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Investigation of the structural performance of a masonry domed mosque by experimental tests and numerical analysis

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Abstract. Historical masonry mosques are the most important structures of Islamic societies. To estimate the static and dynamic behavior of these historical structures, an examination of their restoration studies is very important. In this study, Kara Mustafa Pasha Mosque, which was built as a domed mosque by Kara Mustafa Pasha between 1666-1667 in Amasya, Turkey, has been analyzed. This study investigates the structural behavior and architectural features of the mosque. In order to determine specific mechanical properties, compression and three-point bending tests were conducted on materials, which have similar age and show similar properties as the examined mosque. Additionally, a three-dimensional finite element model of the mosque was developed and the structural responses were investigated through static and dynamic analyses. The results of the analyses were focused on the stresses and displacements. The experimental test results indicate that the construction materials have greatly retained their mechanical properties over the centuries. The obtained maximum compression and tensile stresses from the analyses have been determined as smaller than the materials' strengths. However, the stresses calculated from dynamic analysis might cause structural problems in terms of tensile stresses.

Keywords: masonry mosque; finite element model; experimental tests; static analysis; time history analysis

1. Introduction

Masonry mosques are regarded as the best structural examples of Islamic architecture in the world. They are typically built in the center of settlements since they are gigantic and magnificent in respect to the surrounding structures. Initially, mosques were built with simple methods and shapes. Ancient masonry mosques were constructed as small and low forms with columns and beams. Large columns divided the interior sections of mosques; however, these caused some problems in terms of the structural integrity and the usage of large spans. With the advancement of

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architecture and engineering, construction methods for masonry mosques began to change. The significant change in the construction of mosques was the use of arches and great domes instead of simple columns and beams. The domes proposed an efficient method of spanning over large openings and had been used in place of the simple beams. The use of domes was truly a great achievement since the arches force the sandstones and bricks to resist compression and prevent the materials from being exposed to the tensile stress effects. Therefore, great domes became the main element of the masonry mosques.

Masonry domed mosques are very complex with respect to their structural behavior and seismic resistance. Thus, they require strict construction standards and advanced engineering. Nowadays, different sizes, styles, and materials may be used for domes depending on the mosque's size, style, and structural conditions. It is imperative to identify various types of domes and their structural capabilities. In order to determine the structural protection requirements for these structures, a better understanding of their behavior and structural integrities is needed. These structures should be protected and preserved for the next generations since they are part of the cultural heritage.

Earthquakes have tested the performance of these historical mosques for centuries. These mosques, which are still stable even today, are good examples of structural stability. However, there are cases of damaged mosques in which the minarets are identified as the most vulnerable elements (Kiyono and Kalantari 2004, Bayraktar *et al.* 2007, Seker 2011, Dogangun and Sezen 2012, Milani 2013). By means of advanced engineering and computer technology, the structural analyses of historical mosques and the determination of their structural behavior have been more easily performed to determine design and safety requirements. The proper definition of the structural behavior and failure reasons of these structures are the most important step in terms of restoration and retrofitting. Thus, the structural behavior and seismic performance of different style masonry structures have been investigated by several researchers (Lourenco 2002, Kiyono and Kalantari 2004, Toker and Unay 2004, Bayraktar *et al.* 2007, Dogangun *et al.* 2008, Aras *et al.* 2011, Votsis *et al.* 2012, Oliveira *et al.* 2012, Ural *et al.* 2012, Milani 2013, Uysal and Cakir 2013) . However, researchers have rarely investigated domed mosques and the inherent complexities (Camlibel 1998, Krestevska *et al.* 2007, Seker 2011). Kara Mustafa Pasha Mosque, which is a domed mosque, is the focus of this study. This mosque is located in the county of Merzifon-Amasya in Turkey. Owing to its historical significance, this paper mainly focuses on material properties and structural performance of Kara Mustafa Pasha Mosque. In this aspect, compression and three-point bending tests on the construction materials were conducted and a three-dimensional finite element model of the mosque was developed, to investigate the structural performance of the mosque.

2. Kara Mustafa Pasha Mosque

2.1 General description

Amasya is located in the Central Black Sea Region of Turkey and it is one of the oldest settlements in the Anatolia. Amasya has a magnificent history that goes back to the Hittites civilization (Menc 2000). It has been a loyal host to several civilizations and cultures. Amasya has numerous valuable historical monuments and structures. One of the most notable examples of these cultural heritages is Kara Mustafa Pasha Mosque, one of the most remarkable historical structures in Merzifon, which is the largest county of Amasya.

Many historical structures in Turkey have been built in honor of former Sultans and Pashas. Kara Mustafa Pasha Mosque is one of them. Kara Mustafa was a very famous Pasha in the Ottoman Empire and he was born in Merzifon, Amasya. When he was a grand vizier in the Ottoman Empire, the Kara Mustafa Pasha Complex was constructed in Merzifon. It consisted of the mosque, fountain, library, and some buildings to be used as a seminary. The complex was constructed between 1666 and 1667. Nowadays, many parts of the complex are still standing and are considered as the most important historical heritages in Merzifon, Amasya (Menc 2000).

2.2 Architectural properties of the mosque

The mosque, as the biggest structure of the complex, is located at the center of the complex and is a quite plain domed structure (GPS: N 40.87250 - E 035.46487). The Google Earth view of the Mosque is presented in Fig. 1 and the southwest view is shown in Fig. 2. The mosque has a rectangular shaped plan and a hemisphere covered by the great dome. The great dome stands on four sandstone columns. The dome is 8 meters in height and 16 meters in width. The transition from the hemisphere dome to the rectangular plan is achieved by tromps. All structural loads are transferred to the main walls via tromps. Thus, it is considered that the tromps strengthen the stability of the dome (Cerkez 2005). The main walls of the mosque have a square plan (17 meters x 17 meters). There are rectangular windows with sandstone frames on all of main walls (Fig. 3). The interior section of the mosque is illuminated by these windows as seen in Fig. 4. Fig. 4 also presents several internal and external views of the mosque. Additionally, the interior part of the mosque extends through the north side that contains the entrance of the mosque. The mosque has a minaret on the western side. The minaret rises as a slender form on a square base.

Fig. 1 Location of Kara Mustafa Pasha Mosque (Edited from Google Maps 2013)

Fig. 2 South-West view of Kara Mustafa Pasha Mosque

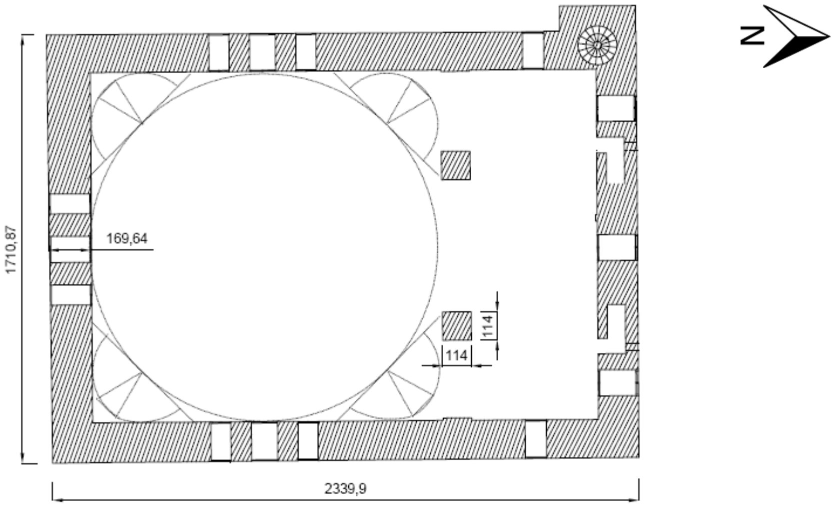


Fig. 3 Drawings of the Kara Mustafa Pasha Mosque complex (by HusamettinYelken)

(a) South-West corner

(b) South wall

Fig. 4 Interior views of the mosque

(c) East wall

(d) North wall (entrance)

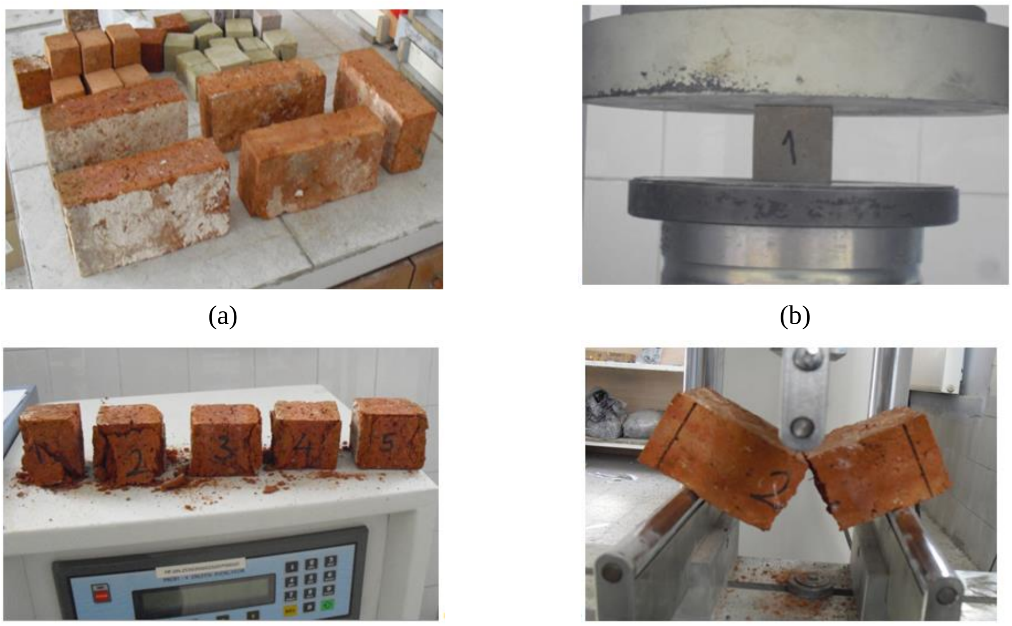
Fig. 4 Continued

2.3 Experimental tests of the materials

Masonry structures that existed in this region and which were built in the same period had the same construction materials and the same workmanship (Karaesmen 2008, Cakir 2011). The use of materials for historical constructions depends on their local availability. Sandstones, limestones, and bricks have been the most commonly used materials in masonry structures in Anatolia because of their availability, high strength, and softness. Among those, the principal materials of the masonry structures in Turkey are stones and handmade bricks. When the Kara Mustafa Pasha Mosque was examined, it has been determined that the dominant construction materials are yellow color cutting sandstones and handmade bricks.

However, it is quite difficult to determine the mechanical properties of the materials used in the historical masonry structures. The use of several different materials affects the exact determination of the material properties in historical structures. In this study, several experimental tests were conducted to determine the mechanical properties of the sandstone and bricks of the mosque. The mechanical properties of sandstones and bricks were obtained by testing the samples at the laboratories of Department of Civil Engineering at Ataturk University and Erzurum Regional Division of Highway. The sandstone and brick samples have been taken from Sofular Mosque, which was built in 1502, in Amasya, Turkey. The materials taken as samples are yellow cutting sandstones and handmade bricks which are also the materials used in Kara Mustafa Pasha Mosque. The materials used in both structures are of the same period and they are used in the same city. Thus, it is assumed that the test on the materials might be considered as representative of the behavior of all the sandstones and bricks in the structure. For the mechanical properties of sandstones and bricks, prisms specimens of 50 mm× 50 mm× 50 mm and 50 mm × 100 mm × 200 mm were prepared for the tests (Fig. 5(a)). The compressive strength of the sandstone and brick samples were obtained from compression tests on 5 cubes according to TS 699, Turkish Building Code (Table 1 and Table 2) (TS 699:2009). The bending strength of the material samples was obtained from three-point bending tests on 5 prisms (50 mm × 100 mm × 200 mm) according to TS EN 1467 and 1469, Turkish Building Codes (Table 3 and Table 4) (TS EN 1467:2012, TS EN 1469).

The compressive strength values of sandstones varied between 43.96 MPa and 57.19 MPa. From the compression tests, the average compressive strength obtained for sandstones was determined as 50.92 MPa. The tensile strength generally varied between 7.45 MPa and 7.61 MPa. The average of the tensile strength value was found to be as 7.55 MPa. With regards to handmade



(a) (b) (c) (d)

Fig. 5 (a) Masonry specimens, (b) compressive test, (c) typical failure patterns and (d) three-point bending tests

Table 1 Compressive test results for the sandstones

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density, in kg/m^3	Failure Load (kN)	Compressive Strength (MPa)
1	50	49	51	2469	140.13	57.19
2	51	50	50	2434	118.96	46.65
3	50	50	51	2341	109.91	43.96
4	50	50	50	2415	128.87	51.55
5	49	50	50	2389	135.35	55.24

Table 2 Compressive test results for the handmade bricks

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density, in kg/m^3	Failure Load (kN)	Compressive Strength (MPa)
1	51	50	49	1936	42.32	16.59
2	51	51	50	2125	49.11	18.88
3	50	50	51	2156	48.31	19.32
4	50	50	50	1964	39.63	15.85
5	51	50	50	2090	42.89	16.74

bricks, the compressive strength values of handmade bricks ranged from 15.85 MPa to 19.32 MPa and the average compressive strength was determined as 17.49 MPa. The tensile strength varied

Table 3 Three point bending test results for the sandstones

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density, in kg/m^3	Failure Load (kN)	Tensile Strength (MPa)
1	50	201	100	2229	7.92	7.61
2	51	200	100	2336	7.82	7.50
3	50	201	99	2141	7.77	7.45
4	50	200	101	2458	7.92	7.60
5	49	200	100	2372	7.90	7.58

Table 4 Three point bending test results for the handmade bricks

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density, in kg/m^3	Failure Load (kN)	Tensile Strength (MPa)
1	50	200	101	1906	2.81	2.70
2	51	200	100	2173	2.74	2.64
3	50	201	100	2006	2.93	2.82
4	50	200	101	1947	2.76	2.65
5	49	200	100	2068	2.75	2.65

between 2.64 MPa and 2.82 MPa and the average tensile strength obtained was 2.69 MPa. According to the Turkish Earthquake Code (TEC 2007), modulus of elasticity (Ed) for masonry units can be calculated by $Ed = 200f_d$, where f_d is the average compressive strength of masonry units. The equivalent values of density for the construction materials are determined by the means obtained from ten specimens test. In addition, in the scope of this study, linear elastic material behavior is considered and the stiffness degradation is ignored. The mechanical properties used in all numerical analyses are summarized in Table 5.

Table 5 The mechanical properties of the materials

Mosque Components	Young modulus (N/m^2)	Poisson's ratios	Density (kg/m^3)	Average compressive strength (MPa)	Average tensile strength (MPa)
Walls, Columns, Arches (Sandstone)	10.18E+9	0.17	2358	50.92	7.55
Main dome (Brick)	3.49E+9	0.15	2037	17.49	2.69

3. Finite element model and analyses

3.1 Numerical model

The determination of the seismic behavior of historical structures is difficult to obtain by the use of common engineering methods. Masonry structures are composed of sub units that have different shapes and materials, which have different properties. In this case, the finite element analyses (FEA) is the most preferred method for masonry structures. Thus, the estimation of static and dynamic behavior of historical structures with finite element method has been one of the most preferred methods recently. Three-dimensional finite element model has been conducted for the mosque investigated in the context of this study. In this scope, FEA program, ANSYS Workbench, has been used to analyze the mosque with SOLID186 elements, which has 20 nodes and three degrees of freedom per node. The three-dimensional model is consisted of 67047 nodes and 35575 solid elements (Fig. 6). Since the minaret is independent of the main part of the mosque, the minaret has not been included in the numerical model.

In the previous studies, Landolfo *et al.* (2007) constructed a mosque, which is located in Macedonia by 1:6 ratios in the laboratory, and they conducted several retrofitting tests on the constructed model by ensuring the accuracy of the laboratory test results with the numerical analyses. Moreover, Dogangun *et al.* (2008) conducted several analyses by making use of ANSYS software to determine the damage to the masonry minarets and they identified that the damage considered by the software comply with the damage determined with the use of finite element method. Betti and Vignoli (2008) designed the finite element model of the Romanesque church to observe the earthquake effects on the structure and they ensured the accuracy of the damage to the structure by the numeric analyses. Thus, this approach is considered as an efficient method to conduct proper performance analyses of the historical structures.

The static and dynamic analyses were performed on the numerical model. The obtained analyses results were too complicated to present each node or element and therefore, contour pictures, bars and scale tables were used to present analyses' results. In the following sections, the static and dynamic analyses are investigated and discussed with analyses' results.

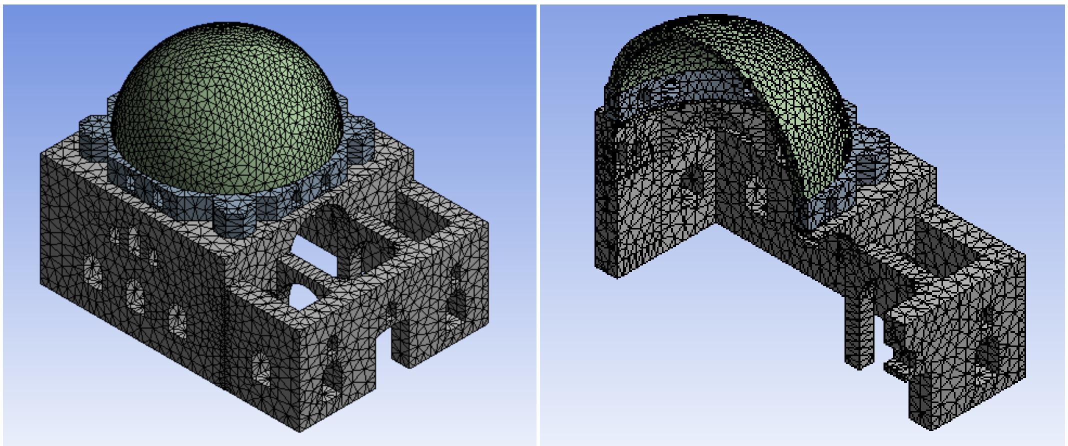


Fig. 6 The three dimensional finite element model of Kara Mustafa Pasha Mosque

3.2 Static analysis

Masonry structures have generally large masses due to the heavy construction materials such as stones, bricks, and mortars. Self-weight loads consist of own weight of the structural components and the weight of permanently attached objects. Thus, self-weight of masonry structures is an

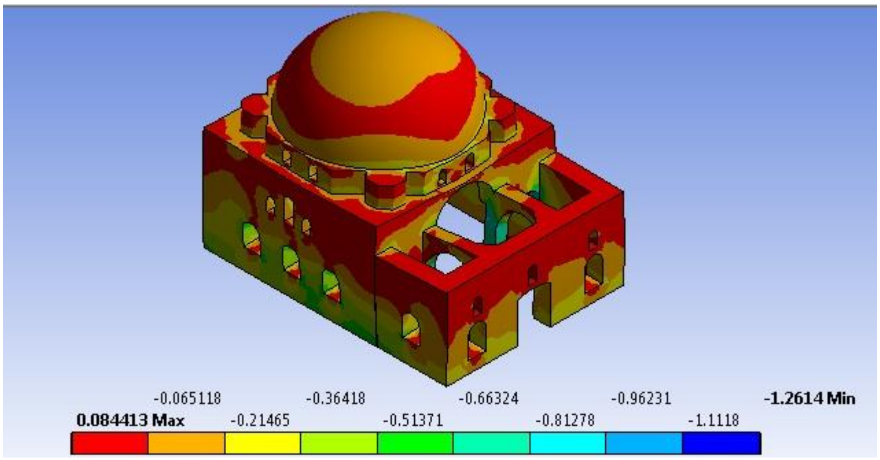


Fig. 7 The maximum compression stress contours for the mosque (MPa)

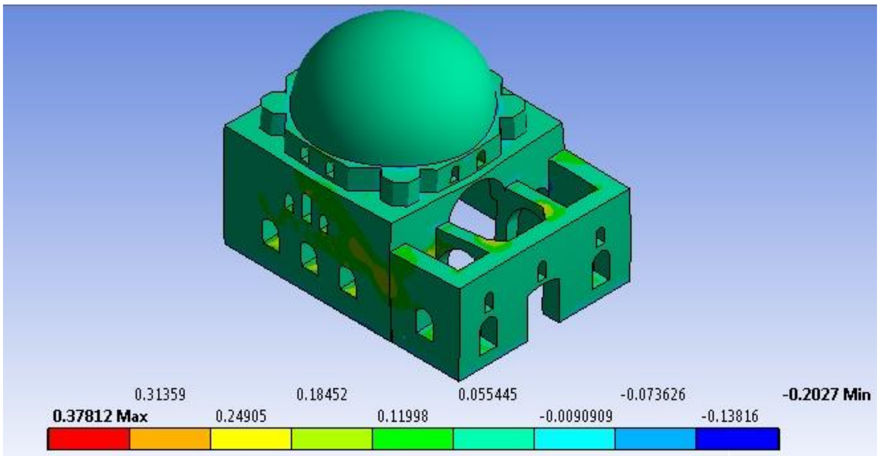


Fig. 8 The maximum tensile stress contours for the mosque (MPa)

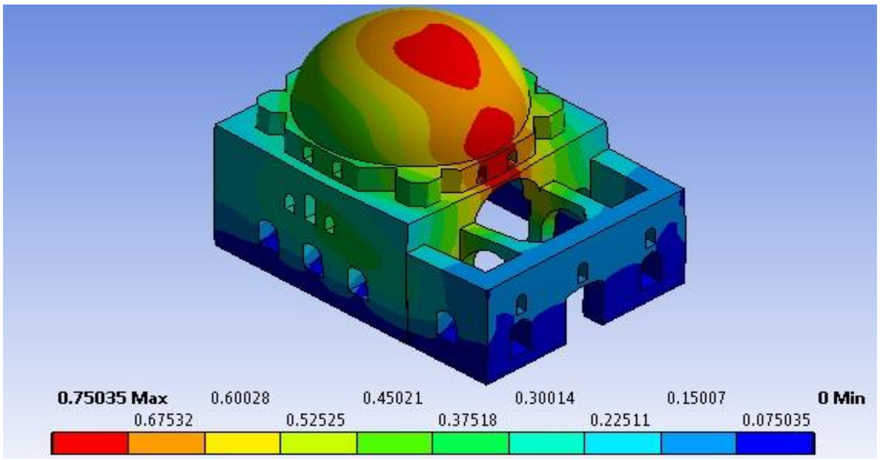


Fig. 9 The vertical displacement contours for the mosque (mm)

important parameter for these type structures (Karaesmen 2008, Camlibel 1998). Therefore, Kara Mustafa Pasha Mosque has been primarily performed by its self-weight in the static analysis. Maximum compression stresses were calculated about 1.26 MPa and it is observed that they have occurred at the base of the columns as compressions (Fig. 7). Additionally, the maximum tensile stresses were found to be about 0.38 MPa and occurred above the top of the arch at the entrance of the mosque and the edges of the windows (Fig. 8). Furthermore, maximum displacements have occurred at the top of the dome and are found to be about 0.75 mm (Fig. 9).

3.3 Modal analysis

The modal analysis is primarily used for the seismic analyses of the investigated mosque. Modal analysis of the structure includes the combination of different modes of vibrations. In the combination, the Square-Root-of-Sum-of-Squares (SRSS) method is considered for 30 modes (Fig. 10). According to the obtained modal analysis results, it has been determined that the mosque is adequately rigid in terms of seismic demands; however, first section at the entrance of the mosque and the upper parts of the entrance walls (transition zones) are the most precarious parts according to the modal analysis. For the first four modes, frequencies, periods, cumulative mass participation factors and mode shapes (calculated from the modal analysis) are presented in Table 6 and Fig. 11. According to data presented in Table 6, it is shown that the first period is around 0.15 s and the period is below 0.1 in the second mode. This result proves that the mosque investigated in this

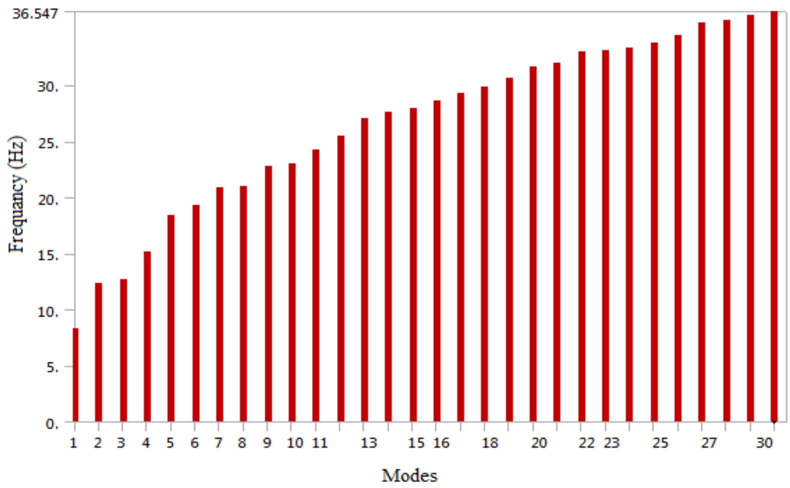


Fig. 10 Mode frequencies

Table 6 First four mode frequencies, periods and ratio eff. mass to total mass for x and y

Mode Number	Frequency (Hz)	Period (s)	Ratio Eff. Mass To Total Mass X Direction	Ratio Eff. Mass To Total Mass Y Direction
1	8.29	0.12	0.38E-05	0.15E-09
2	12.31	0.08	0.35	0.926E-03
3	12.63	0.08	0.29	0.25E-02
4	15.12	0.07	0.68E-05	0.11E-05

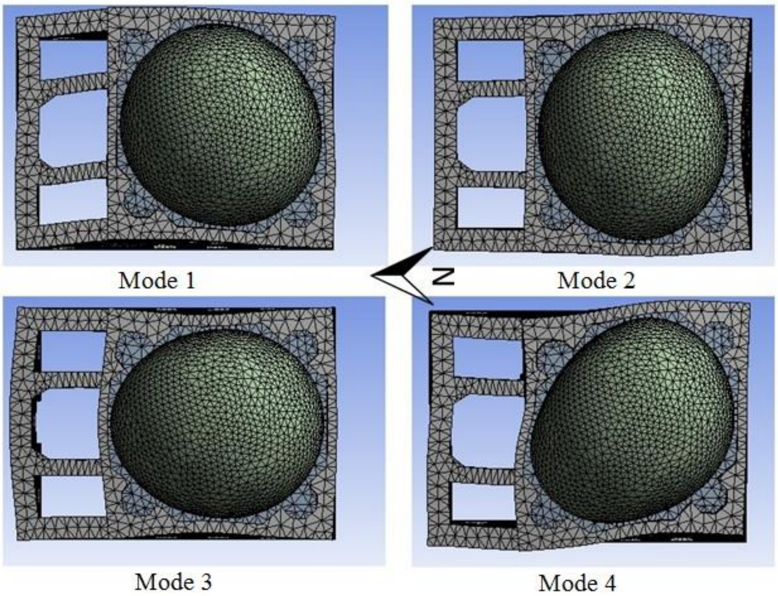


Fig. 11 Mode shapes of the first four modes

paper shows a more rigid behavior than the other type of structures that are widely examined in the literature. In concrete structures, the period value increases with respect to the number of floors constituting a ratio of 1 over 10. For example, the first period of a reinforced concrete structure which has three floors frame system and 9 m height is considered to be around 0.3 s.

3.4 Time history analysis

Masonry structures are vulnerable to earthquakes and seismic effects, which are most common reasons for collapse in masonry structures. Therefore, it is very crucial to determine the earthquake performance of the masonry structures located in the active seismic zones. According to Turkish Disaster and Emergency Management Presidency, Merzifon is settled in a first-degree (the most dangerous) earthquake prone zone in which maximum ground acceleration is assumed as 0.4 g (AFAD 2013). Therefore, earthquakes are considered to be the most important threats for the historical structures such as Kara Mustafa Pasha Mosque. A recent research showed that the horizontal waves have more dangerous effects than the vertical waves on masonry structures; and many ancient and new masonry structures have been destroyed due to horizontal waves so far (Meyer 2006). Therefore, in this study, the horizontal ground motions records (N-S) of Kocaeli earthquake on August 17, 1999, which is one of the strongest earthquakes in Turkey with a magnitude of 7.4, were taken into consideration. The acceleration records of Kocaeli earthquake at Duzce station are presented on Fig. 12.

The double arched entrance of the mosque, which has less rigidity than the main part, is a slender part of the mosque that may be subjected to greater stress values and deformations than other parts of the mosque during an earthquake. The maximum compression stress contours for the mosque are shown on Fig. 13. As seen from the figure, the maximum compression stresses are about 5.23 MPa around the lower parts of the main columns and backside fill walls. The maximum

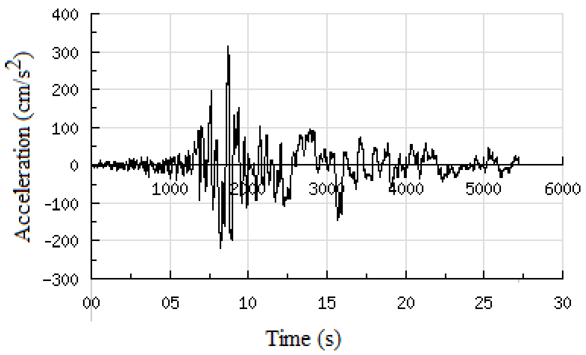


Fig. 12 The acceleration records of Kocaeli earthquake (N-S record) (NEMC 2012)

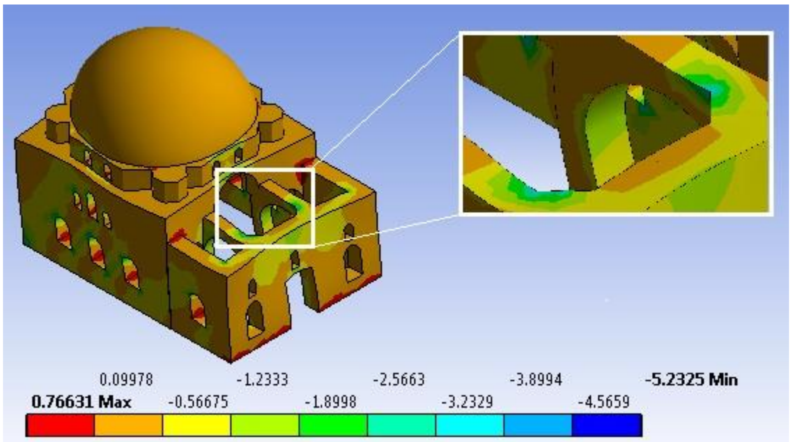


Fig. 13 The maximum compression stress contours for the mosque (MPa)

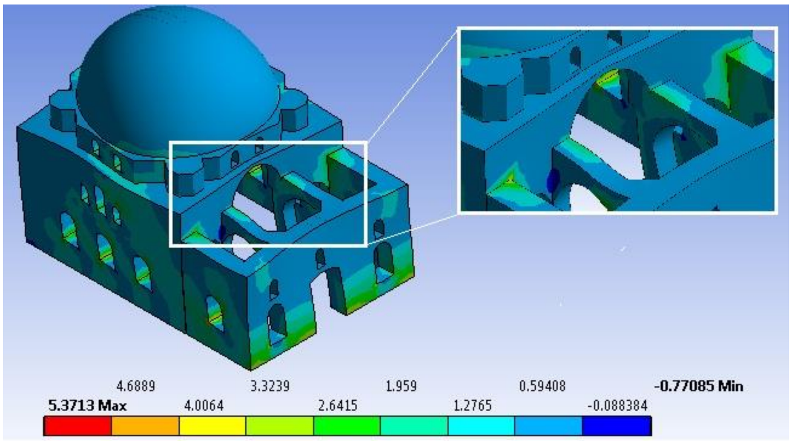


Fig. 14 The maximum tensile stress contours for the mosque (MPa)

tensile stress contours for the mosque are shown on Fig. 14. It is recorded that the maximum tensile stresses are about 5.37 MPa around the connection of the entrance arch, the windows sides, and the upper parts of the entrance wall. Furthermore, the lateral displacement occurred at the top of the dome and it is about 4.61 mm (Fig. 15).

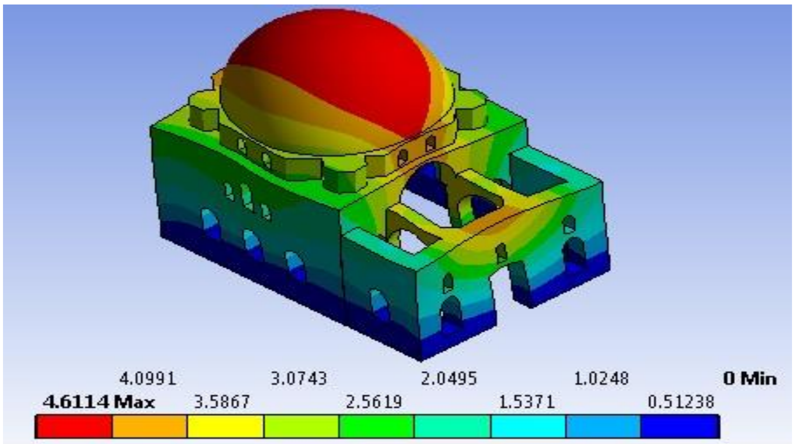


Fig. 15 The lateral displacement of the mosque (mm)

4. Discussion of results

In this section, the results of the experimental tests and numerical analysis are discussed and compared with other studies in the literature. Previously conducted experimental tests on brick materials showed that the maximum compressive and tensile stresses were 31.12 MPa and 3.44 MPa for the bricks (Cancelliere *et al.* 2010). In another study, the mechanical properties of Bricks used in castle structures of Byzantine period has been characterized by Kurugöl and Tekin (2010), where the average compression strength of 14.40 MPa and the average tensile strength of 5.10 MPa were found. Tercan *et al.* (2005) carried out some experimental tests on eight different sandstone specimens. It was determined that the minimum and the maximum compression strength of the sandstones were 21.27 MPa and 87.53 MPa and the minimum and the maximum tensile strength were 1.96 MPa and 6.34 MPa, respectively. In addition, some laboratory tests on sandstones prisms carried out by Günaydın (2006). According to the laboratory tests on the sandstones, the minimum compression strength was 58.05 MPa and the maximum compression strength was 78.49 MPa.

The static analyses results indicated that the maximum compressive and tensile stresses occurred at the base of the main columns and on top of the arch at the entrance of the mosque, respectively. When the maximum tensile stress contour is examined, the stresses are outstandingly changed in window sides and in top parts and corner points of the arches. As expected, these changes are not observed on the filled walls. As compared with the experimental tensile stress values for the construction materials, the tensile stress value is comparably very low. Furthermore, the maximum displacements are calculated on top of the main dome vertically. A similar study about domed mosque conducted in Turkey has shown that the maximum tensile stresses generally occur on top of the main domes and the main arches. Furthermore, the maximum compressive stresses similarly occurred at the base of the main columns and on top of the arch at the entrance of the mosque, respectively (Seker 2011).

The modal and dynamic time history analyses showed that the maximum compressive and tensile stresses occur at the entrance of the mosque and the upper parts of the entrance walls. The vibration periods of the mosque are found to be convenient among these sorts of structures according to the modal analysis conducted (Seker 2011). The time history analysis indicated that the most critical section of the mosque is the arches at the entrance and windows sides. As shown on Fig. 14, the maximum tensile stress was about 5.37 MPa. Tensile strength has reached a value, which is treated as high for masonry units. Therefore, those critical parts at the entrance of the mosque are prone to failure for Kara Mustafa Pasha Mosque. The stresses generated through the analyses indicated that the maximum tensile stress value, which is considered as 0.38 MPa by the static analysis, is increased by 1420% and reached to a value of 5.37 MPa by the dynamic analysis. Additionally, it is also observed that the compression stresses increased from 1.261 MPa to 5.23 MPa with a rate of 415%. The analyses prove that the most risky parts of the structure in terms of displacements is the top point of the structure and dynamic analyses showed that this top point has reached a maximum value of 0.75 mm displacement vertically and maximum 4.61 mm displacement horizontally. The maximum calculated displacements were almost 5 mm for the Kocaeli earthquake and it occurred at the top of the main dome.

When the displacement values are compared, the Turkish earthquake code specifies the following maximum relative displacement requirement for masonry structures (Dogangun *et al.* 2008, Uysal and Cakir 2013).

$$\Delta_{i\max} \leq \frac{0.02 \cdot h_i}{R} \tag{1}$$

where h_i is the story height, and R is the behavior factor related to the ductility of structure. If this requirement is applied to the Kara Mustafa Pasha Mosque (h_i = 15m, R = 2), the corresponding maximum allowable top displacement is 0.15 m. The static and dynamic displacements achieved are lower than the values generated through the formula. In this respect, it is seen that the maximum displacement values are within the allowable limits.

5. Conclusions

Masonry domed mosques are among the most important historical structures in terms of their construction period, intended uses, heritages value and structural properties. Hence, they constitute an important part of the cultural heritage in the world and their preservation for the next generation is crucial. They are mostly survived since they have a special load carrying capacity and material used. However, some of the mosques collapsed or lost their function due to some failure reasons. The determination of the mosque components and their construction materials are necessary and important in order to predict collapse reasons. Therefore, this study focuses on these effects and investigates a historical domed mosque, Kara Mustafa Pasha Mosque, in Amasya by means of experimental tests and numerical analyses.

Results of the analyses show that the construction materials have kept their mechanical properties. The structural stability of the mosque for static case is treated to be safe in terms of both stresses and displacements. According to time history analysis conducted in accordance with the records of Kocaeli Earthquake in 1999, the maximum displacement is almost five times more than the values of displacements assessed in static condition. The maximum compression and tensile stresses assessed in dynamic condition are significantly higher than the static analysis results. Nevertheless, they are lower than the material strengths obtained from the experimental tests. Although these tensile stresses do not exceed the sandstone tensile strength, it may be considered as risky in terms of creating problems for structural stability. In addition, the arch section, which is located at the entrance of the mosque, is considered to be the most critical part in case of an earthquake. Thus, it is advised to take several measures towards earthquakes in this part of the mosque.

Acknowledgments

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