Characteristics of Anatolian stone arch bridges and a case study for Malabadi Bridge

A. Doğangün and A. Ural
Karadeniz Technical University, Department of Civil Engineering, Trabzon, Turkey

ABSTRACT: Many civilizations settled in Anatolia which is one of the oldest settlements of the world due to the geographical conditions and they constructed some marvellous historical structures. This study investigated the geometrical and structural characteristics of historical stone arch bridges in Anatolia. For this aim at first, constructed arch bridges are surveyed considering their lengths, heights, arch spans and number of arches etc. The Malabadi Bridge, one of the most famous historical heritage bridges, is selected as a case study. Finite Element Method is used for the modelling. Support settlements are considered in the analyses. The prototype modelled with continuum elements at macro-level and an analysis performed including nonlinear material behaviour is discussed.

1 INTRODUCTION

A lot of construction materials were used for the historical structures like stone, brick, adobe or timber etc. Unfortunately many of the historical structures constructed with these materials except for the stone, have not lasted to the present time. Stone is one of the most durable materials. Therefore this material has been commonly used in historical structures. But it is not easy to construct every form using this material. Nevertheless stone was to play a part in the prestige of ancient nations, as in case of pyramids in Egypt. In later periods, large pre-hispanic monuments in Mexico, the great monumental walls of China, Roman, Byzantium walls, temples, and palaces, fortresses are among other examples. Reflecting signals of more recent medieval periods, Inca's approach to shape the stone into monumental sizes constitutes another greatly attractive achievement (Sevgili et al. 2005).

Historical structures are some of the most important heritages for the technical and historical researches. They are called as "architectural heritage" in technical, historical and intellectual media and very popular research topic in the present time. Castles, bridges, mosques and city walls etc. all reflected cultural values from their construction periods. Archaeological researches, monitoring and ultrasonic non-destructive tests have been mostly used for the inspecting the characteristics of these structures.

Historical structures deteriorate due to climatic changes, aging, earthquakes, floods, wars, biological colonization and some support settlements etc. (Ural et al 2007). If a historical structure has lasted to present times it must be maintained to survive into the future. Any restoration and conservation research must be done attentively.

Anatolia has a lot of historical structures, built in various periods, due to the geographical conditions and diversity of civilizations. Mesopotamian and Hittite remains are still visible in the eastern part of the peninsula while Hellenistic and Greco-Roman structures are frequently encountered on the western areas (Sevgili et al. 2005). The first examples of arches were seen in the underground tombs of the Sumerians in Mesopotamia around the years 3000BC (Toker and Ünay 2004). Also mosques, minarets and arch bridges constructed with stone are the greatest historical structures remain from the Turkish history. In spite of this abundance, they suffered badly due to some big battles through history. More recently the Turkish government has given attention to these structures and recognised the need to conserve and restore them.

2 STONE ARCH BRIDGES

Transportation and trading are among the important reasons for people to build arch bridges on the rivers from the early civilizations. They were built with stone before iron, steel or concrete bridges were introduced and most of them are still in strong condition. The keystone is the most important part of the arch form of these bridges. It holds the other arch stones together and the arch would collapse without this stone. The keystone was put in the place at the mid-span of the arch and the other stones leaned against it (Fig. 1a). Although the keystone is visible at some Roman arch bridges, it is not much possible to recognize at the Turkish arch bridges due to the similar shape and sizes of arch other stones. During construction process of the bridge, some wooden frame can be used to provide the arch stones to be put in position (Fig. 1b). The wooden frame removed after finishing the stones are in position.

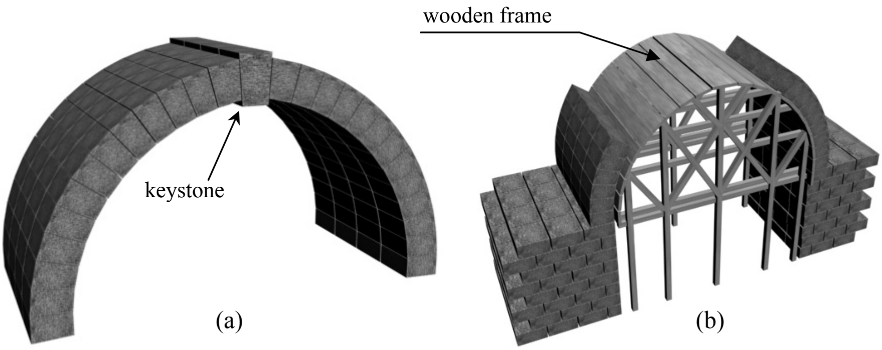


Figure 1: Some features and stages of a simple arch form, (a) the keystone, (b) constructing arch stones.

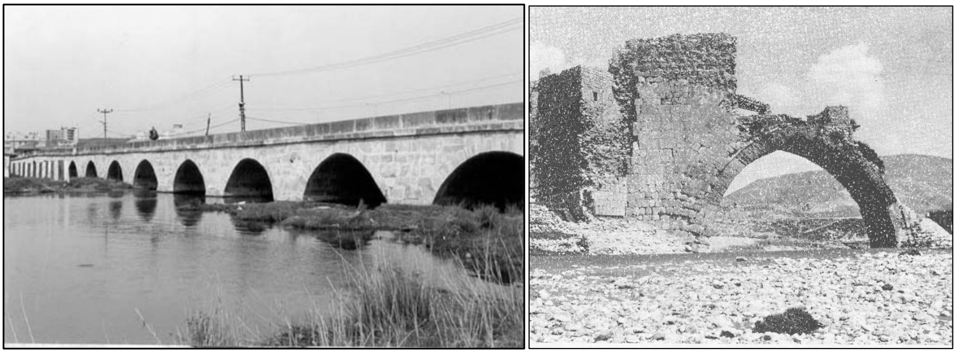
Le Pont du Gard, built by the Romans over two thousand years ago is one of the most famous arch bridges on the world as seen from Fig. 2. The technique mentioned above was used to construct this marvellous example.

Figure 2: Le Pont du Gard (Sevgili et al. 2005).

2.1 Turkish Stone Arch Bridges

Stone arch bridges are some of the most important historical structures of Turkey. They occupy an important place among historic engineering items. These bridges were built as a result of local funding and by the labours of the local inhabitants. They were usually built out of the downtowns. Unfortunately, they have generally not been given the importance they deserve. It has not been interesting or valuable to the people and researchers, because they see so many stone arch bridges. Nevertheless some studies have been done by the media or government to emphasize the importance of architectural heritage and also stone arch bridges. Turkish stone bridges; from medieval to the end of Ottoman period by Çulpan (2002), our stone bridges by Tunç (1978) and our bridges on our roads by TCK (1988) are mainly guided national authors to the literature survey. Although they all present unique symbols of heritage like other monuments they are exposed to natural or man-made hazards and most are not restorable.

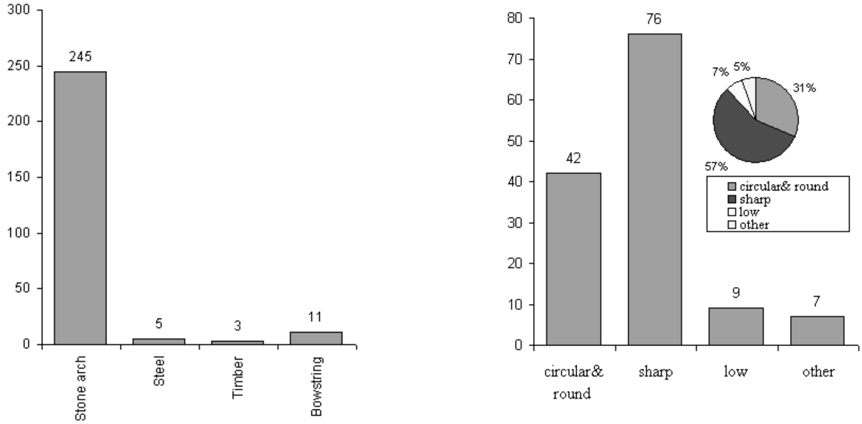
An archive study that takes in account very different parameters consisting of historic contents and engineering profile was carried out for the bridges. In this study of bridges: (a) name, (b) location, (c) construction period, (d) construction materials, (e) total length, (f) height, (g) road width, (h) number of arches, (i) span of arches, (j) type of arches, (k) cutwaters, (l) conservation studies, (m) special remarks were noted. These items have been noted for 264 different bridges till just now, and existing ones have been tabulated in Excel format as an archive. It should be noted that our archive study is continuing, and it will be meet some other values for the bridges. Some of this data is presented graphically below.



(a) (b)

Figure 3: Bridge samples from Anatolia peninsula, (a) Uzunköprü Bridge (2006), (b) Hasankeyf Bridge (Tour of Turkey 2006).

The 10 longest arch bridges in Turkey are given in Figure 5a. Uzunköprü Bridge is the longest bridge among them (Fig. 3a). This bridge is near Edirne and over the Meriç River. It was built in 1443 during the Ottoman period by Sultan Murad II. It is 1266m long and ~5.5m wide. It has 174 arches and the biggest of these arches has a span of 13.10m. Due to the construction area being swamped; it was constructed very long to pass that area. These interesting characteristics made it famous among Turkish arch bridges, especially the length of it. Çobandede Bridge is one of the highest (30 m) bridges in Anatolia. According to the research; Hasankeyf and Malabadi bridges have very long arch span around 40m. This is very high value such masonry stone bridges. Unfortunately Hasankeyf Bridge (Fig.3b) is in very poor condition and most parts of the bridge are collapsed. The values of arch spans for ten bridges are compared in Figure 6.

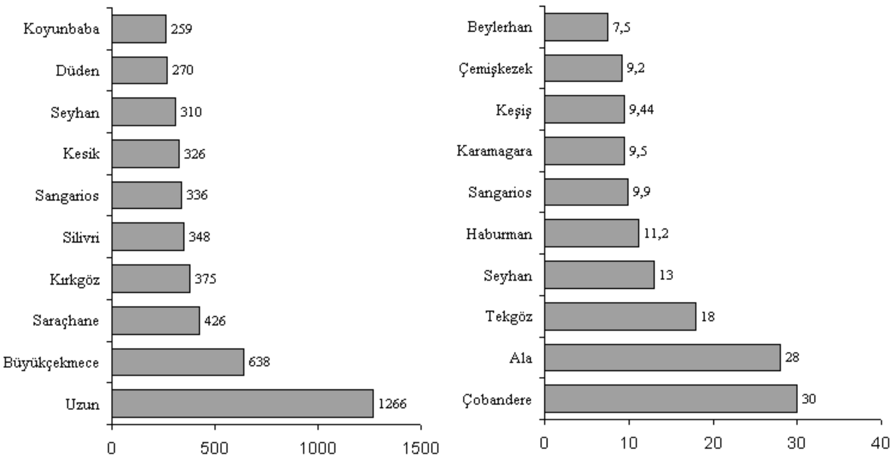


(a) Comparison according to structural materials (b) Comparison according to arch types

Figure 4: Numbers for bridge materials and types of arch.

Almost all the historical bridges are constructed with stone. The number of the stone arch bridges is 245; the others are only 19 bridges as shown in Figure 4a. Most stone arch bridges are made of either sandstone or limestone. In some bridges special stones such as Köfeki stones were used at it was assumed that they harden with time.

Different arch types were used in the historical bridges. Pointed arches had been mostly preferred as shown in Figure 4b. The second preferred arch type is circular (semi-circular or depressed arch shaped). In some bridges both types were used for the main and flood arches in same bridge.



(a) Top ten longest historical bridges in Turkey (b) Top ten highest historical bridges in Turkey

Figure 5: Longest and highest historical bridges in Turkey according to the survey.

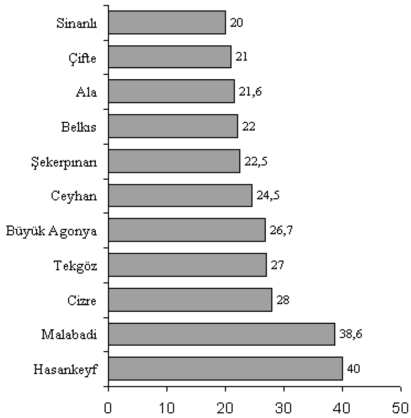


Figure 6: Ten longest arch spans for the historical bridges.

2.2 The Malabadi Stone Arch Bridge

The Malabadi Stone Arch Bridge is a magnificent Artuklu structure on Batman River between the provinces of Diyarbakir and Batman. According to its inscription, the bridge was built in 1147 – 1148 by Timurtas Bin ilgazi of the Artuklu. It is the widest of all stone arch bridges existing in Anatolia. It is interesting to note that the bridge connects the two sides of the river not on a straight line but by making curves. There are two boarding facilities for passengers on both legs of the bridge. (Diyarbakir, 2007)

It was once the only bridge across the river in this area, and was in continuous use until the 1950s, when a new road bridge was opened upstream. The span of the bridge crosses perpendicular to the river, and there are angular breaks in the east and west approaches. The approaches rise from ground level to meet the central span, which is a pointed arch high over the deepest part of the river. Constructed from coloured solid masonry, the approaches have small arches built into them to let flood-waters through. Two of the piers of the bridge sit in the river; the western support is decorated with two carved figures, one standing and one sitting (Answers.com 2007). The bridge is 150 m long and 7 m wide, 19 m in height. The spandrels of the main arch incorporate small rooms for weary travellers.

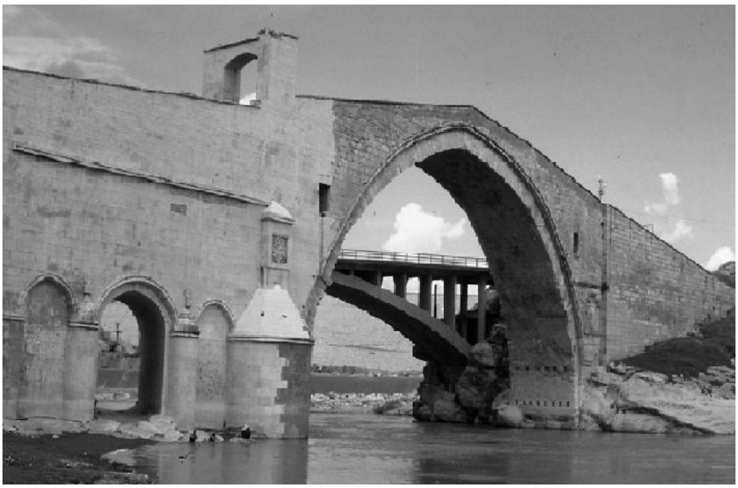


Figure 7: The Malabadi Bridge.

The numerical applications are performed with LUSAS (2006) software which has a wide range of finite element types and material models. Two analyses cases are considered as dead load only and some support motions to determine the general behaviour of the bridge. As stated above due to the long arch span, the Malabadi Bridge may expose some support settlements. Therefore, vertical displacement applied to the supports marked up in Figure 8a to determine the support effects to the main arch. Nonlinear material behaviour is considered as Drucker-Prager criterion and 8 noded solid elements used for the mesh generation. The model has been considered composed by two different materials for the different structural elements; the arch and the spandrel walls. Due to the low affects, the material properties of lateral parapets are neglected. The 3-D finite element model with generated meshes is shown each vertical section, plan and perspective in Figure 8. Due to difficulty to determining the material characteristics, properties of materials are considered from the similar stone arch bridges on the literature.

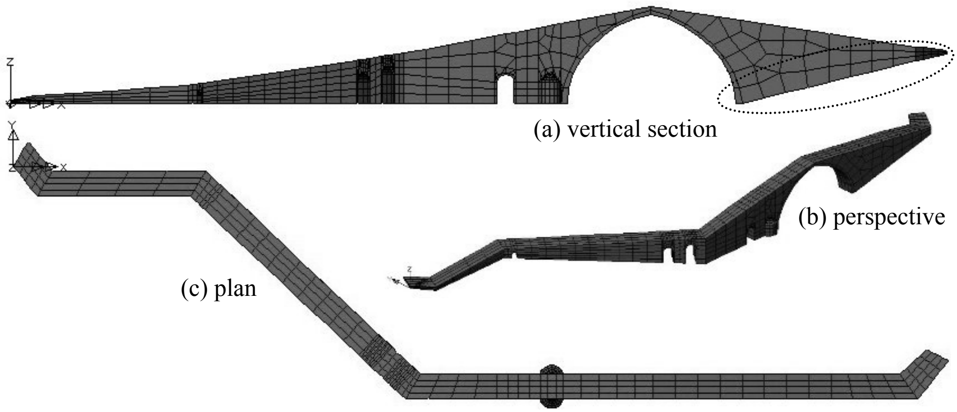


Figure 8: 3D Finite element model of the Sample Bridge, (a) view, (b) perspective, (c) plan.

It is found from the linear static analysis that the structural form of the bridge is perfect. The maximum vertical displacements occurred on the arch form about just 9.7 mm. Also maximum equivalent stresses occurred on the same area of the bridge as the acceptable and expected values. Therefore the bridge may not be exposed any damage from the self weight.

The nonlinear analysis is performed for the second case study considering the support motion on the right pier of the span (Fig. 8a). The supports on the right base of the bridge are prescribed with vertical displacements and the strains are observed from the deformed shape of the bridge (Fig. 9).

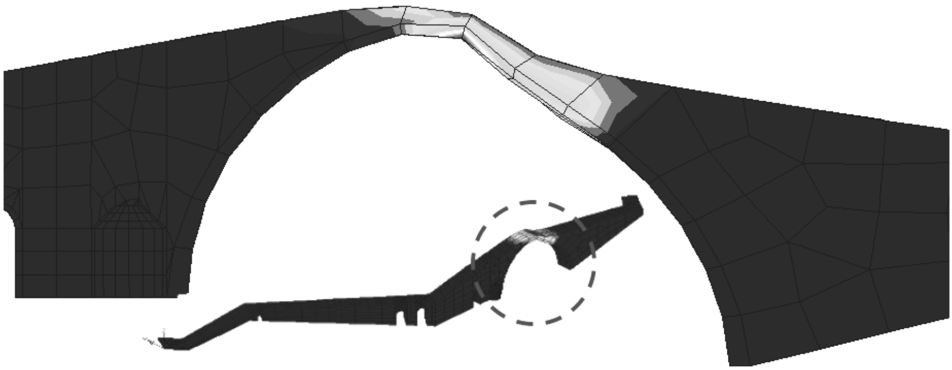


Figure 9: Deformed mesh of the bridge with strain contours.

Main arch is considerably affected due to the support settlements. Especially maximum equivalent strains are occurred on the mid-span of the arch that clearly seen from above and the right side of the arch has a serious damaged. After the nonlinear analysis, a graph from the following figure is drawn from the maximum equivalent strain and total load factor values.

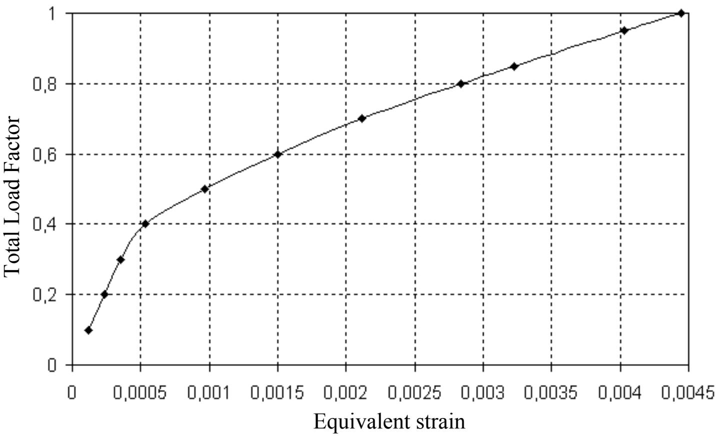


Figure 10: Load-Strain graph on the node of the maximum strain occurred.

According to this graph, the bridge acts with nonlinear behaviour from the value of 0.35 of total load factor and perhaps most of the failures occur over the 35 mm of vertical displacement.

3 CONCLUSIONS

Statistical and general information about Turkish stone arch bridges are given in this paper. The archive study on surveying the present Turkish stone arch bridges is still being continuing and many other bridges on the Anatolia peninsula will be added to the database in the future. According to this archive study; Turkey has a lot of arch bridges remained from the past civilizations and most of them were constructed using with stone. Most arches are in pointed or circular type, and most of them are perfect condition results of some restoration and conservation studies.

Also a case study on Malabadi arch bridge is performed both self weight and support motion cases. Malabadi arch bridge, remains from 12^{th} century and has a widest arch between stone arch bridges in Anatolia. Results from the self-weight analysis, the bridge has perfect conditioned, and from the nonlinear support motion, failures occur on the mid-span of the main arch about over the 300 mm of the vertical displacement. Also from literature, the mid-span of stone arch bridges has similar maximum values and these locations can be most take care on the strengthening studies.

The earthquake characteristics of the historical arch bridges are one of the important studies and must be discussed with comprehensive analyses. Because, earthquakes are always number one enemy due to their weak response. The subject of seismic response on this sample bridge is also continued with another work.

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