Journal of Structural Engineering & Applied Mechanics (2023) 6(4):268-281
DOI 10.31462/jseam.2023.04268281

RESEARCH ARTICLE

Determination of the seismic performance of a historical masonry structure using the equivalent seismic load method

Musa Yetkin[1*], Hakan Erkek[2], İbrahim Özgür Dedeoğlu[3], Yusuf Calayır[1]

[1] Firat University, Department of Civil Engineering, Elazig, Türkiye
[2] Osmaniye Korkut Ata University, Department of Civil Engineering, Osmaniye, Türkiye
[3] Batman University, Department of Civil Engineering, Batman, Türkiye

Article History

Received 24 February 2023
Accepted 22 August 2023

Keywords

Historical masjid
Masonry structures
Equivalent earthquake load method
Seismic performance
Finite element model

Abstract

Mosques and masjids are the most important parts of Islamic culture in terms of their architectural and structural characteristics. These structures also provide an important insight into the construction techniques and historical process of the region in which they were built. Many of these structures are still in use around the world. However, most historical mosques and masjids are vulnerable to earthquakes or are not strong enough. Therefore, it is important to know the risk status of these important structures with respect to earthquake forces and to carry out the necessary strengthening works. In this study, the performance of the historical Ahi Musa Masjid (built in 1185) was investigated using the linear earthquake solution method, which provides a practical approach to determining the earthquake performance of historical structures. Firstly, studies were carried out to determine the geometric and material properties of the historical Masjid. A finite element model of the historical Masjid was then constructed and linear performance analyses were performed under vertical loads and equivalent earthquake loads. As a result of the analyses, the displacement ratios, compressive and shear stresses of the historical Masjid were obtained and evaluated according to the collapse prevention performance level for the earthquake level DD-3, which is one of the performance levels recommended for historical structures of local importance in the Guidelines for the Management of Earthquake Risks for Historical Structures. The aforementioned stress and drift ratio values remained below the reference values. In conclusion, the Masjid will safely withstand the potential effects of an earthquake.

1. Introduction

Türkiye is located in the Alpine-Himalayan seismic belt where earthquakes occur intensively due to its tectonic position. Historical and instrumental earthquake records show that destructive earthquakes have occurred in a large part of our country. For these earthquakes 1924 Horasan-Erzurum (6.8), 1928 Torbalı-İzmir (6.5), 1935 Erdek-Balıkesir (6.4), 1939 Erzincan (7.9), 1943 Ladik-Samsun (7.2), 1949 Karlıova-Bingöl (6.7), 1953 Yenice-Çanakkale (7.2), 1957 Abant-Bolu (7.1), 1966 Varto-Muş (6.9), 1970 Gediz-

* Corresponding author (musayetkin@firat.edu.tr)

Kütahya (7.2), 1976 Muradiye-Van (7.5), 1983 Erzurum-Kars (6.9), 1992 Erzincan (6.8), 1999 Gölcük-Kocaeli (7.8), 1999 Düzce (7.5), 2003 Bingöl (6.4), 2011 Van (7.2), 2020 Sivrice-Elazığ (6.8), 2020 İzmir (6.9) earthquakes in the last century can be given as examples [2]. As can be seen from the examples given, our country is frequently struck by major earthquakes. These earthquakes have caused serious loss of life and property and have damaged many types of structures such as inns, bathhouses, caravanserais, mosques, churches, minarets and bridges. Some of these structures are historical artefacts and our cultural heritage. It is very important to protect these historical structures and pass them on to future generations intact. For this reason, it is necessary to determine the current condition of these structures, and those that need strengthening should be strengthened as a matter of urgency. Studies to determine the structural behavior of historical structures in our country are often carried out by researchers. Aksoy and Aydoğmuş [3] investigated the earthquake performance of the historical Kargı Han structure using linear elastic material properties. As a result of the analyses, they concluded that the compressive and shear stress values exceeded the values recommended for masonry structures in the Türkiye Building Earthquake Code and that the weak sections should be improved and the joints should be renewed to improve the earthquake performance of the structure. Aslan [4] investigated the behavior of the historical Süleymaniye Mosque under earthquake acceleration records and found that the performance of the Mosque is generally good. However, Aslan [4] stated that some parts of the Mosque may be damaged due to excessive tensile stress in the face of a severe earthquake. Şeker [5] studied the structural performance of the historical Alaca Minaret Masjid and, based on the results of static and dynamic analyses, identified the parts of the Masjid that could be damaged in a possible earthquake and stated that these areas should be restored using appropriate techniques. Çakır et al. [6] attempted to determine the structural behavior of the historical İşhan Church. As a result of the analyses, they found that stress increases occurred mainly in the transition zones of different materials and geometric shapes and recommended that measures should be taken to prevent stress increases in these regions. Çakır et al. [7], in their study to determine the structural behavior of the historical Lala Pasha Mosque, identified the most critical parts of the Mosque based on the analysis results and made some recommendations to strengthen these parts. Ercan [8] experimentally compared the conditions of the historical Grand House structure before and after retrofitting with the operational modal analysis method, and performed dynamic analyses by updating the finite element model created for the structure in the light of the experimental results, and stated that the earthquake performance of the structure improved after retrofitting, and the first modal frequency increased by approximately three times. Güllü and Karabekmez [9] created a finite element model of the historical Kurtuluş Mosque and performed non-linear analyses under artificial earthquake records. As a result of the analyses, they found that the displacement and tensile stresses in some parts of the Mosque exceeded the allowable limits, and therefore there was a risk of damage in these areas. Kocaman et al. [10] investigated the structural performance of the historical Erzurum Yakutiye Madrasah in terms of static and dynamic aspects. They found that the structure was in good static condition, but in dynamic terms the stresses increased at the joints of the minaret with the walls and the minaret could collapse in a ground motion effect similar to the 1992 Erzincan and 1999 Düzce earthquakes. Maraş et al. [11] created a finite element model of the historical Sütlü Minare Mosque and performed time domain analysis under real acceleration records. As a result of the analyses, they observed that the possible crack zones occurring in the Mosque were similar to the crack zones occurring in the Mosque after the 2020 Sivrice-Elazığ earthquake. Kumbasaroğlu and Çelik [12] analyzed the historical Yanıkoğlu Mosque under self-weight and earthquake forces calculated according to the equivalent earthquake load method. As a result of the analysis, they determined the performance level of the structure as limited damage. Çarhoğlu et al. [13] determined the structural behavior of the Kümbet Mosque in Kars province by linear analyses under twenty different earthquake acceleration records. They compared the results obtained from each analysis (displacement, stress and base shear force values) with each other. Korkmaz et al. [14] performed dynamic analysis of the historical Kurşunlu Mosque

(Rize) under three different earthquake acceleration records. The displacement and stress values obtained for each acceleration record were evaluated. Kocaman et al. [15] performed dynamic analyses for the historical Erzurum Lala Pasha Mosque using nine different earthquake acceleration records. Based on the results of the analyses, the in-plane and out-of-plane horizontal load bearing capacity of the structure and load-bearing walls were determined. They examined the adequacy of the relations proposed in the earthquake code and in the literature in estimating this capacity. Kazaz and Kocaman [16] performed static analysis of the historical Erzurum Lala Pasha Mosque under its own weight and dynamic analysis under the acceleration records of the 1992-Erzincan Earthquake. The authors stated that the existing calculation methods can be used with some modifications to determine the lateral load resistance of historical masonry mosques and their bearing walls. Aşıkoğlu et al. [17] performed the seismic performance evaluation of the historical Kurşunlu Mosque (Kütahya) before and after retrofitting with non-linear pushover and dynamic analyses. Kamanlı et al. [18] conducted a static analysis of the Sille Ak Mosque in Konya, which has an important place in terms of Turkish Islamic art, according to the Türkiye Building Earthquake Code–2018.

In the study, the behavior of the historical Ahi Musa Masjid was investigated. A finite element model of the Masjid was created and linear performance analysis was performed. As the earthquake effect, the forces calculated according to the equivalent earthquake load method were applied to the structure. While determining the performance of the Masjid, the Guidelines for the Management of Earthquake Risks for Historical Structures (GMERHS-2017) was utilized [1]. The performance of the Masjid was determined for the Collapse Prevention damage level, which is one of the target performance levels recommended by the guideline for historical structures of local importance.

2. Historical Ahi Musa Masjid

The historical Ahi Musa Masjid, which is a registered cultural asset and owned by the General Directorate of Foundations, was built by a person named Ahi Musa in 1185. The year of construction coincides with the end of the Artuqid period and the beginning of the Seljuk period. The Masjid is located in the historical Harput Neighborhood, 5 km northeast of Elazığ city center and included in the UNESCO World Heritage List. It is thought that the Masjid, located to the south of the historical Esadiye (Aslaniye) Mosque, was built as a unit of the Esadiye Mosque. It is mentioned in the sources that the structure has an inscription, but the inscription has not survived to the present day. It is the only Ahi structure in Harput and it is important in terms of showing the existence of the Ahi community in Harput [19-21]. Visuals of the historical Ahi Musa Masjid are given in Fig. 1.

The historical Ahi Musa Masjid has a rectangular plan extending in the east-west direction and there is a tomb adjacent to the south wall of the Masjid, which is approximately half the size of the Masjid. The structure is accessed from the east through a single entrance door and the tomb through a door opening from the south wall of the Masjid. There is a mihrab niche in the west wall of the Masjid, two window openings in the north wall, and a window opening on the east façade where the tomb section is located. There is no complete information about the restorations that the Masjid has undergone to date, and some sources state that it was restored in 1995 and 2012 [20-22]. Some images and views of the Masjid taken in the past are given in Fig. 2.

The historical Ahi Musa Masjid has a masonry structural system. The masonry walls of the Masjid consist of smooth cut stones and it was observed that no other materials were used in the construction of the Masjid. Various experimental studies have been conducted to determine the material properties of the masonry walls. In this study, the results obtained in a previous experimental study for wall elements constructed using similar stone specimens were used [23]. The elasticity modulus, compressive strength, density and Poisson's ratio of the stone walls of the historical Ahi Musa Masjid were assumed to be 5490 MPa, 12.34 MPa, 1839 kg/m^3 and 0.2, respectively.

Fig. 1. Some views of historical Ahi Musa Masjid

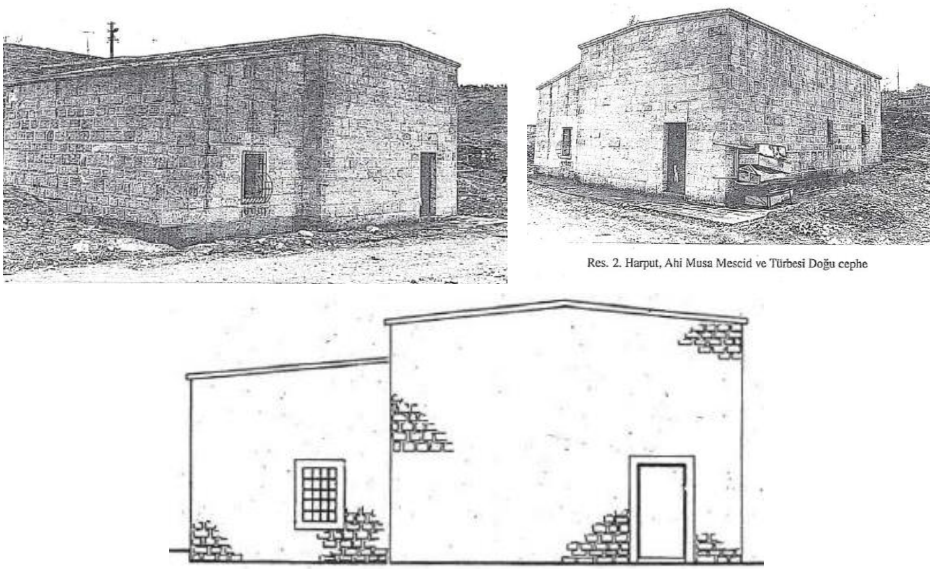


Fig. 2. Some images and views of Ahi Musa Masjid taken in the past

3. Guidelines for the management of earthquake risks for historical structures

Historical structures are built with traditional materials such as adobe, brick, wood and stone, and often provide us with an idea about the period in which they were built. According to the Code of Protection of Cultural and Natural Properties, structures built with these traditional materials until the end of the 19th century are considered historical structures and are taken under protection. These historical structures are expected to meet the target performance levels against earthquakes that may occur according to their importance class. Otherwise, it is thought that the historical structure will not be able to protect its identity under existing loads or in the face of natural disasters such as earthquakes, and may be damaged or destroyed if necessary measures are not taken. For the target performance levels of historical structures, there is a guideline published by the General Directorate of Foundations for GMERHS-2017 [1]. According to this guideline, historical structures are classified as historical structures of local significance, national significance and universal significance. The target performance levels for each classification are given in Table 1. For Table 1, DD-1 refers to earthquake ground motion with 2% probability of exceedance in 50 years and a return period of 2475 years, DD-2 refers to earthquake ground motion with 10% probability of exceedance in 50 years and a return period of 475 years, and DD-3 refers to earthquake ground motion with a 50% probability of exceedance in 50 years and a return period of 72 years.

Within the scope of the study, the historical Ahi Musa Masjid was evaluated according to the Collapse Prevention (CP) performance level for the DD-3 earthquake level recommended in the GMERHS-2017 guideline. In the analyses using linear calculation methods for this performance level, the rules that the calculated strengths in the predicted earthquake effect reduced by vertical load and Ra ≤ 3 can be exceeded by a certain ratio (~1.5 times) and the drift ratio in the unreduced earthquake effect should not exceed 1.0% are specified in the guideline as stress and strain limits [1].

4. Equivalent earthquake load method

The equations given in the Türkiye Building Earthquake Code–2018 (TBEC-2018) [24] were used to determine the equivalent earthquake loads acting on the structure. TBEC-2018 states that the equivalent earthquake load is calculated using the equation given in Eq. 1.

$$V_{tE}^{(X)} = m_t\, S_{aR}\left(T_P^{(X)}\right) \geq 0.04\, m_t\, I\;\; S_{DS}\, g \tag{1}$$

where, m_t is the total mass of the structure, S_aR is the reduced design spectral acceleration, $T_p{}^{(X)}$ is the dominant natural vibration period of the structure in the x-direction and g is the gravitational acceleration. S_aR is calculated according to Eq. 2.

$$S_{aR}(T) = \frac{S_{ae}(T)}{R_a(T)} \tag{2}$$

For Eq. (2), $S_{ae}(T)$ is the horizontal elastic design spectral acceleration and $R_a(T)$ is the earthquake load reduction coefficient.

Table 1. Target performance levels recommended in the GMERHS-2017 [1]

Performance Levels to be Selected According to the Importance of Historical Structures	National significance	Universal significance	
	DD-3 Limited Damage (LD)	DD-2 Limited Damage (LD)	DD-1 Limited Damage (LD)
Local significance	DD-3 Controlled Damage (CD)	DD-2 Controlled Damage (CD)	DD-1 Controlled Damage (CD)
	DD-3 Collapse Prevention (CP)	DD-2 Collapse Prevention (CP)	DD-1 Collapse Prevention (CP)

The above equations were used to calculate the equivalent earthquake loads of the historical Ahi Musa Masjid. In calculating these values, the location of the Masjid, the soil and the earthquake level to be calculated are important. As the Masjid is a historical building of local importance, the CP performance level analysis was performed for the DD-3 earthquake level among the performance levels specified for such structures in Table 1 [1].

As the location of the Masjid is a protected area, no soil class survey was carried out. When the projects of the International Complex (Fig. 3), built approximately 100 m east of the Masjid, were examined, it was seen that the soil class was determined to be ZC according to the soil survey report. Therefore, the soil class in the study was accepted as ZC.

The equivalent earthquake loads of the Masjid and the parameters used to calculate these loads are given in Fig. 4. Some of these parameters were determined using the interactive website tdth.afad.gov.tr [26].

The reduced earthquake loads of the Masjid were calculated to be 6086.64 kN and 9242.59 kN for the x and y directions, respectively, and the unreduced earthquake loads were to be 15216.6 kN and 23106.47 kN for the x and y directions, respectively. These loads were applied from the floor level as uniformly distributed loads proportional to the wall cross-sectional areas in the relevant direction for each direction to be calculated. Two different combinations, G+Ex and G+Ey, were used in the performance analysis of the Masjid.

Fig. 3. Location of the historical Ahi Musa Masjid and the International Harput Religious Complex [25]

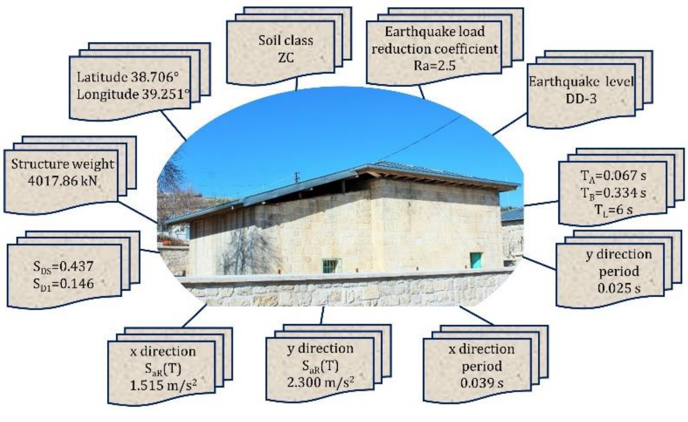


Fig. 4. The parameters used to calculate equivalent earthquake loads

5. Finite element model of the masjid

The finite element modelling and analysis of structures has become increasingly widespread with the development of knowledge and technology. Finite element model analysis is widely used by many researchers for masonry structures. Finite element modelling of masonry structures is divided into three as detailed micro modelling, simplified micro modelling and macro modelling.

The method used for modelling masonry structures is selected according to the level of accuracy required. Detailed micro modelling is a precise method in which the material properties of each unit are evaluated separately, but the solution time for solving the entire large volume structures is long, so it is usually preferred for solving small structures or parts of large structures. Simplified micro modelling is a type of modelling in which the dimensions of the masonry units are expanded by half the thickness of the mortar layer, the mortar layer is neglected, the masonry units are separated from each other by interface lines and it is assumed that cracks will occur at these interface lines. In macro modelling, an equivalent composite material is selected to reflect the material properties of all the units that make up the structure and is often preferred for modelling large systems since it significantly reduces computer solution time [27]. The representation of these modelling techniques on a masonry wall element is given in Fig. 5.

Firstly, the Ahi Musa Masjid was surveyed in detail and its geometric dimensions were determined. Then, the finite element model of the historical Ahi Musa Masjid was created using macro modelling technique. ANSYS program was used for finite element modelling [29]. The masonry walls were created using the Solid 65 element, which is widely used for linear and non-linear analyses of masonry structures. The Masjid is assumed to be fixed supported on the soil. In the finite element modelling of the Masjid, 22991 nodes and 18219 quadrilateral prismatic elements were used. The finite element model of the Masjid is given in Fig. 6.

Modal analyses were performed for the finite element model of Ahi Musa Masjid. The first five mode shapes obtained as a result of the modal analyses are given below (Fig. 7).

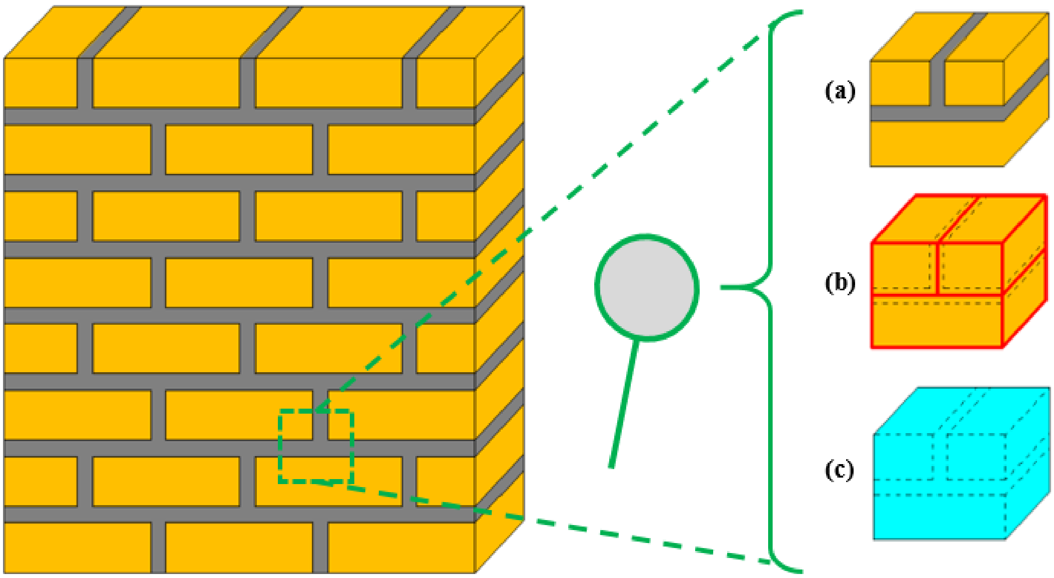


Fig. 5. Modelling of masonry structures with (a) detailed micro modelling, (b) simplified micro modelling and (c) macro modelling techniques [28]

6. Results and discussion

The linear analysis of the historical Ahi Musa Masjid under vertical loads (roof load) and equivalent earthquake loads was carried out. Two different solutions for G+Ex and G+Ey combinations of the equivalent earthquake load were performed. As a result of the analyses, the drifts, compressive strength and shear strength checks of the Masjid were carried out according to the limits specified in the GMERHS-2017 guideline. Each wall was evaluated individually and maximum values were obtained for each façade. The name codes of the wall façades are given in Fig. 8.

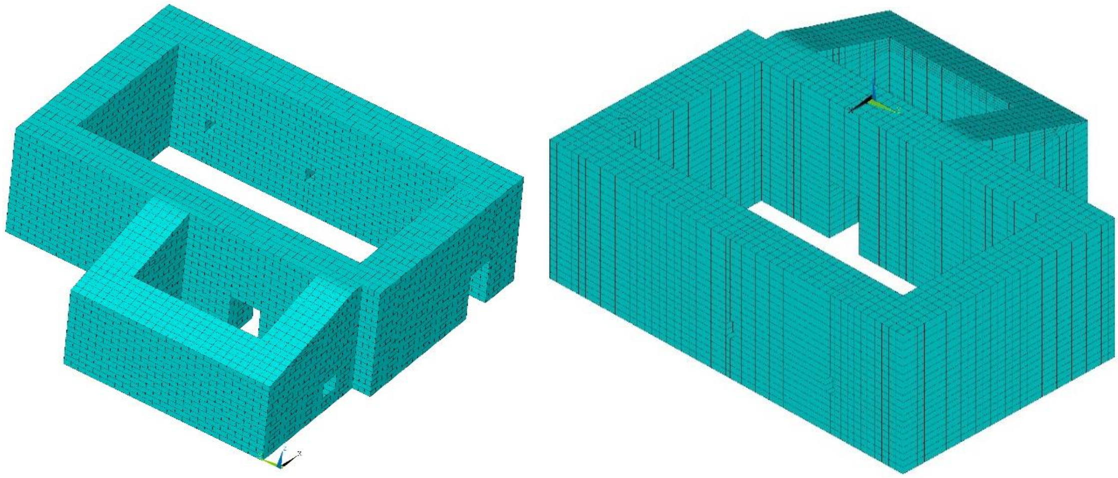


Fig. 6. Finite element model of the historical Ahi Musa Masjid

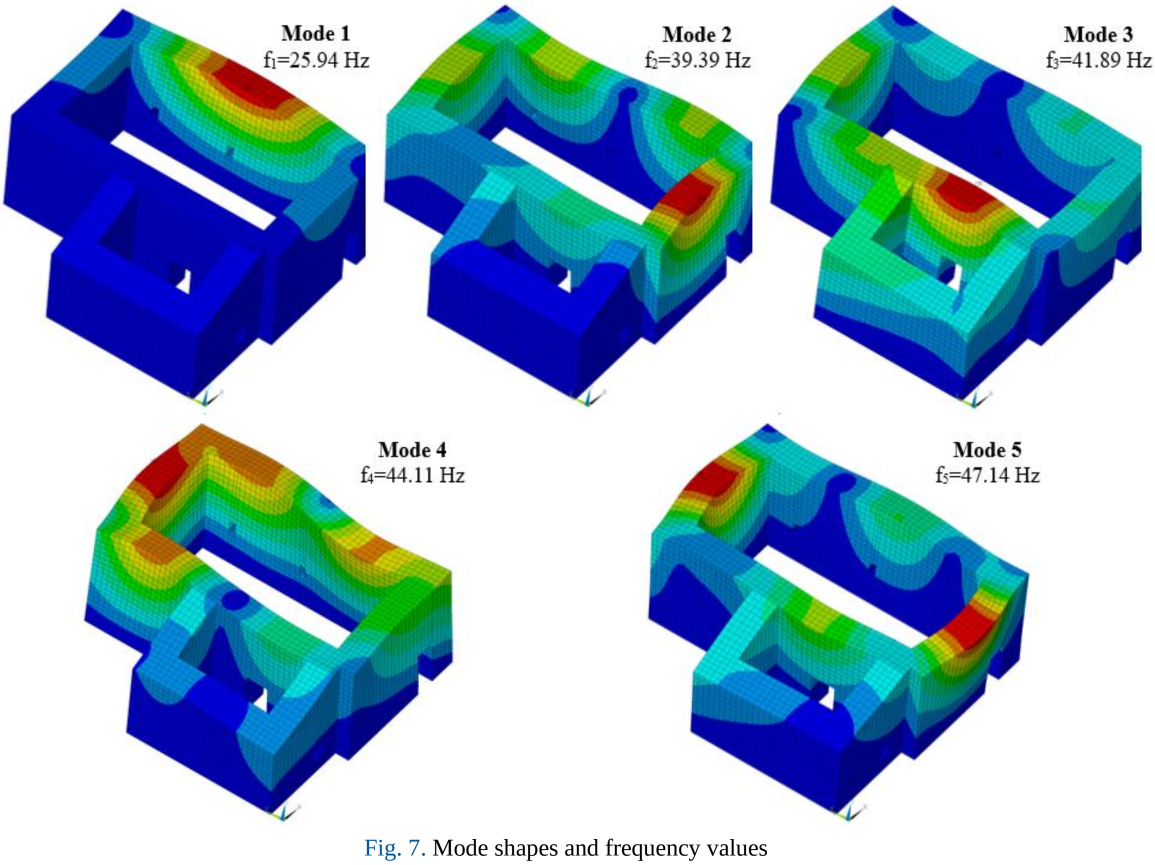


Fig. 7. Mode shapes and frequency values

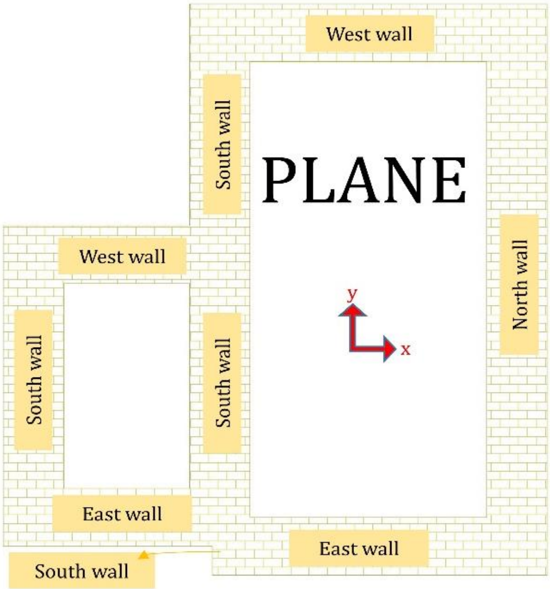


Fig. 8. Name coding of wall façades

6.1. Drifts control

It is acceptable for structures to drift within certain limits under the effect of earthquakes or similar loads. However, if these limits are exceeded, some structural damage is likely to occur. The drift rate limits vary according to the targeted performance level. In order to check that these limits are not exceeded, the maximum values of the drift ratios occurring in the structure should be accurately determined. The drift ratio is calculated as the ratio of the difference between the horizontal displacements of the points at different levels to the height difference. The maximum drift ratios obtained for the walls on each façade of the Masjid from the analysis of the historical Ahi Musa Masjid under the earthquake effect are given in Table 2.

For the values given in Table 2, the maximum horizontal drift ratios calculated for all walls of the historical Ahi Musa Masjid are smaller than the limit value (1.0%) for the CP performance level in the GMERHS-2017 [1] guideline. It is thought that the most important factor affecting this situation is that the 120 cm thick walls of the Masjid increase the lateral drift stiffness of the Masjid considerably.

Table 2. Maximum drift ratios obtained from the analysis of the Masjid under earthquake effect

Wall façade	Earthquake direction	Drift ratio (%)	CP Performance Level Limit (<%1.0)
West	x	0.054	√
	y	0.170	√
East	x	0.050	√
	y	0.165	√
South	x	0.079	√
	y	0.094	√
North	x	0.242	√
	y	0.085	√

6.2. Compressive stresses control

The historical Ahi Musa Masjid consists of walls using cut stone as masonry units. The compressive strength value for these walls was selected as 12.34 MPa based on the results of the experimental study conducted by Gönen and Soyöz [23]. The maximum compressive stress values obtained for the walls on each façade of the Masjid in the analyses performed for the CP performance level are given in Table 3. The values obtained should not exceed ~1.5 times the stone wall compressive strength of 12.34 MPa for CP performance level [1].

The absolute maximum compressive stress values obtained from the analyses of the Masjid for the CP performance level did not exceed the stone wall compressive strength of 12.34 MPa for all walls. The compressive stress contour plots for these performance level solutions are given in Fig. 9.

6.3. Shear stresses control

The forces such as earthquakes etc. cause shear stresses in the structures. These stresses are resisted by the shear strength of the walls in masonry structures. If the shear strength of the walls is exceeded, damage is expected to occur. The characteristic shear strength of the walls can be calculated using Eq. (3) in TBEC-2018 [24] and is given below:

$$f_{\mathrm{vk}} = f_{\mathrm{vk0}} + 0.4\sigma_{\mathrm{d}} \leq 0.1 f_{\mathrm{b}} \tag{3}$$

Here, f_{vk} is the characteristic shear strength of the wall obtained using the average vertical stresses in the wall, f_{vk0} is the characteristic shear strength in the absence of axial stresses, σ_d is the vertical compressive stress calculated under the joint effect of vertical loads and earthquake loads multiplied by the load coefficients, and f_b is the standardised average compressive strength of the masonry unit [24]. In this study, for the initial shear strength f_{vk0} of the walls, the value of 0.10 MPa given in TBEC-2018 (Table 11.3) for walls constructed using natural or artificial stone masonry units and general purpose mortar was used. The maximum shear stress values obtained from the analyses for the CP performance level are given in Table 4 for the walls on each façade of the Masjid.

When the shear stress values obtained from the analyses of the Masjid for the CP performance level were analyzed, it was determined that the calculated shear stresses were not exceeded in any of the wall. Shear stress contour plots for CP performance level solutions are given in Fig. 10.

6.4. Determination of the earthquake performance of the Masjid

The performance levels that can be selected for historical buildings depending on the importance of the building are given in Table 1. As can be seen from Table 1, more than one performance level is envisaged for a building of a certain significance. While a more advanced performance level is recommended for universal importance, a lower performance level is recommended for local importance. A higher level of performance, i.e. less damage in the event of a major earthquake, may require a comprehensive intervention. For the historical Ahi Musa Masjid, an assessment was made for the CP performance level.

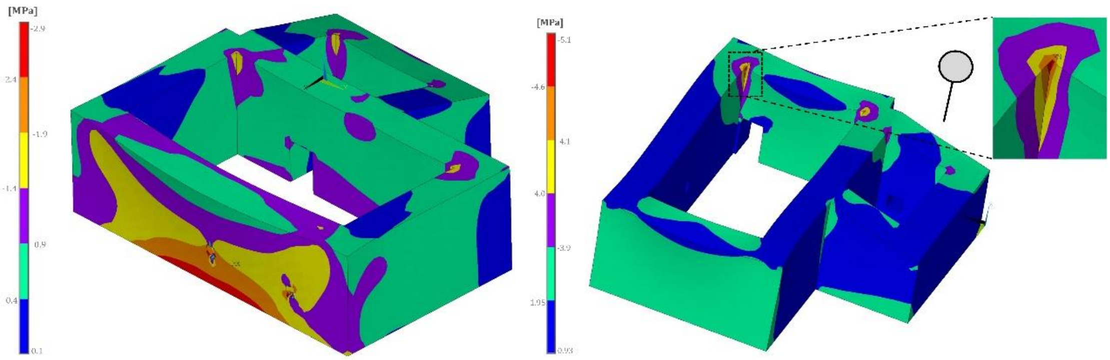
The maximum drift ratio obtained for the linear solutions of the historical Ahi Musa Masjid under earthquake effect is 0.242%. In GMEHRS-2017 [1], the drift ratio limit for CP performance level is 1.0%. This shows that the Masjid is below the CP performance level in terms of drift ratios.

The compressive and shear stresses of the historical Ahi Musa Masjid were checked for CP performance level depending on the solutions performed under vertical load and earthquake effect reduced by $Ra \leq 3$. In terms of compressive stresses, 5.08 MPa value was obtained as the largest value in absolute value. This value is lower than the stone wall compressive strength of 12.34 MPa. In terms of shear stresses, values in the range of 0.88-1.41 MPa in absolute value were obtained and these values are lower than the shear stress values calculated in the range of 0.96-3.2 MPa in absolute value for each wall.

The linear earthquake solutions of the historical Ahi Musa Masjid showed that the historical Ahi Musa Masjid provided CP performance level when evaluated in general in terms of drift ratios, compressive stresses and shear stresses.

Table 3. Maximum compressive stress values in absolute value obtained from the analysis of the Masjid under vertical load and reduced predicted earthquake effect

Wall façade	Earthquake direction	Compressive stress (MPa)	CP Performance Level (<12.34 MPa)
West	x	2.00	√
	y	1.57	√
East	x	2.34	√
	y	5.08	√
South	x	2.34	√
	y	4.50	√
North	x	2.34	√
	y	5.08	√



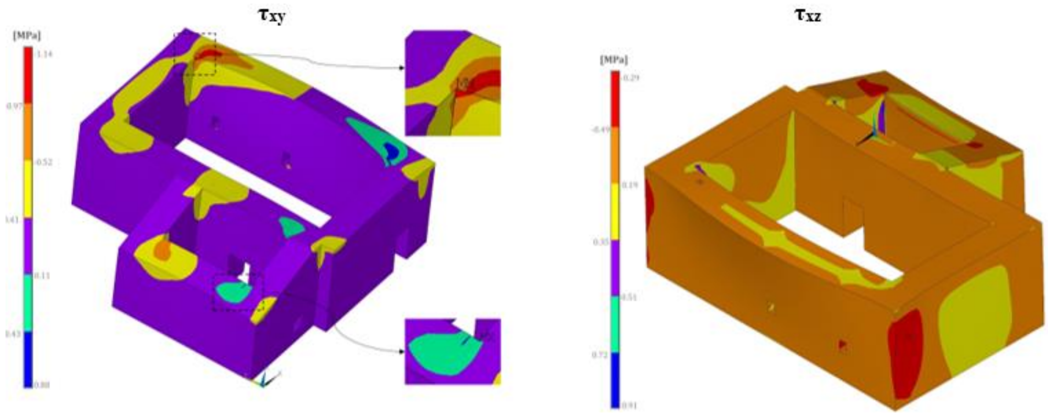
(a) x-direction solutions (b) y-direction solutions

Fig. 9. CP performance level compressive stress contour plots

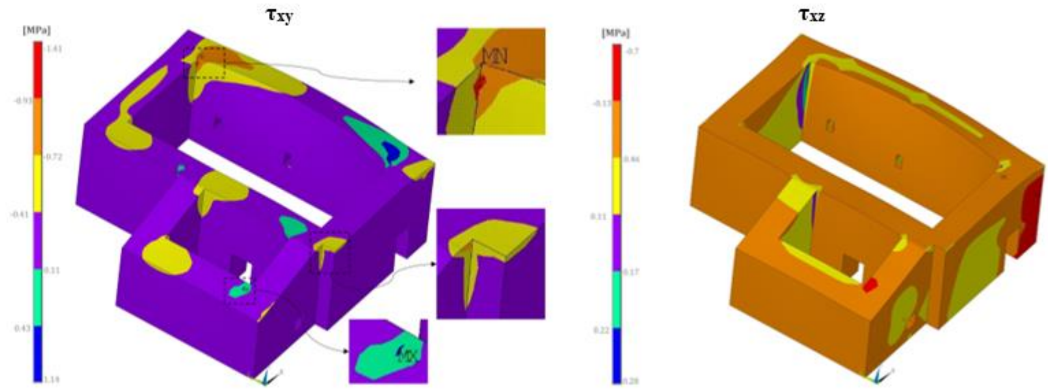
Table 3. Maximum shear stress values in absolute value obtained from the analysis of the Masjid under vertical load and reduced predicted earthquake effect

Wall façade	Earthquake direction	Shear stress (MPa)		CP Performance Level Limit (Occurring < Calculated)
		Calculated (MPa)*	Occurring (MPa)	
West	x	1.20	0.88	√
	y	1.10	0.98	√
East	x	0.96	0.91	√
	y	3.20	0.91	√
South	x	1.56	0.88	√
	y	2.85	1.14	√
North	x	1.55	1.14	√
	y	3.20	1.41	√

* Calculated shear stress values are multiplied by 1.5.



a) x-direction solutions



b) y-direction solutions

Fig. 10. CP performance level shear stress contour plots

7. Conclusions

Historical structures, which are the reflection of past cultures to the present, are the cultural heritage of societies. While many new structures today cannot show sufficient strength under loads such as earthquakes, these cultural heritage structures have been able to survive for centuries. It is important to know the structural conditions of these structures in order to show the adventure of these structures to future societies and to ensure that these historical structures can be left to these societies as cultural heritage.

In this study, the historical Ahi Musa Masjid, which was built about nine centuries ago, was examined. Firstly, studies were carried out to determine the geometric and material properties of the structure and then a finite element model of the Masjid was created. The equivalent earthquake loads calculated using the earthquake spectra selected specifically for the location of the Masjid and the vertical loads of the structure were applied to this finite element model according to the Guidelines for the Management of Earthquake Risks for Historical Buildings (GMEHRS-2017) prepared by the General Directorate of Foundations and linear earthquake analyses were performed. As the target performance level of the Masjid, the Collapse Prevention (CP) performance level, which is one of the performance levels recommended for historical structures of local importance in GMEHRS-2017, was used. As a result of the analyses, the following results were obtained:

- In terms of drift ratios, a drift ratio below the limit value (1.0%) was obtained.
- In terms of compressive stresses, values lower than the stone wall compressive strength of 12.34 MPa were obtained.

• In terms of shear stresses, no wall shear stress exceeded the calculated shear stress value.

The linear earthquake solutions of the historical Ahi Musa Masjid showed that the Masjid provided the Collapse Prevention (CP) performance level, which is the most advanced level in terms of performance levels. While the linear calculation method is sufficient when the structural behavior is close to the elastic limit, the non-linear behavior calculation method is more appropriate when the inelastic deformations are significant in cases close to collapse. Although this study provides a practical approach for determining the earthquake performance of historical structures, it would be useful to perform non-linear behavior solutions in the process of determining the earthquake behavior of the historical Ahi Musa Masjid. It should also be noted that the material properties were not experimentally determined in this study and therefore were selected based on the studies in the literature.

Conflict of interests

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

Funding

This research received no external funding.

Data availability statement

No new data were created or analyzed in this study.

References

[1] GMEHRS (2017) Guidelines for the Management of Earthquake Risks for Historical Structures. General Directorate of Foundations. Ankara, Turkiye.

[2] URL-1. http://www.koeri.boun.edu.tr/sismo/2/deprem-bilgileri/buyuk-depremler/. Accessed 23 Jan 2023.

[3] Aksoy E, Aydoğmuş F (2017) The earthquake analysis of historical monuments: The case of Kargı Han. In: Uluslararası Katılımlı 6. Tarihi Yapıların Korunması ve Güçlendirilmesi Sempozyumu. Trabzon, Türkiye (in Turkish).

[4] Aslan A (2016) Earthquake Performance Evaluation of Süleymaniye Mosque Depending On Local Soil Conditions. PhD Dissertation, Yıldız Technical University.

[5] Şeker BŞ (2017) Investigation of the structural performance of Alaca Minaret Mosque. Vakıflar Dergisi 48:137-143.

[6] Çakır F, Şeker BŞ, Doğangün A (2014) Assessment of structural performance of historical Ishan church. Građevinar 66(5):433-443.

[7] Cakir F, Seker BŞ, Durmus A, Dogangun A, Uysal H (2015) Seismic assessment of a historical masonry mosque by experimental tests and finite element analyses. KSCE Journal of Civil Engineering 19(1):158-164.

[8] Ercan E (2018) Assessing the impact of retrofitting on structural safety in historical buildings via ambient vibration tests. Construction and Building Materials 164:337-349.

[9] Güllü H, Karabekmez M (2016) Gaziantep Kurtuluş camisinin deprem davranışının incelenmesi. Dicle Üniversitesi Mühendislik Fakültesi Mühendislik Dergisi 7(3):455-470 (in Tuırkish).

[10] Kocaman İ, Kazaz İ, Okuyucu D (2018) Tarihi Erzurum Yakutiye Medresesi'nin yapısal davranışının incelenmesi. Journal of Science and Engineering 20(58):36-51 (in Turkish).

[11] Maraş MM, Özmen A, Sayın E, Ayaz Y (2022) Seismic assessment of the historical Sütlü Minaret Mosque. Periodica Polytechnica Civil Engineering 66(2):445-459.

[12] Kumbasaroğlu A, Çelik A (2019) Eşdeğer deprem yükü yöntemi kullanılarak tarihi bir yığma yapının sismik performans düzeyinin belirlenmesi. Erzincan Üniversitesi Fen Bilimleri Enstitüsü Dergisi 12(3):1590-1600 (in Turkish).

[13] Çarhoglu Aİ, Zabin P, Korkmaz KA (2014) Kars Kümbet camisinin deprem davranışının incelenmesi. Gazi University Journal of Science Part C: Design and Technology 2(1):189-196 (in Turkish).

[14] Korkmaz K, Zabin P, Çarhoğlu A, Nuhoğlu A (2014) Rize Merkez Kurşunlu Camisi'nin deprem davranışının incelenmesi. Sakarya University Journal of Science 18(3):149-156 (inTurkish).

[15] Kocaman İ, Kazaz İ, Gürbüz M (2017) Tarihi yapıların sismik yük kapasitelerinin değerlendirilmesi: Lala Paşa Cami Örneği. 4. Uluslararası Deprem Mühendisliği ve Sismoloji Konferansı. Eskişehir, Türkiye (in Turkish).

[16] Kazaz İ, Kocaman İ (2018) Seismic load capacity evaluation of stone masonry mosques. Journal of the Faculty of Engineering and Architecture of Gazi University 33(2):557-573.

[17] Aşıkoğlu A, Avşar Ö, Lourenço PB, Silva LC (2019) Effectiveness of seismic retrofitting of a historical masonry structure: Kütahya Kurşunlu Mosque, Türkiye. Bulletin of Earthquake Engineering 17:3365-3395.

[18] Kamanlı M, Jaihoon EH, Ünal, A (2019) TBDY 2018'e göre tarihi Sille Ak caminin statik analizi. Selcuk University Journal of Engineering Sciences 18(3):134-151 (in Turkish).

[19] Çakmak Ş (2006) Hüzünlü Kent: Harput. Sanat Tarihi Dergisi 15(2):137-164 (in Turkish).

[20] Danık E (1998) Harput Ahi Musa Mescid ve Türbesi. Türk Kültürü Araştırmaları 34(1-2) (in Turkish).

[21] Memişoğlu F (1973) Harput Bakırcılığı. Türk Etnografya Dergisi 63:37-58 (in Turkish).

[22] URL-2. https://harput.web.tr/harputun-tarihi-eserleri/harputun-turbeleri/ahi-musa-mescidi-ve-turbesi/. Accessed 23 Jan 2023.

[23] Gönen S, Soyöz S (2021) Investigations on the elasticity modulus of stone masonry. Structures 30:378-389.

[24] TBEC (2018) Türkiye Building Earthquake Code. Disaster and Emergency Management Presidency. Ankara, Turkiye.

[25] URL-3. https://www.google.com.tr/maps. Accessed 23 Jan 2023.

[26] Türkiye Earthquake Hazard Maps Interactive Web Application, https://tdth.afad.gov.tr. Accessed 23 Jan 2023.

[27] Lourenço PB (1996) Computational Strategies for Masonry Structures. PhD Dissertation, Delft Technical University of Technology.

[28] Calayır Y, Yetkin M, Erkek H (2021) Finite element model updating of masonry minarets by using operational modal analysis method. Structures 34:3501-3507.

[29] Ansys Inc (2015) Finite Element Software, Swanson Analysis System.