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# Appraisal of Structural Behavior of Afyon Sandıklı Ulu Mosque

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**Abstract:** Historical buildings are important to cultural heritage as they carry their many features to the next generation. These structures are evidence displaying the history, reflecting people's behaviors and culture in the past, as well. The mosques are one of the masterpieces of Islamic culture concerning their structural and architectural properties. The present study focuses on the structural behaviors' historical masonry buildings in Turkey. The main purpose of this paper is to investigate the structural behavior of the domed mosque and to determine the static and dynamic effects. For this purpose, Afyon Sandıklı Ulu Mosque has been numerically modeled and it has been numerically analyzed. As a result of the analysis, the behavior of the structure under the earthquake effects is obtained. The most affected parts of the structure are determined, and the structural behavior is examined depending on the displacement and stresses over the structure. Finally, assessments on the mosque has been made about the obtained results.

**Keywords**: Masonry mosques, Time History Method, finite element method, seismic assessment, cultural heritage

# Afyon Sandıklı Ulu Camii'nin Yapısal Davranışının Sonlu Elemanlar Analizi Kullanılarak Araştırılması

**Özet :** Tarihi yapılar sahip oldukları özellikleri gelecek nesillere aktarmakta ve bu nedenle de kültürel mirasımız açısından önem taşımaktadır. Tarihi binalar, geçmişte insanların davranışlarını ve kültürünü yansıtan, tarihi gösteren bir kanıt niteliğindedir. Tarihi yapılarımızın en önemlileri arasında yer alan camiler aynı zamanda tarihi İslâm kültürünün, yapısal ve mimari özellikleri bakımından en önemli parçalarıdır. Bu çalışmada, Türkiye'deki tarihi yığma yapıların yapısal davranışlarına odaklanılmaktadır. Bu yazının amacı, kubbeli caminin yapısal davranışlarını araştırmak ve statik ve dinamik etkilerini tespit etmektir. Bu amaçla Afyon Sandıklı Ulu Camii sayısal olarak modellenmiş ve analiz edilmiştir. Analizler sonucunda, yapının deprem etkisi altındaki davranışı elde edilerek yapının en çok etkilenen bölgeleri belirlenmiş ve yer değiştirmeye bağlı olarak yapısal davranış incelenmiştir.

**Anahtar kelimeler**: Tarihi Camiler; zaman tanım alanı, sonlu elemanlar metodu, sismik değerlendirme, kültürel miras

## 1. Introduction

It is not possible to learn, understand and pass on a country's civilization history without researching historical structures. Many historical buildings constitute the most important parts of our culture in our country in Anatolia, which has a rich history of civilization [1]. Mosques are also of great importance among these structures concerning engineering and architecture. The structural

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analyses of historical buildings possess a very difficult task due to the lack of information on material properties and regulations, and due to the restrictions on investigation methods for historic structures.

It is important to determine and evaluate the structural safety of historic buildings under earthquake. Evaluating structural behavior and conservation methods for historic buildings requires an interdisciplinary study. At this stage, specify the wall material properties of historical buildings and to model them in a way that represents the actual behavior in the analysis programs is very important [2].

Historical structures were built based on the masters` knowledge and experience without design standards or scientific studies [3]. Structural performances of historical buildings are in variety with their geometry and defined material properties. Therefore, when modeling historical buildings, defining the material properties and the accurate geometrical shape of the structure are the critical steps in the procedure [4]. Historical structures have low ductility because of their brittle structural components. They may have severe damage during severe earthquakes. Many historical buildings are located in a high seismic zone in Turkey [5].

There are many studies in the literature about historic masonry structures. Almost every aspect of the subject has been examined experimentally and numerically, Some of them about minarets and mosques are; Seker et al. (2014) developed a three-dimensional finite element model of the mosque to determined its structural behavior and architectural features through static and dynamic analyses [6]. Koseoglu and Canbay (2015) investigated a damaged single domed mosque of 16th century classical Ottoman Architecture and its dome which have tructural damage. They proposed a rehabilitation method suitable for the amelioration of the observed damage and, the results of the structural analyses conducted had been compared with the observed damage [7]. Mutlu and Sahin (2016) modeled the eastern minaret of "The Grand Mosque" in Bursa by Sap2000 structural analysis software using different structural modeling. Four different finite element models were produced and the modal analysis of all of them were carried out [8]. Aslan (2016) evaluated earthquake behaviour the Suleymaniye mosque.The structural behavior under the earthquake effects was obtained at the end of the analyses and the most affected areas of the structure were determined and The results are evaluated and compared for the structure [9]. Altunisik et al (2016) studied the seismic earthquake behaviour of Kaya Çelebi Mosque through finite element model in SAP2000. Maximum displacements, tensile, compressive and shear stresses were evaluated. After the analyses, it was seen that the displacements and compressive/shear stresses within the code limits, whereas tension stresses exceeded the maximum values at some local regions [10]. Altunisik and Genc (2017) studied the seismic behaviour of the Hüsrev Pasha Mosque. Structural analyses were performed under dead load and earthquake load, and the mode superposition method was used in analyses. according to the their study; the reduction of the window openings reduction affected the structural behavior of the mosque positively according to the Maximum displacements, maximum–minimum principal stresses and shear stresses results [11]. Sözen et al (2018) Investigated the seismic performance and stress distributions of the Garipler Mosque. Static and dynamic analyzes revealed that the stress concentrations occurred at the vaults near the minaret [12]. Yazgan and Unay (2019) examined Sinanpasa Kulliye's Imaret to assessed effects of man-made interventions and additions on the structural performance by conducting numerical model representing the original state of target structure [13]. Kılıç et al (2020) constituted a finite element model (frame elements and shell element model) of Sehzade Mehmet mosque minaret to determine its linear dynamic behaviour by mode superposition method in Turkish Earthquake Codes. Mosque's stone-based construction material properties were determined by nondestructive testing methods. the both (frame elements and shell element model) models results were compared [2].

This paper aims to investigate the structural behavior Afyon Sandıklı Ulu Mosque in Turkey. For this purpose, the domed mosque has been numerically modeled and has been numerically analyzed under static and dynamic loading cases. As a result of the analysis, the behavior of the structure under the earthquake effects is obtained. The most affected parts of the structure are determined, and the structural behavior is examined depending on the displacement and stresses over the structure. Finally, assessments on the mosque have been made about the obtained results.

## [1]. Seismicity of Afyon and Afyon Sandıklı Ulu Mosque

Afyonkarahisar center including the above inspection area is located in the southwest of Turkey's expansion tectonics, which Akşehir─Simav tectonically active fault system (ASFS) is located in the central part. ASFS, which is approximately 420km long in the area between Karaman in the southeast and Balıkesir-Sındırgı in the northwest. It is the most important source of earthquakes in the Afyonkarahisar city center and the surrounding area (Figure 1). Therefore, there is a risk of earthquakes up to 7.0 in this region due to the tectonic properties of ASFS [14].

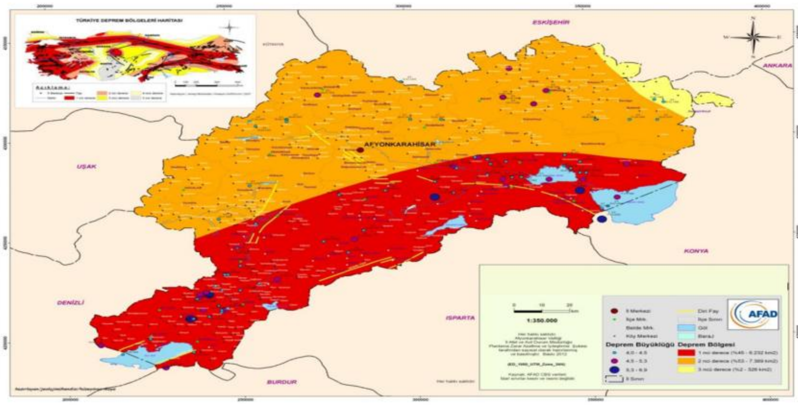



Figure 1. Afyonkarahisar earthquake map [15]

Sandıklı Ulu Mosque, which is in Yukarıpınar area in the bazaar in the neighborhood of Sandıklı Cuma, is the largest in Sandıklı. In 708 (1308/1309), the slave of architect Naib was built by Aydemir by the son of Alaettin Keykubat [16]. According to the information obtained from the archives of the foundation, the Great Mosque was built in the 14th century with a wooden pole and earthen roof and in the 16th century, the minaret and Harim sections were rebuilt. Besides, Mehmet Saadettin Aygen's book “Afyon Karahisar Mosques” is mentioned that the minaret has been built in 1526. Besides, the building underwent a major restoration in 1932. The last section of the reinforced concrete on the northern and western facades of the Ulu Mosque was added later [17]. The large mosque in Sandıklı is shown in Figure 2. Historical mosque 14.54m x 14.42m. it is Square in size and has a single dome.

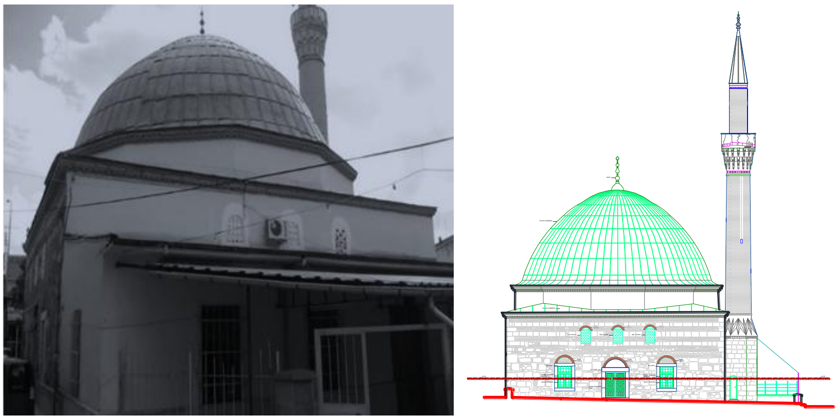


Figure 2. Exterior view and north facade the plan of Afyon Sandıklı Ulu Mosque [17].

To determine the damages that may occur in the structures under the effect of an earthquake in this region, studies should be carried out especially for the buildings of historical importance in the region [7].

## 2. Structural Model of The Mosque

The numerical model of the historical mosque was created in three dimensions by the finite element method using shell and solid elements in this study. Solid elements provide very useful findings and results, especially in the modeling of historical structures. The fact that the solid element has a rigid structure and has limited rotational ability, especially in masonry structures, coincides with the behavior of materials used in historical structures [18].

Both the finite element model and earthquake analysis were performed by using SAP2000 (v.21) package software [19].

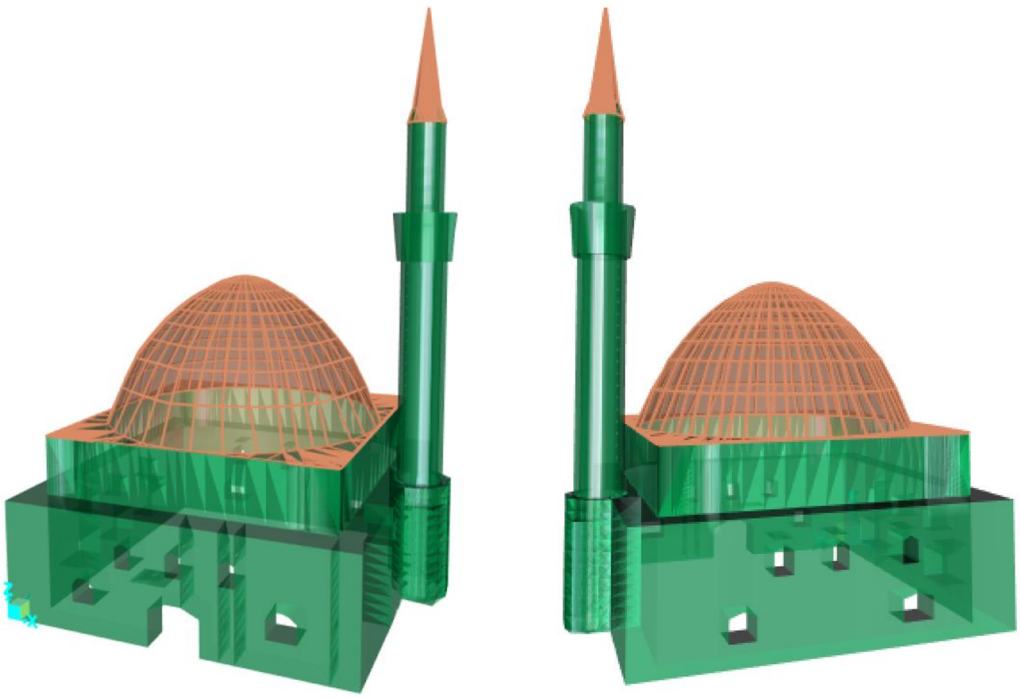


Figure 3. 3D model of Ulu Mosque

The structural model of the Afyon Sandıklı Ulu Mosque is given in Fig. 3. Since the minaret is adjoining with the Ulu mosque, it was also modeled in the study to the mosque. The prepared model consists of 9322 joints, 4915 solid elements, and 894 area elements. Solid elements have used the structure for walls, whereas dome and cone are modeled with shell elements for better representation of connections. Later, joint connectivity at area sections was checked in detail.

Table 1. Material properties [20]

| Structural Element | Element Type | Model Type | Modulus of Elasticity (MPa) | Unit Volume Weight (kN/m$^3$) | Poisson Ratio | Structural Element |
|---|---|---|---|---|---|---|
| Stone (Walls) | Stone | Solid | 8500 | 21.9 | 0.2 | Stone (Walls) |
| Minaret | Stone | Solid | 3000 | 20 | 0.2 | Minaret |
| Cover (Dome, Cone) | Cover | Shell | 3000 | 20 | 0.18 | Cover (Dome, Cone) |

The material properties and model types used in the structural model are obtained from previous studies and presented in Table 1. [20]

## 3. Dynamics Analysis of The Mosque

In this study, the behavior of the Afyon Sandıklı Ulu Mosque, under earthquake loading, was investigated. For this purpose, analyses were performed for four different earthquake levels defined in Turkish Earthquake Code, TBDY 2019 [21]. Based on the geo-location of the mosque, a short period ($S_{DS}$) and 1 second period ($S_{D1}$) design spectral acceleration values were determined using the Turkey Earthquake Hazard Map for each earthquake level. Time history records were artificially generated via SAP2000 (v21) software to be compatible with the response spectra are given for each earthquake level. Earthquake time history records, generated for four earthquake levels, are applied to the structure. Target design spectra and response spectra obtained from artificially generated earthquake time histories are shown in Fig. 4 and artificially generated ground acceleration time histories are figure out in Fig. 5-6-7-8.

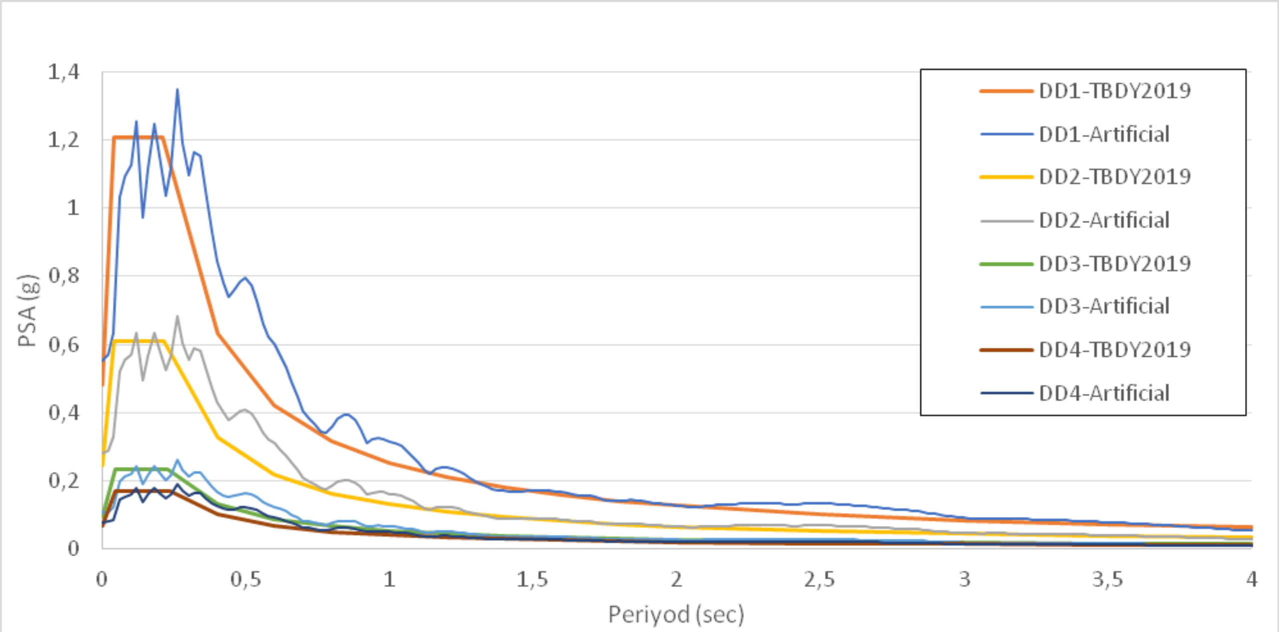



Figure 4. TBDY2019 design spectrums and response spectrums of artificially generated earthquake time histories

**4. Results and Discussion**

The minaret top displacement, minaret base total shear force, dome top displacement, and mosque total base level shear force results are obtained from the time domain analysis for four different earthquake levels for Afyon Sandıklı Ulu Mosque. These levels are presented in Figure 9.

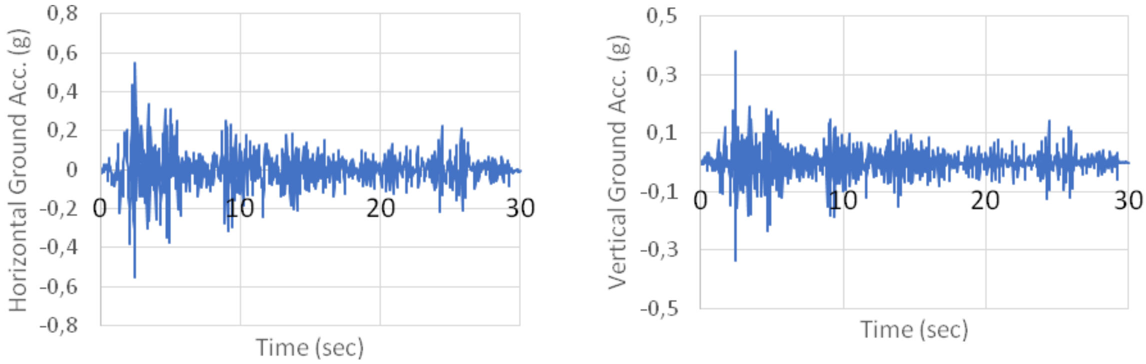



Figure 5. Artificial earthquake time history for DD1 level

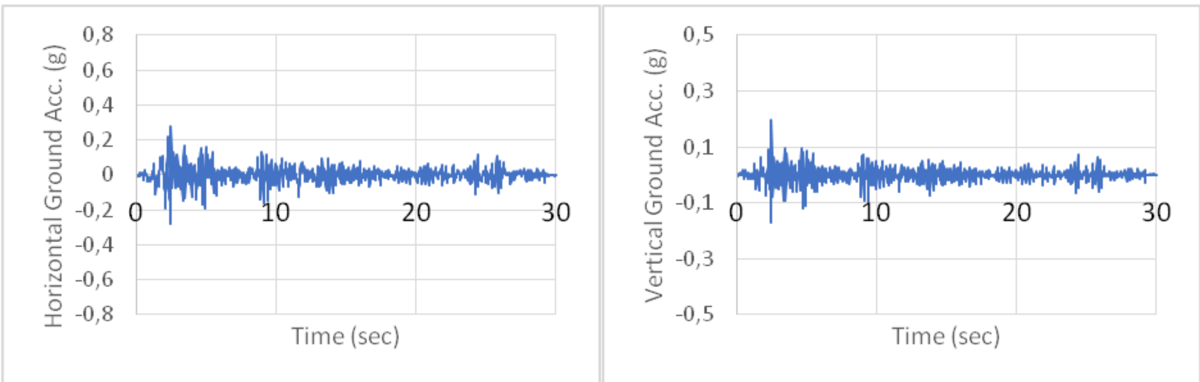



Figure 6. Artificial earthquake time history for DD2 level

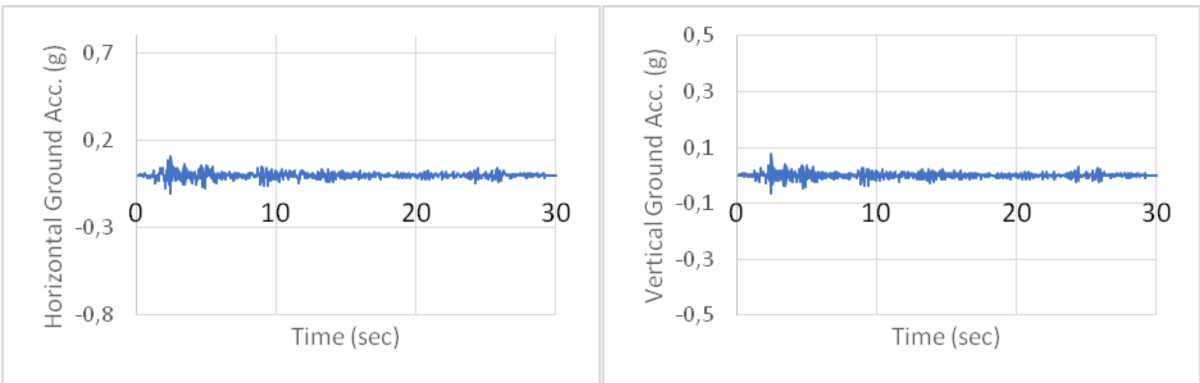



Figure 7. Artificial earthquake time history for DD3 level

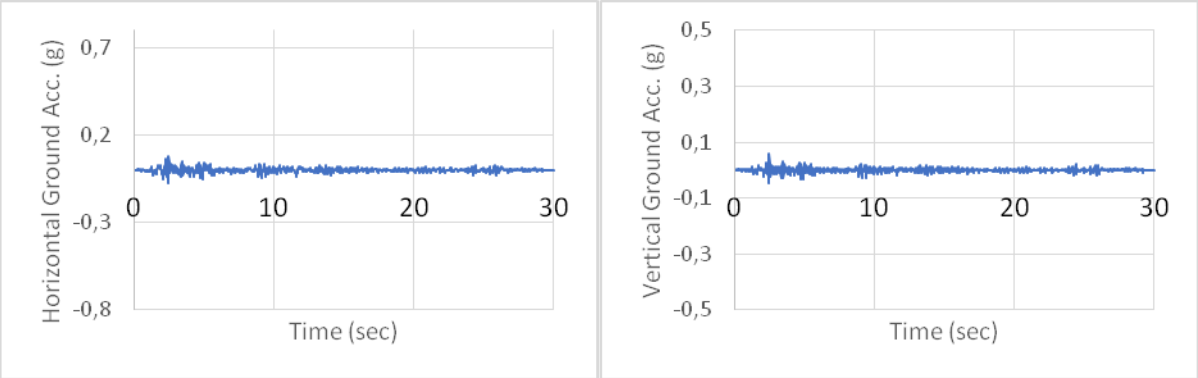



Figure 8. Artificial earthquake time history for DD4 level

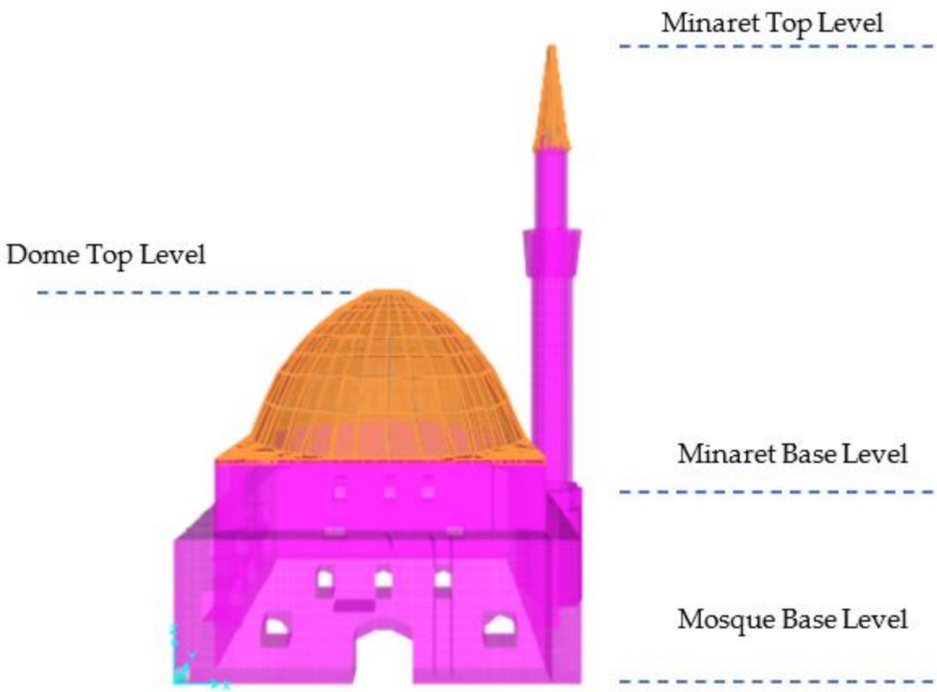
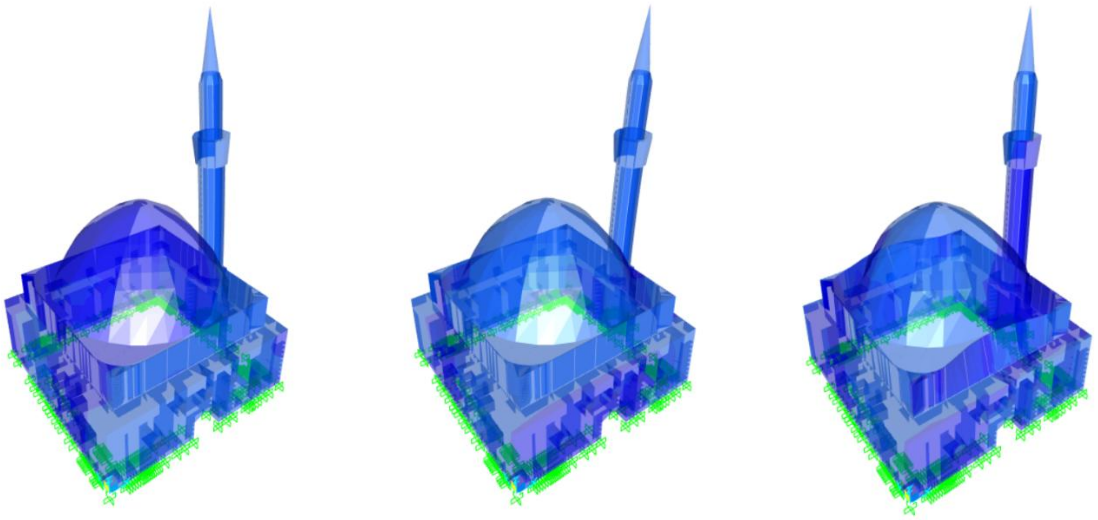



Figure 9. Levels where earthquake analysis results are evaluated

### 4.1. Dynamic Analyzes Results

Modal analysis was carried out to determine the dynamic properties of the mosque structure. The structural analysis model, period and frequency of the first three modes obtained from dynamic analyses for the Afyon Sandıklı Ulu Mosque are shown in Figure 10. According to the dynamic analysis results, the first and second modes are in X and Y directions, respectively. The dynamic analysis also has shown that the third mode is compression mode.



1. Mode
T=0.43sn (f=2.34Hz)

2. Mode
T=0.33sn (f=3.00Hz)

3. Mode
T=0.10sn (f=9.86Hz)

Figure 10. The shape, period and frequency of the first 3 modes of the studied mosque

### 4.1.1. Minaret Top Displacement Results

The minaret top displacement values obtained from the time history analyzes for each earthquake level are given graphically in Figure 11. It is seen from the graph that the maximum lateral displacement of minaret top level is for DD1 earthquake level 7.25cm, for DD2 earthquake level 3.71cm, for DD3 earthquake level 1.47cm and for DD4 earthquake level 1.10cm, respectively.

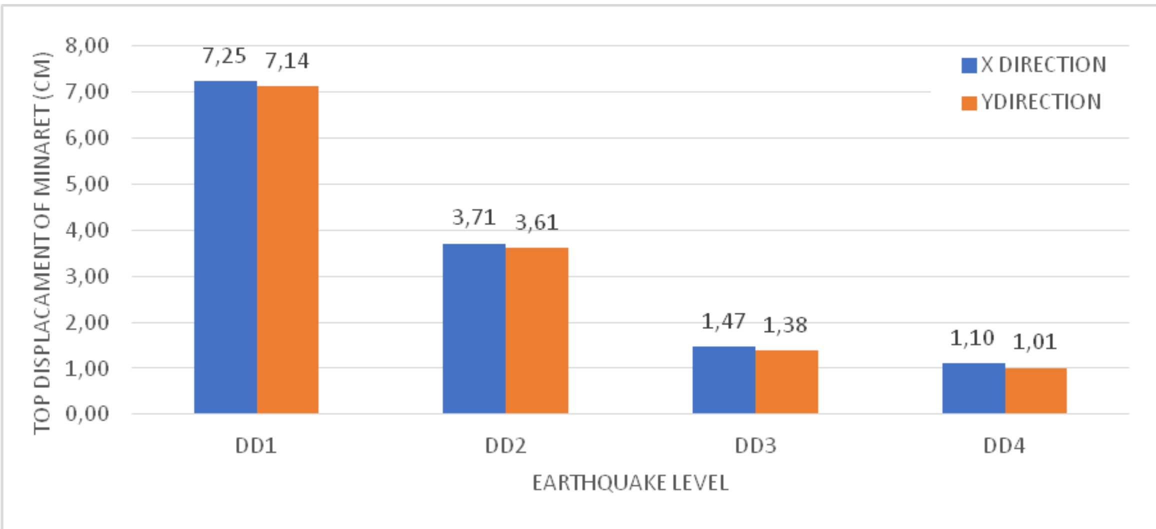



Figure 11. The maximum lateral displacement of the top of the minaret according to earthquake levels

### 4.1.2. Minaret Total Base Shear Results

The minaret total base values obtained from the time history analyzes for each earthquake level are given graphically in Figure 12. The graph shows that maximum total shear values at minaret base level are for DD1 earthquake level 660.6kN, for DD2 earthquake level 335.3kN, for DD3 earthquake level 129.8kN and for DD4 earthquake level 95.3kN, respectively.

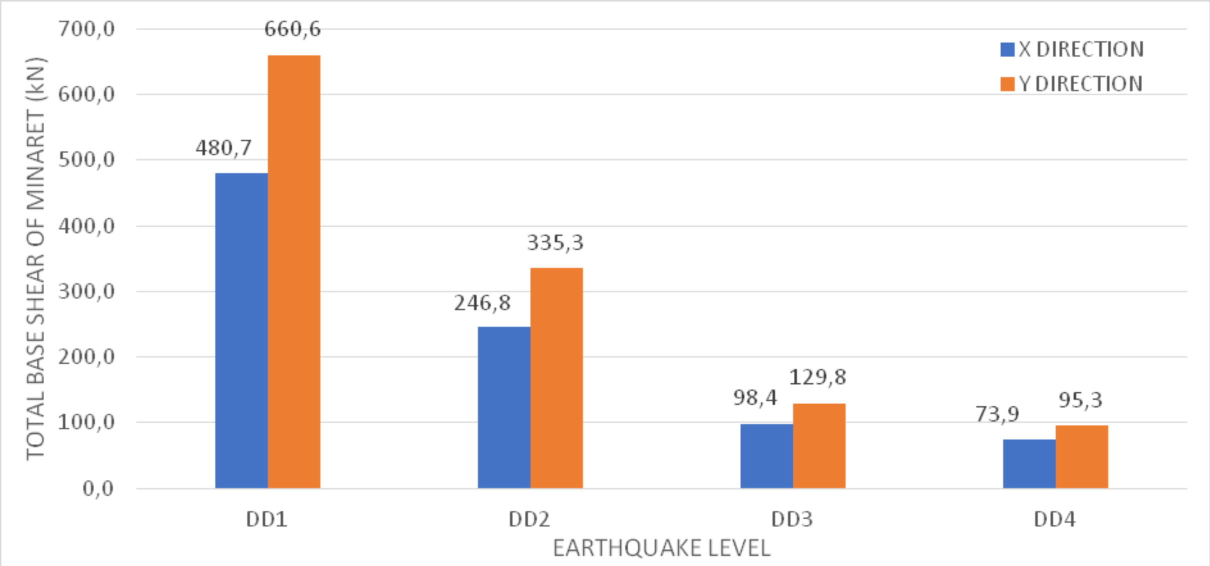



Figure 12. The maximum total shear force at the base level of the minaret according to earthquake levels

### 4.1.3. Dome top Displacement Results

The dome top displacement values obtained from the time history analyzes for each earthquake level are given graphically in Figure 13. It is seen from the graph that maximum lateral displacement of dome top level is for DD1 earthquake level 0.224cm, for DD2 earthquake level 0.113cm, for DD3 earthquake level 0.043cm and for DD4 earthquake level 0.032cm, respectively.

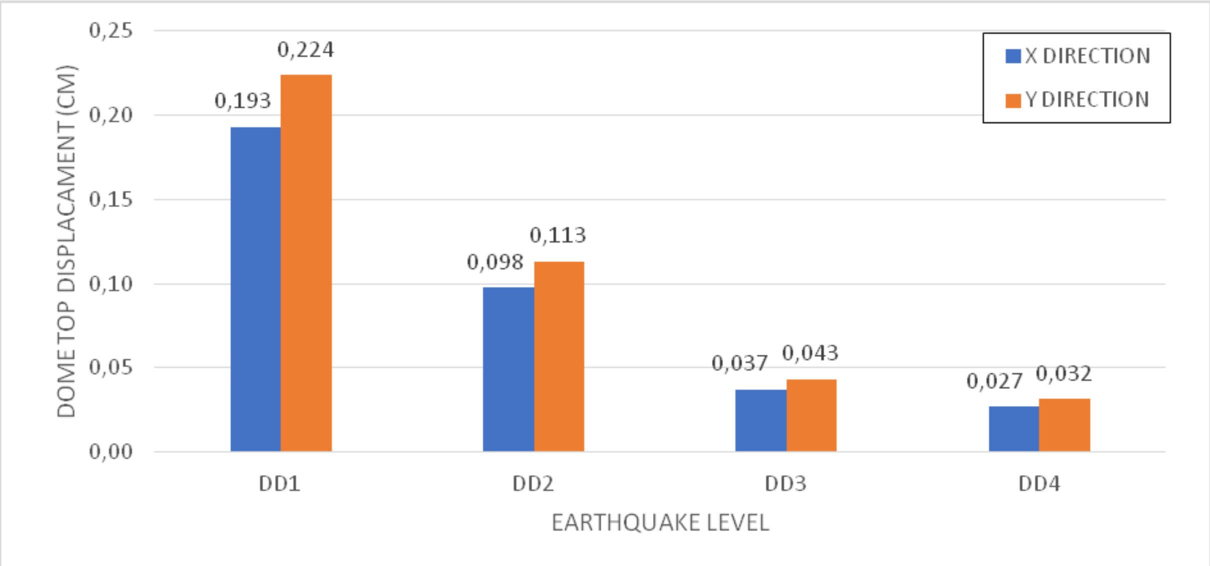



Figure 13. Maximum lateral displacement of the top of the dome according to earthquake levels

### 4.1.4. Total Base Shear Results at the Base Level of the Mosque

The total base shear values at the base level of the mosque obtained from the time history analyze for each earthquake level are given graphically in Figure 14. The graph shows that maximum total shear values at the base level of the mosque are for DD1 earthquake level 7435.3kN, for DD2 earthquake level 3796.5kN, for DD3 earthquake level 1435.7kN and DD4 earthquake level 1035.0kN, respectively.

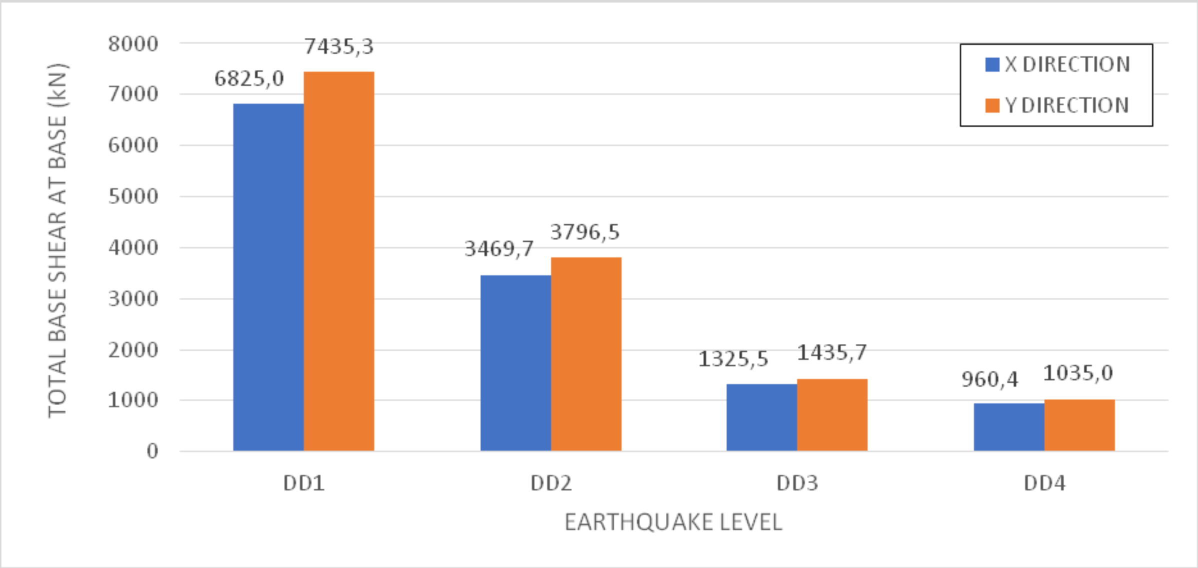



Figure 14. The maximum total shear force at the base of the mosque according to earthquake levels

The results described in the paper and the effectiveness of the performed method are discussed at the conclusion. Any limitations regarding the possibility and scope of use of the results should also be indicated.

## 5. Conclusions

Earthquakes are one of the major threats to historical and culturally significant buildings in Turkey in terms of active tectonics and seismicity. Therefore, it is important to examine the safety of structures under possible earthquakes. In this study, the earthquake behavior of the historical mosque in Afyon province is discussed.

In this study, the earthquake behavior of the Afyon Ulu Mosque was examined by time history analysis. It is observed from the analysis result data for maximum earthquake DD1 that maximum lateral displacement of minaret and dome top level are 7.25cm and 0.224cm, respectively. Furthermore, the total base shear value at the minaret base is for DD1 earthquake level is 660.6kN, and maximum total shear values at the base level of the mosque are for DD1 earthquake level 7435.3kN.

The structure is not affected seriously due to DD4 earthquake level, lateral displacements and total shear values are very limited. The behavior of the main structural system is very rigid, and the displacements are limited. This is a result of the advantage of the small mosque plan.

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