Seismic Assessment of Historical Timber Bekdemir Mosque

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***Abstract*—Timber, which is one of the oldest building materials from the past to the present, is used as a local material in forested areas. Timber is a frequently preferred material due to its high tensile-pressure strength. Due to the widespread supply of timber materials in the Black Sea Region of Turkey, mosques were built with a timber structure. In historical timber mosques, the walls, columns, and roof material are made of wood. It is necessary to preserve and transmit to the further generation the historical timber mosques, which have the architectural characteristics of the period in which they were built with the building materials and construction techniques. Since Turkey is an earthquake zone, it is important to analyze the seismic behavior of historical buildings. Although there are many studies in the literature on the behavior of historical buildings during earthquakes, there are limited studies on timber mosques. To investigate the behavior of the timber mosques, which constitute the importance of the study, during the earthquake, a historical mosque with timber structures in the province of Samsun was determined as the study area. In this context, the mosque was created in three dimensions with the ETABS program to make the finite element analysis, and dynamic analyzes were made to determine its seismic behavior. As a result of the analysis, it has been determined that the mode shapes formed in the building with high mass participation rate are in the form of translation in both orthogonal directions, high stresses occur on the timber masonry wall that forms the harim, high stresses occur under the effect of earthquakes, and the boundary stress values are exceeded in the columns that are not rigidly connected to each other in the floor. As a result, proposal have been made to transfer the originality of this type of mosques, which are a part of cultural heritage, to future generations and to strengthen them for the continuity of identity.**

Keywords—culturel heritage; finite element method; ETABS; timber mosques; Samsun; seismic analysis; urban identity

I. INTRODUCTION

Historical buildings provide information about the period in which they were built, the architectural features of the period, the architectural style, building technology and ideology. The physical environment, which form according to culture, history, and geography, gives information about the traditions and norms of societies. Wood, which is one of the oldest building materials from the past to the present, has been widely used as vernacular architecture in Turkish architecture because it is a local material. Although natural wood is mostly used in traditional dwellings, it has also been used in monumental buildings because of its distance passing capacity.

The first timber mosque in Anatolia, 13th century. was built at the beginning. Timber mosques, the characteristics of Central Asian architecture, were built during the Great Seljuk State, Anatolian Seljuk, Principalities and Ottoman Empires periods. The building material of the walls, columns and roof of the masonry mosques build wood. Structures have been built with different building materials in accordance with different climatic regions of Turkey. Wood, stone, brick, and adobe materials are widely used in dwellings and historical buildings in Turkey. Wood, which is a building material, is used as a very common local material in the Black Sea Region of Turkey due to the forested areas. It is a frequently preferred material due to the high stress-compressive strength of wood. Due to this feature, it is an important material in terms of earthquake resistance. The preservation and sustainability of timber mosques, which have a place in the urban memory of the society they belong to and reflect the identity of the city, are important. Since Turkey is located in an earthquake zone, it is necessary to analyze the behavior of historical buildings under seismic effects. It is very important for the continuity of cultural heritage to model and analyze these structures architecturally and statically, to examine their seismic behavior, to preserving its unique and structural strengthening works with restoration through computer programs.

Although there are many studies examining the seismic behavior of historical buildings in the literature, studies examining the seismic behavior of timber structured historical buildings are very limited. Pagano, Ruggieri, Zampilli, and Salerno [16] suggested a method designed to assess the systemic capacity of a historic timber-framed masonry system. The in-plane mechanical behavior of a single wall is analyzed at two different scales and modeled with a multi-scale approach. In the study, the mechanical behavior of a single wall is analyzed at two different scales and modeled with a multi-scale approach. In the study of Poletti and Vasconcelos [18], the seismic behavior of timber frame walls was investigated by considering different filling types such as masonry infill, lath and plaster and timber frame with no infill. In this study, static cyclic tests have been performed on unreinforced timber frame walls in order to study their seismic capacity in terms of strength, stiffness, ductility and energy dissipation. In the study of Tsai and D'Ayala [22], lateral force, response spectrum and step-by-step pushover analyzes were made by comparing two structures that were severely affected by the earthquake. The results show that the proposed FE model with finite translational and rotational stiffness can be used successfully to evaluate the fragility of frames. Based on the methodology of the study, an evaluation methodology is proposed to optimize a retrofit strategy to protect these precious structures from future earthquakes and avoid unnecessary interventions. In another study of the same authors, linear analysis of Dieh-Dou timber structures, used as a traditional temple in Taiwan with Finite Element Model was performed under earthquake [8].

Based on a case study of Çalik, Bayraktar, Türker, and Ashour [6], the dynamic behavior of seven historical timber mosques with different geometric dimensions selected using the Ambient Vibration Testing and the Enhanced Frequency Domain Decomposition (EFDD) method in the Eastern Black Sea Region of Turkey were compared. As a result, empirical natural frequency formulas were developed for the first three modes based on the geometrical dimensions of the mosque with regression analysis. In the study of Branco and Neves [3], the effect of redundancy and ductility on the seismic behavior and strength of a long span timber structure was evaluated. Çelik and Birdal [7] made models of a historical mosque with a timber system, and because of static model analysis due to vertical loads, retrofitting proposals have been made for strengthening such mosques without ignoring their originality. Luo, Li, Wang, and Wang [15] examined the seismic performance of ancient timber structures under different earthquake records. The earthquake resistance of the buildings was analyzed by creating a finite element model.

Based on the satisfactory seismic performances of traditional timber construction systems, Ugalde, Almazán, María, and Guindos [23] conducted a research on the improvement of seismic timber design under earthquakes records and made proposal for timber structures to be constructed today. In the book of ICOMOS [13] on structures includes the uses of timber, material properties, laboratory analyzes and examples. The use of timber material in restoration and retrofitting proposals is given. Porcu, Bosu, and Gavrić [20] aimed to provide design purposes by analyzing the non-linear behavior of modern timber structures.

Although there are other papers [9; 11; 12; 14; 17; 19; 21] in the literature on historical timber mosques, timber materials, standards and timber structures in present, these studies are limited. In this context, this study, which is unique in that it has not been studied in the literature, aims at the continuity of cultural heritage by analyzing the earthquake behavior of historical timber structures.

II. ARCHITECTURAL PROPERTIES OF THE MOSQUE

Historical buildings provide information about the period in which they were built, the architectural features of the period, the architectural style, building technology and ideology. Bekdemir Mosque is located in the Kavak District of Samsun province. The mosque, which was built with the masonry timber structures, consists of two floors, the ground floor and the mahfil floor (women's specific space) (Fig.1).

According to Koniholm's findings in 1994, the ground floor of the mosque was built in 1596 and the mahfil floor was built in 1599 [1]. When the mosque was first built, it was not in its current location, it was built in a cemetery along the river and moved to its current location in 1876. The upper floor was rebuilt during the fire. It is stated that there is a minaret made of pine in the northwest corner of the mosque and it was destroyed in 1923, although a new minaret was built in its place [4]. The mosque does not have a minaret in present.

The length of the north and south façades of the building, which has a nearly square form, is 10.15 meters, and the length of the east and west façades is 10.55 meters. While the portico in the north is 2.65 meters, the porticoes in the east and west have a width of 1.55 meters. The eaves of the building from the porticoes are 1 meter [2]. The length of the north and south façades of the harim (main spaces) of the mosque is 7.50 m, and the length of the east and west façades is 7.45 m.

There is a semi-open space covered with U-shaped porticoes on the north, east and west of the mosque. On the north side, which is the entrance of the mosque, there is the last congregation area. The entrance of the mosque is narthex on the north side. There is an L-shaped stairs on the right side of the entrance door to reach the mahfil floor of the mosque. The mahfil floor is located along the east, west and north facades of the mosque. There are 18 timber columns in the part of the mosque surrounded by porticoes and 8 timber columns on the mahfil floor. While there are 7 timber columns equally spaced in the east and west sides of the mosque, there are 6 timber columns on the north side. While the bottom and top of the timber columns of the mosque from the ground to the upper cover are square, the middle parts are circular. Timber masonry walls were built by interlocking at the corners, called the kurtbogaz crossing technique.

The wall of the harim is connected by timber masonry wall with a thickness of 5 centimeters, which are interlocked at the corners with a kurtbogaz crossing technique. The corner joints of the masonry walls are connected by the channeled timber fitting technique of the horizontal timbers called çalmaboğaz. Oak was used in the construction of the mosque [2].

The mihrab is located on the south wall of the entrance door axis to the north of the mosque. The pulpit is on the west side of the mihrab. The mosque is covered with flat horizontal timbers from the inside. The roof with wide eaves carried by timber columns in the portico is covered with Marseille type tiles. There are fourteen windows in two rows in the harim of the mosque. While there are two windows in the form of two orders in the east, west and south directions of the mosque, there are two windows in a single order on the north facade. On the ceiling of the harim, it is decorated with a detail that shrinks from square to octagon.

Root paint was used in the ornaments with floral motifs on the mihrab, mihrab wall, pulpit, mahfil, ceiling and portal of the mosque [4].

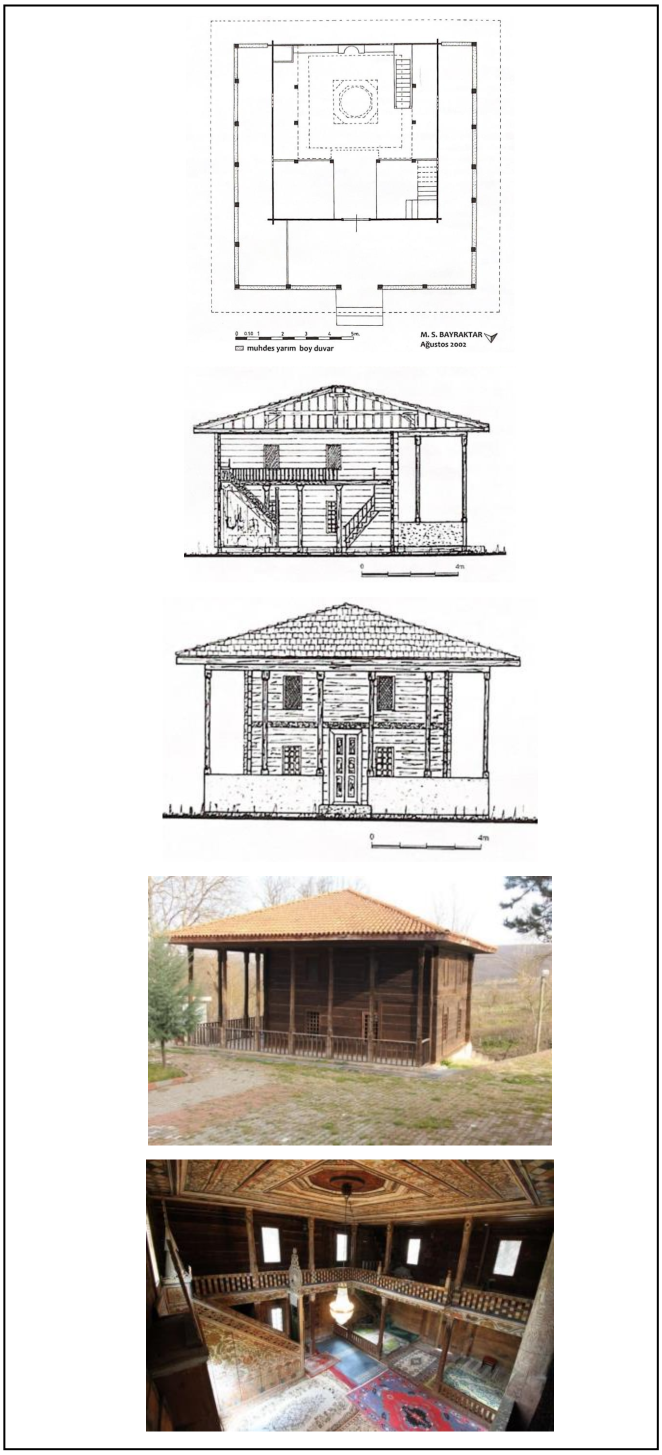

Fig. 1. *Bekdemir Mosque plan, section and view [2] [24]*

III. FINITE ELEMENT MODEL OF THE MOSQUE AND MATERIAL PROPERTIES

It is important to determine the earthquake effect that causes the most destructive damage in buildings, to prevent irreversible damage. With the advancement of technology, it can be analyzed by modeling the structures by using 3D programs in the computer environment. The stress and displacement values that will occur in the structure on the modeled structure can be determined. According to these analyzes, it is possible to protect the damages that will occur in the structure by taking the necessary strengthening and reinforcement with restoration works.

TABLE I. PHYSICAL AND MECHANICAL PROPERTIES OF OAK TIMBER [25]

Unit weight (kg/cm³)	**Young Modulus (kgf/cm²)**		**Shear modulus (kgf/cm²)**
	E (Parallel to fibers)	**E (Perpendical to fibers)**	
890	125000	6000	10000
Tensile strength (parallel to fibers) (kgf/cm²)	**Compressive strength (perpendical to fibers) (kgf/cm²)**	**Compressive strength (parallel to fibers) (kgf/cm²)**	**Shear Strength (kgf/cm²)**
110	100	100	10

TABLE II. HORIZONTAL LIMIT DISPLACEMENT VALUES [25]

Status	Limit Drift
Intact	1/120 (0.0083)
Minor Damage	1/60 (0.0166)
Modarate Damage	1/30 (0.0333)
Serious Damage	1/15 (0.0666)
Collapse	>1/15 (>0.0666)

In this context, in the first stage, the architectural construction details of a historical timber mosque selected as the case study were examined. For the analyzes to reflect reality at the best level, the historical building was modeled in the ETABS [10] program. According to the plan and section dimensions of the mosque, a 3D model was created in the digital program. In the program, columns and beams were formed with bar elements, and masonry walls with shell elements. As a result, the historical building was analyzed by ETABS program using the finite element method. Since the construction material of Bekdemir Mosque is oak, linear elastic material property was used for oak in the analysis. These material properties are given in Table I and displacement limits are given in Table II.

Timber has been one of the first building materials used in buildings to meet the shelter needs of people. In the past, timber masonry techniques were used in the building, then the timber frame system was discovered. The material selection and usage knowledge of the old, which shows a time-dependent and traditional development, and today's natural wood material usage technique show little difference. For example, the technique used in Phrygia for the first time in the timber roof building and the techniques used today are very similar to each other [25].

IV. LINEAR DYNAMIC ANALYSISES OF THE MOSQUE

A. Modal Analysis

Effective mode shapes and periods are given in the figure. When the mode 3 shape is examined, it is seen that the mode shape is a translation in the X direction (Fig. 2). With the translation effect, out-of-plane displacements are observed in the timber masonry wall in both directions. Large displacements are observed in the columns in the middle part directly connected to this timber masonry wall. In mode 4, which is another effective mode in the X direction, the columns on the first axis of the northern façade are translation. While no significant displacements were observed in the other mosque parts in this mode, displacements appeared in the beams connecting the columns on the first axis to the harim and other columns (Fig. 3).

In Mode 5, which has the highest mass participation rate in the Y direction, the movement emerges as the translation of the columns on the first axis of the mosque portal, together with the columns and walls of the harim (Fig. 4). In the translational movement in the sanctuary, it is seen that the northern façade makes more translations than the southern façade (qibla wall). In the 12th mode, which is one of the effective mode shapes in the Y direction, the movement appears as the translation of the mass outside the harim in the north-south direction. In the mosque plan, both façade columns on the second axis starting from the northern façade emerge as the building parts with the highest displacement value (Fig. 5).

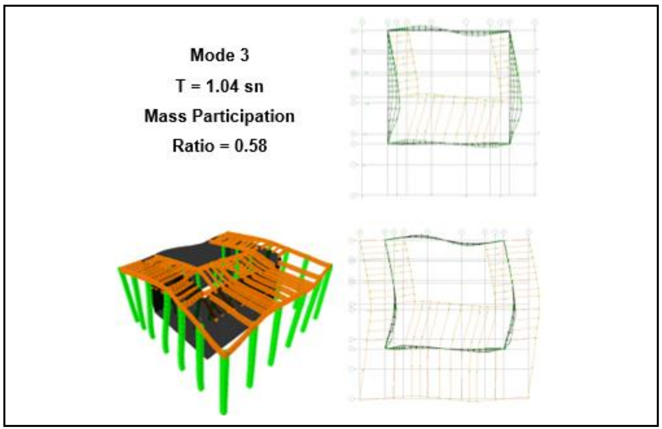

Fig. 2. *3th mode shapes of the mosque*

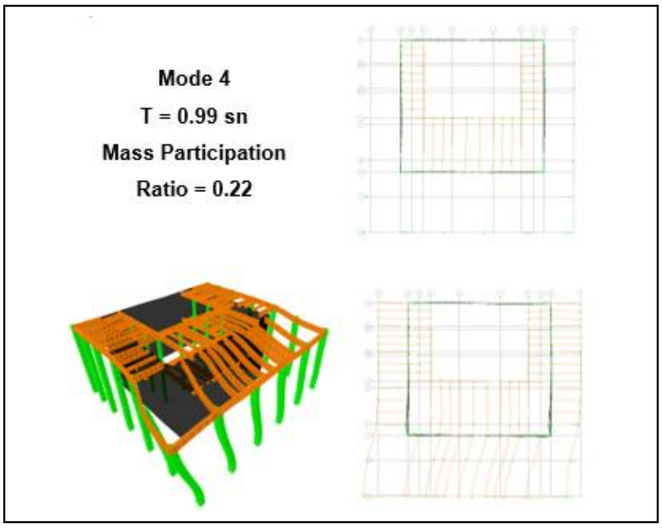

Fig. 3. *4th mode shapes of the mosque*

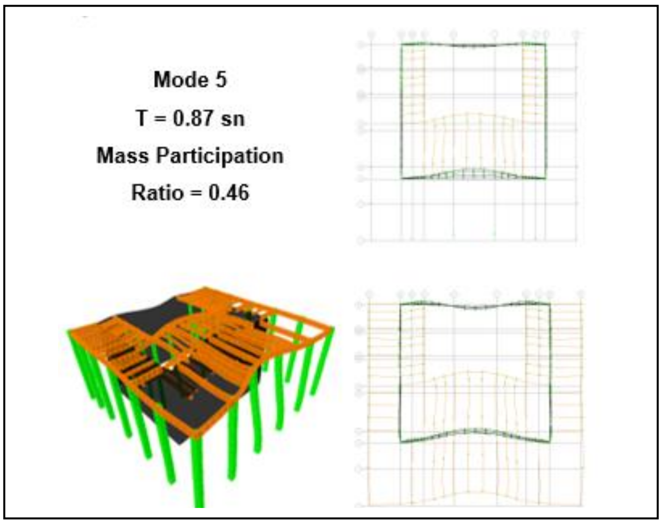

Fig. 4. *5th mode shapes of the mosque*

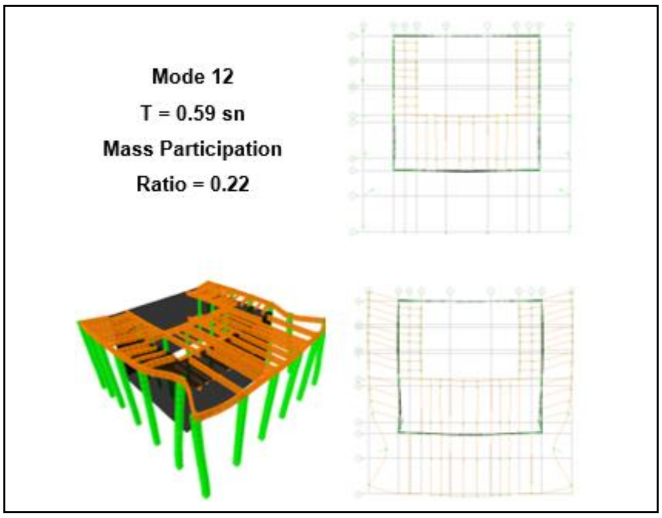

Fig. 5. *12th mode shapes of the mosque*

B. Time History Analysis of The Mosque Under Acceleration Records of Erzincan Earthquake

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.

Samsun is also located on this fault line (Figure 6). The historical wooden Bekdemir Mosque, selected as the case study, is in Samsun Province of Turkey, which is in the earthquake zone. It is important for conservation to determine the parts of the historical mosque that have the potential to be damaged in a possible earthquake. Accordingly, the acceleration record values of a magnitude 6.8 earthquake that occurred on March 13, 1992 at 19:19 in Erzincan, where is an eastern country of Turkey, and that caused major damages to the buildings in Samsun, Turkey were examined in the analyses. Samsun province, located on the North Anatolian fault line, lies in the east-west direction due to the pressure between the Arabian 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. Records of the earthquake that occurred in 1992 when 653 people died and 6702 buildings [5] were severely damaged are given in the Figure 7. 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 [27]. 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.

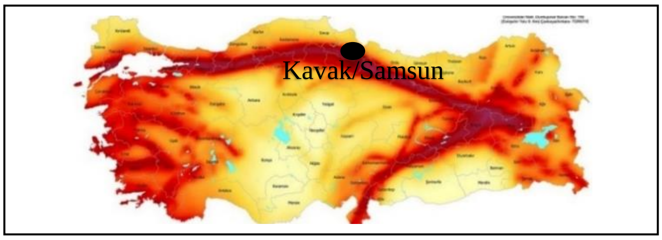

Fig. 6. Seismic Hazard Map of Turkey and Location of Kavak District Samsun Province in Turkey [26]

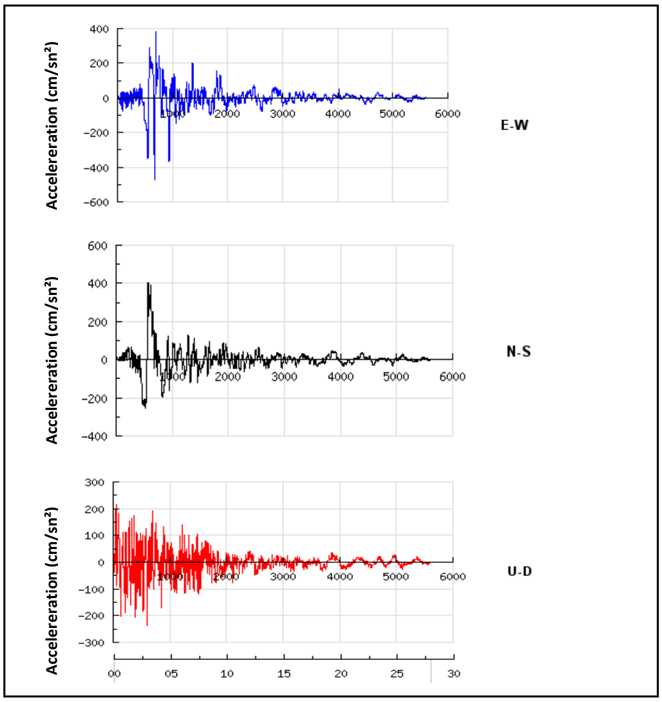

Fig. 7. *Acceleration Record Values of Erzincan (cm/sec2)*

1) *North-South (NS) Direction*

The principal stress values occurring on the harim of the timber masonry walls under the earthquake acceleration record in the north-south direction are given in the Figure. The maximum value is 7700 MPa, which is quite a high value. These high values are at the upper points of the timber masonry wall, especially close to the corner joints. The principal stress value across the wall is approximately 1100 MPa. The stresses are above the safety stress value (Fig. 8).

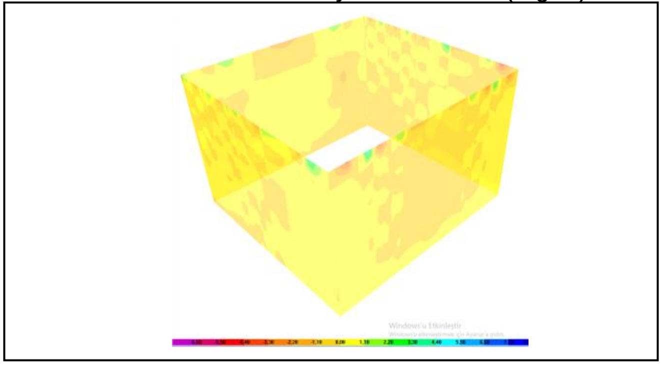

Fig. 8. *Principal stress propagation at Step 580*

The shear stress distribution under earthquake records is given in the figure. The highest shear stress value of the historical building is 350 MPa. While the high values of the stress values are obtained at the upper points of the masonry timber wall, the shear stresses formed in the other parts of the wall are around 50 MPa. The stresses determined as a result of the analyzes are above the safety stress value (Fig. 9).

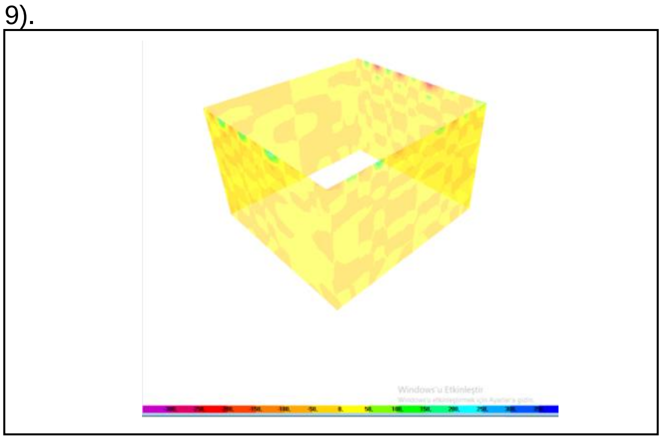

Fig. 9. *Shear stress propogation at Step 580*

The drift values are obtained by dividing the drift by the story height. The drift values of the historical timber mosque at same point are given in Table 3. Drift limit values are given for timber structures. It was determined that the values obtained as a result of the analyzes were within the limit values [15].

The calculated stress values in some selected columns are given in the Table IV, depending on the normal force and moment values formed under the earthquake acceleration record in the north-south direction. Columns exceeding the safety stress value were determined as C35 and C37 (Fig. 10).

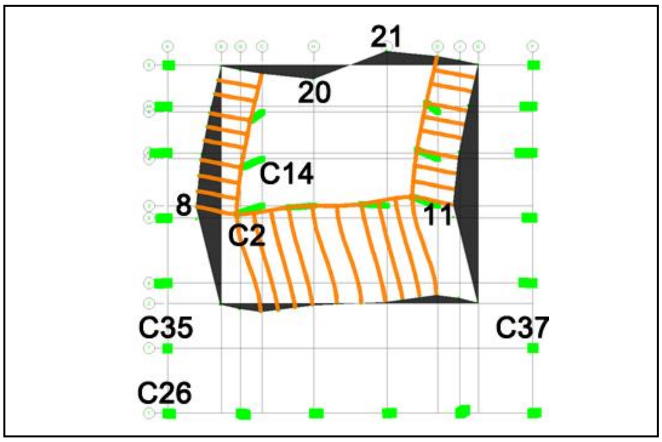

Fig. 10. *Deformation propogation at Step 580*

TABLE III. THE HIGHEST DRIFT VALUE OF SAME POINTS OF THE HISTORICAL BUILDING IN THE NS DIRECTION

Point ID	Drift	Limit Drift Value	Comparison
20	0.0006	0.0083	0.0006<0.0083
21	0.0006	0.0166	0.0006<0.0166
8	0.000098	0.0333	0.000098<0.0333
11	0.000097	0.0666	0.000097<0.0666

TABLE IV. STRESS CALCULATIONS OF SAME COLUMS OF THE HISTORICAL TIMBER MOSQUE IN THE NS DIRECTION

Column	N (kg)	F (cm^2)	M (kg.cm)	W (cm^3)	Stress (kg/cm^2)	Safety Value (kg/cm^2)
C37	494,46	625	-329046	2604	-125,571	110
C2	-1909,54	625	-6898,13	2604	-5,70432	110
C35	504,13	625	334465	2604	129,2494	110
C26	2125,78	225	-1251,83	562,5	7,222436	110
C14	-33,42	225	1891,75	562,5	3,214578	110

2) *East-West (ES) Direction*

In the analysis under the earthquake recording in the east-west direction, it is seen that the stresses on the harim of the masonry timber walls have high values at the top of the wall, at the corner points and at the middle surface of the qibla wall. The maximum value is 2800 MPa. The values obtained are above the safety stress value (Fig. 11).

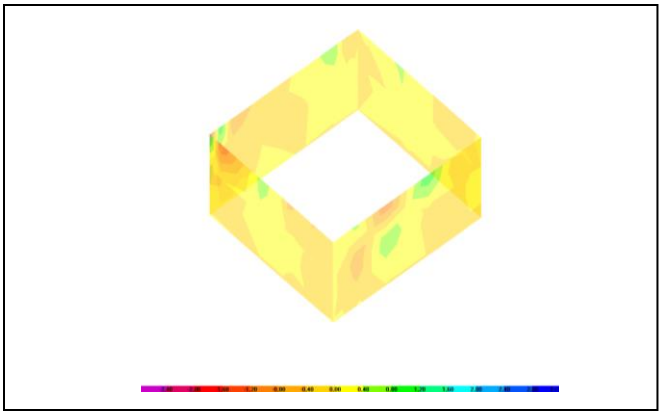

Fig. 11. *Principal stress propogation at Step 700*

The shear stresses formed under the earthquake recording in the east-west direction are given in the Figure 12. At the upper points of the harim of the masonry timber walls, shear stresses are high. Values are above the safety stress value.

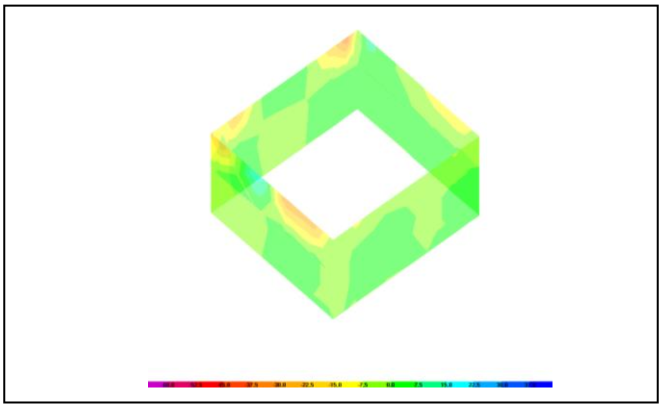

Fig. 12. *Shear stress propogation at Step 700*

The translation values at the points where the highest displacements occur because of the analyzes are given in the Table V. The obtained values are below the given limit values.

TABLE V. THE HIGHEST DRIFT VALUE OF SAME POINTS OF THE HISTORICAL BUILDING IN THE EW DIRECTION

Point ID	Drift	Limit Drift Value	Comparison
3	0,000013	0.0083	0,000013<0.0083
14	0,000016	0.0166	0,000016<0.0166
36	0,000135	0.0333	0,000135<0.0333
402	0,000012	0.0666	0,000012<0.0666

The calculated stress values in some columns selected depending on the normal force and moment values formed under the earthquake acceleration record in the East-West direction are given in the Table VI. It is seen that the safety stress value is under the earthquake record in this direction. As a result of the analyzes made, it was determined that while the safety stress value was exceeded under the earthquake acceleration records in the north-south direction, it was not exceeded in the east-west direction.

TABLE VI. STRESS CALCULATIONS OF SAME COLUMS OF THE HISTORICAL TIMBER MOSQUE IN THE EW DIRECTION

Column	**N (kg)**	**F (cm^2)**	**M (kg.cm)**	**W (cm^3)**	**Stress (kg/cm$^{2)}$**	**Safety Value (kg/cm$^{2)}$**
C37	8,12	625	1798	2604	0,703468	110
C2	-175,21	625	19630	2604	7,258066	110
C35	-7,63	625	460,44	2604	0,164612	110
C26	-10,59	225	4759	562,5	8,413378	110
C37	8,12	625	1798	2604	0,703468	110

V. CONCLUSION

Historical buildings, which are one of the components of cultural heritage, form the unique identities of cities. The identities of cities are lost because of the damage of structures exposed to various external influences in process of time. Earthquakes, whose intensity, and time cannot be predicted, are one of the natural disasters that most damage historical structures. The damages that will occur in historical buildings can be determined in advance by analyzing them under the most severe earthquake acceleration records so far. Historical timber mosques, which are built using the local building material timber in forest areas, are an important part of the cultural heritage. It is necessary to analyze these structures under earthquake acceleration records, to analyze their seismic behavior and to conservation them with restoration works. In this study, it was aimed to determine the seismic performance of a historical timber mosque in the Kavak district of Samsun province. For this purpose, the mosque has been modeled with the finite element method so that it can be analyzed under earthquake acceleration records. Within the scope of the study, firstly, modal analysis was performed with the finite element method. In the second stage, the historical building was analyzed under earthquake loads in the orthogonal direction as north-south and east-west. The results obtained because of the analyzes made on the historical building determined as a case study are as follows:

- When the mode shapes of the mosque are examined, the effective mode shapes emerge as translations in both orthogonal directions. Out-of-plane displacements are observed in the 5 cm thick timber masonry wall that forms the harim, perpendicular to the direction of movement.
- The columns on the west and east sides, which are on the second axis in the plan on the northern side of the mosque, have high displacement values since they are not connected to each other by beams in the floor plane. These results reveal the necessity of providing rigidity by designing a frame system in such structures.
- As a result of the analysis, it is seen that the principal and shear stresses formed under the earthquake load have values far above the safety stress values and occur predominantly at the upper points of the timber masonry wall. The findings show that the thickness of the timber masonry wall is insufficient. At the points where the stress is high, the beams with higher rigidity point this masonry wall. When the mosque was first built, creating a frame system with columns and beams, and designing it as masonry with timber material is determined as a factor that improves the seismic behavior of the mosque. In order to conservation the historical structure in restoration works, it is necessary to close the upper parts of the masonry wall with wide beams and to increase the rigidity of these beams by connecting the beams passing over the portico.
- In the analyzes made on the historical building, the displacements that occur under the earthquake load in the north-south and east-west directions are within the limit values. The displacements caused by the earthquake load effect on the mosque are at a level that does not endanger the seismic safety of the building.
- When the stress calculations made on the columns of the timber masonry mosque are examined, it is seen that the safety stress values are exceeded only in the C35 and C37 columns under the earthquake record in the north-south direction. The reason for exceeding the value in these columns was determined as the lack of sufficient rigid connection to the other columns. For these columns to be rigid, the necessity of forming a frame system is emphasized.
- For the seismic behavior of such timber buildings to be more stable and safer, it is considered important to increase the thickness of the timber masonry walls and to create frame systems that continue in both directions.

It is thought that the results of the study will be beneficial to the technical staff and related restoration works in this field. It is hoped that the earthquake behavior of historical timber mosques will be analyzed and preserved in future restoration works.

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