Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost

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*Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost –
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ABSTRACT: This paper describes the procedure adopted in the analysis and design of repair measures of a historical masonry arch bridge, carried out at Universidade do Minho. The bridge under study crosses over Vizela River, near Guimarães. A detailed survey carried out allowed concluding that remedial measures were necessary in order to restore safety. The bridge load capacity was also assessed by means of a simple computational tool based on the limit analysis theory. To assure the safety use of the bridge, by light traffic and people, repair measures were proposed in accordance with the modern principles of intervention in historical structures.

1 INTRODUCTION

Portuguese masonry arch bridges were built throughout centuries, spanning from the Roman period to modern times, and thus representing an invaluable architectural and cultural heritage. 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 and repair works that bridges were submitted along the centuries generally implies a difficult dating process, leading sometimes to erroneous classifications.

With time, the deep change of loads for which bridges were initially built, the decay of the materials and the lack of maintenance have led to different states of damage, in many circumstances not compatible with their use or even their safety. The most common generalized damage observed in Portuguese bridges is related to 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. On the other hand, localized damage is essentially related with longitudinal cracking of the arches at the intrados, movement of abutments and the lack of plumbness of the spandrel walls. However, some of the causes of the afore-mentioned damage could be avoided if bridges were submitted to periodical inspections. It is well known that the implementation of both periodical inspections and the reduction of the traffic load can efficiently contribute to decrease the structural degradation rate of masonry bridges.

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

By their own nature, structures belonging to cultural heritage constructions present a set of specific features that effectively limit the application of modern codes. Instead, recommendations regarding adequate approaches to guide the intervention in architectural heritage, within a rational and scientific procedure and within a cultural context are available (ICOMOS, 2001). Aspects as 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 when dealing with cultural heritage constructions.

This paper presents the survey of a Portuguese damaged granite stone masonry arch bridge, the assessment of its load capacity and finally describes the adopted repair measures to restore safety, compatible with the modern principles of intervention in structures with heritage value.

2 SURVEY AND DAMAGE PATTERN

The multi-span Negrelos Bridge is located close to Guimarães over the Vizela River. Although considered to be a Roman bridge, there are no available documents to clearly corroborate this hypothesis. As the major part of the bridges, Negrelos Bridge was an important structure of Minho road network in ancient times. With time, the bridge has lost its regional importance, though still assuming a great significance to the local network.

The bridge has a flat roadway, supported by three semicircular granite stone masonry arches, with different free spans (8.0 m + 6.4 m + 8.0 m), as schematically represented in Figure 1. The bridge reaches a total length of approximately 30 m and has a roadway width of about 3.0 m. The central arch is supported by two massive piers, endowed with two triangular cutwaters at upstream and two rectangular cutwaters at downstream. Within a governmental program to clear the river from pollution, a drainage pipe was placed on the left shore, on top of an embankment made beneath arch A1 and close to the left abutment, see Figure 1 (the pipe is not visible).

Both the spandrel walls and the parapets were built with stone masonry, but successive repair works carried out over the years have changed some original characteristics as it can be noticed by the parapet wall partially rebuilt with concrete blocks.

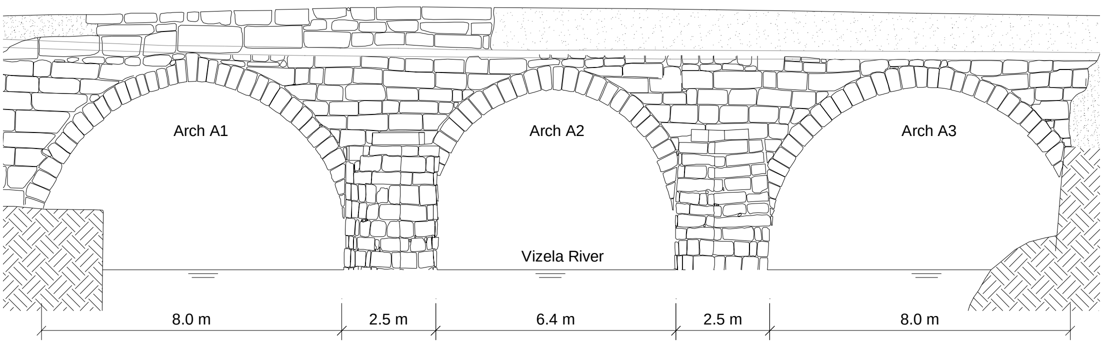


Figure 1. Negrelos Bridge (upstream view).

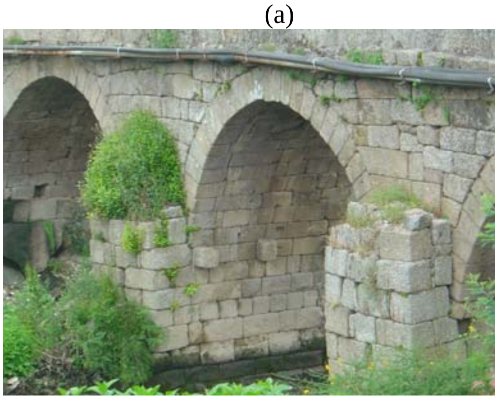
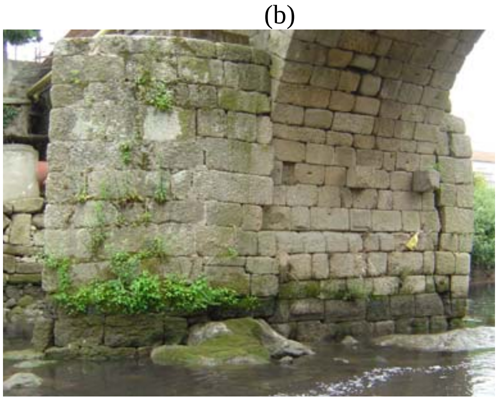
Fearing for the bridge safety, which was originated and supported by its visual aspect, the local authorities requested a complete survey on the bridge, as well as the definition of a set of remedial measures in order to restore safety, if necessary. However, any repair measures to be adopted ought to take into account the architectural significance of the bridge. The survey carried out has showed that the bridge presented a pronounced damage state, where damage was mostly characterized by:

- Extensive longitudinal cracking exhibited by the central arch (A2), close to the downstream spandrel wall, clearly visible at the intrados, see Figure 2a. This is mainly caused by earth pressure in the spandrel walls.
- Lateral movements of the spandrel walls near the left abutment, which became out of plumb, most likely originated by lack of maintenance in conjunction with increasingly heavy loads, see Figure 2b.
- Generalized damage caused by vegetation, spread all over the bridge, see Figure 2c, d.
- Extensive cracking in the left downstream cutwater and minor cracking in the other

three cutwaters, mainly due to existing vegetation and the lack of adequate stone imbrication, see Figure 2c, d. Also, some stone blocks were cracked. Most probably, some of the cutwaters were built or extended after the construction of the bridge.

The deficient maintenance of the bridge along the years together with heavy traffic loads seem to be the main causes of the damage pattern found during the survey, that led the bridge to its actual poor condition. Naturally, the antiquity of the bridge, the water pollution and the decay of the materials also contributed to the actual degraded state.


(a) (b)

(c) (d)

Figure 2. Relevant damage: (a) longitudinal cracking in the central arch; (b) spandrel wall out of plumb; (c) vegetation and cracks in the downstream cutwaters (downstream view); (d) vegetation and cracks in the left pier (upstream view).

3 CARRYING CAPACITY ASSESSMENT

Besides the necessary repair measures to be undertaken, also a numerical assessment in terms of carrying capacity was required in order to appraise the safety conditions of the repaired bridge to be used by light vehicles. Here, the objective of the numerical analysis is just to have a good estimation of the maximum load that the bridge can sustain prior to failure.

Among the available computational methods proposed in literature to compute the carrying capacity of masonry arch bridges, from hand-based methods to advanced non-linear tools, the rigid block computational limit analysis method is the most generally applicable (Livesley, 1978; Gilbert & Melbourne, 1994). However, the applicability of limit analysis to masonry structures modeled as assemblages of rigid blocks connected through joints depends on some basic hypotheses. The first hypothesis requires that the limit load occurs at small overall displacements, which is true for most cases. The second hypothesis is that masonry has zero tensile strength, which can be justified by the relatively low or even zero tensile strength. The third hypothesis requires that shear failure at the joints is perfectly plastic, which can be considerable acceptable since this assumption is supported by experimental results. Finally, the fourth hypothesis is that the hinging failure mode at a joint occurs for a compressive load independent from the rotation. In the case of masonry crushing, this hypothesis might be questionable, but crushing behaviour (except for columns) seems to have minor importance in the response of masonry structures, particularly in stone arch bridges.

Within the limit analysis method the load distribution is known but the load magnitude that the bridge can carry is unknown, but it can be easily computed. Therefore, limit analysis is a very practical computational tool since it only requires a reduced number of material parameters and it can provide a good insight into the failure pattern and limit load.

Here, Negrelos Bridge was modeled as an in-plane three-span semicircular arch bridge with a 0.50 m arch thickness and a flat pavement (Gilbert, 2005). The necessary geometrical data was obtained from topographic surveying and visual inspection, see Figure 1. In the absence of in-situ test results, the material properties were considered to assume typical values found in similar structures (Oliveira & Lourenço, 2004; Oliveira & Lourenço, 2005). In particular, a value of 8 N/mm^2 was adopted for the masonry compressive strength (PIET, 1970), whereas for the horizontal passive pressure a conservative value equal to half of the classical value given by Rankine theory was used (Smith et al., 2004).

Besides the self-weight of the materials (masonry and fill), a rolling load composed by the standard Portuguese vehicle (RSA, 1983) was considered. This standard vehicle is composed by three axles equally spaced by 1.5 m and with a 200 kN load per axle.

Using a computer program developed within the rigid block limit analysis method (Gilbert, 2005), the minimum failure load factor is equal to 1.67. Figure 3 illustrates the associated four hinges failure mechanism found, where both the dead and live load pressures applied to the arch, the hinges and the thrust-line are showed.

Assuming that the vehicle crosses the bridge from left to right, the minimum failure load factor was found for the vehicle central axle positioned at 31.9 % of the left arch free span (arch A1), as illustrated in Figure 3. Since symmetrical geometry and vehicle are used, the same result is obtained considering that the vehicle crosses the bridge from right to left instead. Since the local authorities are planning to close the bridge to heavy traffic after concluding the repair works, it can be considered that the bridge will present safety conditions to be crossed by light traffic.

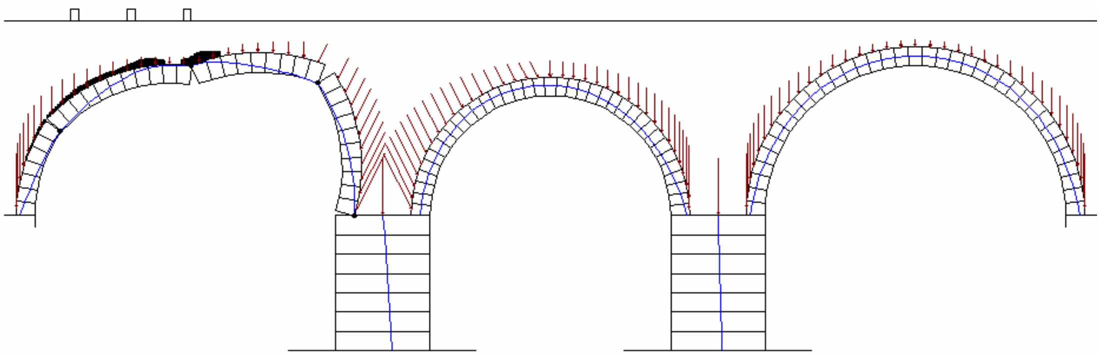


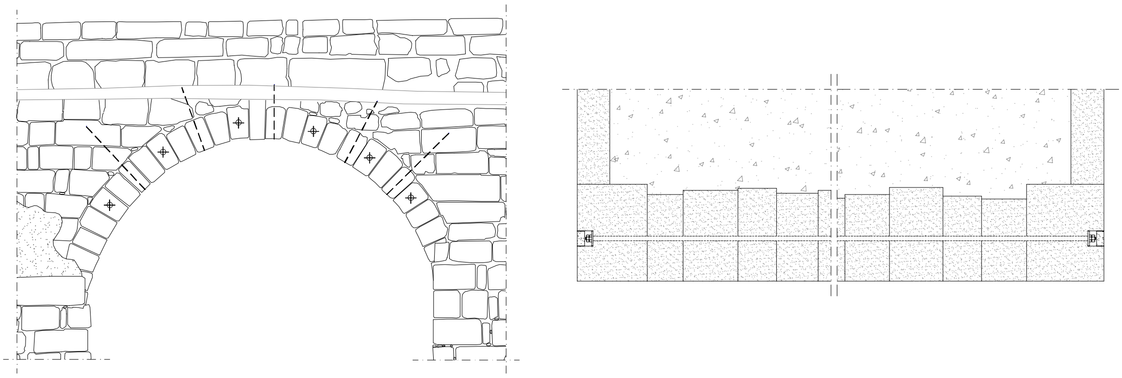
Figure 3. Minimum load failure mechanism of Negrelos Bridge.

4 REPAIR MEASURES

4.1 *Description of the remedial measures*

The detailed visual inspection carried out showed that a set of repair actions were necessary, namely to stop the progression of the longitudinal cracking along the central arch, to counteract the outward movement of the spandrel walls, to prevent the failure of the cutwaters and to clean all vegetation from masonry. As stated above, the historical and architectural importance of Negrelos Bridge forced that any strengthening measures had to be designed in accordance with the principles that guide structural interventions in historical constructions.

To prevent any additional increase of the longitudinal cracking in the intrados of the central arch as well as to assure its future stability, a set of four horizontal stainless steel anchors across the full bridge width, endowed with cylindrical steel anchorage plates at each side of the arch, were proposed, see Figure 4. Also, two additional shorter stainless steel anchors were used close to each springing. In addition, it was recommended a light injection of the arch, at the intrados.

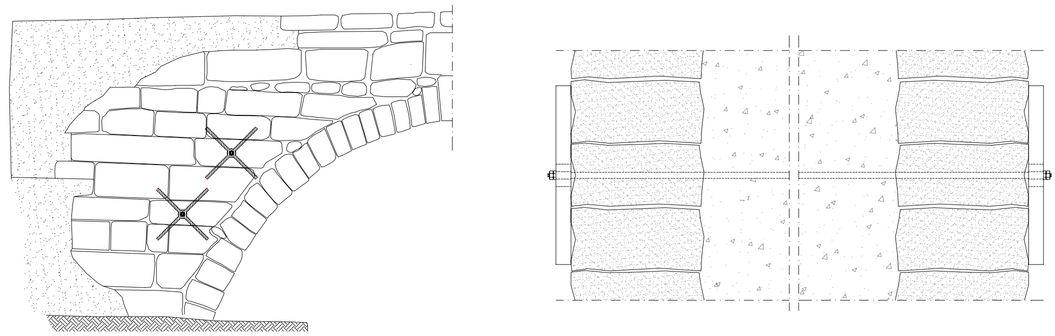


(a) (b)

Figure 4. Strengthening of the central arch: (a) adopted anchor scheme; (b) full bridge width anchors.

For the connection between the arch and the spandrel walls a similar solution was developed. Five stitching anchors in each side of the arch were used with the purpose of linking the spandrel walls to the external arch voussoirs, see Figure 4a.

In order to face the out-of-plumbness of the spandrel walls above the left arch, it was decided to use two horizontal stainless steel anchors across the full bridge width provided with cross-shaped anchorage plates at the extremes, see Figure 5. The shape of the plates was due to aesthetic reasons.



(a) (b)

Figure 5. Strengthening of the spandrel walls: (a) anchor cross-shape plates; (b) transversal elevation view.

To repair high level of damage found in the downstream cutwaters, with some stones cracked and others out of their original place and disconnected from the piers, the dismantling and subsequent rebuilding of the most deteriorated areas was proposed. On the other hand, the upstream cutwaters, less damaged but also in a poor condition, are to be injected with a lime-based grout after conclusion of the joint repointing works.

All infesting vegetation is to be removed using the most adequate procedures, and all masonry joints that show degradation are to be carefully cleaned and repointed.

In order to prevent the fines from being washed out of the fill material, leading to voids and thus affecting the carrying capacity of the bridge, it is recommended to execute an adequate waterproofing and drainage of the pavement.

4.2 *Execution*

The intervention started with the cleaning and repointing of damaged masonry joints. Special care was put on the removal of vegetation, in order to cause the least possible damage to masonry. All repointing works were done with a lime-based mortar designed to match as close as possible the stone colour, see Figure 6a, b. At the same time, the preparatory works leading to the injection of the upstream cutwaters and central arch were begun, see Figure 6b, c.

(a) (b) (c)

Figure 6. (a) Joint repointing of piers and arches; (b) joint repointing and injection works of an upstream cutwater; (c) injection works of the central arch.

After dismantling, the rebuilding of the downstream cutwaters was carried out using the same stones, previously numbered, or when not able to be used, with similar stones from the region, see Figure 7a. During the rebuilding, the stones in a same course were connected to each other and to the piers by means of stainless steel cramps, at every three courses. The link between two consecutive courses was achieved through the use of vertical stainless steel latches.

Both the transversal full bridge width tying strengthening of spandrel walls and central arch, by means of anchors, was carried out using the same technique. In each anchor, after drilling an oversized hole using a rotating cutting device, a stainless steel rod was placed in the hole and subsequently grouted under low pressure. In order to prevent generalized material injection it was decided to use a sleeve involving the rod. No tension was applied to the rods other than a tightening force resulting from their adjustment using a dynamometric wrench. While in the spandrel walls anchors it was decided to use cross-shaped anchorage plates, see Figure 7b, in the all eleven arch anchors the hole was made good with a slip taken from the drilled stone cores, see Figure 8.

(a) (b)

Figure 7. (a) Rebuilding of a downstream cutwater; (b) cross-shaped anchorage plate.

(a) (b) (c)

Figure 8. (a) Cylindrical-shaped anchor plate used in the arch anchors; (b) stone slip taken from a drilled core; (c) final visual aspect of a stitching anchor.

5 CONCLUDING REMARKS

The main results of a detailed survey performed on a damaged historical masonry arch bridge are here reported. This damage level threatened the normal usage of the bridge as well as its future stability. Given the historical significance of Negrelos Bridge and taking into account its rehabilitation and protection, a set of remedial measures were designed and executed aiming at restoring the bridge safety, in accordance with the principles that guide interventions in architectural heritage constructions.

The computational program based on the rigid block limit analysis theory used in this work has reveled to be a very simple and practical tool toll in the estimation of the carrying capacity of masonry arch bridges.

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