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Research Article

Dynamic Analysis Of Historical Sultan Hamit Masonry Arch Bridges

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ABSTRACT

There are many historical bridges belonging to various civilizations in our country. Historical bridges also help us understand the sociological, economic and cultural structures of civilizations that lived from past to present. Some of the historical bridges have been deformed due to natural events and human factors and some have been destroyed. It is extremely important to know the behavior of these bridges against earthquakes, since a large part of our country is located in a region with high earthquake risk. For this reason, the dynamic behavior of structures is examined with numerical and experimental studies, and earthquake analyses are made using earthquake acceleration records obtained from past earthquakes. With the result of these studies, it is aimed to strengthen the weak parts of the structures. Therefore, it is necessary to evaluate the behavior of historical masonry bridges that have survived to the present day, in order to carry out restoration and protection. In this study, the historical Sultan Hamit I-II and III bridges in the Askale district of Erzurum province are examined. These bridges were modeled in three dimensions using the SAP2000 finite element program. First of all, static analyses of the bridges under their own weight were performed. The dynamic properties of the bridges were determined by using modal analyses. After the dynamic properties of the bridges were obtained, dynamic analyses were evaluated with time-history analysis.

Introduction

It is seen that masonry structures are used quite widely in the past. These structures are constructed such as brick, stone and mud in which brick and stone are used as a load-bearing system. Although the structures used today are generally reinforced concrete, masonry type structures are still used extensively in rural areas. Historical bridges have been an important part of both cultural heritage and transportation since their construction. It is necessary to take protective measures in order the historical structures not to be damaged, that have experienced many natural disasters. When structures of madrasahs, bridges, mosques, churches etc., are examined, which have survived from ancient times to the present, it is seen that almost all of them are constructed with the masonry technique. Masonry structures do not consist of load-bearing walls formed with homogeneous mixtures like reinforced concrete structures. For this reason, the analysis methods to be used in their examination are different when considered steel or reinforced structures. However, modeling of load-bearing elements in heterogeneous structures is quite difficult. For this reason, it is great importance to know all aspects of the mechanical behavior of masonry structures. In addition, the cracking patterns that will occur on the walls may vary depending on the force they are affected, due to the heterogeneity. In this context, many studies have been carried out on historical masonry structures in recent years. Riva et al. [1] using the ABAQUS program, examined the Asinelli Tower in Bologna, Italy, with macro modeling technique and gave information about the seismic behavior of the tower. The Griffith Bridge in Ireland was investigated by Fanning and Boothby [2] using the distributed crack model, and as a result of this study, the bearing structures of the bridge were modeled. The bridge's behavior under static loads has been investigated. It was determined that the model made reflects the bridge behaviors. Galasco et al. [3] performed the 3D modeling of historical masonry bridges and buildings with the nonlinear macro modeling method, compared the modeling with the experimental data, and obtained reliable results. Aoki et al. [4] investigated the dynamic analysis of the three-span stone arch Rakanji Bridge in Japan, using the finite element method. With the environmental vibration test, accelerometers were placed in certain parts of the bridge and vibration records were taken. Thus, the experimental dynamic properties of the structure (mode shapes, damping ratios and frequency) were determined. As a result of the studies, the experimental and theoretical dynamic properties of the bridge were compared. Karaton et al. [5] performed the dynamic analysis of historical masonry Malabadi Bridge under different earthquake loads, and evaluated the nonlinear seismic responses of the bridge. Tubaldi et al. [6] analysed the geometric and mechanical strength and the collapse of the bridge piers on multi-span masonry bridges. Sayın et al. [7] examined the historical Uzunok Bridge in Malatya with the macro modeling method, and performed linear and non-linear analyses using the acceleration records of the 2003 Bingöl earthquake. Castellazzi et al. [8] improved the finite element model in their study and applied it to a 15-span railway bridge. According to this study, the current structural condition of the bridge and the strengthening works were evaluated. Korkmaz et al. [9] analysed the Timisyat Bridge in Rize with the finite element method by modeling it in three dimensions and aimed to determine the behavior of stone arch bridges under seismic loads. Ten earthquake accelerations were used for the seismic effect in the study, in which dynamic analyses were performed in the time history method. As a result of the study, the stress and displacement data determined separately for each earthquake record and these results were evaluated. Çakır and Uysal [10] evaluated the modal parameters and dynamic responses of reinforced brick masonry arches using experimental and numerical tests. Çalık et al. [11] evaulated the historical Küçük Fatih Mosque in Trabzon and applied vibration tests before and after the renovation. The benefits of ambient vibration tests in improving the finite element model and the structure behavior were examined. Türker et al. [12] investigated the dynamic behavior of the masonry arch bridge model, which was created in the laboratory at 1/10 scale, using experimental and analytical methods. For this purpose, a finite element model of the bridge was created using the SAP2000 program. Dynamic properties were determined by making modal analysis on the bridge model. Experimental dynamic properties of the structure (mode shapes, damping ratios and frequency) were determined by the environmental vibration test. As a result of the study, comparisons were made between the experimental and analytical results, and it was seen that there were differences in terms of frequencies. Özkaya et al. [13] investigated the seismic behavior of the historical Kireçli Bridge in their study. Three dimensional finite element model of the bridge was generated and nonlinear dynamic and static pushover analyses were performed on the model. In these analyses, the greatest displacement occurred in the middle region of the bridge. Onat and Sayın [14] examined the dynamic behavior of the historical Tağar Bridge in their study. For this purpose, they created a three-dimensional finite element model of the bridge using the ANSYS finite element program. Linear and non-linear seismic analyses of the Tağar Bridge were carried out. Güllü [15] examined the behavior of the historical Cendere Bridge under seismic effects in the study. For this purpose, a finite element model of the bridge was created using the SAP2000 program.

The study showed that the tensile strength of the bridge can be exceeded in the arch part. Öncü et al. [16] examined the historical Tuzluca Bridge, which has a single span, using the ANSYS program, formed the three-dimensional model of the bridge and evaluated its behavior under the dynamic and static loads. As a result of the study, the limited damage performance level of the bridge was examined. Gönül and Sakcalı [17] examined the historical Irgandı Bridge in Bursa. The bridge was modelled with the finite element technique. ANSYS program was used for the analysis and the stress distributions and displacements of the bridge was obtained. On the other hand, there are several numerical studies about masonry arch bridges in the recent literature [18-21]

In this study, the historical masonry Sultan Hamit I, II and III Bridges in the Askale district of Erzurum province, those have a single span, were evaluated numerically (Figure 1). These bridges are located at close distances to each other. Three dimensional finite element model of the bridges were generated with SAP2000. Static analyses of the bridges were obtained under their own weight, and natural vibration frequencies, period and mode shapes were determined by modal analysis. In addition, earthquake analyses of the bridges were evaluated with two different earthquake records. For the dynamic analyses, 1992 Erzincan and 2020 Elazığ earthquakes acceleration records was considered as a seismic effect. The damping in the bridges is assumed to be Rayleigh type damping. Also, potential damage areas were evaluated considering the stress distributions obtained from the dynamic analyses.

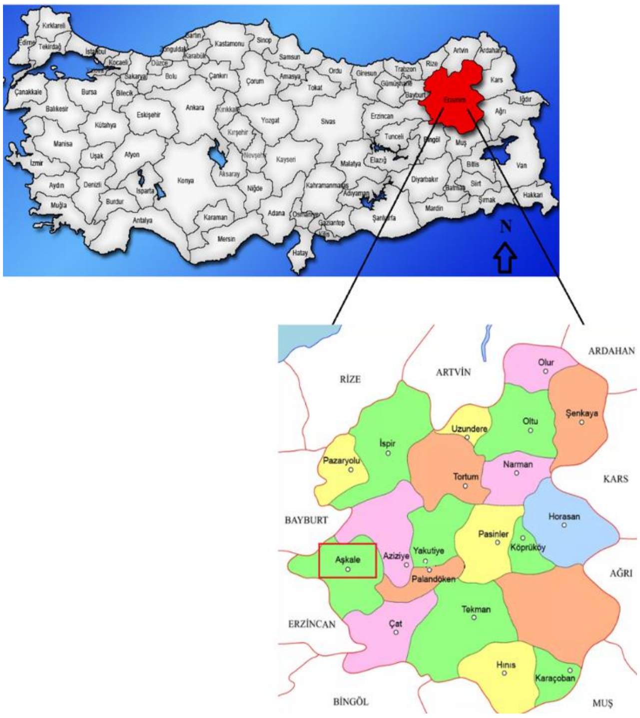

Figure 1. Location of the bridges

Structural Features of Sultan Hamit I Bridge

Sultan Hamit I Bridge, which is approximately 6.3 m wide and 16.5 m long, has an arch span of 3.0 m from the thalweg level of the river (Figure 2). The span width of the bridge is 6.9 m and the arch thickness of the bridge is approximately 0.60 m. There is a rubble masonry lined up around the beginning and end connections located at the lower parts of the tempan walls of the bridge. However, the cut stone weave texture is seen at the upper parts of the bridge. The original construction material used in the bridge is generally basalt stone. It is thought that the bridge was built during the Ottoman period in the 20th century. It is located approximately 20 km southwest of Aşkale district of Erzurum province. The geometric features of the Sultan Hamit I Bridge is given in the Figure 3.

Figure 2. Sultan Hamit I Bridge

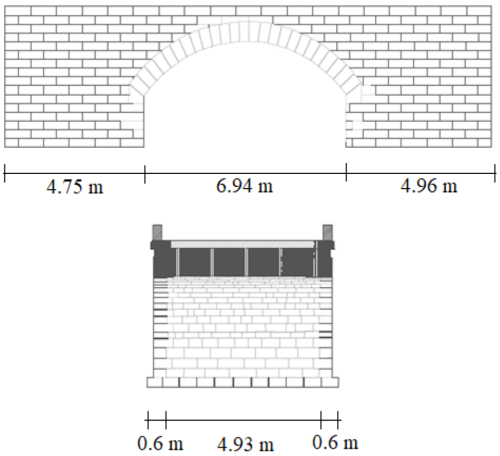

Figure 3. Geometric properties of Sultan Hamit I Bridge

Structural Features of Sultan Hamit II Bridge

Sultan Hamit bridge, which has a single arch span, has a height of 5.2 m from the thalweg level of the river. The span width of the arch is 3.2 m, while its height from the stirrup line is approximately 1.55 m. The bridge is shown in Figure 4. The tempan walls of the historical bridge were built using coarse stone and the filling part was built using rubble material. In the bridge, basalt stone is used for the construction material. It is thought that the bridge was built in the 20th century during the Ottoman period. It is located approximately 20 km southwest of Aşkale district of Erzurum province. The geometric features of the Sultan Hamit II Bridge is shown in the Figure 5.

Figure 4. Sultan Hamit II Bridge

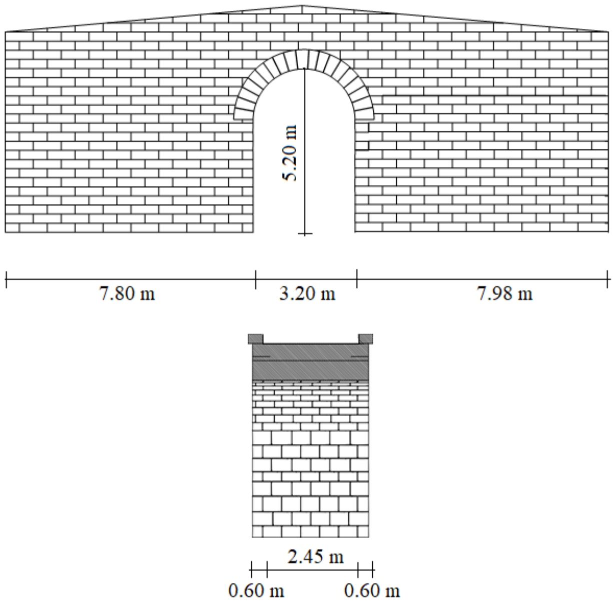

Figure 5. Geometric properties of Sultan Hamit II Bridge

Structural Features of Sultan Hamit III Bridge

Sultan Hamit III Bridge, which is approximately 7.2 m wide and 10.5 m long, has an arch span of 4 m based on the thalweg level of the river. The span width of the bridge is 3 m and the arch thickness of the bridge is approximately 0.4 m. There is a row thin face stones on the upper level of the arch keystone. There is no water flow on the river bed and it is filled with gravel and rubble. Basalt was used as the construction material at the Sultan Hamit III Bridge. This bridge was built in the 20th century during the Ottoman period. Like other bridges, it is located 20 km southwest of Aşkale. It is shown in Figure 6. Also, the geometric features of the Sultan Hamit II Bridge is given in the Figure 7.

Figure 6. Sultan Hamit III Bridge

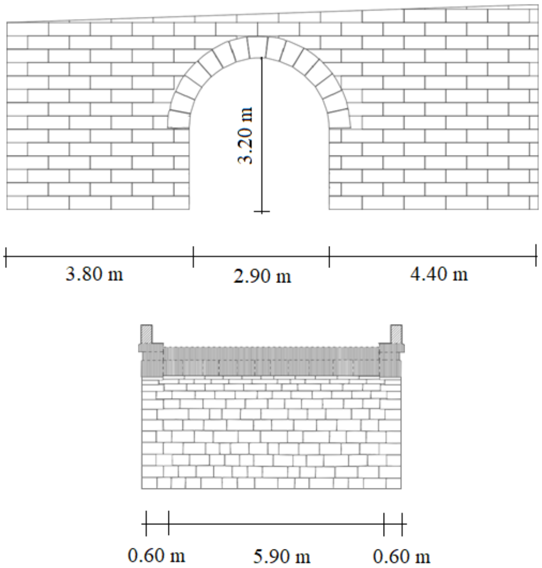

Figure 7. Geometric properties of Sultan Hamit III Bridge

Modeling and analysis methods of historical masonry structures

Three-dimensional modeling is used in historical masonry structures to obtain more realistic results. Three modelling approaches are generally used for numerical analyses of historical structures. Detailed micro modeling is more suitable for modelling to smaller structures or part of the large structures. Therefore, micro modeling is used when a detailed analysis of a part of the structure or its structural elements is needed [22]. When we consider the macro modeling method, it provides more accurate results because all structural factors are considered as a composite element without any distinction between blocks, bricks, stones and mortar. It can reflect the common properties of these factors. The macro modeling method takes less time than the micro modeling method as an analysis process. Therefore, it is frequently preferred for big structures. This method neglects the interaction between the mortar and masonry elements and considers all of them as a composite. However, when the literature is examined, it was seen that the macro modeling technique is frequently used in the numerical analysis of large historical structures [23, 24]. Sultan Hamit bridges are modeled with SAP2000 program using a hexahedral eight-node solid element, with three degrees of freedom at each node. The bridges are modelled with the macro modeling method. Three-dimensional model of the bridges is composed of four elements: arch, filler, floor and side walls. In the finite element model of the bridges all degrees of freedom were taken into account to be fixed at the ground level. In this study, the material properties of the bridges were taken in the literature [25]. Table 1 show the material properties of the bridges.

Table 1 Material properties of Sultan Hamit bridges [25]

Material properties	Elastic modulus (MPa)	Poisson ratio	Density (kg/m^3)
Arch	2109	0.20	2350
Tempan wall	2209	0.20	2350
Filling	1800	0.15	1600
Slab	2209	0.20	2350

Sultan Hamit I Bridge

Sultan Hamit I Bridge model is generated using 3627 nodal points and 2796 solid elements. Three dimensional model of the bridge was shown in Figure 8.

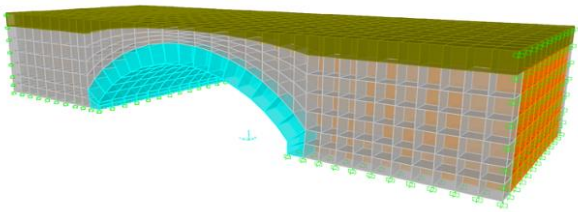

Figure 8. Three dimensional model of the Sultan Hamit I Bridge

Sultan Hamit II Bridge

Sultan Hamit II Bridge model is modeled using 4383 nodal points and 3392 solid elements. Three dimensional model of the bridge was given in Figure 9.

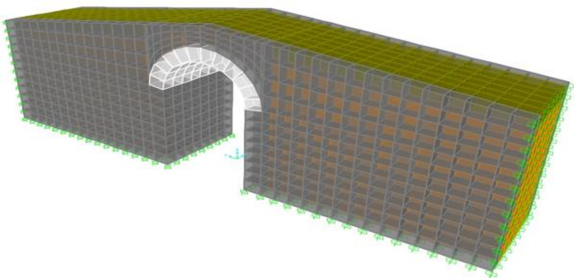

Figure 9. Three dimensional model of the Sultan Hamit II Bridge

Sultan Hamit Bridge III

Sultan Hamit III Bridge model is modeled using 3040 nodal points and 2310 solid elements. Three dimensional model of the bridge was presented in Figure 10.

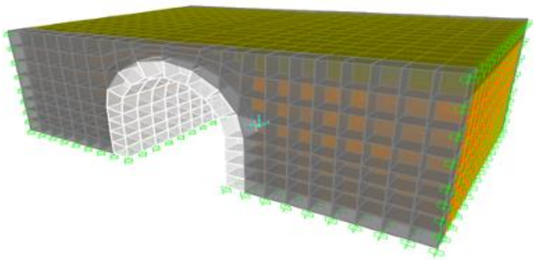

Figure 10. Three dimensional model of the Sultan Hamit III Bridge

RESEARCH FINDINGS

Static Analysis of Sultan Hamit I-II-II Bridges

Static analyses of Sultan Hamit bridges were carried out under their own weight. Static analyses of the bridges were made under their own weight according to the material properties presented in Table 1. Maximum displacement, maximum tensile and compressive stresses that occur as a result of the analyses of the bridges are discussed in this section.

After the static analysis of Sultan Hamit I Bridge, it is observed that the maximum vertical displacement occurred in the middle of the bridge span in the z-axis direction. The maximum displacement was calculated as 0.4654 mm. When the maximum tensile and compressive stresses of the bridge are examined, the maximum tensile and compressive stress were obtained as 68.867 kPa and 326.864 kPa, respectively.

For the Sultan Hamit II Bridge, it is observed that the maximum vertical displacement obtained in the middle of the bridge span in the z-axis direction. The maximum vertical displacement was calculated as 0.3027 mm. The maximum tensile and compressive stress of the bridge were acquired as 133.395 kPa and 182.358 kPa, respectively.

After the static analysis of Sultan Hamit III Bridge, the maximum vertical displacement occurred in the middle of the bridge span. The maximum vertical displacement was calculated as 0.1579 mm. After the analysis, the maximum tensile and compressive stress of the bridge were obtained as 83.717 kPa and 119.869 kPa, respectively.

Modal Analysis of Sultan Hamit I-II-II Bridges

Analytical modal analyses were performed for determining the dynamic characteristics of the Sultan Hamit Bridges. As a result of the analyses free vibration periods, mass participation ratios and mode shapes of the bridges were calculated for the first 100 modes. The sum of the calculated effective mass participation ratios was found to be more than 90% of the total mass of the bridges for 100 modes.

Sultan Hamit Bridge I modal analysis results

The period values of the first three modes of the bridge were calculated as 0.03744 s, 0.03666 s and 0.02965 s, respectively. The frequency values and mode shapes of the first 3 modes of Sultan Hamit I Bridge were presented in Figure 11.

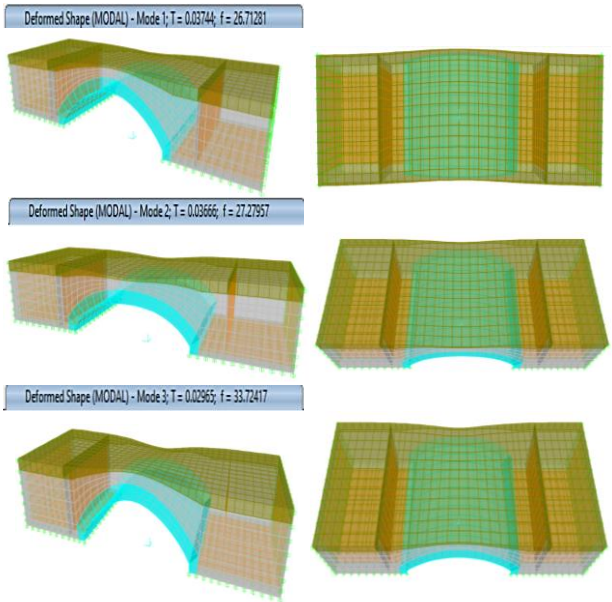

Figure 11. Frequency values and mode shapes of the first 3 modes of Sultan Hamit I Bridge

Sultan Hamit II Bridge modal analysis results

The period values of the first three modes of the bridge were found as 0.09584 s, 0.05741 s and 0.04434 s, respectively. The frequency values and mode shapes of the first 3 modes of the Sultan Hamit II Bridge were shown in Figure 12.

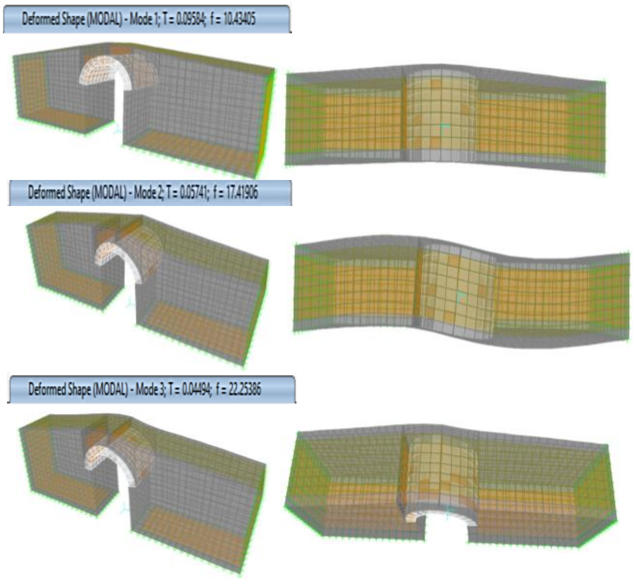

Figure 12. Frequency values and mode shapes of the first 3 modes of Sultan Hamit II Bridge

Sultan Hamit III Bridge modal analysis results

The period values of the first three modes of the Sultan Hamit III Bridge were calculated as 0.02721 s, 0.02063 s and 0.01877 s, respectively. The frequency values and mode shapes of the first 3 modes of the bridge were given in Figure 13.

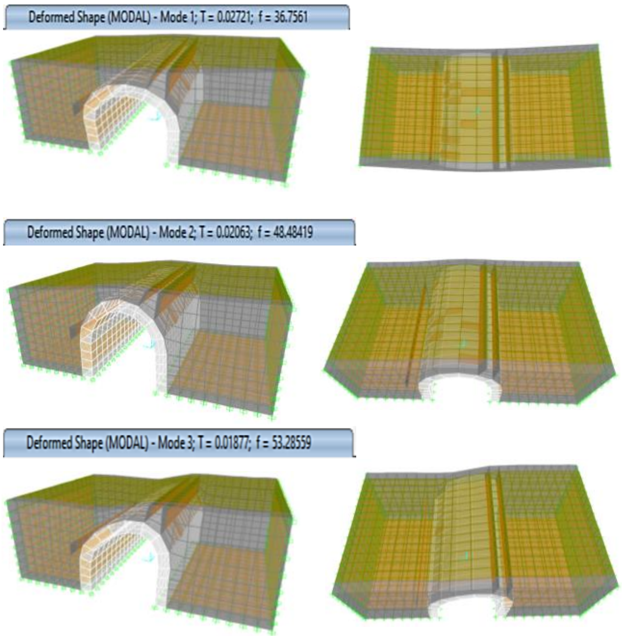

Figure 13. Frequency values and mode shapes of the first 3 modes of Sultan Hamit III Bridge

Dynamic Analysis of Sultan Hamit I-II-II Bridges

For the dynamic analysis of Sultan Hamit Bridges, the acceleration records of the 1992 Erzincan and 2020 Elazığ earthquakes were used for the time history analyses. SAP2000 finite element software was used in the dynamic analyses. In the analyses, the integration time step was chosen as 0,01 s. Also, HHT-α algorithm was used for for the analysis. In the dynamic analyses, 5% damping ratio was used for the Rayleigh damping coefficients. East-West component of the earthquakes were applied in the y direction of the bridge. As a result of the analyses, the maximum stress and displacements occurring on the bridge were examined. For the displacements three nodal points which are top of the bridges were selected. These nodal points number are 1087, 1025 and 3258 for Sultan Hamit I, II and III Bridge, respectively. Maximum displacement values for 1992 Erzincan and 2020 Elazığ earthquakes were given in Figure 14 and 15 for Sultan Hamit I bridge. Maximum displacement values for the same earthquakes were shown in Figure 16 and 17 for Sultan Hamit II Bridge. For Sultan Hamit III Bridge, the maximum displacements were presented in Figure 18 and 19 for Erzincan and Elazığ earthquakes.

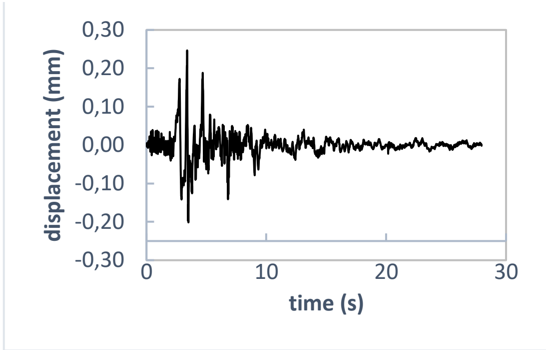

Figure 14. The displacement graph of the nodal point 1087 for the Erzincan earthquake

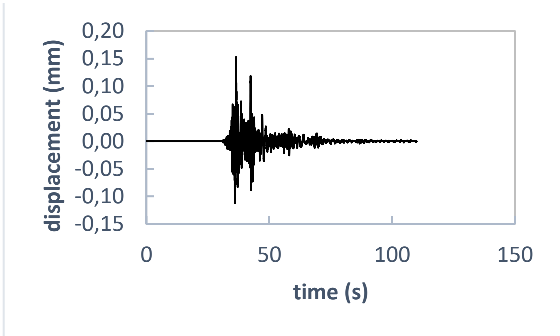

Figure 15. The displacement graph of the nodal point 1087 for the Elazığ earthquake

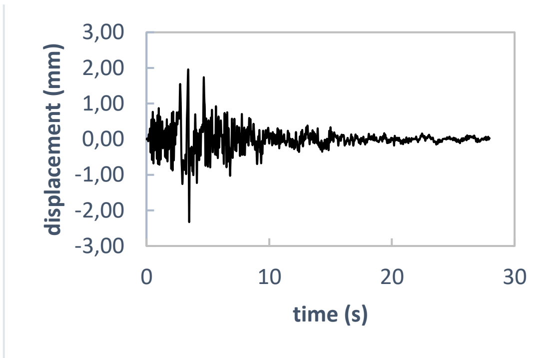

Figure 16. The displacement graph of the nodal point 1025 for the Erzincan earthquake

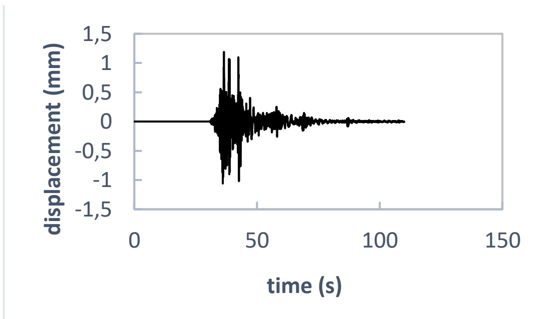

Figure 17. The displacement graph of the nodal point 1025 for the Elazığ earthquake

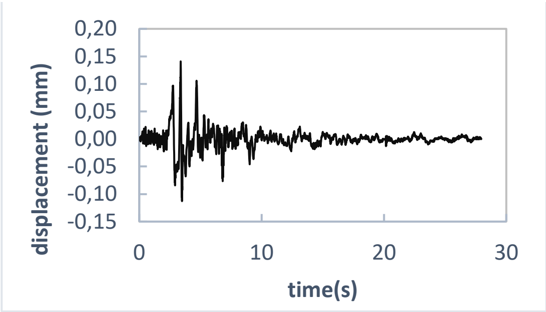

Figure 18. The displacement graph of the nodal point 3258 for the Erzincan earthquake

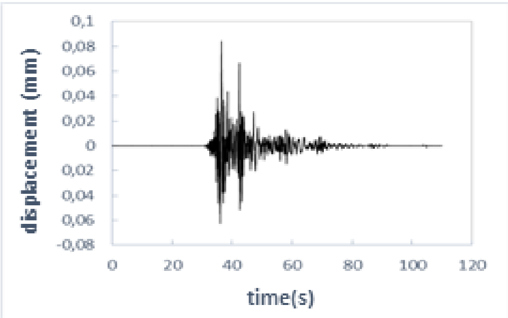

Figure 19. The displacement graph of the nodal point 3258 for the Elazığ earthquake

Also, the maximum compressive and tensile stress values of the bridges for the 1992 Erzincan and 2020 Elazığ earthquakes were given in Table 2.

Table 2 Analysis results

	1992 Erzincan		2020 Elazığ	
	Max. com. stress (kPa)	Max ten. stress (kPa)	Max. com. stress (kPa)	Max. ten. stress (kPa)
Sultanhamit I	497.36	318.72	428.90	319.13
Sultanhamit II	862.07	681.18	556.78	449.58
Sultanhamit III	215.75	143.44	177.37	113.80

Results

In this study, the static and dynamic analyses of the historical Sultan Hamit Bridges located in the Askale district of Erzurum province were investigated. Three dimensional model of the bridges and analyses were obtained with SAP2000 program. First of all, static analyses of the bridges under their own weight were performed. Also, natural frequencies, periods and mode shapes of the bridges were determined by modal analysis. In the dynamic analyses of the bridges were obtained by using the 1992 Erzincan and 2020 Elazığ earthquakes' acceleration records. Maximum displacement and stress values of the historical bridges were investigated according to the different earthquake accelerations. After the dynamic analyses maximum displacement values were determined under the 1992 Erzincan earthquake's acceleration records for the Sultan Hamit I, Sultan Hamit II and Sultan Hamit III bridges. Similar studies will contribute to the transfer of cultural heritage to future generations.

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