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Structural performance of renovated masonry low bridge in Amasya, Turkey

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Abstract. Masonry bridges are the vital components of transportation systems. Although these bridges were constructed centuries ago, they have served a purpose from ancient times to the present day. However, the bridges have needed local renovation and therefore have been rebuilt over different periods in many places. This study focuses on Low Bridge, which is an example of renovated masonry bridges in Turkey. It essentially assesses the structural behavior of the masonry bridge and investigates the integrity of the renovated components. For this purpose, the mechanical properties of the bridge material have been primarily evaluated with experimental tests. Then the static, modal and nonlinear time history analyses have been carried out with the use of finite element methods in order to investigate the structural behavior of the current form of the bridge.

Keywords: bridges; earthquake/seismic behavior; dynamic analysis; finite element method; mode shapes; modeling; time history

1. Introduction

Throughout history, roads and bridges constitute one of the most important ways of connecting people and businesses. Bridges are used to overcome difficult terrains and earth features, such as rivers, hollows, and holes. Presently, bridges are built using modern construction materials, such as reinforced concrete or steel. However, large portions of existing bridges in the world are still classified as masonry bridges. Therefore, masonry bridges have undertaken a very important and fundamental role in transportation systems in many parts of the world.

Several masonry bridges can carry heavy traffic loads all over the world. However, some of the masonry bridges have collapsed or had renovations because of several reasons, such as earthquakes, floods and human impact. With regional renovations, undamaged parts of the bridge have been preserved, and damaged parts have been rebuilt with original or new materials. This approach is manifested throughout history in many different configurations. One of the most notable examples of these structures is the Mostar Bridge in Bosnia and Herzegovina. The bridge was blown up during the Bosnian War in 1993 and was completely demolished. UNESCO rebuilt

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this bridge with the original materials in 2004 (Cakir 2011). Another example is Low Bridge in Amasya, Turkey. The bridge partly collapsed during the 1865 and 1881 floods; in addition, the bridge was badly damaged in the 1939 Erzincan earthquake. Therefore, the masonry bridge has been renovated and rebuilt several times throughout history. Hence, the bridge form has had several modifications in the course of time.

The investigation of the structural performance of masonry bridges has been an important research topic in the field of structural engineering community. When the literature on structural performance of historical masonry bridges is reviewed, several experimental and numerical studies are available in literature. For example, Fanning and Boothby (2001) focused on full-scale testing of stone arch bridges. In this study, three-dimensional numerical models of three masonry arch bridges were generated and the structural performances of the bridges were investigated with nonlinear analyses. Felice (2009) investigated the load-carrying capacity of multi-span masonry arch bridges. Pela *et al*. (2009) also investigated seismic assessment of masonry arch bridges with experimental and numerical analyses. In another study, Milani and Lourenco (2012) studied the static non-linear behavior of masonry bridges. In the study, two real scale masonry bridges were analyzed; the structural behavior was investigated using nonlinear models. Furthermore, Pela *et al*. (2013) focused on seismic assessment procedures for masonry arch bridges. Reccia *et al*. (2014) also conducted on the structural behavior of masonry arch bridges. The majority of the current literature about the structural performance of the masonry bridges concentrates on the bridges that have integrity of all structural components. However, the renovated masonry bridges and the masonry bridges that have traces of different civilization have not been studied in detail. Therefore, this study focuses on Low Bridge, which is an example of renovated masonry bridges in Turkey. The main objective of this study is to observe the positive and negative impacts of renovations on the structural performance of the masonry bridge. A further aim of the study is to reveal the adaptation between structural parts from different periods throughout history. The originality of this paper is that it takes the effects of changes made in different periods of history into consideration, and it also evaluates the integrity of components belonging to different civilizations. In this scope, the main focus has been given to material properties, and material characteristics have been defined through compression and three-point bending tests. In the next step, three dimensional finite element model of the current structure has been developed and the performance of structural components has been observed through non-linear static, modal and nonlinear time history analyses.

2. Low Bridge

2.1 General description

Amasya is one of the oldest settlements of Anatolia, and it is located in the Central Black Sea Region in Turkey (Fig. 1). According to historical records, the history of the city goes back to the Hittites. Therefore, Amasya is primarily a cultural destination, and it has had a rich cultural heritage. One of the well-known historical structures is Low Bridge in the city center. Since the bridge is located in social and cultural activity areas, it is intensely used in the present day.

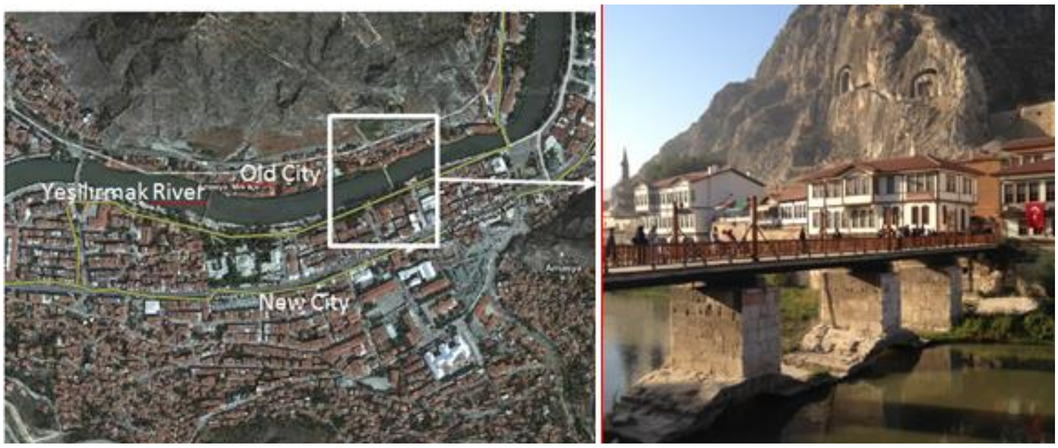
The bridge was built in 2nd century over the Yeşilırmak River, which longitudinally divides the city, and it has been linked between the old and new city (Fig. 2(a)). The bridge was originally designed as a masonry arch bridge and was constructed with hewn stones in the Roman period.

Since Yeşilırmak River has risen throughout the years, the abutments and the lower parts of the arches have remained shallow. Therefore, the bridge has been called the "Low Bridge-Alçak Köprü" because of its shape (Fig. 2(b)).

The bridge has been exposed to many destructive effects since the time when it was built. The bridge spandrels completely collapsed at an unknown date and the piers, which are also known as stone towers, were added to the highest point of the Roman arches in the Ottoman period. Subsequently, timber frames were added to the bridge piers by order of Ziya Pasha who was governor in Amasya in 1865 (Menç 2000).

The timber frames and the piers were partly destroyed again during a flood in 1881 and the bridge became unusable. According to orders of Atif Bey, who was a governor in Amasya, the stone piers were renovated and new timber frames were constructed on the piers (Menç 2000). Moreover, the bridge was moderately damaged in the 1939 Erzincan earthquake, and the bridge was renovated with minor changes. However, the timber frames were damaged due to heavy floods in the 1950s, and a reinforced concrete slab was added to the bridge instead of the timber frames (Fig. 3). Eventually, the bridge was renovated in 2009 and has reached its current form.

Fig. 1 Map of Turkey (Adopted from Wikipedia)



(a) (b)

Fig. 2 Low Bridge (Adopted from Turksatmaps)

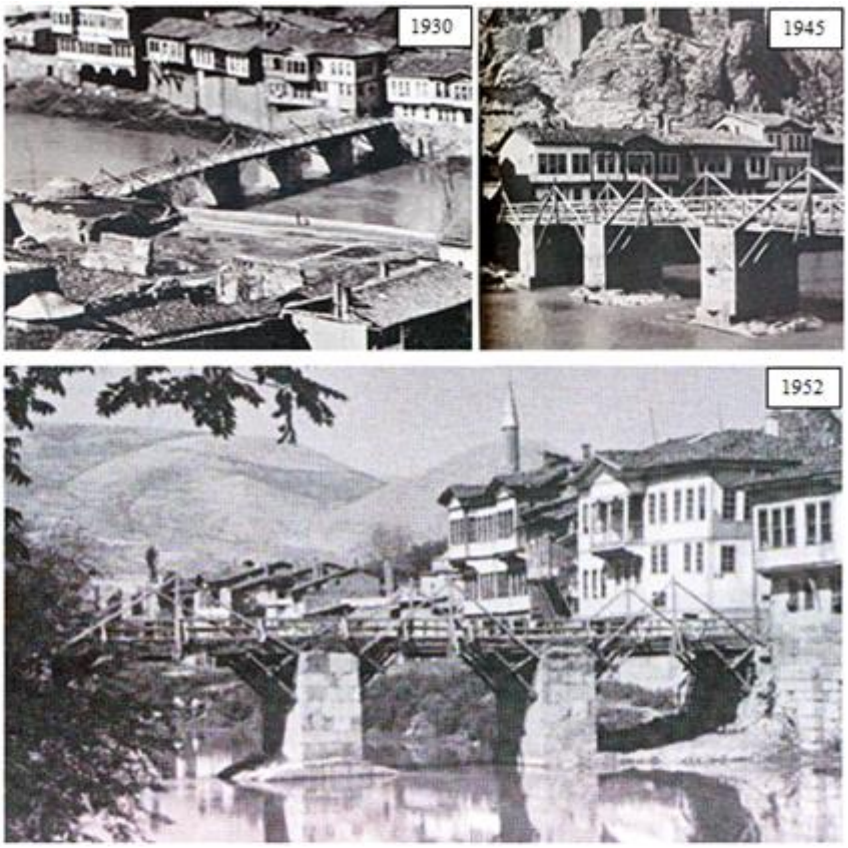


Fig. 3 The old pictures of Low Bridge (Menç 2000)

2.2 Geometrical survey

Historical masonry bridges are very complex structures although they have very simple architectural shape. As a well-known fact, the shapes of masonry bridges are one of the important factors for their structural behavior (Cakir and Mohammadi 2013). Therefore, in the first phase of the study, a geometrical survey was conducted. According to this survey, it was discovered that the bridge consists of three major parts. The first and oldest parts are the Roman arches. The second parts are the Ottoman piers and the third parts are the Turkish slab. Therefore, the bridge has a unique architectural shape, and it reflects three different civilization effects. Fig. 4 provides a schematic detail of the components of the Low Bridge.

The bridge has four Roman arches and four piers. With respect to the curve of extrados or intrados, the arches can be classified as semicircular arches. Voussoirs were the wedge-shaped one-meter stone blocks and the intrados spans of the arches varied between 6 m and 7 m. The lower parts of the arches (from the skewback) are under water, and these points are the foundation of the bridge due to the rise of the riverbed (Fig. 5). In this bridge, having the shape of a rectangle (3.5×5 m), the Ottoman piers have dual functions (Fig. 6). One is carrying the vertical loads, such as dead load and live load, and the other is resisting the horizontal loads, such as wind loads, creep movements, and water flow effects. Because of these, the piers were designed symmetrically to safely transmit the loads to the Roman arches and also to resist any lateral loads due to the wind or flow of the stream. The superstructure, which is the highest point of the bridge, is the Turkish slab. This deck slab, which has 0.75 m thickness, was made of reinforced concrete paving road. In addition, two timber frames were constructed to make the bridge safer for the pedestrians passing through the bridge. When all the components come together, the total bridge is almost 51 m. in length and 6 m in width. Moreover, the total height of the bridge is almost 10 m from the skewbacks to the deck slab. As of today, the bridge does not open to vehicle traffic, and the bridge is only visited as a historical heritage site (Fig. 7).

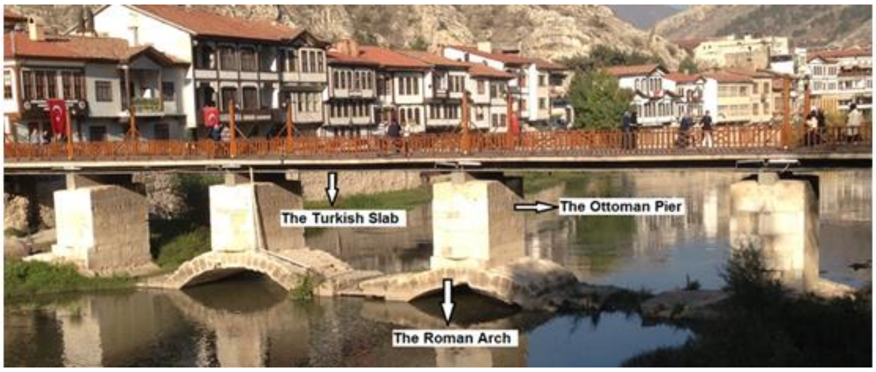


Fig. 4 Structural components of the bridge

Fig. 5 Semicircular Roman arch

Fig. 6 Rectangular Ottoman pier

Fig. 7 Reinforced concrete paving road

2.3 On-site investigation and observed damages

In the second phase, the authors carried out an in-situ investigation in order to evaluate the present condition and structural problems of the bridge. During the service life, the bridge has been exposed to many destructive effects. Therefore, the bridge was subjected to various heavy loads. The visible signs of deterioration in the structure were visually examined in the light of the structural features and architectural characteristics. The deteriorations of the structural elements and the decay of the structural materials have caused damage to the structural elements. In addition, during the structure's service life, construction materials have deteriorated and lost their qualities due to environmental conditions. The main problems of the structure are the damage to the structural elements, the loss of material, and the decrease in structural strength. One of the facades of the piers has been partly demolished on the mortar, and many irregular micro cracks have been observed between the arches.

Fig. 8 Huge stones and upper branches came with water (Anonim 2014)

The binding material between the masonry units has partially eroded. These abrasions may have caused the vicinity of the structural resistance to be weak. The most deteriorated parts of the bridge are the skewbacks of the arches. In some cases, abrasion and degradations are also noticed on the stone units of the masonry piers. In addition, the bridge has been subjected to several undesired materials, such as upper branches and stones, which come from floodwater (Fig. 8). Hence, the historical structure has also been locally damaged due to the heavy flood effects. The increases of river water velocity and flow rate have led to scour for the bridge, and some stones have separated from the bridge (Fig. 9). These types of damages are very dangerous because they may cause fatal and destructive crashes and fractures. In addition, they cause differential movement of the bridge components. Therefore, these damages should be seriously considered, and some precautions should be taken to avoid or to abate their effects. In addition, the deformations can be seen on the piers (Fig. 10).

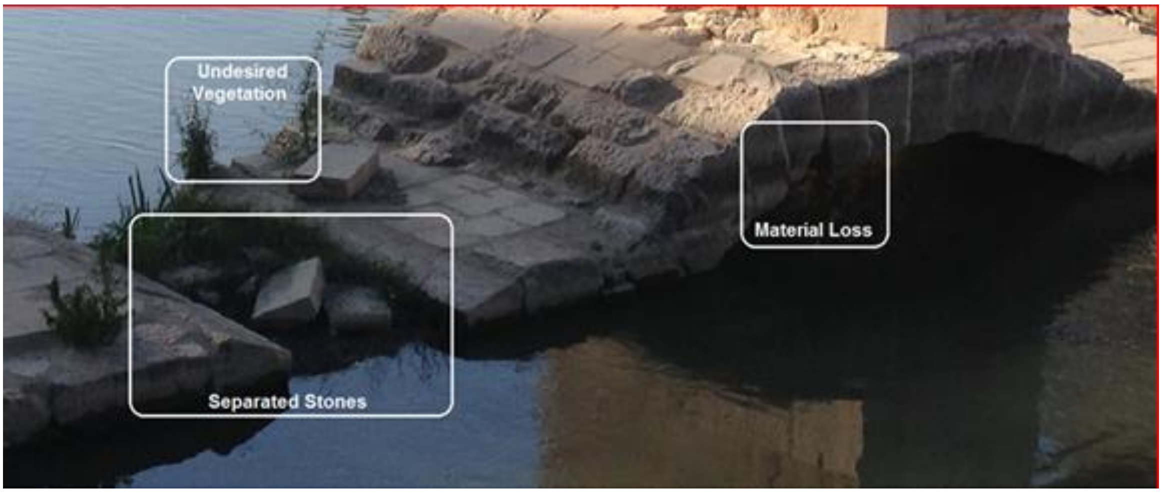


Fig. 9 The separated stones and material loss of the arches

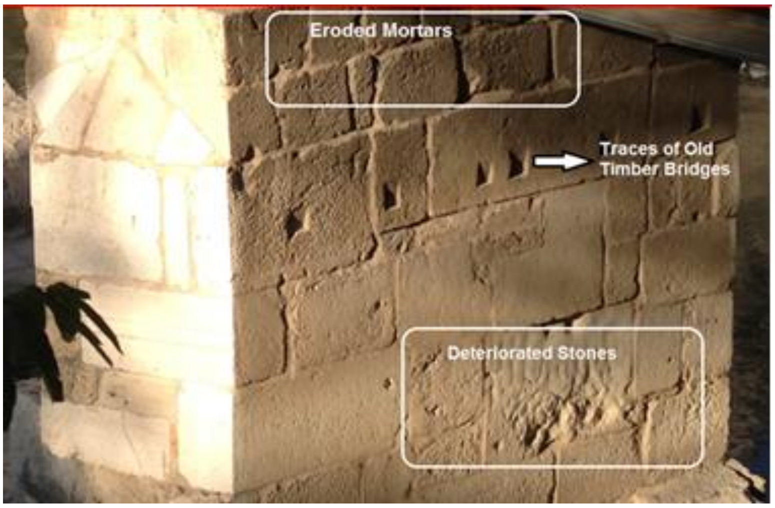


Fig. 10 The structural problems of the piers

3. Experimental tests of the materials

The use of materials for historical construction depends on their local availability. Sandstone, limestone, and handmade bricks have been the most commonly used materials in masonry structures in Anatolia because of their availability, high strength, and softness (Uysal and Cakir 2013). Among those, the principal materials of the masonry structures in Turkey are stones and handmade bricks. It is determined that the dominant construction materials are hewn stones in the Low Bridge.

In this study, some laboratory tests were performed on the masonry specimens in order to determine their mechanical properties. Hence, the represented stone samples were randomly collected from around the bridge and then were prepared with the dimensions of 50×50×50 mm^3 and 50×100×200 mm^3 (Fig. 11). Experiments were conducted to obtain information on the compressive strength, tensile strength, and density. Therefore, the stones were subjected to compressive tests and three-point bending tests. The tests were conducted at the laboratories of the Department of Civil Engineering at Ataturk University, Turkey. In the experimental examination, the compressive strength of the stone samples were obtained from compression tests on five cubes following the guidelines of TS 699, Turkish Building Code (Table 1) (TS 699:2009). The bending strength of the material samples was obtained from three-point bending tests on five prisms according to TS EN 1467 and 1469, Turkish Building Codes (Table 3) (TS EN 1467:2012, TS EN 1469).

Fig. 11 (a) Preparation of the specimens, (b) Three-point bending test, (c) Compression test, (d) Density test

Table 1 Compressive test results for the stones

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density (kg/m^3)	Compressive Strength (MPa)
1	49	50	50	2650	42.42
2	51	50	50	2641	41.15
3	50	51	49	2612	40.94
4	50	50	50	2622	40.52
5	51	51	50	2682	42.29

Table 2 Three point bending test results for the stones

Specimens	Depth (mm)	Length (mm)	Height (mm)	Density (kg/m^3)	Tensile Strength (MPa)
1	50	200	100	2619	2.51
2	51	200	100	2635	2.62
3	50	201	101	2653	2.59
4	50	200	101	2680	2.65
5	50	200	100	2665	2.43

According to experimental tests of the materials, the compressive strength values of the stones changed between 40.52 MPa and 42.42 MPa. From the compression tests, the average compressive strength obtained for the stones was determined as 41.46 MPa (Table 1). The tensile strength generally varied between 2.43 MPa and 2.65 MPa and the average value for tensile strength was found to be as 2.56 MPa (Table 2). In addition, the average density of the stones was determined as 2646 kg/m^3. Furthermore, the standard deviation of compressive strength was calculated as 0.846, while the standard deviation of tensile strength was calculated as 0.089. According to the Masonry Standards Joint Committee (MSJC 2005), the modulus of elasticity is determined as a function of masonry compressive strength. Therefore, in this study, Young modulus (E) for masonry units were calculated by E=200f_d formula where f_d is the average compressive strength of masonry unit (TEC 2007).

4. Finite element model and analysis

The finite element analysis (FEA) is one of the most useful and preferred methods in the field of engineering science. In order to analyze a structure, a numerical model is developed to represent the structure. The finite element method (FEM) is widely used in the analysis of masonry structures because of their complexity. In this study, firstly, the most suitable numerical model was prepared using FEA program, ANSYS Workbench (2012). In the modeling process, SOLID 65 elements, which has eight nodes and three degrees of freedom per node, was preferred for the description of the bridge. The three-dimensional model was discretized with 16629 nodes and 2646 solid elements (Fig. 12). The static and dynamic analyses were performed on the numerical model. The obtained analyses results were too complicated to present each node or element and, therefore, contour pictures, bars, and scale tables were used to present the results of the analyses. Moreover, it has been considered fixed boundary conditions in the foundation sections and

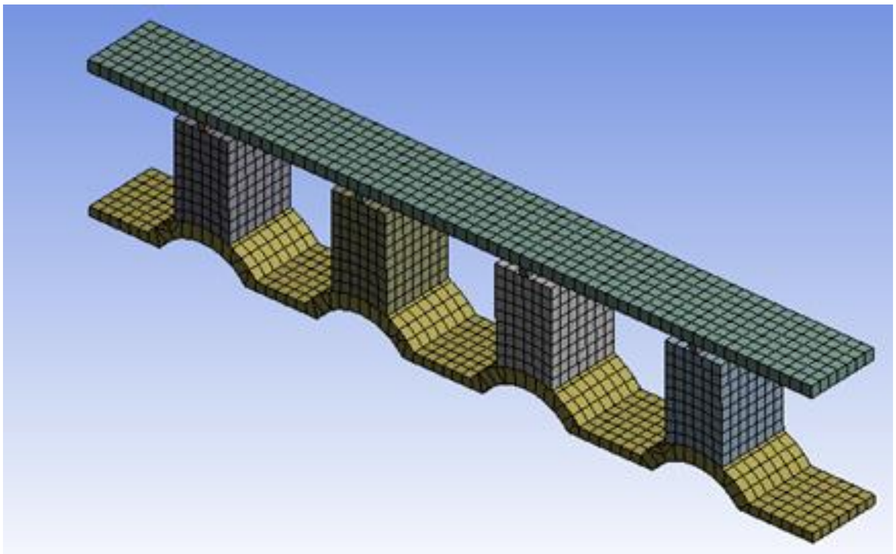


Fig. 12 Finite element model of the bridge

Table 3 Material properties of the materials

Materials	Young Modulus (N/m^2)	Poisson Ratio	Density (kg/m^3)	Cohesion (MPa)	Angle of Internal Friction	Flow Angle
Arches	8.3E9	0.15	2650	0.5	38°	15°
Piers	8.3E9	0.15	2650	0.5	38°	15°
Concrete	3E10	0.18	2300	3.0	32°	0°

sidewalls. In this study, the non-linear analysis has been performed based on the Drucker-Prager failure criterion (Drucker and Prager 1952), and the material properties to be used for the analysis are presented in Table 3.

4.1 Non-linear static analysis

The aim is to determine the non-linear static behavior of the bridge in this section of the study. Therefore, Low Bridge has been primarily performed by its self-weight in the non-linear static analysis. Fig. 13 provides schematic contours about the displacement of the components of the masonry bridge. When the components were individually investigated, the maximum displacement was observed in the vertical direction and on the top point of the slab reaching a value of 1.65 mm (Fig. 13(d)).

The investigation of the principal stresses observed in the structural stability system of the bridge showed that 1^{st} principal stresses occurred in the bearing section, and the maximum values were achieved between the superstructure and the bearing parts, and tension stress was determined as 1.98 MPa (Fig. 14). The 3^{rd} principal stresses occurred at the location between the superstructure and pier. The maximum compression strength in this section is found as 1.99 MPa (Fig. 15).

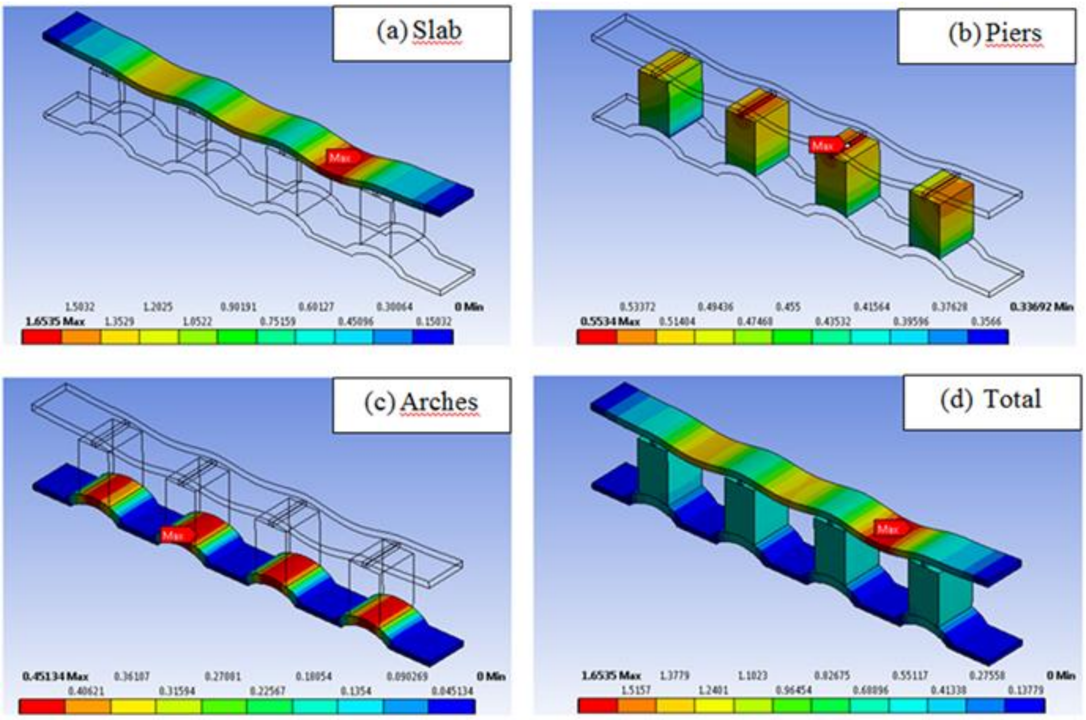


Fig. 13 Deformation of (a) Slab, (b) Piers, (c) Arches, (d) Total (mm)

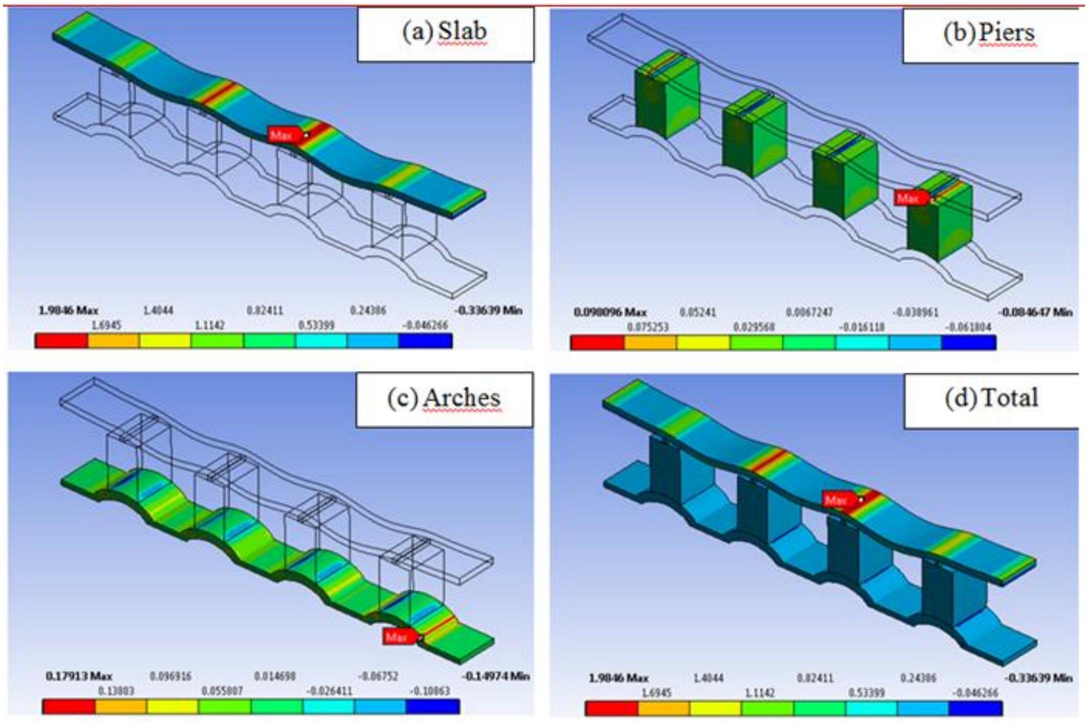


Fig. 14 1st Principal Stress of (a) Slab, (b) Piers, (c) Arches, (d) Total (MPa)

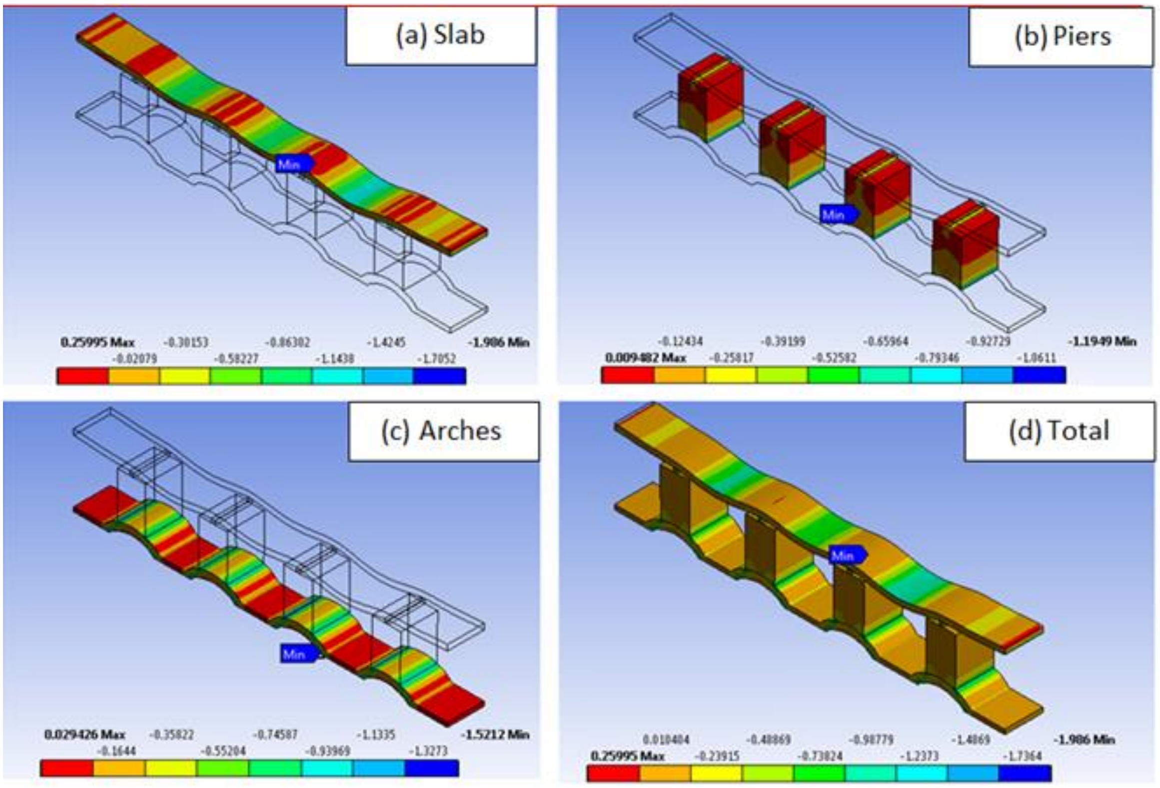


Fig. 15 3rd Principal Stress of (a) Slab, (b) Piers, (c) Arches, (d) Total (MPa)

4.2 Modal analysis

Modal analysis of vibration is simply used to determine mode shapes and characterizing resonant frequencies (Celep and Kumbasar 2011). Modal analysis changes from a multiple degree of freedom problem to a vibration problem. In the dynamic analysis of Low Bridge, mode shapes and mode vibration periods were primarily determined and the first four mode frequencies, periods, and mass participation ratios were summarized in Table 4. Furthermore, the first four mode shapes were shown in Fig. 16.

Table 4 The first four mode frequencies, periods, and mass participation ratios

Mode Number	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	8.229	0.1215	0.748E-24	0.477	0.119E-22
2	12.661	0.0789	0.970E-06	0.973E-26	0.448E-02
3	13.974	0.0715	0.761E-19	0.188E-04	0.205E-20
4	15.053	0.0664	0.248E-04	0.580E-23	0.126E-01

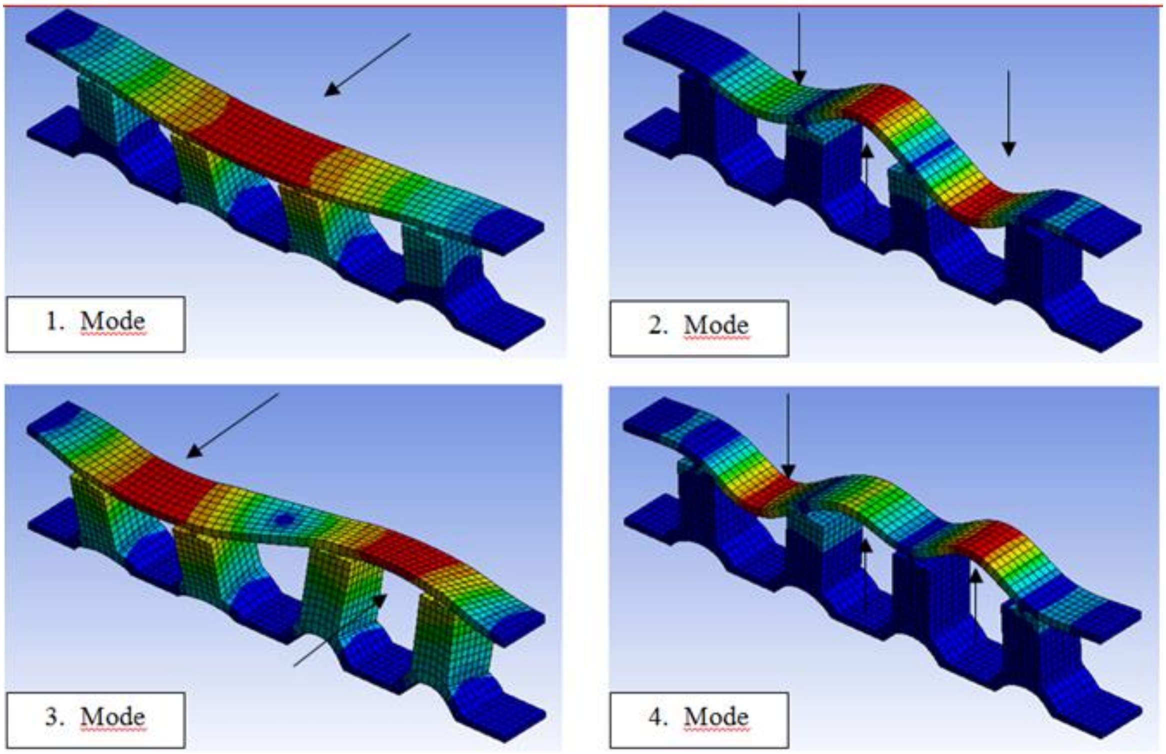


Fig. 16 The mode shapes of the first four modes

4.3 Non-linear dynamic analysis

Low Bridge was built in active earthquake prone zone. Seismic load is a function of the mass of the structure and the intensity of the ground acceleration. In regions subjected to earthquake motion, the behavior of the structure is very important for engineers. Historical structures are at risk when encountering seismic events, and these structures are usually deficient in resisting seismic loads. Amasya and its surrounding cities are in areas prone to seismic activities. The Amasya city center is a first-degree earthquake prone zone, which is expected to have acceleration values between 0.4 g (Fig. 17). Therefore, many destructive earthquakes have taken place in this area in the past. Seismic records show that the most powerful events occurred on March 13, 1992 in Erzincan. Erzincan is located at a seismic prone zone near Amasya. When the Erzincan earthquake occurred, it not only affected Erzincan but also other neighboring cities. The earthquake had an estimated magnitude of 6.8 on the surface wave magnitude scale and resulted in 497 deaths, 2000 injuries, 4157 severely damaged buildings in addition to the 5453 moderately damaged and 7867 slightly damaged buildings (NEMC 2012). The acceleration records of Erzincan earthquake at centre station were considered and the input ground motion was applied only in the horizontal direction (East and West) in Fig. 18.

Fig. 19 shows the lateral displacement time history at different level of the bridge. When the figure examined, it shows that the maximum displacements reached a value of 2.86 mm over the superstructure. The lateral displacements reached values of 1.42 mm and 0.35 mm in second pier and second arch, respectively.

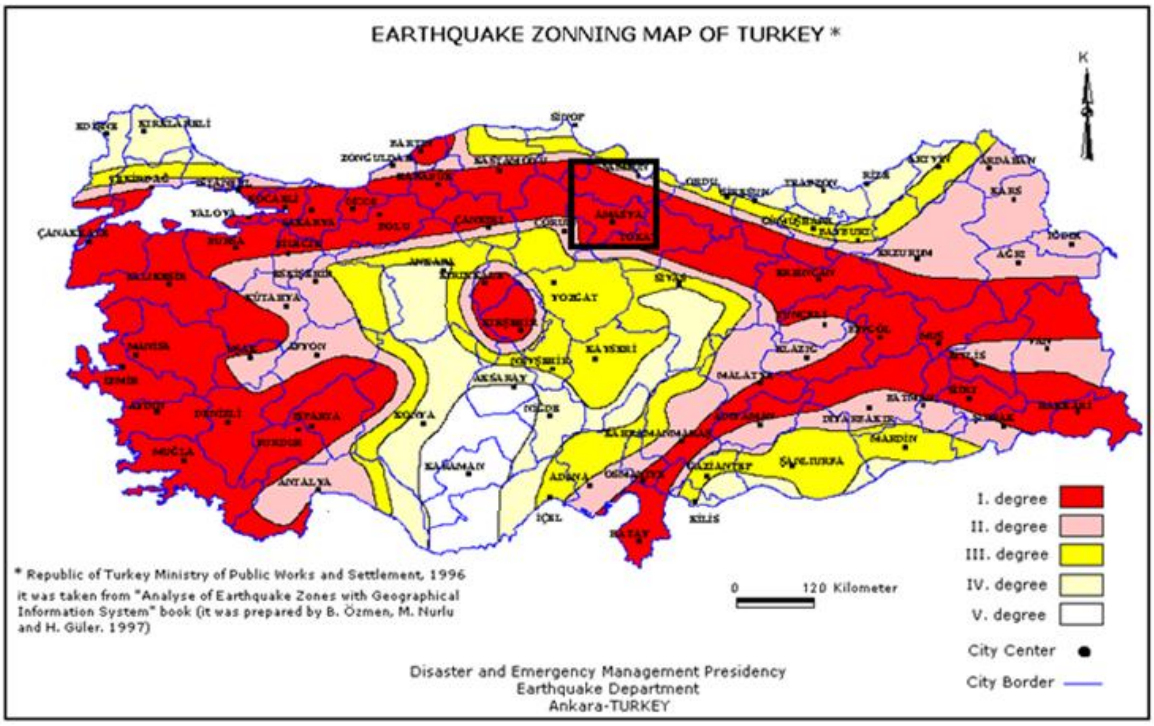


Fig. 17 Earthquake map of turkey (AFAD 2013)

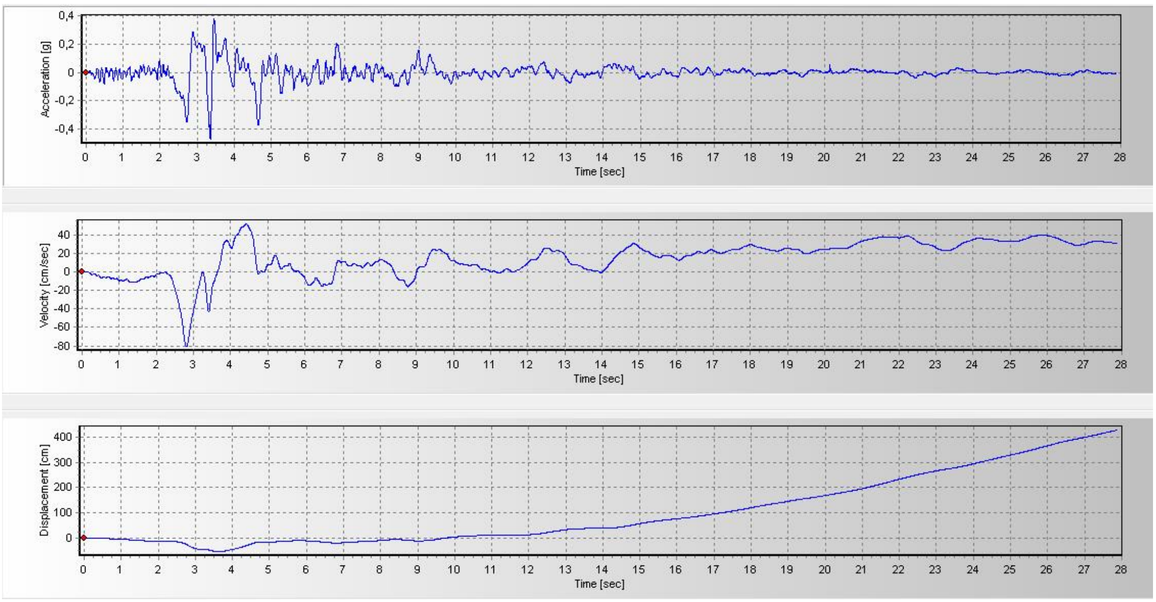


Fig. 18 Ground motion records (E-W) of Erzincan earthquake (AFAD 2013)

The critical stresses derived through this method were intensified in the supports of the main arch that carries the piers. In particular, tension stresses were encountered in the supports of main arch system and in the bottom sections of the main bearing elements. Furthermore, the examination of the principal stresses reflects that 1st principal stresses were encountered as tension stresses in the superstructure of the bridge and in the support point, which is between the slab and the piers parts. The maximum of those values were found to be as 3.27 MPa, 1.21 MPa and 2.47 MPa in the slab, pier and arch, respectively (Fig. 20).

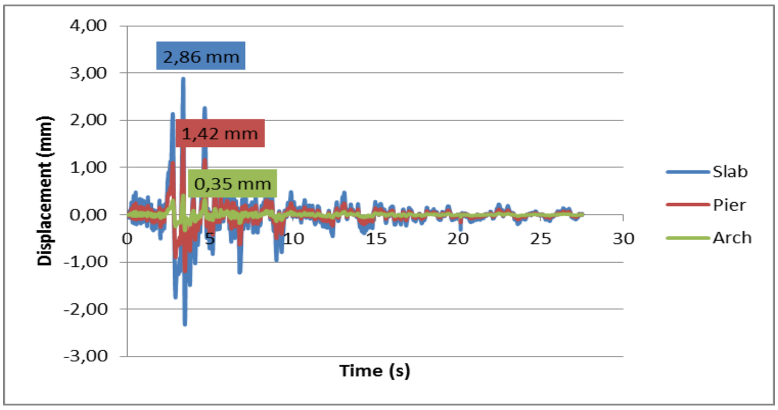


Fig. 19 Lateral displacement of the bridge components

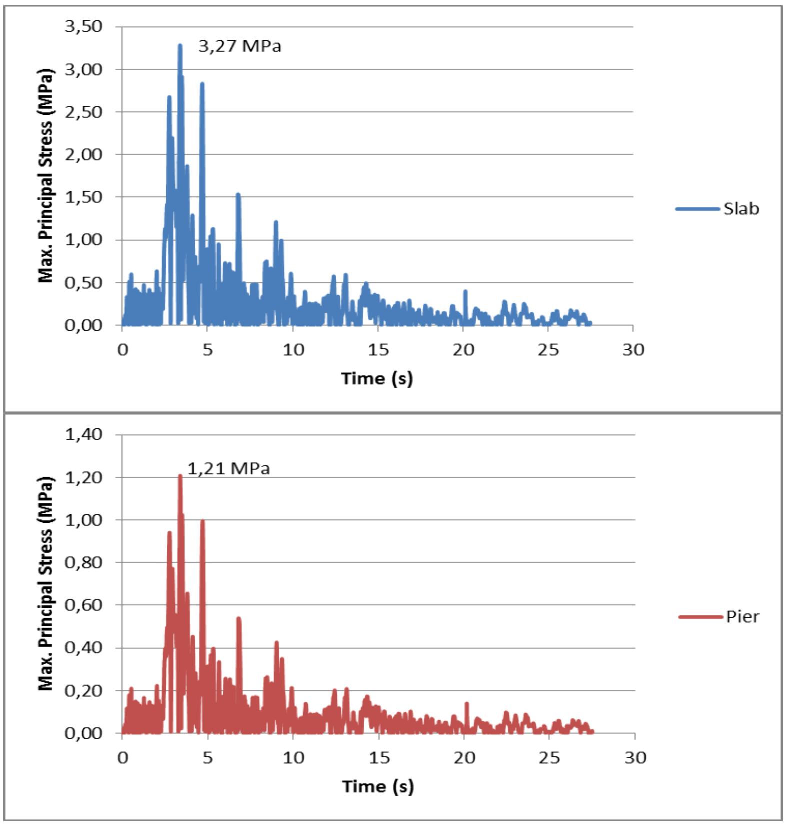


Fig. 20 Maximum principal stress in the bridge components (MPa)

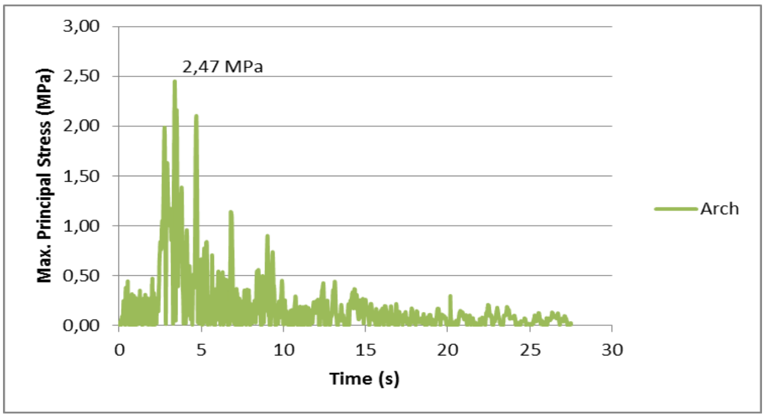


Fig. 20 Continued

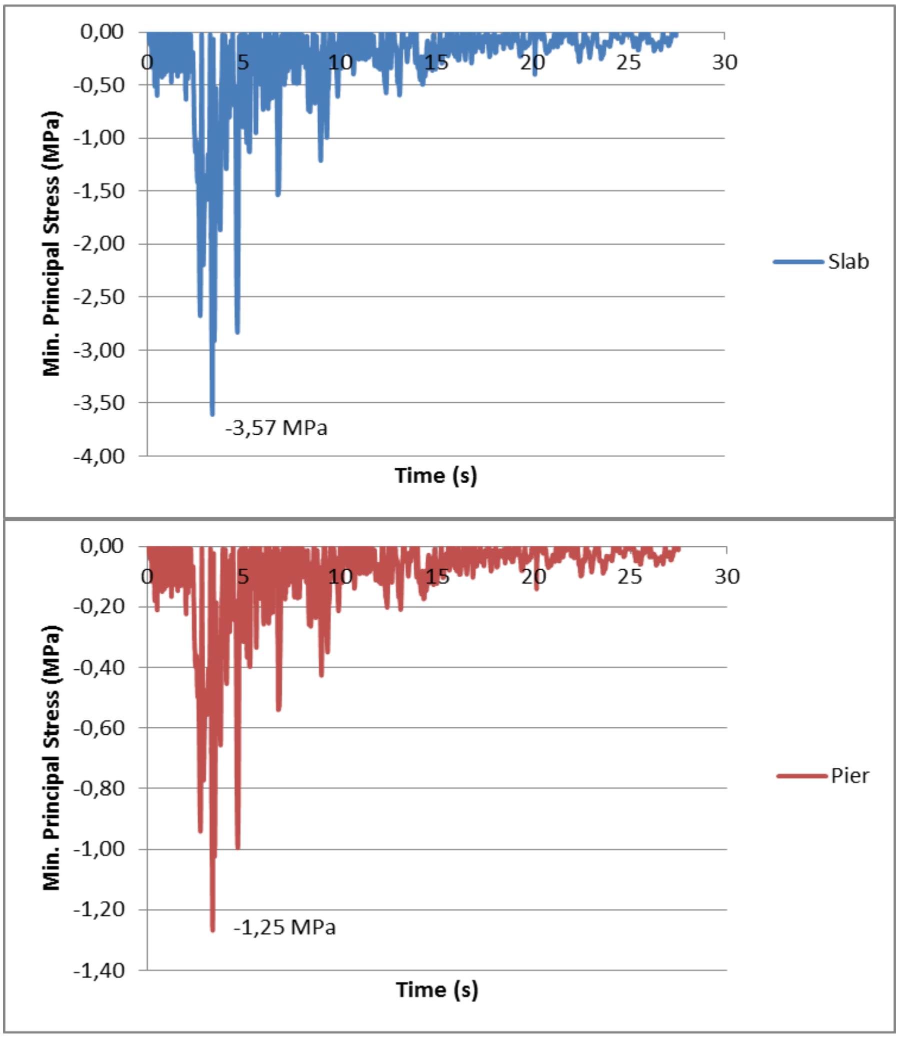


Fig. 21 Minimum principal stresses in the bridge components (MPa)

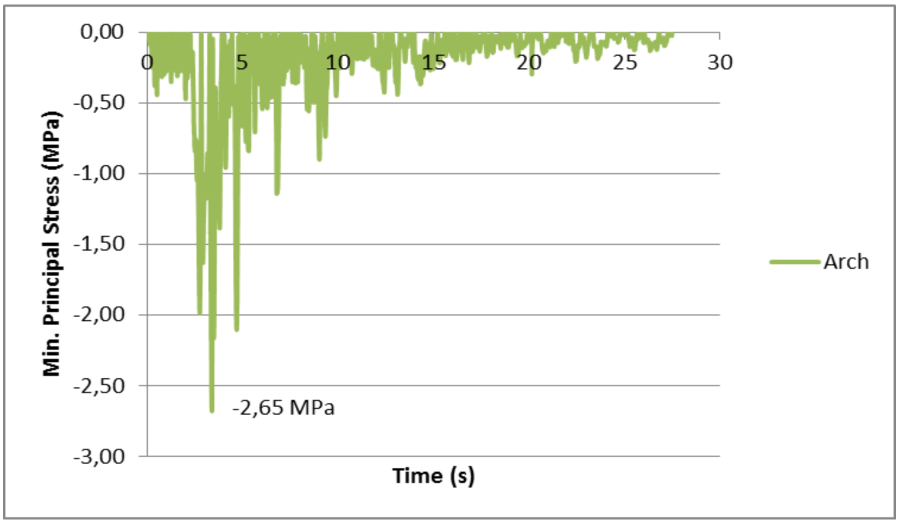


Fig. 21 Continued

3rd principal stresses occurred as compression stresses and were intensified in the lower and support sections of the main arches. In particular, the stresses intensified the skewback points of the arches and the transient zone between the arches and the piers. When the bridge components examined, in the slab section, the maximum compression stress was found as 3.57 MPa; in the pier section, it was found as 1.25 MPa; in the arch section, it was found as 2.65 MPa (Fig. 21).

5. Results and discussions

This study mainly focuses on historical bridge "Renovated Masonry Low Bridge" situated in Amasya, which is located in a seismically active zone of Turkey. In terms of architectural detail, the bridge has three main components, arches, piers and slab. The objective was to analyze damage mechanisms and seismic vulnerability of the bridge and bridge components. First, a brief description of structural features and architectural characteristics of the bridge is presented. A 3D numerical model was prepared in order to show behavior of the structural components and its probable local and global weaknesses under seismic actions. The FEA is applied to predict structural behavior and seismic vulnerability in weak zones of the structure under expected seismic intensity.

In this section, the results of the analyses are discussed and compared with the previous studies. When the static analysis results are examined, the maximum displacements are observed in the maximum span of the bridge. In terms of maximum tensile stresses, the stresses are outstandingly changed in the corner points of the arches and the piers. The modal analyses show that the first mode shape of the bridge has translation in Y direction, the second and fourth mode shapes have almost sinusoidal shape of the slab section of the bridge while the third mode are under the effect of torsion. The findings that are obtained from the static and modal analyses are similar to Boothby *et al*. (2005), Pela *et al*. (2009), Fragonara *et al*. (2011).

The dynamic analysis results indicated that the maximum compressive and tensile stresses occurred at the base of the arches and on top the superstructure, respectively. When the maximum tensile stress contour is examined, the stresses are outstandingly changed in piers and in top parts and springer points of the arches. As compared with the experimental tensile stress values for the stones, the tensile stress values in the piers and arches, which were constructed with the stone, is comparably low. Furthermore, the findings of the analyses show that the maximum lateral displacements occurred in the slab and upper parts of the bridge. The maximum displacements were calculated as 2.86 mm. Previous research in the literature (Dogangun *et al*. 2008, Cakir and Uysal 2014, Seker *et al*. 2014, Cakir *et al*. 2014) has suggested to use the following equation for maximum relative displacement requirement of masonry structures. Therefore, this study also considers this equation for the comparison of displacement values.

$$\Delta_{i\max} \leq \frac{0.02 \cdot h_i}{R} \tag{1}$$

Where h_i, R are the height of the structure, and the behavior factor related to the ductility of structure, respectively. For Low Bridge h_i=15 m, R=2 and the corresponding maximum allowable top displacement is 0.15 m. The study indicated that the displacements obtained from static and dynamic analyses are found to be lower than the values obtained from the above formula. Therefore, it can be concluded that the displacements are in the allowable limits.

The examination of the results proves that the bridge keeps up with its initial performance and this shows the complexity of its structural behaviors. However, the geometrical changes on the bridge may be caused by the structural damages. It is well known that bending moment does not occur in the arches owing to its curvature properties. However, because of the interaction with other components, and the fact that the load is almost never symmetric, the bending moment will always be present. In addition to the bending moments, there are also horizontal thrusts in arches, especially in complex structures. All these conditions will impose tensile stresses in the cross sections of the arch structure. Since increasing the dead loads reduces the tensile stresses, cross-section dimensions of arches are often very large. This is especially true in historic masonry structures, where engineers in maintaining the stability of arches recognized the contribution from the self-weight. Therefore, potential failures because of geometrical changes should not be neglected because these changes cause irreversible effects on the structure in a negative manner.

6. Conclusions

Many masonry bridges have been accepted as historical monuments, and they must be protected with convenient restoration methods and suitable construction materials. Therefore, it is important to understand the construction materials, structural components, and their structural integrity. An essential understanding of the structural behavior of masonry arch bridges requires information about their structural elements. An understanding of their load carrying capabilities and an estimation of the structural integrity and intensity of load on them is needed in order to better understand the performance of masonry bridges and how they have been able to survive changes in the structural components. This study mainly focused on a renovated masonry bridge and its structural components. In this study, experimental and numerical analyses were carried out in order to determine the structural behavior of Low Bridge in Amasya, Turkey. A further aim of the study is to reveal the adaptation between structural parts from different periods throughout history. The originality of this paper is that it takes the effects of changes made in different periods of history into consideration, and it also evaluates the integrity of components belonging to different civilizations. In this scope, the main focus was given to material properties, and material characteristics were defined through compression and three-point bending tests. In the next step, three dimensional finite element model of the current structure was developed and the performance of structural components was observed FEA.

Results of the analyses show that the structural integration between the components plays an important role in the dynamic behavior of the structure. Critical stresses were calculated in the region between the arches and the piers. Moreover, the supports of the slab and the piers might be enforced during the earthquake when the deformations in the dynamic analyses are considered. It is also detected that the supports of the arches that carry the piers of the bridge deserve special attention since they have a considerable effect in the structural performance. In addition, it is predicted that the analyses conducted in the scope of this study, and the results of these analyses, will encourage and inspire other studies. Different materials, geometrical forms, and different earthquake ground motions must be studied further to better understand main and adjacent structures' dynamic effect and interaction.

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References

AFAD (2013), Republic of Turkey Prime Ministry, Disaster and Emergency Management Precidency, Earthquake Department, http://www.deprem.gov.tr/sarbis/shared/DepremHaritalari.aspx. 09.11.2013.

Anonym (2014), http://suluovagazetesi.com/giris.asp?kategori=9&kelime=&SF=277.

ANSYS (2012), 14.0 Release, Finite Element Analysis Program, USA.

Boothby, T.E., Yurianto, Y. and Erdogmus, E. (2005), "Experimental replication of masonry arch bridge spandrel wall collapse", *TMS J.*, December 2005.

Cakir, F. (2011), "Assessment of structural integrity and seismic retrofit of masonry bridges using micropiles", MSc., Thesis, Department of Civil, Architectural and Environmental Engineering, Graduate College of the Illinois Institute of Technology, Chicago, USA.

Cakir, F. and Mohammadi, J. (2013), "Micropiles applications for seismic retrofitting of historical bridges", *Int. J. Eng. Appl. Sci*., **5**(2), 1-8.

Cakir, F., Seker, B.S. and Dogangun, A. (2014), "Assessment of structural performance of historical Ishan Church with experimental tests and numerical modeling", *Gradevinar, J. Croatian Soc. Civ. Eng.*, **66**(5), 433-443.

Cakir, F. and Uysal, H. (2014), "Seismic performance of historical masonry clock tower with adjacent walls", *Earthq. Struct.*, **7**(2), 217-231.

De Felicia, G. (2009), "Assessment of the load-carrying capacity of multispan masonry arch bridges using fibre beam elements", *Eng. Struct.*, **31**(8), 1634-1647.

Dogangun, A., Acar, R., Sezen, H. and Livaoğlu, R. (2008), "Investigation of dynamic response of masonry minaret structure", *Bull. Earthq. Eng*., **6**(3), 505-517.

Drucker, D.C. and Prager, W. (1952), "Soil mechanics and plastic analysis or limit design", *Quart. Appl. Math.*, **10**, 157-165.

Fanning, P.J. and Boothby, T.E. (2001), "Three-dimensional modelling and full-scale testing of stone arch bridges", *Comput. Struct.*, **79**(29), 2645-2662.

Fragonara, L.Z., Ceravola, R., Quattrone, A. and De Stefano, A. (2011), “Experimental testing of a masonry arch bridge model subject to increasing level of damage”, *4th International Conference on Advances in Experimental Structural Engineering*, Lombardy, Italy.

Menç, H. (2000), *Amasya: Throughout History*, First Edition, Net Ofset Publishing, Ankara, Turkey. (in Turkish)

Milani, G. and Lourenço, P.B. (2012), “3D non-linear behavior of masonry arch bridges”, *Comput. Struct.*, **110**, 133-150.

NEMC (2012), National Earthquake Monitoring Center, Bogazici University Kandilli Observatory and Earthquake Research Institute, Turkey, http://www.koeri.boun.edu.tr/sismo/Depremler/tLarge2.htm, 05.11.2013.

Pela, L., Aprile, A. and Benedetti, A. (2009), “Seismic assessment of masonry arch bridges”, *Eng. Struct*., **31**(8), 1777-1788.

Pela, L., Aprile, A. and Benedetti, A. (2013), “Comparison of seismic assessment procedures for masonry arch bridges”, *Constr. Build. Mater*., **38**, 381-394.

Reccia, E., Milani, G., Cecchi, A. and Tralli, A. (2014), “Full 3D homogenization approach to investigate the behavior of masonry arch bridges: The Venice trans-lagoon railway bridge”, *Constr. Build. Mater*., **66**, 567-586.

Seker, B.S., Cakir, F., Dogangun, A. and Uysal, H. (2014), “Investigation of a masonry domed mosque by experimental tests and numerical analyses”, *Earthq. Struct*., **6**(4), 335-350.

TS 699 (2009), “Methods of testing for natural building stones”, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey. (in Turkish)

TS EN 1467 (2012), “Natural stone-rough blocks-specifications”, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey.

TS EN 1469 (2006), “Natural stone products-slabs for cladding-requirements”, Turkish Building Code, Turkish Standards Institution, Ankara, Turkey.

TEC (2007), “Specification for structures to be built in disaster areas”, Turkish Earthquake Code, Ministry of Environment and Urbanization of Turkey.

Uysal, H. and Cakir, F. (2013), “Static and dynamic analyses of the historical Erzurum Watchtower”, *Found. Preservation Turkish Monum. Envir.*, TAC Foundation, **1**, 72-80. (in Turkish)

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