Diagnosis and repair of a historic stone masonry arch bridge

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ABSTRACT: The D. Zameiro Bridge is a multi-span stone masonry arch bridge built between the 12th and 13th centuries that crosses the Ave River in a rural area 40 km North of Porto, Portugal. The bridge is composed of eight arches of different span, with a total length of 130 m. The bridge has been subject to several conservation and repair works along its existence. In 2001, a flood caused the partial collapse of a pier and of the adjacent arches close to left bank. The bridge was repaired in 2003, but a new accident in 2004 caused the collapse of two piers and adjacent arches near the right bank. This paper presents a brief historical note, discusses the inspection works carried out after the collapses and provides the possible reasons for such extreme events. Afterwards, the paper reports the repair works carried out, taking into account the architectural significance of the construction.

1 INTRODUCTION

The D. Zameiro Bridge is a Mediaeval multi-span arch bridge over the Ave River, near the city of Vila do Conde, located about 40 km North of Porto, in the Northern part of Portugal. The bridge has a humpback pavement, supported by eight stone masonry arches of different spans, (maximum clear span of 13.4 m), as schematically illustrated in Figure . The bridge reaches a total length of 130 m and has an average width of 4 m. All the arches present a semicircular shape except one that is a pointed-arch, most probably due to a reconstruction during the Gothic period or afterwards. The arches are supported by massive piers, endowed with triangular cutwaters at upstream and rectangular cutwaters at downstream, see also
Figure .

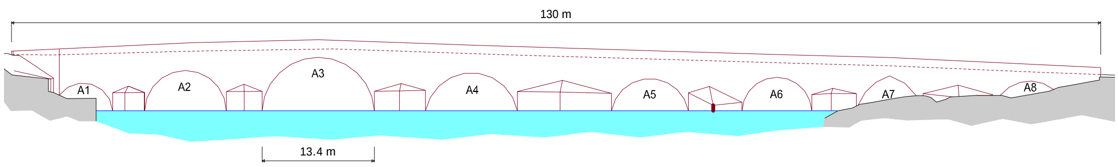

Figure 1 : D. Zameiro Bridge (upstream view)

The bridge, built between the 12th and 13th centuries, is located in a very old path connecting the cities of Porto and Barcelos, being part of the historic Portuguese pilgrimage route from Lisbon to Santiago de Compostela, Spain. It is currently included in a section of the national road EN 306 that has been declassified in the 1970's, when it was substituted by a variant of the road including a new bridge at downstream. The D. Zameiro Bridge is in the way to be classified as a Portuguese national monument since 1996 (IGESPAR 2008).

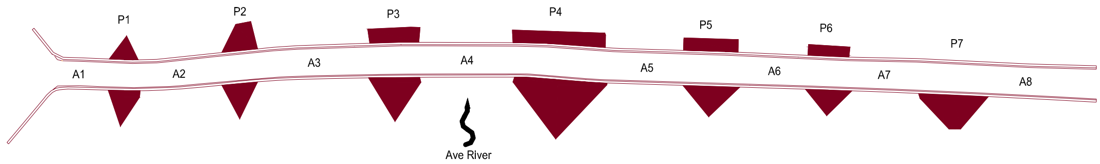

Figure 2 : D. Zameiro Bridge (plan view).

D. Zameiro Bridge is placed in the path of an ancient Roman road connecting Braga and Lisbon, two of the most important cities of Western Iberian Peninsula during the Roman Empire. During the 10th and 11th centuries the region where the bridge is constructed was easily reached by pirates, as it is not far away from the coast (around 10 km from the coast following the river). Therefore, the coast was not very populated, while the interior valleys concentrated most of the population (cities like Braga or Guimarães were very important at those times). In the middle of the 12th century piracy dropped substantially thanks to the conquest of Lisbon by the Portuguese King, as this port was a very important scale for pirates. Then, the coast was repopulated. As the ancient Roman path was in between the interior and the coast, it became (again) a very important connection between Porto and the Northern part of Portugal, thus leading to the construction of the D. Zameiro Bridge during the end of the 12th century and beginning of the 13th century.

Until the 19th century, this was the most important bridge of the region, before another bridge was constructed in the city of Vila do Conde. Up to the 1970's the bridge was subjected to an intense daily traffic load (it was integrated in the Portuguese national roadway network), but since that period onwards it has been subjected to local traffic only, implying a substantial load reduction.

2 COLLAPSES AND PAST INTERVENTIONS

It is thought that the bridge has collapsed several times along its history. However, it has been reported that during several floods, the water level was almost at the crown of the largest arch, without causing any visible problem. Little weirs have always existed on downstream side, but smaller than the current one. During the 1960's an intervention to reconstruct the upstream cutwaters took place. In that period, also the downstream cutwaters were reconstructed. In 1998, an intervention was carried out mainly to remove the infesting vegetation and a tree that had grown inside the cutwater of pier P2. Also some cracks were repaired. During this intervention it was found that the spandrel wall and the cutwater of pier P2 were highly damaged due to the roots of the existing tree.

2.1 Collapse in 2001

In March 2001, the Authorities decided to close the bridge to traffic because of the existing damage in the bridge, mainly in pier P2. This preventive measure was taken mainly because a bridge near Porto (made of masonry piers and steel deck) collapsed some days before due to intense rainfall and high flow. Two days after the decision has been taken, the pier P2 and arch A3 collapsed partially due to the combination of its bad condition and high flow. The survey carried out in 2002 (Fonseca 2002) highlighted the following problems in the bridge:

(1) Partial collapse of pier P2 and arch A3;
(2) Longitudinal cracks along the intrados of some arches, either on upstream or downstream sides;
(3) Presence of vegetation, moisture and efflorescences;
(4) Presence of cement mortar in some joints and absence of mortar in other joints;
(5) Material degradation.

In 2003, the bridge was repaired, being carried out the following works:

(1) Rebuilding of the missing parts of pier's foundation;
(2) Rebuilding of pier P2 and arch A3;

(3) Tying of spandrel walls;
(4) Removal of vegetation and cleaning of the bridge;
(5) Removal of existing cement mortars and joint repointing using a lime-based mortar;
(6) Construction of a new pavement.

2.2 Collapse in 2004

In 2004 the existing downstream weir was rebuilt with a higher height. The former walls were in a bad state. The work began in the right side of the river for which a temporary embankment was built on the upstream right side of the bridge. Then, the embankment was removed and constructed in the left side (again on the upstream side) to proceed with the works on this side of the river. In October 2004, when the works were started at the left side, the piers P5 and P6 and the adjacent arches A5 and A6 collapsed partially, see also Fig.2.

Due to the presence of the embankment on the left side, all the river flow was passing through the arches on the right side. Moreover, the weir gates were opened causing an increase of the flow. Following the collapse in October 2004, a temporary embankment was built on the upstream of the bridge in order to deviate the river flow from arches A5 to A8. The survey carried out on the bridge at the end of 2007 and beginning of 2008 allowed to identify important structural damages (Corallo et al. 2008). The main problems found are listed below, see also Fig.3, Fig.4, and Fig.5:
(1) Partial collapse of piers P5 and P6, involving also the upstream cutwaters;
(2) Partial collapse of arches A5 and A6;
(3) Loss of backfill material;
(4) Partial collapse of the pavement and of the upstream parapet;
(5) Several cracks in the spandrel walls, at both sides of the bridge;
(6) Presence of vegetation, moisture and efflorescences;
(7) Absence of mortar in some joints and presence of cement mortar in others;
(8)Lack of a suitable drainage system.

Figure 3 : Upstream view of the collapsed arches and piers before the construction of the temporary embankment

(a) (b)

Figure 4 : Main structural damage: (a) arch A5; (b) arch A6 (upstream view).

The collapse mode observed is consistent with the hypothesis of scouring of the foundations associated to the high water velocity. This conclusion was also reached numerically by modelling the arches with discrete blocks and imposing vertical settlements to one of the piers. On the other hand, a simplified calculation of the hydrodynamic thrust over the structure allowed to realize that the water pressure itself originates negligible tensile stresses in the masonry (Richardson and Davis 2001).

(a) (b) (c)

Figure 5 : Main structural damage: (a) arch-spandrel separation, (b) moisture and efflorescences, (c) vegetation and deficient drainage system

3 REPAIR OF THE BRIDGE

Constructions having an important architectural heritage value present a set of specific features that limit the use of modern codes. In these cases, available recommendations regarding the most suitable approaches to guide the intervention in architectural heritage structures within a rational scientific framework are to be used. Aspects as minimum repair to assure safety and durability requirements, respect for the original conception and the compatibility between new and existing materials are essential issues of the modern principles of intervention in architectural heritage constructions (ICOMOS 2001).

3.1 Repair proposal

In order to repair the high level of damage found in the bridge, it was decided to perform the dismantling and subsequent rebuilding of the most deteriorated parts of foundations, piers, arches, cutwaters, spandrel walls and parapets (Fonseca 2007). These works should be carried out using the same stones as much as possible. A fill material similar to the existing one should be used in the reconstruction. Due to aesthetic reasons, the pavement should be made of cubic granite blocks, similar to the pavement that existed before the works carried out in 2003. The stitching of the most affected spandrel walls was also proposed. The repair measures proposed to restore safety of the bridge also included the strengthening of the arch, to assure the transversal stability of the structural elements.

After the rebuilding of the damaged areas, the infesting vegetation was to be removed in order to allow cleaning properly the bridge. Additionally, all masonry joints that show degradation should be carefully cleaned and repointed using a suitable lime-based mortar. The same applied to joints filled with cement mortars, which had to be removed. In order to minimize the appearance of humidity and efflorescences at the intrados of arches, to reduce the lateral pressure on the walls and to prevent the fines from being washed out of the fill material, it was proposed the waterproofing of the pavement and the complete reconstruction of the drainage system.

3.2 Repair works

The intervention started with the propping of the damaged arches and the rebuilding of the structural elements, namely the missing parts of the foundation, piers P5 and P6 and respective cutwaters, arches A5 and A6, spandrel walls and parapets. This operation was carried out using the same stones, previously numbered, or when not able to be used, with similar stones from the region, see Fig.6 (a), (b).

The replacement of the backfill was done resorting to successive layers of soil and gravel watered with a lime-based mortar.

The rehabilitation works included the strengthening of arches A5 e A6 with the purpose of prevent any additional increase of cracking at the intrados as well as to assure its future stability. The adopted strengthening measure comprises the use of six horizontal stainless steel anchors across the full bridge width, endowed with cylindrical steel anchorage plates at each side and covered by a stone slip, as illustrated in Fig.7 (a), (b).

No tension was applied to the rods other than a tightening force resulting from their adjustment. Also, additional stainless steel cramps were used in the spandrel walls, see Fig.7 (a), (b).

(a) (b)

Figure 6 : Repair works: (a)numbering of the stones; (b)rebuilding of the spandrel wall.

(a) (b)

Figure 7 : Repair works: (a) strengthening of the arch with transversal anchors; (b) strengthening of the spandrel wall with steel cramps.

Given the historical importance of the bridge, cleaning of the masonry was performed avoiding any aggressive cleaning product that could cause degradation of the stone. Thus, cleaning of the bridge was done resorting to water jet cleaning, see Fig.8 (a), (b).

The removal of vegetation, roots and biological colonies was carried out through the application of biocide, as to cause the least possible damage to masonry. Joint repointing was performed with a lime-based mortar designed to match the stone colour as close as possible, see also Fig.8 (a), (b).

(a) (b)

Figure 8 : Repair works (a) cleaning of the bridge; (b) joint repointing using lime-based mortar.

Waterproofing membranes were applied below the pavement, with replacement of the existing infrastructures. Also a new pavement was constructed, including a suitable drainage system. Figure shows an overview of the bridge after the conclusion of the repair works.

Figure 9 : Bridge after the rehabilitation (upstream view).

4 CONCLUSIONS

This paper addresses the partial collapse of a Portuguese historic masonry arch bridge. An interdisciplinary approach was followed, involving:

(1) the history of the bridge, structural problems occurred and repair works carried out in the past;

(2) inspection of existing damage;

(3) structural analysis based on simple computations to understand the causes of collapse.

This approach allowed to establish the diagnosis following the partial collapse in 2004. Scouring of the foundation appears to be most probable cause of collapse. In masonry arch bridges subjected to low traffic loads (or pedestrian ones) and periodic high river flows, as D.Zameiro Bridge, scouring becomes much more critical than the load carrying capacity.

Afterwards, the paper describes the measures proposed to repair the bridge and the works carried out during the last trimester of 2008 and first trimester of 2009. The measures foreseen and the repair works carried out tried to follow the current conservation principles, where a balance between minimum intervention, authenticity, non-invasivity and safety requirements has to be sought.

Finally, it should be mentioned that the absence of periodic maintenance works and the lack of suitable drainage systems are two of the most important (indirect) causes of damage of masonry arch bridges in the Northern region of Portugal.

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REFERENCES

Corallo C., Cuzzilla R., Darain K., Mekonen D., Murcia J. 2008. D. Zameiro Bridge: survey and repair proposal. University of Minho (available at www.msc-sahc.org).

Fonseca A.A. 2002. Structural survey report (in Portuguese). Afassociados SA and FEUP, Porto, Portugal.

Fonseca A.A. 2007. Rehabilitation of D.Zameiro Bridge over Ave River (in Portuguese). Afassociados SA and Estradas de Portugal SA, Porto, Portugal.

ICOMOS 2001. Recommendations for the analysis, conservation and structural restoration of architectural heritage. International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage.

IGESPAR, www.monumentos.pt (accessed in March 2008).

Richardson E.V., Davis, S.R. 2001. Evaluating scour at bridges. Hydraulic Engineering Circular 18, US Federal Highway administration.