Analysis of Historical Structures with Finite Elements Method

Filiz Karakuş[1*]

[1*] Ankara Yıldırım Beyazıt University, Faculty of Architecture and Fine Arts, Departmant of Architecture, Ankara, Turkey, (ORCID: 0000-0002-7562-3435), fkarakus@ybu.edu.tr

Abstract

Historical masonry structures are important parts of our cultural heritage and the transfer of these structures to future generations is one of the most important problems in the field of conservation. These structures can be damaged by long-term natural events or sudden natural causes such as earthquakes, floods, avalanches, as well as adverse environmental conditions and human-based reasons. Finite element analysis is the most appropriate method for the structural analysis of historical masonry structures, which have survived until today and are the magnificent structures of the periods they were built. The load bearing behavior of historic masonry structures is quite different and complex from other structures due to the elements and materials that make up the structural system. In this study, calculations and results based on finite element method are presented in order to determine the structural behavior of Cenabi Ahmet Pasa Tomb located in Ulucanlar Street in Ankara Province, Altındağ District in the face of a possible earthquake and to determine the earthquake resistance.

Keywords: Historical masonry structure, finite elements, Cenabi Ahmet Pasha Tomb.

Sonlu Elemanlar Yöntemi ile Tarihi Yapıların Analizi

Öz

Tarihi yığma yapılar kültürel mirasımızın önemli parçaları olup bu yapıların gelecek kuşaklara aktarılması koruma alanındaki en önemli sorunlardan birisidir. Bu yapılar uzun süreli doğa olayları ya da deprem, sel, çığ gibi aniden oluşan doğal nedenlerle olduğu gibi olumsuz çevre koşulları ve insan kaynaklı nedenlerle de bozulabilmektedir. Günümüze kadar varlıklarını sürdüren ve yapılmış oldukları dönemlerin görkemli yapıları olan tarihi yığma yapıların yapısal çözümlemesi için en uygun yöntem sonlu elemanlar analizidir. Tarihi yığma yapıların yük taşıma davranışı, yapısal sistemi oluşturan elemanlar ve malzemeler nedeniyle diğer yapılardan oldukça farklı ve karmaşıktır. Bu çalışmada Ankara İli, Altındağ İlçesi Ulucanlar Caddesi'nde bulunan Cenabi Ahmet Paşa Türbesi'nin olası bir deprem karşısında yapısal davranışının belirlenmesi ve deprem dayanımının saptanması amacıyla sonlu elemanlar yöntemine dayalı olarak yapılan hesaplamalar ve sonuçları sunulmuştur.

Anahtar Kelimeler: Tarihi yığma yapı, sonlu elemanlar, Cenabi Ahmet Paşa Türbesi.

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* Corresponding Author: fkarakus@ybu.edu.tr

1. Introduction

The historical, architectural and artistic value of each of the historical masonry structures is different, as well as the material properties, construction techniques, structural system properties and the destructive effects they are exposed to. In historical masonry structures, the carrier system consists of foundations, walls, columns, pillars, floors, arches, vaults, domes and other roof (roof, wooden roof, etc.) elements. We see that materials such as wood, stone, brick, adobe and mortar as binders are widely used in these buildings (Karakuş: 2019).

Historical buildings have a very complex load-bearing behavior due to the intense and continuous interaction of domes, vaults, arches, columns and walls that form the carrier system (Keypour et al: 2007). The structural behavior of historical buildings depends on the material properties, form and dimensions used and the combination of different elements (Croci: 1998).

Structural analysis of historical masonry structures differs from the analysis and calculations made for new structures and the reasons mentioned above make it difficult to analyze these structures structurally (Ünay: 2002). In these structures, uncertainties about the physical and mechanical properties of materials such as stone, brick, and mortar that form the carrier system also reduce the reliability of the results of the analysis.

In order to determine the load-bearing system behavior of historical buildings, many criteria such as the geometric form of the building, the materials used and the loads affecting the structure, and the foundation and ground condition should be considered.

The most appropriate method to be used to determine the structural performance of historical buildings is numerical analysis (Mainstone: 1997). Structural system behavior and performance of historical buildings are determined by numerical method in three stages. In the first stage, a model of the building is prepared mathematically. In the second stage, a numerical analysis is made against the loads affecting the structure by using an appropriate analysis method. The results obtained after this stage are evaluated. However, it is very important that the evaluations made at this stage are understood by disciplines other than engineering (Can and Ünay: 2012). The conservation of cultural and architectural heritage is a field that is of interest to many disciplines such as architecture, engineering, art history, archeology and requires collaboration. For this reason, it is very important that the results obtained are understood by experts working in fields other than engineering.

The bearing systems of the historical masonry structures, which have survived until today and are the magnificent structures of the times they were built, differ from today's modern structures. For these reasons, the most appropriate method for structural analysis of these structures is finite element analysis (Can et al: 2012; Croci: 1998).

Numerical modeling can be defined as the conversion of structural system components made of different materials and having variable cross-section geometry into mathematical terms in a correct and harmonious manner according to the basic rules of mechanics (Can et al: 2012). Unlike modern buildings, historical buildings, which have irregular plan geometry, are built as a whole without dilatation, especially in parts that differ in mass and height, especially in parts where the mass difference is large during an earthquake and these cracks affect the seismic behavior of the structure (Betti and Vignoli: 2008).

There are two approaches to modeling masonry structures: micro modeling and macro modeling. In micro modeling technique, mortar used as binder and stone or brick material are modeled separately, while in macro modeling, the materials are modeled as a single material, not separately. In the micro modeling approach, the stresses and load flow that lead to a decrease in stiffness can be observed. Since the mortar in the joints is weaker than the masonry units, the micro modeling technique, which is a method that focuses on the joints, is a method preferred for the detailed analysis of a part of the structures or structures that are not large. In this method, since the mechanical properties of the mortars need to be fully known, a detailed material study is required before modeling (Lourenço: 2006; Saraç: 2003). Difficulties are encountered due to the lack of experimental data on macro models and the complexity of non-isotropic material behavior. In some studies, using anisotropic material behavior and the concept of plasticity, applications that show different hardening / softening properties in different directions give very good results (Lourenço: 2006). Numerical modeling can be defined as the conversion of structural system components made of different materials and having variable cross-section geometry into mathematical terms in a correct and harmonious manner according to the basic rules of mechanics (Can et al: 2012). Unlike modern buildings, historical buildings, which have irregular plan geometry, are built as a whole without dilatation, especially in parts that differ in mass and height, especially in parts where the mass difference is large during the earthquake and these cracks affect the seismic behavior of the structure (Betti and Vignoli: 2008).

In the finite element method, which was developed as a result of the developments in computer technology and the desire to transfer the problems to the computer environment, the main logic is to divide the whole into a finite number of elements and explain the general behavior of the system in detail with the reactions of the elements that make up the system. For the accuracy of the solution in the finite element method, the modeling should be done correctly and the behavior of each element should be represented in the most realistic way (Şenel: 1996). In this method, which is preferred in terms of time and economy, it is possible to use different building element models such as rod, plate, shell or solid together.

In this study, the results of the calculations made based on finite element method in order to determine the structural behavior of the Cenabi Ahmet Pasa Tomb located in Ulucanlar Street in Ankara Province, Altındağ District against a possible earthquake and to determine the earthquake resistance are presented. However, general assumptions were made regarding the properties of the materials during modeling, since analyzes could not be performed in the laboratory environment to determine the physical and mechanical properties of the stone, brick and mortar materials that make up the building. This situation constitutes the limitations of the study.

2. Analysis of Cenabi Ahmet Pasa Tomb with Finite Element Method

Cenabi Ahmet Pasa Tomb was built in 1565-66 and is located in the same courtyard with the mosque with the same name and

Azimi Hacı Esat Tomb (Figure 1). The octagonal planned building is made of cut stone in a masonry system and its dome is lead-plated (Figure 2). The mass features, plans and facades of the tomb reflect the characteristics of the Ottoman tombs (Figure 3) (Başkan:1998).

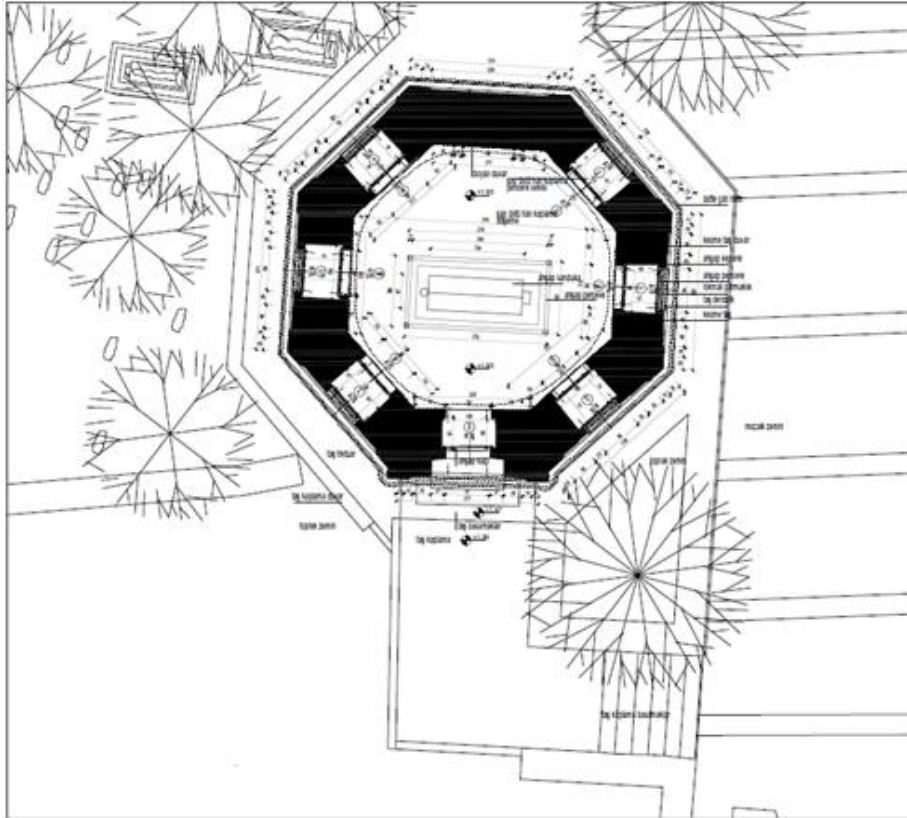Figure 1. Cenabi Ahmet Pasa Tomb view from the courtyard

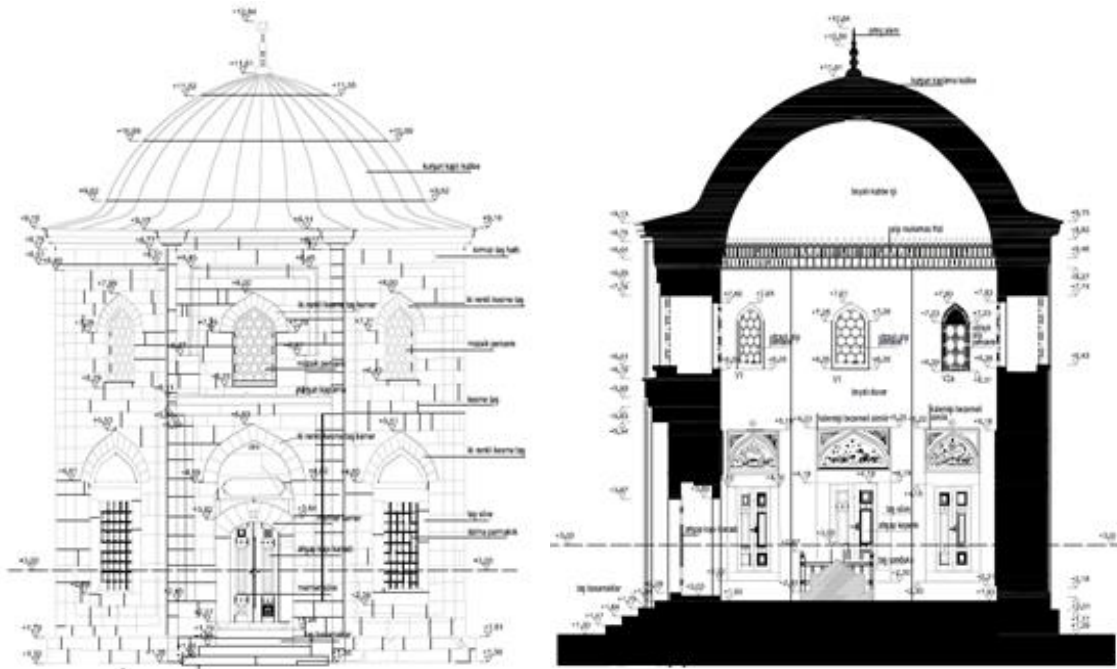Figure 2. Plan of Cenabi Ahmet Pasa Tomb

Figure 3. Cenabi Ahmet Pasa Tomb, north facade and F-F Section

Structural analysis of Cenabi Ahmet Pasha Tomb was made by using the SAP2000 program with finite element analysis method. This method starts with the digital modeling of the whole or part of the building. During this process, which is called the decomposition of the structure, the structure is divided into shapes and numbers of elements suitable for the purpose of the method used (Vintzileou: 2007). The purpose of digital modeling is to determine the behavior of the elements that make up the structural system of the building under various loads or effects. Since the carrier system in historical buildings is often complex, some simplifications are required during the modeling of the building. For this, the mechanical properties of the materials that make up the carrier system must be defined correctly (Can and Ünay: 2012).

In this study, the mathematical model of the building was created by using the existing survey projects. The dome and walls of the building are modeled with SHELL elements (Figure 4). In the study, the properties of the materials that make up the carrier system were selected by taking into account the values obtained in previous similar studies and recommended for masonry structures in the current Earthquake Regulation (Turkey Building Earthquake Regulation). It has been accepted that stone and brick materials have the characteristics of a single material together with the mortar used, and the elasticity module and unit weight assumptions were made accordingly. In addition, two different loading cases are considered in which the effects caused by the constant loads and ground motion defined by the earthquake spectrum are taken into account. Spectrum was applied in two different directions as Qx and Qy.
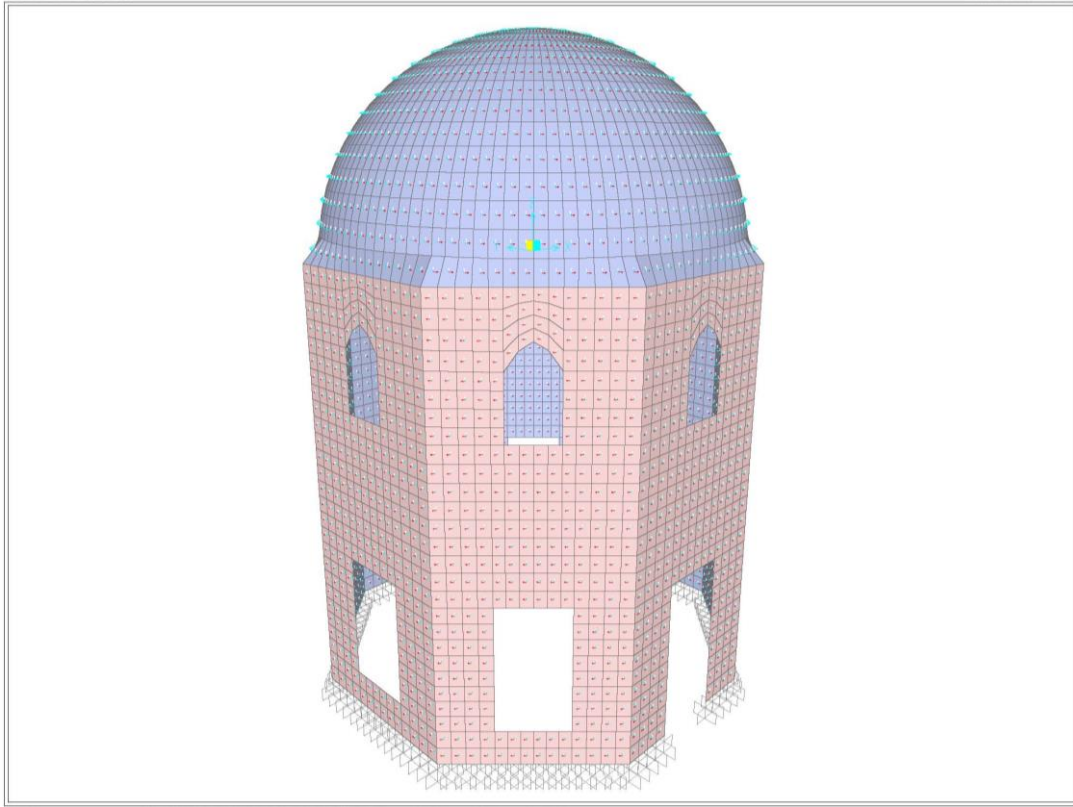
Figure 4. Cenabi Ahmet Pasa Tomb SAP2000 modeling

In the structural analysis model, the shell element direction indicated with red arrows indicates 11 horizontal direction, and the direction indicated with white arrows indicates 22 vertical direction. Since there is no exact data about the ground, the foundation of the building is not shown in the model and it is accepted that the superstructure works with the foundation. The walls and the dome are made of different materials. Therefore, different material properties are defined for both. 450 MPa was used as material elasticity for stone walls and 1200 MPa for brick dome. 24 kN / m³ was used for the unit volume weight of both materials and 2.4473 ton / m³ was used as the unit volume mass. These material parameters used are entered in the define / materials section in SAP2000 as follows (Figure 5).

Figure 5. SAP2000 material definitions

Cenabi Ahmet Pasa Tomb is located in Ankara Province, Altındağ District. In the earthquake map prepared by the Earthquake Research Department, Altındağ is located in the 4th degree (Turkey Building Earthquake Regulation). earthquake zone (Figure 6). Accordingly, the effective ground acceleration in Turkey earthquake codes are expressed in 0.1 g (Turkey Building Earthquake Regulation).
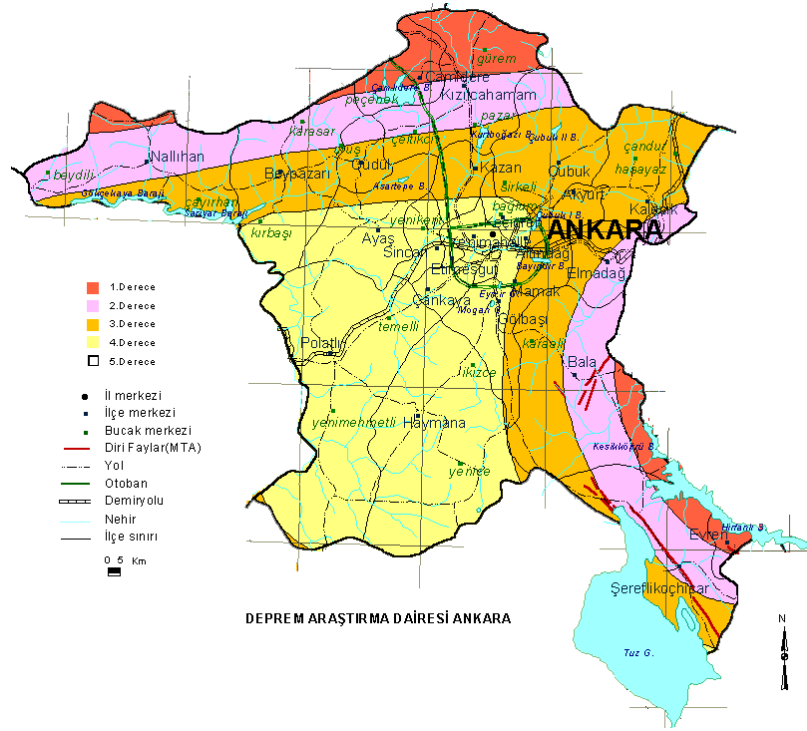
Figure 6. Earthquake Map of Ankara (URL-1)

The modal combination method was used in earthquake loading. In order to use the modal combination method, masses, sufficient mode number estimation to be taken into account and the response spectrum function must be defined. As a result of the number of modes considered according to the earthquake regulations, the total of effective masses calculated for each mode should never be less than 90% of the total mass of the building in each of the vertical x and y horizontal earthquake directions (Turkey Building Earthquake Regulation). According to the modal analysis made for the structure, the number of modes was chosen as 26, giving the total mass participation rate of 90% and above in both directions. Accordingly, the modal analysis results are as follows (Table 1).

Table 1. Modal Participating Mass Ratios

TABLE: Modal Participating Mass Ratios						
OutputCase	StepType	StepNum	Period	SumUX	SumUY	SumUZ
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless
MODAL	Mode	1	0.278212	2.588E-09	0.77206	0.00015
MODAL	Mode	2	0.271534	0.73933	0.77206	0.00015
MODAL	Mode	3	0.155222	0.74167	0.77206	0.00015
MODAL	Mode	4	0.101115	0.74167	0.77255	0.00018
MODAL	Mode	5	0.100275	0.75578	0.77255	0.00018
MODAL	Mode	6	0.094654	0.75578	0.87439	0.05685
MODAL	Mode	7	0.088941	0.87733	0.87439	0.05687
MODAL	Mode	8	0.088425	0.87733	0.88001	0.82651
MODAL	Mode	9	0.055412	0.87733	0.88009	0.82651
MODAL	Mode	10	0.054962	0.87749	0.88009	0.82651
MODAL	Mode	11	0.052271	0.88484	0.88009	0.82651
MODAL	Mode	12	0.051971	0.88484	0.88702	0.82662
MODAL	Mode	13	0.049333	0.88484	0.88702	0.85503
MODAL	Mode	14	0.046436	0.88521	0.88702	0.85503
MODAL	Mode	15	0.046081	0.88521	0.88707	0.85505
MODAL	Mode	16	0.045666	0.88572	0.88707	0.85505
MODAL	Mode	17	0.039846	0.88572	0.88707	0.86005
MODAL	Mode	18	0.037687	0.88572	0.89958	0.86011
MODAL	Mode	19	0.037653	0.89951	0.89958	0.86011
MODAL	Mode	20	0.034846	0.89951	0.89967	0.86012
MODAL	Mode	21	0.034723	0.89954	0.89967	0.86012
MODAL	Mode	22	0.033907	0.89962	0.89967	0.86012
MODAL	Mode	23	0.033512	0.90043	0.89967	0.86012
MODAL	Mode	24	0.033455	0.90043	0.89971	0.86035
MODAL	Mode	25	0.033364	0.90348	0.89971	0.86035
MODAL	Mode	26	0.033236	0.90348	0.90314	0.86036

Acceleration spectrum chart has been prepared according to the principles specified in the Turkey Building Earthquake Regulations. Since there is no exact data about the ground, the ground class was selected as IV class to stay on the safe side. Since the building is a masonry structure, R = 2.5 was used as the earthquake load reduction factor (Figure 7). Accordingly, the

acceleration spectrum graph is as follows (Figure 8). The acceleration spectrum chart prepared was entered in the Define / Functions / Response Spectrum section of SAP2000 as follows (Figure 9).

R	Zemin Sınıfı	T_A	T_B
2.5	4	0.20	0.90

Figure 7. Soil class and earthquake load reduction coefficient

| T	S(T)	Ra(T)	S(T) / Ra(T)
0.00	1.00	1.5	0.67
0.10	1.75	2	0.88
0.20	2.50	2.5	1.00
0.90	2.50	2.5	1.00
1.00	2.30	2.5	0.92
1.10	2.13	2.5	0.85
1.20	1.99	2.5	0.79
1.30	1.86	2.5	0.75
1.40	1.76	2.5	0.70
1.50	1.66	2.5	0.66
1.60	1.58	2.5	0.63
1.70	1.50	2.5	0.60
1.80	1.44	2.5	0.57
1.90	1.38	2.5	0.55
2.00	1.32	2.5	0.53
2.10	1.27	2.5	0.51
2.20	1.22	2.5	0.49
2.30	1.18	2.5	0.47
2.40	1.14	2.5	0.46
2.50	1.10	2.5	0.44
2.60	1.07	2.5	0.43
2.70	1.04	2.5	0.42
2.80	1.01	2.5	0.40
2.90	0.98	2.5	0.39
3.00	0.95	2.5	0.38
3.10	0.93	2.5	0.37
3.20	0.91	2.5	0.36
3.30	0.88	2.5	0.35
3.40	0.86	2.5	0.35
3.50	0.84	2.5	0.34
3.60	0.82	2.5	0.33
3.70	0.81	2.5	0.32
3.80	0.79	2.5	0.32
3.90	0.77	2.5	0.31
4.00	0.76	2.5	0.30
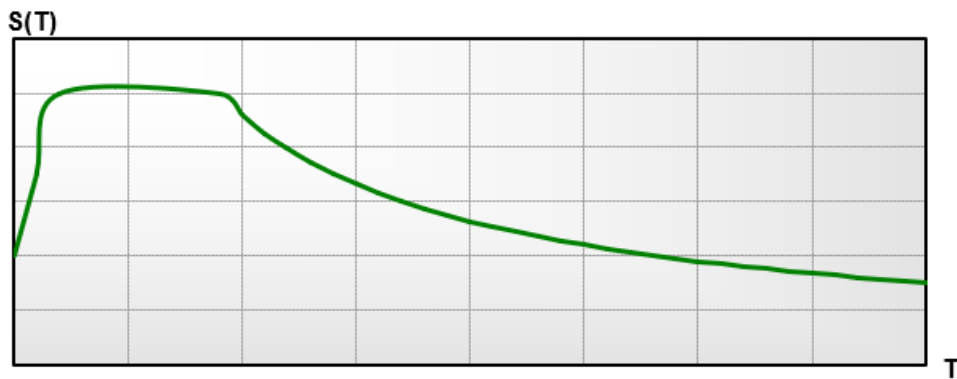
Figure 8. Design Acceleration Spectrum Graph
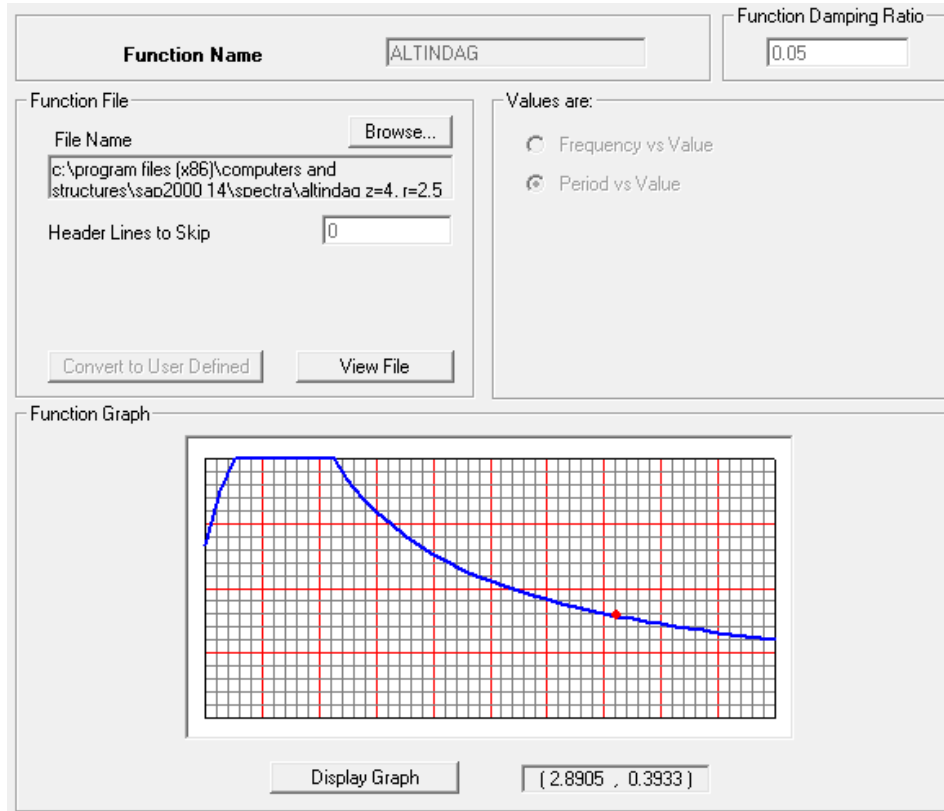
Figure 9. Acceleration spectrum chart in SAP2000

After the definitions are completed, the analysis cases are defined. These are DEAD, MODAL, SPECX and SPECY. DEAD and MODAL load cases are automatically generated by SAP2000.

For MODAL analysis case, the number of modes has been changed to 26. SPECX and SPECY analysis cases are defined as follows (Figure 10);

$$V_t = W \frac{A_0 IS(T)}{R_a(T)}$$

scale factor

$$V_t = m.g.A_0 I \frac{S(T)}{R_a(T)}$$

Scale factor = 9.81 x 0.1 x 1 = 0.981
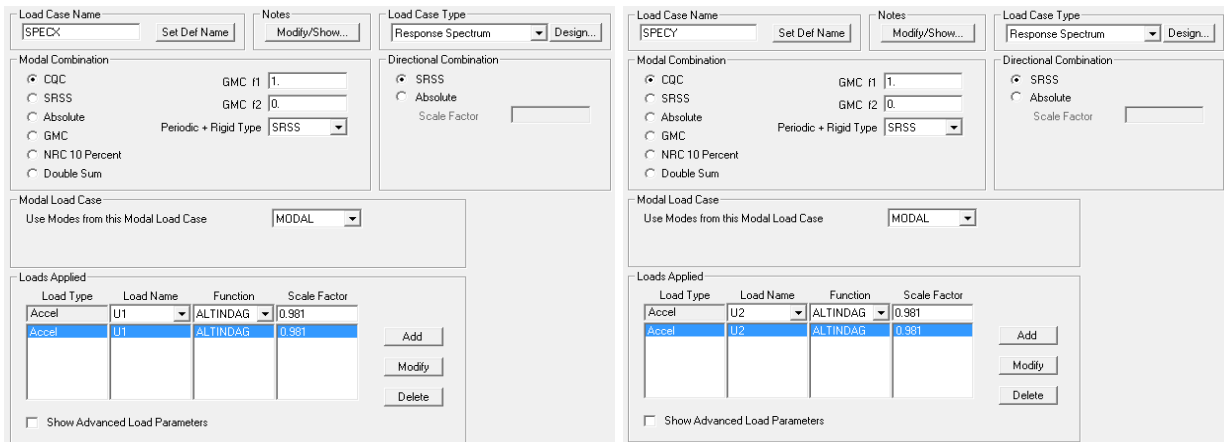
Figure 10. Defining SPECX and SPECY analysis cases

After defining the loading cases, two load combinations were created (Figure 11). These;

COMB1 = DEAD + SPECX + 0.3 x SPECY

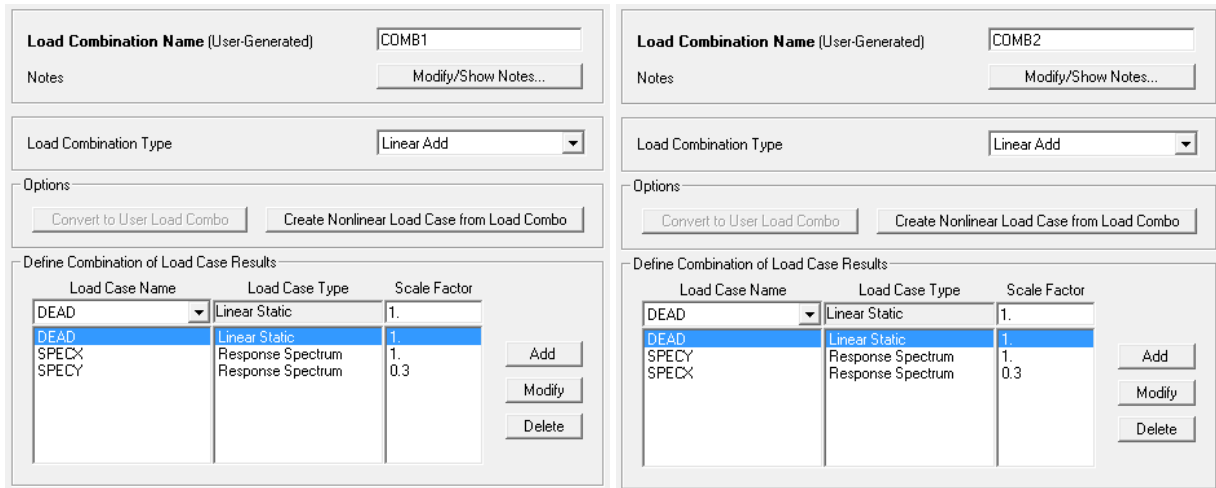COMB2 = DEAD + SPECY + 0.3 x SPECX

Figure 11. Creating COMB1 and COMB2 load combination

After the structural analysis, the exaggerated deformed shape and maximum displacement of the structure were determined. In an earthquake in the X direction, the largest displacement is 2.5 mm in the dome, and in a Y direction earthquake the largest displacement is 2.6 mm (Figure 12-13).
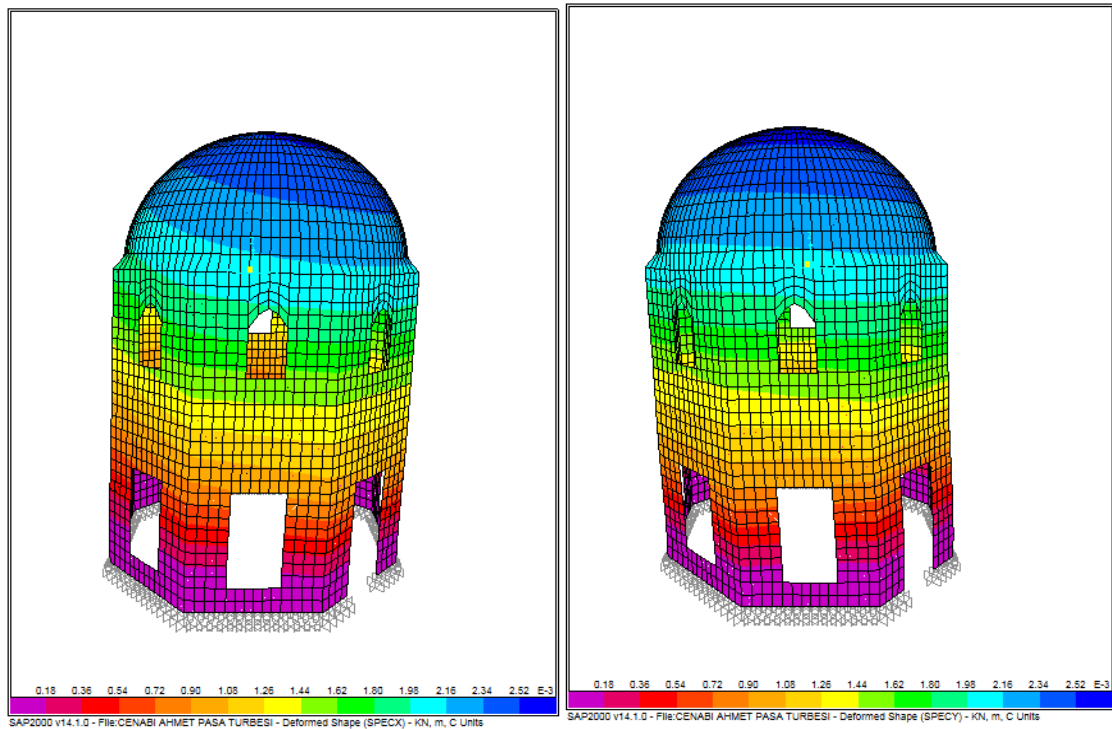

Figure 12. Displacement caused by earthquakes in X and Y direction.
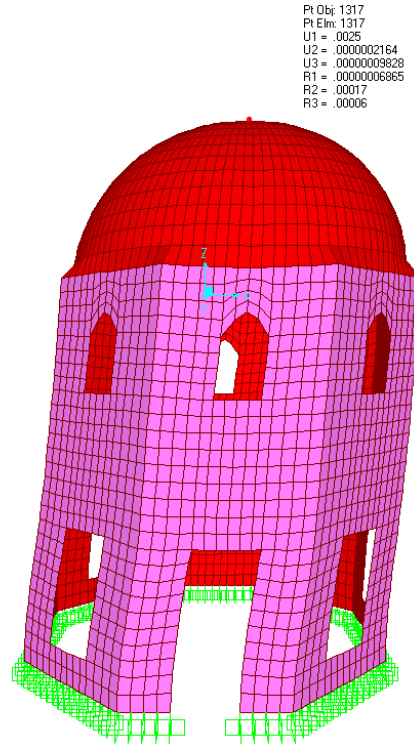
Figure 13.The maximum displacement at the top of the building in the event of an earthquake.

As can be seen, in the event of an earthquake, the maximum displacement in the earthquake direction (U1) at the top of the building is 2.5 mm. Since the walls and the dome have different allowable stress values, the stress checks will be made separately for the wall and the dome. Stress controls are as follows.

Wall Stress Controls:

The permissible compressive stress in stone walls is 0.9 MPa, tensile stress 0.135 MPa and shear stress 0.53 MPa. When both load combinations are considered, the comparisons with the maximum stresses and the allowable stresses on the wall are as follows (Figure 14);

AreaElem	OutputCase	StepType	S11Top	S22Top	S13Avg	S23Avg	basınç (0.9 Mpa)		çekme (0.135)		kayma (0.53 Mpa)	
3255	COMB1	Min	-0.24	-0.354	-0.008092	0.00198	-0.240	ok				
3975	COMB1	Max	0.132	0.012	0.003047	0.003815			0.132	ok		
4400	COMB2	Min	-0.177	-0.647	-0.005586	-0.035	-0.647	ok				
5182	COMB2	Max	0.017	0.076	0.042	0.033			0.076	ok		
2222	COMB2	Max	0.005144	-0.035	0.063	-0.001962					0.063	ok
4521	COMB2	Min	-0.046	-0.517	-0.004848	-0.125					-0.125	ok

Figure 14. Maximum stresses and allowable stresses in the wall

Dome Stress Controls:

The permissible compressive stress in brick elements is 2.4 MPa, tensile stress 0.36 MPa and shear stress 1.05 MPa. When both load combinations are considered, the comparisons with the maximum stresses and the allowable stresses in the dome are as follows (Figure 15);

AreaElem	OutputCase	StepType	S11Top	S22Top	S13Avg	S23Avg	basınç (2.4 Mpa)		çekme (0.36)		kayma (1.05 Mpa)	
1404	COMB1	Min	-0.063	-0.059	-0.013	-0.001117	-0.063	ok				
32	COMB2	Max	0.146	-0.035	0.066	0.001491			0.146	ok		
134	COMB2	Min	0.023	-0.156	-0.016	0.016	-0.156	ok				
22	COMB2	Max	0.072	0.051	-0.008846	-0.037			0.051	ok		
40	COMB2	Min	-0.00211	-0.053	-0.102	-0.012					-0.102	ok
147	COMB2	Max	0.048	-0.08	-0.002655	0.022					0.022	ok

Figure 15. Maximum stresses and allowable stresses in the dome

The maximum and minimum values of all stresses are used in the above table to make comparisons with the allowable stresses. Stress charts for COMB1 and COMB2 are as follows for the whole structure. Compressive and tensile stresses and shear stresses are displayed in various colors in finite element analysis programs. In this way, the areas of the building that will pose a danger in the face of earthquakes and other loads can be easily determined.
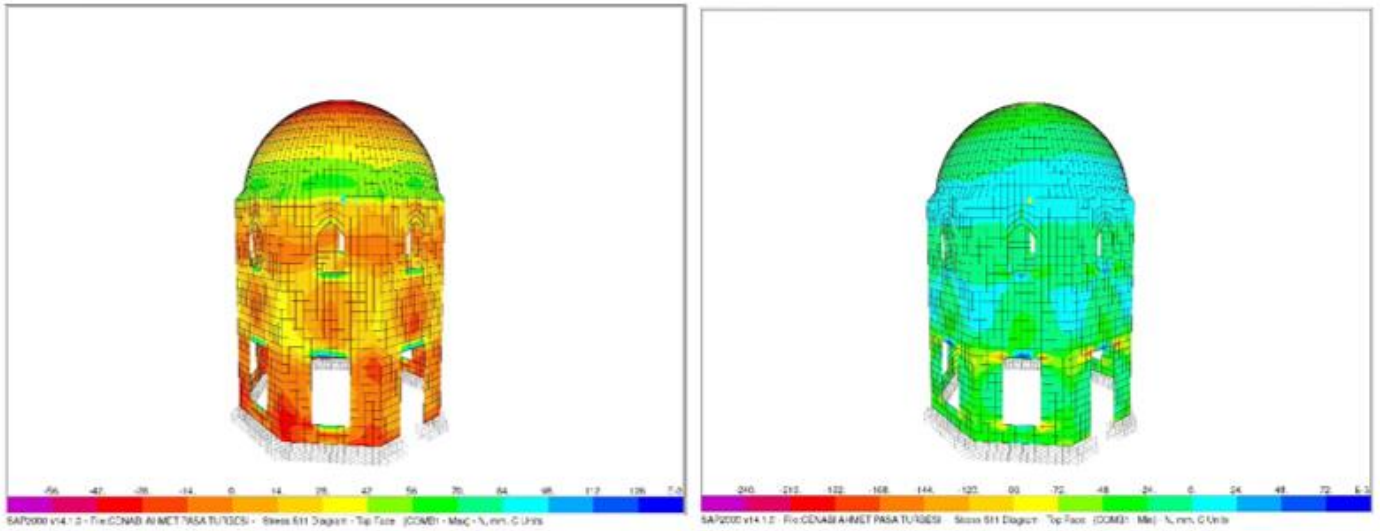

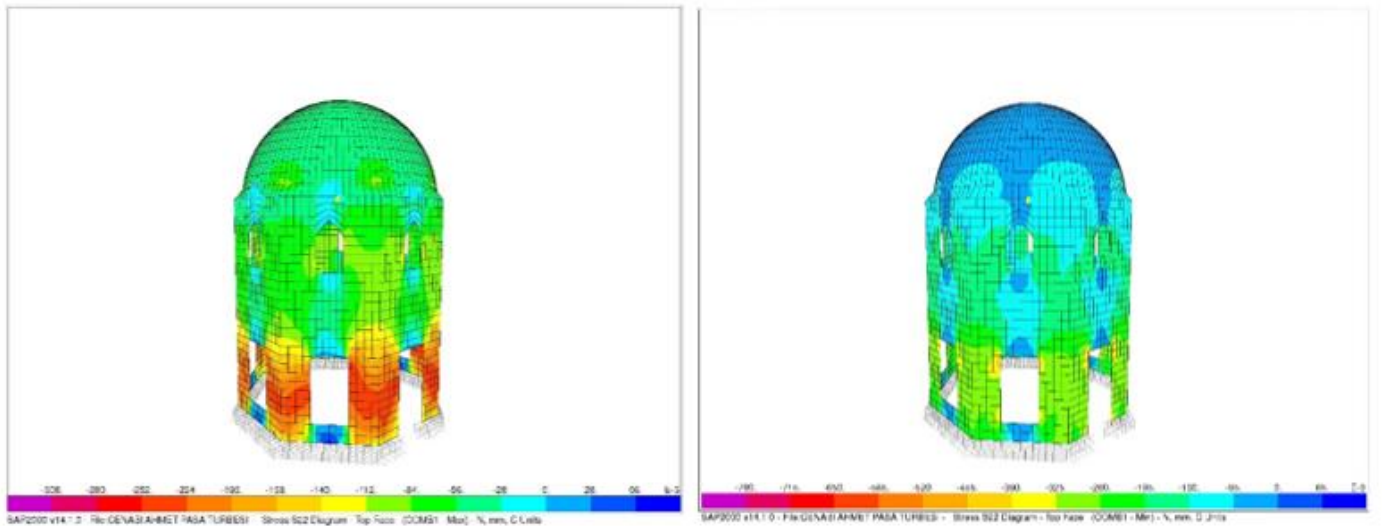Figure 16. Cenabi Ahmet Pasa Tomb, S11 Diagram-Top Face (COMB1-Max and COMB1-Min.)

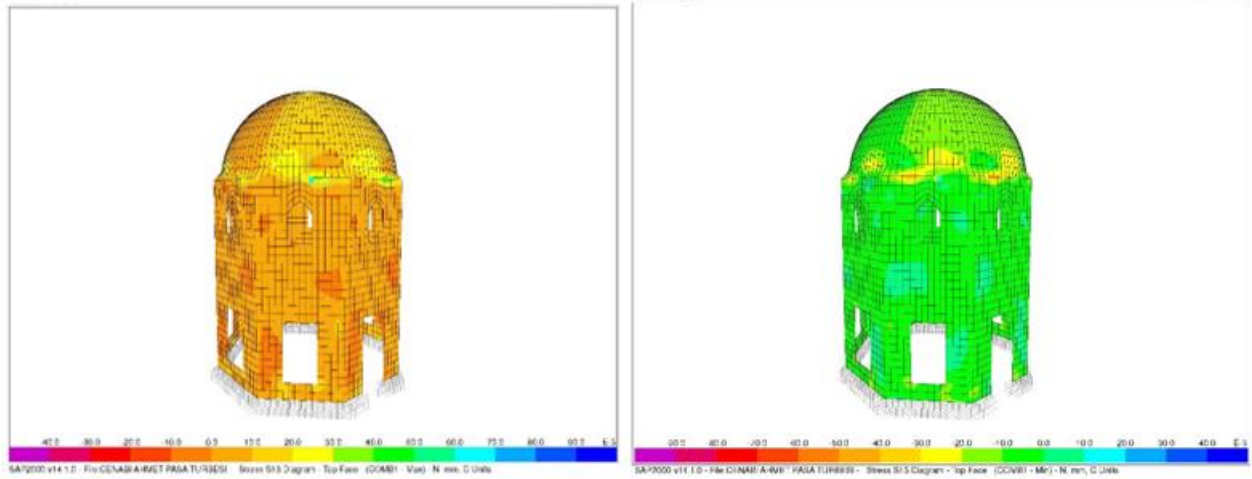Figure 17. Cenabi Ahmet Pasa Tomb, S22 Diagram-Top Face (COMB1-Max and COMB1-Min.)

Figure 18. Cenabi Ahmet Pasa Tomb, S13 Diagram-Top Face (COMB1-Max and COMB1-Min.)
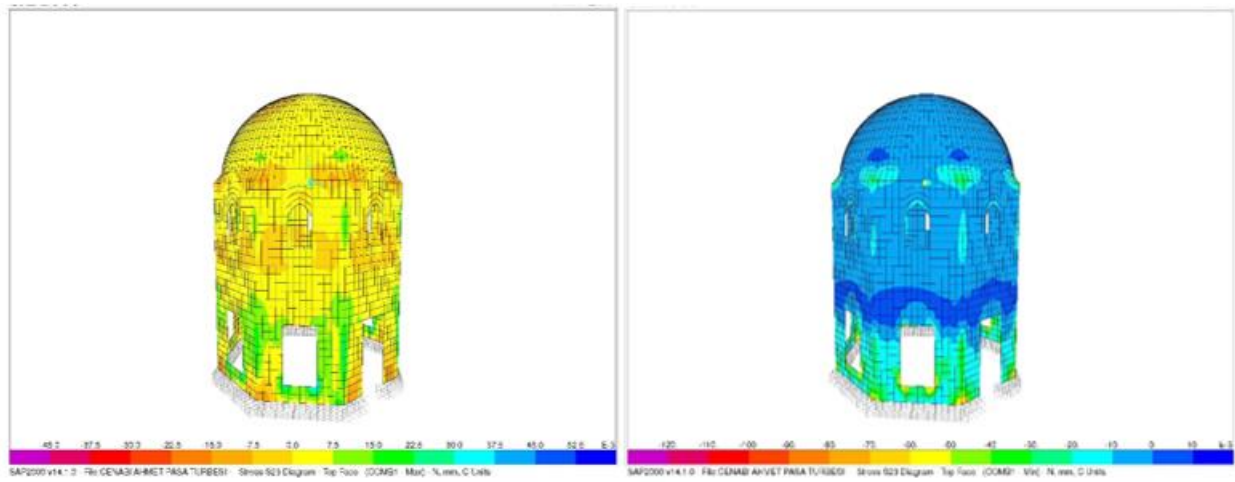

Figure 19. Cenabi Ahmet Pasa Tomb, S23 Diagram-Top Face (COMB1-Max ve COMB1-Min.)
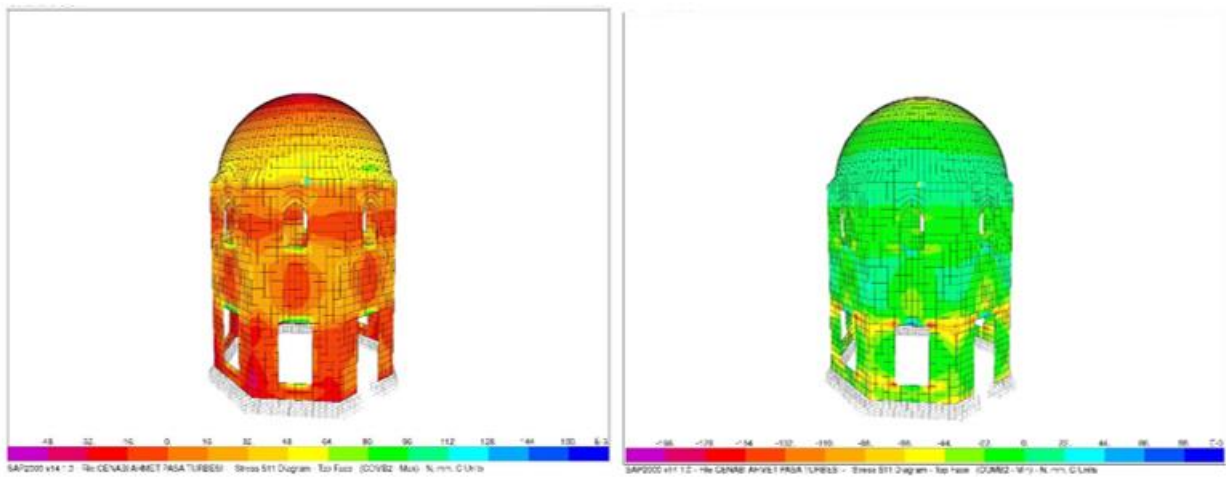

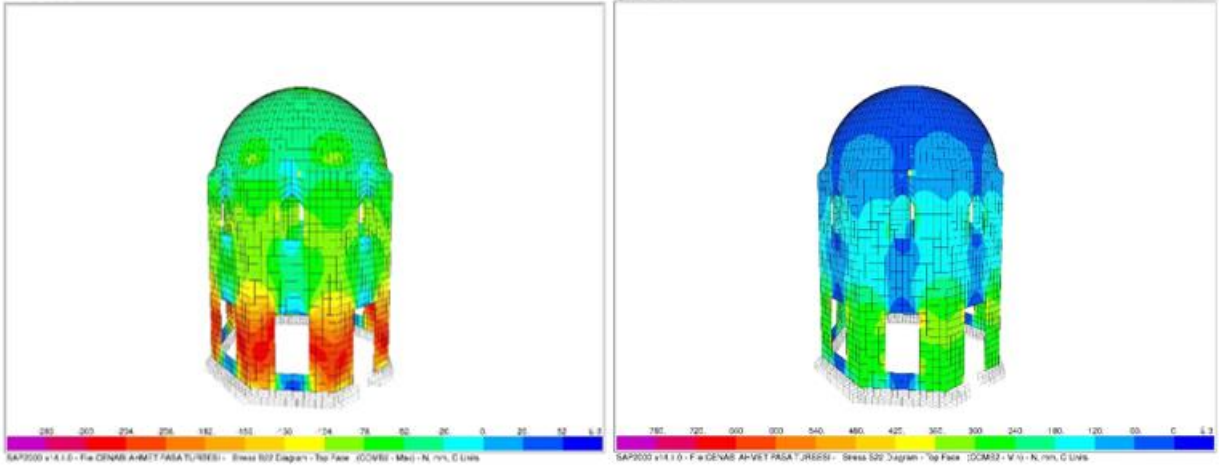Figure 20. Cenabi Ahmet Pasa Tomb, S11 Diagram-Top Face (COMB2-Max ve COMB2-Min.)

Figure 21. Cenabi Ahmet Pasa Mosque, S22 Diagram-Top Face (COMB2-Max ve COMB2-Min.)
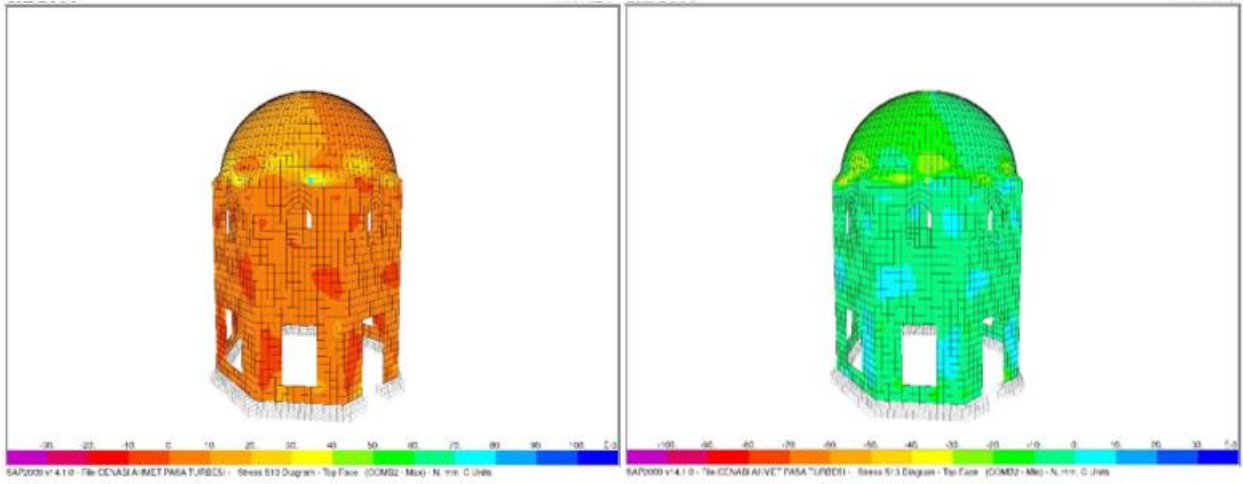

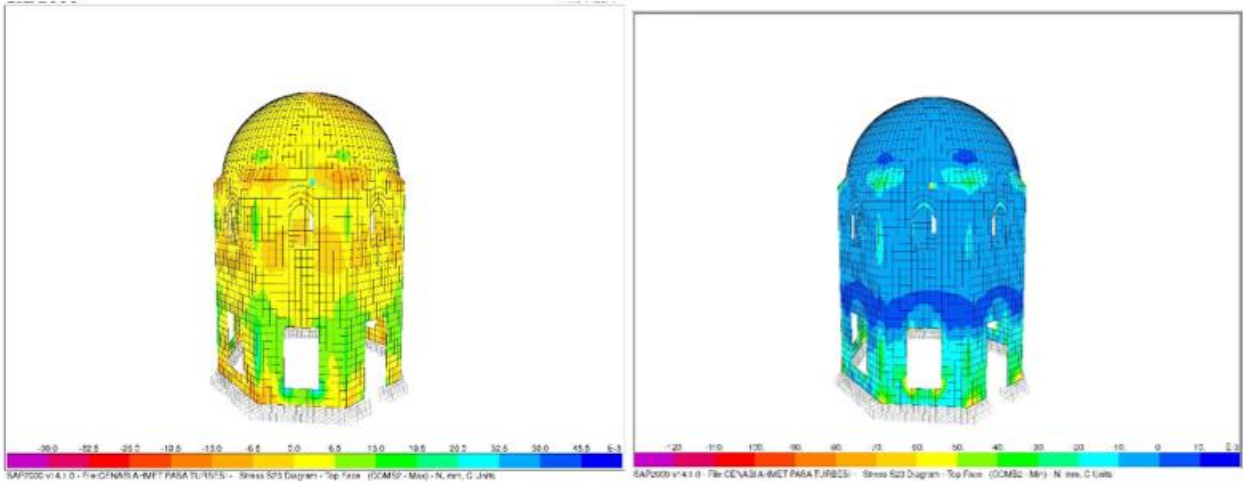Figure 22. Cenabi Ahmet Pasa Tomb, S13 Diagram-Top Face (COMB2-Max ve COMB2-Min.)

Figure 23. Cenabi Ahmet Pasa Tomb, S23 Diagram-Top Face (COMB2-Max ve COMB2-Min.)

3. Conclusion

As can be seen from the tables above, no adverse situation was observed as a result of the earthquake loading in terms of stresses on both the dome and the stone walls of the building. It has been observed that the building has sufficient security according to the earthquake shadow it is located in.

The most important factor that determines the strength and performance of the structural system in historic masonry structures is its resistance to various loads and external influences. For this reason, the loads affecting these structures must be calculated correctly and transferred to the calculation model while performing structural analysis. The most appropriate method for determining earthquake resistance in historic masonry structures is finite element analysis.

Historical buildings are more suitable for modeling with shell and plate elements due to the geometric features of their carrier systems. Presentation of internal forces in shell and plate elements with maps showing the axis force distribution or stress distribution allows the calculation results to be easily evaluated. It is thought that it would be beneficial for institutions working on historical buildings in our country to have such modeling done in their project studies (survey, restoration and restitution projects) in order to clearly determine the structural status and earthquake resistance of the buildings in question. In addition, material analyzes made in these project studies will provide more accurate results in the modeling.

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