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SEISMIC RESPONSE OF SINGLE SPAN MASONRY ARCH BRIDGES LOCATED IN ELAZIĞ AND MALATYA

Alper Özmen[1], Erkut Sayin[2]

[1] Inonu University, Department of Civil Engineering, Malatya, Turkey
[2] Firat University, Department of Civil Engineering, Elazığ, Turkey
e-mail: [1]alper.ozmen@inonu.edu.tr, [2]esayin@firat.edu.tr

ABSTRACT: Historical masonry arch bridges are a major portion of the transportation network in the world. They are mostly constructed with brick and stone materials. These structures are reasonably important, for transferring the history and life style of ancient societies. They have to protect against the unexpected effects (i.e., floods, fire, and earthquake). Due to these factors, seismic behavior of these structures must be well known. In this paper, three different single span masonry arch bridges (Veli Palas, Musa Palas and Mavilik) were chosen as a case study. ANSYS software was used to generate three-dimensional finite element model of the bridges. 1992 Erzincan, 1999 Düzce and 2003 Bingöl earthquake records were used for dynamic time history analyses. Displacements, principal stresses, potential damage regions and seismic response of masonry bridges were evaluated after the dynamic analyses.

KEYWORDS: Dynamic Analyses; Masonry Bridge; Finite Element Model; Seismic Response

1 INTRODUCTION

Historical structures i.e., churches, mosques, towers, or bridges are one of the most important cultural heritages. They have been built for different aims and they have social, cultural and economic traces of the period where they are constructed. Masonry arch bridges which constitute major portion of the cultural heritage are still important components of the European bridge stock. In Turkey, there are many historical masonry bridges reached today from the Roman, Byzantine, Seljuk and Ottoman periods. Earthquakes and floods are the most critical integrity risk for masonry arch bridges but these structures were designed for gravity loads, not for earthquake excitations. Also, unavoidable decay of materials, important change in bridge load and lack of maintenance over time have led to varying degrees of damage. Therefore, most of the masonry bridges are not compatible with their current use and some of them are not safe structurally. In order to protect structural integrity of these structures and avoid cultural and economic losses, structural assessment of these structures is important. In the last decades many different studies performed about dynamic behavior of historical masonry arch bridges. Şeker and Özkaynak [1] evaluated the seismic performance of Hundi Hatun Bridge which is located in Amasya, Turkey.

Dynamic and static analyses of the bridge was performed with ANSYS software. Jara et al. [2] investigated the seismic vulnerability of five masonry bridges in Mexico. Dynamic properties of the bridges were evaluated by conducting a campaign of environmental vibration measurements. Also, fragility curves were created to investigate the seismic vulnerability of the bridges. Sokolović et al. [3] examined the effects of longitudinal cracks in a single span masonry arch bridge on structural behavior of the system. They followed a comprehensive examination methodology in the study. Aydin and Özkaya [4] investigated the behavior of single span masonry arch bridges under static vertical loads applied on different places of the structure. Olmos et al. [5] identified the dynamic characteristics of the masonry historical bridges. Also, they developed numerical models that allow the correct identification of the structural components of the bridges. Zampieri et al. [6] presented a simplified method, based in pushover analyses, to evaluate the seismic behavior of arch bridges. Numerous studies are available on the seismic evaluation of masonry arch bridges in the recent literature [7-19].

The aim of this paper is to the seismic behavior of three single span masonry arch bridges which are located in the city of Malatya and Elazığ, Turkey. Three dimensional (3D) models of masonry arch bridges are generated with finite elements. For this purpose, ANSYS software is used for creation of finite element models of the bridges. To obtain the seismic response of masonry bridges, three different acceleration records are used. In consequence of dynamic analysis, displacements, principal stresses and potential locations of damages are evaluated.

2 DESCRIPTION OF THE BRIDGES

Three single-span masonry arch bridges, whose names are Veli Palas, Musa Palas and Mavilik, were chosen as a case study. While the Musa Palas and Veli Palas bridges are located in the city of Elazığ, the Mavilik Bridge is located in the city of Malatya, Turkey. The bridges were constructed during the Ottoman period. However, there is no clear information about when they were constructed. The bridges are open to pedestrian and vehicle traffic today. Locations of these bridges are given in Fig. 1.

Figure 1. Location of the bridges

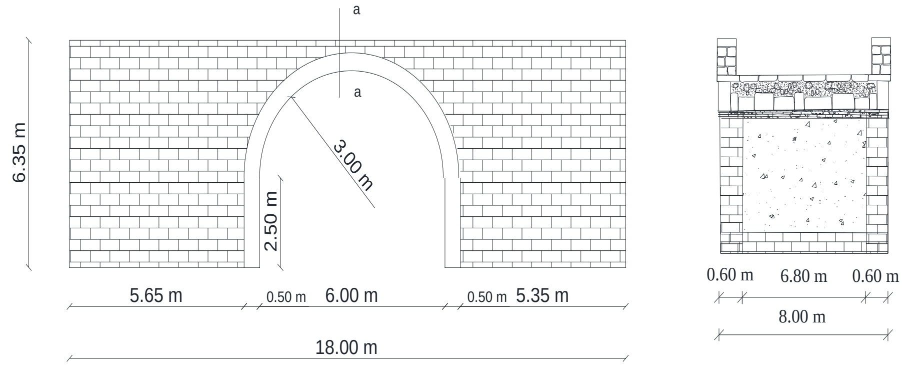
2.1 Veli Palas Bridge

Veli Palas Bridge is located in Baskil, Elazığ and on the 34th km on the highway between the cities of Elazığ and Malatya. The bridge has been restored several times. The last restoration was done by 8th Regional Directorate of Highways in 2015. It is 18.00 m long, 8.00 m wide and 6.35 m in height.

The bridge has one arch whose span is 6 m. Also, the thickness of arch and spandrel walls is 0.50 m and 0.60 m, respectively. Different views of the Veli Palas Bridge can be seen in Fig. 2 and geometrical characteristics of the bridge are given in Fig. 3.

a) Upstream view b) Downstream view

Figure 2. Different views of Veli Palas Bridge



a) Front view b) Cross-Section

Figure 3. Geometrical characteristics of Veli Palas Bridge

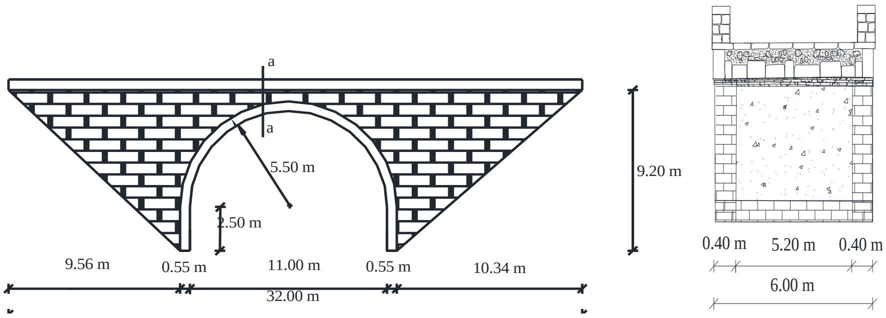
2.2 Musa Palas Bridge

This bridge is located in Baskil, Elazığ. It is located on the 40th km on the highway between the cities of Elazığ and Malatya.

a) Upstream view b) Downstream view

Figure 4. Different views of Musa Palas Bridge

It is 32.00 m long, 6.00 m wide and 9.80 m in height. It has single arch with a span of 11 m and the thickness of arch and spandrel walls is 0.55 m and 0.40 m, respectively. General view of the bridge is shown in Fig. 4. Also, the geometrical characteristics of the bridge are given in Fig. 5.



a) Front view b) Cross-Section

Figure 5. Geometrical characteristics of Musa Palas Bridge

2.3 Mavilik Bridge

Mavilik Bridge is located in Arapgir, Malatya. It is 28.50 m long, 6.00 m wide and 5.72 m in height. The bridge has one arch. Its span is 9.15 m.

a) Before restoration

b) After restoration

Figure 6. Different views of Mavilik Bridge

The bridge has 0.60 meters thick side walls and an arch. The bridge was restored by 8th Regional Directorate of Highways. Different views of the bridge are shown in Fig. 6. Also, the geometrical characteristics of the bridge are shown in Fig. 7.

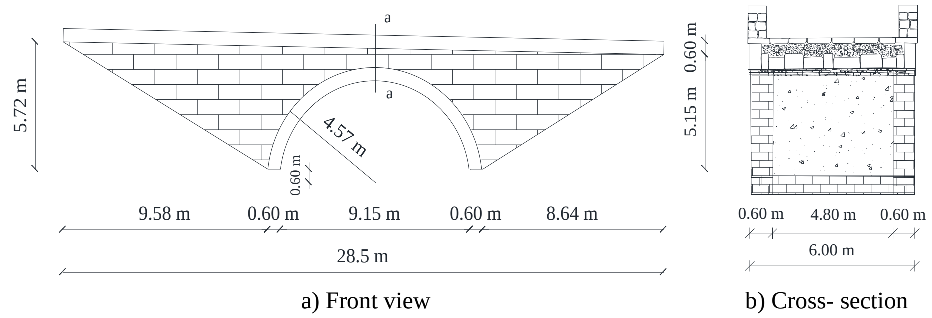


Figure 7. Geometrical characteristics of Mavilik Bridge

3 NUMERICAL MODEL OF THE BRIDGES AND SEISMIC ANALYSES

Historical masonry bridges were usually constructed with stone, mortar and infill material. Numerical modelling of Masonry Bridge is quite complex due to the interaction of these materials [20, 21]. There are several modeling approaches for finite element modelling of masonry structures. Two of them are frequently preferred to the finite element modeling of these structures. These approaches are referred as micro-modeling and macro-modelling. Micro-modelling can be divided into two as detailed micro modeling and simplified micro modelling. Modelling approach is chosen based on the size of the structure and the level of precision. Also, low computational effort is important. Macro-modelling is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation [22]. This modelling is valuable when a balance between efficiency and accuracy is needed [23-25]. In this study, macro-modelling approach which take into account the masonry as a composite was used to generate the numerical model of the bridges. 3D finite element model of the Veli Palas, Musa Palas and Mavilik bridges consists of 8513 nodes, 5174 solid elements; 22186 nodes, 13628 solid elements and 9222 nodes, 5324 solid elements, respectively. These finite element models were generated using ANSYS finite element software. In the finite element model of the bridges, SOLID186 element was used. The SOLID186 element, which is accounted for by twenty nodes having three degrees of freedom at each node, is utilized in the bridge's 3D finite element model. SOLID186 element geometry is given in Fig. 8 [26].

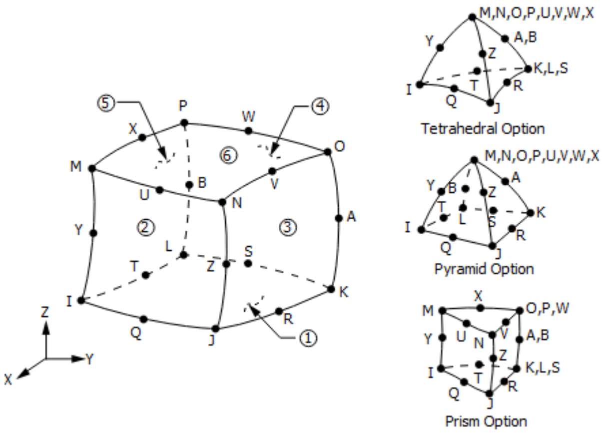
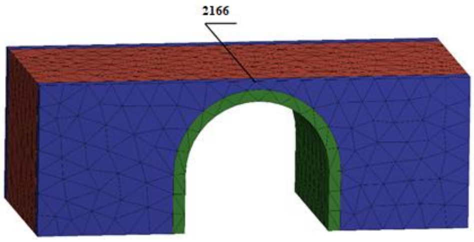
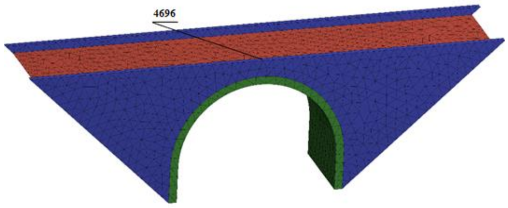


Figure 8. SOLID186 element geometry [26]

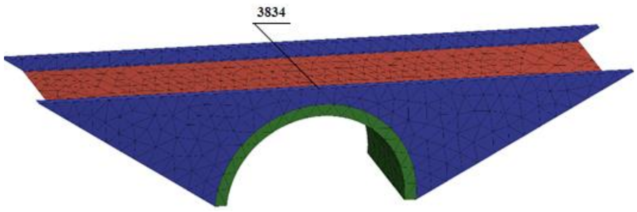
In the finite element model of the bridges, the boundary conditions were defined by restraining all degrees of freedom under the bridge abutments. For the 3D finite element model of the bridges, different parts of the bridges (arch, spandrel wall and infill) were modelled separately. The presented 3D finite element model of the masonry bridges and considered nodal points are shown in Fig. 9.



a) Veli Palas Bridge



b) Musa Palas Bridge



c) Mavilik Bridge

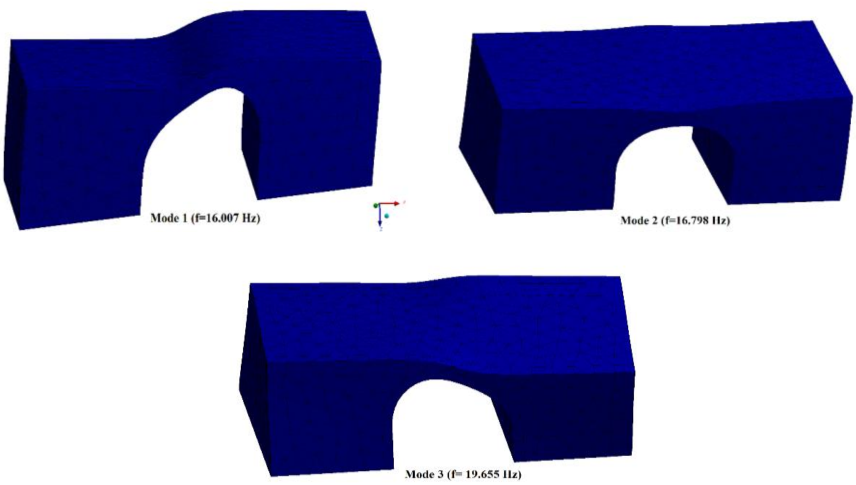
Figure 9. 3D Finite element model (FEM) of the bridges

In the finite element model of the bridges, three different material properties were considered for the arch, side walls and infill. It is not simple to obtain the material properties of historical structures. The identification of these properties for such historical structures through non-destructive testing is a difficult and expensive process. Also, many tests must be performed to obtain any meaningful statistical significance [27]. Therefore, similar material properties which were obtained from the relevant papers in the literature were used in the analysed bridges. These material properties are given in Table 1 [15, 18, 28-30]. Also, compressive strength of the stone material was considered as 15 MPa. According to the recommendation of previous studies, tensile strength of the masonry units was accepted as equal to one-tenth of its compressive strength. This assumption is also in a good matching with the testing results of earlier studies [28, 31-33].

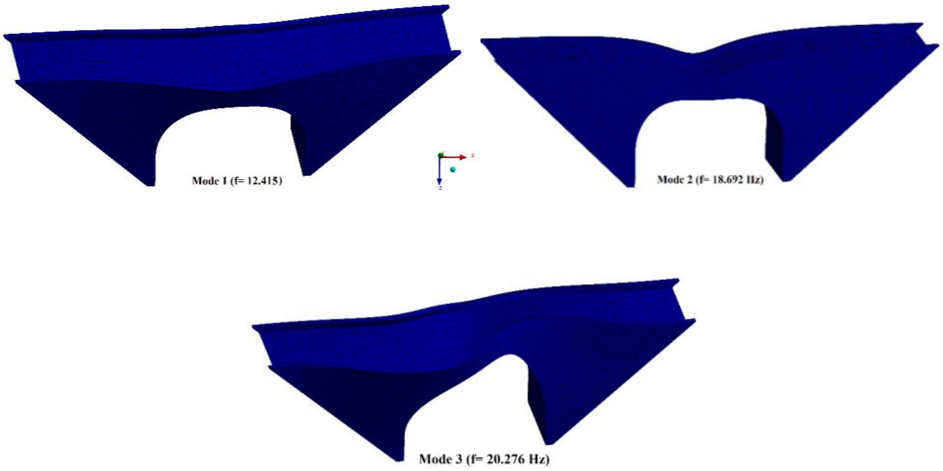
Table 1. Material properties of the bridges

	Elasticity Modulus (MPa)	**Poisson ration**	**Unit weight (kg/m^3)**
Arch	3000	0.2	2500
Spandrell Wall	2500	0.2	2000
Infill	1500	0.2	1500

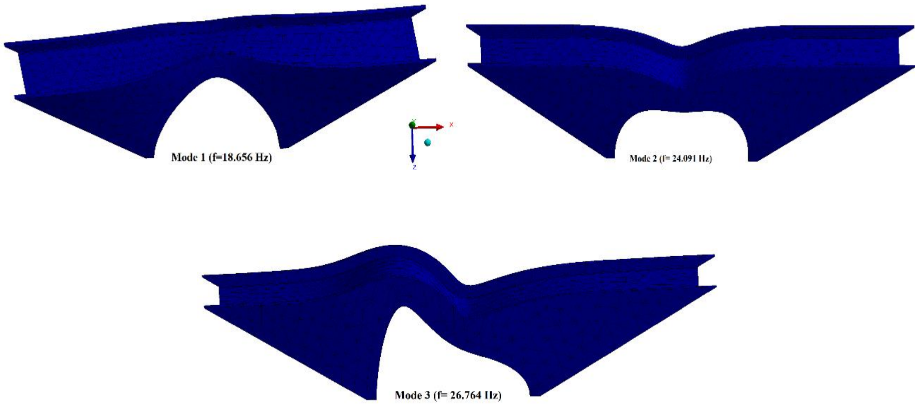
Dynamic characteristics of the bridges were determined by analytical modal analysis. In the analysis, 5% damping ratio was used for the Rayleigh damping coefficients [12, 13, 34]. The frequencies and first three mode shapes of the bridges obtained from the modal analysis are shown in Fig. 10.



a) Veli Palas Bridge



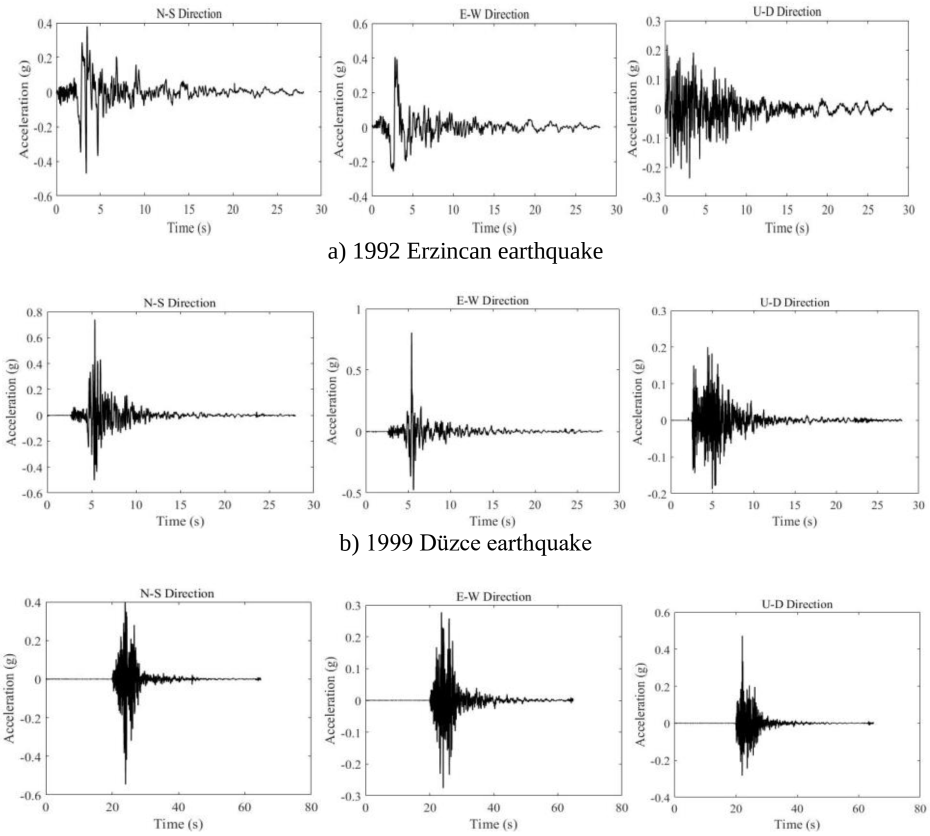
b) Musa Palas Bridge



c) Mavilik Bridge

Figure 10. Mode characteristics and natural frequencies of the bridges

For the dynamic analyses of the bridges, three different earthquakes (13 March 1992 Erzincan, 12 November 1999 Düzce and 1 May 2003 Bingöl) were used. Acceleration records of the earthquakes are given in Fig. 11.



a) 1992 Erzincan earthquake

b) 1999 Düzce earthquake

c) 2003 Bingöl earthquake

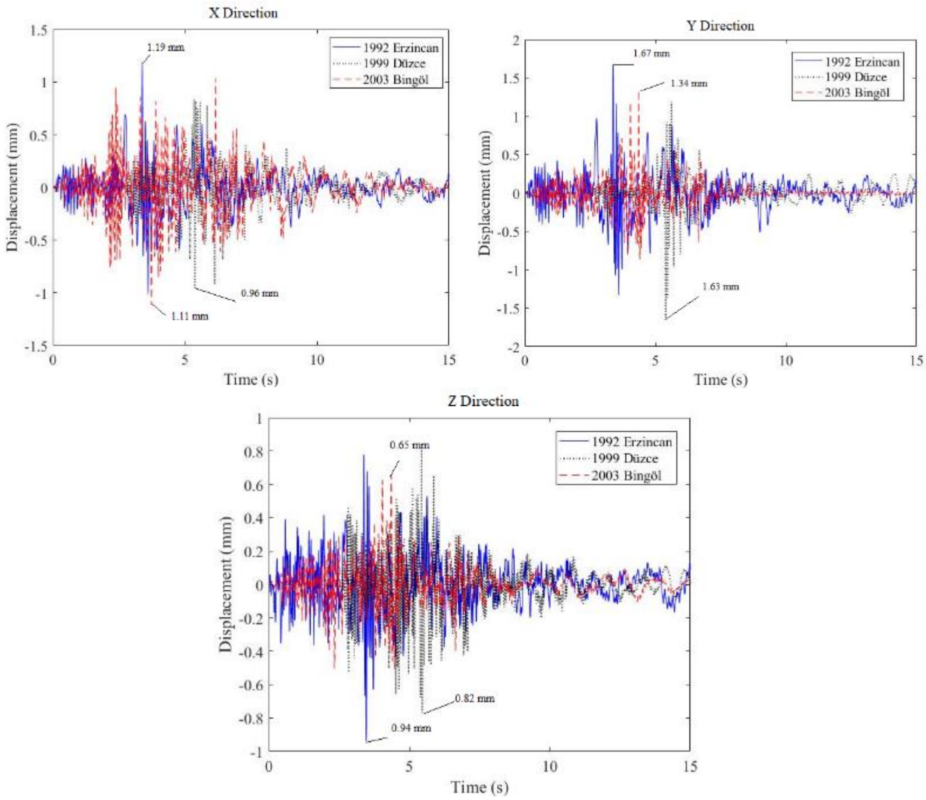
Figure 11. Acceleration records of the earthquakes

These selected acceleration records were scaled in accordance with the bridge's location. For this purpose, Seismomatch software was used [35]. For the scaling parameters, the earthquake level of seismic ground motion was chosen as DD-2, representing a 10% probability of exceedance in 50 years (475 years return period) according to Turkish Building Earthquake Code 2018 [36]. Because of the large memory required, the most effective 15 seconds of the earthquake acceleration records were used in the dynamic analyses. The Newmark method was considered for solution of equilibrium of motion. In the dynamic analysis, the viscous damping was accepted as 5% as being proportional to the stiffness and mass matrices.

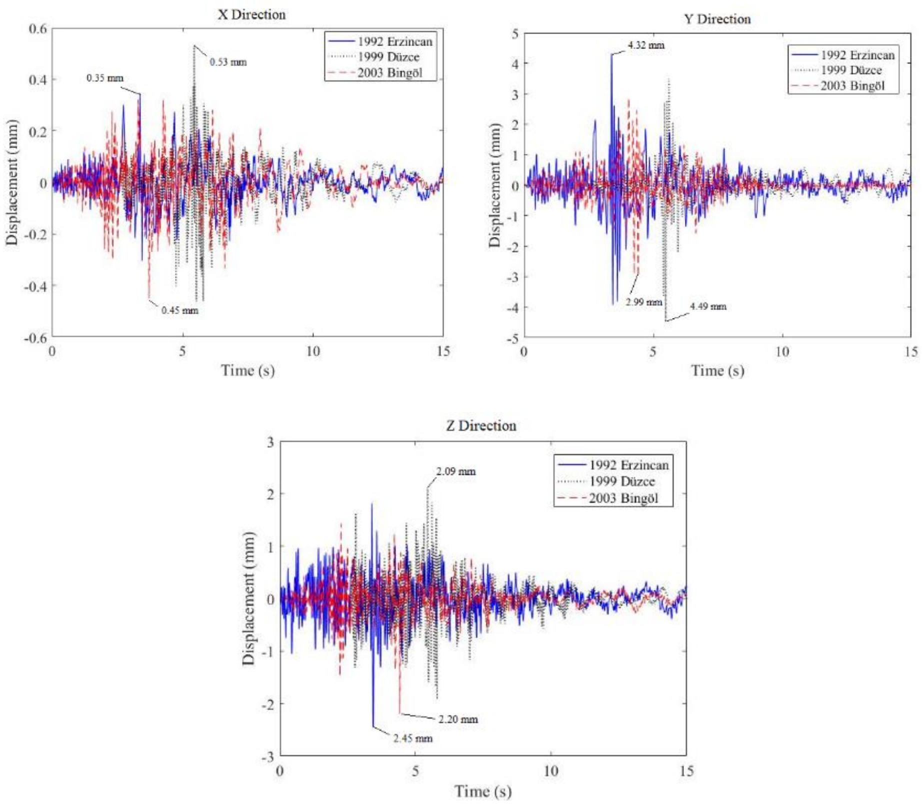
After the dynamic analysis, the absolute peak displacements in the x, y and z directions of the selected nodal points, which were given in Fig. 9 for Veli Palas, Musa Palas and Mavilik bridges, were presented in Table 2 for three different earthquakes. Also, time histories of these nodal points were given in Fig. 11. When the time histories graphs were examined, the absolute peak displacements were obtained river flow direction (y direction) in all earthquakes for all bridges. Also, the absolute peak displacement was achieved in the 1999 Düzce earthquake for the Musa Palas Bridge in y direction.

Table 2. Absolute maximum displacement values

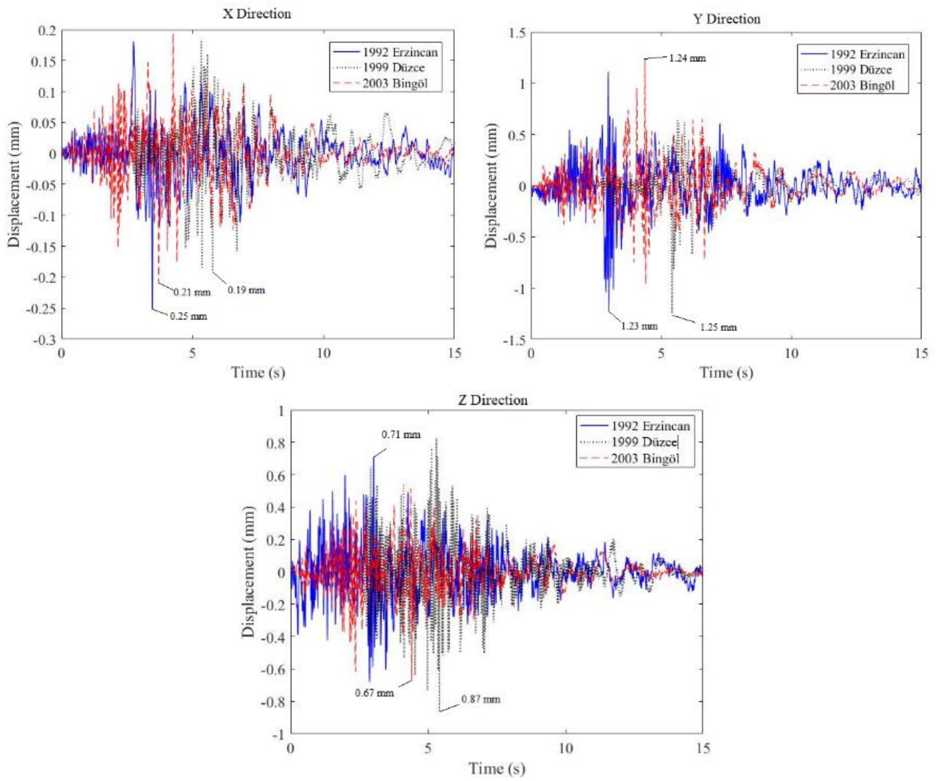
	Earthquake	x(mm)	y (mm)	z (mm)
Veli Palas Bridge	1992 Erzincan	1.19	1.67	0.94
	1999 Düzce	0.96	1.63	0.82
	2003 Bingöl	1.11	1.34	0.65
Musa Palas Bridge	1992 Erzincan	0.35	4.32	2.45
	1999 Düzce	0.53	4.49	2.09
	2003 Bingöl	0.45	2.99	2.20
Mavilik Bridge	1992 Erzincan	0.25	1.23	0.71
	1999 Düzce	0.19	1.25	0.87
	2003 Bingöl	0.21	1.24	0.67



a) Veli Palas Bridge



b) Musa Palas Bridge



c) Mavilik Bridge

Figure 12. Time History Graphs of Selected Nodal Points

Table 3 shows the comparison of the maximum and minimum principal stresses on the bridges subjected to the 1992 Erzincan, 1999 Düzce and 2003 Bingöl earthquakes.

Table 3. Maximum and minimum principal stresses

	1992 Erzincan	**1999 Düzce**	**2003 Bingöl**
	Max. / Min. Prin. Stress (MPa)	Max. / Min. Prin. Stress (MPa)	Max. / Min. Prin. Stress (MPa)
Veli Palas Bridge	2.4 / 2.1	1.6 / 0.28	0.31 / 0.83
Musa Palas Bridge	1.3 / 0.15	0.67 / 1.1	0.93 / 0.74
Mavilik Bridge	0.5 / 0.48	0.61 / 0.51	0.33 / 0.31

Also, the time histories of the maximum and minimum principal stresses of the bridges subjected to the 1992 Erzincan, 1999 Düzce and 2003 Bingöl earthquakes were plotted in Fig. 13.

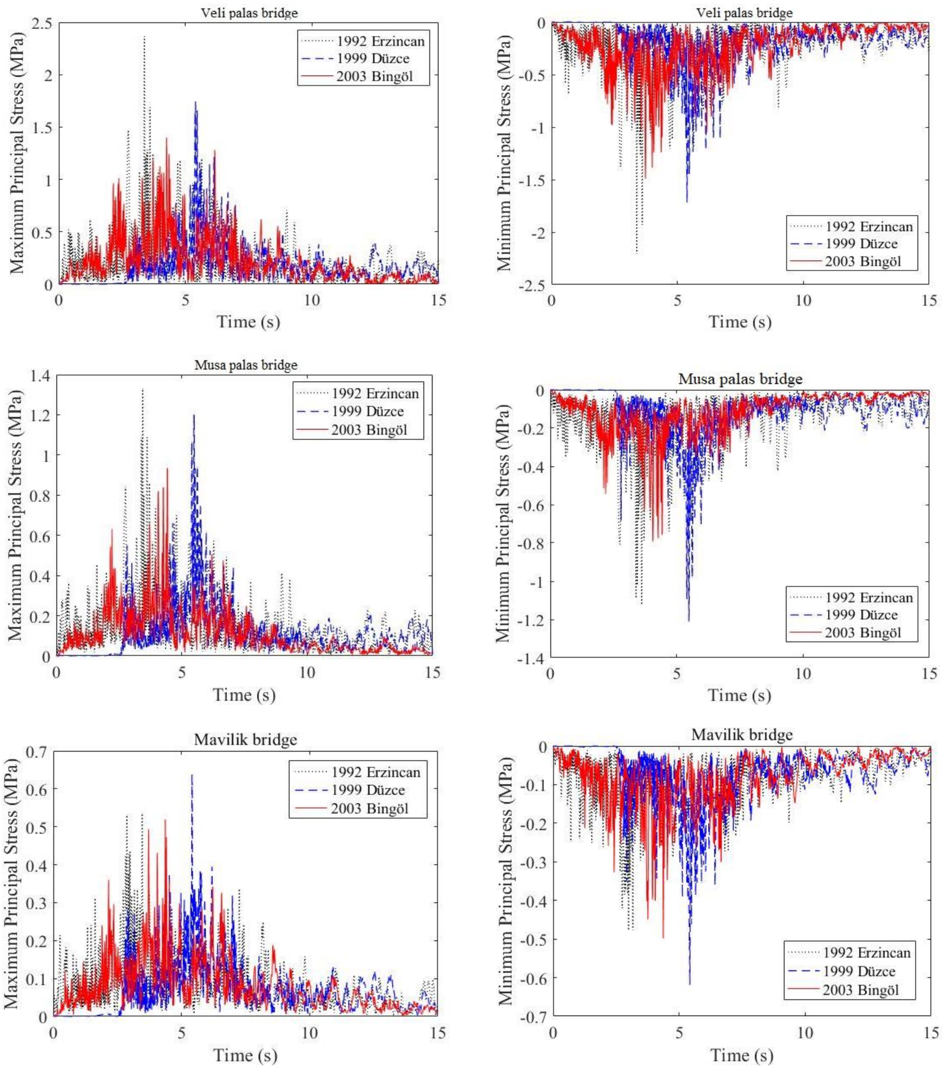
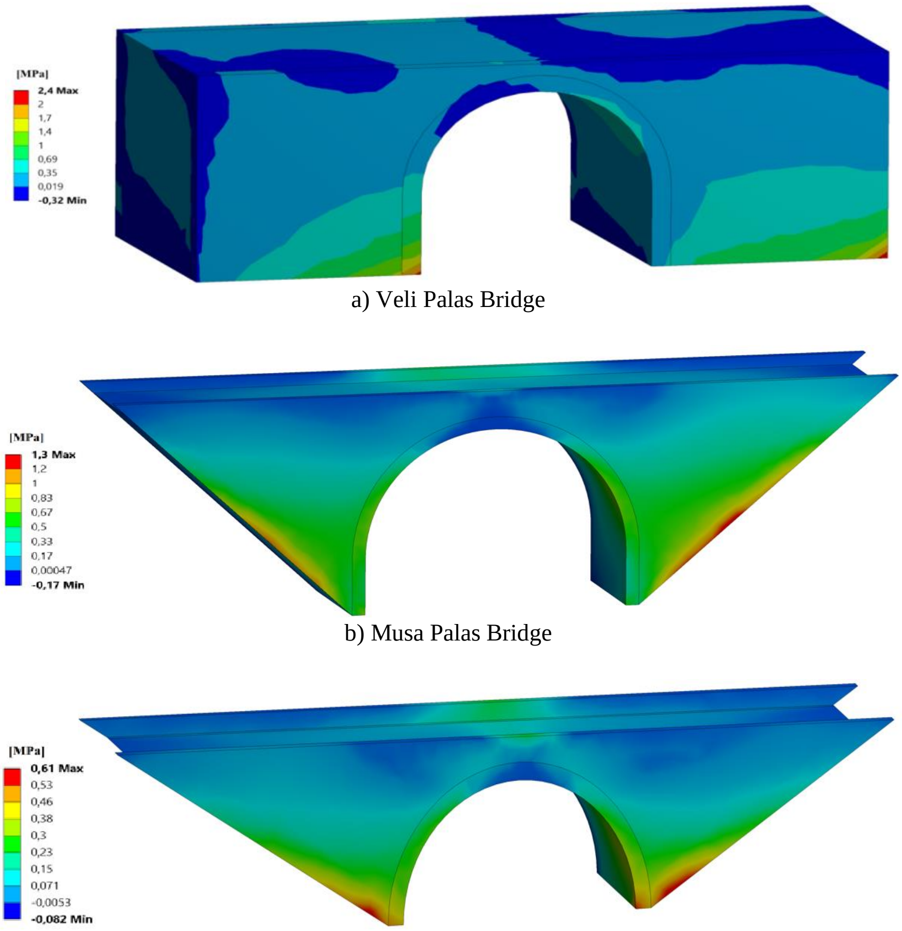


Figure 13. Time histories of maximum and minimum principal stress

The highest maximum and minimum principal stress values were obtained at the Veli Palas Bridge under the 1992 Erzincan earthquake in all dynamic analyses. For Mavilik Bridge, maximum and minimum principal stress values were achieved under 1999 Düzce earthquake. Also, maximum and minimum principal stress for Musa Palas Bridge were obtained under 1992 Erzincan and 1999 Düzce earthquakes, respectively. Maximum and minimum principal stress contours were given in Fig. 14-15. These stress contours present the distribution of the peak values. Also, contour diagrams have quite importance for dynamic analyses, because they show the region of potential damages. It was seen from

Figs. 14-15 that maximum and minimum principal stress were occurred at the base of the arch and below part of the spandrel walls of the bridges. If the stress values found in the analyses exceed the compressive or tensile strength of the bridge material, some cracks or crushes can occur initially at these regions.

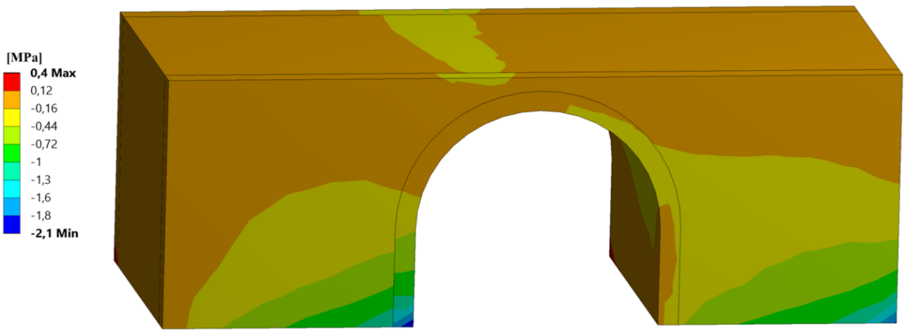


a) Veli Palas Bridge

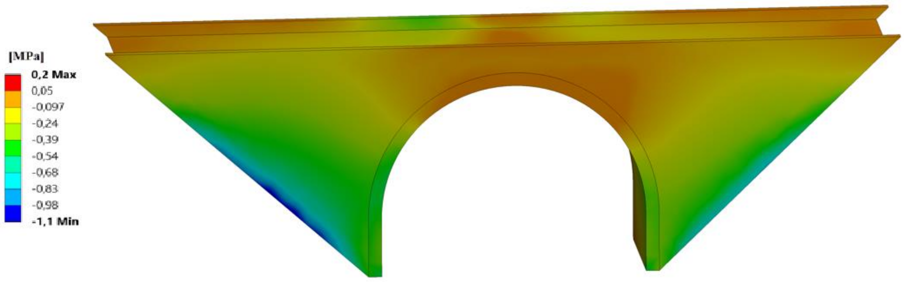
b) Musa Palas Bridge

c) Mavilik Bridge

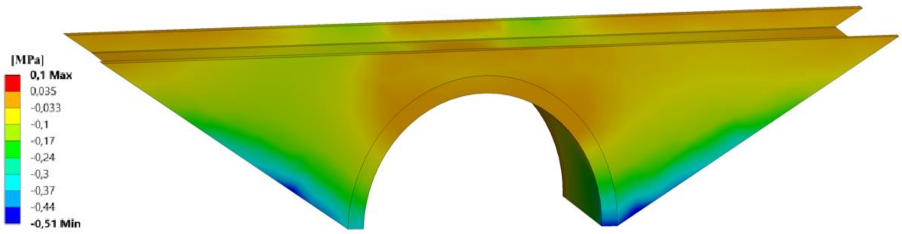
Figure 14. Maximum principal stress contours



a) Veli Palas Bridge



b) Musa Palas Bridge



c) Mavilik Bridge

Figure 15. Minimum principal stress contours

4 CONCLUSIONS

Historical masonry bridges are one of the most essential parts of the transportation systems. For transfer these structures to the next generation, structural behavior of these structures under different earthquakes should be known. In this study, dynamic analyses of the three single span historical masonry arch bridge were performed under 1992 Erzincan, 1999 Düzce and 2003 Bingöl earthquakes. Displacements, principal stresses and seismic behavior of masonry bridges were investigated after the dynamic analyses. In this study, the authors obtained following information.

- Maximum displacement was obtained under the 1992 Erzincan earthquake in river flow direction (y direction) for Veli Palas Bridge. But the maximum displacement was obtained in the acceleration records of the 1999 Düzce earthquake for Musa Palas and Mavilik Bridges in the y direction. In addition, the maximum displacement values obtained in the y direction for all earthquake accelerations for the Mavilik Bridge are very close to each other.

- Highest maximum and minimum principal stress were obtained under 1992 Erzincan earthquake for Veli Palas Bridge. For Musa Palas and Mavilik Bridges, maximum principal stress was occurred under 1992 Erzincan and 1999 Düzce earthquakes, respectively. Also, minimum principal stress was achieved under 1999 Düzce earthquake for Musa Palas and Mavilik Bridges. Both the maximum and minimum principal stress obtained around at the base of the arch and below part of the spandrel walls of the investigated bridges. All obtained maximum and minimum stress values after the analyses below the compressive and tensile stress of the masonry unit considered in this study. But the minimum tensile stress which was obtained for Veli Palas Bridge under 1992 Erzincan earthquake exceeded the tensile strength of the masonry unit.
- Maximum and minimum principal stresses were obtained at the base of the arch and below part of the spandrel walls for all of the investigated bridges. If these stress values occurred in the dynamic analyses exceed the compressive or tensile strength of the bridge material, possible damages (cracks or crushes) can obtain at these regions.

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