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Historical Stone Arch Bridges' Damage Causes and Repair Techniques

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Abstract: Many historical stone arch bridges have been exposed to the different environmental effects, which could cause structural damage, at different times. Under these natural or human-induced effects such as floods, earthquakes, the bridges were partially or completely damaged. The repair of the historical arch bridges has been repaired against to these damages. The success of the repair work depends on both a detailed archaeological-historical survey and a detailed structural evaluation process carried out together. It is very important to determine the answers to questions such as date and time of construction of the structure, whether there was any interruption in the construction process, the scheme and the order of the damages of the structure, what were the repairs and strengthening done in the structure and whether there was any change in the use of the environment. After these process, the repair method is determined considering many alternatives such as partial or complete disassembly for remodeling of the bridge, regional repair or regional strengthening, full strengthening of the upper structure, removal of excess weight over the bridge, balancing of mass and stiffness distribution, improvement of structural interaction between arches and feet, strengthening of foundation system of the bridge. In this study, the repair methods against the damages occurred on the historical masonry arch bridges exposed to different damages have been tried to be evaluated.

1. Introduction

Historical stone arch bridges are structures that play an important role in connecting the past and the future. These historical bridges constitute our cultural heritage. Therefore, historical bridges need to be transferred to future generations safely and in a healthy way. Historical stone arch bridges suffered many damages due to the external effects and misuse caused by them, and the damages resulting from these damages need to be repaired correctly. But while repairing these damages, the main purpose of the historical bridge should be to restore the old strength without disturbing the historical texture.

Erdal carried out his work on the control and maintenance management of bridges. This study examined the types of deterioration in stone bridges [1]. Yucel and Namli, investigated the effect of water and other factors on the distortion around the bridge legs. They determined that the deterioration around the bridge legs was closely related to the river regime, bed material and foot type, and it was necessary to investigate the rivers where the bridges would be built and that the most suitable bridge foot type could be determined under the light of these data. In this study, the measures to be taken against the distortions occurring around the bridge pillar, the changes in the speed and pressure area were examined [2]. Bayraktar et al., examined the effect of finite element model improvement on earthquake behavior of historical bridges. They selected the Sinik bridge in Trabzon for this study. They then compared the experimental and theoretically obtained dynamic characteristics of the bridge. Under the light of these data, they updated the finite element model of the bridge and formed the most realistic model [3]. Ural et al., gave general and statical information about historical arch bridges. They presented structural damage occurring at arch bridges in the Karadeniz region and presented repair-strengthening procedures. They gave repair-strengthening techniques applied on stone arch bridges [4]. Alaboz, carried out studies on the current status of the Architect Sinan bridges in the Marmara region, determining what caused the damage and developing appropriate repair recommendations [5]. Korkmaz et al., conducted a dynamic analysis of the historical stone arched Timisvat Bridge in Rize. They compared the displacement and stress values obtained as a

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result of the analyzes made in the time domain [6]. Firat and Eren, investigated their effect experimentally by applying different FRP reinforcements on the damaged belts. The reinforcement technique was numerically modeled on the applied belts by means of the structural analysis program. They compared experimental and numerical results [7]. Alpaslan et al., investigated the effect of local stiffness increase on building behavior due to local reinforcement in historical buildings. In their study, they examined the results of dynamic analysis in case of strengthening by applying more rigid material to undamaged, damaged and damaged areas of a historical masonry bridge. In dynamic analysis, they showed that the deteriorated elements in the historical structure affect the structure behavior negatively due to load transfer [8]. Koc, the effects of different FRP reinforcement techniques which can be used in damaged stone arch systems on belt behavior were investigated. The reference belt sample was loaded until failure. Six belt samples other than the reference sample were first damaged by applying 75% of the reference sample collapse load [9]. Ilerisoy and Sagir,. the impacts of bridges that have witnessed history, deterioration and destruction caused were discussed. Studied the factors discussed above in Erzincan Tercan Kotur Bridge [10]. Eren, made experimental investigation of various repairing techniques applied to damaged masonry arches [11].

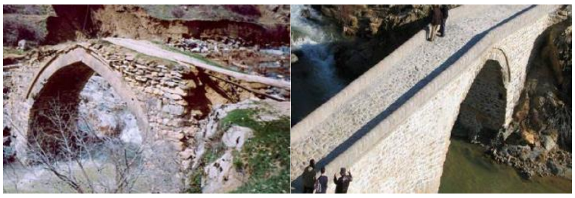
In this study, natural and overloading of historical stone bridges such as earthquakes, floods, ground damages and over time damages caused by alteration of river bed, damages caused by alteration of bridge slope, wars, faulty repairs were evaluated and repair methods investigated.

2. Damages and Causes of Historical Stone Arch Bridges

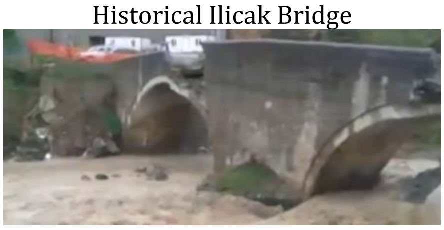
Many stone arch bridges that survived to the present day were influenced by structural damage in the process. Bridges were damaged under these natural or man-made effects such as floods and earthquakes. Analysis of design differences and damage-causing mechanisms that cause structures to react differently under the same influences was a priority in the protection and repair of structures. Damages in stone arch bridges were mostly caused by floods, earthquakes and human-caused damages.

2.1. Flood Damage

Our country has located in temperate climate zone. However, rivers with irregular regimes could produce floods that cause significant structural damage to river bed during rainy seasons. The bridges on this route were the most damaged structures from floods [5]. In addition to the water force, the tree trunks that the stream incorporates during the floods also damaged the bridges. Although most of the historical bridges had flood cutters, many arch bridges were damaged due to floods. As a result of the flood of the Ilıcak Bridge in Bitlis, the tempan wall and deck were largely destroyed. The bridge, which was restored in 2005, was completed by KGM in 2006 (Figure 1). The Akcaabat Osmanbaba Bridge was completely destroyed as a result of excessive rain water carving the bridge's feet [12].



Historical Ilicak Bridge



Osmanbaba Bridge

Figure 1. Examples of bridges damaged and destroyed by floods

2.2. Earthquake Damage

Due to the presence of many active faults in our country, it could be affected by destructive earthquakes. The bridges were constructed of stone material with high resistance to pressure stresses. Therefore, it could withstand high stresses under vertical loads. However, they were vulnerable to damage under horizontal forces caused by earthquakes (Figure 2). In order to compensate for these horizontal forces, metal elements could be used which could meet the tensile forces such as tension, clamp and tenon.

Figure 2. Bridges damaged by the 2001 Bhurj earthquake and the Koyna earthquake in India

After the Umbria Marche earthquake in 1997, a major collapse occurred in the central opening was shown in Figure 3.

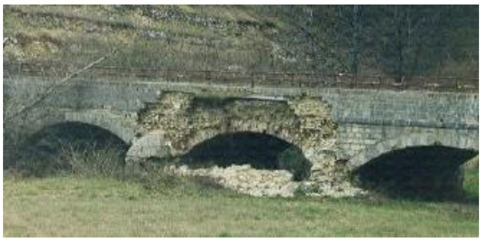


Figure 3. Injured bridge [13]

2.3. Human damage

Human damage; design errors, wars, changes made for functional purposes, misapplications brought about by information and technical deficiencies [5].

2.4. Damage caused by river bed replacement

Changes in the river bed caused the amount of water to pass through a narrower section to increase the flow rate. This effect would increase to higher levels in flood situations. Since the sand quarries established on the sides of the rivers also had a direct effect on the rivers regime, the amount of granular material carried in the rivers varies and could cause carving on the bridge legs.

2.5. Overload

The stone material and the arch form were very important considering that the compressive force carrying capacity of the bridge arches continued to function smoothly. However, the increase in loads on the fill could cause swelling and collapse of the façade walls, and as a result of overloading, the horizontal forces created by the belt stones could not be compensated and separations could occur in the arch vaults and disintegration of the keystones (Figure 4) [5].

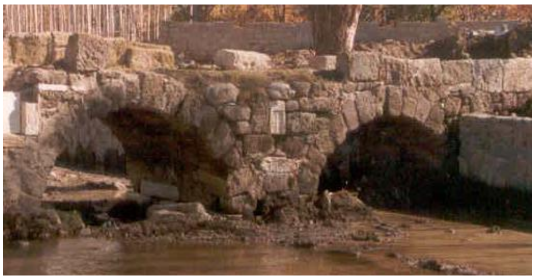


Figure 4. Damage to the historical Dortgoz Bridge on the road route

2.6. Changing the bridge slope

Changing the inclination of the bridge could cause distortion on the structure as it would generate new fill loads to the arches. In addition, the dynamic effects of the vehicle traffic that would pass through it caused damage to the belts and feet.

2.7. Wars

The wars that have been going on for centuries have targeted the works of a culture or civilization and posed a threat to the bridges. Mostar Bridge, dated 1566, was demolished in an attack in 1993 and was rebuilt in 2004.

2.8. Inproper Repairs

Failure to use sufficient knowledge and technical knowledge during repairs or interventions performed without detailed analysis of the structure could cause damage after application [5].

2.8.1. Inappropriate material use

Failure to use appropriate materials in building materials and binder mortars was among the most common repair mistakes. When choosing a building material, the appropriate stone should be selected by taking into consideration the physical characteristics of the original material, the strength and core weight of the material, the void ratio, the capillary water absorption value and the chemical content, the environmental conditions and the relationship with other building materials. Due to the difference in strength, imbalance in the stiffness distribution would result and regional damage would result.

The chemical composition of the building material must have been such that it does not interact with the binder and air it was in contact with. For example, as a result of the use of cement with lime-based stones, moisture in the air could cause new salt compounds in the stone material. The salt compounds formed in the stone cavities could disintegrate the stones due to the increased in volume (Figure 5).

Figure 5. Damage caused by salting and freezing-thawing of stones

2.8.2. Wrong detail application

As with many conventional structures, the failure to apply the details used in the connection of structural elements in bridges could lead to various damages. In bridges, the use of metal elements in the vertical and horizontal directions to connect the stones to each other was common. Stones were made with each other by clamping lead obtained from iron with low carbon content and this process generated ease of application since the lead was placed in liquid state (Figure 6).

During the construction of the arches and walls, care must be taken to ensure that the dimensions of the stones and their interlocking distance, in particular the integrity of the surrounding stones with the arch vaults, were achieved.

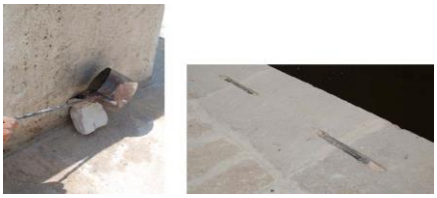


Figure 6. Stones and lead castings connected with sutures, Saraçhane Bridge repair

2.8.3. Changing belt form

During some repairs, the arch form were changed consciously or unconsciously. Some faulty repaired not only disrupt the architectural authenticity of the structure, but also changed the static balance of the bridge. Changing the belt shape made the push line more unfavorable than the ideal belt curve (Figure 7).

Figure 7. Deformed arch after repair, Buyukcekmece Bridge

2.9. Damages caused by plants

Our country was rich in vegetation because of its abundant rainy. Under the effect of elongation of the roots, plants caused cracking and disintegration of large rock fragments [4]. Weaknesses in the bridge pavement and drainage system also formed the basis for the formation of vegetation (Figure 8). Apart from the plants that damage the structure with their roots, various types of fungi were also fed with minerals such as calcium, aluminum, iron and potassium within the building blocks of the bridge. As a result, acids released the binders on the structure.

Figure 8. Giresun, Dereli road Yavsan Bridge and Savsat Bridge in district of Artvin

2.10. Ground Damage

As a result of the change of direction of the river bed, the carving of the foundations of the bridges occurred. As a result of these engravings, some settlements occurred on the bridges. These settlements could cause cracks and fractures (Figure 9) [4].

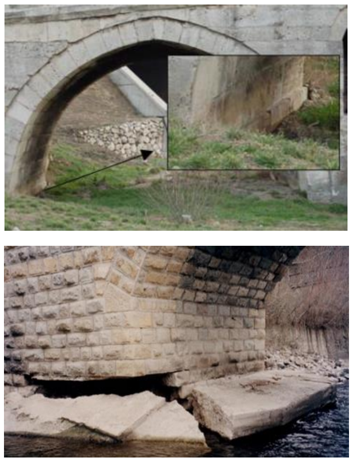


Figure 9. Trabzon, Macka road Mataraci Bridge

2.11. Damage depend on time

Among the most important reasons for the damage of arch bridges was temperature differences between day and night and the recurrence of natural phenomena such as wind and rain over time (Figure 10) [4].

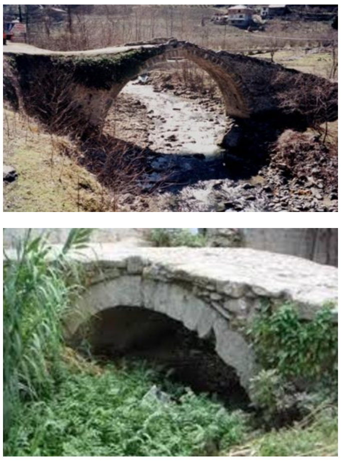


Figure 10. Kinali bridge and Ozbek bridge

2.12. Damages due to coating material and drainage problems

Poor coating and drainage system caused surface water to leak into the filling area of the bridge. As a result of this, the filling material was crushed and thrown away from the structure and gaps occurred in the filling (Figure 11). In addition, water leaking into the filler could cause expansion in temperature changes.

Figure 11. Historical Hersan and Ilicak bridges in Bitlis

3. Repair and Strengthening Techniques of Damages at Historical Stone Arch Bridges

Historical stone arch bridges should be constructed in such a way that they did not affect the visuality of the bridge while remaining faithful to its original condition and did not disturb its structural spirit. It was very important to make modeling by making visual and experimental studies before the restoration and reinforcement of historical buildings. The following steps could be followed for these operations.

- ❖ Determination of the current situation
- ❖ Conducting experimental studies
- ❖ Modeling
- ❖ Calibrate the initial model to reflect the actual situation

Measures should be taken against damages in historical stone arch bridges. Continuous maintenance of historical bridges could prevent many damages. If necessary, repair and reinforcement was mandatory. The method chosen for repair and reinforcement should be safe, economical, fast and continuous. Considerations in practice:

- ❖ If the damage was local, a local repair should be performed.
- ❖ If local damage was excessive, a general repair was required.
- ❖ If the repair disrupted the aesthetics of the structure, it was more appropriate to perform a hidden repair.
- ❖ As repairs and reinforcements changed the rigidity of the system, it would be more accurate to arrange the calculations accordingly.
- ❖ Once you decided to repair or strengthen, the project must be designed in accordance with the regulations currently in effect.
- ❖ It was important that the contractor undertaking the repair was experienced in this field.
- ❖ Repair or reinforcement should be checked under the supervision of technical personnel.

3.1. Injection filling of cracks

Historical stone arch bridges were built under pressure. Bridges which were subjected to strong dynamic effects were weak against tensile stresses and thus cracks occurred in the vertical direction due to tensile stresses. The direction and shape of these cracks were very useful in determining the causes of damage.

Cracks in stone arch bridges should be filled by injection. Before the injection, the crack must be revealed by removing the previously made plaster. Afterwards, hoses should be placed at certain intervals (approximately 50-100cm) on the cracks based on the crack width and covered with hydraulic lime material that would not leak over the crack. After a minimum of 24 hours, the appropriate material must be injected into the crack using the injection pump to remove the damage. Injection material should be applied at the lowest point and should not be stopped until it reaches the upper point (Figure 12).

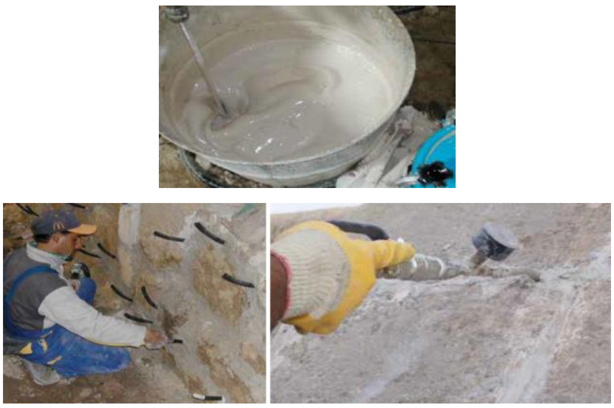


Figure 12. Injection application

3.2. Making anchors with steel bars

In case of disintegration between the stones, it was ensured that the stones were interlocked together by the method applied with steel bushes or anchors (Figure 13).

Figure 13. Use of steel tenon

Horizontal anchorage could prevent the progression of cracks. This process opened the cylindrical slots along the full width of the bridge to the belt side faces respectively. Sheath pipes and stainless steel bars with permeable grout mortar were placed in the opened slots. The low pressure graut mortar was pumped into the sheath pipe. The tension force was applied to the stainless steel bars with a torque wrench. The hole heads were closed (Figure 14) [14].

Figure 14. Horizontal anchorage application [15]

3.3. Partial completion of demolished sections

Reconstruction was a special case. In order to rebuild the damaged area, documents such as technical data, survey, photo of the department to be built were needed. In the light of these data, point intervention method could be applied in the collapsed parts of the bridge. The high water permeability and flowering resistance of the mortars to restore the destroyed parts was important for the future (Figure 15).

Figure 15. Reconstruction of the demolished part with mortar

One of the types of damage often seen in historical arch bridges was the large destruction of side railings. One of the weakest parts of the bridges was the railing stones, which were built in one row. In addition, due to pedestrian and vehicle traffic, some cracks, abrasions and abrasions occurred in the superstructure of the bridge. Guardrails generally formed parts of all bridges that need to be repaired due to vehicle crashes as well as deterioration over time (Figure 16).

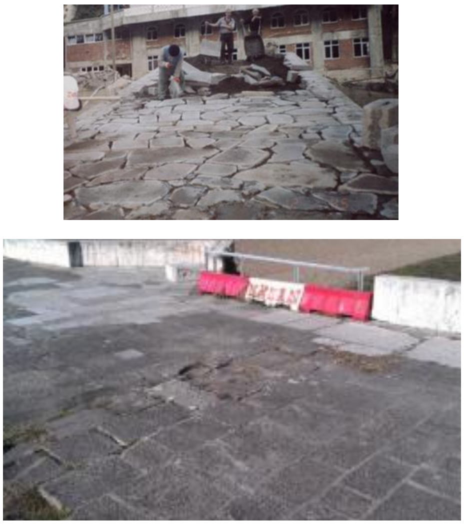


Figure 16. Superstructure repair

3.4. System repair

Restitution project was one of the most difficult works for bridges to construct the completely demolished arch structure again. As the original geometric structure of the belt was difficult to estimate, the characteristics of the destroyed belt should be determined very well, the new one should be made in accordance with the original and projected as a result of the analyzes. At the end of the examination at Orenkit Bridge, the location of the damaged arch was determined and wooden molds were made. Then, from the arch stones side wall and fill materials were placed in the middle and the top structure was built with a single row of cut stones. In the last stage, the bridge railings were completely replaced (Figure 17). As a result of the studies, the belt was replaced by the belt which was destroyed [4].

Figure 17. Repair works at Orenkit Bridge [4]

3.5. Environmental drainage

The elements forming the bridges in places exposed to acid rain or sulphate effect deteriorate prematurely. This caused different stresses in the superstructure and caused damage to the bridges. Therefore, it was extremely important to prevent the surface and groundwater from having a negative impact on the bridge. For this purpose, a proper drainage system should be built around the bridge to remove water from the environment [4].

3.6. FRP Reinforcing with Rods and Fabric

Energy damping of stone arch bridges exposed to strong dynamic loads caused structural damage and cracks. For this reason, additional elements, FRP (fibrous polymer) rods, which would add ductility to the bridge during the reinforcement and received tensile stresses should be placed. The raw material of FRP fabrics was carbon, glass or aramid based fibers. Most preferred were carbon based fabrics which were very easy to use and practical. These fibers were used to increase the bearing capacity and ductility by placing them on the walls and arches. This method was a solution method applied to keep the parts at risk of disintegration together. However, they were generally not preferred because it disrupted the original structure of the bridge (Figure 18).

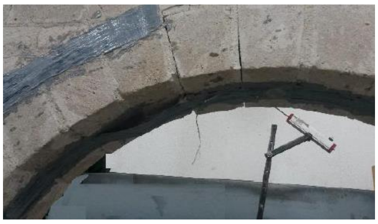


Figure 18. FRP strengthening [9]

4. Results

The main factor in the damage of historical stone arched bridges was the flood damages. Flood damage could cause considerable damage to the foot of the bridge, although there was flood splitter in the bridges. Flooding, tree trunks and other drifting materials could cause serious damage to bridges and cause destruction. In addition to flood damages, damages could also occur due to earthquake effects. Great bridge weight increased earthquake impact strength. Depending on the severity of the damage, it could cause partial or complete damage to the bridge. Human-induced damage, such as overloading, changing the slope of the bridge, wars, and lack of proper material, often occurred in local areas of the bridge. The restoration of these damages caused by various reasons locally or general was very important for our cultural heritage. In addition, it was important to have a certain knowledge for repair and strengthening works. Otherwise, the restoration works would not ensure that these structures would survive for many years and this historical wealth would be wasted. It was important to pay attention to the works to be done, the historical structure of the repair and strengthening of the historical tissue was not damaged. Considering the level reached by today's technology, there were many methods and options for repair. In these applications, it was very important to understand the real behavior of the bridge and arrange the applications according to this behavior. It was also very important that the archive and feasibility studies were carried out meticulously. The date of repair should be done without damaging the tissue and care should be taken to keep the parts reflecting the characteristics of the period. Injection filling of cracks could be applied to locally damaged areas of the bridge without damaging. Bridges exposed to strong dynamic loads also caused structural damage. For this reason, additional elements, FRP reinforcing could be applied locally. Bridges damaged as a result of damages could be repaired partially or completely.

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