



Journal of Materials and Engineering Structures

Research Paper

Seismic Behaviour of a Single Span Historical Masonry Bridge

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ARTICLE INFO

Article history:

Received : 6 January 2023

Revised : 12 April 2023

Accepted : 29 April 2023

Keywords:

Masonry arch bridge

Finite element model

Near and far-fault ground motion

Seismic behavior

ABSTRACT

A major portion of the cultural heritage consists of old structures that are susceptible to earthquakes. These structures are prone to significant damage from natural disasters, particularly earthquakes. This study's primary goal is to assess the historical masonry bridge's seismic response to strong far-fault ground motions (FFGM) and near-fault ground motions (NFGM). The historical Sultan Suyu Masonry Bridge is used as a case study in this study. It was created with three-dimensional finite element software. The time history response of the bridge model is contrasted with one another in terms of stresses and displacements produced for FFGM and NFGM. The assessments take into account the FFGM and NFGM of the 1999 Düzce, 1999 Kocaeli, and 1992 Erzincan earthquakes, which had nearly equal peak ground accelerations. The results show that FFGM is equally significant as NFGM and that FFGM could be used in conjunction with NFGM to further evaluation of historical masonry arch bridges.

1 Introduction

Historical structures, i.e., churches, mosques, towers, or bridges, are one of the most important cultural heritages that connect the past to the present. They have been built for different purposes, and they have social, cultural, and economic traces of the period where they were built. Some of them kept up their stability until today without any restoration, but most of them are in a poor situation. There are many dangerous factors for historical structures, such as floods, human vandalism, and earthquakes. One of the primary factors contributing to the loss of cultural heritage is probably earthquakes. Assessment tasks that enable comprehension of the history and discussion of the structures' current condition must be completed to conserve historical structures [1]. Historical masonry bridges are one of these historical structures. Arches are the main structural form for masonry structures and bridges. It was used to span large distances and usually subjected to compressive forces because of its geometric form. Different cultures and civilizations used various arch forms for both functional and decorative purposes. Some of the preliminary examples of arches dating back to 3000 BC were found in the

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Sumerian underground tombs located in Mesopotamia [2]. Masonry arch bridges have an important percentage in European railway networks, and approximately 65% of these bridges are older than 100 years. Because of its geographic location and cultural heritage, Turkey has many historical structures and stone masonry arch bridges. Most of the historical stone bridges seen in Anatolia, Turkey, were built as single span during the Ottoman period. Decay of materials, a persistent lack of maintenance, and loading that is not suitable for the period in which they were built affect masonry arch bridges [3]. Approximately 1300 of these bridges are still in service [4]. It is important to protect these structures and transfer them safely into the future. Past earthquakes have shown that these structures are vulnerable to seismic events. In order to safely transfer the historical masonry bridges to future generations, their structural behavior should be known. To investigate the seismic behavior of masonry bridges, different studies were conducted in the literature. However, there are limited examples of the effects of NFGM and FFGM on the seismic behavior of stone-masonry bridges. A larger velocity pulse defines NFGM. In this case, a large amount of energy is created in the structures at the beginning of the ground motion, which might greatly increase structural damage. Smaller pulse velocities are caused by FFGM, which usually generates a resonance effect in medium- to high-rise buildings [5-7]. Different engineering structures including tunnels, nuclear power plants, buildings, bridges and dams were evaluated in regards to NFGM and FFGM in recent studies. Akköse and Şimşek [8] assessed the seismic response of a concrete gravity dam subjected to NFGM and FFGM, taking into account interactions between the dam, water, sediment, and foundation rock. They obtained that the seismic response of the concrete gravity dam subjected to NFGM is greater than that of those subjected to FFGM. Akkar et al. [9] used 145 NFGM to estimate the maximum interstory drift and maximum ground story for general moment-resisting frame behavior. Adanur [10] selected the Fatih Sultan Mehmet and Boğazici Bridges in Istanbul, Turkey, as numerical examples. They investigated the earthquake performance under the NFGM and FFGM effects. These bridges were compared with displacements and internal forces for each fault effect. Zhang and Wang [5] examined the effect of NFGM and FFGM earthquake records on the seismic behavior of a concrete-weight type dam. They selected the Koyna gravity dam for numerical application. The results derived from the analyses showed that the NFGM had a more serious effect on the dam than the FFGM. Sevim et al. [11] investigated the effects of NFGM and FFGM on the seismic behavior of an Ottoman historical masonry arch bridge with numerical and experimental methods. They compared displacements and stress results obtained from NFGM and FFGM. Analysis results indicated that NFGM causes higher seismic demand for both displacements and stresses compared to FFGM. Moreover, Simos et al. [12] stated that FFGM is more destructive than its NFGM counterpart in their study on long span masonry stone bridges. Güllü and Karabekmez [13] examined the impacts of NFGM and FFGM earthquakes on the seismic responses of a historical stone masonry mosque with the help of soil-structure interaction (SSI) analysis and a fixed base solution. They used four different earthquake acceleration records for the analysis. After the analyses, they reported that FFGM caused high oscillations when compared to NFGM. They suggested that FFGM can be considered together with NFGM when determining the earthquake behavior of historical mosques. Özmen and Sayın [7] investigated the seismic behavior of multi-span masonry arch bridges under NFGM and FFGM earthquakes. They used four different earthquake acceleration records in the dynamic analyses. Altunışık et al. [14] evaluated two severely damaged historical masonry mosques and investigated the earthquake behavior of these mosques according to the NFGM and FFGM. For this purpose, two devastating earthquake acceleration records (the 2011 Van earthquakes) were used for linear time-history analyses. At the end of the study, they showed that both FFGM and NFGM have significant effects on historical structures based on their earthquake properties.

The aim of this study is to investigate and compare the seismic behaviour of masonry arch bridges subjected to NFGM and FFGM excitations. The numerical assessments are performed on the historical Sultan Suyu masonry bridge in Malatya, Turkey. The masonry bridge is generated using a three-dimensional (3D) finite element model. Dynamic analyses of the bridge are performed for NFGM and FFGM using the ground motion records of the 1999 Düzce, 1999 Kocaeli, and 1992 Erzincan earthquakes.

2 Near and Far-Fault Ground Motions

A ground motion with a significant velocity pulse is a characteristic of NFGM, as evidenced by recent large earthquakes. At the onset of the earthquake, this condition significantly increases the energy input to structures [6, 13, 15-17]. Structures exposed to NFGM tend to experience higher degrees of damage, resulting in larger property and life losses [11]. One of the significant characteristics of NFGM is the pulse-type feature. However, FFGM arises as a response to smaller pulse velocities. Due to the resonance effect, the periods could cause structural damage in medium to high structures [13, 18]. In this research, NFGM is defined by three points: ground motion records acquired around faults with

obvious velocity pulses (pulse period > 1.0 s), distances of faults of ground motion records (< 10 km), and peak ground velocity/peak ground acceleration ($PGV/PGA > 0.1$ s). These points for NFGM were used in past studies in the literature [10, 11, 14]. A comparison of strong NFGM and FFGM is demonstrated in Fig. 1.

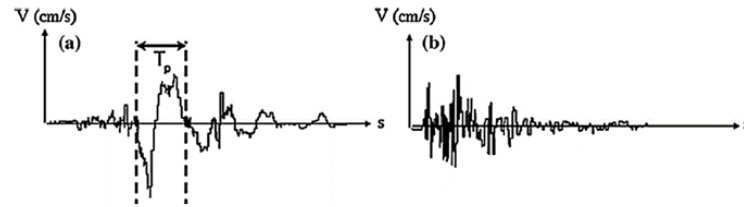


Fig. 1 – The time-histories of strong ground motion velocities.
(a). near-fault strong ground motion (b). far-fault strong ground motion [9]

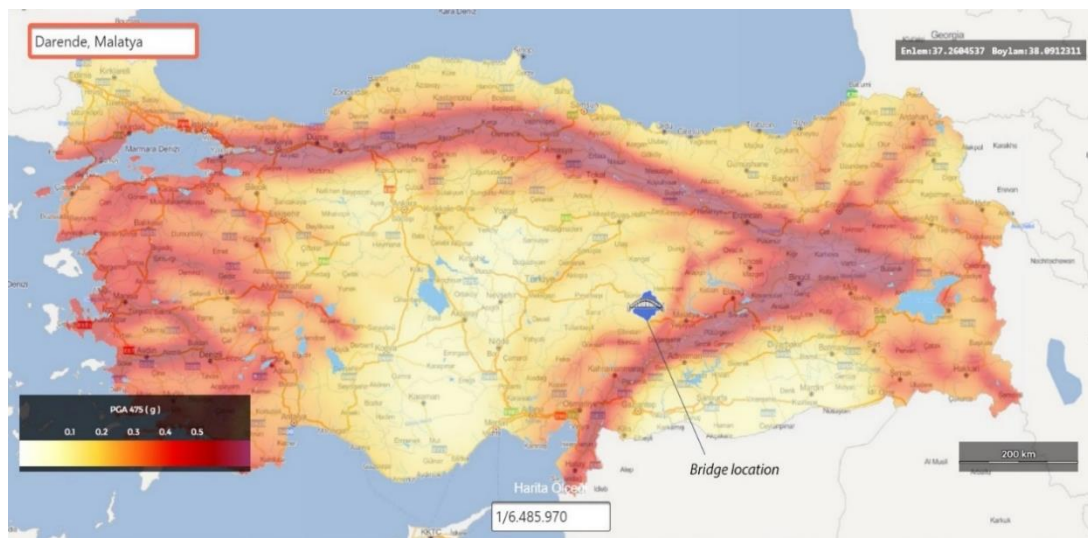


Fig. 2 – Interactive earthquake hazard map of Turkey and location of the bridge

Table 1 – Selected near and far-fault ground motion records

Fault For Strong Ground Motion	Earthquake Name	Record Station	Scale factor	V_{s30} (m/s)	PGA (g)	PGV (cm/s)	PGV/PGA (s)	M_w	Distance to Fault (km)
Near-Fault	1999 Düzce	Düzce	0.34	281.86	0.18	19.04	0.11	7.14	0.00
Far-Fault	1999 Düzce	Bolu	0.23	293.57	0.17	11.36	0.07	7.14	12.02
Near-Fault	1999 Kocaeli	Yarımca	0.71	297.0	0.17	76.01	0.46	7.6	1.38
Far-Fault	1999 Kocaeli	Düzce	0.47	281.86	0.15	35.32	0.24	7.6	13.6
Near-Fault	1992 Erzincan	Erzincan	0.36	352.05	0.18	19.65	0.11	6.69	0.00
Far-Fault	1992 Erzincan	Tercan	1.93	320	0.17	79.12	0.47	6.69	65.34

In this paper, NFGM and FFGM records of 1999 Düzce, 1999 Kocaeli, and 1992 Erzincan were used in the analysis. These records were scaled with Seismomatch software [19] taking into account the location of the bridge based on the Interactive Earthquake Hazard Map of Turkey. Fig. 2 shows the Interactive Earthquake Hazard Map of Turkey and the site of the Sultan Suyu Bridge.

Selected NFGM and FFGM records used in this research are given in Table 1. Amplitudes (acceleration, velocity, and displacement) of the selected NFGM and FFGM are given in Figs. 3–5. These figures show that NFGM is significantly different from FFGM in terms of velocity pulses. NFGM has a long-period velocity pulse compared to FFGM. Also, response spectra were obtained considering the bridge location for the design earthquake, which represents a 10%

exceedance probability in 50 years (475-year return period) according to the 2018 Turkish Earthquake Code [20]. Figure 6 displays the response spectra of the selected earthquakes and the earthquake code.

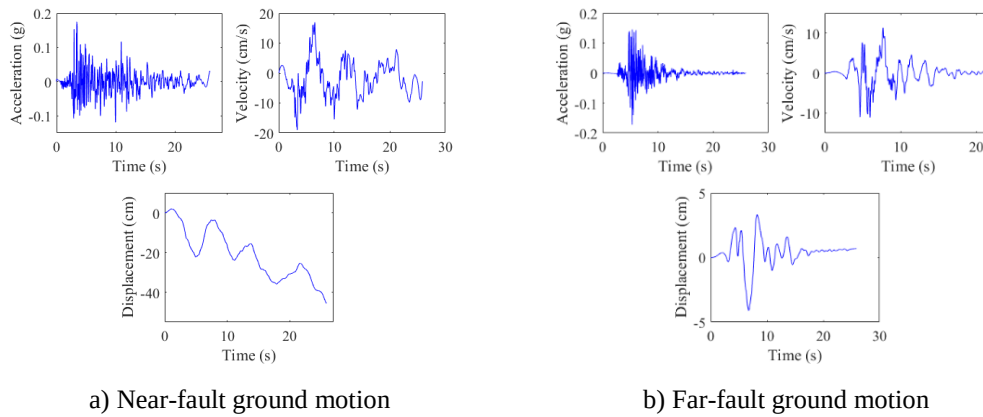


Fig. 3 - Ground motion records of 1999 Düzce earthquake

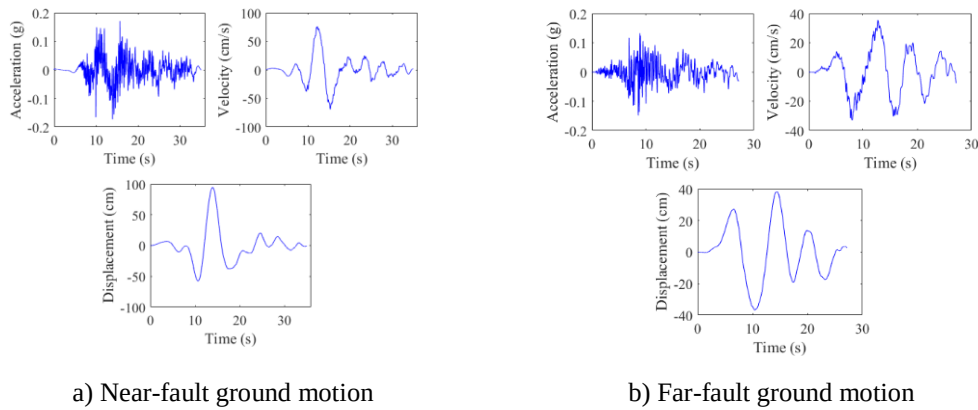


Fig. 4 – Ground motion records of 1999 Kocaeli earthquake

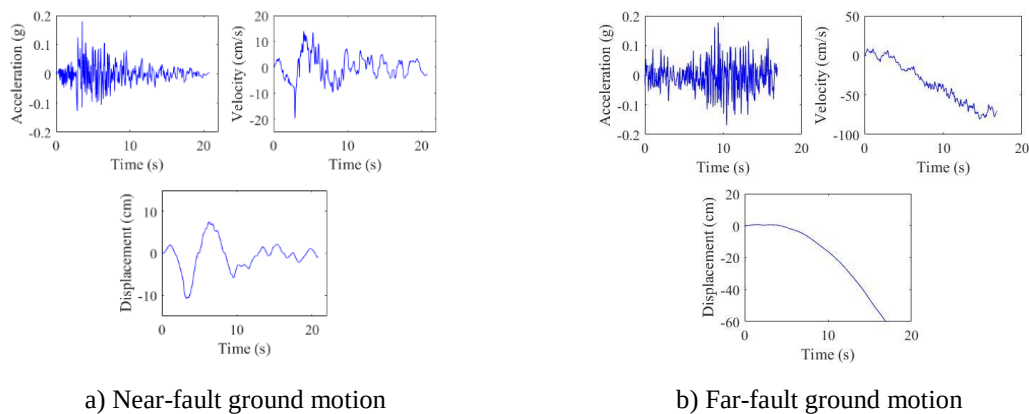


Fig. 5 - Ground motion records of 1992 Erzincan earthquake

3 Sultan Suyu Bridge

Masonry bridges are part of the architectural and cultural heritage. Also, they are an invaluable part of the railway and road networks in the countries [21]. The case study structure, the historical masonry arch Sultan Suyu bridge, is in Darende, which is the town of Malatya, Turkey. The bridge dates from the Ottoman Empire period. It has one arch. It is 24 meters

long, 6 meters in width, 8 meters in height and has a span of 12 meters. The bridge has 0.50 meters thick side walls and an arch. The bridge is open to vehicle and pedestrian traffic today. Sultan Suyu bridge can be seen in Fig. 7. Also, the geometrical characteristics of the bridge are given in Fig. 8.

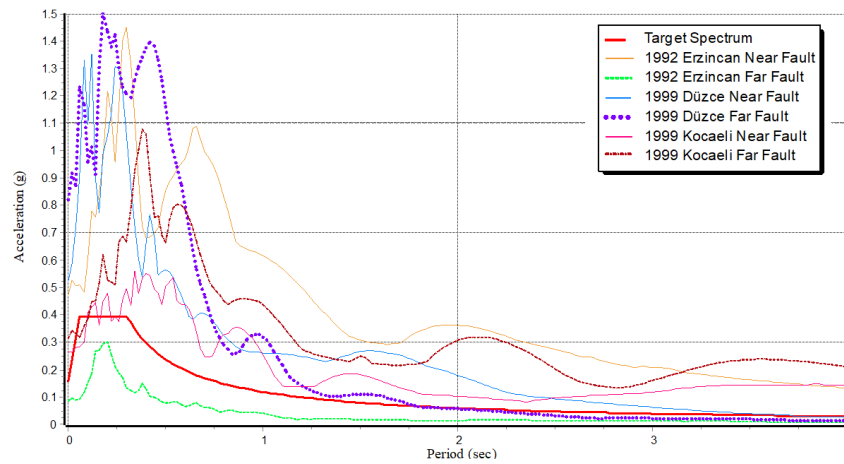


Fig. 6 – Response spectra of the selected ground motions and earthquake code



Fig. 7 – Different views of historical Sultan Suyu Bridge

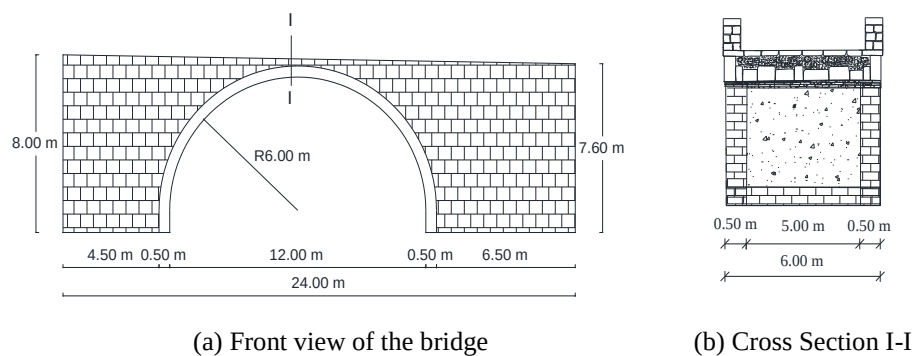


Fig. 8 – Geometrical properties of the bridge.

4 Numerical modeling and analysis

There are several modeling approaches for masonry structures; nonetheless, three of them are widely employed for these structures' finite element modeling. These approaches are macro modeling, simplified micro modeling, and detailed micro modeling (Fig. 9). It is chosen based on the size of the structure and the level of precision. The material characteristics of the masonry units and mortar are used one by one in the detailed micro modeling and are coupled to one

another using interface/contact elements. This approach demands high computational effort. In the simplified micro-modeling, the mortar layer is disregarded, and the masonry units are separated from one another through the interface lines. The mortar layer and masonry units are not separated in the macro-modeling approach. They are considered to be a single composite material. These modeling methodologies can be used depending on the required level of simplicity and accuracy [3, 22]. Because of the low computing effort, macro-modeling is suitable to generate finite element models of large-scale structural models [23–27]. Therefore, this approach was used in many research studies [28–33]. The bridge was modeled in three dimensional and dynamic analyses were done using ANSYS software [34]. The macro modeling method was considered in the analysis. The finite element model of the bridge was built with 2556 nodes and 10629 solid elements. The 3D finite element model of Sultan Suyu Bridge and considered nodal point (2489) is shown in Fig. 10.

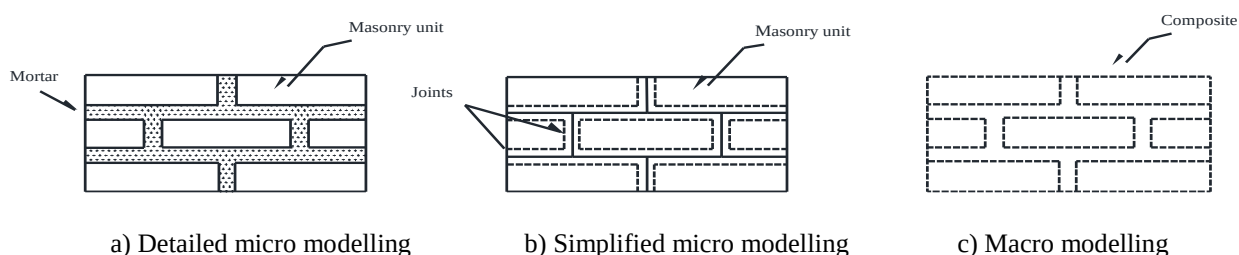


Fig. 9 – Modeling approaches for masonry structures [22]

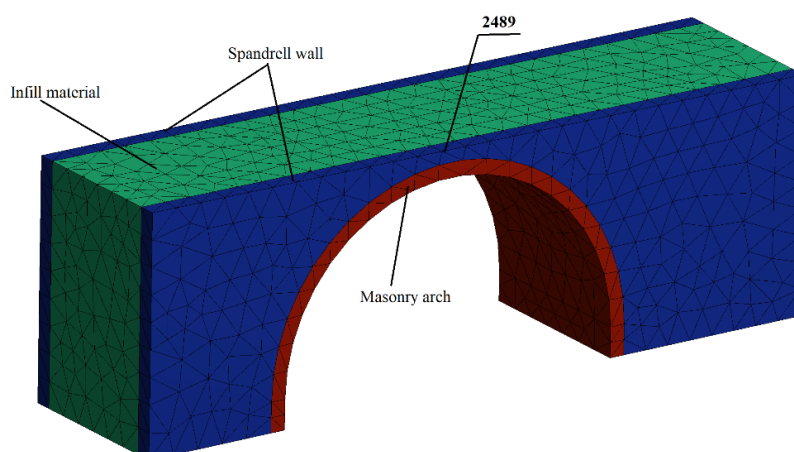


Fig. 10 – Three-dimensional finite element model of the bridge and selected nodal point

Table 2 – Material properties of masonry arch Sultan Suyu Bridge

Material	Elasticity modulus (kN/m ²)	γ (t/m ³)	ν	f_t (MPa)	f_c (MPa)	c (MPa)	ϕ (°)
Arch	3E6	1.6	0.25	1.5	15	-	-
Spandrel walls	2.5E6	1.4	0.20	1.5	15	-	-
Filler material	1.5E6	1.3	0.05	-	-	0.35	40

The bridge is supported by a rock layer, and therefore, the boundary conditions were defined as fixed at the foundation level in the finite element model of the bridge. The 3D finite element model of the bridge uses the SOLID186 element, which is characterized by twenty nodes, each having three degrees of freedom. This element has been used in many studies that examined the behavior of masonry structures in the past [35, 36]. The SOLID186 element can exhibit different types of mechanical behavior, such as elasticity, plasticity, large deflection, stress stiffening, and large strain capabilities [34]. Determining the material properties of historical structures is not an easy task, and taking test samples from these structures can be inconvenient due to their importance and sensitivity. The material properties of the Sultan Suyu Bridge, including Poisson ratio, unit weight, elasticity modulus, and compressive strength, are presented in Table 2, which were obtained

from relevant studies in the literature [37-40]. Additionally, based on earlier findings, it was considered that the tensile strength of stone is equal to one-tenth of its compressive strength [13, 37, 41].

Table 3- Comparison of maximum absolute displacements of the selected nodal point

Earthquake	x direction (mm)	y direction (mm)	z direction (mm)
1992 Erzincan near fault	0.018	0.59	0.17
1992 Erzincan far fault	0.028	0.63	0.19
1999 Kocaeli near fault	0.026	0.68	0.22
1999 Kocaeli far fault	0.019	0.54	0.16
1999 Düzce near fault	0.023	0.62	0.18
1999 Düzce far fault	0.026	0.63	0.21

5 Results and Discussion

The convergence of the Arabian, African, and Eurasian plates is one of the seismically active zones on the globe, and Turkey is positioned there. Historical structures may be subjected to NFGM and FFGM in seismically active regions. In this paper, 3 NFGM and 3 FFGM earthquake records were utilized to analyze NFGM and FFGM effects on historical bridges. Dynamic analyses of the masonry arch Sultan Suyu bridge exposed to both NFGM and FFGM were evaluated. The Rayleigh damping constants were calculated for a 5% damping ratio. In Fig. 11, the displacement values along the bridge length were compared for the 1999 Düzce, 1999 Kocaeli, and 1992 Erzincan NFGM and FFGM. Fig. 11 showed that maximum displacement values were obtained for the 1999 Kocaeli NFGM earthquake records. The displacement values for the 1999 Düzce earthquake derived from the NFGM and FFGM earthquake records are quite close to each other. In addition, the displacement values achieved for the 1992 Erzincan FFGM earthquake were higher than the displacement of the near-fault records of the same earthquake.

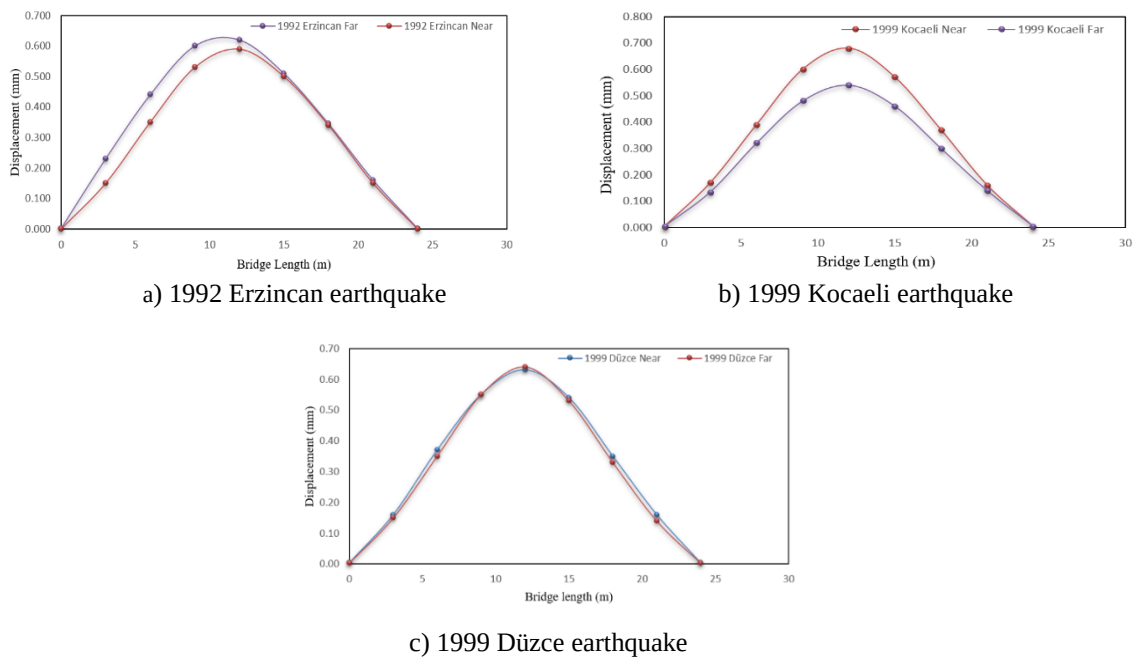


Fig. 11 – Displacement along the bridge length

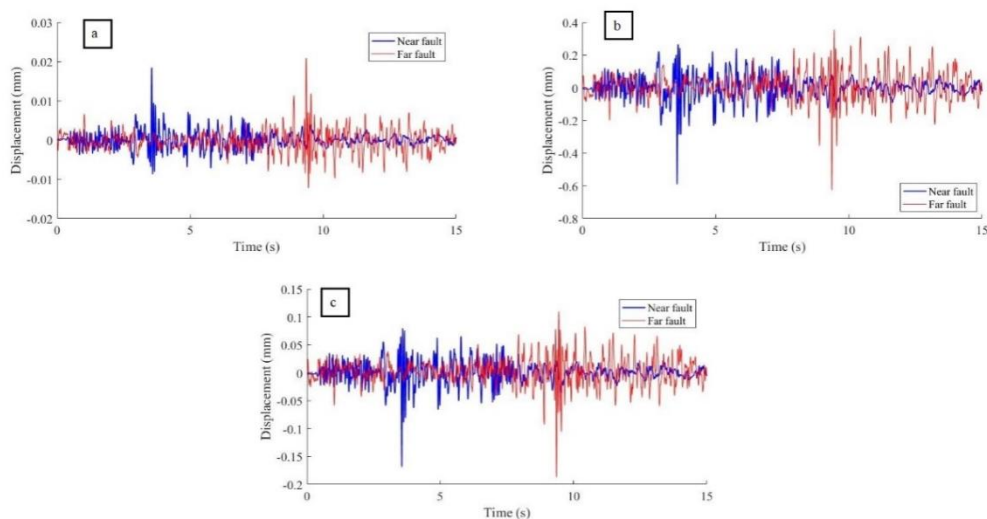


Fig. 12 – Time histories of nodal point 2489 for 1992 Erzincan earthquake a) x direction b) y direction c) z direction

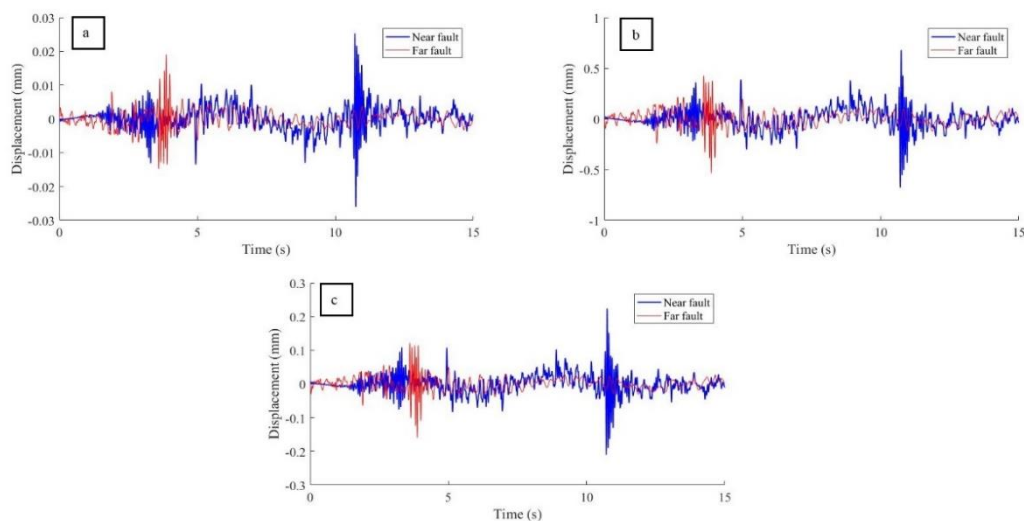


Fig. 13 – Time histories of nodal point 2489 for 1999 Kocaeli earthquake a) x direction b) y direction c) z direction

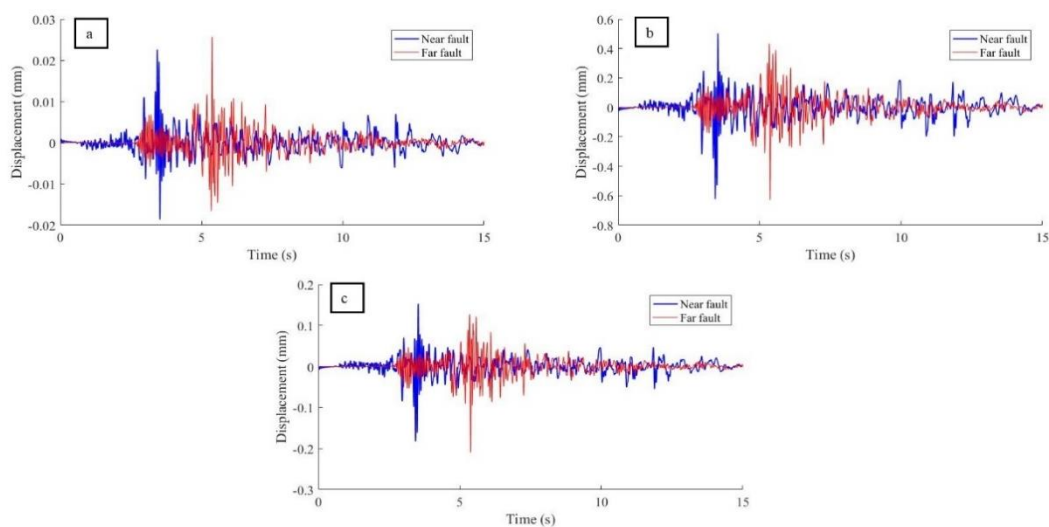


Fig. 14 – Time histories of nodal point 2489 for 1999 Düzce earthquake a) x direction b) y direction c) z direction

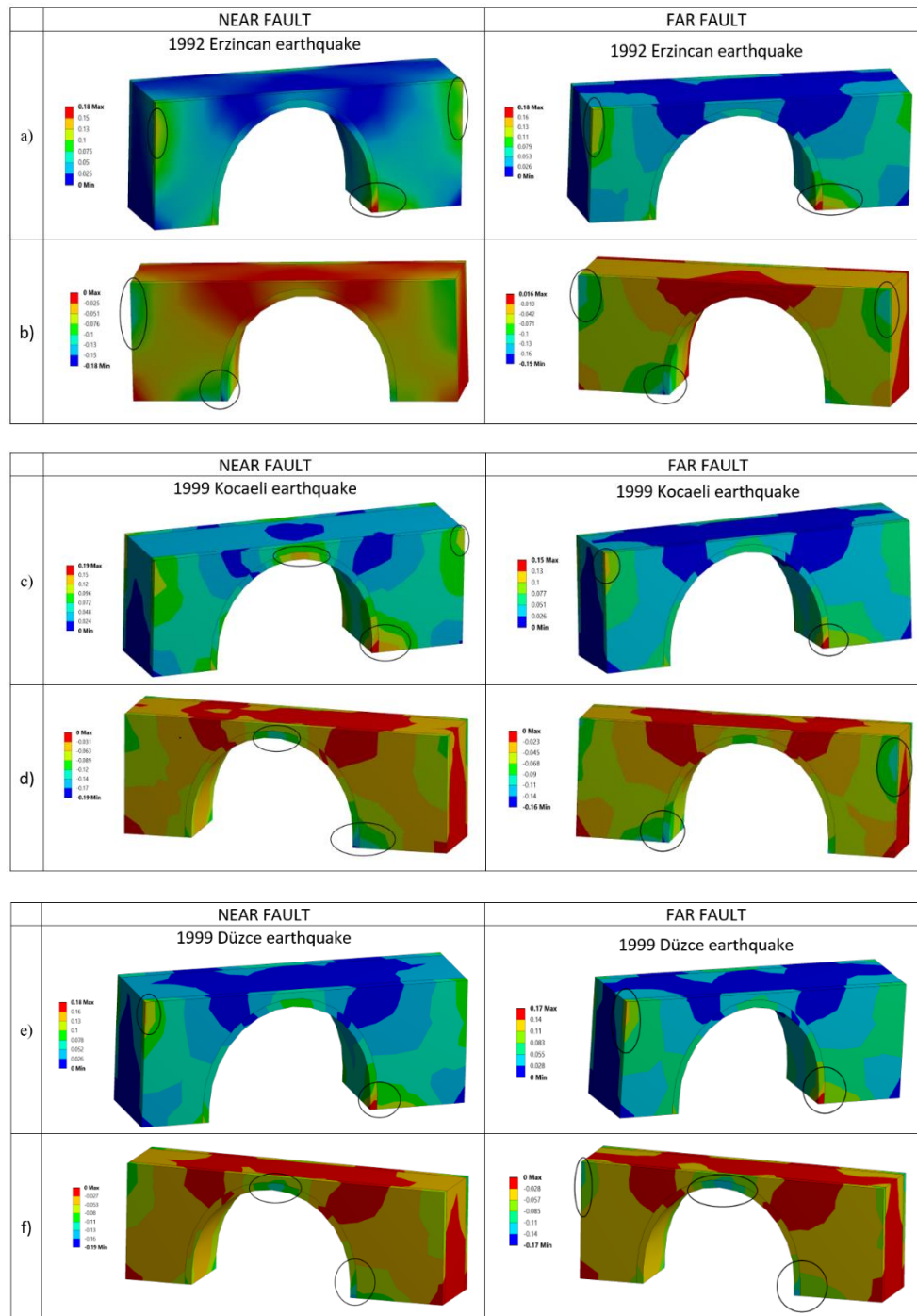


Fig. 15 – Comparison of maximum and minimum principal stress contours of the bridge (units are in MPa)

Table 4 - Maximum and minimum principal stress for near and far-fault earthquakes

Earthquake	Maximum Principal Stress (MPa)		Minimum Principal Stress (MPa)	
	Near-fault	Far-fault	Near-fault	Far-fault
1992 Erzincan	0.176	0.184	-0.177	-0.187
1999 Kocaeli	0.186	0.154	-0.194	-0.158
1999 Düzce	0.182	0.167	-0.186	-0.170

Also, the absolute maximum displacement values of the selected nodal point (node 2489), which is located in the top middle of the arch, were compared for the investigated NFGM and FFGM earthquake records. Time histories of the selected nodal point can be shown in Figs. 12–14 for all earthquake records. When the absolute maximum displacements of NFGM and FFGM earthquakes were compared, it could be observed that the effects of the far-fault were bigger than the near-fault effects for the 1992 Erzincan and 1999 Düzce earthquakes. Nonetheless, the near fault occurred with higher displacement compared to the far fault in the 1999 Kocaeli earthquake. In previous studies, it was found that for the seismic assessment of historical structures, FFGM records should be evaluated as much as NFGM records [5, 11, 12, 14, 35, 40]. Also, maximum absolute displacements of selected nodal points were presented in Table 3.

Fig. 15 shows the comparison of minimum and maximum principal stress contours for the 1999 Kocaeli, 1999 Düzce, and 1992 Erzincan earthquakes. Also, critical regions in terms of high stress were marked on the bridge. According to the analysis results shown in Fig. 15, minimum and maximum principal stresses generally occurred in regions around the base of the arch, at the side of the spandrel wall, and in the middle of the stone arch. Furthermore, during the NFGM and FFGM earthquakes, the tensile and compressive strengths of the stone investigated in this study were not exceeded. Therefore, no probable cracks or damages are expected. The maximum and minimum stresses obtained from the NFGM and FFGM are close to each other and are given in Table 5.

6 Conclusions

The purpose of this research is to present the results of NFGM and FFGM analysis, which were utilized to analyze a historical single-span masonry bridge. To this end, the historical Sultan Suyu masonry bridge was selected as a case study. The bridge's 3D finite element model was created using solid elements through a macro model technique, and time-history assessments were evaluated with three earthquake records. The following results were obtained for the investigated historical bridge:

When comparing displacement values along the bridge for the 1992 Erzincan and 1999 Kocaeli earthquakes, the NFGM was higher than the FFGM. For the 1999 Düzce earthquake, the displacement values for NFGM and FFGM are remarkably similar.

The absolute maximum displacements occurred at the highest point of the bridge. When comparing the absolute maximum displacements of NFGM and FFGM earthquakes at the selected nodal point, far-fault results gave higher displacement values than near-fault results for the 1992 Erzincan and 1999 Düzce earthquakes. However, the NFGM results of the 1999 Kocaeli earthquake produced higher displacement values compared to FFGM results. Among the investigated earthquakes, the largest displacement was achieved under the NFGM of the 1999 Kocaeli earthquake.

When maximum and minimum principal stresses were compared for NFGM and FFGM earthquakes, similar values were obtained.

Also, the highest maximum and minimum principal stresses for NFGM were obtained for the 1999 Kocaeli earthquake, and the highest maximum and minimum principal stresses for FFGM were achieved for the 1992 Erzincan earthquake. Obtained stress diagrams can be used to determine the potential damage regions. The principal stress diagrams of NFGM and FFGM were quite similar. Also, near and far-fault earthquakes did not change the potential damage regions.

The characteristics of the considered earthquakes affect the response of the structure. For this reason, considering near and far-fault records for different earthquakes will provide a more detailed evaluation during the investigation of the seismic behavior of historical bridges.

According to the results of this paper, FFGM is significant, and it is important to use with NFGM for seismic assessments of historical stone masonry bridges. In future studies, it will be beneficial to use FFGM combined with NFGM for the seismic behavior of historical masonry bridges.

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