Arch Bridges
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REPAIR OF STONE MASONRY ARCH BRIDGES

Daniel V. Oliveira* **and Paulo B. Lourenço†**

*Assistant Professor, Department of Civil Engineering
School of Engineering, University of Minho
Campus de Azurém, 4800-058 Guimarães, Portugal
email: danvco@civil.uminho.pt, url: www.civil.uminho.pt/masonry

†Associate Professor, Department of Civil Engineering
School of Engineering, University of Minho
Campus de Azurém, 4800-058 Guimarães, Portugal
email: pbl@civil.uminho.pt, url: www.civil.uminho.pt/masonry

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Abstract: *This paper deals with the analysis and design of repair measures concerning two Portuguese masonry arch bridges, carried out at University of Minho. The first example is related with a masonry bridge built in the 19th century, composed of six pointed stone arches and located in the center of Portugal. The second example is a medieval masonry bridge composed of three semicircular stone arches and located in the North of Portugal. Repair measures adopted to re-establish the safety of the bridges are described. These measures were conceived in order to respect the modern principles of structural intervention in architectural heritage.*

1. INTRODUCTION

During centuries, the construction of bridges represented a feat since it required an enormous economic effort and specialized technical skills. Often, their construction took generations. By making possible the connection between different regions, bridges allowed the exchange of goods and thoughts, thus, representing an important factor to reach economic and cultural development.

Existing masonry arch bridges in Portugal were built throughout centuries, from the Roman period to modern times, representing a priceless architectural and cultural legacy. Nowadays, it is still possible to find Roman bridges, characterized by their flat pavements and semicircular arches of equal dimensions, as well as the more flexible medieval bridges, with larger central spans, with semicircular or pointed arches, cutwaters and humpback pavements. However, the successive maintenance works that bridges were unavoidably submitted to across time resulted in a difficult dating, leading sometimes to erroneous classifications.

With time, the deep change of loads for which bridges were built, the decay of the materials and the lack of maintenance have led to states of damage, in many circumstances not compatible with their use or even their safety. The most common generalized damage observed in bridges in Portugal are the absence of mortar in the stone joints, the existence of vegetation and biological colonization, the presence of humidity and efflorescences and the accelerated decay of the materials. Localized damage is essentially related with longitudinal cracking of the arches at the intrados, movement of abutments and the lack of plumbness of spandrel walls. However, some of the afore-mentioned damage could be avoided if bridges were submitted to periodical inspections in order to detect and eradicate its causes, procedure here named as preventive maintenance. It is known that the implementation of both periodical inspections and reduction of the traffic load can efficiently contribute to diminish the structural degradation of masonry bridges.

The presence of damage, namely cracking, is not inevitably a sign of danger, since it may produce only a redistribution of stresses, for which failure risk might be absence. Nevertheless, when damage threatens safety of historical bridges, it becomes necessary to assure their structural stability, by carrying out repair and strengthening measures, motivated by both the importance they still assume in the actual road network and the architectural, historical or social value they represent.

Structures belonging to the architectural heritage, by their nature, present a set of specific features that limit the application of modern codes. Instead, recommendations regarding adequate approaches to guide the intervention in architectural heritage within a rational scientific procedure and within a cultural context are available[1]. Minimum repair to assure safety and durability requirements, the respect of the original conception and techniques and the compatibility between new and existing materials are essential issues of the modern principles of intervention in the architectural heritage.

This paper presents the survey on two damaged stone masonry arch bridges and describes the repair measures proposed to restore safety, compatible with the principles of intervention in structures with heritage value. Different degrees of damage imply the adoption of different repair measures, in accordance with the observed damage.

2. BOUTACA BRIDGE

The Boutaca bridge is located in Batalha, in the center of Portugal, close to the Batalha monastery. This bridge was built in 1860, across the Calvaria stream, and it belonged to the old road that made the connection between the two biggest Portuguese cities.

The Boutaca bridge has a flat roadway, supported by six pointed masonry arches equally spanned, as illustrated in Figure 1. Lateral masonry walls, supported by a buttressing system, make the connection between the pointed arches and a semicircular masonry tunnel, belonging to the old railway network. The bridge reaches a total length of 60.0 m and has a roadway width of 7.0 m. At the ends, it is noticeable the existence of four box-houses used by road-menders.

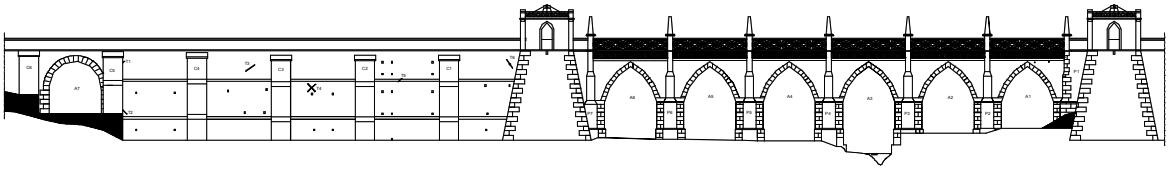


Figure 1: Boutaca Bridge: railway tunnel, masonry wall supported by buttresses and six pointed arches (downstream view).

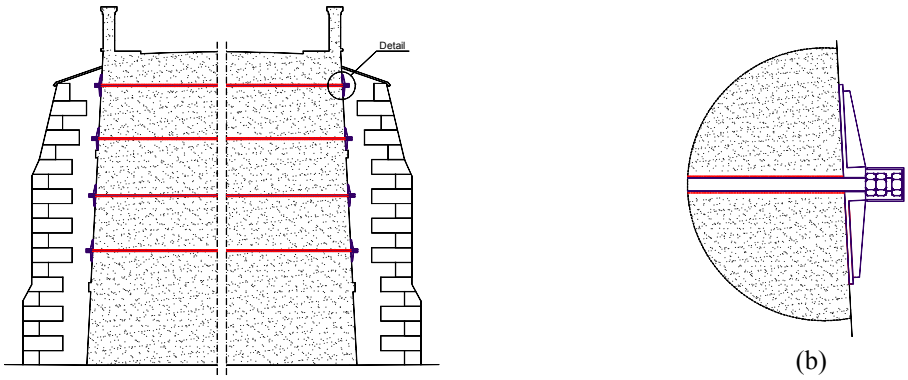
Due to its uncertain safety conditions and taking into account its heritage value, a survey of the Boutaca bridge was requested[2]. The detailed inspection carried out allowed to detect damage in several areas. The absence of periodic maintenance works promoted the growth of vegetation, as well as the lost of plaster and painting in large areas of the bridge. The deficient drainage system of the pavement caused the occurrence of humidity and biological colonization, detected in the visual inspection, see Figure 2. It was also found some minor longitudinal cracking at the intrados of some arches, as well as cracking in the buttresses, due to lateral forces generated through the fill and caused by dead and live loads.

The survey detected four metallic tie rods endowed with anchorages on one side of the bridge (downstream), to bind the walls. The anchorages were much deteriorated, with visible corrosion, and rather deformed being not possible to detected similar anchorages on the other side (upstream). The excessive deformation of the anchorages, as well as cracking in buttresses seem to indicate that masonry walls suffered outward movements after the placement of the tie rods and that buttresses may be overload.

(a) (b) (c)

Figure 2: Main damage: (a) vegetation; (b) humidity; (c) corroded anchorage (downstream view).

Taking into account the rehabilitation and the protection of the bridge, a set of remedial measures were recommended[3], in accordance with the principles that guide interventions in the architectural heritage. To prevent the outward movement of the masonry walls and to lighten the load in the buttresses, it was proposed the execution of a set of horizontal anchors across the full width of the road, endowed with patress plates, which have been designed to be aesthetically attractive. Four vertically aligned tie rods between each two buttresses were adopted, as illustrated in Figure 3. For each anchor, a hole is drilled and a stainless steel rod with 39 mm diameter is placed inside. At the ends, two cylindrical stainless steel patress plates are tightened up. A slight force is applied to the tie rods by means of a dynamometric wrench, in order to put them in tension.



(a) (b)

Figure 3: Strengthening of the masonry walls: (a) general view; (b) detail of the patress plate.

With respect to the slight cracking observed in two of the arches, it was decided no to perform any intervention since their safety is not threatened. Instead, periodical visual inspections are highly recommended.

In order to reduce the lateral pressure on the walls and the appearance of humidity at the intrados of arches it was proposed to perform the waterproofing of the pavement and the reconstruction of all the drainage system. Also, the cleaning and removal of infesting vegetation in the bridge should be periodically carried out. The missing plaster and painting should be replaced, using materials as similar as possible to those used in the construction.

3. DONIM BRIDGE

The Donim bridge, located in Guimarães over the Ave river, was built most likely during the 15th or 16th century. In ancient times, Donim bridge was an important structure of Minho road network. With time, the bridge has lost its significance and, nowadays, it is mainly used for local travels.

The bridge has a flat roadway, supported by three semicircular stone masonry arches, with different spans (6.6 m + 11.8 m + 9.4 m), as schematically illustrated in Figure 4. The bridge reaches a total length of 62.0 m and has a roadway width of 3.4 m. The central arch presents the larger span and it is supported by two massive piers, endowed with two triangular cutwaters at upstream and two rectangular cutwaters at downstream. On the right shore it is possible to find a flood arch, with a span of 2.7 m, constituting a 4th arch.

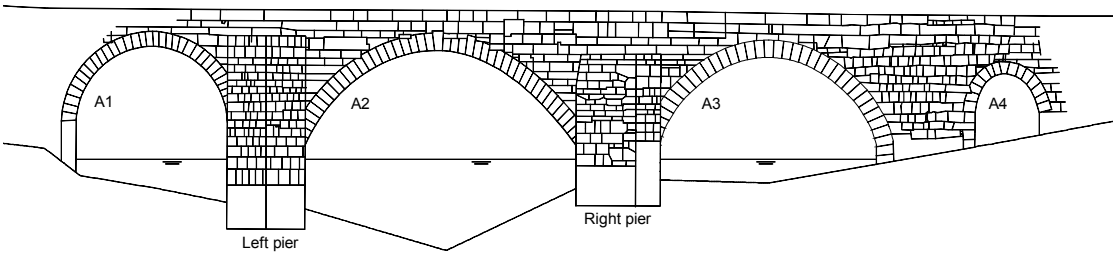


Figure 4: Donim bridge (upstream view)

The spandrel walls as well as the parapets were built with stone masonry, but successive maintenance works carried out over the years have changed some original characteristics as it can be notice by the parapet wall partially rebuilt with concrete blocks and the granitic paving-stone pavement built during the 20th century.

Due to the precarious safety conditions, the local authorities requested a complete survey on the bridge, as well as the definition of a set of remedial measures, compatible with the modern principles of intervention, in order to restore the safety of the structure.

The survey[4] has showed that the structure presents a pronounced damage state. Both the left arch (A1) and the flood arch (A4) present extensive longitudinal cracking, clearly visible at the intrados, see Figure 5. The right pier is very damage, where some stone blocks are cracked and a foundation stone is missing. The vegetation, spread all over the bridge, caused severe damage to the right cutwater. The spandrel walls were subjected to lateral movement and are clearly out of plumb. The general damage pattern observed was originated by the lack of maintenance in conjunction with increasingly heavy loads.

(a) (b) (c)

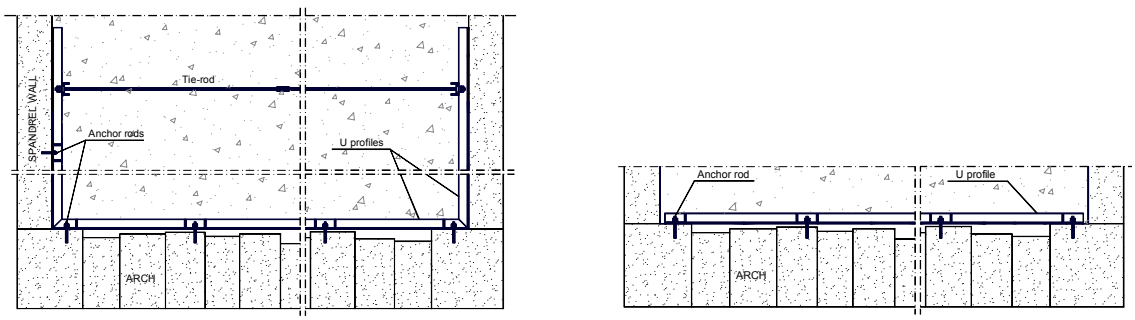
Figure 5: Relevant damage: (a) cracks in the left arch; (b) cracks in the flood arch; (c) cracks in the right cutwater.

Regarding the assessment of the safety conditions of the bridge, a numerical analysis was carried out aiming at the understanding and justification of the damage observed. The geometric data necessary for the analysis was obtained by topographic surveying and visual inspection. A tri-dimensional finite element model was created, where both the non-linear material behaviour of masonry and the infill were considered in the analysis[4, 5]. The results allowed understanding the influence of the infill in the behaviour of the spandrel walls and to

justify the observed longitudinal cracking at the intrados of the arches. Both the detailed visual inspection and the numerical analysis pointed out that the strengthening of the bridge was necessary, namely to counteract the outward movement of the spandrel walls, to prevent their failure and to stop the progression of the longitudinal cracking along the arches, in order to re-establish the safety conditions of the bridge.

Given the historical significance of Donim bridge, the design of any strengthening measure was necessarily conditioned by the fulfilment of modern principles related to structural intervention. Therefore, the remedial measures designed and proposed to restore the safety of the bridge comprehend the structural strengthening of the arch A1, the flood arch and the cutwater of the right pier[6].

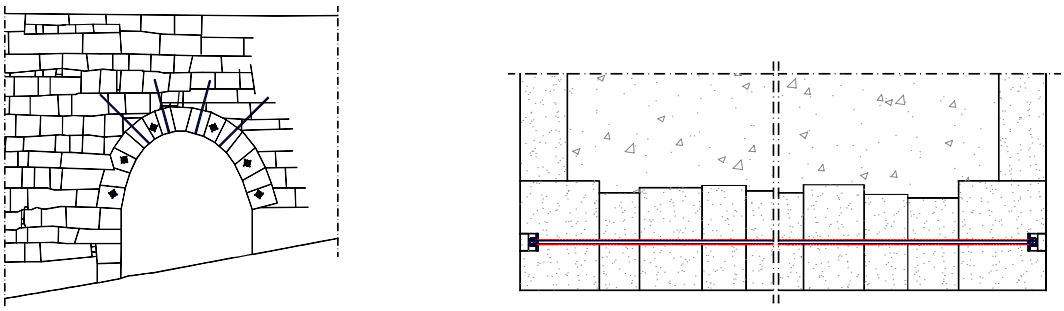
To reduce the enormous longitudinal cracking in the intrados of arch A1 (crack width greater than 8 cm) and return joint's thickness to its original width, the infill above the arch A1 will be removed and the voussoirs will be pushed in by means of rope-stretchers placed along the intrados of the arch, for which the arch must be previously propped along its entire span. The adopted strengthening comprises the fixing of six stainless steel U profiles to the extrados of the arch and to both spandrel walls, by means of anchor rods, as illustrated in Figure 6. A stainless steel tie rod, with a diameter of 16 mm, placed at the top of the vertical profiles and tightened by means of a dynamometric wrench binds the spandrel walls together and reduces considerably the bending of the profile. Close to the crown, the proximity of the pavement allowed only the use of a U profile clamped to the arch with anchor rods. After the completion of these works, the infill is put back in its place and the prop can be finally removed.



(a) (b)

Figure 6: Strengthening of the arch A1 with U profiles: (a) in general; (b) close to the crown.

The cracking pattern observed in the flood arch has showed fewer degree of damage, with maximum crack width lower than 4 cm. Here, the objective was not to return the arch to its original geometry but to prevent any further spreading of the arch and to assure its stability. Thus, it was proposed to use six horizontal anchors across the full width of the bridge, endowed with cylindrical anchorage plates at each side of the arch, see Figure 7.



(a) (b)

Figure 7: Strengthening of the flood arch: (a) adopted anchor scheme; (b) horizontal anchors.

In each anchor, after drilling an oversized hole using a rotating cutting device, a stainless steel rod with 16 mm of diameter involved by a sleeve, is placed in the hole and subsequently grouted with a cement solution, injected under low pressure between the rod and the sleeve. The use of the sleeve increases the efficiency of the anchor system since it inflates, preventing the injected grout to be lost in voids within the structure, or flee through cracks.

No tension is applied to the rods other than a tightening force resulting from their adjustment using a dynamometric wrench. Following grouting of the anchors, the hole is made good with a slip taken from the cores.

For the connection between the arch and spandrel walls a similar solution was developed. Four stitching anchors in each side of the arch (see Figure 7a), ranging between 1200 mm and 1500 mm length, were used with the purpose of linking the spandrel walls to the external voussoirs.

The high level of damage found in the right cutwater, with several stones cracked and out of their original places, will be repaired by the dismantling of the most deteriorated areas. The rebuilding will be carried out using the same stones, previously numbered, or when not able to be used, with similar stones from the region. During the rebuilding, stones in a same course will be connected to each other by means of stainless steel cramps, at every three courses. The link between two consecutive courses is achieved through the use of vertical stainless steel latches. The repair of the cutwater still includes the replacement of the missing foundation stone block.

In order to prevent the fines to be washed out of the fill, leading to voids and thus affecting the load capacity of the bridge, it is recommended to execute the waterproofing and drainage of the pavement. To complete the repair measures, the masonry joints that show degradation will be cleaned and re-pointed using a sand-lime mortar, designed to match as close as possible the colour of existing stone.

4. CONCLUSIONS

Results of a survey on two Portuguese stone masonry arch bridges, built in different periods, are described and the principal sources of damage are pointed out. The necessary repair measures proposed to restore safety conditions, compatible with modern principles of structural intervention in the architectural heritage, are reported in detail.

Some common aspects to both interventions are the need for cleaning and removal of

infesting vegetation, the execution of the waterproofing and drainage of the pavement and the execution of urbanistic adjustments in the areas surrounding the bridges in order to integrate traffic limitations.

5. REFERENCES

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