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Seismic vulnerability of historical masonry structures with irregular geometry

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Professional paper

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Seismic vulnerability of historical masonry structures with irregular geometry

Historical masonry buildings with irregular geometric layouts, which cover a large floor area, display poor seismic behaviour. Stresses occur because of irregularities in plan or elevation, and consequent unbalanced mass distributions. The gravity and earthquake analyses are applied in this study on the analytical model of the historical Gazanfer Aga Madrasah. The analyses are used to examine the performance of the building under earthquake effects. The importance of analytical modelling technique in the analysis of irregular masses is emphasized.

Key words:
historical masonry structures, seismic behaviour, analytical modelling, finite element analysis

Stručni rad

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Potresna osjetljivost povijesnih zidanih konstrukcija nepravilne geometrije

Povijesne zidane građevine koje pokrivaju veliku površinu nepravilnog oblika pokazuju loše ponašanje pri potresu. Pojavljuju se naprezanja zbog nepravilnosti u tlocrtu ili visini građevine, a posljedica su neuravnotežene raspodjele masa. U ovom istraživanju je proveden proračun ponašanja povijesne medrese Gazanfer Aga na analitičkom modelu pri djelovanju vlastite težine i potresa. Proračun je proveden kako bi se ocijenilo ponašanje građevine pri potresu. Naglašena je važnost metode analitičkog modeliranja u proračunima neuravnoteženih masa.

Ključne riječi:
povijesne zidane građevine, potresno ponašanje, analitičko modeliranje, metoda konačnih elemenata

Fachbericht

Saadet Toker Beeson, Joseph Kubin, Ali Ihsan Unay

Seismische Vulnerabilität geometrisch unregelmäßigen historischen Mauerwerks

Historische Mauerwerksbauten, die größtenteils geometrisch unregelmäßig angeordnet sind, verhalten sich unter Erdbebeneinwirkungen ungünstig. Spannungen treten aufgrund der Unregelmäßigkeiten im Grundriss oder entlang der Höhe auf, sowie aufgrund der entsprechenden unausgeglichenen Verteilung der Massen. In dieser Arbeit werden die Einwirkungen vertikaler und seismischer Lasten an einem analytischen Modell der historischen Gazanfer Aga Madrasah berechnet. Die Analysen werden angewandt, um das Verhalten des Gebäudes unter Erdbebenlasten zu untersuchen. Die Bedeutsamkeit analytischer Modellierungstechniken in der Analyse unregelmäßiger Massen wird hervorgehoben.

Schlüsselwörter:
historisches Mauerwerk, seismisches Verhalten, analytische Modelle, Finite-Elemente-Analyse

1. Introduction

The conservation of cultural heritage and its transfer to future generations have been among the significant research and practice topics of the 21st century. Being the focal point of many disciplines such as architecture, engineering, history of art, and archaeology, this topic has surely been discussed widely by sound and righteous causes in interdisciplinary groups. Parallel to the widespread use of computers, the analysis methods in structural engineering provide more accurate and certain results in a much shorter time. Several computer programs that ease up data transfer and enable transferring the results to construction drawings have been developed for the analysis and design of contemporary engineering buildings. However, historical buildings are rather different than modern buildings in terms of structural system and configuration. The most appropriate method to analyze historical buildings, such as prestigious monuments, palaces, bridges, and castles, is the finite element analysis [1, 2].

The analytical modeling is the most crucial part of the finite element analysis of historical buildings. It can be defined as the conversion of load bearing members of different materials to mathematical terms consistent with the basic principles of mechanics. With the exception of extraordinary structural forms, the load transfer mechanism – as foreseen by the basic principles of structural mechanics - has an important role in determining the geometry and dimensions of structural members of contemporary structures. However, this is not valid for the load bearing systems of historical buildings. Also, the irregular and large contemporary reinforced concrete and/or steel buildings could be turned into buildings that have regular schemes by using expansion joints. Although they separate the pieces of the structure from each other physically and provide distinct structural behaviors, expansion joints do not require change of the irregular plan scheme. The modern building codes and standards necessitate this separation for larger buildings. Factors like temperature differences, time dependent deformations - such as creep and shrinking - and foundation settlements, negatively affect the structural behavior of buildings that have large dimensions in plan, and consequently lead to excessive stresses in some load bearing members. Unfortunately, historic buildings were constructed as a whole without any expansion joints despite their irregular plan schemes and elevations. The interfaces of different masses are prone to develop cracks especially during an earthquake, and these cracks increase the irregularity in the structure [3, 4].

This study presents the results of the finite element analyses performed to determine the structural behavior of Gazanfer Aga Madrasah with regard to earthquake action, and to identify its seismic resistance. The term "madrasah" was used to denote the higher education institutions in the Muslim world until the first half of the 20th century. The madrasahs had shown great improvements in terms of architectural layouts over time. When the idea of a "complex" first settled down, the centerpiece was always the mosque due to its moral value with the other pieces, such as madrasahs, tombs, fountains, and baths, merely placed around. Over time, parallel to the importance given to education in Seljuk and Ottoman periods, the madrasahs started to gain increasing importance and they started to be regarded as important landmarks. Just as the mosques of the Muslim world, the Ottoman madrasahs in Anatolia and Balkans have their own architectural styles. The plan scheme of the madrasah is based on the main theme of the arid climate, which is the courtyard.

Figure 1. Gazanfer Aga Madrasah [7]

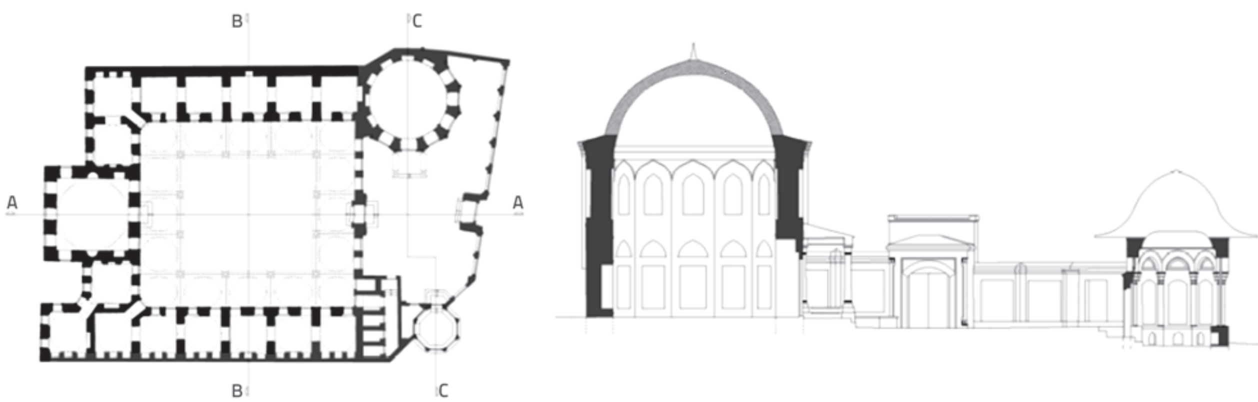

Figure 2. Gazanfer Aga Madrasah layout plan and section

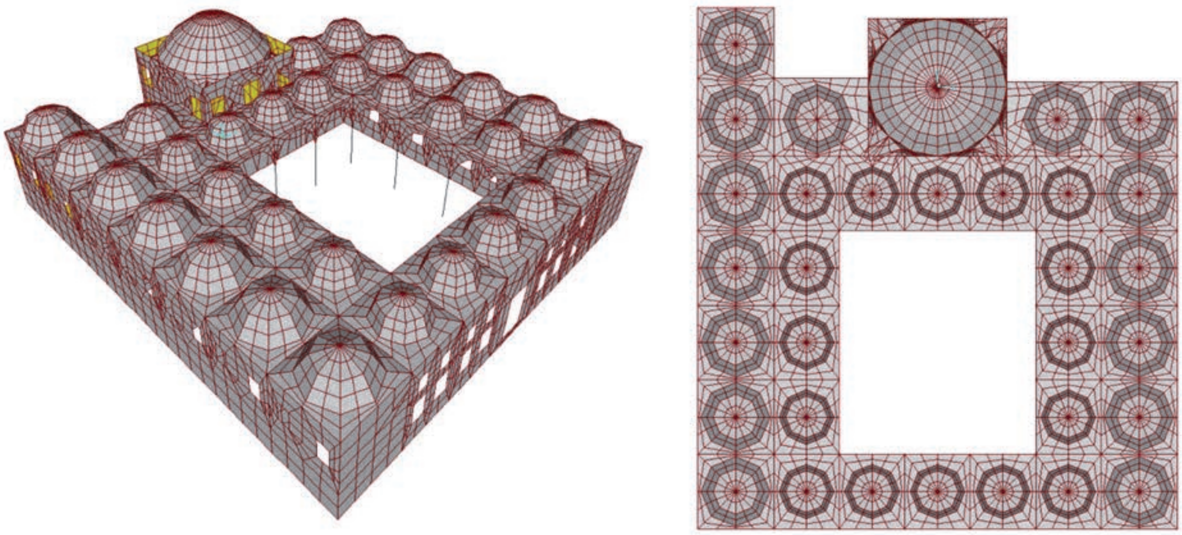

Figure 3. Finite element model of Gazanfer Aga Madrasah

In Gazanfer Aga Madrasah, the rectangular inner court, which is bordered by the riwaq, is surrounded by other spaces such as teacher rooms, student rooms, and the classrooms behind the riwaq (Figure 1). It has a very scattered plan scheme and involves serious mass irregularity (Figure 2). These two factors are important considering that the building is located in the earthquake prone historic peninsula of Istanbul. Originally built in 1595, Gazanfer Aga Madrasah today serves as a caricature and humor museum [5, 6].
The building is rectangular in shape and measures 40 m x 28 m. A 7 m diameter dome covers the 8.5 m x 8.5 m main space. The thickness of the dome is 50 cm, and it is supported by one-meter-thick walls. The height of the dome from the supports is 3.5 m, while the total height from the ground level reaches up to 10 m. Some records claim that this structure underwent repairs after the 1908 earthquake [8].

2. Finite element model and main features of structural analysis

The finite element model of the Gazanfer Aga Madrasah, given in Figure 3, was prepared in accordance with the specifications and characteristics of the SAP2000 software [9]. All the necessary geometric dimensions were obtained through the conducted surveys. The modeling and analysis parameters are listed as follows:
- The main dome, half domes, little domes, the walls of the main space, and all other walls were modeled by SHELL elements.
- The model was prepared by using 7882 nodes and 7523 SHELL elements.
- The columns supporting the arches in the courtyard and the iron tensile rods were modeled by FRAME elements.
- Absolute continuity was obtained by connecting the joints of the SHELL elements that constitute the domes, arches and walls, to one another.

Table 1. Material properties of the finite element model

Characteristic / Element type	Modulus of elasticity E [kN/m²]	Unit weight [kN/m³]	Mass [t/m³]
Brick dome and the pendentives (with mortar)	1.200.000 (1 200 MPa)	24	2.45
Stone walls (with mortar)	450.000 (450 MPa)	24	2.45
Marble columns	2.000.000 (2 000 MPa)	24	2.45
Iron tension members	200.000.000 (200 000 MPa)	76.82	7.83

- The small pillars supporting the arches around the inner courtyard were connected to the ground by means of fixed supports. Connections between the arches and the FRAME elements that represent the pillars were obtained by means of hinge connections to prevent moment transfer.
- Characteristics of structural materials were chosen using the data from previous researches as found in international literature, and the values for masonry materials suggested in the current Turkish Earthquake Codes [10, 11].
- Modulus of elasticity and unit weight values were adopted by assuming that the masonry units and mortar are a single material.
- Two different loading conditions were applied in the model. Gravity loads and seismic loads were taken into consideration when applying the loads. The spectrum was applied in two primary directions as EQx and EQy loadings.
- For convenience in the evaluation of the results, two different loading conditions, i.e. G + EQx (gravity loads and earthquake loading in X direction), and G + EQy (gravity loads and earthquake loads in Y direction) were defined.
- Spectral calculation was made for the first 60 modes.

- No reductions were made during evaluation of earthquake load or dead load results (R=1). Moreover, the obtained stress values were compared to the tripled allowable stress values. Some material characteristics that were taken into consideration in the finite element analysis of the Gazanfer Aga Madrasah are summarized in Table 1.

The spectrum curve used in the dynamic analysis of the Gazanfer Aga Madrasah is given in Figure 4. The spectrum curve was obtained through the records of the 1999 Northwest Turkey earthquake [12]. The code spectrum was employed to evaluate the response of this structure. The code spectrum is stochastic and not dependent on a single time history.

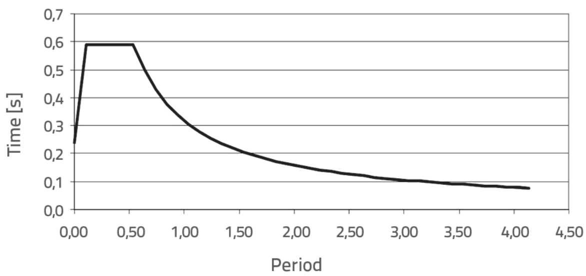

Figure 4. Spectrum curve for dynamic analysis

3. Finite element analysis

Turkish Earthquake Codes suggest compressive allowable stress values of f_{all} = 0.8 MPa and f_{all} = 0.3 MPa for brick and stone masonry walls, respectively. Seismic resistance of Gazanfer Aga Madrasah could be interpreted through the comparison of stress values calculated in the analyses to allowable stress values stated in the codes. During evaluation of results, no reductions were made in earthquake load or dead loads (R=1). In addition, the allowable stress values were tripled and used as the limit values. Thus, as explained above, the limiting stress value for the dome and the vaults was defined according to suggested values given in the Turkish Earthquake Code:

$$f_m = 0,8 \times 3 = 2,4 \text{ [MPa]} \quad (1)$$

while the bearing stress for stone in the walls and arches was assumed to be:

$$f_m = 0,3 \times 3 = 0,9 \text{ [MPa]} \quad (2)$$

The allowable tensile stress value could be assumed as amounting to 15 % of the specified allowable compressive stress value. Thus, the allowable tensile stress value for the dome and the vaults could be taken as:

$$f_{m(vlačno)} = 2,4 \times 0,15 = 0,36 \text{ [MPa]} \quad (3)$$

while it was assumed as:

$$f_{m(vlačno)} = 0,9 \times 0,15 = 0,135 \text{ [MPa]} \quad (4)$$

for stone in the walls and arches. The shear stress values obtained through dynamic analysis (the S12 stresses in shell elements) were compared to the limit shear values (τ_m) obtained by the equation:

$$\tau_m = \tau_o + \mu \cdot \sigma \quad (5)$$

In this equation:
τ_m - wall limit stress
τ_o - allowable wall failure stress
μ - friction coefficient (could be taken as 0.5)
σ - wall vertical stress.

As shown in Table 2, the wall cracking stress for brick in the main dome, pendentives, and small domes, was assumed as:

$$\tau_o = 0,15 \times 3 = 0,45 \text{ [MPa]} \quad (6)$$

The cracking stress for stone in the walls and arches was assumed to be:

$$\tau_o = 0,10 \times 3 = 0,30 \text{ [MPa]} \quad (7)$$

As suggested in the earthquake codes, assuming that the vertical stress level for the walls would not exceed the allowable compressive stress values determined for relevant structures, the allowable shear stress value for the main dome, pendentives, and small domes was taken to be:

$$\tau_m = 0,45 + 0,5\,(2,4/2) = 1,05 \text{ [MPa]} \quad (8)$$

and the allowable shear stress value for stone in the walls and arches was taken to be [10]:

$$\tau_m = 0,30 + 0,5\,(0,9/2) = 0,53 \text{ [MPa]} \quad (9)$$

Table 2. Allowable stresses for material groups

Material type	Allowable compressive stress [MPa]	Allowable tensile stress [MPa]	Allowable shear stress [MPa]
Brick dome and pendentives	2.4	0.36	1.05
Stone walls and arches	0.9	0.135	0.53

The structural analysis of Gazanfer Aga Madrasah was conducted according to the specified load combinations by

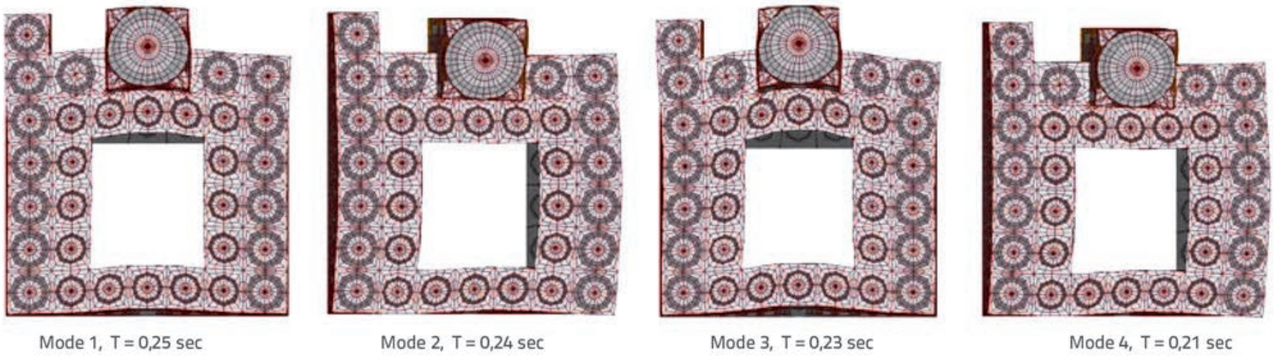

Figure 5. First four mode shapes and periods

Table 3. Periods of modal shapes and mass participation proportions

Mode	Periods of modal shapes [s]	Mass participation proportion in X direction	Mass participation proportion in Y direction
1	0.25	0	0.42
2	0.24	0.70	0.42
3	0.23	0.70	0.47
4	0.21	0.73	0.47
5	0.19	0.73	0.47
60	0.04	0.90	0.90

means of the SAP2000 finite element analysis software. The interpretation of results was made regarding the most unfavorable results, and according to the color-coded shapes and stress distribution maps of SAP2000 [9]. Table 3 shows the periods of modal shapes. and the mass participation proportions and the first four mode shapes can be seen in Figure 5.
The total calculated weight of the building was 37394 kN; the total base shear under the calculated seismic effect applied in the southwest-northeast direction (X direction according to the model) was 15060 kN; and the total base shear calculated under the seismic effect applied in the southeast-northwest direction (Y direction according to the model) amounted to 11184 kN. According to these results, the base shear that the structure is exposed to is equal to 40 % of its total weight in X direction and to 30 % of its weight in Y direction. As can be seen in Figure 6, the largest displacement along X direction due to the earthquake loading in this direction is Δ_x=16 mm, while this value along Y direction due to the earthquake loading in Y direction is Δ_y=18 mm. Displacements in Figure 6 increase from lighter to darker shades. The darkest colors show the above mentioned maximum displacements.
Among the stresses calculated for SHELL elements in the seismic analysis of Gazanfer Aga Madrasah, the most explanatory results about the seismic behavior of the structure were obtained through the tensile and compressive stress values in vertical direction (S22 according to the SAP2000 output format) with respect to the local axis of every structural element, and the shear stress values (S12 according to the SAP2000 output format). When the analytical model was prepared, a special attention was paid to locate all SHELL elements in rectangular shape parallel to the local axes of the general SHELL elements defined in the software. As the structure has a very complex

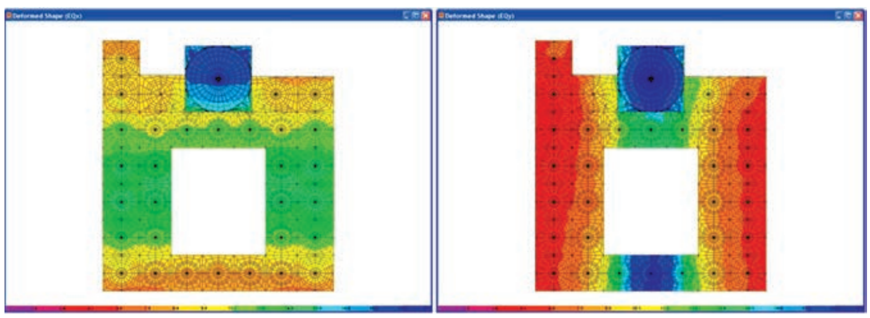

Figure 6. Displacements in color codes along X and Y directions due to earthquake loadings. Dark colors represent larger displacements

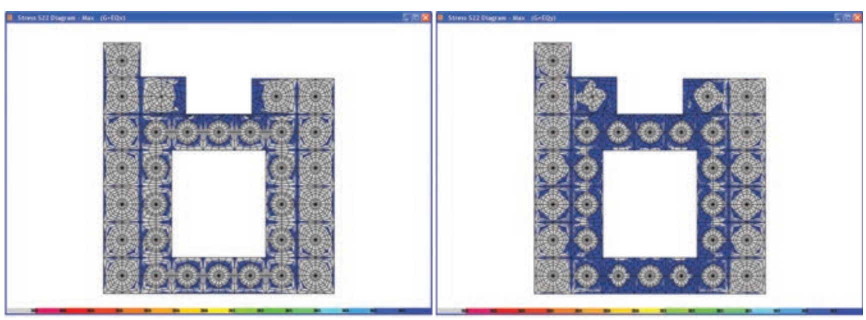

Figure 7. S22 tensile stresses shown in dark colors at small domes due to G+EQx and G+EQy loads

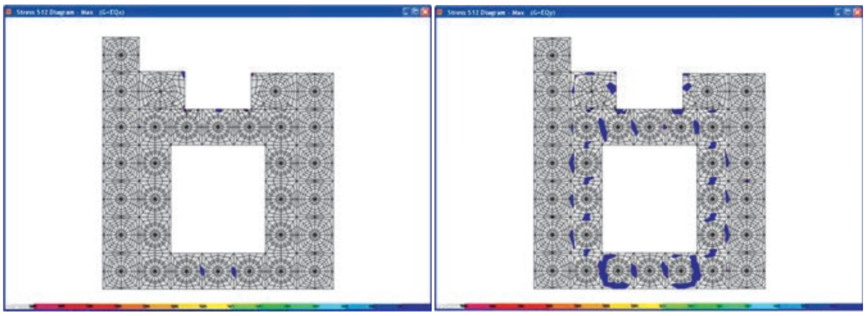

Figure 8. S12 shear stresses shown in dark colors at small domes due to G+EQx and G+EQy loads

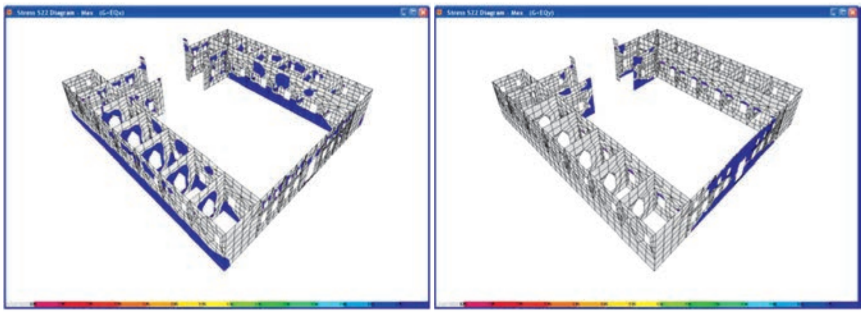

Figure 9. S22 tensile stresses (due to G+EQx and G+EQy loads) above limit values shown in dark colors at main dome and pendentives

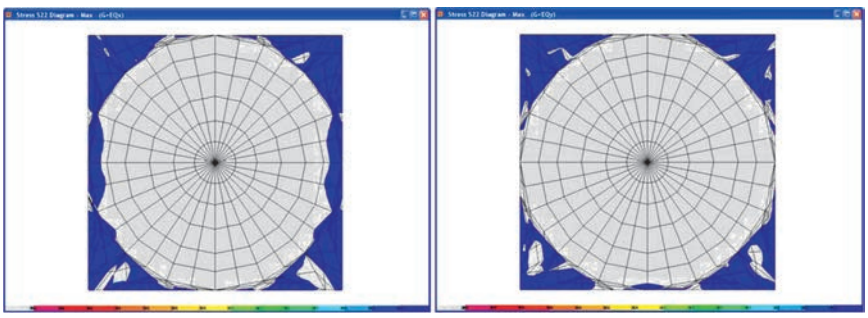

Figure 10. S22 tensile stresses (due to G+EQx and G+EQy loads) above limit values shown in dark colors at main dome walls

geometry, this approach is expected to simplify the interpretation of the principal stress values obtained in the structural analyses. Hence, S22 and S12 values, which are more practical to understand and more convenient for interpretation, were used when assessing structural capacities of structural members.

These stress values correspond to vertical compressive stress and shear stress values under earthquake effect, respectively. Characteristic structural members that determine the structure's behavior were assessed for the S22 and S12 stress values by using stress maps that were developed separately for G + EQx and G + EQy load combinations, as shown in Figure 7 and Figure 8. Figure 7 shows the S22 tensile stresses on the small domes under the G + EQx and G + EQy load. The dark colored zones in the figure are the sections that have tensile stress values in excess of the limit value $f_{m(tensile)} = 0.36$ MPa.

The S12 shear stresses on the small domes under the G + EQx and G + EQy loading are given in Figure 8. The suggested allowable shear stress for brick domes ($\tau_m = 1.05$ MPa) is not exceeded. In both loadings, any stress value larger than 0.5 MPa is presented in dark colors in order to show the locations of the largest shear stresses. The S22 tensile stresses in the main dome and pendentives, resulting from G+EQx and G+EQy loads, are shown in Figure 9. The dark colors indicate the parts that have tensile stress values greater than

Table 4. Maximum stresses (S22) acquired at various building components

Group			**G+EQx loading** [MPa]	**G+EQy loading** [MPa]
The main dome and pendentives	Top surface	**Compressive**	-0.8	-1.1
		Tensile	1.0	1.2
	Bottom surface	**Compressive**	-1.5	-1.4
		Tensile	1.1	1.3
The walls	Top surface	**Compressive**	-1.1	-1.1
		Tensile	0.7	0.8
	Bottom surface	**Compressive**	-1.1	-1.0
		Tensile	0.5	0.6
The small domes	Top surface	**Compressive**	-1.5	-2.3
		Tensile	1.9	2.7
	Bottom surface	**Compressive**	-2.3	-3.2
		Compressive	1.3	2.6
The arches	Top surface	**Tensile**	-2.0	-3.1
		Compressive	0.5	0.9
	Bottom surface	**Tensile**	-2.4	-3.2
			0.2	1.2

Table 5. Maximum shear stresses (S12) acquired at various building components

Group		G+EQx loading [MPa]	G+EQy loading [MPa]
The main dome and pendentives	Top surface	0.5	0.5
	Bottom surface	0.4	0.2
The walls	Top surface	0.4	0.5
	Bottom surface	0.4	0.4
The small domes	Top surface	1.0	1.4
	Bottom surface	1.1	1.0
The arches	Top surface	1.2	1.3
		0.6	1.6

$f_{m(tensile)}$ = 0.36 MPa, which is the limit tensile stress for brick. The limit compressive stress (f_m = 2.4 MPa) is not reached in any part of the main dome and pendentives. The largest compressive stress is around 0.1 MPa.

The S22 tensile stresses on the stone walls due to G + EQx and G + EQy loadings are given in Figure 10. The dark colored zones in the figure show the parts of the wall with tensile stress values greater than 0.135 MPa, which is the specified limit value for the walls. The limit compressive stress value (f_m = 0.9 MPa) is not reached in any part of the walls.

In the analyses, the shear stresses (S12), the suggested allowable shear stress for the walls (τ_m = 0.53 MPa), and the suggested shear stress value for the brick domes (τ_m = 1.05 MPa), are not exceeded at any point under the G+EQx and G+EQy loads.

The structural system members of the building were assessed in detail under four categories as "the main dome and the pendentives", "the walls", "the small domes" and "the arches", under the G + EQx and G + EQy loads, with respect to S22 and S12 stresses. The largest tensile and compressive stresses, along with the largest shear stresses for the top and bottom surfaces of the SHELL elements for each and every group members, are given in Table 4 and Table 5.

4. Evaluation of the analysis results

It is very difficult to estimate elastic properties of historical structures. Effects of time, cracks and settlements over time, and lack of detailed information about the structural system members or the surveys, could be listed as some of the most important factors that call for a nonlinear analysis. However, in this study, the finite element analysis of Gazanfer Aga Madrasah was made using the linear elastic material properties to assess its overall seismic performance. If a structure as big as Gazanfer Aga Madrasah were modeled and assessed by nonlinear elastic analysis methods, the iterations in the analysis would bring up doubts about the accuracy of the process even if a very detailed analysis model is developed [13]. Based on the analysis results, the following observations cab be made about the behavior and performance of Gazanfer Aga Madrasah during a probable earthquake:

- The maximum displacements under the earthquake load at the top of the dome in X-direction and Y-direction are 18 mm and 16 mm, respectively. The corresponding spectrum curve is given in Figure 4. Considering that the top point of the dome is 10 m above the ground level, this value is acceptable as it is within the acceptable range with respect to 0.0018-displacement ratio. Although it is possible to observe cracks in the wall within this relative displacement range, it can still be stated that, considering the material type, the failure is highly unlikely.
- It is not only the maximum displacement that determines the seismic performance of a structure. The displacement ratio in all points of the structure should also be analyzed. It is equally possible to observe the probable seismic behavior of a model by converting the displacements to local stress values.
- Rigidity is not uniform within the structure. Thus, it may be misleading to interpret the results by considering the lowest mode periods. In order to obtain reliable results, the analyses were performed by using the first 60 mode periods.
- Observations on the analysis results show that stress values suggested in the Turkish Earthquake Codes for the masonry structural materials are not exceeded at the load bearing members of Gazanfer Aga Madrasah.
- The allowable tensile stresses are exceeded only at the corners of the openings and at the bottom corners of the walls in small patches. Taking meshing shapes and the support conditions into account, these stresses could be considered to be within the acceptable range in the lateral loadings. It should be kept in mind that the material properties of the load bearing structural members were specified according to the values given in literature, and according to the values suggested in applicable codes. Considering the age of the building, it could be said that the material decay and/or loss of material in structural members could affect structural behavior of the building. However, as the displacements and the stress values obtained in the analyses are within the acceptable range, the structure is unlikely to experience a seismic performance problem.

5. Conclusions

Accurate definition of the dimensions of the structural members, and material properties, are the two very important conditions for a reliable finite element analysis. The finite element analysis is the most reliable method for determining the seismic performance of historical buildings. It is not very difficult to satisfy these conditions for a building model with a regular structural system. However, it is more crucial to accurately model the historic buildings as they generally do not display linear elastic material properties, but have variable geometric dimensions and material properties. They can also involve the use of multiple materials like brick + mortar + timber or stone + mortar in a single load bearing member. Gazanfer Aga Madrasah is one of these buildings with very complex features, and its sophisticated and irregular geometry makes the analysis and assessment highly challenging. The irregular plan layout affects seismic performance of historic buildings as they lack the means that would provide the structure with a more regular seismic behavior. Expansion joints, which are required by the modern engineering design rules and current codes, are among the means that enable regular behavior of structures, even when their structural layout is irregular. Due to its age, Gazanfer Aga is missing the modern design features to improve its seismic performance. Appropriate analyses were therefore needed to assess its structural performance so as to take adequate action to protect its historical value.

It should be kept in mind that structural performance of historic buildings can not exactly be determined by linear elastic analysis methods. In addition, it may not be possible to accurately determine whether the load bearing capacity of structural members is exceeded or not. However, they constitute a good starting point to identify the basic problems in historical buildings. If problems are detected during linear analyses, then the nonlinear analyses should be conducted. Nonlinear methods could offer more reliable results when the material properties are defined in detail. However, the nonlinear analysis methods could be even more misleading during iterations, in the analyses of large buildings and in case of sophisticated geometric configurations.

It is crucial for an accurate seismic analysis to model structures with complex geometries - like Gazanfer Aga Madrasah - as a whole, even when some main masses in the structure are integrated by means of very small structural members. Linear elastic analysis methods are therefore sufficient to determine the general structural behavior and seismic performance of buildings of this scale. In this study, the Gazanfer Aga Madrasah was evaluated as a whole with the constituting structural members, to assess its overall seismic performance. Despite its irregular layout and indeterminate material characteristics, the stress levels are mostly within the limits set by the modern earthquake codes. Tensile stress values are only exceeded at the corners of the openings, and the bottom corners of the walls. The displacements are acceptable when the overall size of the structure is considered. The rigidity of the structure was also observed; it is irregular throughout the structure as could be expected from a large geometry. Though it is possible to state that the structure displays a sound seismic performance, nonlinear analyses will be more informative due to the change in the building's rigidity, its complex geometry, and unknown material properties, and cracks and settlements that occurred in its lifetime.

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