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Investigation of Seismic Behavior of the Historical Yeşiltepe Bridge

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Abstract: Historic arch bridges, a common feature of Turkish infrastructure, represent a significant aspect of the country's cultural heritage. To ensure their continued existence and preservation, it is essential to conduct a detailed examination of their structural features and behaviours. This study aimed to investigate the performance of the historic Yeşiltepe Bridge under earthquake conditions. To achieve this, the bridge was modelled using the SAP2000 finite element software, enabling a deeper understanding of its structure and the prediction of its behaviour during an earthquake. In order to ascertain the dynamic behaviour of the historical bridge, modal analysis and nonlinear time history analysis were conducted. The results of the modal analysis yielded period values, mass participation rates and mode shapes for the bridge. The time history analysis yielded displacement, base shear force and stress values for the historical structure, which were subsequently presented in graphical form. The data obtained from the study enabled the identification of the critical regions of the structure exhibiting the highest stress concentration values.

Keywords: masonry; bridge; heritage

1. Introduction

Historic arch bridges, which are scattered across various landscapes, are not only masterpieces of engineering and architecture but also crucial bearers of cultural and historical significance. These bridges, which are often centuries old, represent the technological advancements of their era and have stood the test of time, enduring various environmental challenges. However, as resilient as they are, preserving these historic structures in the face of modern environmental threats, particularly seismic activities, requires a thorough understanding of their structural behaviour and material integrity.

The study of historic arch bridges extends beyond mere appreciation of their aesthetic and cultural value; it involves a rigorously scientific examination to ensure their longevity and safety [1,2]. Preservation efforts for such structures often leverage advanced analytical tools like SAP2000 for finite element analysis, enabling engineers and conservationists to predict how these bridges can withstand seismic forces [3]. There are many studies in the literature examining the seismic behavior of masonry bridges. Some of these studies are given below.

In their study, Altunışık et al. [4] examined the impact of arch thickness on the structural behaviour of a historical masonry arch bridge. In order to achieve this, they analysed the behaviour of the bridge under dead and live loads. The study revealed that the arch thickness affects the structural behaviour of the bridge.

Özmen and Sayın [5], conducted an investigation into the historical Dutpınar bridge's seismic resilience. The model was analysed using the acceleration records of the Bingöl earthquake that occurred in 2003 on the building model. The analysis yielded the largest and smallest shear stresses and deformations.

Sakcali et al. [6], examined the Irgandı Bridge, which has a masonry arch structure in Bursa. They created a finite element model of the structure and performed modal and linear dynamic analysis under different earthquake acceleration records. The results of the study indicated that the largest displacements were achieved in the upper part of the bridge. Additionally, the researchers observed that the largest principal stresses occurred in the support region.

Saydan et al. [7], investigated the behavior of the historical Mısırlıoğlu Bridge, a masonry arch bridge in Konya, in response to freezing and thawing effects. They determined the mechanical properties of the bridge's construction materials through experimental studies. Afterwards, they developed a finite element model of the bridge using the ANSYS program. Modal analysis was performed to explore the influence of freeze-thaw cycles on the bridge's period and mode shapes. The findings indicated a rise in the period values following the occurrence of a freeze-thaw event.

Sözen et al. [8], conducted a study on the seismic behaviour of a historical masonry arch bridge. The researchers created two models of the bridge in the ANSYS computer program: one representing the modified form and the other the original. They then performed static and time-history analyses to examine the bridge's displacements and stresses. Additionally, the study found that the bridge's stiffness increased with the change in its form.

Akin et al. [9] investigated the dynamic behavior of the historic Tağar Bridge, which is a masonry bridge, by employing various damping rates. The researchers modelled the bridge using finite element method (FEM) in the SAP 2000 software and analysed its response using earthquake acceleration records. The study assessed the stresses and displacements obtained from the analysis.

Yilmaz et al. [10] examined the seismic performance of Murat Bey Bridge. The bridge is constructed with a masonry arch structure. A finite element model of the bridge was created using the SAP2000 computer program. A modal analysis and a time-history analysis were conducted on the aforementioned model. The results of the analyses yielded the maximum stress and displacement values on the bridge. The authors indicated that the maximum compressive stresses were observed at the base of the arch, while the maximum tensile stresses were concentrated in the spandrel walls.

Çavuşlu [11] conducted a settlement creep analysis and seismic analysis of the historical Çüngüş Bridge in Diyarbakır province. The seismic analysis was based on the earthquakes that occurred in Kahramanmaraş and its surrounding areas in 2023. The results of the creep analysis indicated that the greatest damage and deformation of the bridge occurred in the arch section. The results of the seismic analysis demonstrated that the earthquakes in question significantly impacted the seismic safety behaviour of the historical Çüngüş Bridge.

Karalar and Yeşil [12] examined the effect of arch height on the static and dynamic behaviour of single-span masonry arch bridges. In their study, the researchers examined a bridge in Karabük under near-fault (NF) and far-fault (FF) ground motions. The results of the study indicated that the maximum movements decreased as the arch height of the bridge increased in response to near-fault and far-fault ground movements.

Nemutlu et al. [13], in their study, they examined the earthquake behavior of a historical masonry bridge using five different ground motion records. A nonlinear analysis was performed on the bridge. The analysis revealed the presence of tensile cracks in both the heel region of the bridge and the middle of the arch.

Ozturk et al. [14], constructed models of the historical Sultan Hamit I–II and III bridges in Erzurum using the SAP2000 program. A static analysis, modal analysis and dynamic analysis were conducted on the models under their own weight. The dynamic analysis was conducted using acceleration records from the 1992 Erzincan earthquake and the 2020 Elazığ earthquake. The results of the analysis indicated that the greatest displacement was observed in the 1992 Erzincan earthquake.

Özmen and Sayın [15], conducted a nonlinear dynamic analysis of a masonry bridge with structure-ground interaction and fixed supports in their study. The researchers employed acceleration records from the 1992 Erzincan, 2003 Bingöl and 2020 Sivrice earthquakes as the basis for their analysis. The seismic behaviour of the building was examined and compared between the structure-ground interaction model and the fixed support model. The results of the study indicated that the periods, principal stresses and displacements increased when the structure-soil interaction was taken into consideration.

Shabani and Kioumarsi [16], constructed a three-dimensional finite element model of the masonry arch bridge utilizing accelerometer sensors in accordance with the results of operational modal analysis. The effect of soil-structure interaction (SSI) on the seismic response of the bridge was also examined. Following the examinations and analyses, it was concluded that the most sensitive parts of the bridge are the middle piers and arches. They then proceeded to make recommendations regarding the reinforcement of the bridge and to develop numerical models. It was concluded that strengthening techniques had the effect of improving the seismic response of the bridge.

The investigation of the seismic performance of ancient bridges is of great importance in terms of the preservation of these structures and the transfer of knowledge about them to future generations. Turkey is situated on active fault lines and is among the regions with a high risk of earthquakes. In light of this, it is imperative to enhance the earthquake resilience of significant cultural heritage assets, particularly historical edifices. Upon examination of the current condition of the Yeşiltepe Bridge, it has been observed that structural weaknesses have occurred as a result of the natural and human-induced effects it has been exposed to over time. Consequently, it is of paramount importance to evaluate the seismic performance of the bridge, not only to ensure the structural integrity of the structure itself, but also to guarantee the sustainability of the cultural heritage it represents.

The Yeşiltepe Bridge is a structure of historical significance situated within the Çayeli district of Rize. This bridge, constructed during the Ottoman period, occupies a significant position within the cultural heritage of the region, both in terms of its architectural features and structural aesthetics. The objective of this study is to examine the multifaceted aspects of historic arch bridges, encompassing their historical and cultural significance and the technical challenges involved in their preservation. Such studies are crucial not only for maintaining the structural integrity of these bridges but also for ensuring that they continue to serve as functional components of infrastructure while preserving their historical essence. In order to achieve this objective, a nonlinear dynamic analysis of the historical Yeşiltepe Bridge in Rize will be conducted. The acceleration data of the earthquakes that occurred in Kahramanmaraş in 2023 will be employed in the dynamic analysis.

2. Historical Yeşiltepe Bridge

The Yeşiltepe Bridge is a historical arch bridge situated in the Çayeli district of Rize. The bridge is constructed from stone. The piers of the bridge, which have a width of 2.9 m and a height of 14 m, are situated on the bedrock in the stream bed. The appearance and location of the bridge are illustrated in Figure 1, while Figure 2 depicts the geometric features of the bridge.

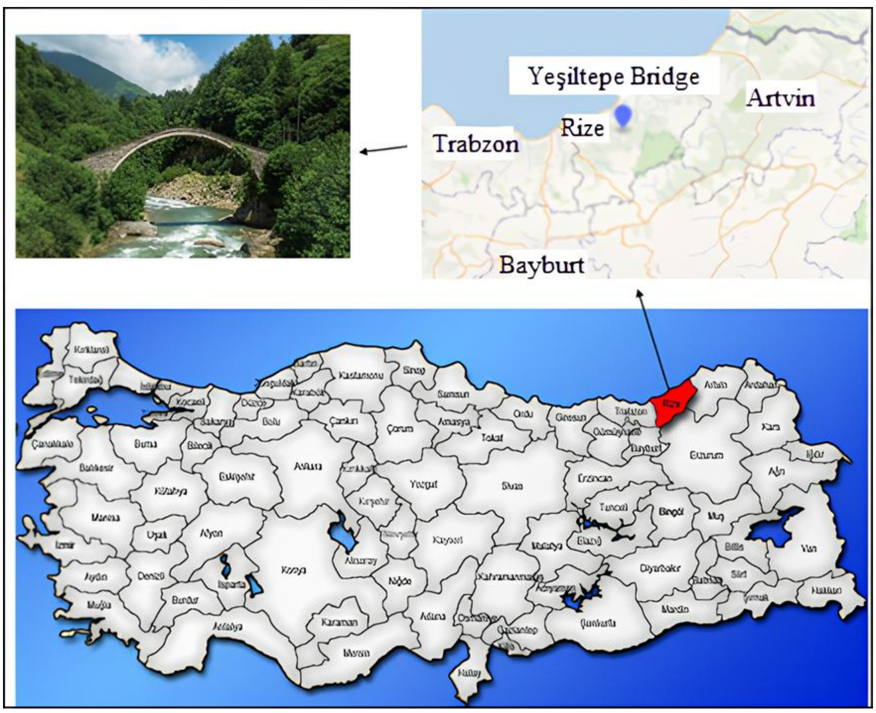


Figure 1. Location and appearance of the bridge.

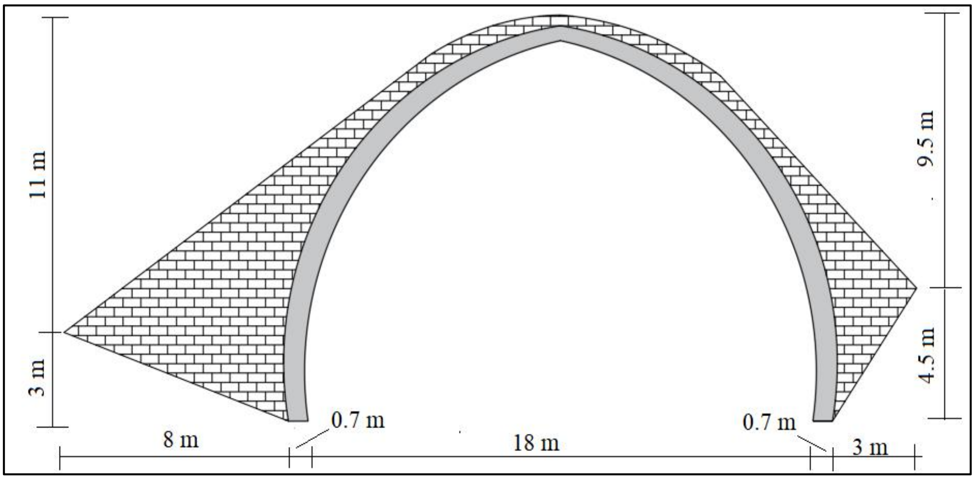


Figure 2. The dimensions of the historic bridge.

Choosing material properties accurately is crucial in analysing historical structures. The precise determination of material properties is of great importance for the theoretical analysis of structures with a long history, such as historical bridges. Due to the difficulties in determining the material properties of these structures, existing studies in the literature were examined to determine the relevant material properties [13,17,18]. Table 1 presents the fundamental physical and mechanical properties of the materials under consideration in this research. Additionally, Figure 3 depicts the axial stress-strain graphs utilized in the SAP2000 analyses of masonry materials.

Table 1. Properties of the material used [13,17,18].

Material	Modulus of Elasticity (MPa)	Poisson's Ratio	Density (kN/m^3)
Stone	3500	0.25	22

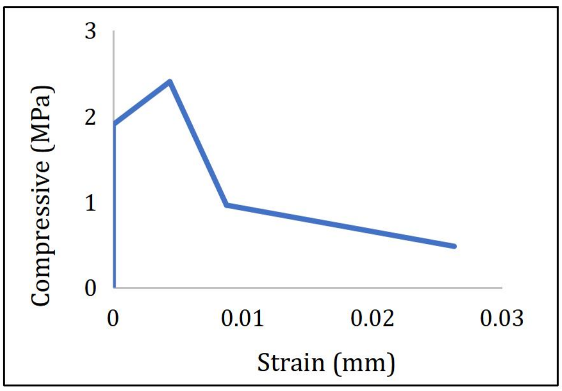


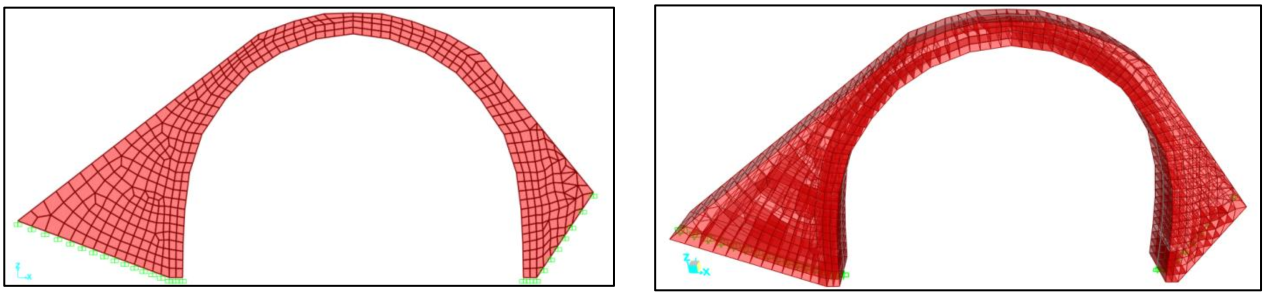
Figure 3. Nonlinear material properties of the stone [13,17].

3. Finite Element Model of the Bridge

For the engineering analysis and design of the Yeşiltepe Kaptanpaşa Bridge, a three-dimensional (3D) model was created using the SAP2000 program. SAP2000 is a powerful analysis and design software widely used in the field of civil engineering. A detailed analysis was carried out using this programme, taking into account the geometry of the bridge, the material properties and the loading conditions.

The 3D model of the bridge was created using the finite element method. The finite element mesh allows the analytical modelling of different sections and components of the bridge. A total of 528 nodes and 460 shell elements were used in the model. Nodes represent specific points on the bridge, while shell elements represent the surface and structural elements of the bridge. These elements are used to analyse the bearing capacity, deformations and stresses of the bridge.

Fixed support conditions are provided in the areas where the bridge is in contact with the ground. Fixed support refers to the points where the foundation of the bridge is firmly connected to the ground. These points limit the horizontal and vertical movement of the bridge, increasing the stability and durability of the structure. Fixed supports ensure the safety and longevity of the structure by preventing the bridge from shifting and rotating. The finite element model of the Yeşiltepe Bridge is given in Figure 4.



(**a**) Two-dimensional view. (**b**) Three-dimensional view.

Figure 4. The finite element model of the Yeşiltepe Bridge.

4. Seismic Parameters

Acceleration records of two previous earthquakes in Turkey were used to determine the dynamic behavior of the masonry arch bridge. Earthquake data regarding the location of the bridge and the DD-2 earthquake ground motion level defined in the Turkish Building Earthquake Regulation 2018 [19] were obtained from the Turkey Earthquake Hazard Map interactive web application [20]. The obtained earthquake data are shown in Table 2. Table 3 contains information about the earthquake used in the seismic analysis. In Table 3, PGA shows the maximum ground acceleration, while PGV shows the maximum ground speed.

Table 2. Earthquake data [20].

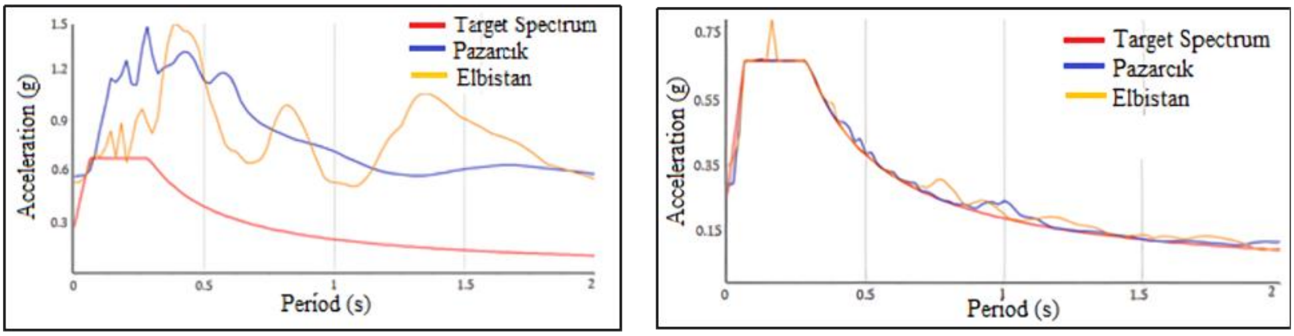
Parameter	Definition	Value
Earthquake Ground Motion Level	Earthquake ground motion level with 10% probability of exceedance in 50 years (recurrence period 475 years)	DD2
Ground Class	Medium firm to firm layers of sand, gravel or very solid clay	ZC
S_s	Short period map spectral acceleration coefficient	0.562
S_1	Map spectral acceleration coefficient for a 1-second period	0.129

Table 3. The Earthquake used in the analysis [21,22].

Earthquake	Component	Station	Magnitude	Original		Matched	
				PGA (g)	PGV (cm/s)	PGA (g)	PGV (cm/s)
Pazarcık	East-West	Pazarcık	7.7	0.56724	127.49302	0.29797	52.07612
Elbistan	East-West	Nurhak	7.6	0.53075	72.50548	0.35227	59.63471

Upon examination of Table 3, it was observed that there was a notable decline in PGA and PGV values following the matching process. For instance, the PGA values for the Pazarcık and Elbistan earthquakes decreased by 47.47% and 33.63%, respectively, following the matching process. The PGV values decreased by 59.15% and 17.75%, respectively.

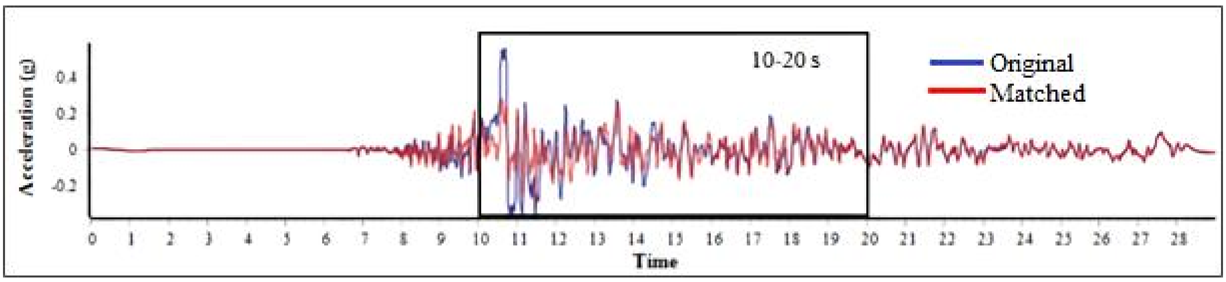
The SeismoMatch program was used to facilitate the matching process of the area close to the arch bridge. The original and matched response spectra obtained from the SeismoMatch program are shown in Figure 5, and the original and matched acceleration records are shown in Figure 6. To reduce the analysis time, the 10–20 s interval of the Pazarcık earthquake acceleration record and the 30–40 s interval of the Elbistan earthquake acceleration record were used.



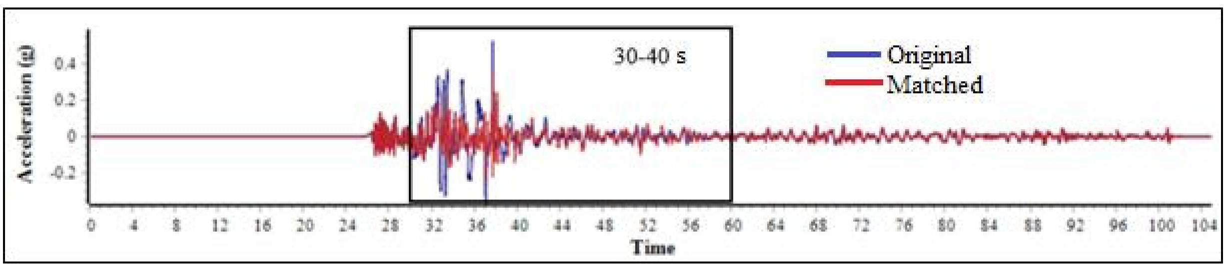
(**a**) Original.

(**b**) Matched.

Figure 5. Original and matched response spectra [22].



(**a**) Pazarcık earthquake.



(**b**) Elbistan earthquake.

Figure 6. Original and matched acceleration records [22].

5. Results and Discussion

5.1. Modal Analysis

Mode shapes play a significant role in the dynamic behaviour of arch bridges. The damping ratio was chosen as 5% for the modal analysis. While performing modal analysis, solutions were made for 50 modes. The mass participation rates obtained for some modes as a result of modal analysis are shown in Table 4. The initial six mode shapes and period values derived from the modal analysis are presented in Figure 7.

Table 4. Mass participation ratios.

Mode	Period (s)	Mass Participation Ratio		
		x direction	*y* direction	*z* direction
1	0.084	0.000	0.478	0.000
2	0.049	0.000	0.498	0.000
3	0.034	0.000	0.739	0.000
4	0.025	0.000	0.739	0.000
5	0.021	0.276	0.739	0.001
6	0.020	0.276	0.834	0.001
45	0.005	0.577	0.977	0.408
46	0.005	0.577	0.977	0.408
47	0.005	0.577	0.977	0.408
48	0.005	0.577	0.977	0.408
49	0.005	0.577	0.978	0.408
50	0.004	0.577	0.980	0.408

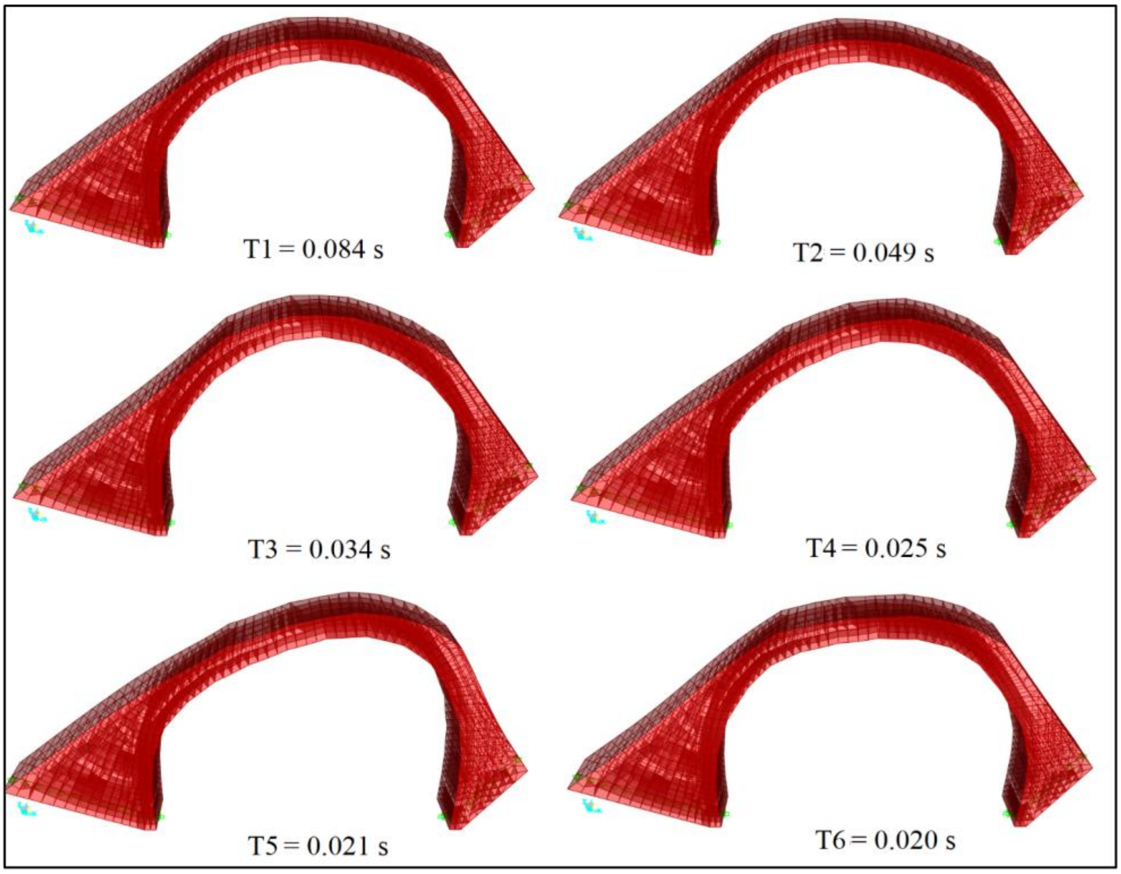


Figure 7. First 6 mode shapes and period values.

Upon examination of Figure 8, it becomes evident that the bridge will be subjected to the greatest acceleration values if its period falls within the range of 0.06–0.3 s. Since the period of the bridge is in this range, it will be exposed to the highest acceleration values.

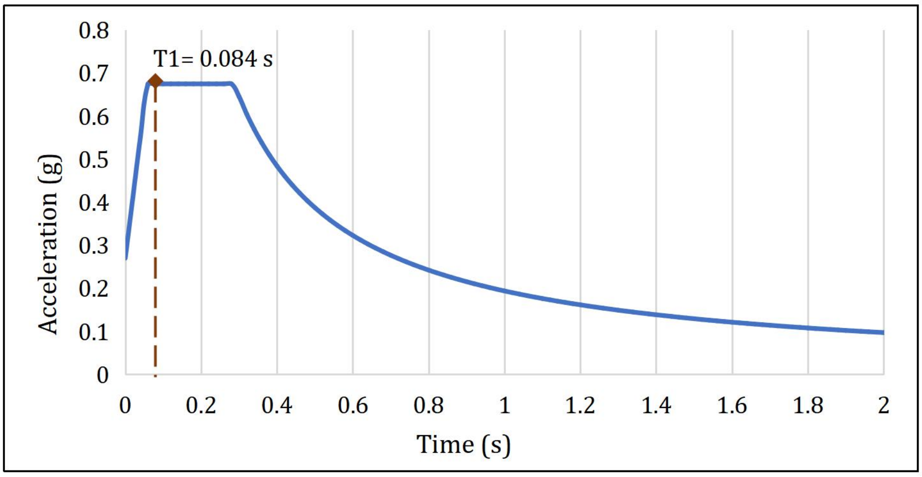


Figure 8. Design spectrum.

5.2. Time History Analysis

To investigate the seismic behaviour of the historical bridge, nonlinear time history analyses were performed in the SAP2000 program using the acceleration records of the earthquakes given in Table 3. As illustrated in Table 4, the highest mass participation rate of the first mode was observed in the *y* direction. Consequently, time history analyses were conducted solely in the *y* direction (width direction).

Figure 9 illustrates the largest base shear forces obtained in the *y* direction as a result of the time history analysis.

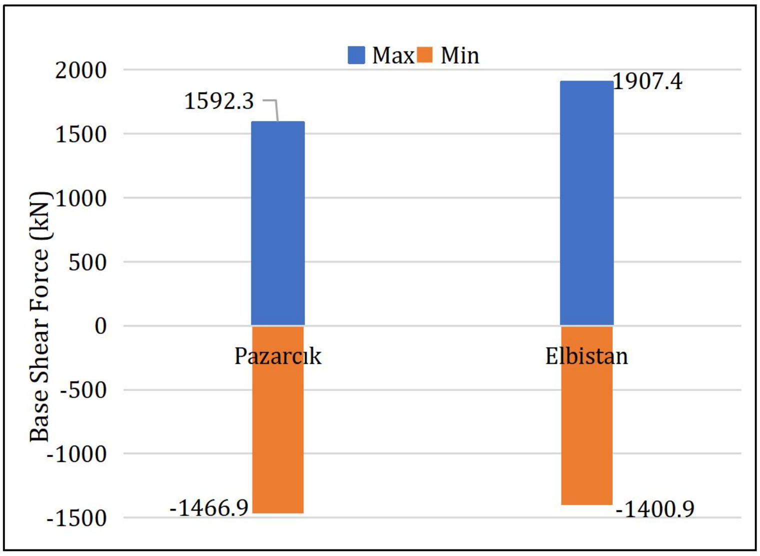


Figure 9. Base shear forces.

As illustrated in Figure 9, the Elbistan earthquake was responsible for the largest base shear force. The greatest base shear force obtained from the Elbistan earthquake is 20% greater than the base shear force obtained from the Pazarcık earthquake.

Figure 10 illustrates the time-dependent change in displacements in the *y* direction at the peak resulting from both earthquake loadings.

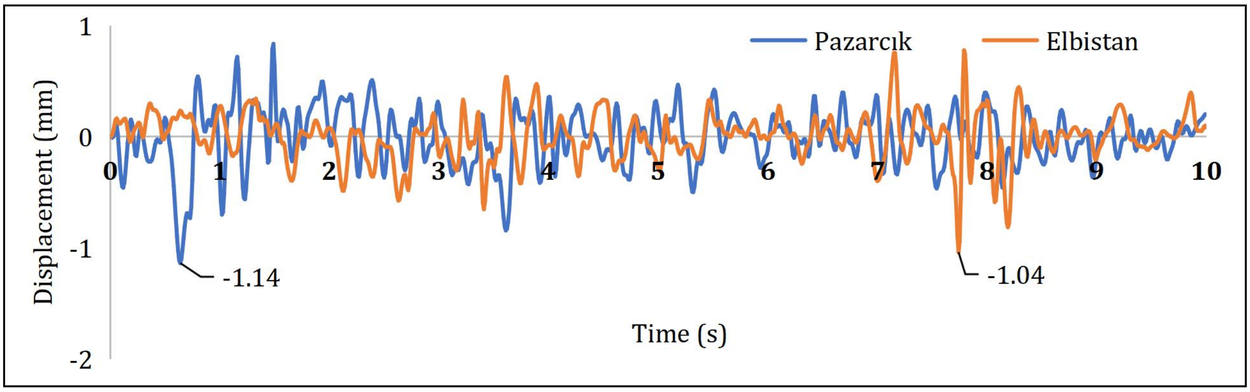
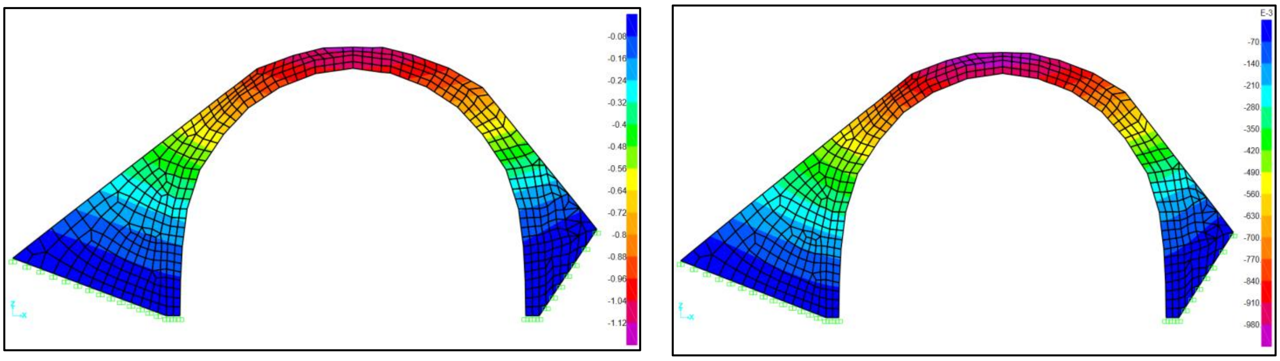


Figure 10. Time - displacement graph.

As illustrated in Figure 10, the greatest displacement values in the *y* direction, as determined by time history analyses, were 1.14 and 1.04 mm for the Pazarcık and Elbistan earthquakes, respectively. Given the bridge's considerable rigidity in the *y* direction, it is anticipated that the displacements will be relatively minimal.

Figure 11 illustrates the displacement contours obtained for the Pazarcık and Elbistan earthquakes as a result of time history analysis.



(**a**) Pazarcık earthquake. (**b**) Elbistan earthquake.

Figure 11. Displacement contours (mm).

As illustrated in Figure 11, the magnitude of displacement increased with height in response to both earthquake loading scenarios. While comparable contours were obtained as a result of both earthquake loadings, the highest displacement values were obtained from the top point of the bridge.

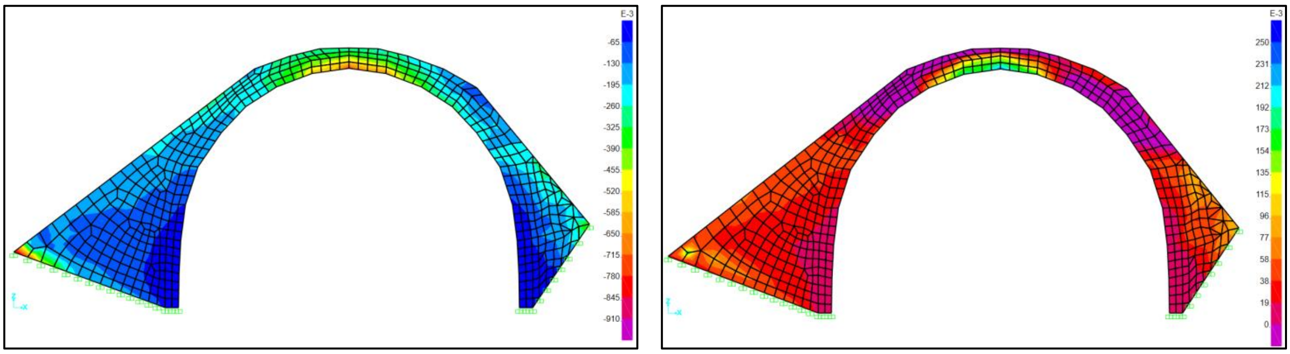
Table 5 presents the maximum stress values on the bridge resulting from time-history analyses for the Pazarcık and Elbistan earthquakes.

Table 5. Maximum stress values.

Earthquake	**Stress (MPa)**		
	Compressive	**Tensile**	**Shear**
Pazarcık	0.938	0.249	0.546
Elbistan	0.961	0.288	0.515

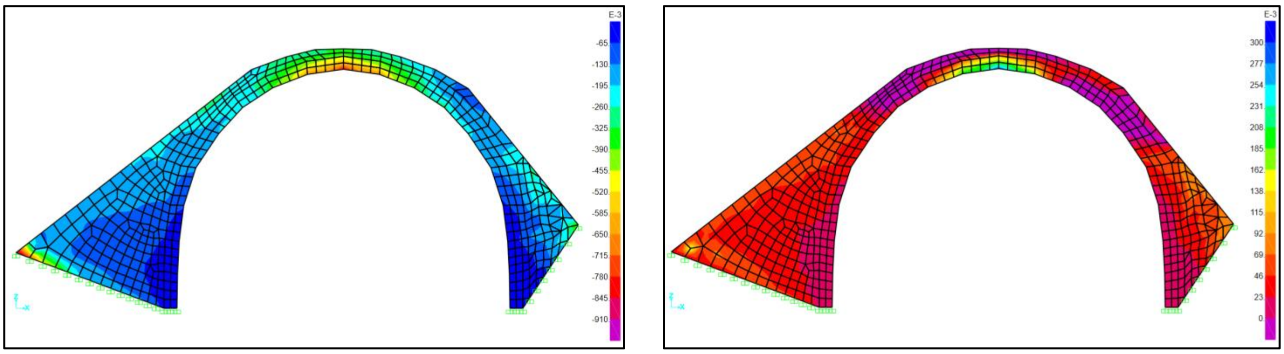
Upon comparison of Table 5 with Figure 3, it is evident that the highest compressive stress experienced within the bridge structure does not exceed the compressive strength of the stone. However, the tensile stress exceeds the tensile strength of the stone. Consequently, damage to the bridge may occur in areas where tensile stresses accumulate.

Figures 12 and 13 illustrate the normal stress contours obtained for the Pazarcık and Elbistan earthquakes, respectively, as a result of time-history analyses.



(**a**) Compressive stress (MPa). (**b**) Tensile stress (MPa).

Figure 12. Pazarcık earthquake normal stress contours.

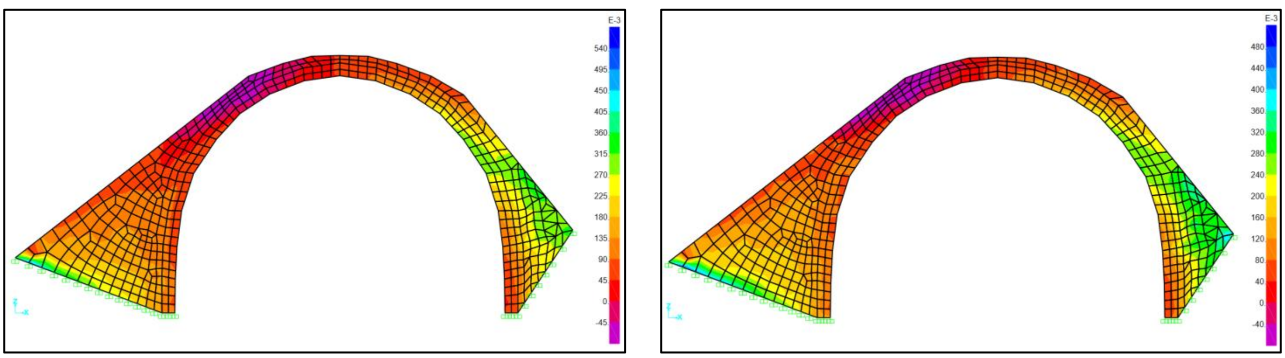


(**a**) Compressive stress (MPa). (**b**) Tensile stress (MPa).

Figure 13. Elbistan earthquake normal stress contours.

As illustrated in Figures 12 and 13, the compressive stresses reached their greatest values in the upper parts of the arch and the edge supports of the bridge, while the tensile stresses were concentrated in the upper parts of the arch, as a consequence of both earthquake loads.

Figure 14 illustrates the shear stress contours resulting from both earthquake loadings.



(**a**) Pazarcık earthquake. (**b**) Elbistan earthquake.

Figure 14. Shear stress contours.

As illustrated in Figure 14, comparable shear stress contours were generated as a consequence of both earthquake loadings. And the shear stresses reached their maximum values at the edge supports of the bridge as a consequence of both earthquake loadings.

6. Conclusions

The present study examined the seismic behaviour of the historical Yeşiltepe Bridge. In order to achieve this, a finite element model of the bridge was created in the SAP2000 computer program. A modal analysis and a nonlinear time-history analysis were conducted on the aforementioned model. In the time-history analyses, acceleration records of two major earthquakes that occurred in Kahramanmaraş in 2023 were utilised.

The following results were obtained from the modal analysis.

- The first period of the bridge was calculated to be 0.084 s. This period value corresponds to the largest acceleration values in the design spectrum.

The following results were obtained from the time history analysis.

- It was determined that the largest displacement values occurred at the top of the bridge as a result of both earthquake loadings.
- As a result of the Elbistan earthquake loading, a 20% greater base shear force occurred compared to the Pazarcık earthquake.
- Upon examination of the maximum stress values occurring on the bridge, it was observed that for both earthquakes, the compressive stresses were below the compressive strength of the stone, while the tensile stress exceeded the tensile strength of the stone. Consequently, it is postulated that in the event of a potential earthquake, damage may occur in areas where tensile stresses are concentrated.
- Upon examination of the regions where the stresses reach their highest values, it becomes evident that the upper parts of the arch and the edge supports of the bridge are particularly susceptible to damage.

When the results obtained are evaluated, the authors make the following recommendations.

- Carbon fiber reinforced polymer (CFRP) strips can be applied to areas of the bridge subject to tensile stresses. CFRP strips have high tensile strength and can help the bridge better absorb tensile stresses. In addition, reinforcement can be made using steel plates in areas where tensile stresses are concentrated, especially in the upper parts of the arch and the edge supports of the bridge. These plates can reduce the stresses exceeding the tensile strength of the stone, making the structure more durable.
- The authors recommend that the above-mentioned strengthening methods be implemented in computer programs, taking into account the structure-soil interaction in future studies.

Author Contributions

P.U.E.: Conceptualization, supervision, methodology, writing—review & editing, project administration. A.E.S. and E.Ş.: methodology, writing—review & editing.

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Data Availability Statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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