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Research Article

Comparison of Classical and Voxel Model Analyses of the Gaziantep Hüseyin Paşa Mosque Observed During the February 2023 Earthquake

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Classical structural model,
Voxel structural model,
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Abstract

In order to examine the structural behavior of the Gaziantep Hüseyin Pasha Mosque, whose behavior was observed in the February 6, 2023 earthquake, point cloud readings were taken for survey purposes and core samples were taken from the masonry stone elements to determine the material axial load capacity and shear strength. Earthquake spectra were taken from the nearest earthquake station, station TK0723, from AFAD data, and the structure was modeled and analyzed using classical and voxel model methods. In the classical modeling method, the structure is measured with traditional methods and the internal and external dimensions and element thicknesses are determined. Then, these elements are defined in the 3D model, material properties and element definitions, geometric shapes of the elements are made with the engineer's prediction, and the structural relationship and load transfer definitions between the dome, pendentive, arch, load-bearing wall and column elements are left to the engineer's interpretation. In voxel modeling, the structure is transferred to the 3D model as a whole by means of auxiliary programs and methods due to the photographic scanning of the structure as a whole. In this way, the structure is directly modeled as a whole without any element definition, dimensioning or element load transfer relationship acceptance in the 3D model. In this way, the structure and structural element behavior during the construction phase and the entire structure load transfer are not interfered with during the analysis phase. By comparing the behavior and damages of Gaziantep Hüseyin Pasha Mosque under the detected earthquake with the results of the two analytical methods obtained, the realism of both models and their behavior under the earthquake were examined. In both modeling methods, stress concentrations are observed in the arches and the dome-arch-over-arch connections, but in the classical modeling, it was determined that these concentrations were more intense and the resulting damages were less than the stress concentrations obtained in the classical model. In the voxel model, it was observed that there were similar stress concentrations, but the stresses were more distributed as a result of the voxel model analysis. It was determined that the damages that occurred after the earthquake behavior of the mosque overlapped with the scattered stress concentrations in the voxel model. As a result of the comparison of both models, it was concluded that the results obtained with the element definition in the classical modeling did not overlap with the structural behavior, and the behavior obtained by modeling the structure as a whole overlapped more with the earthquake behavior of the structure.

1. Introduction

Earthquakes leave permanent effects on historical and cultural assets, as they do on all structures. These values that have stood for centuries have been damaged and/or destroyed in today's earthquakes. Repair and reinforcement of these structures, which are our cultural heritage, are important. According to the "Venice Charter", which was established in May 1964 and of which our country is a member, it is stated that historical structures are a job that requires expertise [5].

With the Amsterdam Declaration published in 1975 and the Declaration of Recommendations on the Protection and Contemporary Role of Historic Areas (UNESCO 30 November 1976, Nairobi), it is considered that local governments will be funded and policies will be improved in this regard. [6]

In this study, the behavior of the Hüseyin Paşa Mosque located in the Şahinbey district of Gaziantep province under the earthquakes that occurred on February 6, 2023 was determined by observations and measurements. Earthquakes are a natural laboratory in determining the behavior of structures.

In addition, in our civil engineering education system, the load-bearing systems of historical masonry buildings and the behavior of domes, arches, pendentives and stone wall elements are either not explained or not given enough attention.

For these reasons, there are great difficulties of acceptance and approach in analyzing masonry structures, especially our mosques, in line with their real behavior.

In addition to the structural elements defined in the classical method, there are also difficulties in connecting these structural elements to each other.

With the development of technology, a point cloud map, that is, a precise survey of the structure, can be created topographically. In this way, the structure can be measured as a single piece, as a whole, as data.

Voxel is the three-dimensional form of the smallest unit defined as a pixel in a two-dimensional plane. In this sense, voxel refers to the three-dimensional form of any point defined in space [8] (Giordano, Mele, & De Luca, 2002). Voxel modeling allows the masonry structure to be loaded into ready-made programs as a whole without defining

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any carrier element at this stage. In this way, the difficulty of defining elements and determining the relationships between these elements is eliminated. Naturally, analyses closer to the real behavior of the masonry structure can be made.

History of Hüseyin Pasha Mosque: It was built by Hüseyin Pasha, the chamberlain of Urfa Governor Ali Pasha, between 1718 and 1719. During the Antep Defense (1920-1921), the minaret and some domes of the mosque were destroyed by cannonballs and rebuilt in 1953 [2] (Altın, 2015).

The stones used in the construction of the Hüseyin Paşa Mosque are made of cream-colored, hard cut stones with a limestone structure, which are widely found in the region. These stones are called "keymık stone" and the "stone joint that does not pass through the akçe" technique is used in the construction [4] (Ataş, 2023). Gaziantep mosques are generally divided into four groups according to the plans of their prayer halls. These are in the plan with two naves parallel to the qibla, in the plan with multiple domes, in the plan with a central dome resting on four columns and the side sections covered with vaults, and in the plan with a single dome. Hüseyin Paşa Mosque is the only example in this group in the class of multiple-domed mosques and is the only example of its class in terms of regional architecture. The side and rear walls of the mosque are supported by mass buttresses [7].

February 2023 Earthquake and Hüseyin Pasha Behavior of the Mosque: Gaziantep province is close to seismically active fault lines and the main important earthquakes of the region are; a large earthquake that occurred in 1822 in the Türkoğlu-Antakya segment and was estimated to be approximately Mw 7.5 [3] (Ambraseys & Jackson, 1998).

Figure 1. View of the mosque in 1890

In recent years, earthquakes of magnitude Mw 5.5, 5.8 and 4.6 occurred in June, July and August of 1971 and caused serious damage. Earthquakes of magnitude Mw 4.4 occurred in 1978 and Mw 5.0 occurred in 1986 and caused some damage [1]. Gaziantep province also suffered damage from the earthquakes centered in Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) in February 2023. After the earthquake, the 9.80 m. section of the mosque minaret above the 2nd balcony collapsed on the dome (Figure-2). The dome closest to the minaret has been damaged by impact (Figure-3). When the general condition of the mosque was examined with observation and point cloud, it was observed that cracks occurred in the carrier arches of some domes and on the edges of the dome (Figure-4). It was also determined that the dome stones moved from their places due to the depletion of the adhesion of the connection mortars.

Figure 2. Minaret damage

Figure 3. Dome damage

Figure 4. Carrier arch damage

Material Properties: In order to obtain information about the strength of the cut stone building material used in the mosque's load-bearing stone walls, core samples were taken from the load-bearing walls for use in modeling. Free compression and splitting tensile tests were performed on these samples, 6 core samples with a diameter of 53 mm were obtained for the tests, 8 core samples with a height of 53 mm and 3 core samples with a diameter of 26 mm were obtained, (Figure-5).

Figure 5. Core samples

The values obtained from the core samples taken are given in Table 1 and Table 2. According to the data obtained from the experiments, the average compressive strength of the wall sample was found to be 8.62 Mpa (Table-1), the average tensile strength was found to be 2.39 MPa (Table-2) and were used in the analysis models. The specific gravity of the keymium stone used in modeling was taken as 2.7 tons/m³.

However, it is accepted that the mortar used in the combination of stone blocks will disintegrate under the reversible and repetitive earthquake load and lose its tensile properties [12] (N. Bayülke,2018). Therefore, in the model analyses performed, it is predicted that cracks and separation will occur in the regions where tensile stresses occur. In both analytical analyses performed, these regions were compared with the cracks and separations of the real structure after the earthquake behavior and the result was evaluated.

Table 1. Axial pressure test results

Sample No.	L (Length)	P (Load)	Uniaxial Compressive Strength
1	53mm.	15.3 kN	6.94 MPa
2	53mm.	29.4 kN	13.33 MPa
3	53mm.	23.8 kN	10.79 MPa
4	53mm.	24.6 kN	11.15 MPa
5	53mm.	25.6 kN	11.60 MPa
6	53mm.	23.2 kN	10.52 MPa
MID=			10.72 MPa
Standard deviation =			2.10
Strength =			8.62 MPa

Table 2. Splitting tensile test results

Sample No.	L (Length)	P (Load)	Splitting Tensile Strength
1	26mm.	10.8 kN	4.99 MPa
2	26mm.	8.3 kN	3.83 MPa
3	26mm.	8.3 kN	3.83 MPa
4	53mm.	13.9 kN	3.15 MPa
5	53mm.	10.4 kN	2.36 MPa
6	53mm.	10.2 kN	2.31 MPa
MID=			3.41 MPa
Standard deviation =			1.02 MPa
Strength =			2.39 MPa

2. Analysis and evaluation

In order to determine the geometrical condition of the structure before and after the earthquake, data was collected for survey purposes using the point cloud method (Figure-6). Point cloud readings were obtained by laser scanners in field measurements and consist of approximately 24 million points before the earthquake and 36 million points after the earthquake with three-dimensional coordinates. These measurements were carried out with distance measuring devices called TLS (Terrestrial Laser Scanner). Point cloud readings provide high accuracy in obtaining the current condition of the structure and enable modeling and detailed damage status.

Voxel model technique/method was used to create the building model from point cloud data. Voxel is the three-dimensional equivalent of a pixel. While pixel defines a point in two dimensions, voxel expresses the graphic information that defines a point in three-dimensional space. Voxel modeling is based on the principle of slicing the obtained point cloud cluster at certain intervals and superimposing the plan or section planes obtained from these slices. This method allows the building model to be represented in three dimensions in detail. Figure 6 shows the relief of Hüseyin Paşa Mosque obtained from the point cloud and Figure 14 shows the voxel model view of this point cloud.

Figure 6. Survey obtained from the Hüseyin Pasha Mosque point cloud

The data of station TK.2703, located approximately 3.5 km away from Hüseyin Pasha Mosque, was used for the records of the earthquakes that occurred in February 2023. Information about the station is given in Table 3.

Table 3. (Data of station TK.2703)

Recording Station	AI_274_GZT
Station Coordinates	37.05885 K, 37.35073D Date: WGS84
Altitude	851m
Location	Meteorology Directorate
Station Address	Gaziantep
History of Seismic Survey	October 13, 2008

Building Type	Container

The acceleration time graphs in the E (east-west), N (north-south) and U (vertical) directions taken from the TK.2073 station for the Elbistan earthquake are as follows. These acceleration time graphs in data format are reflected in the mosque structure in both classical analysis and voxel model analysis.

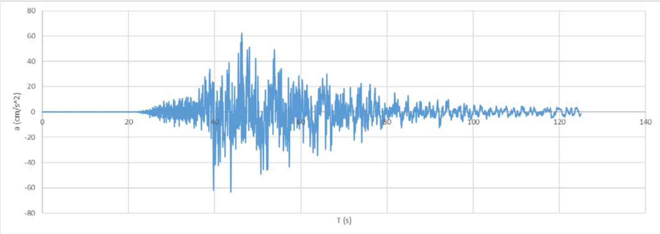

Figure 7. Acceleration-time graph of TK.2703 station Elbistan earthquake in the E direction

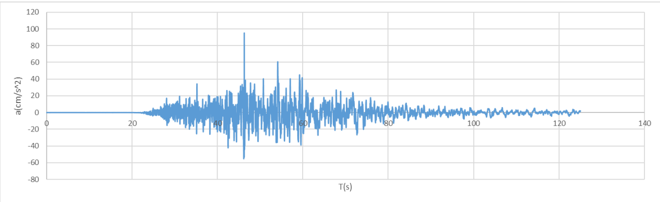

Figure 8. TK.2703 station Elbistan earthquake N direction acceleration-time graph

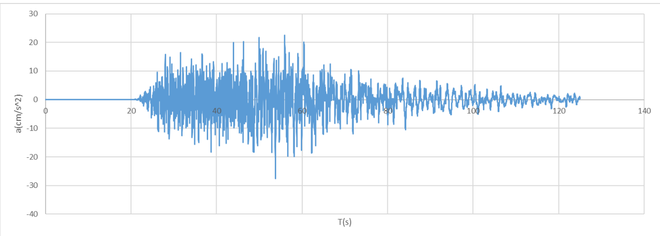

Figure 9. U direction acceleration-time graph of TK.2703 station Elbistan earthquake

The acceleration time graphs in the E (east-west), N (north-south) and U (vertical) directions taken from the TK.2073 station for the Pazarcık earthquake are given in the figures below.

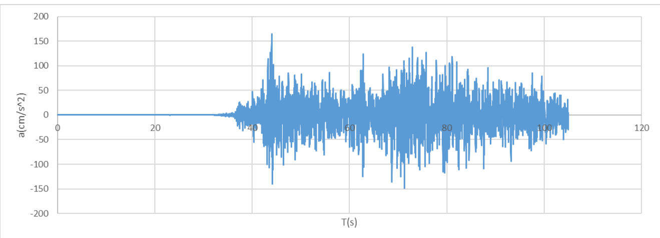

Figure 10. TK.2703 station Pazarcik earthquake E-direction acceleration-time graph

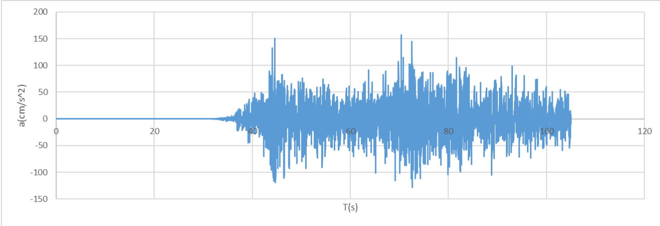

Figure 11. TK.2703 station Pazarcik earthquake N direction acceleration-time graph

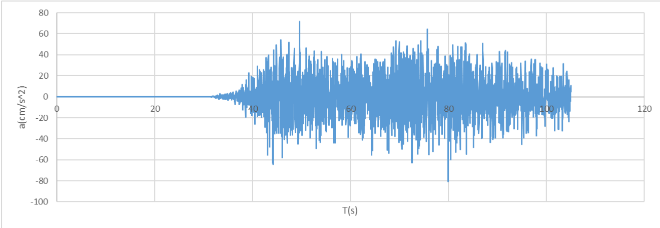

Figure 12. TK.2703 station Pazarcik earthquake U-direction acceleration-time graph

The mosque was first modeled with the classical method as undamaged. In this modeling, the dome, pendentive, arch and load-bearing stone wall elements were defined and modeled. It was analyzed with a three-dimensional analytical program. (Figure 13), dead loads were applied to the dome as filling loads. Within these loads, there was then a mixture of straw and soil screed (locally called mud) on the mosque and a 4 mm lead sheet coating on top. In the voxel model of the mosque (excluding the minaret section), the structure was modeled as undamaged. (Figure 14). The loads were again applied to the domes, but the elasticity modulus affects the behavior in the modeling of the upper loads and the filler under the lead sheet. Therefore, after several analyses on the elasticity modulus, a result close to the material behavior of the load was obtained.

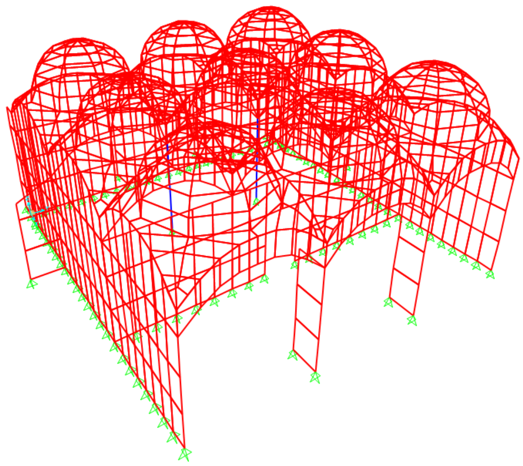

Figure 13. Classical Modeling of the Mosque

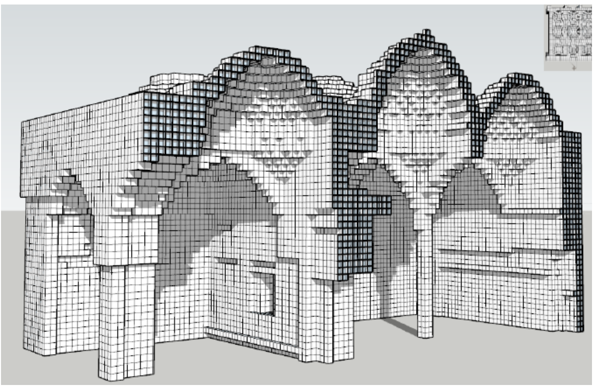

Figure 14. Mosque Voxel Modeling

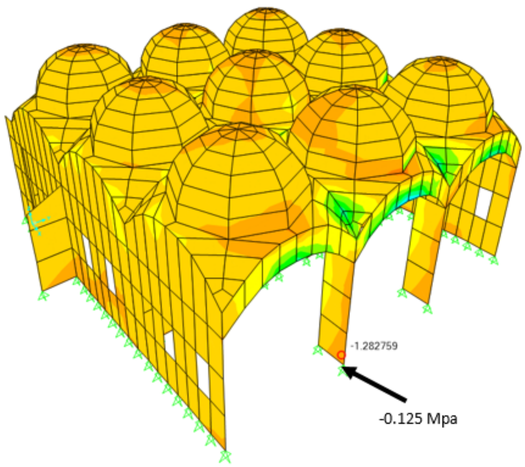

Figure 15. Classical Model Shell Stress -0.125 MPa

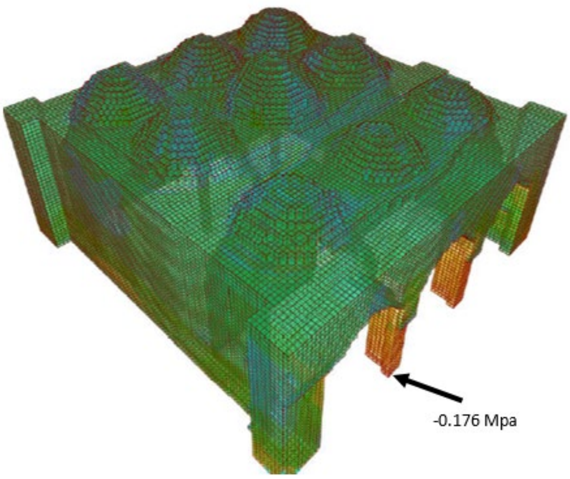

Figure 16. Voxel Model Solid Stress -0.176 MPa

Under the filling loads and earthquake loads of the structure, in the classical model, the measured shell element stress value at a specified point (front facade bearing wall close to the ground) showed a value of -0.125 MPa (Figure-15), while the solid body element stress value at the same point was analyzed as -0.176MPa in the voxel model (Figure-16). Although the stress values are approximate in both models, it was observed that the stress concentrations were greater in the classical model and the stresses showed a more dispersed distribution in the solid body model. The dimensions of the modeled elements are also effective in this situation. In the classical model, the element dimensions vary according to the place, but in some places the element size reaches 100 cm. In the voxel model, since no element definition is made, the structure is subjected to analysis as a whole. Here, a cube element was defined as the general size and it was deemed appropriate to optimize and evaluate all dimensions as 20X20X20 cm. Within the scope of voxel modeling, the dimensions of the unit cube model can be changed in areas requiring detailed evaluation and analysis. In this way, smaller elements and a more detailed analysis can be obtained. In this context, the dimensions of the "keymık stone" known as Gaziantep stone used in the structure in question caused the selection of model dimensions.

As a result of the examined models, it was naturally observed that there were stress concentrations in the arches and the dome-arch-over-arch connections in both models. However, in the classical model, stress concentrations due to the element size and the relationship of the elements give larger values. However, the deformations, cracks and damages that the mosque structure, which was tested under an earthquake, received are less than in the classical analysis. The voxel model analysis gave results closer to the structural behavior under a real earthquake.

Since the structure is a stone masonry structure in earthquake behavior, the formation of cracks due to tensile force is an expected movement. However, while the behavior is observed in the element size defined in the classical modeling, since the element definition is not made in the voxel model, it is seen that the stresses give the real distribution and therefore the stress distribution close to the existing crack map.

In the classical model, element size and definition do not allow stress distribution as in the voxel model.

3. Conclusions

Both analyses were made in a three-dimensional analytical program, but in classical modeling, the structural geometric conditions of the dome arch, pendant and load-bearing walls and their structural connections and relations with each other were not fully known, so these elements and their connection relations were modeled with experience and engineering assumptions. In addition, in classical modeling, linearity is a concern in the geometric definitions of the load-bearing elements, and the element elasticity modules and thicknesses were determined according to approximate acceptance and were defined with the same properties throughout the element.

There is a straw-soil mixture coating on the dome, which was made due to the construction technique of the period, and a lead sheet on top of it. These layers were transferred to the model as loads in the classical model. However, as a result of the calculations and comparisons, it was observed that the element stress concentrations were more intense in the classical model. It was determined that the structure, which is a natural experimental setup, has a known time acceleration graph and whose damages have been determined, was subjected to less damage than the obtained stresses and the predicted damage.

In the voxel modeling method, the geometry of the structure as a whole, the dome, arch, pendant and load-bearing walls, are directly transferred to the model by completely taking them from the point cloud readings, while the structural connections and relations between the elements are transferred including the damages from the point cloud readings and it provides the closest acceptance to the real situation and the minimization of the error related to it. With this modeling method, all structural defects including the deformations in the walls and other load-bearing elements are transferred to the model, while the formation of the structural elements as layered solid voxel elements also allows the definition of different elasticity modules within the same element in the required regions. The previously mentioned straw-soil mixture on the dome and the lead plate section are defined with a different elasticity module and are defined as elements affecting both the load and trench behavior in the model. When the results of the voxel model analysis are examined, it is understood that there is no excessive stress concentration, the stresses are transferred by spreading to a wider surface, the element integrity is not impaired despite the formation of joint discontinuities as in the real case, and it is observed that voxel modeling gives more realistic results in determining the damage status, geometric irregularity and stress distribution.

In this context, it was understood that the use of voxel modeling method would be appropriate in preparing the reinforcement proposal of the structure and determining the performance to be calculated after reinforcement.

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