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# Dynamic Analysis of Historical Masonry Arch Bridges under Different Earthquakes: The Case of Murat Bey Bridge

**Elif Gözde ÇUBUK[1] , Erkut SAYIN[1*], Alper ÖZMEN[2]**
[1] İnşaat Mühendisliği, Fırat Üniversitesi, Mühendislik Fakültesi, Elazığ, Türkiye
[2] İnşaat Mühendisliği, İnönü Üniversitesi, Mühendislik Fakültesi, Malatya, Türkiye
[1]elifcubuk4@gmail.com, [*1]esayin@firat.edu.tr, [2]alper.ozmen@inonu.edu.tr

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**Abstract:** Historical structures, which constitute an important part of our cultural heritage, should be well protected and carried into the future. Masonry arch bridges are significant part of these structures. In this study, the single-span Murat Bey Bridge in the province of Kütahya, built in 1460, was studied as a numerical application. Firstly, three dimensional finite element model of the bridge was constituted with SAP2000 finite element program. Static analysis of the bridge under its own weight was carried out. The modal analysis method was used to obtain the dynamic characteristics of the bridge. Then, time-history analysis method was applied for seismic evaluation of the bridge. For this purpose, the acceleration records of the 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes were taken into consideration. As a result of the dynamic analyses carried out, the displacement and stress graphs occurring on the bridge were examined. The highest displacement and stress values on the historical bridge were obtained from the acceleration records of the 2011 Van earthquake.

**Key words:** Historical masonry bridges, finite elements, dynamic analysis.

## Tarihi Yığma Köprülerin Farklı Depremler Altında Dinamik Analizi: Murat Bey Köprüsü Örneği

**Öz:** Kültürel mirasımızın önemli bir parçası olan tarihi yapılar en iyi şekilde korunmalı ve geleceğe taşınmalıdır. Yığma kemer köprüler tarihi yapıların önemli bir kısmını oluşturur. Bu çalışmada, Kütahya ilinde 1460 yılında inşa edilmiş tek açıklıklı Murat Bey köprüsü sayısal uygulama olarak dikkate alınmıştır. İlk olarak köprünün üç boyutlu modeli SAP2000 sonlu eleman programı yardımıyla oluşturulmuştur. Köprünün statik analizi kendi ağırlığı altında yapılmıştır. Dinamik karakteristikleri ise modal analiz metodu ile elde edilmiştir. Daha sonra köprünün sismik değerlendirilmesi için zaman tanım alanı metodu kullanılmıştır. Bu amaçla, 1998 Adana, 2003 Bingöl, 2011 Van ve 2020 Elazığ depremleri dikkate alınmıştır. Dinamik analizler sonucunda köprüden elde edilen yerdeğiştirme ve gerilme grafikleri elde edilmiştir. Köprüde en büyük yerdeğiştirme ve gerilme değerleri 2011 Van depremi ivme kayıtlarından elde edilmiştir.

**Anahtar kelimeler:** Tarihi yığma köprüler, sonlu elemanlar, dinamik analiz.

## 1. Introduction

Historical structures are an important part of the cultural heritage. In Turkey, there are many historical structures such as bridges, mosques, churches etc. reached today from the Roman, Byzantine, Seljuk and Ottoman periods. Protection and transfer to the next generation of these structures is important. These historical structures can be damaged or ruined under earthquake, wind and traffic loads. Many of them are located in medium or high seismic areas. Also, these structures are exposed to large earthquake forces because they are heavy and rigid. In order to protect structural integrity of these structures, assessment of the seismic behaviour of these structures is necessary. Historical masonry bridges are one of the most important part of transportation, commercial and architecture since the ancient times. These bridges which are important historical structures of a country were built in different spans, shapes and sizes in the world. Also, these bridges are still valuable components of transportation systems in many countries. They constituted a large part of Europe's road and railway bridge stock. According to the Sustainable Bridges project, more than 40% of railway bridges and 25% of the existing road bridges are masonry arch bridges [1]. In Turkey, an important percentage of masonry arch bridges in the railway network, such that 6966 of the 24196 culverts and 245 of the 2012 railway bridges are made of masonry material. Also, there are 2063 masonry arch bridges in the road network [2]. Although there were many masonry bridges in

** Corresponding author: esayin@firat.edu.tr. Yazarların ORCID Numarası: [1] 0000-0001-9566-7200, [1*] 0000-0003-0266-759X, [2] 0000-0003-1335-3780

Turkey, studies on these structures are relatively rare when compare the other structures. Accurate analysis methods are necessary to protect and restoration of historical bridges.

Different studies were performed about structural assessment and behaviour of historical masonry structures in the literature. Frunzio et al. [3] evaluated the results of a three dimensional finite element model analysis of a stone masonry arch bridge built in the Roman age, performed involving non-linear material behaviour, in which the structural role of the spandrel walls and filling was involved. Milan and Lourenço [4] evaluated the nonlinear behaviour of three dimensional of two masonry arch bridges through finite element code. Sayın et al. [5] generated the historical Uzunok Bridge with three dimensional finite element and they assessed linear and nonlinear analyses of the bridge. Altunışık et al. [6] assessed the arch thickness effect on the structural behaviour of masonry arch bridges under live and dead loads. As a case study, they selected Göderni historical arch bridge in Turkey. Güllü and Jaf [7] investigated soil structure interaction effect on a historical masonry stone arch bridge. For this purpose, they were evaluated the Mataracı Bridge with three dimensional nonlinear time history analyses. Özmen and Sayın [8] evaluated the seismic behaviour of the historical masonry Dutpınar Bridge under the 2003 Bingöl earthquake. As a result of the study, the maximum and minimum principal stresses were occurred at right and left arch base of the bridge and the maximum displacement was obtained at the top of the bridge. Sevim et al. [9] investigated linear dynamic analyses of two historical masonry arch bridges with operational modal analysis. Hökelekli and Yılmaz [10] examined the in-plane and out-of-plane non-linear structural responses of the spandrel walls of a historical masonry bridge in Bartın-Turkey. Sakcalı et al. [11] investigated historical Irgandı Bridge which is located in Bursa. They evaluated seismic behaviour of the bridge by linear dynamic analysis. Şeker and Gökçe [12] studied behaviour of Hundi Hatun (Kunç) Bridge located in Amasya city under the effect of increasing traffic loads. Analyses were carried out according to the most unfavourable situation. Radnić et al. [13] investigated static and dynamic analysis of the old stone bridge in Mostar. They assessed influence of vertical load, temperature change and seismic action. Gönen et al. [14] investigated stress contours and displacement values of the historical Murat bridge under dead loads. For this purpose, linear elastic response of the bridge was evaluated. Güllü [15] investigated Cendere Bridge under earthquake effects. Firstly, 3D finite element model of the bridge was consisted using solid element and the earthquake behaviour of the bridge was investigated with time-history analysis for linear elastic behaviour. Özodabaş and Artan [16] carried out a study to investigate historical Muş Murat Bridge. Stress regions of the bridge was investigated after earthquake, flood, and traffic loads. Akın et al. [17] assessed the seismic behaviour of a historical masonry bridge under different damping types. For this purpose, mass proportional, stiffness proportional and Rayleigh damping types were used. 1992 Tunceli earthquake acceleration records were used as seismic effect.

This paper presents the seismic behaviour of historical Murat Bey Bridge. The bridge was evaluated under 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes acceleration records. For this purpose, the historical bridge was constructed with three dimensional finite element model by SAP2000 finite element software and seismic behaviour of the bridge was investigated. Also, the displacement and stress graphs occurring on the bridge were examined after the dynamic analysis.

## 2. Historical Masonry Bridges

Arch is a structural form that is frequently used in masonry structures. It can span large distances and it generally subjected to compressive forces because of its geometric form. For this reason, it is the most preferred form. Stone and brick are the main construction materials for the masonry structures and arches because they have high compressive strength. There have been serious developments in arch forms over time. Different cultures and civilizations used various arch forms in order to both functional and decorative purposes. Some of the preliminary examples of arches were dated back to 3000 BC found in the Sumerian underground tombs located in Mesopotamia. Although it is not certain whether it was the Sumerians who discovered the arch form, the Romans put them to good use in both efficient and amazing ways. The ancient Romans constructed stone arches for bridges and aqueducts to across obstacles. Due to the geographical location and rich cultural heritage, Turkey has many historical structures and also stone masonry arch bridges. In Turkey, the best examples of bridge architecture were constructed in the 16$^{th}$ century of Master Builder Sinan [18]. Many masonry bridges of various sizes, shapes and materials were built from past to present. These masonry bridges have different parts. The main part of masonry arch bridges is spandrel wall, arch, backfill and foundation. Arch is the significant segment of historical structures. Also, one of the oldest architectural forms used for the historical structures. Typical components of masonry arch bridges are shown in Figure 1.

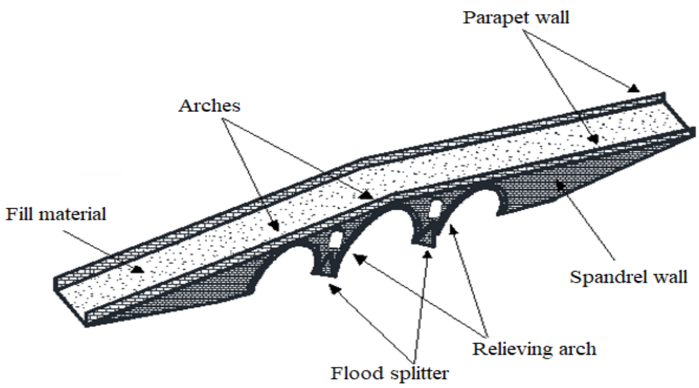
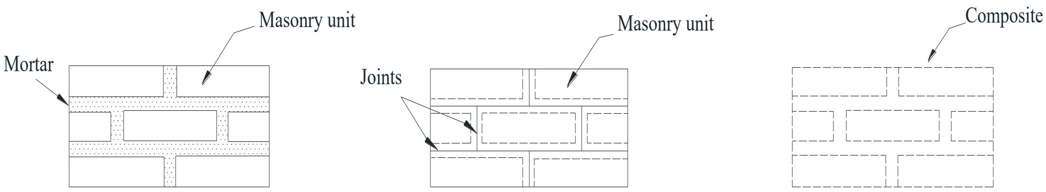



**Figure 1**. Typical components of masonry arch bridge

### 3. Description of the bridge and structural analysis

Numerical modeling of masonry structures is complex due to the interaction between masonry units and the mortar. Masonry is a heterogeneous material which exhibits distinct directional properties due to the mortar joints which act as planes of weakness. Finite element method is frequently used to numerical modelling of masonry structures. For modelling historical masonry structures, three modelling techniques are commonly used. According to the size of the structural system, detailed micro, simplified micro and macro modeling techniques have been frequently used in the modeling of masonry unit. These modelling techniques are given in Figure 2.



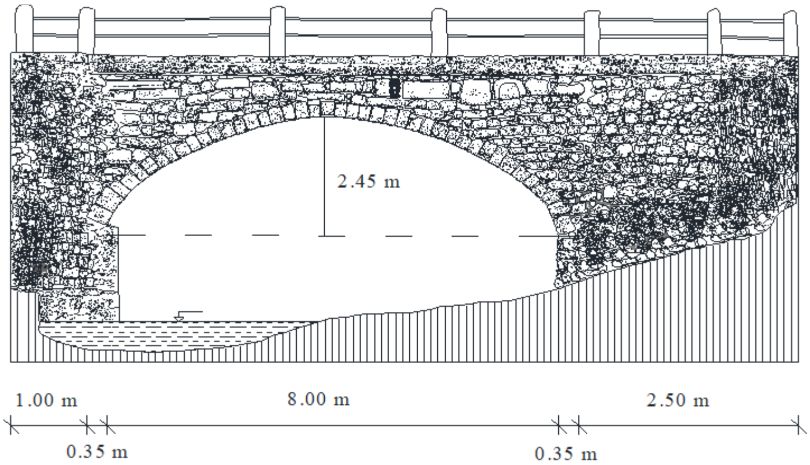

a) Detailed micro modelling b) Simplified micro modelling c) Macro modelling

**Figure 2.** Modelling techniques of masonry structures [19]

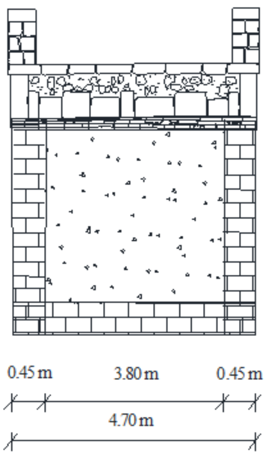
Masonry unit and mortar materials are modelled separately in the detailed micro modelling. Although this is a precise modelling technique, the time required for the analysis of the complete structure takes very long. For this reason, it is preferred for the analysis of small buildings or parts of large structures. In the simplified micro modelling, dimensions of masonry unit are extended as much as half thickness of the mortar. Thereby, the masonry units are separated from each other with interface lines and the mortar layer is neglected. Masonry unit and mortar is considered as a homogenized domain in the macro modelling [19]. When the literature is reviewed, it can be seen that macro-modelling was used to model full-scale historical structures because of its low computational effort [20-23].

The case study structure is the historical Murat Bey Bridge in Kütahya, Turkey. It was built in 1460 during the Ottoman period. It has single arch. The arch is made of cut stones and other parts of rubble stone. The bridge is 12.20 m long and 4.70 m wide, 2.45 m in height and span of 8 m. The thickness of spandrel walls and arch are 0.45 m and 0.35 m, respectively. Also, there are balustrades on both sides of the bridge. The bridge is good condition and open to vehicular and pedestrian traffic nowadays (Fig. 3). The section properties of Murat Bey Bridge were shown in Figure 4.

**Figure 3.** Murat Bey Bridge




a) Plan view




b) Section view

**Fig. 4.** Geometrical properties of Murat Bey Bridge

Three dimensional (3D) model of the bridge was generated by using SAP2000 program (Figure 5). This program can be used for linear and non-linear analyses of 3D model of the structures. 5796 nodal points and 4580 solid elements were used in the finite element model of the historical bridge. The nodal point 131 on the top of the bridge was also given in the Figure 5. Also, all degrees of freedom were taken into account to be fixed at the foundation level in the finite element model of the bridge.

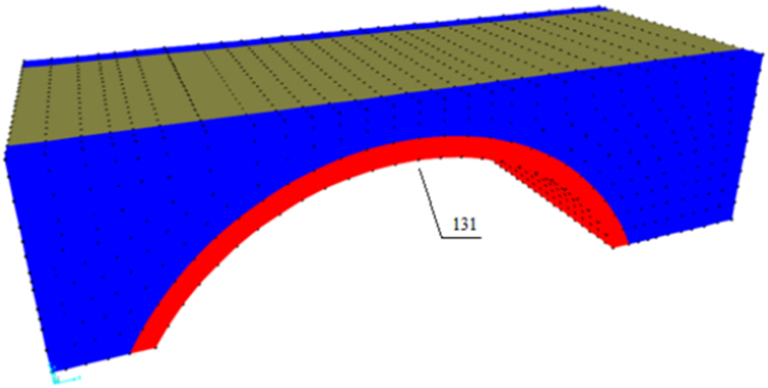



**Fig. 5.** Three dimensional finite element model of the Murat Bey Bridge

The bridge was modelled with the macro-modelling where the structure is considered as an isotropic and homogeneous material. Arch, spandrel wall and filling material were considered as three different material properties. It is not easy to determine the material properties of historical structures. Also, historical structures are important and sensitive structures therefore it may be inconvenient to take test samples from these structures. For this reason, similar material properties in the relevant literature were used (Table 1) [24-25]. Compressive strength of the stone material was considered as 20 MPa. Also, it was assumed that tensile strength of stone is 1/10 of compressive strength in accordance with previous studies [26].

**Table.1.** Material properties of Murat Bey Bridge

| Material | Elasticity modulus ($kN/m^2$) | Density ($t/m^3$) | Poisson ratio |
|---|---|---|---|
| **Arch material** | 2.5E6 | 2.3 | 0.2 |
| **Spandrel walls** | 2E6 | 2.2 | 0.2 |
| **Filling material** | 1.2E6 | 1.4 | 0.2 |

Firstly, static analysis of the bridge under dead load was carried out. Maximum displacement under dead load obtained at the vertical axis (z axis) on the middle of the bridge arch span. Maximum displacement of the marked point in Figure 5 was obtained as 0.569 mm in z direction. The deformed shape of the bridge was presented in Figure 6.

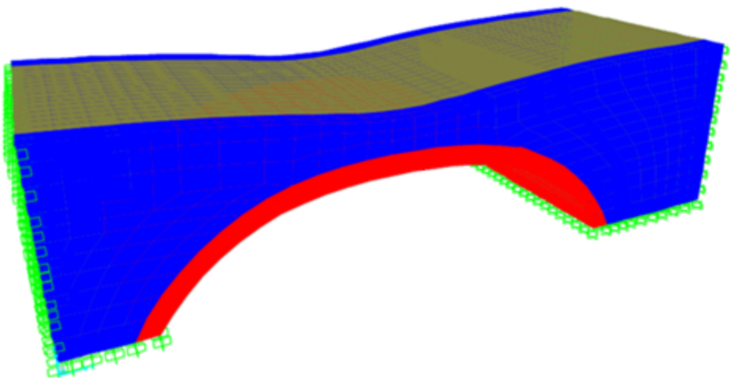
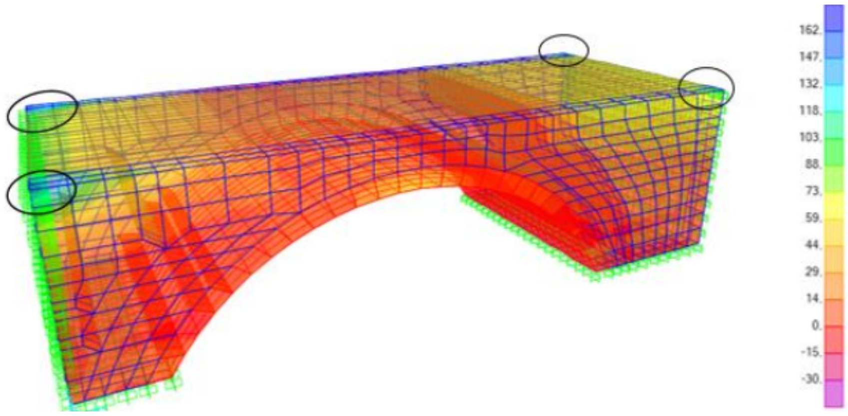
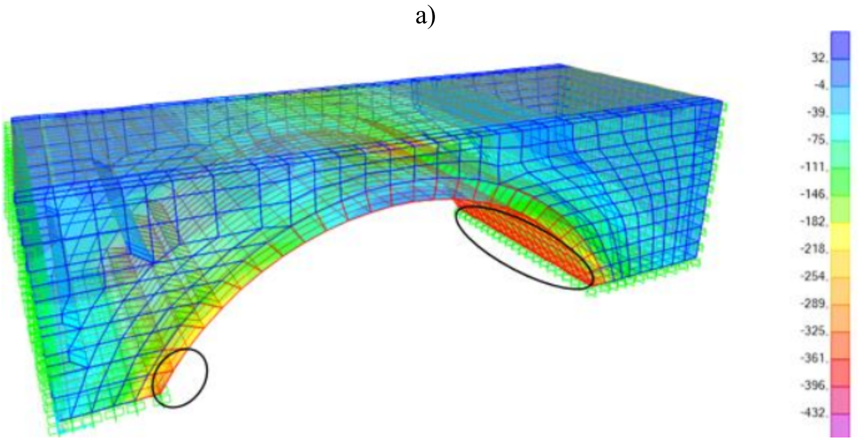


**Fig. 6.** Deformed shape of the bridge under its own weight

At the end of the static analysis, the maximum tensile and compressive stresses contours of the bridge were presented in Figure 7. Maximum tensile and compressive stress occurred as 162.89 kPa and 431.35 kPa, respectively. These high stress contours were marked in the circle in Figure 7.



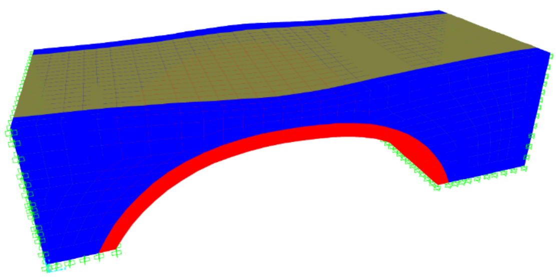

a)



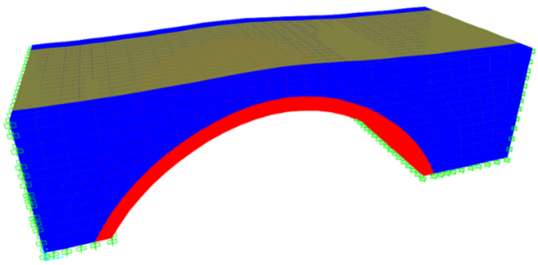

b)

**Fig. 7.** Static analysis a) maximum tensile contour b) maximum compressive contour

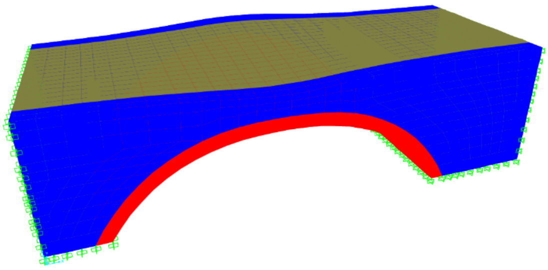
Modal analysis was performed to determine the dynamic characteristics of the Murat Bey Bridge. In this analysis, mode shapes, free vibration periods and mass participation ratios of the structures were acquired. In the analysis, 5% damping ratio was used for the Rayleigh damping coefficients [27-29]. Dynamic characteristics were calculated for the first 100 modes. Mass participation ratio was found greater than 90% for the first 100 modes. The first three modes of the bridge obtained from the modal analysis were shown in Fig. 8.



a) first mode ($f_1$ = 24.8016 Hz)



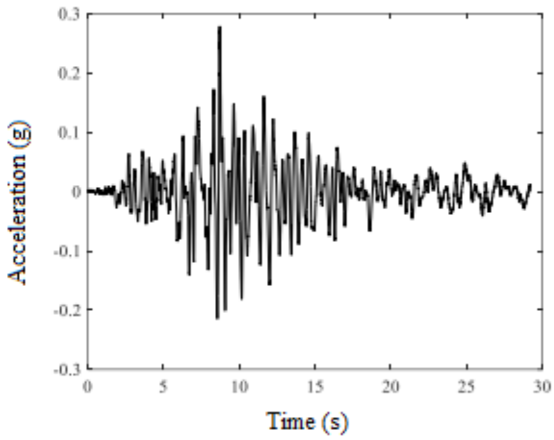
b) second mode ($f_2$ = 24.8694 Hz)



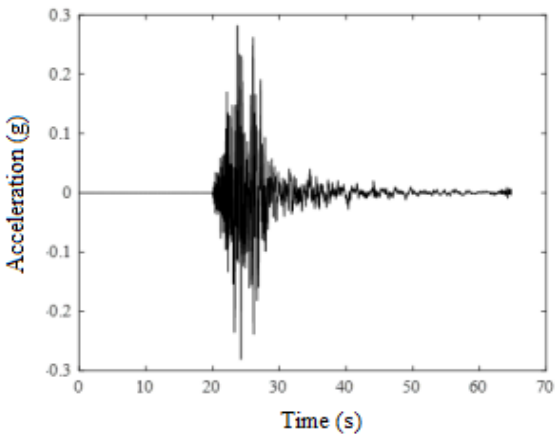
c) third mode ($f_3$ = 34.0892 Hz)

**Fig. 8.** First three mode shapes and frequencies of the bridge

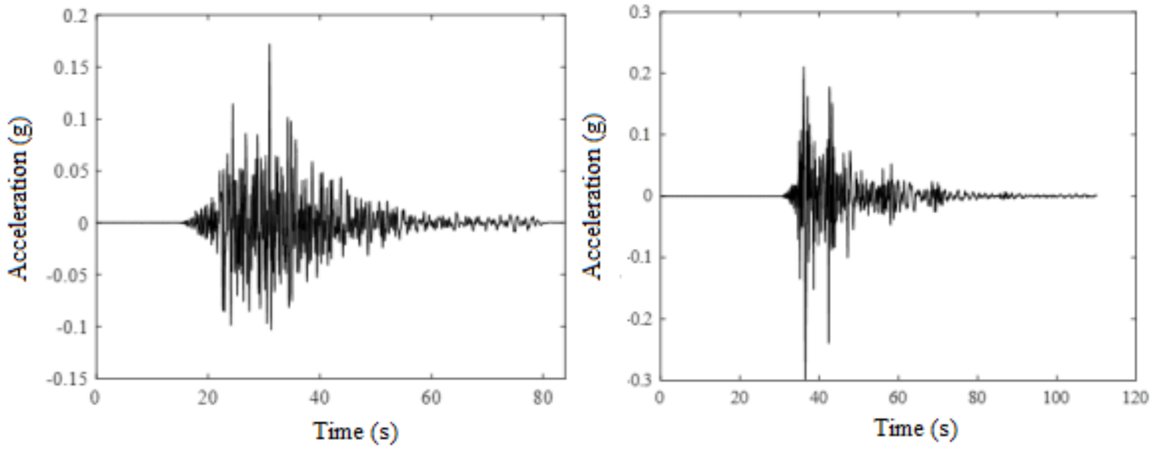
For the dynamic analysis of the bridge, 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes acceleration records were used (Fig. 9). East-West component of the earthquakes were applied in the flow (y) direction of the bridge. In the dynamic analysis, the most effective 20 seconds of earthquake acceleration records were used because of the large memory required. The integration step was selected as 0.01 sec. Also, HHT-α method was considered for solution of equilibrium of motion.




a) 1998 Adana



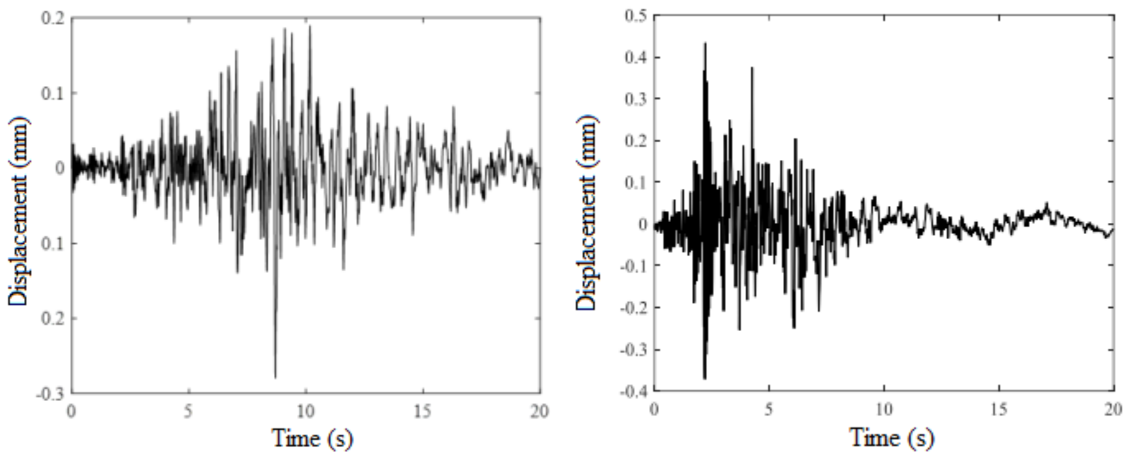

b) 2003 Bingöl



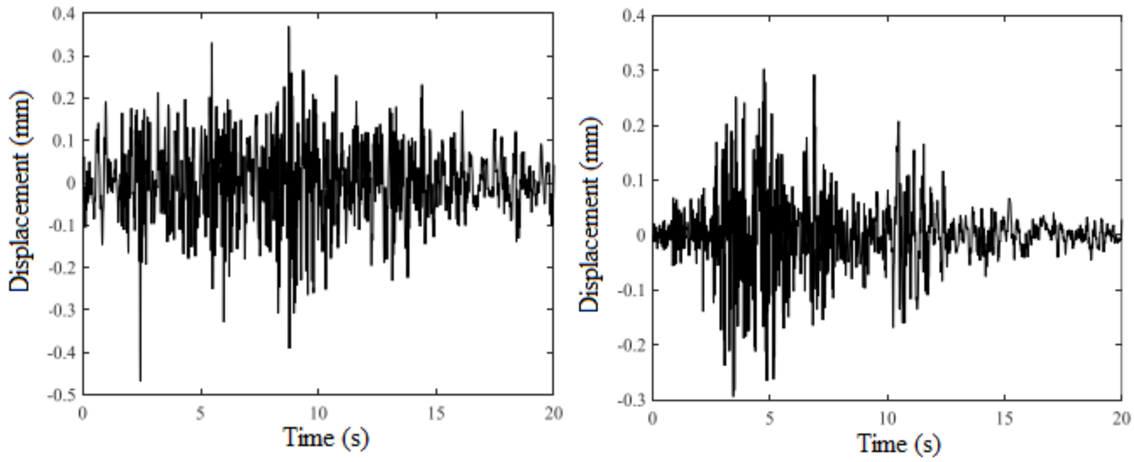

c) 2011 Van d) 2020 Elazığ

**Fig. 9.** East-West component of the selected earthquakes

These selected earthquake acceleration records were scaled according to bridge's location. 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) [30]. After the dynamic analysis, the horizontal displacements (flow direction) for the node 131 were obtained. The time histories of the displacements subjected to the selected earthquakes were given in Fig. 10. These displacement values for 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes were obtained as 0.279 mm, 0.434 mm, 0.468 mm and 0.303 mm, respectively.




a) 1998 Adana b) 2003 Bingöl




c) 2011 Van

d) 2020 Elazığ

**Fig. 10.** Time history graph of the nodal point 131

All these displacement values for the nodal point 131 were given in Figure 11. As shown in Fig. 11, the highest displacement value was occurred for the 2011 Van earthquake.

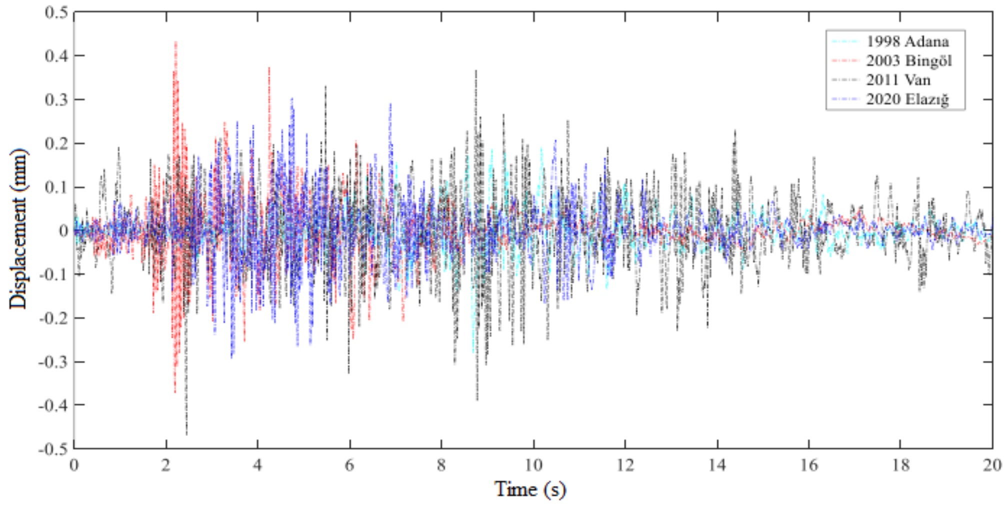
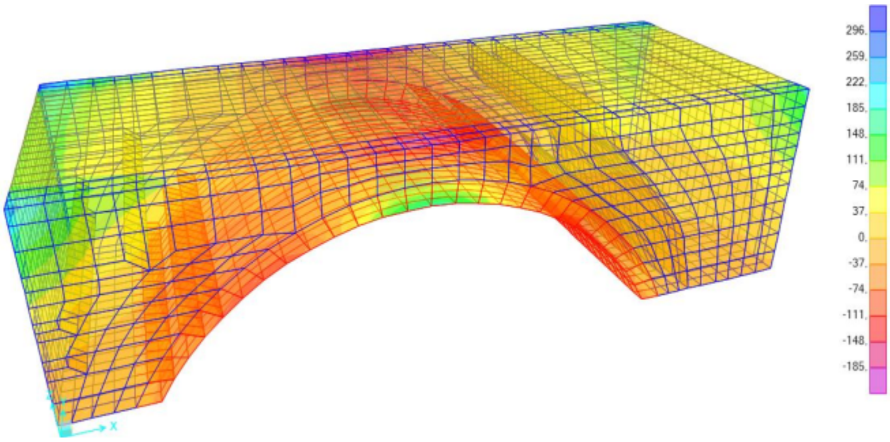
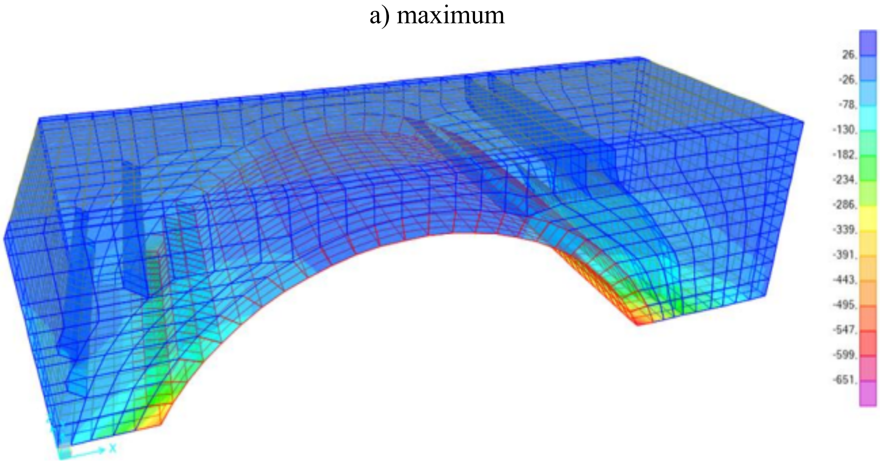



**Fig. 11.** Time history graph of the nodal point 131 for all selected earthquakes

Also, the time histories of the maximum and minimum stress contours of the bridge subjected to the selected earthquakes were obtained. In the dynamic analyses, dead load of the bridge was considered with the earthquake load. When the 1998 Adana earthquake was considered, maximum and minimum stress contours of the historical bridge were obtained as Figure 12.



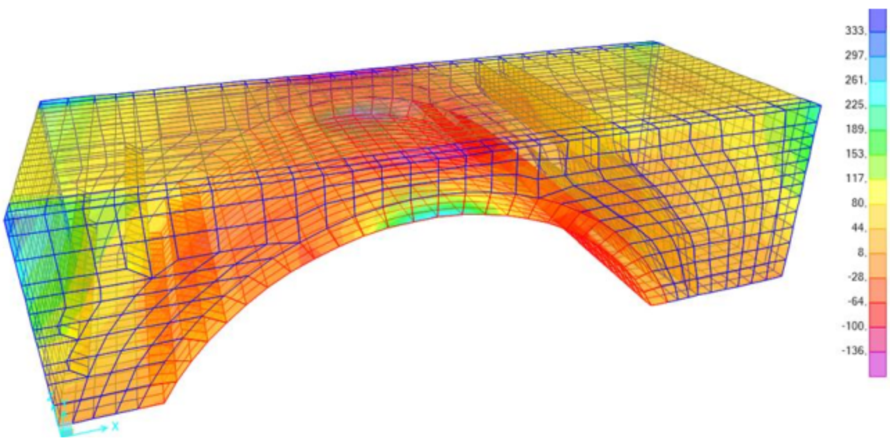

a) maximum



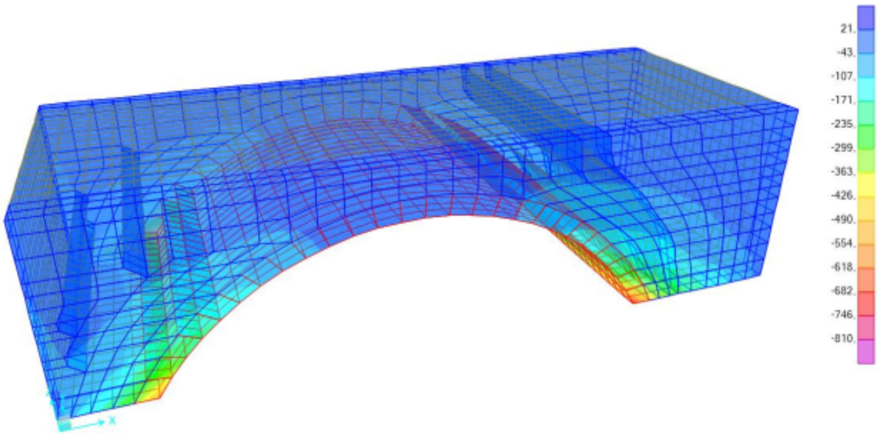

b) minimum

**Fig. 12.** Stress contours of the bridge for 1998 Adana earthquake

In this analysis, maximum and minimum stress values were achieved as 295.82 and -650.81 kPa, respectively. For the 2003 Bingöl earthquake acceleration records, maximum and minimum stress contours of the bridge were shown in Figure 13.



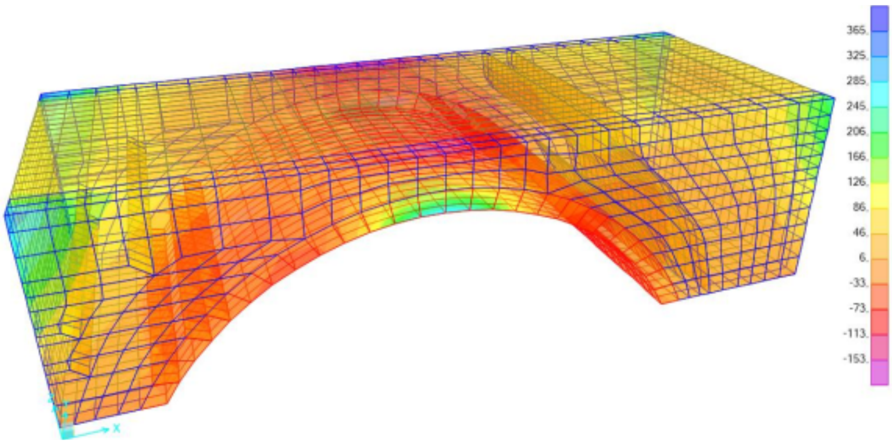

a) maximum



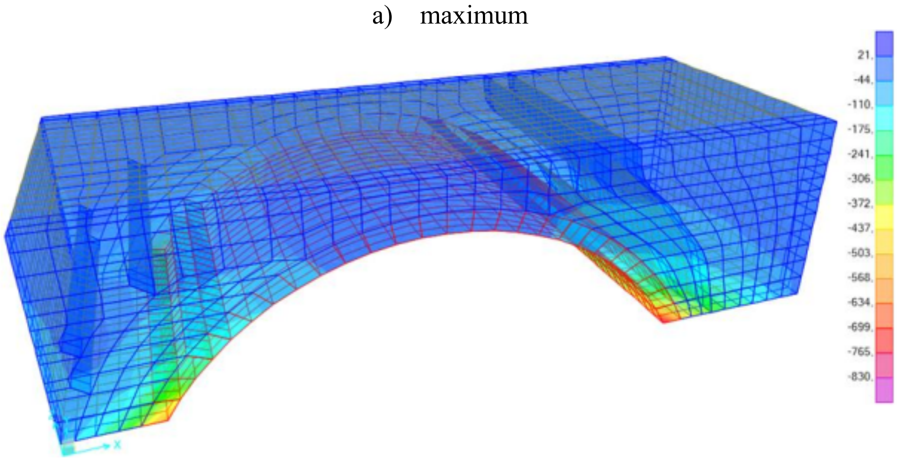

b) minimum

**Fig. 13.** Stress contours of the bridge for 2003 Bingöl earthquake

As seen in Figure 13, the maximum and minimum stress values were acquired as 332.50 and -809.08 kPa for 2003 Bingöl earthquake, respectively. When the 2011 Van earthquake was evaluated, maximum and minimum stress contours of the bridge were obtained as Figure 14. In this analysis, maximum and minimum stress values were achieved as 364.77 and -829.33 kPa, respectively.



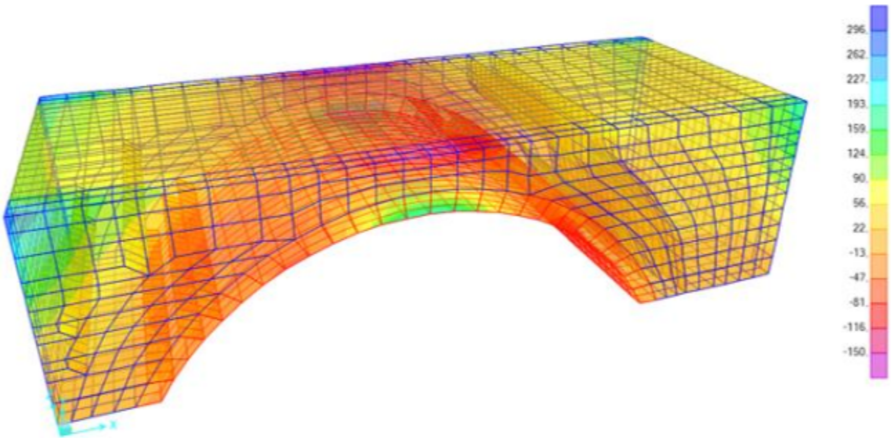

a) maximum



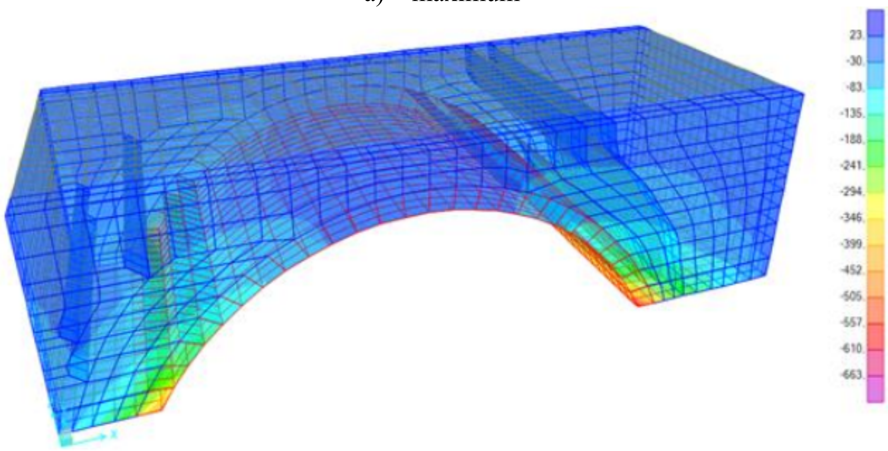

b) minimum

**Fig. 14.** Stress contours of the bridge for 2011 Van earthquake

Also, maximum and minimum stress contours of the bridge were shown in Figure 15 for the 2020 Elazığ earthquake acceleration records. As seen in Figure 15, the maximum and minimum stress values were obtained as 295.72 and -662.40 kPa, respectively.




a) maximum




b) minimum

**Fig. 15.** Stress contours of the bridge for 2020 Elazığ earthquake

When all the earthquake accelerations used in the analysis were evaluated, the highest stress values were obtained for the 2011 Van earthquake.

## 4. Conclusions

This paper aimed to investigate the dynamic analysis of historical masonry bridge. As a numerical application, the single-span Murat Bey Bridge built in 1460 located in Kütahya was selected. SAP2000 finite element software was used to constitute three dimensional finite element model of the bridge. Natural frequencies, period and mode shapes of the bridge determined by modal analysis. In the dynamic analysis, 5% damping ratio was used for the Rayleigh damping coefficients and seismic evaluation was investigated using 1998 Adana, 2003 Bingöl, 2011 Van and 2020 Elazığ earthquakes. The displacement values and stress contours of the bridge were investigated for these selected earthquakes. The highest displacement value was obtained as 0.468 mm at 2011 Van earthquake. Also, maximum and minimum stress contours of the bridge were investigated for the selected earthquakes with dynamic analysis. It is possible to see that high compressive stresses were concentrated arch base of the bridge. Also, it was seen that tensile stresses reached higher values in the regions where spandrel walls connect side slopes. The highest stress values were achieved at 2011 Van earthquake. However, the obtained compressive and tensile stresses as a result of the dynamic analysis were below the compressive and tensile stress considered in the study.

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