment complex in the past. These structures are of a substantial place in the cultural heritage and require detail structural investigation and preservation so that they are able to hand down to future generations. The preservation of these structures has been stipulated by law; but unfortunately, many rulers and engineers are not aware of the details of issues or various preservation techniques being performed. The applications intended to preserve or restore the historic structures may cause the deleterious effects on the structural safety and original identity. In this paper, non-destructive testing procedure was applied to assess the dynamic behavior of a monumental masonry mosque, the "İskenderpaşa Mosque" in Trabzon, Turkey. The dynamic-based assessment includes the following main steps:

- non-destructive testing (ambient vibration testing);
- extraction of experimental dynamic characteristics (natural frequencies, mode shapes and damping ratios) using Enhanced Frequency Domain Decomposition (EFDD) Method;
- FE analysis for the numerical dynamic characteristics and comparison of experimental and numerical results;
- determination of possible uncertain parameters of the FE model in order to minimize the differences between the experimental and numerical dynamic characteristics.

2. İskenderpaşa Mosque

The monumental masonry mosque under study is located in the city of Trabzon in north-east Turkey. The city has many historic monuments (Sümela Monastery, Hagia Sophia Church and its tower, Atatürk Villa, Zağanos and Tabakhane Bridges, Gülbahar Hatun Mosque, Zağanos Bastion and Armony Building) built by diverse civilizations (Roman, Byzantine and Ottoman) at different times. The İskenderpaşa Mosque is one the most important Ottoman masonry mosques in Trabzon. The available documents in historical records show that the structure was constructed by İskender Pasha, who was one of the governors of Trabzon of the Kanuni era, in 1529. The mosque was constructed with the single unit mosque approach of the Ottoman mosque typology and it was restored expanding with various annexes in different periods. Mosque is a 16th century work of art typified with a single dome settled on stone walls, a smooth minaret made of stone-brick masonry and a last gathering place covered hipped roof (Fig. 2(a)). This typology was preserved its original form until 1874. At that time, the northern wall was removed and replaced with two stone columns, a small dome settled on arches and half-domed vaults and also a last gathering place was added (Fig. 2(b)). After nine years (1882-1883), the last gathering place was demolished and a relatively larger last gathering place was constructed (Fig. 2(c)). The last repairing on the mosque was carried out in 1897 with the expansion of the last gathering place to the present form (Fig. 2(d)) (Tuluk 2007, Açıcı 2017).

Today, İskenderpaşa Mosque is notable for its historical-monumental value and it is still in service to mankind. The mosque, which dates back to sixteen century, consists of a rectangular prayer place (11.16 m × 16.80 m) and a rectangular last gathering place (16.67 m × 7.67 m) adjacent to this place horizontally. The sustaining walls' thicknesses vary between 0.79 m and 1.03 m. The mosque has a great

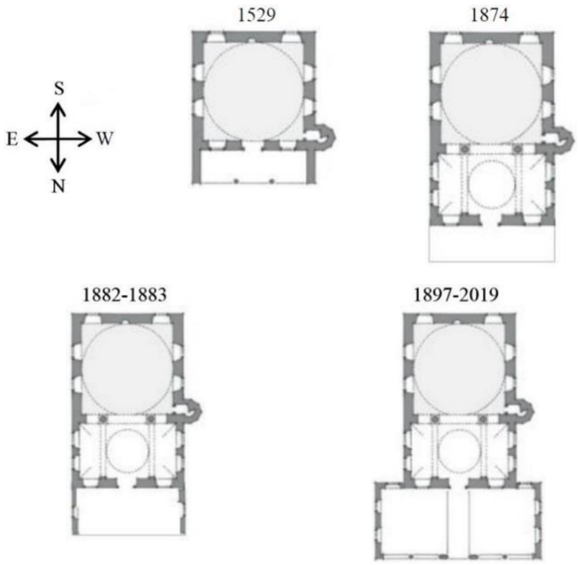


Fig. 2 Physical development stages of Trabzon İskenderpaşa Mosque (Tuluk 2007)

dome with 9.15 m diameter, small dome with 4.44 m diameter and one minaret with 23.23 m height. The minaret is adjacent to western wall of the mosque and the minaret's balcony is accessed through a small door from the prayer place. In addition, there are two and half-domed vaults and two cylindrical columns in the prayer place. Fig. 3 shows the external and internal views of the mosque.

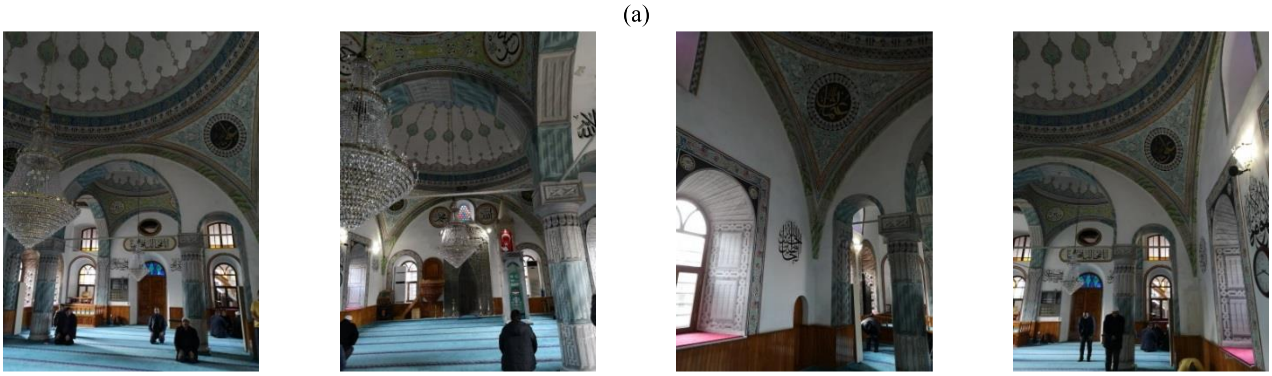
3. Experimental dynamic characteristics

Modal testing is a quite popular method for the identification of data on dynamic characteristics of structures. Two methods, called as Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA) have currently been used to obtain the dynamic characteristics of structures experimentally. In EMA (often called input-output modal identification or force vibration testing), the structures vibrate by a known input force using artificially excited such as impulse hammer, hydraulic shaker, and response of structures measure. In OMA (often called output-only or non-destructive testing), the structures vibrate by an unknown input force using natural excitations such as earthquake, wind, blasting and response of structures measure. This method is therefore also called as Ambient Vibration Testing (AVT). It should be noted that, excitation of structures in operational condition is not cheap and easy, due to their sizes. Hence, the most practical and economical method for the identification of dynamic characteristics is based on the use of the structural response against ambient vibration. In addition, extra equipment is not needed to vibrate the structures and do not require any destruction of the structures under evaluation, this particularly important for historic structures.

The experimental dynamic characteristics (natural frequencies, mode shapes and damping ratios) of the mosque were obtained using AVT. There exists many dynamic characteristics identification methods used for extracting the dynamic characteristics such as the Operating Vectors Method, the Complex Exponential Method, the Polyreference Time Domain Method, the Enhanced Frequency Domain Decomposition (EFDD) and the Stochastic Subspace Identification (SSI) methods. In the study, EFDD in the frequency domain was used. Theoretical background about the methods can be found in the literature (Ewins 1984, Felber 1993, Peeters 2000, Bendat and Piersol 2004, Jacobsen *et al.* 2006, Rainieri *et al.* 2007).

AVT was performed on the mosque to determine the its

(a)



(b)

Fig. 3 External view (a) and internal view (b) of the İskenderpaşa Mosque

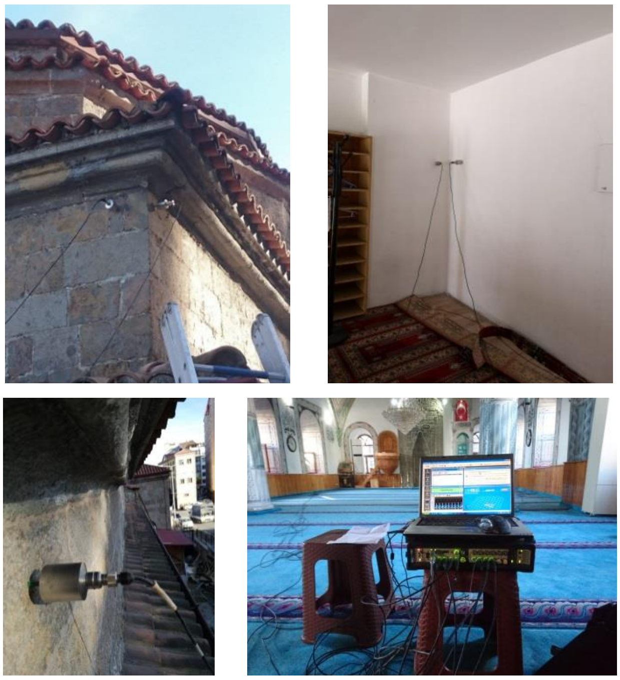


Fig. 4 The accelerometer connections and test equipment

dynamic characteristics experimentally. During the test, a B&K 3560 data acquisition system with 17 channels and B&K 8340-type uni-axial accelerometers having 10V/g sensitivity, uni-axial signal cables, PULSE and OMA software were used as the test equipment. The frequency range was selected as 0-25 Hz and nine accelerometers were located at the top of the mosque (more vibrations occur on the upper part of the structures) in transverse and longitudinal directions (Fig. 4). The accumulated data with B&K 3560 was then transferred into PULSE Labshop software (PULSE 2006) and Operational Modal Analysis software (OMA 2006) for signal processing. The modal parameters were then extracted using the EFDD and SSI methods. Some parameters considered during the measurements are below:

- ➢ measurement time was considered as 30 minutes;
- ➢ frequency span was selected as 0-25 Hz;
- ➢ FFT analyzer for lines and averages were selected as 400 and 100 respectively;
- ➢ multibuffer for sizes and update were considered as 50 and 500 m respectively.

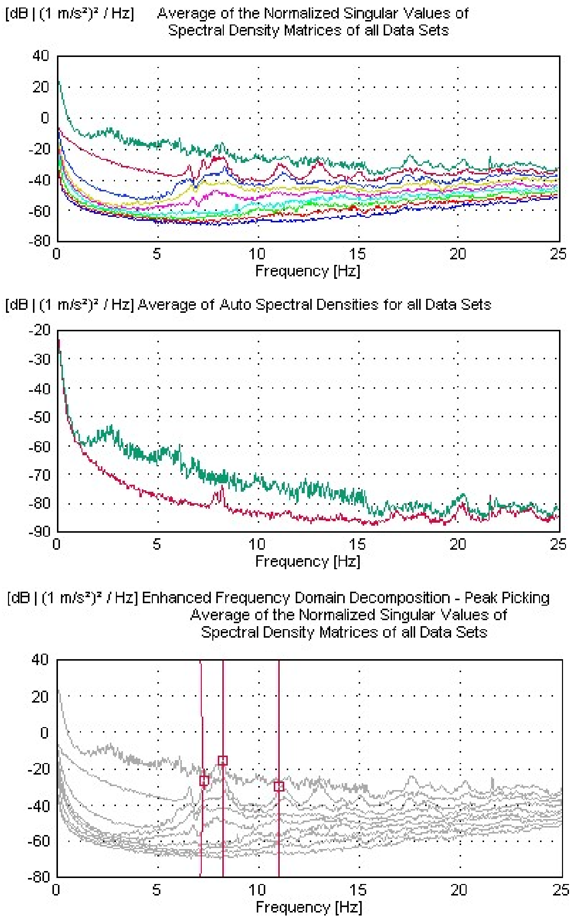
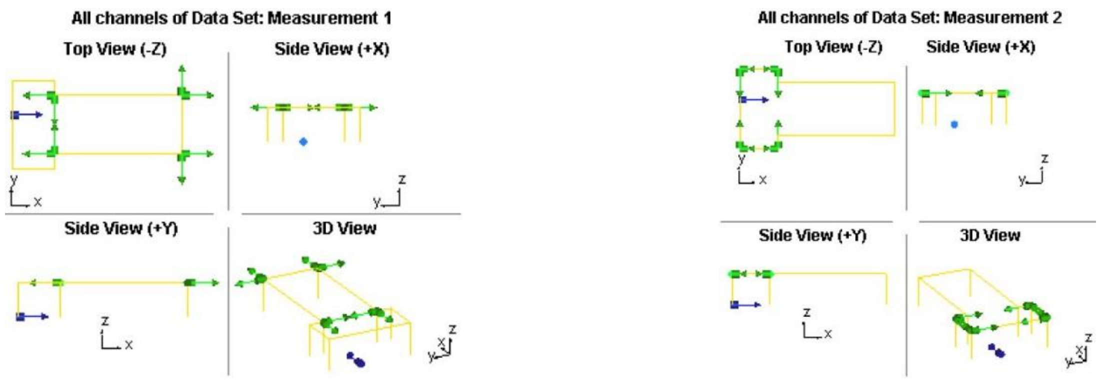


Fig. 6 ANSVSDM, AASD of the data sets, and selected picks from the SVSDM of the data sets obtained using EFDD method for the mosque

In the measurements, nine accelerometers were employed and measurements were carried out during fifteen-minute intervals. Owing to the scarce number of accelerometers and channels in data acquisition system, one of the accelerometers was used as a reference accelerometer.



(a) First step (b) Second step

Fig. 5 Accelerometers layout considered in the AVTs

Eight accelerometers were moved from one place to another and obtained signals from each place were combined through reference accelerometer. The measure-ments of mosque were therefore performed in two separate steps. A representative model generated in PULSE software for the mosque and accelerometers layout, along with their directions, are presented in Fig. 5.

Average of the normalized singular values of spectral density matrices (ANSVSDM) of all data sets, the average of the auto spectral densities (AASD) of the data sets, and selected picks from the singular values of spectral density matrices (SVSDM) of the data sets obtained using EFDD method for the mosque are given in Fig. 6. As shown, the first three natural frequencies are obtained between the 0-25 Hz frequencies range. Also, some sample time histories of acquired signals for the mosque are shown in Fig. 7. Fig. 8 shows the first three mode shapes of the mosque. As shown, the first one is transverse mode, the second is longitudinal mode, and the third is torsional mode.

The experimental dynamic characteristics identified using EFDD method for the mosque is given in Table 1. As shown in Table 1, the natural frequencies and damping ratios were calculated within the range 7.12-11.02 Hz, and 0.265-1.453%, respectively.

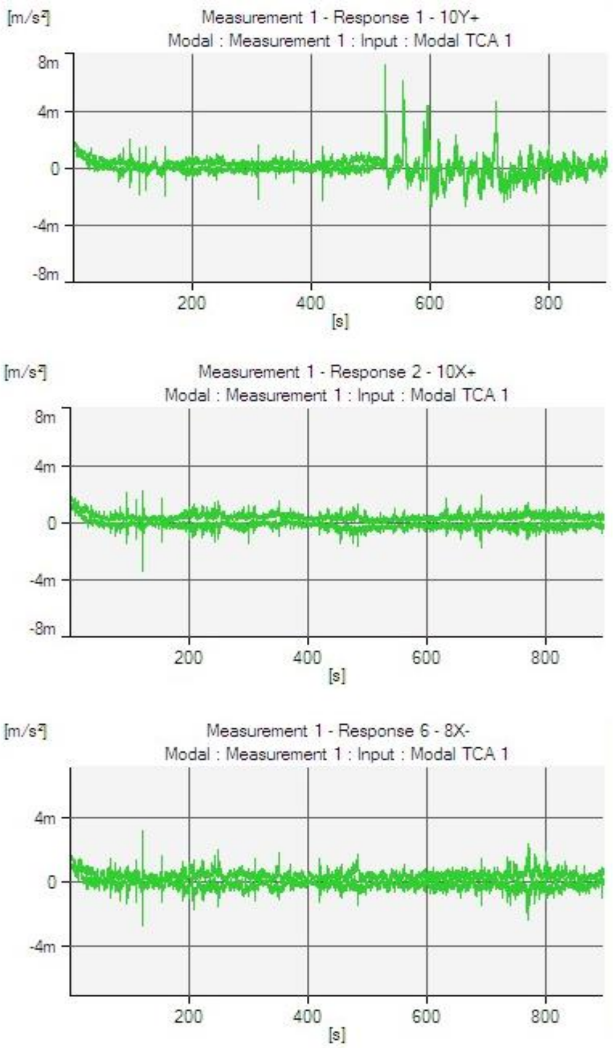


Fig. 7 Some sample time histories of acquired signals

The dynamic characteristics of the İskenderpaşa mosque's minaret were also investigated experimentally and numerically by Bayraktar *et al*. (2011) before repairing and experimentally by Günaydın (2018) after repairing conditions (Table 2). As shown in Table 2, the first seven natural frequencies were obtained within 1.16-15.43 Hz, and 1.04-14.91 Hz for the pre-repair and post repair conditions, respectively. The damping ratios were identified within 0.21-1.04%, and 0.26-2.43% for the pre-repair and post repair conditions.

4. FE model and numerical dynamic characteristics

FE model of the İskenderpaşa Musque was constructed in ANSYS software (ANSYS 2015) taking account of the

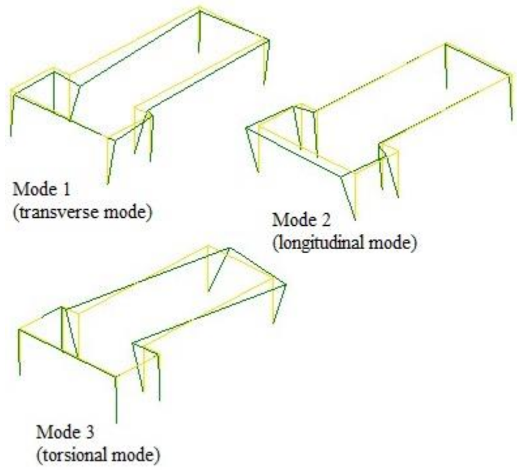


Fig. 8 The first three experimental modes of the mosque

Table 1 Dynamic characteristics of the mosque obtained from the EFDD method

Mode	Frequency (Hz)	Damping Ratio (%)
1	7.12	1.453
2	8.20	0.499
3	11.02	0.265

Table 2 Dynamic characteristics of the İskenderpaşa mosque's minaret presented in literature

Mode	Natural frequencies		Damping ratio (%)	
	Pre-repair	Post-repair	Pre-repair	Post-repair
1	1.16	1.04	0.75	2.43
2	1.24	1.06	0.33	0.93
3	6.30	6.40	0.28	0.26
4	6.35	7.15	0.42	1.03
5	11.41	13.58	0.74	0.61
6	15.02	14.32	1.04	1.93
7	15.43	14.91	0.21	1.21

relievo drawings. For three-dimensional modelling of the mosque, 3-D twenty-node solid element, SOLID186, was used. The element has three degrees of freedom per node, namely translations in nodal x, y and z directions. This 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 features provide easy meshing for models. The supports of the mosque were assumed to be fixed in the model. The FE model of the mosque with its minaret is presented in Fig. 9.

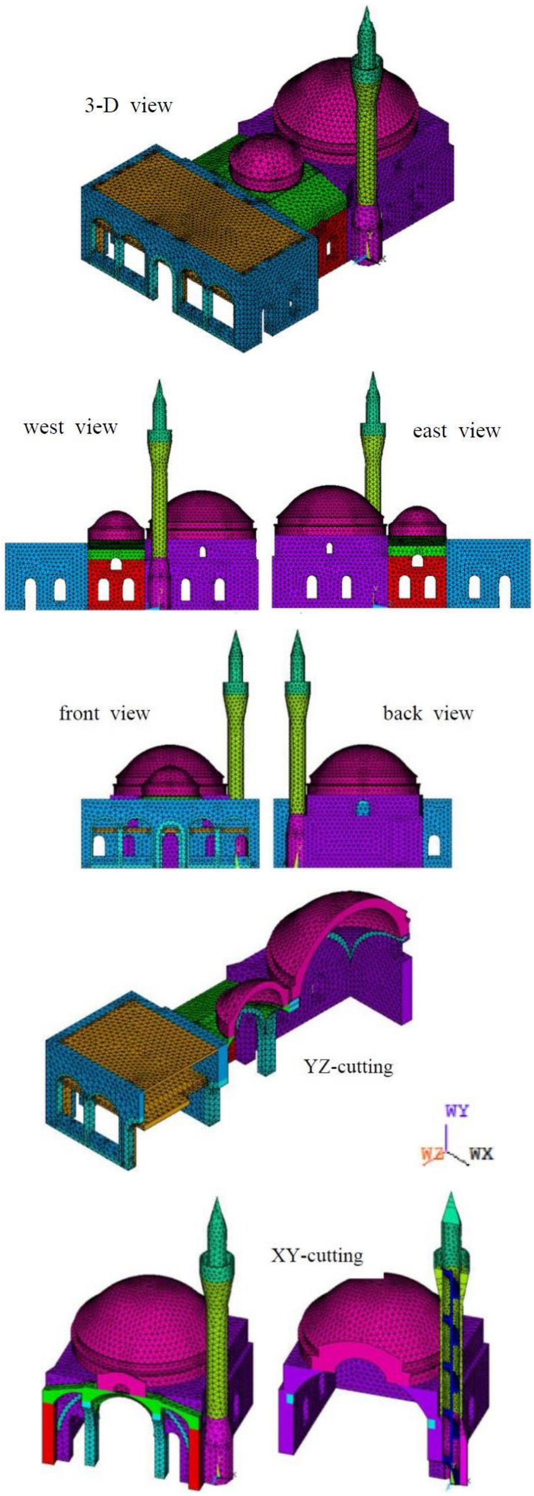


Fig. 9 FE model of the İskenderpaşa Mosque

The mesh range was considered to be 0.45 m. The FE model of the mosque includes 178237 nodes and 102868 solid elements. Five different structural element components exist in the FE model, namely: masonry walls, masonry arches and vault, brick domes, reinforced concrete (RC) annex-elements (columns, beams and floor). In addition, the minaret consists of seven different element components such as pulpit, transition segment, cylindrical body, stairs, minaret-balcony, minaret-pot and spire.

There no exists experimental study related to the material properties of the İskenderpaşa Mosque. The material properties (Table 3) selected for the analyses were taken from the literature (Bayraktar *et al*. 2011, Altunışık *et al*. 2018a, b).

The dynamic characteristics of the mosque were extracted from the FE modal analysis. The first three natural frequencies were obtained as 7.32 Hz, 9.30 Hz and 9.79 Hz, respectively. Mode shapes (Fig. 10) of the mosque obtained as transverse, longitudinal and torsional mode, respectively.

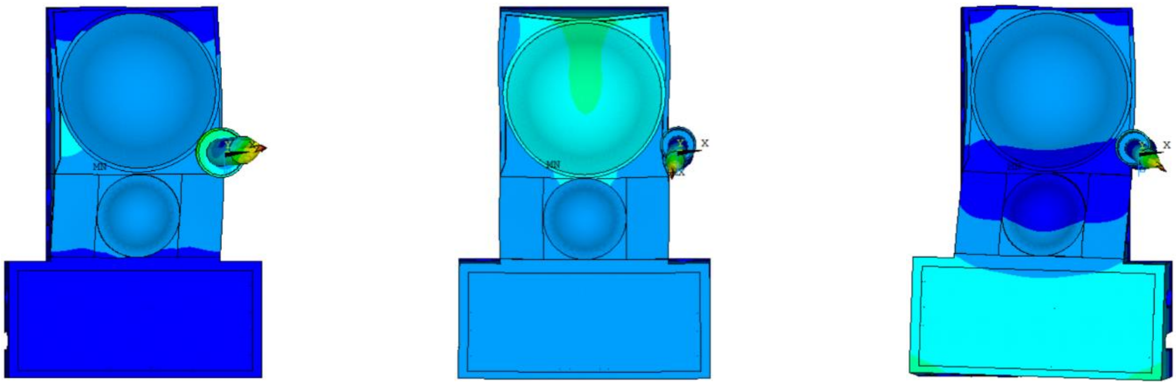
The numerical dynamic characteristics of the İskenderpaşa Mosque minaret were also obtained. The first seven mode shapes and corresponding frequency values are shown in Fig. 11. As shown, the first four modes, sixth and seventh modes were bending modes, and the fifth mode is torsional mode. The first seven frequency values of the minaret were varied in the range from 0.89 Hz to 10.59 Hz.

Table 4 shows the comparison of experimental and numerical natural frequencies for both mosque and its minaret. Despite the material properties were selected from the literature there was not enough correlation between the experimental and numerical natural frequencies, as seen in Table 4. The maximum difference was calculated as 11.83% for the mosque and 45.65% for the mosque's minaret. It is thought that these differences arise from some uncertainties accepted in the FE model. In order to minimize these differences, the FE model must be updated considering the experimental dynamic characteristics taking into account some uncertain parameters.

There generally exists some uncertain parameters affecting the in accuracy of FE model: (a) mathematical equations using in the solution of FE model, (b) meshing sizes, (c) material properties, and (d) boundary conditions. The material properties, in particular, the elasticity modulus of masonry elements is the most uncertain parameter in the FE model updating of the historical masonry structures. This

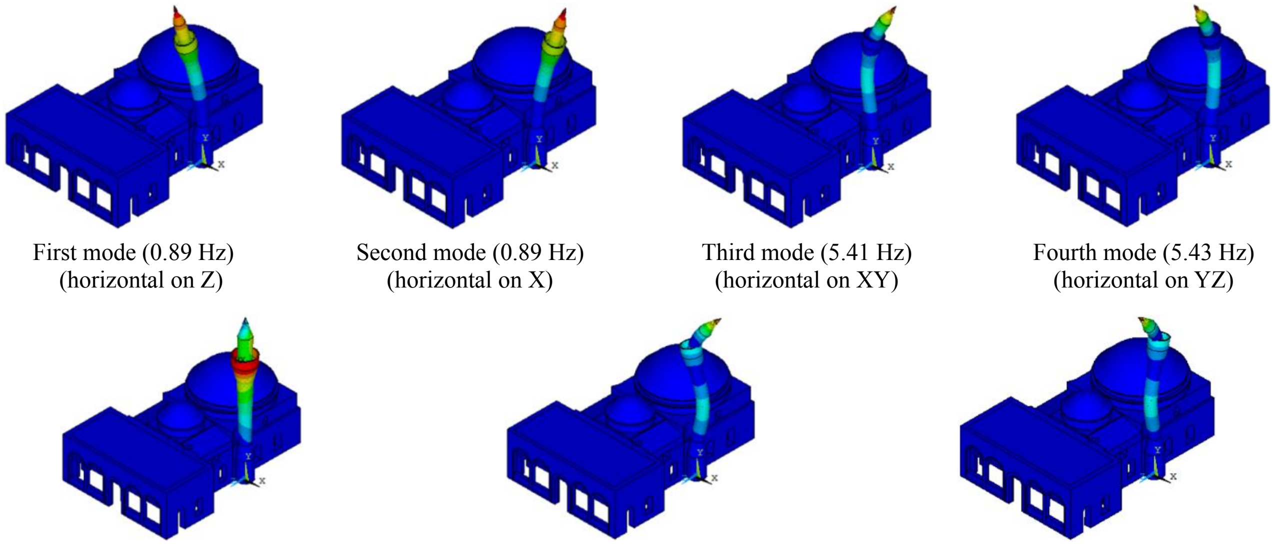
Table 3 Material properties for the FE model

Element	Material properties		
	Elasticity modulus (N/m^2)	Poisson's Ratio	Density (kg/m^3)
Masonry wall	2.00E9	0.2	2200
Masonry arches	2.55E9	0.2	2200
Domes and vault	1.85E9	0.2	1800
RC annex-elements	3E10	0.2	2400
Minarat's elements	1.85E9	0.2	1900
Minaret's spire	2.90E8	0.2	900



Mode 1 (transverse mode) Mode 2 (longitudinal mode) Mode 3 (torsional mode)

Fig. 10 The first three numerical modes of the mosque



First mode (0.89 Hz) (horizontal on Z)
Second mode (0.89 Hz) (horizontal on X)
Third mode (5.41 Hz) (horizontal on XY)
Fourth mode (5.43 Hz) (horizontal on YZ)
Fifth mode (7.38 Hz) (torsional)
Sixth mode (10.54 Hz) (horizontal on XY)
Seventh mode (10.59 Hz) (horizontal on YZ)

Fig. 11 First seven numerical mode shapes of the İskenderpaşa Mosque minaret

Table 4 Comparison of experimental and numerical calculated natural frequencies

Mode	Mosque			Minaret		
	Experimental (Hz)	*Diff. (%)*	Numerical (Hz)	Experimental (Hz)	*Diff. (%)*	Numerical (Hz)
1	7.12	*2.73*	7.32	1.04	*14.42*	0.89
2	8.20	*11.83*	9.30	1.06	*16.03*	0.89
3	11.02	*11.16*	9.79	6.40	*15.46*	5.41
4	-	-	-	7.15	*24.05*	5.43
5	-	-	-	13.58	*45.65*	7.38
6	-	-	-	14.32	*26.39*	10.54
7	-	-	-	14.91	*28.97*	10.59

is because of the non-homogeneity form of the material properties. In order to obtain the further correlation (differences $\leq$ 5 or less) between the experimentally and numerically natural frequencies extracted from the İskenderpaşa Mosque and its minaret the following steps may be helpful: (1) the elasticity modulus and density values can be considered to be not uniform in each masonry wall due to different construction periods and aging effects, (2) the material properties of the RC annex elements, arches, domes and vaults can be reduced or increased, (3) the interaction between structural elements can be checked, and (4) the elasticity modulus and density values can be take into account to be not uniform for the mosque's minaret.

5. Conclusions

Experimental and numerical dynamic behavior investigation of a monumental historic masonry mosque is described in the paper. The following conclusions can be drawn from the study:

- the investigation of dynamic behavior to the ambient levels of vibration has proved to be an effective means for the identification of the experimental dynamic characteristics of masonry mosque and its minaret;
- within the frequency span 0-25 Hz, the first three modes and the first seven modes were clearly extracted for the mosque and its minaret respectively;
- the first three experimental frequencies and corresponding damping ratios were obtained between 7.12-11.02 Hz and 0.265-1.453% respectively for the mosque. In addition, the first seven natural frequencies and corresponding damping ratios were presented in the literature within 1.04-14.91 Hz and 0.26-1.93% respectively for the minaret;
- the first three numerical frequencies were obtained between 7.32-9.79 Hz for the mosque. Maximum difference between the experimental and numerical frequencies was obtained as 11.83%. However the experimental and numerical mode shapes were the similar and obtained as transverse, longitudinal and torsional;
- the first seven numerical frequencies were calculated within 0.89-10.59 Hz for the minaret. Maximum difference between the experimental and numerical frequencies was obtained as 45.65%;
- the comparison of experimental and numerical dynamic characteristics highlighted the necessity of FE model updating procedure, consequently, the updating requirement for the FE model raised;
- the results from this study will enable to assess the dynamic behavior of İskenderpaşa Mosque and help to create a more accurate FE model for the mosque.

Historic masonry monuments are an important part of cultural heritage, and must be protected against deleterious effects such as vandalism, poor maintenance, weathering, man-made, natural phenomena, and particularly seismic ones. Determining the structural behavior of these structures against seismic actions such as earthquake is quite difficult and calls for more attention. This is because of the some complex properties of the historic structures listed above. Accordingly, before commencing any structural assessments on historic structures, detail investigation and structural examination should be performed on these structures, including field surveys, in situ tests, experimental measurements and FE analysis with appropriate model. OMA method has been commonly used for all types structures, particularly historic structures for which dynamic behavior is especially difficult to understand globally. This method is a powerful tool that identifies the current dynamic behavior by extracting the dynamic characteristics, and additionally is used both continuous monitoring of structural health condition and calibrating of numerical results. The conclusion of the study strongly suggests that the OMA method must be practiced on the historic structures to obtain the current dynamic behavior and accurate FE model.

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