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Article

Evaluation of The Effect of Abscissa Part on Seismic Response of Historical Masonry Church

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Abstract. Church buildings, which are the worship buildings of the Christian faith, were built in different plan typologies in different regions. There are many church structures built in Anatolia during the Ottoman Period. During the population exchange period in 1924, Muslims settled in the settlement areas instead of the non-Muslim community in Anatolia. In this period, church buildings were converted into mosque structures due to the change in the religious belief of the people. These structures, which are used by cultures belonging to and which are components of urban identity, have gained a place in the memory of the citizens. For this reason, it is necessary to ensure sustainability by protecting it. Churches have been destroyed either completely or locally due to earthquakes that have occurred over time. In this study, it is aimed to examine the earthquake behavior of the structure used as the Maden Mosque in Amasya. The effects and causes of this structural element on the dynamic behavior of the church, whose apse was destroyed, were investigated and reinforcement suggestions were presented accordingly. The 3D finite element model of the church has been developed, and structural responses were investigated under linear and nonlinear dynamic loads. As a result of the analyses, it has been determined that the most critical parts of the structure are the nave and wall at the west facade.

Keywords: Abscissa, church, finite element model, Gümüş district, nonlinear analysis, urban identity.

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1. Introduction

In the historical process, worship structures belonging to various cultures were built, starting from Pagan structures. Churches are one of these building systems. Since Anatolian geography contains various cultures and beliefs, there are churches and various worship structures in this geography. The first examples of churches tried to create a simple life for their congregations by gathering the first Christians in their homes. The first churches formed because of this were house churches. The oldest example is found in the basement of a Hellenistic eastern-type house dating from 232 in Dura Europos (Syria). With the development of congregations, independent church structures with hall churches emerged. These structures consist of simple, large spaces and annexes of community houses. In the cities where there are chief priests, the construction of double churches draws attention to the conversion of large masses [1].

Basilica planned churches, the main church typology of the early Christian era and the first Byzantine period, consisting of spaces divided into three naves. At the eastern end of the nave in the middle, there is an apse with a half-round plan covered with a masonry half dome. Since the first examples of basilicas had wooden roofs, these structures were damaged by fire and earthquakes. On the western sides of the basilicas, there is a front hall called the narthex, in the case of a courtyard preparation space called an atrium. Early Byzantine architecture, inspired by the baths and tombs of Rome, created centrally planned religious buildings on the one hand. On the other hand, centrally planned churches are covered with domes; It consists of a square, polygonal or circular volume, and symmetrical elements [2]. It is seen that a type of church called a domed basilica was formed in Anatolia in the 5th century as a building type that combines the basilica plan and the central plan. In this plan type, with the addition of the dome to the basilical plan, the interior of the building received more light. In the 6th century, cruciform churches were built by fusing the basilica and domed building principles.

Cruciform churches appear as a Greek cross-type, T-type, and T-type plan with corner space [1]. The structural behavior of churches with these different plan types will be different. Therefore, apart from the plan geometry, other factors should be considered in determining the structural behavior of such structures. Materials, interventions in the building history, and the construction system can be counted among these. It is necessary to examine the earthquake behavior of churches, which have historical and cultural value and are a part of the identities of cities, and restoration works should be carried out.

In a study emphasizing the importance of preserving cultural heritage, two different numerical methods were used in Masonry Church, namely linear kinematic analysis and seismic analysis [3]. In Datrin's study, four strategies were mentioned for the analysis of masonry structures: blockbased models (BBMs), continuum models (CMs), macroelement models (MMs), and geometry-based models (GBMs) [4]. In another study, a masonry church was seismically evaluated with different analysis methods. In this study, adopted and compared are linear and non-linear kinematic analysis, FEM pushover analysis and FEM nonlinear dynamic analysis methods were used [5].

Bartoli, Betti, Galano, and Zini's [6] paper analyzes the historic masonry tower's seismic risk at three different levels of assessment. In this study, the mechanical properties of the masonry walls and the constraints of the surrounding buildings were considered as variables. In another study, the vulnerability of cultural heritage under seismic loads is evaluated based on the Italian national regulation [7]. In this study, simplified global static analyzes, kinematic analyzes based on local collapse mechanisms and detailed global analyzes were performed. Ferrante et al. analyzed the nonlinear dynamic behavior of the historical clock tower using three different geometric models in two different codes [8].

Another study [9] investigated the seismic behavior of the masonry church. The historic medieval church was first analyzed by experimental dynamic tests. Secondly, FEM analysis was performed with the ABAQUS program and the results were compared with the test results. In Di Napoli et al. [10] paper, a historic church with mixed timber−masonry construction as part of earthquake risk reduction discuss their effectiveness on the impact of the post-seismic damage through the application of non-linear static analyzes.

In the study of Lopez et al. [11], FEM analysis was made with geometric parameters from 50 ancient masonry churches. Based on this experiment, seismic fragility formulas were produced. In study [12], eight historical mosques in Iran were modeled with the macro element method and analyzed in order to examine their geometrical properties. Another study [13], a comparative study was conducted by making DEM and FEM analyzes of a masonry church damaged in the earthquake. As a result of the numerical analyzes obtained, reinforcement suggestions were given.

In a study, masonry churches with three naves were classified according to typological, structural and architectural features and the damages caused by the earthquake were analyzed visually [14]. There are many studies in the literature examining the earthquake behavior of churches [5, 15-24].

Betti, Galano, and Lourenço [25] emphasizes that the regional studies are not sufficient and that if there is a monumental structure, non-linear analysis should be made of a single structure. As a result of the literature research, it is aimed to examine the effect of the abscissa part, which is the macro element of a masonry church, on seismic behavior. In this context, examining the earthquake vulnerability of a church with abscissa and without abscissa, whose apse part was destroyed during the earthquake, constitutes the uniqueness of this study.

2. Case Study Description

It is known that the mosque, located in the Maden neighborhood of Gümüşhacıköy district of Amasya province, was built as the Surp Garabed Armenian Church in the early 19th century [26]. The church structure, which is one of the early examples of Byzantine churches, has a basilical plan with three naves [2].

At the eastern end of the space, which is covered with a vaulted roof, carried by two support rows, there is an apse in the form of a semicircle and covered with a masonry semi-dome. The entrance to the building is provided by a wooden double-winged door from the narthex on the west of the building. The epitaph on the door is not read today. The narthex has three domes supported by four columns and is covered with a Turkish-style tile roof.

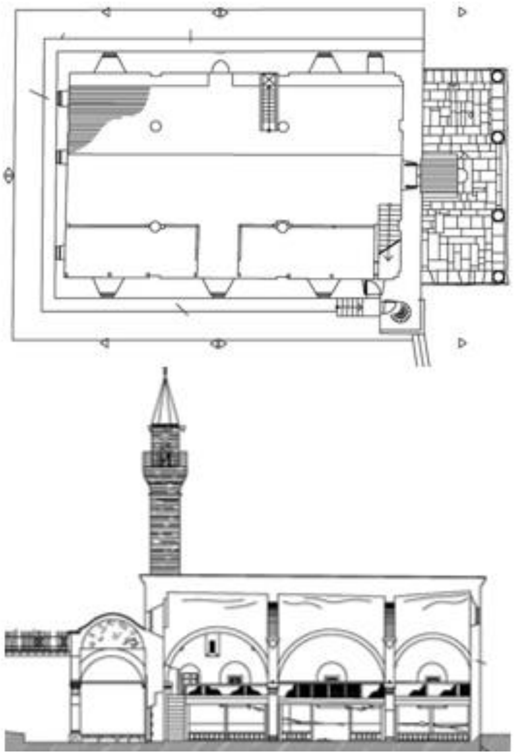

Fig. 1. Maden church a) Plan b) Section c) View d) Narhtex [27].

While the corners of the façade walls are made of stone, the main walls are of cut stone. The roof of the main space is covered with Turkish-style tiles, and there are three-row hedgehog eaves on the roof. The church structure of the church, which was abandoned at the beginning of the 20th century, was converted into a mosque for the needs of the Muslims settled in Gümüşhacıköy after the relocation agreement between the Turks and the Greeks in 1924. This change in function has brought some additions to the structure. It is known that the apse on the eastern façade of the building was demolished after the 1920s, and the façade where the apse is located was closed with a wall [26].

Fig. 2. Maden church a) View b) Narhtex [28].

Pillars are visible in the cracks on the added wall surface and on the outer walls of the east façade. Following the mosque function, a mihrab was added to the south wall (qibla direction) of the building, and a minaret was added to the northern façade of the building. The decorations on the wall and ceiling in the interior of the building were covered by plastering. While it was a church, the woods in the building were converted into preaching lecterns, mahfils, and window covers [29]. After the earthquake in 1996, the building was damaged and closed for worship [26].

Fig. 2. a) The frescoes in the vault b) The cracks formed after the earthquake.

The building, which the Regional Directorate of Foundations restored in 2005 continues to function as a mosque today. With the removal of the vaulted plaster during the restoration. The frescoes of Jesus and his four apostles were unearthed. The location and form of the apse can be seen as traces on the ground on the east façade.

Fig. 3. a) The wooden preaching chair and the mahfil floor b) Pillars on the added wall [28].

3. Finite Element Model of The Church and Material Properties

To determine the seismic behavior of the mosque, which is considered within the scope of the study, a 3D finite element model of the church has been developed numerically. In the second stage, the abscissa part was added to the church by the period's architecture by considering the traces on the existing structure, and the original church model was created. The minaret that was added later was not considered in the models as it was not present in the original church. Material properties were assigned to each part of the structure, which was determined by examining the architectural features from existing projects. Based on the structural geometry, a fixed support condition is assigned. Dynamic loads were applied to the structure, and at the end of these processes, the analysis results were obtained in the form of a color scale on the three-dimensional model. ANSYS program [30], which uses the finite element method, was used to perform the analysis [30]. The finite element model consists of 33885 nodes and 8233 solid elements for the current state of the church and 35854 nodes for the model with abscissa. Solid 186 element used for analysis has 20 nodes and at each node three degrees of freedom [31].

The three-dimensional finite element model of the church is shown in Fig. 4. Analyzes were executed by adopting the macro modeling technique.

Detailed micro modeling, simplified micro modeling, and macro modeling techniques are used as numerical modeling techniques of masonry structures. In detailed micro-modeling, the main element that forms the masonry building element and the mortar that combines them is separate building materials. In simplified micro modeling, the widths of the masonry elements are modeled by expanding them by half the mortar layer thickness. In macro modeling, the main structural element is defined as a composite material with mortar [22]. The walls, arches, and columns of the church are constructed by using rubble stone, all the domes and vaults and the triumphal arch of the porch are made of Khorasan bricks. The average values of physical and mechanical properties given in the regulation were assigned [32].

Table 1. Physical and mechanical properties of materials used mosque [32].

Material	**Rubble Stone**	**Brick**
Young Modulus (MPa)	1230	3900
Poisson Ratio	0,18	0,20
Unit Weight(kg/m³)	2000	1200
Compressive Strength (MPa)	1,35	5,3
Tensile Strength (MPa)	0,135	0,53
Shear Strength (MPa)	0,043	0,35

The physical and mechanical properties of these materials are shown in Table 1. In the TDYKK guideline, the compressive safety stress for the wall consisting of rubble stone elements is a minimum of 1.5 MPa, shear safety stress value is given as 0.056 MPa. The tensile strength of the rubble stone wall was taken as 0.15 MPa and for a brick wall as 0.35 MPa.

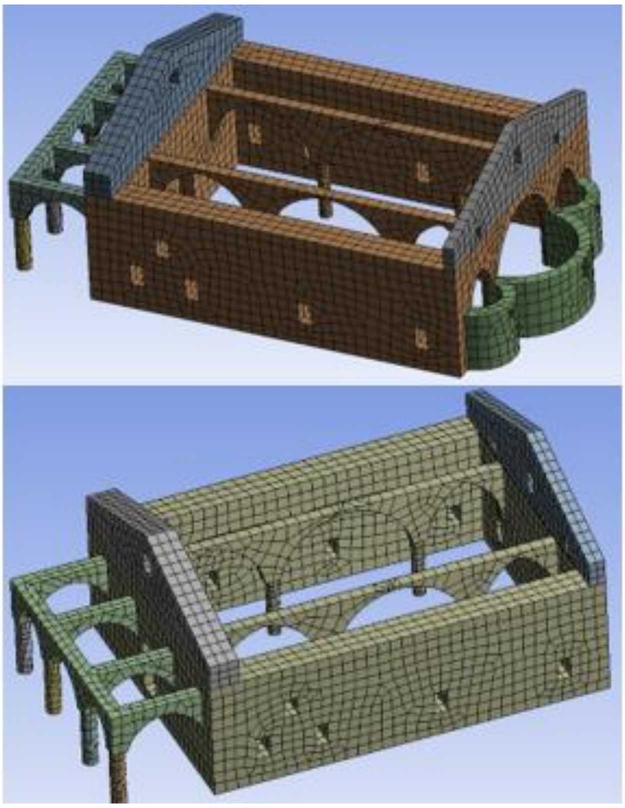

Fig. 4. Finite Element Model of the Church a) with abscissa part b) without abscissa part.

4. Modal Analysis Without Abscissa and With Abscissa

In determining the dynamic behavior of the church, modal analysis that provides the determination of free mod shapes was performed on the mosque. Mod shapes with high practical mass values were determined by the period values on both the model with abscissa and without abscissa.

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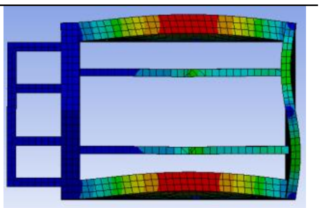
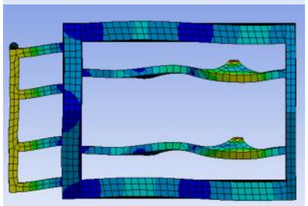
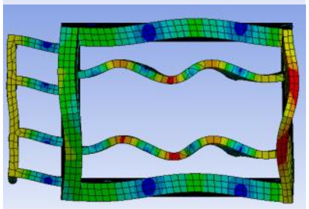
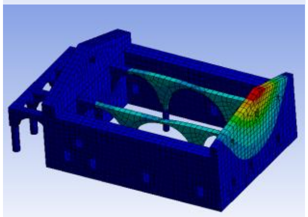
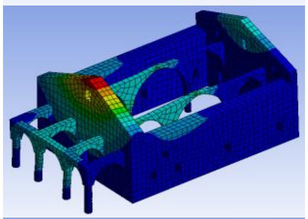
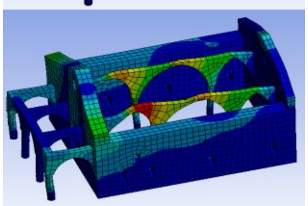
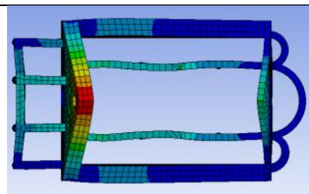
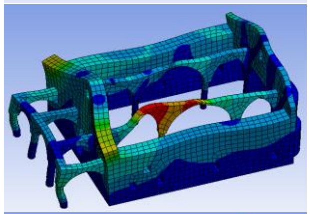
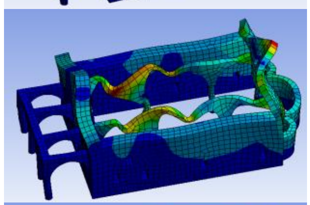
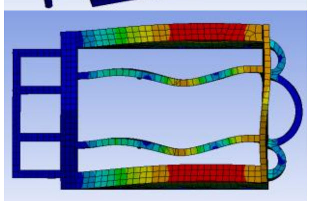
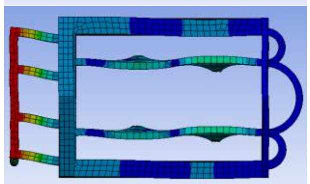
Table 2. Shapes, periods, and mass participation factors of effective modes of church model without abscissa.

Mode	Period (T)(sn)	Long. Mass Participatiom	Trans. Mass Participation	Mod Shape of the without abscissa
7	0.16	0	0.28	
20	0.10	0	0.07	
25	0.088	0	0.19	
3	0.31	0.11	0	
6	0.20	0.15	0	
34	0.06	0.11	0	

In these analyzes, the mod shapes in the X and Y directions, which are orthogonal in the plan, were determined. These mod shapes give important clues about the structure's dynamic behavior, even in an elastic environment. In the first stage, the analysis was carried out on the model without the abscissa part, then on the abscissa part. In the analysis, a practical mass value of approximately 86% was reached by considering the 200 mod shape. In transversal direction, 7, 20, and 25th mod shapes appear as active ones. These three modes constitute 54% of the effective mass of the mosque. While the out-of-plane offset of the outer walls according to the 7th mod shape emerges as an effective movement in this mode, the out-of-plane movement of the triumphal arch in the interior of the church in the 20th mod and the offset of the columns of the porch in this direction comes to the fore. In the 25th mod, on the other hand, while the offset of the triumphal arch, patio, and exterior walls in the interior of the church constitutes the central theme of the movement, it is seen that the out-of-plane displacements of the upper elevations of the western wall of the mosque take high values.

Table 3. Shapes, periods, and mass participation factors of effective modes of church model with abscissa.

Mode	Period (T)(sn)	Long. Mass Participatiom	Trans. Mass Participation	Mod Shape of the with abscissa
6	0.21	0.17	0	
35	0.067	0.13	0	
44	0.05	0.10	0	
7	0.17	0	0.358	
20	0.10	0	0.12	

When the mod shapes in the longitudinal direction of the mosque are examined, it is seen that the 3, 6, and 34 the mod shapes are very effective. In this direction, the out-of-plane movements of the top points of the triangular gable walls on the east and west facades of the church stand out. Again, the movement of the triumphal arch in the nave in this direction through vertical direction comes to the fore.

5. Nonlinear Time History Analysis Ns and Ew Directions

The geography of Anatolia has active fault lines. Significant earthquakes occurred on the Northern Anatolian Fault Line of this geography in 1939, 1943, and 1999. Amasya is also located on this fault line. 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 7.4 earthquake that occurred on August 17, 1999, at 03:02 in İzmit – a western city of Turkey – and that caused significant damages to the buildings in Turkey were used in the analyses. Seismic activity dates to earlier times, with several earthquakes, have occurred in this region between 1045 and 1784. The earthquake that occurred in 1999 resulted in the death of 15851 people and heavy damage to 77297 buildings [33].

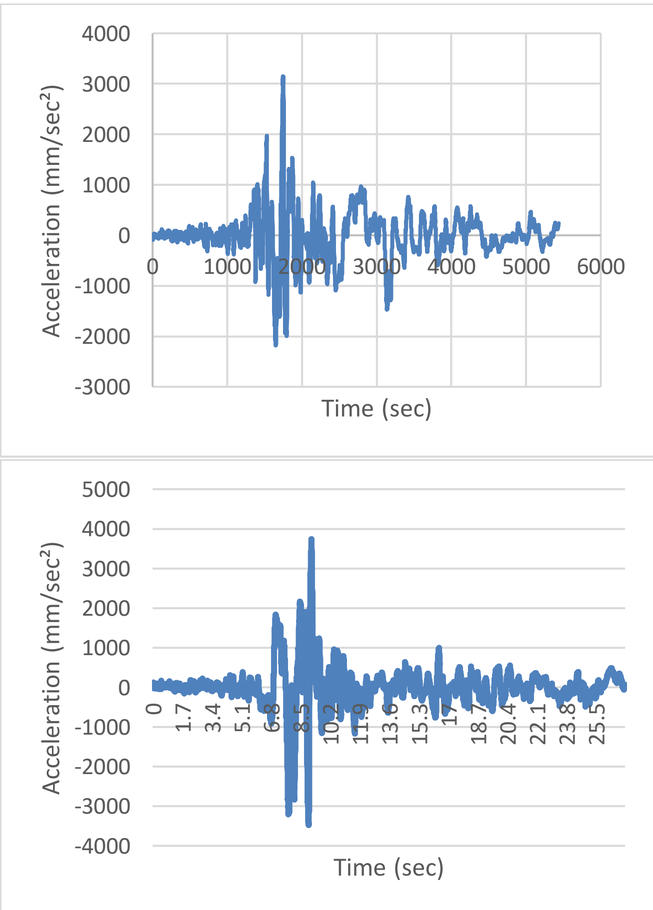


Fig. 5. Acceleration Records of İzmit Earthquake in 1999 a) NS Direction b) EW Direction.

The acceleration record values are presented in Fig. 5. The peak acceleration value was 404.97 cm/sn² on the NS direction, 470.91 cm/sn² on the EW direction, and 238.55 cm/sn² on the downward-upward direction [34]. In time history analysis, EW and NS acceleration components of the earthquake records have been applied to the exact directions of the mosque as inertial loads. Drucker Prager material model can be adopted for stone and masonry parts to execute nonlinear analysis, which has a wide usage area in masonry structures [35].

In Table 4 (1-2), the distribution of the maximum displacements in the models under the earthquake acceleration record in the north-south direction is given. In the model without the abscissa part, the maximum deformations occur at the top of the triumphal arch in the neve, and the maximum value is 28.74 mm. In the model with abscissa, this value increases to 651.75 mm. The decrease in stiffness caused by removing the wall on the west facade increased the offsets in this direction. Table 4 (3-4) the distribution of equivalent plastic strains which occur under the effect of earthquake acceleration in this direction is given. In both models, the maximum values reach their maximum values at the top of the triumphal arch in the nave. These values are 0.000154 and 0.00466 for models with and without abscissa part, respectively. It is seen that the values in the model with abscissa are quite high compared to the model without abscissa. The shear stress distribution is given in Table 4 (5-6) The figure shows that the maximum value is 0.78 MPa for the model without abscissa and 0.61 MPa for the model with abscissa. In the model without abscissa, shear stresses occur only at the top points of the triumphal arch in the nave, while in the model with abscissa, they reach high values in the upper parts of the west facade wall. Also, on the north and south façades, in addition to the top of the porch, shear stresses reach high values. In Table 4 (7-8) the distribution of the regions where the regions exceeding the tensile safety stress under the effect of the earthquake in this direction are given. In the ANSYS Workbench software, these regions are represented in red colors. Therefore, the areas where this value is exceeded should be considered parts of the structure where the risk of the crack formation may occur. In the model without abscissa, there is a risk of cracking at the tops of the main carrier columns and upper elevations where the west façade gable wall meets the exterior walls on the north and south façades. In the model with abscissa, cracks can occur at the top of the porch.

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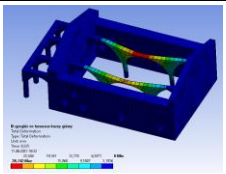
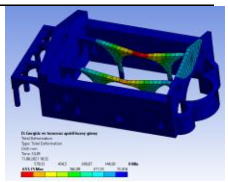
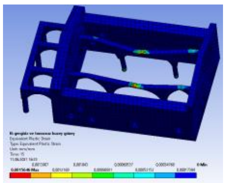
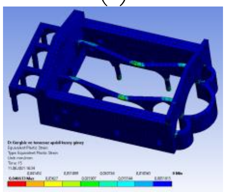
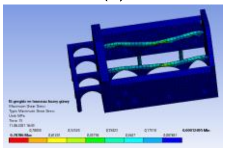
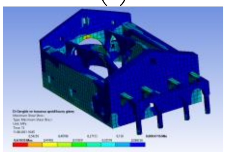
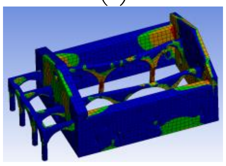
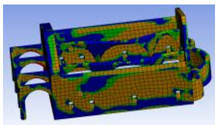
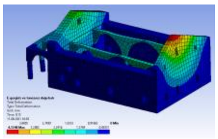
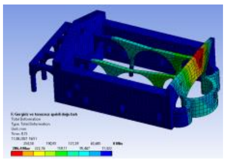
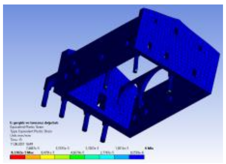
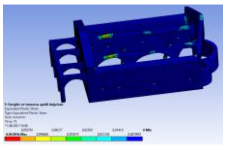
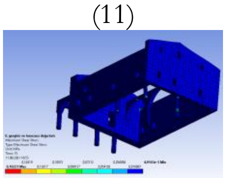
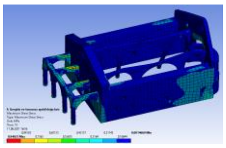
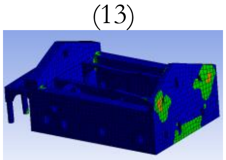
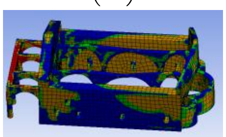
Table 4. Analysis results in north-south (NS) direction and east-west (EW) direction.

Direction	Result	Without abscissa	With abscissa
North-South (NS) Direction	Deformation propagation of the church	 (1)	 (2)
	Plastic Deformation propagation of the church	 (3)	 (4)
	Shear Stress Distribution of the church	 (5)	 (6)
	Crack propagation of the church	 (7)	 (8)
East-West (EW) Direction	Deformation propagation of the church	 (9)	 (10)
	Plastic Deformation propagation of the church	 (11)	 (12)
	Shear Stress Distribution of the church	 (13)	 (14)
	Crack propagation of the church	 (15)	 (16)

The deformation propagation obtained from the analysis under the east-west acceleration record is given in Table 4 (9-10). The maximum value for the model without abscissa is 4.12 mm, occurring at the upper points of the western façade gable wall. Deformations spread downwards from these points, and deformations take high values in the triumphal arch in the nave. In the model with abscissa, the deformations take their maximum values at the top of the west gable, but the total value reaches 286.4 mm. In addition, high deformation values are observed in the abscissa part and the triumphal arch in the nave. The plastic deformation values and distribution that occur under the earthquake record in this direction are given in Table 4 (11-12). In the model without abscissa, deformations occur at the supports of triumphal arch columns in the nave. In the model with abscissa, plastic deformations occur at the supports of triumphal arch columns in the nave and the top points of a triumphal arch. While the maximum value is 0.000083 in the model without abscissa, it is 0.0638 in the model with abscissa. The distributions of shear stresses occurring in an earthquake in this direction are given in Table 4 (13-14). In the model without abscissa, shear stresses take a maximum value of 0.16221 and reach high values at the supports of triumphal arch columns in the nave and partially at the top points of a triumphal arch. In the model with abscissa, the maximum value reaches a value of 0.96 MPa, and the stresses are high in the porch, the entrance facade wall, the area where the west facade wall meets the apse, and the south facade wall meet the west facade wall. In the analysis in this direction, the areas at risk of crack formation are shown with the red colors in Table 4 (15-16). There is no crack formation in the model without abscissa. In the model with abscissa, the top points of the porch stand out as areas at risk of cracking.

6. Results

In this study, a historical church later converted to the mosque was analyzed by creating a 3D model in a computer environment, and linear and nonlinear material properties were assigned to the church masonry parts. The macro modeling technique was used in the analyses. In the modal analysis, it is observed that in the model without apsis part, the mod shapes with large mass participation factors are generally translation ones in two orthogonal directions. But they don't have participation factors bigger than 0.28. These mods call for retrofitting interventions that must prevent plane mechanisms. Other mods having small participation factors occur as local mods, which can cause partial collapse. In the model with the apsis part, the mods having great mass participation factors are also translation ones that do not exceed a ratio of 0.36. These mods also make it necessary to take precautions that will prevent out-of-plane failure. The most vulnerable parts are the triumphal arch, roof, and porch. In the time history analyzes, it is concluded that; the deformations exceed the limit values for the models given in The Earthquake Risk Management Guide for Historic Buildings [32] that defines the limits for the maximum deformation ratio allowable for varying performance levels in the context of dynamic effects (Table 5).

The performance levels given in Table 5 are defined as follows: Limited damage; limited nonlinear behavior (damage) occurs in the load-carrying system elements of the building. Controlled damage, the damage only occurs in repairable load-carrying system elements of the building. Prevention of collapse, severe damage occurs in the load-carrying system elements of the building, and the building is about to collapse partially or completely, but the collapse is prevented.

Table 5. Historical building performance levels and deformation limits.

Level	Max. deformation /Max. height ratio limit	Limit deformation for church EW(mm)	Limit deformation for church NS(mm)
Limited Damage	0.003	36	21
Controlled Damage	0.007	84	49
Prevention of Collapse	0.01	120	70
	EW without abscissa	**EW with abscissa**	
	Deformation value obtained in the analysis for the model (mm)	Deformation value obtained in the analysis for the model(mm)	
Limited Damage	4.12 < 36	286>36	
Controlled Damage	4.12<84	286>84	
Prevention of Collapse	4.12 < 120	286>120	
	NS without abscissa	**NS with abscissa**	
	Deformation value obtained in the analysis for the model (mm)	Deformation value obtained in the analysis for the model(mm)	
Limited Damage	28.74>21	651.75>21	
Controlled Damage	28.74<49	651.75>49	
Prevention of Collapse	28.74<70	651.75>70	

As shown in Table 5, the maximum deformations in the model with apsis part exceed the prevention of collapse limit value in the time history analyzes in both directions. For the model without apsis part, the only limited damage performance level is exceeded. So, a model without an apsis part sufficient to earthquake loads in terms of deformation limits. When the plastic deformation analysis results are compared, it is evident that both models have plastic deformations at the top of triumphal arch for the weak transversal direction. But in the model with apsis, plastic deformations also occur simultaneously for the longitudinal direction. It shows that the model with apsis permits more plastic deformations in the critical triumphal arch. In shear stress figures, it is evident that shear stresses occur only at the top and support a triumphal arch in the model without the apsis part. But in the model with apsis part, shear stresses widen through a large portion of the church, including the west façade wall and the porch. So, also for shear stress distribution, a model with apsis part shows worse performance. According to the figures, which show possible crack regions, the model without apsis part can have cracks at the connections of the south and north walls with the west wall and in the triumphal arch. In the model with the apsis part, these cracks can occur on the porch.

7. Conclusion

In this study, a historical church later converted to a mosque has been investigated in terms of dynamics loads, including nonlinear material behavior. In the linear and nonlinear dynamic analyzes, it has been concluded that the church is more delicate to failure in terms of deformations in the transversal direction loads. Also, mod shapes give practical information for the church parts, which can have damage during earthquake excitation. The model with the apsis part shows less structural performance than the model without the apsis part. The intervention of constructing a wall at the west part of the church after the collapse of the apsis shows positive effect on the seismic behavior of the church in question. For the churches with apsis part, the weak transversal direction of the church must be strengthened at levels from the top of the columns until the top of the perimeter walls. So, it is concluded that the rigidity in both directions plays an essential role in the seismic behavior of these types of churches. It can be said that wooden tie rods which exist at the top of the columns will play an essential role in seismic demand through both directions. It is also concluded that, for the model without abscissa; shear stresses have high values at the top points and at the supports of the nartex. And plastic deformations occur in the same regions. For the model with abscissa, these great values occur at the top of the abscissa and entrance arches. Also, cracks can be seen in both models, at the top of the main entrance arches and main columns at the nartex. The gable walls and the wall at the abscissa are the parts of the church which are very sensitive to lateral deformations. As a main result, the nartex, main entrance, gable walls and the supports of the columns at the nartex are the critical parts of the building. It is hoped that the findings of this research will give a wide projection in the future for technical staff who deal with restoration works.

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