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Structural Performance Assestment of Historical Dilovasi Sultan Suleyman (Diliskelesi) Bridge in Turkey

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Abstract - Masonry arch bridges are regarded as the oldest examples of engineered structures in the world and they reflect the culture of previous civilizations with their various sizes, styles, and spans. These bridges were constructed centuries ago addressing the load-carrying problems of old times. The preservation of these structures receives a great deal of attention in the structural engineering community. In this respect, current study focuses on historical Dilovası Sultan Suleyman (Diliskelesi) Bridge in Kocaeli, Turkey. In order to investigate the structural behavior of the current form of the bridge, Modal and Response Spectrum analyses were carried out utilizing finite element methods.

Keywords: *Masonry arch bridges, Dilovası Sultan Suleyman (Diliskelesi) Bridge, Modal Analysis, Response Spectrum Analysis, Finite Element Method*

1. Introduction

Many masonry bridges have been built in earthquake prone regions of the world and a large portion of them are not seismically safe. Historical arch bridges, encompassing various sizes, styles, and spans reflect the cultures of the previous civilizations. As such, they constitute an important part of the cultural heritage in the world, hence their preservation for the next generation is crucial. Indeed, several of these structures which are over 2000 years old, are already vital components of transportation systems in many communities (Sevim et al. 2011). As a consequence of the long history of arch bridges, many samples exist around the world. Figure 1 provides a typical detail of various components making up a masonry arch bridge. Individual components have their own names that are universally accepted as the terminologies used to identify these components. An essential understanding of the structural behavior of masonry arch bridges requires information about their structural elements.

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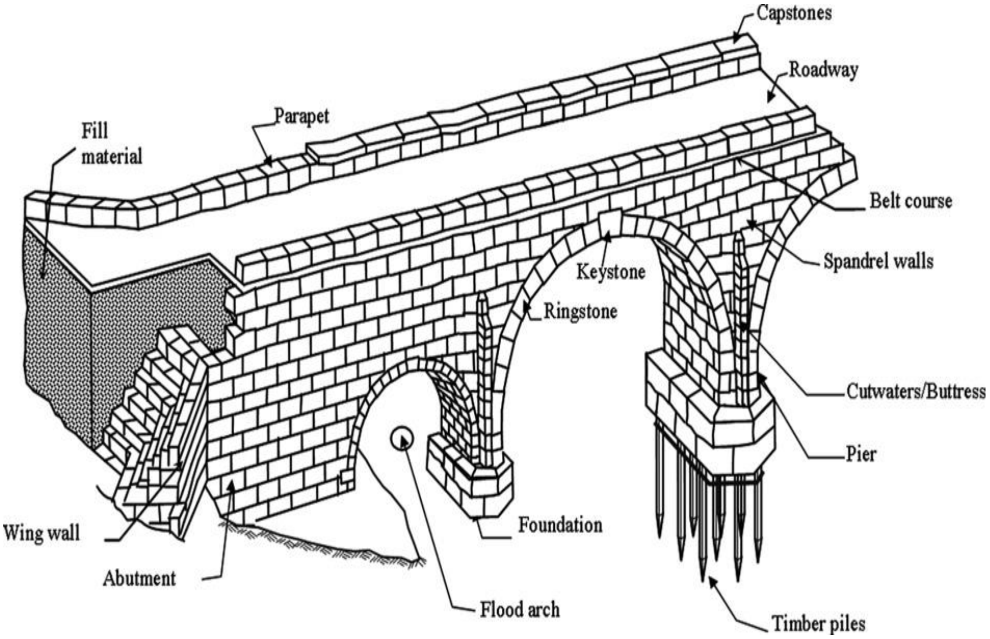

Figure 1: Main components of a masonry arch bridge (Ural et al. 2008)

2. Seismic Behavior of Masonry Bridges

Masonry arch bridges are exposed to many different external and internal effects throughout their lives. An understanding of the load carrying capabilities of these bridges and an estimation of the type and intensity of load on them would be beneficial in order to better understand the performance of these bridges and how they have been able to survive the changes in the loading regime. The fact that many masonry bridges have been able to keep up with these loads and changes is a testimony to the complexity of their structural behaviors. Major loads on masonry bridges are dead loads, live loads, lateral loads, and water and earth forces. Lateral loads are horizontal loads acting on the structures and might be the most dangerous loads for masonry bridges. The most common lateral load is due to earthquake which has a dynamic nature. An earthquake load is a function of the mass of the structure and the intensity of the ground acceleration. Since the nature of earthquakes is random, the timing of the occurrence and the magnitude of the corresponding loads due to earthquake is uncertain. Therefore, the potential damaging effects of earthquakes may become more severe than those of the wind loads. Masonry bridges have large masses due to heavy construction materials such as stones, bricks and mortars. Thus, earthquake load significantly affects masonry bridges. The heavy mass increases the intensity of the force on the bridge. At the same time, the ancient masonry structures lack the structural ductility that is needed to perform well during earthquakes. As a result, the masonry bridges are vulnerable to earthquakes and seismic effects have been among the most important reasons for collapse among masonry bridges. Earthquake loads originate from ground shaking and formation of seismic waves which usually have two major components -- horizontal and vertical. Recent research shows that the horizontal waves are more dangerous than the vertical waves on masonry structures; and many ancient and newer masonry structures have been destroyed due to horizontal waves (Meyer, 2006). According to the reports on earthquake damages on masonry bridges, earthquake damages are observed in the spandrels (Figure 2) or the superstructures (Figure 3) (Cakir and Seker, 2015; Cakir, 2011).

Figure 2: Collapse of spandrel of a masonry bridge during the 1997 Umbria-Marche earthquake

Figure 3: Damages occurred in superstructure of the Misis Bridge during the 1998 Adana-Ceyhan earthquake (Ural et al. 2008)

3. Historical Dilovası Sultan Suleyman (Diliskelesi) Bridge in Kocaeli

Kocaeli is one of the oldest settlements of Anatolia, which is located in the Marmara Region in Turkey. Established at the intersection of a major road and rail routes between Asia and Europe, Kocaeli is one of the most important industrial sites in the Marmara Region today (Figure 4). The history of Kocaeli dates back to much older times. In the early ages, the region was called Bithynia and different cities were established in the region throughout the history named Olbia, Astakos, Nicomedia, Iznikmid, Izmit and Kocaeli respectively. Due to its historical background, Kocaeli is primarily a cultural destination; it has a rich cultural heritage. One of the well-known historical structures in the region is Dilovası Sultan Suleyman (Diliskelesi) Bridge. Since the bridge is located in socially and culturally active areas, it is intensely used in the present day.

Figure 4: Map of Turkey (Adapted from Google Maps)

Dilovası Sultan Suleyman (Diliskelesi) Bridge, ordered by Kanuni Sultan Süleyman and built by Architect Sinan in the 16th century, is 45 meters long. The structure is located on a creek with the same name in the Dilovasi district of Kocaeli. The bridge has a small evacuation eye at the end of the middle belt opening which is 10.60 meters. The relatively smaller arches on both sides of the large arch in the middle are made of limestone cut in sharp forms (Kantaratlas, 2018). The keystone of the belt is placed outwardly (Figure 5).

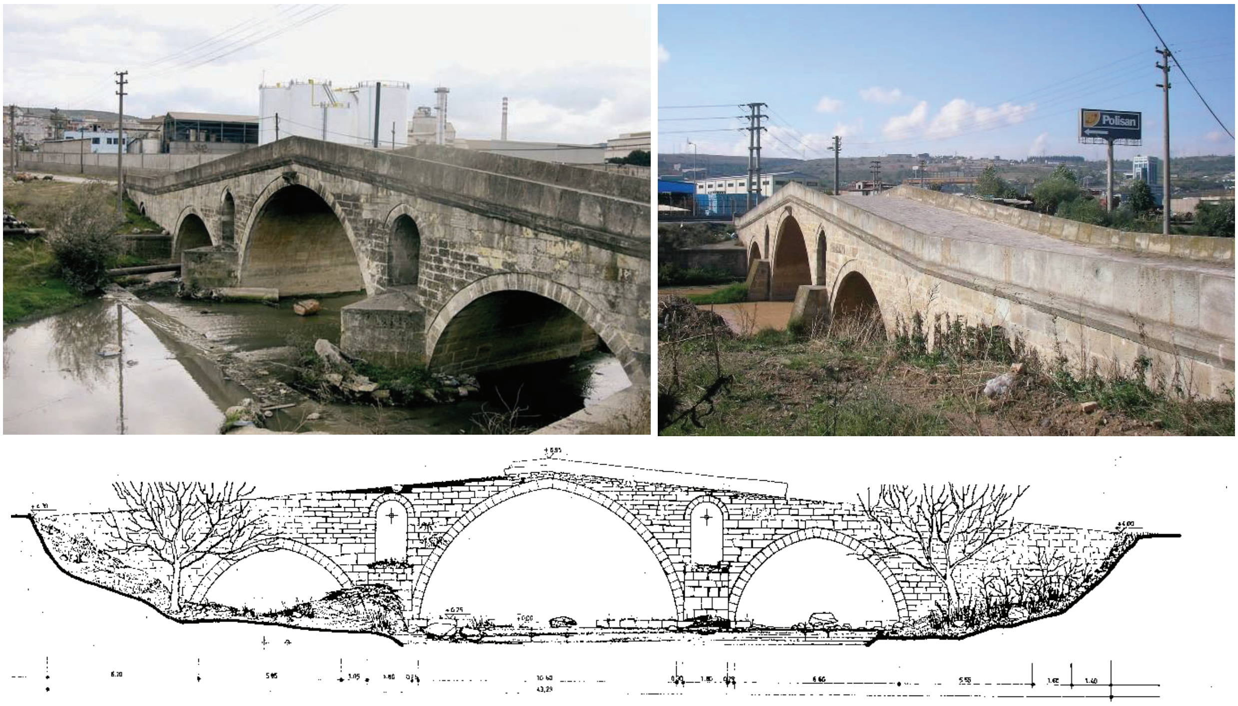

Figure 5: Dilovası Sultan Suleyman (Diliskelesi) Bridge (Kantaratlas, 2018; Şükür, 2008)

4. Structural Performance Assessment of historical Dilovası Sultan Suleyman (Diliskelesi) Bridge

In this study, firstly, the numerical model was prepared using finite element analysis (FEA) program, ANSYS Workbench (2017). In the modeling process, SOLID 65 elements, which have eight nodes and three degrees of freedom per node, was preferred for the description of the bridge. The three-dimensional model was discretized with 317025 nodes and 188775 solid elements (Figure 6). Modal Analysis and Response Spectrum Analysis (RSA) were performed on the numerical model. The obtained analyses results were too complicated to present each node or element, therefore, contour pictures, bars, and scale tables were used to present the results of the analyses. Moreover, fixed boundary conditions were considered in the foundation sections and sidewalls. The mechanical properties used in all numerical analyses are summarized in Table 1 (Cakir and Seker, 2015; Cakir and Uysal, 2014; Cakir et al, 2014).

Table 1: Mechanical properties of the materials

Component of Structure	Young Modulus (MPa)	Poisson's Ratios	Density (kg/m3)
Arches	10000	0.25	2500
Spandrel	8500	0.25	1850

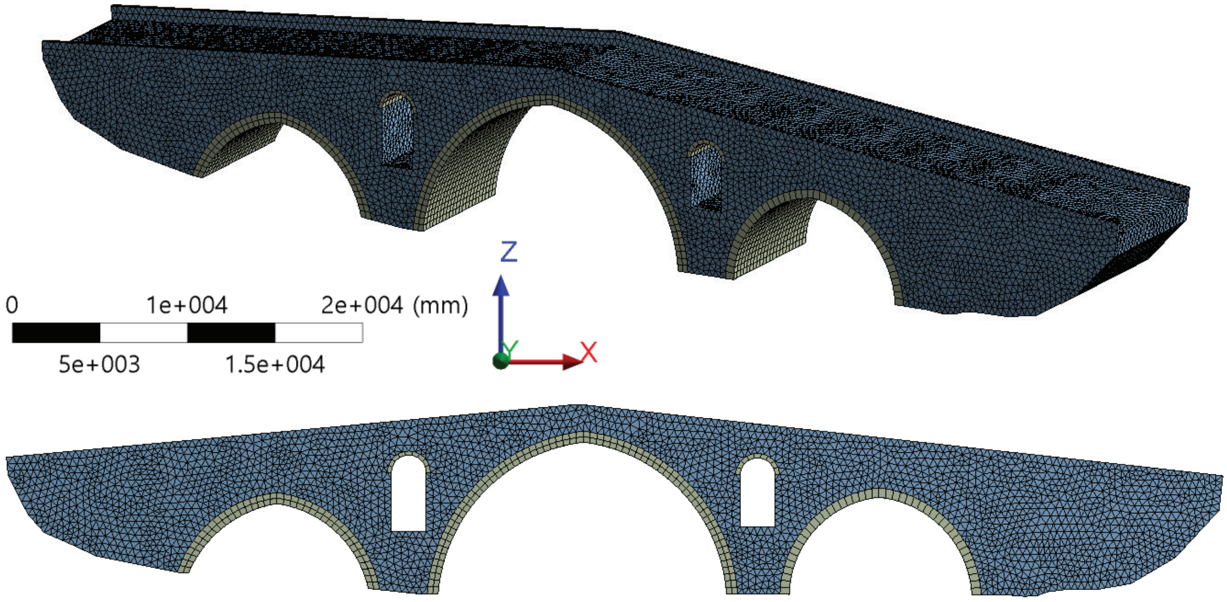

Figure 6: Numerical model of the bridge

The modal analysis of vibration is simply used to determine mode shapes and characterizing resonant frequencies. Modal analysis changes from a multiple degree of freedom problem to a vibration problem. In the dynamic analysis of the bridge, primarily mode shapes and mode vibration periods were determined; the first four mode frequencies, periods, and mass participation ratios were summarized in Table 2. Furthermore, the first six mode shapes were shown in Figure 7.

Table 2: The first six mode frequencies, periods, and mass participation ratios

Mode	Frequency (Hz)	Period (s)	Ratio Eff. Mass To Total Mass X Direction	Ratio Eff. Mass To Total Mass Y Direction	Ratio Eff. Mass To Total Mass Z Direction
1	21.1240	0.47340E-01	0.116013E-08	0.327952	0.281701E-08
2	29.7189	0.33649E-01	0.143925E-08	0.138867E-02	0.388626E-09
3	31.7833	0.31463E-01	0.429338	0.123221E-08	0.846705E-04
4	36.8151	0.27163E-01	0.146073E-10	0.210250	0.259064E-06
5	37.7064	0.26521E-01	0.200814E-03	0.404817E-06	0.967770E-01
6	47.1976	0.21188E-01	0.244307E-02	0.330740E-10	0.877093E-01

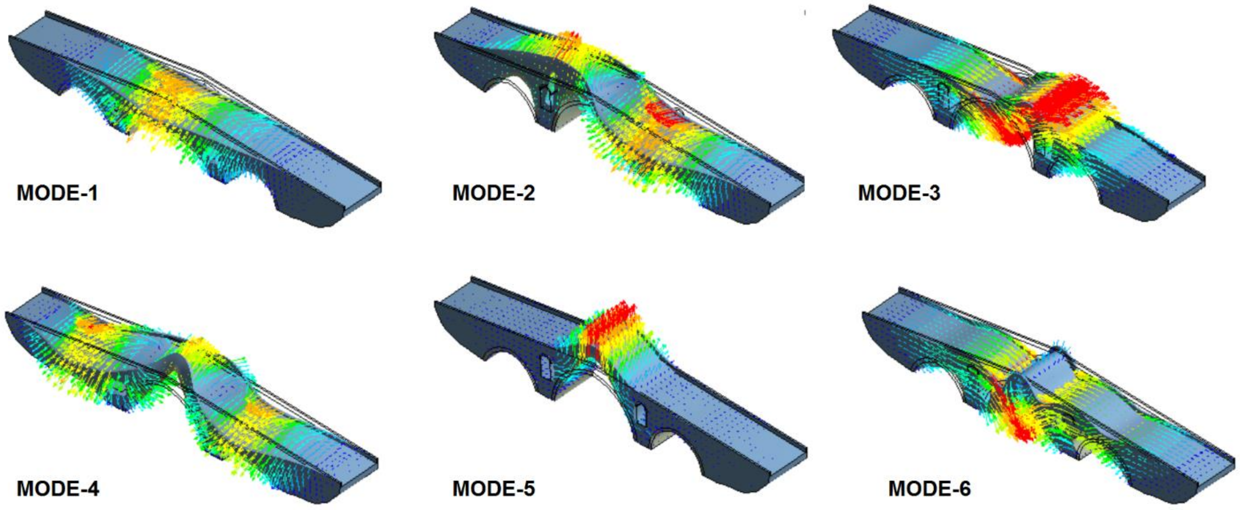

Figure 7: The first six mode shapes

The seismic performance of the bridge was also investigated through RSA conducted on the finite element model in horizontal direction. The response spectrum corresponding to the seismic hazard level was selected by using Turkey's New Earthquake Hazard Map (Figure 8). The simulated ground records for the 475 year return period (the possibility to be exceeded in 50 years is 10%) were used in the evaluation of the bridge.

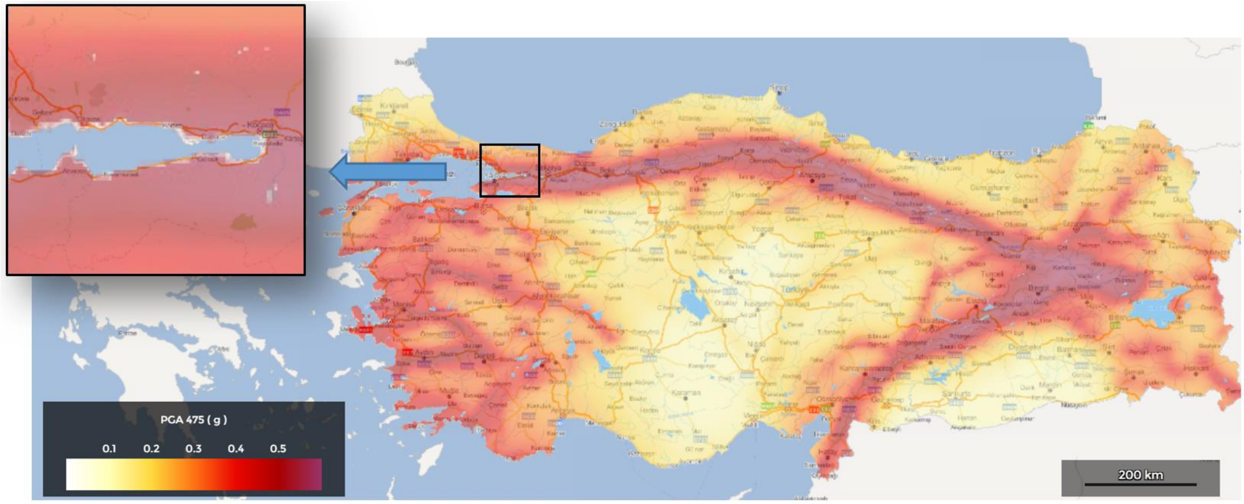

Figure 8: Earthquake Regions Map of Turkey and Kocaeli

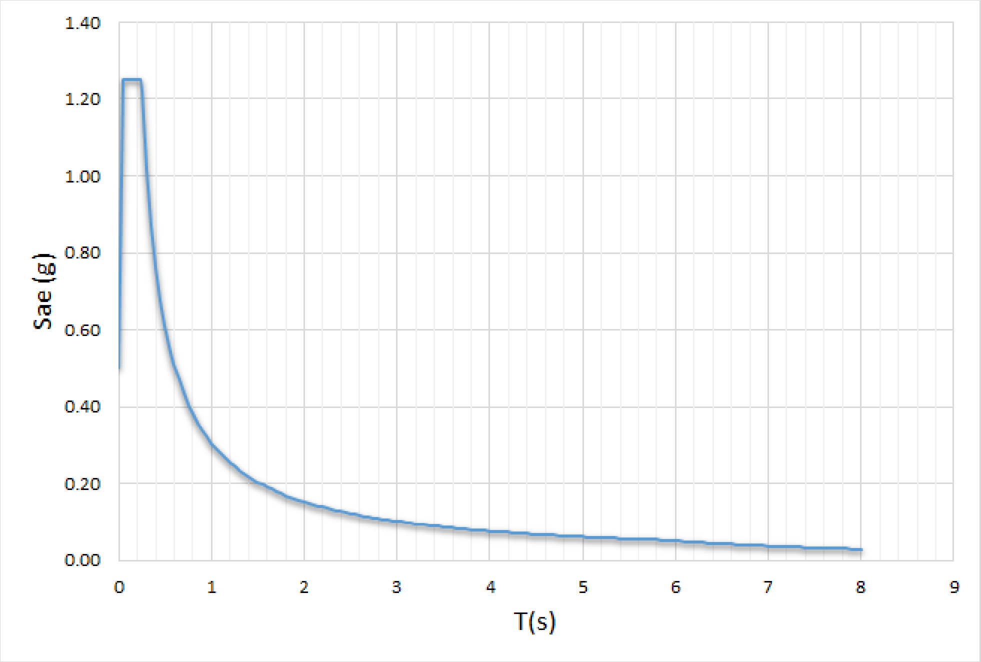

Figure 9: Uniform hazard spectra for the selected seismic hazard level.

The maximum normal stress was found to be 3.6997 MPa around the base section of the small arch of the bridge (Figure 10). The obtained equivalent stress was about 3.0595 MPa around the bridge base (Figure 11). Moreover, the observed maximum lateral displacement was about 1.4514mm at the top of the bridge corresponding to 0.02% drift ratio (Figure 12). Table 3 indicates that at this drift ratio level, the structural response of the bridge is below the immediate occupancy (IO) damage level (0.1%). In the light of the obtained information, it is seen that the structure is quite good in terms of earthquake performance.

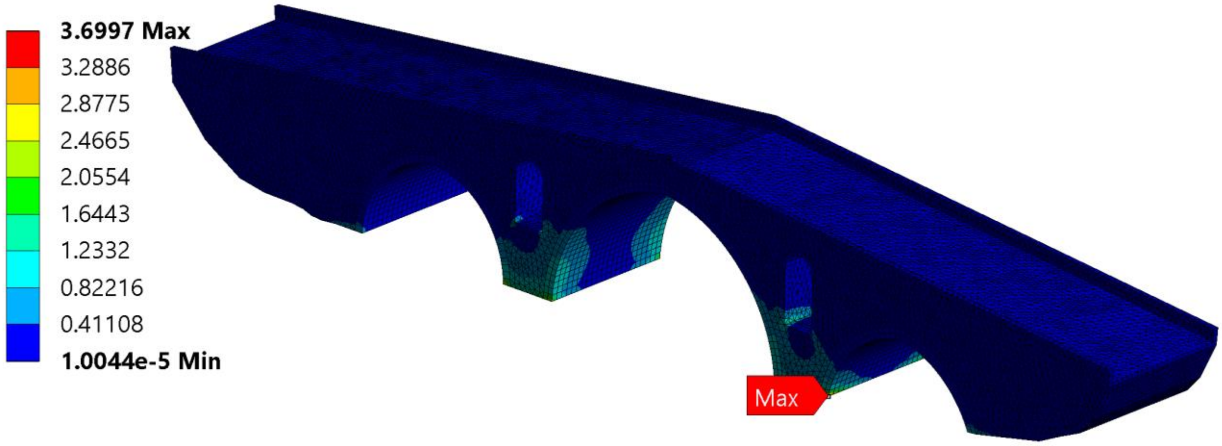

Figure 10: Normal stress obtained from the RSA

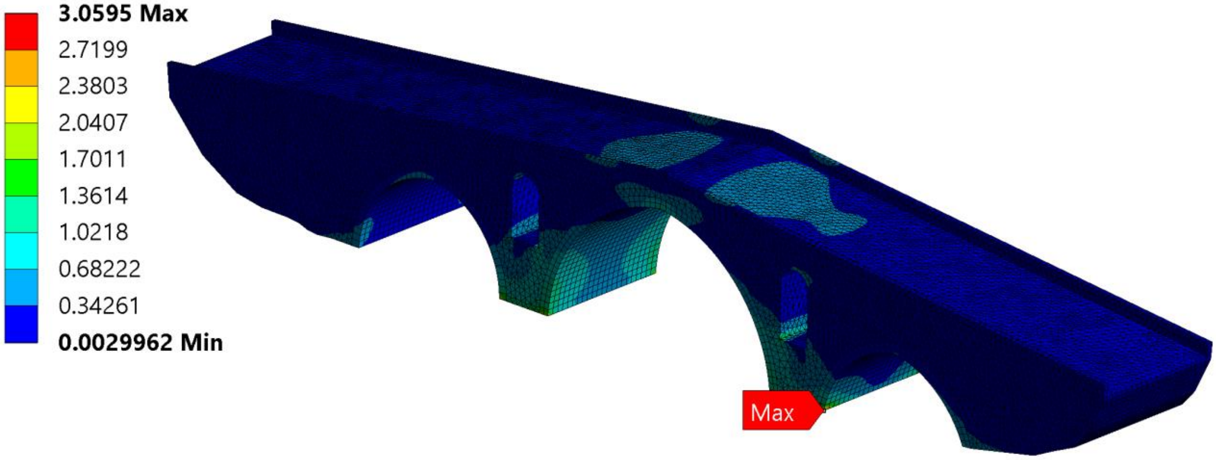

Figure 11: Equivalent stress obtained from the RSA

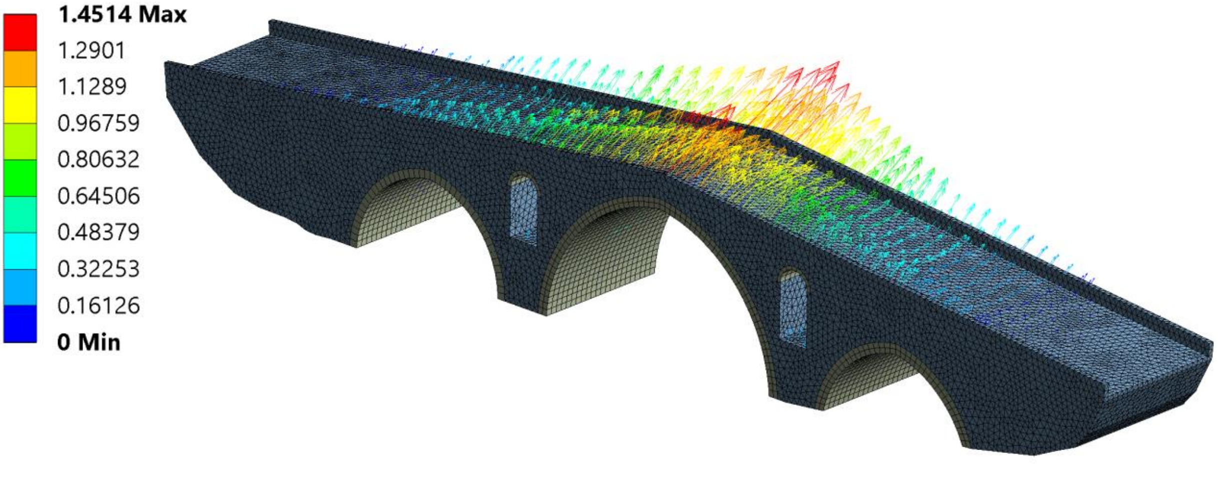

Figure 12: Maximum lateral displacement obtained from the RSA

Table 3: Acceptance criteria for unreinforced masonry in-plane walls and piers

		Primary members			Secondary members	
	Limiting behavioral node	Immediate occupancy (IO) (%)	Life safety (LS) (%)	Life safety (LS) (%)	Life safety (LS) (%)	Life safety (LS) (%)
FEMA 356	Bed-joint sliding	0.1	0.3	0.4	0.6	0.8
FEMA 274	Rocking	0.1	$0.3h_{eff}/L$	$0.4h_{eff}/L$	$0.6h_{eff}/L$	$0.8h_{eff}/L$
ASCE 41	Rocking	0.1	$0.3h_{eff}/L$	$0.4h_{eff}/L$	$0.6h_{eff}/L$	$0.8h_{eff}/L$

5. Conclusions

Historical structures that are built centuries ago reflect the previous civilizations which have passed the world. Today, it is still possible to see some of these structures as a whole. These magnificent structures need to be well protected and preserved due to their historical and cultural values. Many historical structures are located at earthquake prone zones in the world, and the majority of these structures are considered to be seismically inadequate and unsafe. Historical bridges face many inadequacies in terms of seismic performance. Thus, they have to be retrofitted with the convenient restoration methods against earthquake damages. To determine the structural protection requirements for these structures, a deep understanding of their behavior and an effective evaluation of the structural integrity and failure mechanism is needed. The subject of earthquake hazard assessment of a historical structure has gained great attention in the last few decades. A sustained effort on the subject is strongly needed.

This paper briefly investigates the basic principles to be considered in performance-based seismic evaluation of historical structures. The seismic performance evaluation of the historical Sultan Suleyman (Diliskelesi) Bridge in Kocaeli, Turkey is presented. RSA was used for the performance evaluation. The seismic hazard levels, evaluation of existing seismic hazard, selection of earthquake ground motions as well as site geology, geological and tectonic settings of the area, seismic activity of the region and local soil conditions are needed for a thorough evaluation. The results of the analyses show that the critical stresses are calculated in the base section of the bridge and arch. It is also detected that the supports of the arches that carry the spandrel of the bridge deserve special attention since they have a considerable effect in the structural performance.

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