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AN ASSESSMENT OF THE PERFORMANCE OF THE AMASYA BAYEZID II MOSQUE UNDER STATIC AND DYNAMIC LOADS

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ABSTRACT:

Located in the north-central part of Anatolia, Amasya has hosted many civilizations throughout history. The city existed as a major commercial and cultural center during the Byzantine, Seljuk, and Ottoman eras. Many monumental works were gifted by these civilizations to the city, including the Bayezid II Mosque, which was constructed during the Ottoman Empire. In this study, the Bayezid II Mosque was assessed under static and dynamic loads. Results from the static analyses revealed the sections where stress and deformations occurred under static loads. Iron braces were used in these parts to reduce these impacts. Results from the dynamic analyses indicated that the sections of the structure where stresses and deformations have large values are the domes, the minarets, narthex, and the bottom and top points of the columns in the main load-bearing unit. The data derived from this study can serve to guide future restoration efforts.

1. INTRODUCTION

Historical structures that are on an earthquake zone such as Anatolia and that were constructed by utilizing experience and applying production techniques have been subjected to severe seismic effects. Moreover, insensitive human interference with these structures has caused them considerable harm over time (Casapulla et al. 2014). More suitable protection methods that serve to increase the degree of earthquake resistance need to be applied to these historical structures (Roque et al. 2019). In Turkey, a management guide for earthquake risks has been developed for these historical structures (Ahunbay et al., 2017). Monumental and ordinary-use historical structures, even in cases when both types are built as masonry structures, feature different materials, geometry, and structural details (D'Altri et al., 2019). Studies by Fuentes and Ramirez examined these historical structures in detail and found that they had a complex geometry (Fuentes et al., 2019, Ramírez et al. 2019), whereas in the study by Ferrero et al. (2020), it was reported that these structures had a smooth and simple geometry.

This difference in structural analysis results was affected by the degree of difficulty, historical period of the structure's construction, and the architectural approach used in the construction.

The literature features studies that focus specifically on the geometry of historical buildings, such as the study by Perez et al. (2019), and others that focus specifically on the construction approach, like those conducted by Sözen and Çavuş (2019), Cosgun (2012), Karanikoloudis et al. (2020), Saba and Meloni (2018), Castori et al. (2019), Degli Abbati et al. (2019), Milani et al. (2017) and Boschi et al. (2018). In these cited studies, the buildings were modeled in a three-dimensional form and subjected to static and dynamic analyses within the environment of finite elements. From the analyses, the potential collapsing mechanisms and the stress and deformation values were determined.

Studies conducted by Lourenço and Oliveira (2005) and by D'Amato et al. (2020) to analyze certain security and seismic index definitions produced important data on structural behavior. The study conducted by Enea and Yavuz (2013) identified construction problems related to a historical Ottoman mosque and offered restoration and reinforcement suggestions that can serve as a guide for future restoration efforts of historical buildings.

In the study by Masciotta et al. (2017), static and dynamic observation methods were applied to a historical church, and from the results, useful approaches for protecting and caring for such buildings were presented. Borri and Corradi (2018), in their study on the structural security of historical monuments situated in seismic locations of Italy, showed how to achieve this security with minimal effort.

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Securing for future generations the architectural integrity of historical structures considered to be the most significant representatives of Turkey's historical cultural heritage is a major challenge that requires significant effort. This effort includes fulfilling the responsibilities regarding the protection of social artefacts left from other civilizations that existed in Anatolia throughout history. It is important that these artefacts, which have different architectural features and load-bearing units, be protected by preserving the integrity of their essential features. These artefacts, which generally feature a stone-walled dome or vault roofing built with bricks, may have a low level of earthquake resistance since they were built in a masonry style. New production techniques have been developed based on the accumulation of results from disasters over time. Today, damage and deformation can be pre-determined thanks to the ability to perform detailed analyses of artefacts through three-dimensional modelling in a digital setting. Accordingly, significant data have been obtained in the effort to secure the permanent integrity of these artefacts.

This study produced a detailed three-dimensional model of the Bayezid II Mosque in Amasya to perform a static and dynamic analysis of the mosque. As photographs of the mosque had been taken following an earthquake that occurred in the past, the level of damage identified through the analysis performed on the finite elements was able to be used in examining the status of the strength of the mosque today. The accuracy of the results derived from the analysis and modelling are presented in detail in this study.

2. THE HISTORICAL AND ARCHITECTURAL PROPERTIES OF BAYEZID II MOSQUE

Located alongside Yeşilırmak River in Amasya, the central parts of Sultan Bayezid II Mosque include a U-shaped madrasah on the west, an almshouse on the east, a tomb on the southeast, and a water tank and fountains on the north. According to the historical information presented at the entrance to the mosque, it was constructed upon the order of Bayezid II (1486), an Ottoman sultan, in Figure 1 and Figure 2.

The mosque suffered two major earthquakes, one in 1668 and one in 1689, which demolished the domes of the mosque, the almshouse, and one of the minarets and bent the other minaret. The mosque was damaged again by an earthquake that occurred in 1939, which resulted in part of the narthex being damaged.

The mosque was restored after the last two earthquakes. The mosque is 45m x 43m in size, and it was constructed using yellow limestone in Fig. 1(b) (Peker, 2007). The narthex, which is located on the north side of the mosque, is situated between the dextral and sinistral parts of the mosque entrance. The narthex is covered with five domes positioned on six columns. The rectangular main area is reached through the crown gate, which is equipped with stalactites on the mihrab arch. The prayer section is covered with two domes positioned on four capitals, and squinches are used to carry the dome. The sinistral and dextral locations of the main area have two wings covered with three low domes. Accordingly, this mosque features lateral spaces. These parts, along with the main area, are positioned on capitals, and transitions are marked with three sharp arches. The domes carried by walls and the incorporation of other domes have pulleys, and the mosque is illuminated through windows that open on the pulleys and walls.

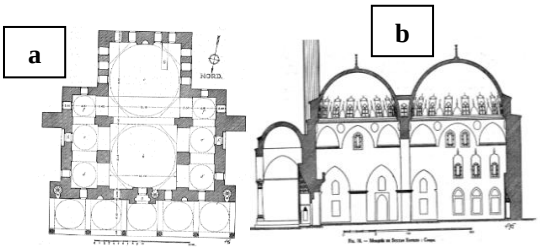


Figure 1. (a) Bayezid II Mosque Plan, (b) Section (Gabriel, 1931)

The diameter of the dome located in front of the mihrab to the south is 15 m, while the dome, separated by a large arch, is slightly oval with a diameter of 14 m. The masonry walls built with yellow limestone rise from a sub-basement and stand 25 cm in height. The narthex was restored between 1952 and 1971 and rebuilt with marble material (Amasya Govenorship, 2007). The minaret rises 25.70 m in height and has 97 stairs (Peker, 2007). As some of the minarets were demolished in the earthquake, the location extending from the minaret balcony to the conical part was restored. The zigzag motifs formed by using red and white stones extend to below the balcony. The parts under the balcony feature stalactites, while the conical locations are covered with lead in Figure 2 (b).

The mihrab walls of the mosque are externally reinforced with three support towers on the eastern and western facades, and the towers are covered with domes. The square praying area within the location of the mihrab is raised by 10 cm on the north side (Peker, 2007). The mihrab built with white marbles features stalactites. The minbar, which is also made of white marbles, is located on the west side of the mihrab. The area where the muezzins gather is built out of wood.

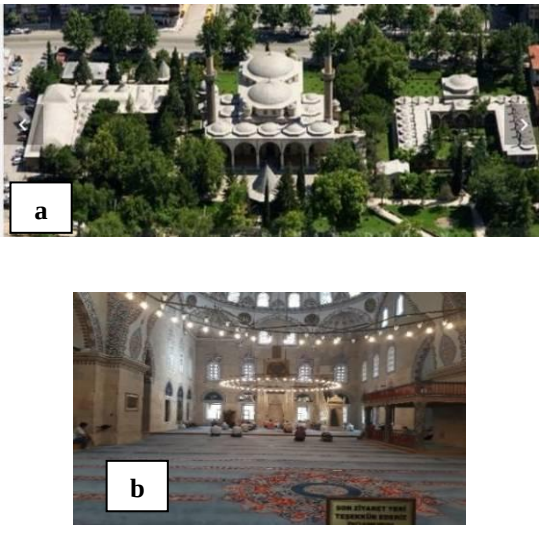


Figure 2. (a) Bayezid II Mosque, (b)The General Appearance, its Interior (URL1, 2020)

3. FINITE ELEMENT MODEL AND MATERIAL PROPERTIES

Studying large buildings like the Bayezid II Mosque through traditional analytical methods is no longer the most sufficient method, as it is very time consuming. With the development of advanced modern computing technology, analysis programs involving finite elements have become popular. The Bayezid II Mosque was able to be modelled in a three-dimension form through these digital environments, allowing for a more realistic observance of structural behaviour. These types of analyses are especially useful to examine buildings with multiple materials and to gain a more detailed geometrical structure of buildings with larger volumes. Analyses were performed using the ANSYS (2019) program, which employs the finite element method. To perform the analyses of the building using the finite element method, the three-dimension model was created first. The geometrical structures of the building, support conditions, and material properties of the relevant parts were assigned to the model. The finite element model was completed with 188950 node points and 54814 solid elements in the ANSYS Workbench. The Solid 186 elements used for analysis had 20 node points, each of which had translational freedom. The properties of the Solid 186 elements are presented in Figure 3 (a) (ANSYS), while the three-dimensional model of the building is presented in Figure 3 (b). Owing to the size of the building, analyses were performed using the linear elastic material properties and macro modelling method. The masonry elements that formed the building and the mixture were regarded as a composite in determining the building properties for this model. Accordingly, analyses performed within the finite element environment are more time efficient (Lourenço, 2008). Due to the size of the mosque model and the high number of node points, the values obtained from the analyses are presented as a color scale in the model.

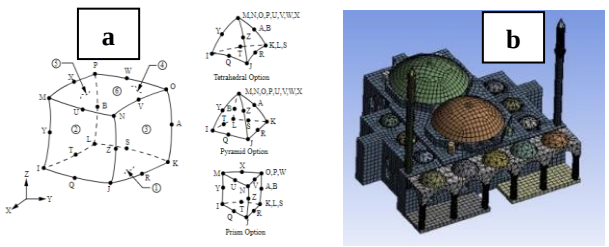


Figure 3. (a) Solid 186 Properties, (b) Building Finite Elements Model

The main mass, narthex, minarets, and arches, were built using face stones, while the domes were built with bricks from Khorasan. The physical and mechanical properties identified in the laboratory tests performed on the materials that were used in another work in the same city were assigned to these parts (Çakır and Koçyiğit, 2016). The physical and mechanical properties of these materials are presented in Table 1.

Material type	Elasticity module (MPa)	Poisson rate	Specific bulk density
Stone	10000	0.17	2358
Brick	3500	0.15	2037

Table 1. Physical and Mechanical Properties of the Materials Used in the Mosque

3.1 Static Analysis

The deformation values obtained from the analysis performed under static loads are presented in Figure 4. Examination of the shape indicated that maximum values, which were determined to be 1.3051 mm, emerged on the main domes and peak points. For the interior, deformations were determined to be most intense on the main arch supporting the dome. The load-bearing corner columns of the narthex had lateral deformations.

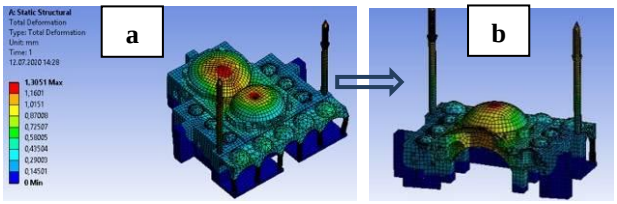


Figure 4. (a) Static Analysis, (b) Maximum Deformation Values

Figure 5 shows that the maximum principal stress values of 0.50591 MPa reach these levels at the peak points of the load-bearing arch under the main dome. These high stress values emerge at the same locations of eight arches carrying two main domes. These arches are connected to each other on the joist hangers via iron braces, which are commonly used to create rigid diaphragm impacts in mosques with large volumes of space (Tanyeli, 2017).

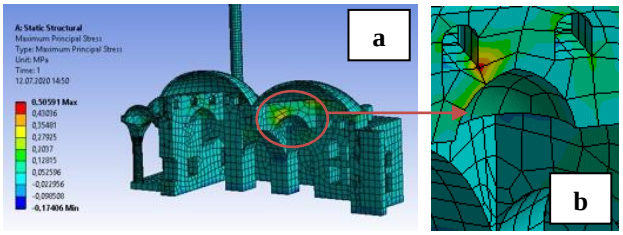


Figure 5. (a) Static Analysis, (b) Principal Stress Distribution

3.2 Modal Analysis

When analyzing static loads of structures to determine their resistance to earthquakes, it is important to first determine their free vibration mode shapes, and the period they were built to accurately observe their potential behavior. In doing this, the deformations of buildings are specified under dynamic loads, and the locations under constraint are detected by calculating the mass participation ratio.

Due to the size of the building, modal analysis was initially performed on the entire mass, and this analysis indicated that the ratio calculated when the minarets were included in the active mass was high, with maximum displacement occurring at the top points. The minarets were then excluded from the model, and the analysis was performed again to examine the form of movement on the other parts of the building. The mode shapes derived from these analyses are presented in Figure 6.

Examination of the shapes of the modes indicated that the minarets, main domes, and narthex were affected by the movement under the impact of earthquakes, with maximum displacements occurring in those locations. The demolished and damaged parts of the buildings, as depicted in photographs in Figure 6 (d) (Amasya Governorship, 2007) taken after the 1939

earthquake, aligned with the potentially damaged parts detected through the analysis.

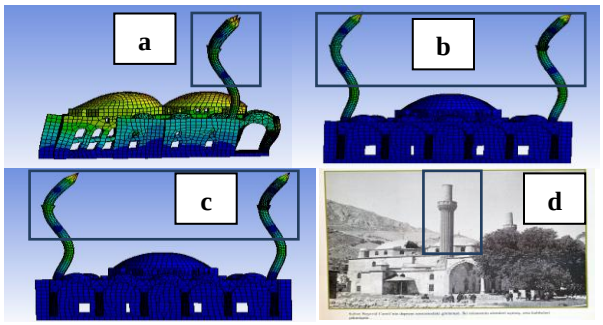


Figure 6. Entire Mass Mode Shapes, (a) Mode 9, (b) Mode 10 and (c) Mode 16, (d) After the 1939 earthquake, Amasya Bayezid II Mosque, (Amasya Governorship, 2007)

The data provided beside the photograph shown in Figure 7 and Figure 8 indicates that the two main domes of the mosque, the last congregation location with domes, and the minaret cones all collapsed after the earthquake.

Moreover, the results achieved in the modal analyses provided important information about the dynamic behavior of the mosque.

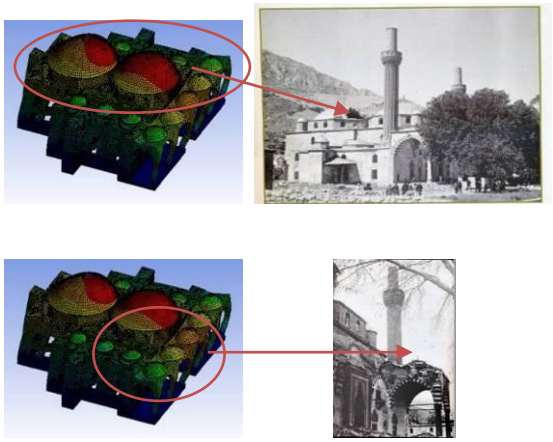


Figure 7. Model 1 with the Minaret Excluded. Mode Shape (T= 0.097 sec.)

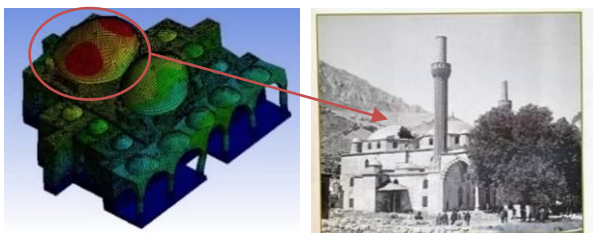


Figure 8. Model 1 with the Minaret Excluded. Mode Shape (T= 0.082 sec.)

3.3 Linear Time History Analysis

The geography of Anatolia has active fault lines. Major earthquakes occurred on the Northern Anatolian Fault Line of this geography in 1939, 1943, and 1999. Amasya is also located on this fault line (Figure 9).

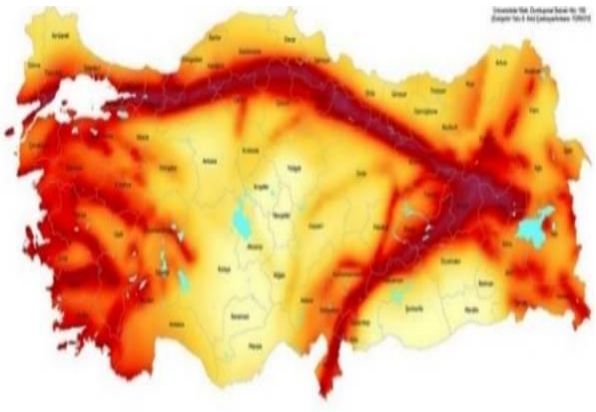
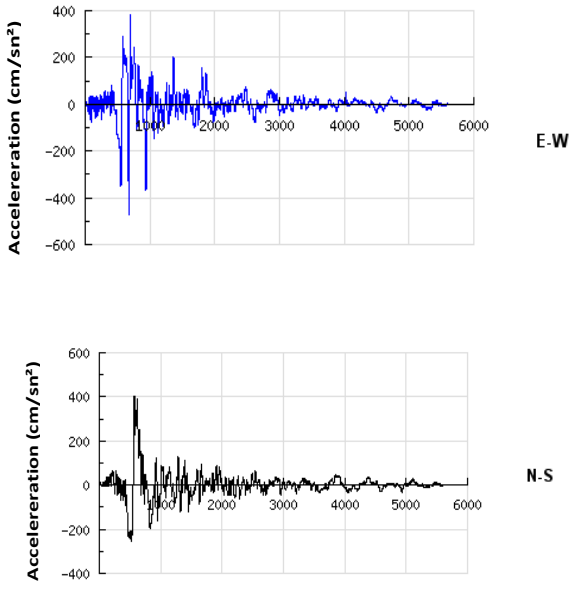


Figure 9. Seismic Hazard Map of Turkey and Location of Amasya (URL2, 2019)

Determining the parts of the mosque that would be potentially subject to damage during an earthquake is critical. Accordingly, the acceleration record values of a magnitude 6.8 earthquake that occurred on March 13, 1992 at 19:19 in Erzincan – an eastern country of Turkey – and that caused major damages to the buildings in Amasya, Turkey were examined in the analyses.

Being located on the Northern Anatolia fault line, the region extends in an east-west direction due to the pressure between the Arabic and Eurasian plates. Seismic activity in this region dates to earlier times, with 17 separate earthquakes having occurred in this region between 1045 and 1784.

The earthquake that occurred in 1992 resulted in the death for 653 people and heavy damage to 6702 buildings (Celep, 2017). The acceleration record values are presented in Figure 10. The peak acceleration value was 404.97 cm/sn² on the north-south direction, 470.91 cm/sn² on the East-West direction, and 238.55 cm/sn² on the downward-upward direction (URL3, 2019).



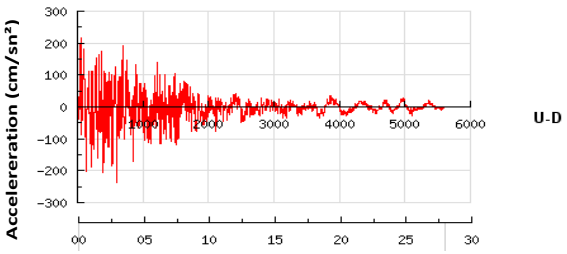


Figure 10. Acceleration Record Values of Erzincan (cm/sec^2)

The vertical axis acceleration values in these graphs refer to the vertical axis time values, and the acceleration values for the earthquake impact direction were transferred over to loads in the same direction of the building. Due to the size of the model, the analyses involved only the symmetry in the north-south direction and were performed on a half-model to save time and effort. By including the ratio of the minarets in the active mass as part of the modal analysis, higher displacement and stress values would emerge in the minarets during earthquakes.

Therefore, the minarets were excluded from the model, as the aim was to assess the stress and displacement values on the main mass. Distributions of the stress and displacement values obtained from the analyses performed for this shape were separately conducted.

3.3.1 Analysis of the Mosque under North-South Direction Acceleration Record: The acceleration record values in the north-south direction were reflected as the acceleration load in the same direction of the construction, and the stress and displacement values that emerged when the acceleration value reached its peak point are presented in Figure 11.

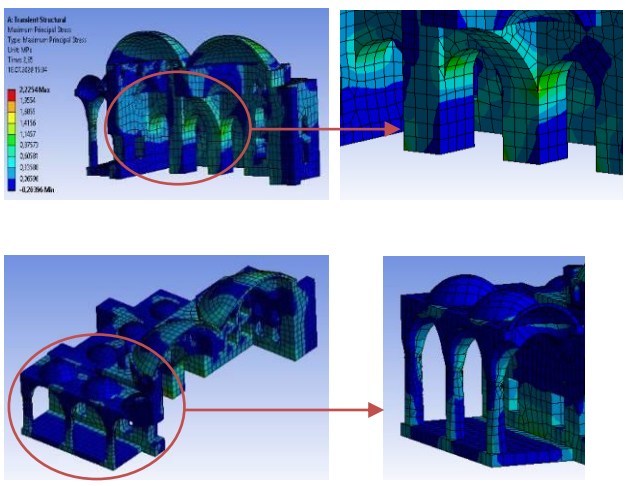


Figure 11. Maximum Principal Stress Distribution

In examining Figure 11, the main domes had high values at the locations of joist hangers on main load-bearing arches and at the locations where the load-bearing narthex columns are joined to the arch system. The greatest stress value was determined to be 2.22 MPa.

The narthex, main domes, and main load-bearing elephant foot would be affected by the seismic impact.

Figure 12 shows the total displacement of the mosque model developed from the displacement analysis.

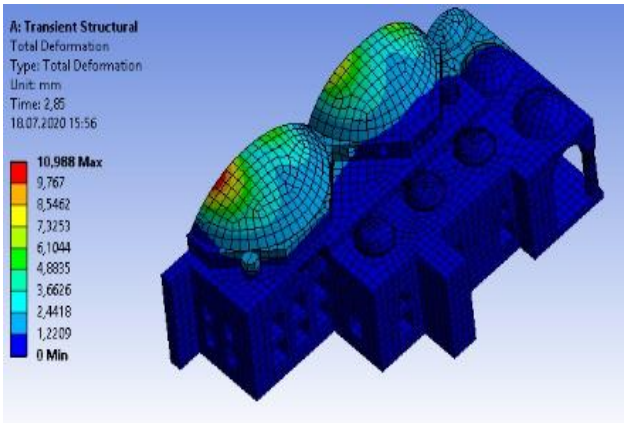


Figure 12. Total Displacement Distribution

The maximum displacement value of 10.988 mm is on one of the main domes of the mosque, and displacements are also quite intense on the other main dome.

3.3.2 Analysis of the Mosque under West-East Direction Acceleration Record: The distribution of principal stresses according to the analysis based on the east-west direction of earthquake acceleration is presented in Figure 13.

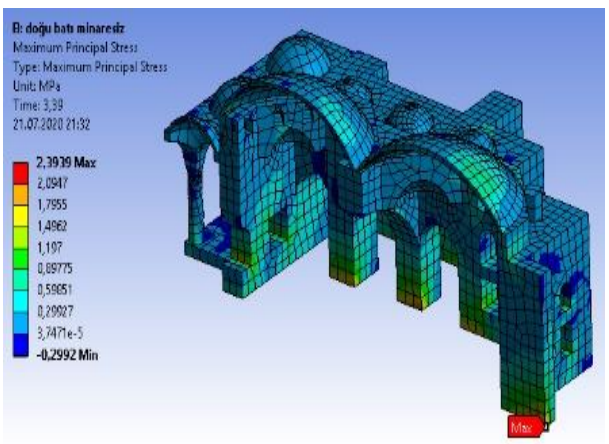


Figure 13. Maximum Principal Stress Distribution

High principal stress values emerged on the braces of the main load-bearing elephant foot and walls in the symmetry axis.

The maximum value was calculated to be 2.3939 MPa. The total displacement values obtained from the analysis are graphically presented in Figure 14.

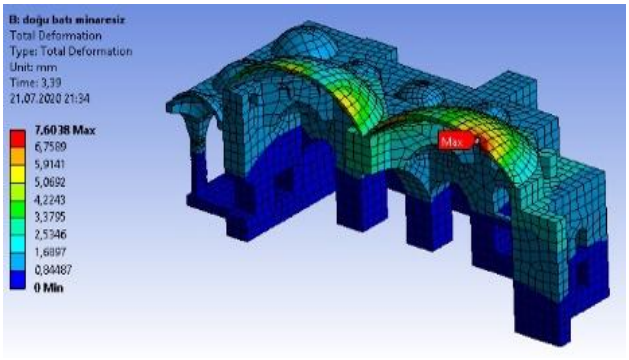


Figure 14. Total Displacement Distribution

The time-history analysis indicated that displacement values were highest on the main domes, with the maximum value being determined as 7.6038 mm.

4. CONCLUSIONS

Many architectural works, such as social complexes, inns, baths, bridges, and mosques, were constructed on the Anatolian territory during the reigns of the Islamic Seljuks and the Ottomans – two important civilizations in Turkish history.

Anatolia has hosted many civilizations, each of which had their own architectural system. Today, many of the structures created by these civilizations remain.

Some of these works, however, have failed to survive due to wars, fires, and earthquakes. Amasya, being a city where the Shahzades of the Ottoman Empire had lived, hosts numerous architectural works from that period.

The Bayezid II Mosque, one of the most important and largest historical structures in this city, was analyzed in this study under static and dynamic loads.

The objective of this study was to determine the parts of the mosque that might be potentially damaged during an earthquake.

It is critical that these works – important examples of Islamic cultural and historic heritage – be preserved and passed down to future generations. Accordingly, it is believed that the results of this study shall serve to guide efforts at protecting buildings against potential earthquakes and at overcoming the harm caused to buildings by the ravages of time.

The mosque was modelled in a three-dimension form and assessed in the finite element environment before performing the analyses. Stress and displacement were found to be the most intense at the arch, the common load-bearing element of two domes, and the joist hangers of this arch according to the static analysis.

Regarding the mosque architecture, the sections were magnified on the arch spring and load-bearing elephant foot, and tensile stress was seen to occur on the peak points of the arches carrying the main domes.

According to the data, these tensile stresses occur as the arches open on the joist hangers due to the horizontal load on the arches. The arches were connected on the joist hangers with iron braces to prevent the tensile stresses from causing too much stress on the system. The same may happen on the capitals in the congregation hall.

The lateral deformations and tensions at these locations necessitate the use of iron braces. It is safe to state that the architects of the Ottoman architecture were aware of this and took the necessary precautions (Çakır and Koçyiğit, 2016). The dynamic analyses indicated that the main domes, the narthex, and the minarets, all of which are involved in the movement of the building, could be damaged.

These locations were in fact seen to be damaged in the photographs taken after the 1943 earthquake, indicating the correctness of the analyses and evaluations. Although ultra-linear analyses were not performed due to the size of the building (Şeker et al. 2015), the linear elasticity analyses provided realistic information about the parts of the building that could be potentially damaged.

Moreover, the results indicated that the macro modelling method and elasticity analyses, which are not as time consuming as other methods and analyses, could offer adequate information.
Nevertheless, it should be noted that every historical building has its own unique architectural design, materials, construction method, and regional structure, and therefore a detailed assessment should be performed considering the properties of the terrain in the specific areas.

The results of this study shall be useful for technical staff and academics working in the area covered in this research.

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