RESTORATION WORKS OF MASONRY ARCH BRIDGES IN ANATOLIA AND BALKANS

M. Elbir¹, H. Sert², S. Yılmaz³, E. M. Partal⁴, H. Demirci⁵, A. Avşin⁶, M. Nás⁷, G. S. Turan⁸
Translation by: H. İ. Korkmaz⁹

ABSTRACT

It is one of the primary tasks of the General Directorate of Highways to repair and maintain the historic bridges which are of great importance in view of our cultural history in accordance with the projects to be developed or caused to be developed, apart from the recently constructed roads and bridges. Pursuant to the inventory records, it has been observed according to their period of construction (as of December 2013) that there exist a total of 1708 each bridges in our country dating back to Hittite Period (1), Urartian (1), Roman (129), East Roman (22), Seljuk (157), Ottoman (1328) and Early Republican (70) periods with 308 each bridges constructed during Ottoman era abroad. Out of 1708 bridges, such bridges are grouped according to their method of construction as follows: Stone (1625), Wooden (26), Iron (30), Reinforced Concrete (27).

The historical bridges the majority of which is located on 1st degree seismic zone and which have proven to be durable for centuries, are considered to serve for a long time in case a relationship between the original construction techniques and soil-foundation-river is established. In this context, during execution of the restoration works which should be carried out in accordance with the least intervention principle, it is of great importance to define original construction systems of the bridges and their material wise characteristics.

In the contents of this paper, the restoration works carried out by the General Directorate of Highways for the Stone – arch bridges which are located on the transportation system and which tend to reflect the architectural – engineering experience attained during the period construction and have become the supplementary elements of cultural history as time pass by, shall be discussed.

¹ Civil Engineer, Head of department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
² Specialist Architect, Director of the Division of Historical Bridges, Department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
³ Senior Architect, Restoration Expert, ⁴ Civil Engineer, ⁵ Senior Architect, ⁶ Senior Architect, Restoration Expert, ⁷ Senior, ⁸ Archaeologist, ⁹ Translator/Interpreter / Division of Historical Bridges, Department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
ABSTRACT

It is one of the primary tasks of the General Directorate of Highways to repair and maintain the historic bridges which are of great importance in view of our cultural history in accordance with the projects to be developed or caused to be developed, apart from the recently constructed roads and bridges. Pursuant to the inventory records, it has been observed according to their period of construction (as of December 2013) that there exist a total of 1708 each bridges in our country dating back to Hittite Period (1), Urartian (1), Roman (129), East Roman (22), Seljuk (157), Ottoman (1328) and Early Republican (70) periods with 308 each bridges constructed during Ottoman era abroad. Out of 1708 bridges, such bridges are grouped according to their method of construction as follows: Stone (1625), Wooden (26), Iron (30), Reinforced Concrete (27). The historical bridges the majority of which is located on 1st degree seismic zone and which have proven to be durable for centuries, are considered to serve for a long time in case a relationship between the original construction techniques and soil-foundation-river is established. In this context, during execution of the restoration works which should be carried out in accordance with the least intervention principle, it is of great importance to define original construction systems of the bridges and their material wise characteristics. In the contents of this paper, the restoration works carried out by the General Directorate of Highways for the Stone arch bridges which are located on the transportation system and which tend to reflect the architectural engineering experience attained during the period construction and have become the supplementary elements of cultural history as time pass by, shall be discussed.

Introduction

It is one of the primary tasks of the General Directorate of Highways to repair and maintain the historical bridges which are of great importance in view of our cultural history in accordance with the projects to be developed or caused to be developed, apart from the recently constructed roads and bridges. In this paper, the restoration works carried out on the stone bridges with arches which are proven to be durable against the factors such as earthquakes, dams and floods for centuries shall be discussed.

1 Civil Engineer, Head of department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
2 Specialist Architect, Director of the Division of Historical Bridges, Department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
3 Senior Architect, Restoration Expert, 4 Civil Engineer, 5 Senior Architect, 6 Senior Architect, Restoration Expert, 7 Senior, 8 Archaeologist, 9 Translator/Interpreter / Division of Historical Bridges, Department of Structures, General Directorate of Highways, Ministry of Transport, Maritime Affairs and Communication, Ankara.
Original Construction Systems of the Stone Arch Bridges

Large stone blocks have been used on the foundations of the stone arch bridges constructed through masonry construction system and various clamping systems have been developed in order to keep the stones together (Fig. 1,2). It has been observed that the main arches of the multi-spanned bridges were placed on the rocky soil to the extent the topography allows (Fig. 3,4) while the foundation layer was constructed on wooden piles on swampy soil with attenuate bearing strength (Fig. 5,6) and on wooden grills on the sound soils (Fig. 8,9). To divert the water, the piers which are all given shape in different forms to downstream and upstream side and receive the loads from the arches function as supports for the forces which vertically generate onto the longitudinal axis of the bridge, thus provide strength against seismicity. The arches, one of the other element of the bearing system works on pressure and several examples of bridges imply that the supports on the arches are formed through flexible connection system made with wooden elements (Fig. 7,8).

If we have a look at the examples of the bridges constructed in different periods, Aspendos (Belkis) Bridge constructed during Seljuk Period in 13th Century on the foundation and ruins which date back to Roman Period is on Köprüçay River in Antalya and it is 220 m length with 7 spans. The foundations of the bridge located on 2nd degree seismic zone is formed through connecting the largely dimensioned stone blocks with each other by way of iron clamps of 1.75 m. (Fig. 1,2).

Malabadi Bridge, built during Seljuk Period (12th Century) is on Batman River in Diyarbakır and it is 220m in length with 5 spans. It is the only stone bridge with the longest arch span survived to date in the world together with the pointed arch of 40.86m span located on rocky soil. To decrease the loads on the foundations, the chambers within the body of the Bridge of Malabadi, located on 1st degree seismic zone, are specifically functioned where one of the rooms includes a toilet (Fig. 3,4).

Fig. 1,2. Aspendos (Belkis) Bridge, Antalya/iron clamps used on the bridge foundations

Fig. 3,4. Malabadi Bridge, Diyarbakır/ the bridge constructed on rocky soil
Kesikköprü constructed during Seljuk Period (13th Century) is located on Kızılırmak River in Sivas District and it is 227m in length with 17 spans in flat pointed form. It is observed that the bridge foundation which is located on 3rd degree seismic zone rests on wooden piles (Fig. 5, 6).

Fig. 5, 6. Kesikköprü, Sivas/ the bridge constructed on wooden piles

Constructed during Ottoman Period (16th Century) Mostar Bridge, was built by Architect Hayreddin, one of Architect Sinan’s disciples in the city of Mostar in Bosnia and Herzegovina and its arch with 28.71m spanning was settled on stone platforms supported by the rocks. During re-construction works executed on the bridge in 2002 through 2003, it has been observed that the springer stones of the arch were settled on a flexible connection system made up of wooden elements (Fig. 7,8).

Fig. 7,8. Mostar Bridge, BIH / wooden beams in line with the arch springer

The Historical Konjic Bridge, one of the masterpieces constructed during Ottoman Period (17th Century) is located on River Neretva in the city of Konjic in Bosnia and Herzegovina and it is 86.20m long with 6 spans in flat pointed arch form. It has been observed that the foundation system of the bridge which is located in 3rd degree seismic zone was formed through wooden grill system which directly settled on the rocky formation (Fig. 9,10).

Fig. 9,10. Konjic Bridge, Bosnia and Herzegovina/ bridge constructed on wooden grills
**Assessment:** It has been understood that the seismic forces transferred by the soil to the structure by way of the flexible energy absorbing elements functioning as “elastomer support” on which the foundations, piers and arches of the masonry bridges which form part of the bearing systems, are settled, tend to decrease. Where the original environmental conditions change / cause to be changed, the dynamic effects of the earthquakes which may have sudden impact on the structure and display substantial changes in short intervals may give way to damages of larger scale for the bridges which lost their stability. Therefore, the problems encountered in the bridge and its vicinity should be well defined and the restoration projects should be prepared accordingly.

**Technical Researches**

**Analysis of the Arch Geometry**

During execution of the restoration works on the stone arch bridges, the original geometry of the arches should be well studied in view of the bridge stability. Where the stability is failed to attain, the arches should be brought to its original form. For example; Çeşnigir Bridge constructed on sandstone blocks the rate of abrasion of which is extremely high (45, 90 %) during Seljuk Period is located on River Kızılırmak in the District of Kırıkkale and it is 135m long with 12 spans in pointed arch form. It is observed that the arch geometry of the Bridge of Çeşnigir, located on 1st degree seismic zone and built over a fractured geometry to settle the foundations on granite sound rocks, was deformed due to the effects of the dam water where the water level was variable and the bridge stability got weakened. During restoration works executed in 2007 through 2010, the damaged sections of the arches which lost their stability were removed and replaced with the original geometry (Fig. 11,12,13).

![Fig. 11,12,13. Stone abrasion / Geometrically deformed arches/arches conforming to the original geometry](image)

**Structural Analysis**

To better understand the structural behavior of the stone bridges against the influential loads, the interaction between the soil-base and river should be well defined. The structural analyses indicate that the tension increases on the bridge where such an interaction leads to a loss in the authenticity of the structure. Such observations are important in view of the techniques applicable for the rehabilitation works to be carried out on the stream bed. For example Sokollu Mehmet Pasha Bridge, constructed by Architect Sinan during Ottoman Period (16th Century) and located on River Drina in Visegrad, Bosnia and Herzegovina, is 179m long with 11 spans in pointed arch form. Located on 3rd degree seismic zone, the profile of the stream bed of the bridge which has long been between the two dams had to undergo changes due to the changes in the water level and flow rate while the bridge foundations formed through wooden grill system exposed.
The results of the structural analyses made according to the prevailing conditions of the Sokollu Mehmet Pasha Bridge within the scope of the restoration projects furnished in 2008 through 2010 imply that the hydraulic loads which give way to tension strength increase the compressive stress on the foundations exposed and the construction of a ground support in the form of raft foundation using compacted stone has been taken as the basis in the manner to include the bridge foundations in order to ensure uniform water flow (Fig. 14, 15).

Fig. 14,15. Sokollu Mehmet Pasha Bridge, BIH / Structural Analysis of the Bridge

Material Analysis

Stone Analysis

Selection of the stones to be used in the restoration of the masonry bridges is made through the test results defining the physical and mechanical properties of the stone samples taken from the quarry which is likely to be used in the repair works at the bridge location, reserve conditions of the respective quarry, availability of the stones at the required dimensions and characteristics along with the factory to cut the stones in the vicinity and determination of the compatibility of the stone with the color and pattern of the original stone. Since the abrasion rate of the original stone (sandstone) used in the Çeşnigir Bridge is excessively high (% 45.90), travertine type stone the hardness degree of which is found to be 2 with low abrasion rate is selected as it was previously used in the restoration works by the General Directorate of Highways. The test results of the stone are tabled below while it has been observed that it meets the above mentioned selection criteria. (District of Kayseri / Bayramhacılı Village travertine quarry / Distance to the bridge location is 190 km) (Fig.16,17).

Results of the Stone Test:

<table>
<thead>
<tr>
<th>Comp. Str. (Mpa)</th>
<th>Frost Attrition (%)</th>
<th>Water Absorp. (%)</th>
<th>Abrasion (%)</th>
<th>Specific Gra. (Ton/m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 Mpa</td>
<td>0.04</td>
<td>0.7</td>
<td>10.28</td>
<td>2.47</td>
</tr>
</tbody>
</table>

Fig. 16,17. Çeşnigir Bridge / Stone abrasion and post restoration


**Grout Analysis**

The grouts for masonry structures provide uniform distribution of the loads which have impact on the structure while they prevent substantial damages through slippage of the stone blocks which are under the effect of the lateral loads such as earthquake, all through the grouting. Therefore, zero joint application should be avoided during execution of the restoration works and the joints should be ranged 5-8mm. The grouts which are of great importance for the stone bridges constructed in the form of masonry structure technique are of substantial significance in view of the harmonization of the original grout mix with the new pattern preparation of which should be based on the original mix ratio and grout pattern during application of the restoration projects. During Research and Development studies conducted for the original grout analyses in 2002 and 2012, it has been found out that the compressive strength of the lime grouts used in Mostar Bridge in Bosnia and Herzegovina is 4.5 Mpa while it is 6.15 Mpa in Sokullu Mehmet Paşa (Drina) Bridge and 6.94 Mpa in Konjic Bridge. In case the ready mix grout is directly applied on the structure (at a rate of 100 %), it is considered that it will not be compatible with the original grout the compressive strength of which is 6-7 Mpa (porosity ranges between 20-40 %) and damage the existing structure. Therefore, the readily available grouts should only be used at a predefined rate within the original grout mix at the bridge –depending on the characteristics of the bridge and the level of damage-. For example, during restoration of the Çeşnigir Bridge located in Kırıkkale Province in 2007 through 2010, it has been found appropriate to make use of the readymade mortars within the grout compatible with the original grout mix at a predefined rate on the foundations and freestone constructions for the purpose of strength improvement in order to fill the gaps of the bridge depending on the nature of the damages at different levels of the structure - due to the fact that the tension values of the bridge which was built through sandstone blocks the abrasion rate of which is high as a consequence of the varying water level of the dam water and that the arch stones are substantially corroded (Fig. 18,19).

![Fig. 18,19. Çeşnigir Bridge subsequent to restoration](image)

**Conclusion**

The bridges the major function of which is to provide accession should first be stabilized in order to allow safe passageway. However, the location, soil material, status of the damages and intervention methods based on the reasons of such damages may vary for the bridge to be restored while any restoration technique applicable for any bridge may not be applicable for the other. The original construction techniques of the stone bridges with arches which are proven to be durable against the factors such as earthquakes, dams, variable water flows and heavy traffic over the centuries -based on the principle of least intervention- should be well studied while the interventions which fail to comply with the masonry construction technique should be avoided during restoration works and the flexible base connection systems should
be protected in their original forms or the foundations should not be made rigid through cement injection or concrete casing. The factors which lead to bridge instability such as the form of arches the geometry of which is destroyed should be brought to their original forms. Care should be attached to select the material most compatible with the original materials used in the bridge during restoration works.

References

10. (*)KGM produced the Application and Restoration Projects for the Historical Konjic Bridge, as force account and approved by the Federal Ministry of Culture and Sports of Bosnia and Herzegovina on 09.02.2006. In addition, the KGM project was awarded the reward of accomplishment in the field of Conservation – Sustentation in the competition for the 10th National Architectural Exhibition and Rewards of the year 2006. In pursuance with the protocol signed with TİKA, the General Directorate of Highways provided the supervision services for the re-construction of the bridge while the bridge was completed in the years 2007 through 2009.
14. (*) The Historical Sokollu Mehmet Pasha Bridge was included in the World Heritage List by UNESCO in 2007. Pursuant to the protocol signed with the TİKA, the supervision and consultancy services for the Restoration and Application Projects were executed by the KGM and they were approved by the Commission for the Conservation of the National Monuments of Bosnia and Herzegovina on 17.06.2010 upon receipt of the affirmative comments by the Agency for the Conservation of the Cultural-Historical and Natural Heritage for the project on 07.04.2010.
15. KGM. *Inventories of the Division of Historical Bridges*, Ankara, Turkey, 2011.


(*) The re-construction of the Historical Mostar Bridge was tendered through the cooperation between the World Bank and UNESCO and the bridge was re-constructed by a company based in Turkey under technical supervision of the General Directorate of Highways. During re-construction of the Mostar Bridge, Ms. Halide Sert, upon nomination by the Prime Ministry had been to Bosnia and Herzegovina for a period of 29 days (06.02.2002 through 30.05.2002) during tendering stage, 128 days (21.03.2003 through 31.12.2003) during reconstruction stage, and 14 days (18.06.2004 through 21.07.2004) during acceptance stage totaling to 171 days.


30. Sert, H. *Historical Çeşnigir (Köprüköy) Bridge Restoration Project and Application*, TMMOB Chamber of Architects, Ankara, Turkey, 2011 (The Book of Papers has not yet been published).


NOT 1: KGM (General Directorate of Highways), TİKA (Turkish Cooperation Agency)
NOT 2: The photographs used within the scope of this paper but the sources of which are not yet defined are taken from the Archives of the Division of Historical Bridges, General Directorate of Highways.
NOT 3: The copyrights for the design, reports and opinions of all type presented for and on behalf of the General Directorate of Highways, Ministry of Transportation of the Republic of Turkey rest on the General Directorate of Highways in accordance with the Law of Intellectual Property Rights numbered 5846.