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Examination of masonry arch bridge's life-cycle assessment under far-fault earthquakes

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Professional paper

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The goal of this study is to examine the historical masonry arch bridge's static and dynamic behavior using far-field fault earthquakes. The first step is to build a finite element model with ANSYS and SAP2000. This is done to see if the greatest possible displacements, primary stresses, and elastic strains compare. From above, the belt's upper side appears to be vital for damage. Furthermore, a historical masonry arch bridge's life cycle assessment is also researched and observed, which results in increased stress and strain values for the bridge, causing its expected life span to be drastically reduced.

Key words:

historical masonry arch bridge, far fault earthquakes, ANSYS, SAP2000, finite element method

Stručni rad

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Ispitivanje procjene uporabljivosti zidanog lučnog mosta izloženog djelovanju potresa dalekog rasjeda

U radu je prikazano statičko i dinamičko ispitivanje ponašanja povijesnog zidanog lučnog mosta izloženog djelovanju potresa dalekog rasjeda. U prvom koraku izrađen je model konstrukcije primjenom metode konačnih elemenata uz pomoć programa ANSYS i SAP2000. Navedeno je napravljeno kako bi se ustanovilo mogu li se usporediti najveći mogući pomaci, primarna naprezanja i elastične deformacije. Iz svega navedenoga, ključni je element oštećenja gornja strana plohe. Nadalje, ocjenjivanjem životnog ciklusa zidanog lučnog mosta, uočene su povećane vrijednosti naprezanja i deformacija mosta čime se njegovo očekivano trajanje drastično smanjilo.

Ključne riječi:

povijesni zidani lučni most, potresi dalekog rasjeda, ANSYS, SAP2000, metoda konačnih elemenata

1. Introduction

The beginning of human history can also be regarded as the beginning of construction activities. It is known that even the oldest known civilizations constructed buildings for different purposes to shelter, defend and survive. Of course, one of the most important of these structures is bridges. Every human civilization throughout history has constructed bridges using varied ways and techniques, from the most basic means to current technology. Because of this, there was a preference for arch-like structures. Although those who found the arch form were Sumerians or Egyptians, it was the Romans who used the arch most functionally and gave the most visually beautiful examples. Milvian Bridge is one of the most important examples. One of the important examples made by the Romans is the Ponte Vecchio built in the 6th century. Prevalent in Turkey are single-span stone arch bridges erected in the 19th century by the Ottomans in Anatolia. Historic bridges still in use in Turkey number roughly 1300. To guarantee the structural integrity of these bridges, it is absolutely essential to prepare for dynamic traffic, wind, and earthquakes [1]. The destructive power of earthquakes is magnified greatly by their abrupt shaking of the ground caused by the shattering and shifting of rocks under the surface [1]. Due to these several issues, masonry bridges were negatively impacted [2]. This includes numerous structural aspects such as quarry stonework, keystone, pavement, etc., and therefore it is critical to think about earthquakes when it comes to ancient masonry bridges. This resonance of structure coupled with the reaction of acceleration, velocity, displacements, stress distribution, etc., might be the major focus of this experiment [3]. Significance effects tend to be seen only with respect to structure height and not complex structures [4, 5]. Because of this, research still needs to be done on structures like the medieval masonry bridge in order to discover whether or not they have seismic vulnerabilities. This topic also comes up as a result of soil-structure interaction, as acceleration, velocity, displacements, stress distribution, and so on due to the complicated masonry constructions all become key issues. [6-9].

A large number of analytical and experimental investigations have been undertaken on the historical bridges due to their historical significance in literature [10-13]. In addition to these studies, Drosopoulos et al. have explored the ultimate failure load of the stone arch with consideration of varied arch heights. Geometry reveals how it influences mechanical behavior in this investigation. Additionally, it has been discovered that when the arch begins to rise (towards the initial, actual geometry), a reduction in the amount of rising produces an increase in the upper limit load until a shallow, flat arch is achieved [14]. Boothby [15] studied the behavioral characteristics of the arch bridges in the presence of various vehicle loads. In order to this end, the bridges studied by Boothby were examined, as well as those which were explored using ANSYS software. Finally, the testing program shows that the linearity of the response to varying loading levels is significant and that permanent deformations are required to adequately evaluate a structure. Additionally, the tests conducted in the field also revealed the breadth of the spectrum of reactions of similar structures, and additionally, some evidence of an incipient mechanism was found. According to the other study, Hatzigeorgiou et al. [16] carried out the investigation. Artha Bridge was modeled using finite elements by Hatzigeorgiou et al. and static and dynamic analysis was performed on the model. The findings in this study reveal that, from the various assessments, it can be concluded that the probable ground settlements at pier support or one or more other supports and the bridge will experience significant damage due to the earthquakes caused by the seismic excitation stress. This was done in research by Arteaga and Morer [17], which utilized limit analysis to examine the effect of different geometric features on bridge structural capacity. As the structural research of masonry arch bridges necessitates the employment of diverse methodologies to gain more comprehensive geometry, it is believed that geometry plays a crucial part in this. Additional experiments conducted by Sarhosis et al. [18] confirmed that masonry arch bridges exhibit an irregular distribution of weight. According to the results of the analysis, increasing the skew angle would result in a twisting arch, which eventually would lead to failure occurring at a lower load. The findings of field testing and FE modeling were reported by Boothby and Fanning [19], who studied three masonry arch bridges. Underneath the bridge structure, an additional LVDT was installed on the reference frame to measure the bridge's structural movements, and then a vehicle of known weight was placed on the frame. In addition, nonlinear FE models were simulated with ANSYS software. To find out, a fair set of material attributes was selected, 3D nonlinear finite element analysis was used, and good results were found. The study conducted by Frunzio et al. [20] is in contrast to the study conducted by Duncker et al. [17]. Using three-dimensional finite element analysis, Frunzio et al. [20] found that the analytical results were simple and convenient for restoration. It has been discovered that when stress levels are kept low, they promise that failure can be deemed absent. On the other hand, stress levels and deformation field distribution work together to indicate the failure process. Conde et al. [21] have another investigation on the matter. It is researched by Conde et al. [21] that the geometry influences the in-service medieval masonry arch bridge collapse load estimation. After seeing the results, it can be said that if idealized data is not available, stone arch collapse loads should be taken into consideration with caution when performing numerical calculations since the approach typically produces an overestimation of the expected load. According to the research of Toker and Unay [22], they used a prototype model for varied loading. Historical Arch Bridge [23] was constructed using finite element analysis. A linear-elastic analysis should be undertaken first to establish crucial structural components and the overall stability of the construction. Following these experiments, unique modeling tools could be used to explore issues of geometric irregularity and how they affect behavior under dynamic loads, such as earthquakes. In his study, in which he gathered ground motion and stresses for the bridge, Ural also explored the seismic analysis of the bridge. Bayraktar et al. [24] did a second investigation. The dynamic characteristics of bridges were discovered by Bayraktar et al. and, along with this, the bridge FE model was revised.

A reduction of average maximum natural frequency differences of 27% to 5% leads in better model agreement of analytical and experimental natural frequencies and mode shapes over time. Additionally, the research of the earthquake found that as the minaret gets taller, the displacement and maximum primary stress both occur at the transition segment, whereas the lowest stress is found at the cylindrical body [24, 25]. A paper published by Brencich and Sabia [26] investigated the same question as the one presented here. Tanaro Bridge was researched by Brencich and Sabia (Brencich and Sabia conducted their investigation on Tanaro Bridge). 18-span masonry building, incorporating dynamic trials, was utilized to obtain the natural frequencies, mode shapes, and damping ratios of this. In calculating the ultimate load-bearing capability of a masonry bridge, consideration should not be given to how much load the bridge can sustain; instead, an evaluation should be conducted that considers the average stress and structural reaction under service load. Results from 3D FEM elastic models have shown that they can provide valuable information for this final purpose. Non-destructive ground-penetrating radar (GPR) was used by Diamanti et al. [27] to examine the possibility of ring separation on masonry arch bridges. To evaluate and update the analytical results, several laboratory experiments were run. The lab experiments had good correlations with the computational simulations and GPR experiments. Computational and experimental simulations have shown that there is significant mortar leakage between the masonry arch rings [27]. Another investigation was conducted by Aydn and Zkaya [28]. They also looked into the loads that cause bridges to collapse. By employing SOLID65 type components in ANSYS [28], it was discovered that the nonlinear static pushover analysis of the given historical arch bridge has demonstrated that the attainable point can be the maximum load or an earlier point. As a result, it can be concluded that, in light of current studies for that type of historical arch bridges, the modelings created with the ANSYS program will not be able to replace an experimental model on their own and that they can only be used in the examination of the behavior after the maximum loading point. Altunşik et al. [2] conducted the other study. Altunşik et al. report on their research into varied arch curvatures. A finite element model of the bridge is used for this reason. The finite element model was redesigned for varying arch curvature to study the curvature effect. The arch curvature appears to have a greater impact on bridge reaction [2]. Breccolotti et al. [29] evaluated the seismic capacity of masonry arch bridges and used finite element modeling to undertake a parametric investigation. The comparison reveals the suggested model's conservative nature in terms of final loads and good agreement in terms of collapse processes. Some structural analyses have been published in the literature to look into the impact of geometry on the structural behavior of masonry arch bridges, but these studies looked at arches and bridges with ultimate loads. As previously stated, only a few research on seismic assessment of historic stone arch bridges are currently available [30-40].

The study's major goal is to develop models of the historical arch bridge to simulate its response to far-offset earthquakes via finite element (FE) techniques and to demonstrate their capability and predicted performance. In addition, utilizing analysis results, it is identified and investigated whether or not historical masonry arch bridge could still support under the aforementioned earth motions. For this research, historical Tokatlı Bridge (built-in Karabuk, Turkey) earthquakes are researched. The first part of this task explains the qualities of the historical masonry bridge, and the following section uses those properties to define the FE models of the masonry bridge. To complete the Life-Cycle Assessment of the Historical Tokatlı Bridge, the following procedure is used. Further details about the antique arch bridges are presented here.

2. Description of the historical Tokatlı bridge

The old Tokatlı Bridge is situated in the Söğütlüdere Canyon in the Safranbolu neighborhood of Karabük. The bridge is built on the riverbed in the east-west axis. The Karabük Provincial Directorate of Culture and Tourism claims that the Tokatlı Bridge was built between the years 1750 and 1790. Even if it is lacking evidence that would help determine the bridge's historical significance, General Directorate of Highways and Ministry of Culture and Tourism inventory slip and registration voucher nonetheless provide details about the bridge.

Figure 1. View Of The Historic Tokatlı Bridge (a) Upstream, (b) Downstream View, (c) Building Survey [41]

Tempan walls and an arch belly were built using pulley-shaped arch and one-eyed bridge stones, along with smooth fine stones. Most of the wall, especially the lower sections, was constructed using the traditional stone masonry style, although the top levels were created using different sizes of stones. The bridge is 4.10 feet wide and 47.26 feet long. The bridge is 30.70 meters above the water's surface. The bridge extends from 33.70 to 13.56 meters in a southeast direction before turning sharply to the east. The width of the bridge is 4.08 meters when crossing it via the west entrance. However, following the bend this width is just 4.21 meters. And, prior to the bridge exit, it is 3.21 meters wide. The images on the following slides show the historical Tokatlı Bridge in Fig. 1.It is crucial in structural analysis to know the material properties of a bridge. However, in older constructions, they can be rather difficult to manage. The building's geometric properties are easy to calculate, but finding a solution to the problem requires approximate numbers when it comes to the building's material attributes. The materials described in the literature that is typically utilized for similar structures are employed in this study. The modulus of elasticity of the material in the analysis is 3X 109 N/mm2, and the Posisson ratio is used to determine the size of the stone arch. The side walls employ a modulus of elasticity (2.5 x 10^9 N/mm^2) and a Posisson ratio (0.2) for the analysis.

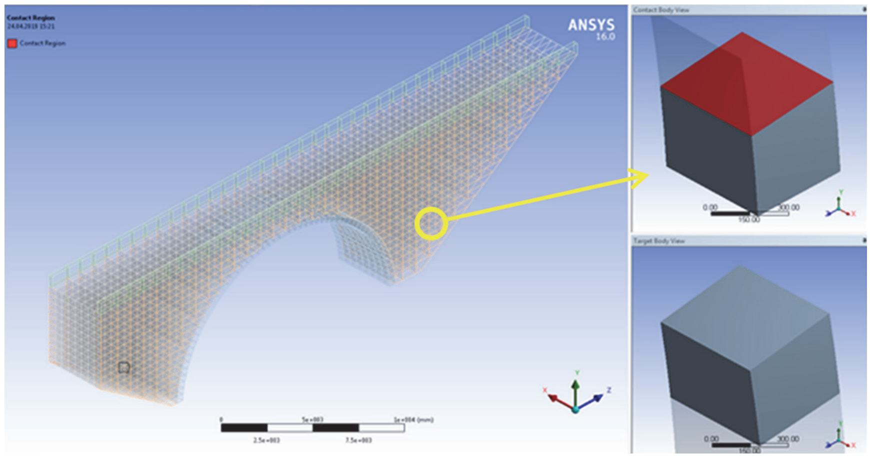

Figure 2. Details of contact surfaces

3. Finite element modeling

Using the finite element program, the FE model of the Historical Tokatlı Bridge is constructed and tested for many earthquake scenarios, including earthquakes that start on a distant fault. The first step is to use the ANSYS 3D nonlinear finite element code to do this. ANSYS [42] solutions have been discovered in a variety of near-fault earthquakes. Despite the fact that both apps use the Finite Element Method as a solution method, the interfaces, graphics, models, mesh approaches, and applied loads differ significantly. The identical geometry, material information, and support conditions were used to recreate this historical Tokatlı Bridge model with the SAP2000 [43] program. The Dynamic and Static testing are also performed. The SAP2000 model was also built with the intention of determining the configuration of the bridge's modes and natural frequencies. To create and compare findings, nonlinear finite element models such as ANSYS and SAP2000 are employed. See the subsections below for more information on the FE model.

3.1. Element types

The Structural FE model of the Historical Tokatlı Bridge divides the structure into tiny and simple pieces that are connected via intersecting nodes that accommodate the desired level of freedom for each component. Three-dimensional eight noded isoparametric elements, Solid65, were used for the masonry material, which was constructed using the ANSYS finite element software. The crack model used in this section employs a smear to allow cracks to form in opposite directions to the dominant stress [44, 45]. Every node of the element has three degrees of freedom; that is, the ability to be translated along the nodal x, y, and z axes. In order for the contact algorithm of the FE model to function, it is necessary to define contact surfaces.

3.2. Contact modeling

Contact mechanics [44] is the study of deformation induced by solid objects touching each other at one or more points. This research defines the interface between the Historical Tokatlı Bridge and its components. Three-dimensional frictional contact surfaces [46] are used to allow the fill material to slide or move relative to the arch barrel and spandrel walls without causing significant tensile strains at the interface between the two materials (Figure 2).

3.3. Meshing

Precisely estimating stress and/or strain values in a FE model requires accurately measuring the mesh size and type. Case studies of different mesh sizes are carried out to simulate the FE model of the Historical Tokatlı Bridge to obtain a suitable mesh density. So, in order to find the best meshing choice, the FE model tests and compares four meshing options: Automatic, Tetrahedrons, Hex Dominant, and Sweep. In the first mesh generation option, which has a total of 6,680 elements and 10,478 nodes, the mesh is automatically formed. In the Tetrahedrons mesh, there are 47818 mesh elements and 162920 node connections. See Table 1 for the attributes of the other meshing options. More nodes in a FE model means greater computation time in ANSYS. Thus, the meshing option that places four Tetrahedrons one on top of the other is selected, as the model's size distribution is more even,

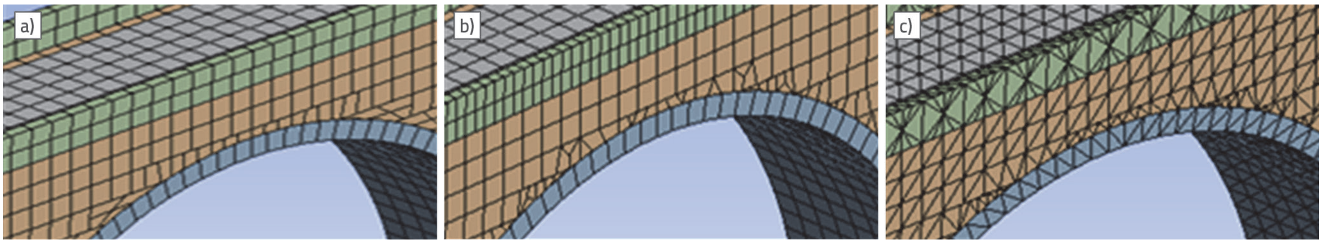

Figure 3. Mesh options: a) Hex dominant mesh; b) Sweep mesh, c) Tetrahedrons mesh

and fewer nodes are needed. Then, the selected meshing option is checked by adjusting mesh size along the length until the results become steady. For the FE model, the biggest mesh size offering consistent results is used. A constant maximum strain value is measured for mesh sizes of 50 mm and 25 mm on the Historical Tokatlı Bridge (0.012443 and 0.012466, respectively). In other words, mesh sizes are input manually and used to define 25 mm as the start/endpoints in the regions of contact and 50 mm as the boundary elsewhere in the model.

Table 1. Numbers of nodes and elements for different mesh types

Number	Mesh type	Nodes	Elements
1	Automatic	104788	6680
2	Hex dominant	126342	13045
3	Sweep	104788	6680
4	Tetrahedrons	162920	47818

3.4. Material model and boundary conditions

Accurate analytical findings require real attributes of the Historical Tokatlı Bridge in the nonlinear FE model. Due to the fact that it is difficult to determine the material qualities, the properties that are usually found in constructions and literature reviews are utilized in this study. The modulus of elasticity of the material in the analysis is 3X 109 N/mm^2, and the Posisson ratio is used to determine the size of the stone arch. The side walls employ a modulus of elasticity (2.5 x 10^9 N/mm^2) and a Posisson ratio (0.2) for the analysis. In studies of literature, it has been discovered that filler materials have little influence on the building's carrier [22]. Because of this, it has been found to have a smaller elastic modulus in the analysis. In order to study the behavior of structures with complex modes, only taking the first ten modes was acceptable [23]. Read on in Table 4 and Figure 6 to learn more about this topic. This table lists the attributes of the material utilized in the analyses in Section 2. Recommended material attributes employed mechanical parameters (modulus of elasticity, poisson's ratio, and unit weight). Also important in FE analyses is having a correct definition of the boundary conditions. The boundary conditions refer to all of the bridge piers having a constant number of translation and rotation degrees of freedom.

Table 2. Materials properties [47]

Material	Modulus of elasticity [N/mm^2]	Poisson ratio	Density [kg/m^3]
Stone arches	3.0 x 10^9	0.25	1600
Side walls	2.5 x 10^9	0.20	1400

4. Far-Fault ground motions

Seismic ground vibrations that have distinct, damaging velocity pulse characteristics are studied in this study. The far-fault ground motions that were used in this study are listed in Table 3. Fig. 4 shows the earthquake records that are analyzed in the studies. One way to characterize the far-fault ground motions is by measuring the amplitude of the velocity pulse (Vp) and the period of the velocity pulse (Tp) [48]. Both Ap and Vp that are part of the Ap/Vp ratio of ground movements are included in this study's ground motion data and are utilized to describe the far-fault ground motions in the study. The amplitude-to-frequency (or voltage-to-frequency) ratio can be a good indicator of the prevailing ground motion

Table 3. Far-fault records used in the analysis

Earthquake	Station/Component	A_p [g]	V_p [cm/s]	A_p/V_p [1/s]
Borrego Mount,1968	Hollywood storage lot / 180°	0.01	2.33	4.7
Friuli, Italy, 1976	Conegliano / 0°	0.03	4.29	7.7
Kobe, 1995	FUK / 0°	0.05	3.52	13.6
Morgan Hill, 1984	San Fran., International airport / 90°	0.06	3.65	16.7
NW California, 1941	Ferndale City Hall / 45°	0.02	0.76	23.6

frequency and energy content [3]. If the Ap/Vp ratio is low, the acceleration pulse will be of longer duration. If the Ap/Vp ratio is high, the acceleration pulse will be of shorter duration. One ground motion set is applied. This table includes 5 different quakes and Ap/Vp values ranging from 4.7 to 23.6 over one second, shown in Table 3.

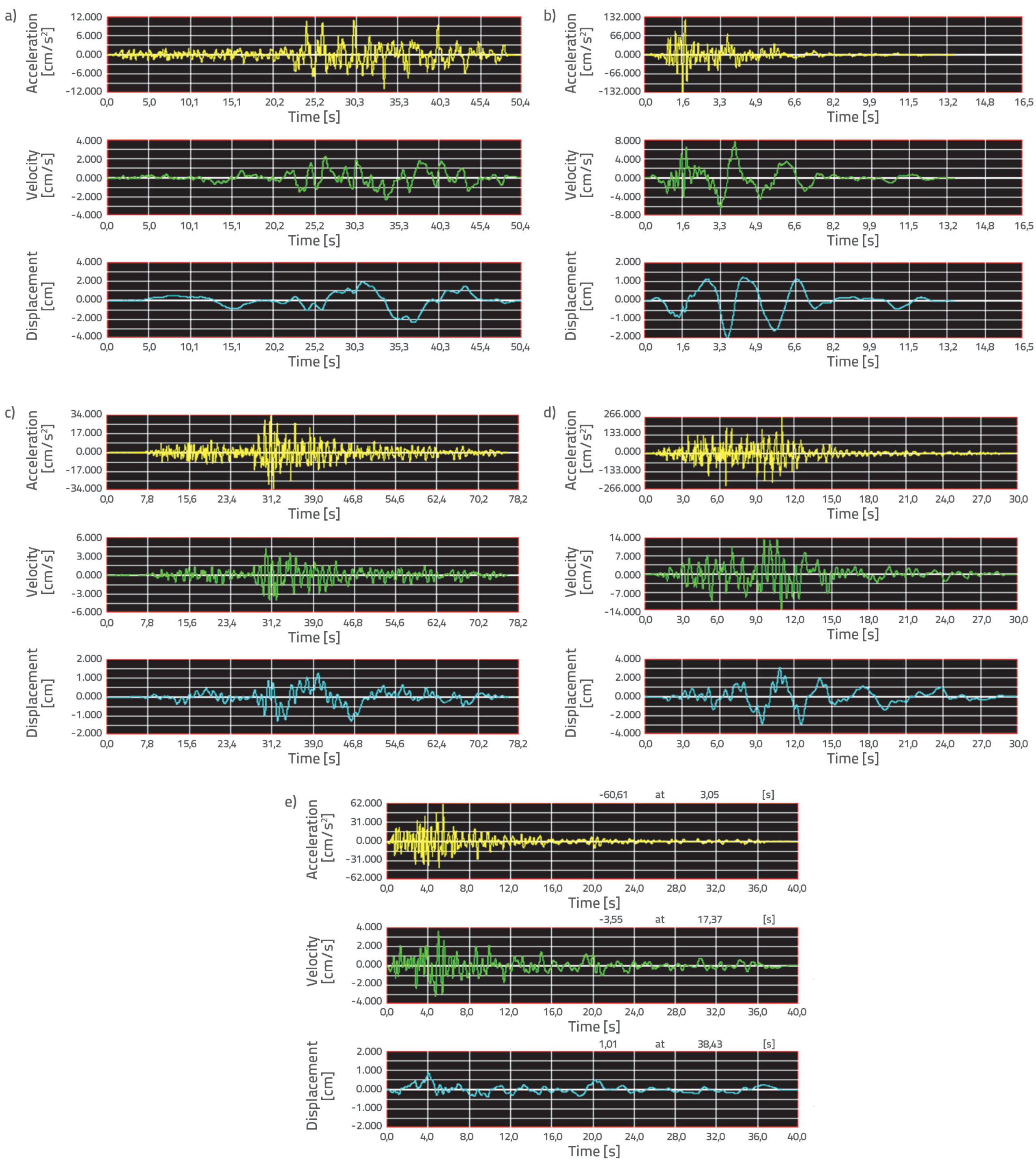

Figure 4. Far Fault Eartquakes: a) Borrego Mount,196; b) Friuli, Italy, 1976; c) Kobe, 1995; d) Morgan Hill, 1984; e) NW California, 1941

5. Analyses results

In this research phase, it is discovered how the historical Tokatlı Bridge behaves in the face of powerful earthquakes. For this reason, fault ground motions with forwarding rupture directivity effect (forward rupture component of ground motion) are specified, as explained above. Prior to the dynamic analysis, the mode forms in SAP2000 are specified. To calculate the characteristic mode forms and other data, the initial step is to determine the finite element model of the Historical Tokatlı insurrection bridge in SAP2000, as shown in Fig. 5. The mode of a structure has a direct impact on general structural behavior. Deformation of the first 10 modes of the Historical Tokatlı with the SAP2000 program's Modal analysis was utilized to identify the forms of the modes. See Table 4 for the structure of the first 10 Mod eras. Dead load analysis is performed under its own weight once the model is created. Fig. 7 displays the maximum deformation, elastic stresses, and stress values that were found during the analysis. ANSYS model is also applied in order to calculate the dead load results for the Tokatlı Bridge, which was compared to the results of the SAP2000 of the Historical Tokatlı Bridge, as seen in Fig. 8. As seen in Figs. 7 and 8, the pressure and tensile stress levels are roughly 20 MPa and 1 MPa, respectively. Because stress and displacement values do not cause the Historical Tokatlı bridge to collapse under conventional earth gravity, it appears that they do not contribute to the bridge's collapse. Analyses revealed that the bridge's own weight is not a threat to the structural integrity of the bridge. The load happening in the middle of the arch span was also distributed throughout the ends of the arch, resulting in maximum strains occurring in these areas. Stress and displacement graphs are displayed in Fig. 9 and 10 during the investigation of the dynamic behavior in the presence of far-fault earthquakes. The largest stresses occur in the central zone, but dynamic movement in any direction other than parallel to the bridge axis causes the bridge to activate the collapse mechanism.

Assuming that the Historical Tokatlı Bridge is unaffected by the additional tensile stress of 0.68 MPa, it may be deduced that the Historical Tokatlı Bridge will not be destroyed under higher normal gravity. Pela et al. [49] recommended for a tensile strength/compressive strength ratio of 1/20 to 1/10 for masonry structures, and this tensile stress can be argued to be acceptable with that ratio. The damage potential is projected to be 1/20 of the tensile strength, whereas the tensile strength/compressive strength ratio is anticipated to be 5%. Damage to structural strength is thought to reduce tensile stress levels by more than 1/20 of 5 %. The tensile strains induced by the large fault event have grown dramatically, as seen in Figures 9 and 10. Given the magnitude of the earthquakes employed in the analyses, it can be estimated that the tensile stress on the Historical Tokatlı Bridge grew to 0.68 MPa while statically loaded, and then increased to 0.74 MPa owing to far fault earthquake effects. It is discovered that several nodes within the finite element model are under a compressive stress of no more than 1 MPa. The results suggest that tensile tension is not the cause of damage during near-fault earthquakes. As fault earthquakes do not exert nearly as much compressive force as the structure has tensile strength, little damage is envisaged as a result of applied pressure. The above two figures show that the tensile stress on the Historical Tokatlı Bridge surface during a major earthquake under fault conditions is between 1 and 1.5 MPa, and the stresses may not be harmful. The upper side of the large belt, the bottom of the belt, and the belt's side are all important for damage to the road surface, as shown in Figs. 9 and 10. But as previously stated, any dynamic movement that is perpendicular to the bridge's axis could potentially lead to a crack in this area, where the greatest stresses occur, and so serve as a trigger for the bridge's collapse. The benefit of this invention is that it makes the crack mechanism better, even if it is only a little bit. The results in the scientific literature about their own weight and the stress from earthquakes agree with these conclusions. These locations can be expected to show cracks with increasing strain, and this will be followed by the collapse process. Dynamics analyses have resulted in the data presented in Table 4. These findings also spark investigations into life-cycle evaluation in the following section.

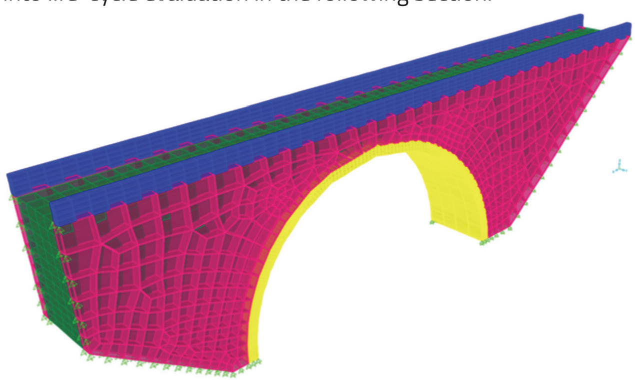

Figure 5. Modeling of Historical Tokatlı Bridge in SAP2000

Table 4. Periods of the first 10 Modes of Historical Tokatlı Bridge

Mod	Period [s]
1	0.04524
2	0.02531
3	0.02342
4	0.01960
5	0.01656
6	0.01360
7	0.01318
8	0.01296
9	0.01200
10	0.01025

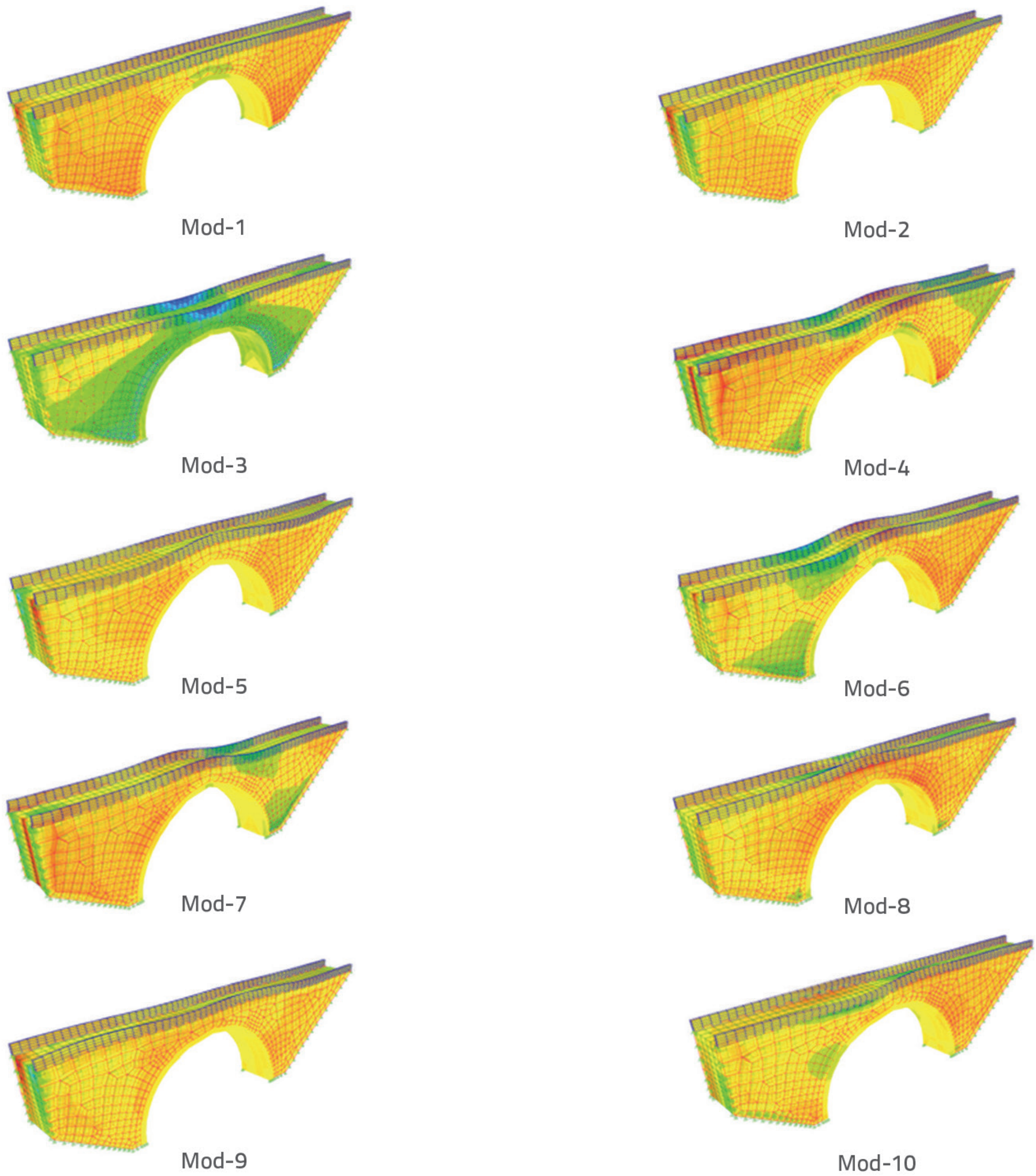

Figure 6. Top 10 Mode shape of Tokatlı bridge

Table 5. Dynamic ANSYS analyses results

Number	Fault	Earthquakes	Historical Tokatlı bridge		
			Deformation [mm]	**Maximum principal elastic strain** [mm/mm]	**Maximum principal stress** [MPa]
1	**Far Fault**	Borrego Mount,1968	1.52	0.00020	0.62
2		Friuli, Italy, 1976	1.60	0.00020	0.61
3		Kobe, 1995	1.56	0.00022	0.67
4		Morgan Hill, 1984	1.53	0.00021	0.64
5		NW California, 1941	1.65	0.00024	0.74

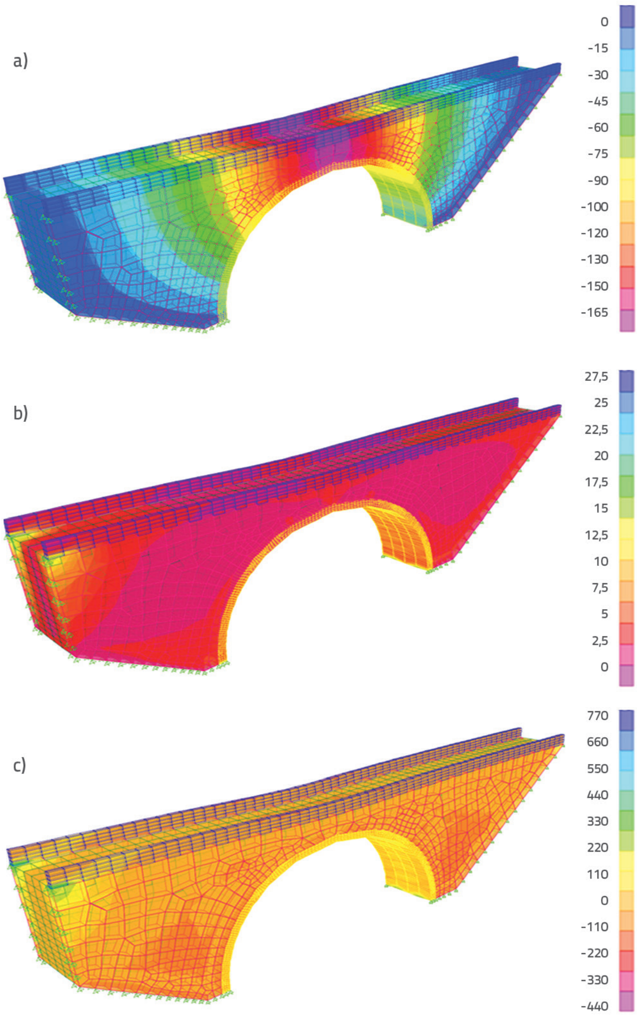

Figure 7. Historical Tokatlı bridge, static analysis in SAP2000: a) Total deformation; b) Maximum principal elastic strain; c) Maximum principal stress

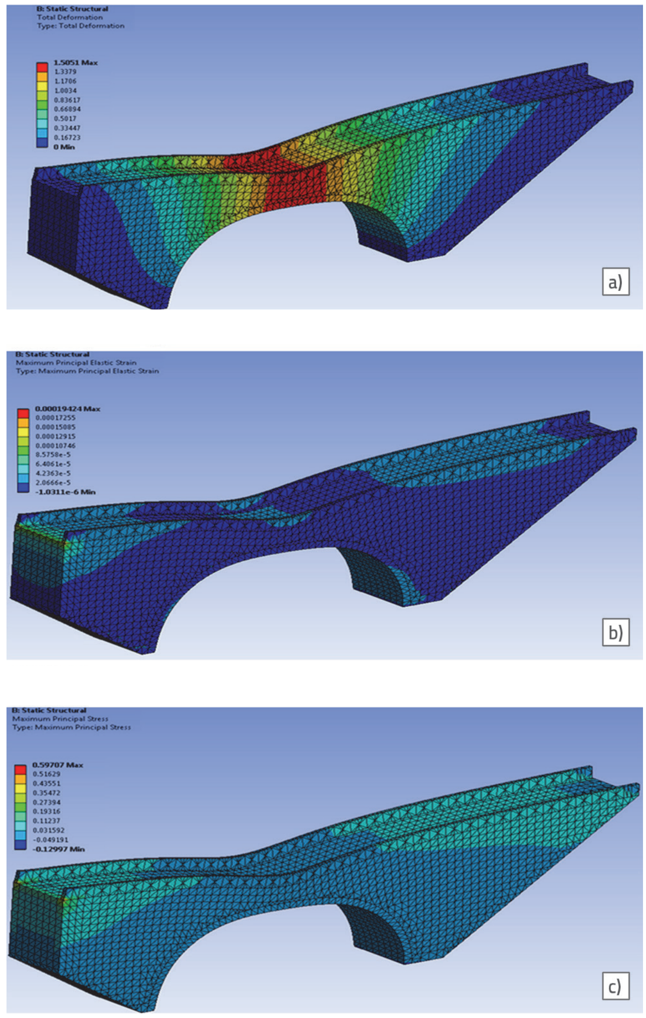

Figure 8. Historical Tokatlı bridge, static analysis in ANSYS: a) Total deformation; b) Maximum principal elastic strain; c) Maximum principal stress

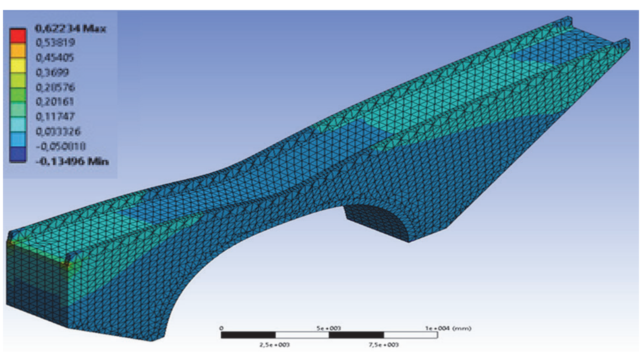

Figure 9. ANSYS results of Historical Arch Bridge Displacements under far fault earthquakes; Borrego Mount, 1968

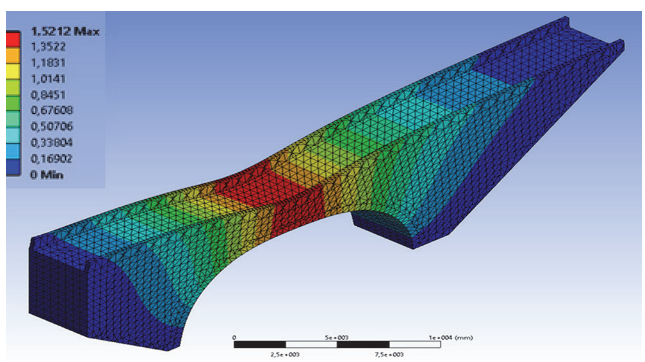

Figure 10. ANSYS results of Historical Arch Bridge, Maximum Principal Stress under Far Fault Earthquakes, Borrego Mount, 1968

6. Life-cycle assessment for historical Tokatlı bridge

Deterioration can be caused due to loads and environmental effects. In the phase of this study, it is investigated to deterioration models for historical masonry bridges due to static loading. Although there are many techniques designed for historical masonary bridge in the literature, such as Harvey [50], Gilbert and Melbourne [51], Fanning and Boothby [46] and etc, all of them are based on the static test data and the effects of long-term deterioration due to traffic loading and enviromental effects are not taken into account [52]. To taken into account these effects, Sustainable Masonry Arch Resistance Technique (SMART) [52] is proposed. Using this technique, it is incorporated long-term service life and it is defined safe long-term loading limits into the assessment. This technique brings together all the existing methods into a single methodology, by considering not only the ultimate load capacity but also the long-term behaviour and residual life for masonry arch bridges [52]. In terms of mathematical relationship, SN type deterioration models have been proposed for masonry by Roberts et al. [54] based on a series of small-scale laboratory tests. Based on test results , a probabilistic model was developed for masonry arch bridges as shown in Equation (1) by Casas, [55]:

$$S = A \cdot N^{-B(1-R)} > 0{,}5 \qquad (1)$$

where S is the ratio of the maximum stress to the average strength ($S=S_{Max}/S_{Av}$), N the number of cycles and R the ratio of the minimum stress to the maximum stress ($R=S_{Min}/S_{Max}$). The value of B is set to 0.04 for the current test data. An endurance limit of 50% was assumed. To establish the practical application of SN curves, examples for stress levels and associated life probability are given in Table 6 [52], based on Casas' model. Furthermore, Tomor [52] obtained static test results and gives as a Figure as seen in Fig.11. When the Fig.11 is observed for compression, the life expectancy for 50% average stress level is around $2x10^8$ cycles. If the stress level is reduced 5% (from 50% to 45%), the life expectancy increases 35 times (from 2×10^8 to 8×10^9). On the other hand, if the stress level is increased 5% (from 50% to 55%), the life expectancy reduces to around 1/20 (from 2×10^8 to 1×10^7) [52]. As mentioned above, when life-cycle assessment is applied on the Historical Tokatlı Bridge under static loading, it is observed that stress values are obtained as 0.5971. Although it is seen that the tensile stresses have not reached the permissible masonry tensile strength and stress values seems to be very small, it is observed that there is no fatigue in the bridge under static loads. Consequently, Damage can not occur over a static loading. It is recommended to consider the life cycle assessment of the historic masonry arch bridge in addition to the static loads for far fault and near fault earthquakes.

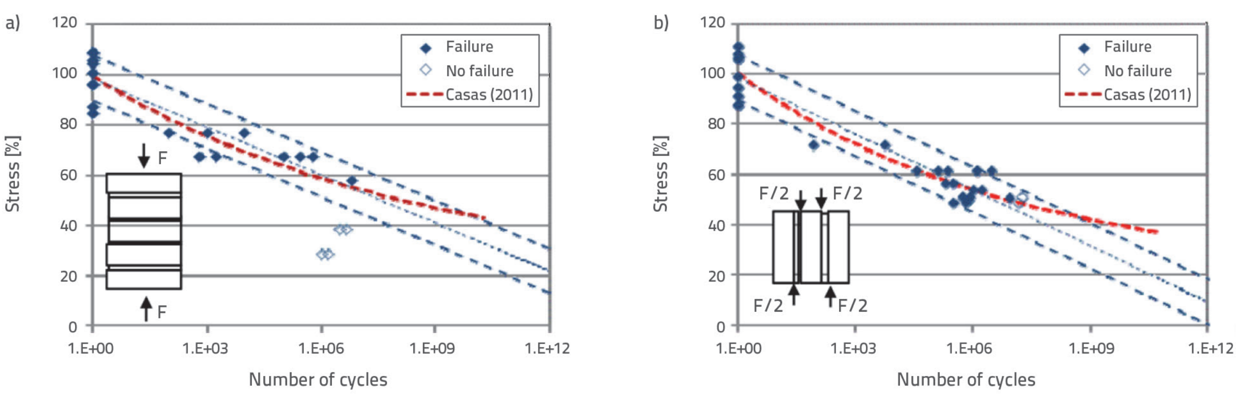

Figure 11. Tomor fatigue test results [52]: a) compression; b) shear

Table 6. Examples of approximate life expectancy based on the model by Tomor [52]

Compression			Shear		
Stress [%]	Life expectancy		Stress [%]	Life expectancy	
	Cycles	Ratio		Cycles	Ratio
45	$8 \cdot 10^9$	35	45	$1 \cdot 10^8$	18
50	$2 \cdot 10^8$	1	50	$7 \cdot 10^6$	1
55	$1 \cdot 10^7$	1/20	55	$6 \cdot 10^5$	1/12

7. Conclusion

This paper describes a detailed analysis of the static and dynamic behavior of the Historical Tokatlı Bridge during various far-fault earthquakes. A finite element model of the Historical Tokatlı Bridge is created using ANSYS and SAP2000, and it is then investigated under various remote faults. Based on the investigation's findings:

- The compressive stresses are found to be much below the masonry compressive strength and are not believed to be dangerous in terms of damage for far-fault earthquakes. Furthermore, the permitted masanory tensile strength has not been met. However, potential damage from displacements has been determined to be critical for the Historical Masonry Bridge. As a result, it's a good idea to pay attention to these damages during the analysis.
- When stress/strain values do not approach the allowable masonry tensile strength, it is noted that raising the stress/strain values for historical masonry bridges may diminish the masonry bridge life expectancy. From this point of view, it is suggested that the life cycle evaluations of historical masonry arch bridges should be considered in future studies, especially for earthquakes with distant faults, due to dynamic effects.
- More laboratory testing and FE studies are needed to develop the numerical prediction technique, according to the experts.

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