HISTORY OF A FAULTY RETROFITTING: THE S. SEBASTIAN BRIDGE IN LOANO (ITALY)

F. Bonfiglietti[1], A. Brencich[2]

[1] Consultant, Loano, Savona County, ITALY.
[2] University of Genoa, Department of Civil, Chemical and Environmental Engineering, Genoa, ITALY.

e-mails: filippo@bonfiglietti.net, brencich@dicca.unige.it

SUMMARY

Masonry bridges are well inside the European monumental heritage; even though protected by the Preservation Authorities, their retrofitting does not always follow rational approaches. In this paper, the case study of the S. Sebastian Bridge in Loano (Italy), a pedestrian bridge dating back to 1691, is discussed. The collapse of the aedicule, and the subsequent collapse of the armilla, are found to be the result of several causes: i) poor and non-rational original design; ii) degradation of poor materials due to environmental actions; iii) wind-induced fatigue collapse of some material; iv) thermal stresses due to the dilatation of a modern concrete pavement. The retrofitting criteria proposed for this case are discussed comparing their effectiveness and the conservation of the monumental value of the bridge.

Keywords: *Masonry bridges, load carrying structure, retrofitting.*

1. INTRODUCTION

Masonry bridges were built in the railway and road European networks mainly from the 18th century (19th century for Italy) up to the ‘30s of the last century [1]. Nevertheless, in Italy there’s a quite large population of single-span pedestrian bridges crossing minor rivers, dating back to the 17th century, that are often addressed as “Roman bridges” due to their high rise. Except the bridges in famous areas, they exhibit poor materials and underwent limited, if any, maintenance works. The S. Sebastian bridge in Loano (Savona County) is one of these bridges.

Even though masonry bridges are protected by the Preservation Authorities, they have to face a professional knowledge scarcely aware, or unaware, of their actual mechanical response. The outcome is that the “retrofitting works” are not always rationally designed, often follow the “reinforced concrete logic” and, furthermore, may alter the historical meaning of the bridge and change its mechanical response [2-6]. An example is provided by road bridges: the need of enlarging the bridge deck leads to the introduction of r.c. slabs supported by the spandrels, which makes the spandrels, instead of the fill, to transfer the load to the arch.

Recent works outlined that arch bridges are complex structures in which all the elements take part in the load carrying system. The arch itself provides only a negligible contribution to the load carrying capacity of the bridge, the rest coming from the arch-fill and arch-spandrel interaction [7-10 among the others]. In many cases, if masonry bridges were studied as a complex structures, the retrofitting works would not so invasive as often happens.

In this paper, the case study of the S. Sebastian Bridge in Loano (Italy, Savona County), a pedestrian bridge dating back to 1691, is discussed. The collapse of the aedicule built just in crown of the spandrels, and the subsequent collapse of the armilla, asked for retrofitting works. Several criteria have been proposed, some recalling to the original building technique and others trying to introduce modern materials (curved steel beams to rebuild the collapsed part) notwithstanding the masonry strength and capacity and, furthermore, without a rational approach and analysis of the causes of the collapse. The aim of the paper is to discuss, starting from a case study, different retrofitting criteria: the ones that follow the mechanical response of a masonry bridge turn out to be the most efficient and less expensive.

2. HISTORY

The bridge, crossing the Nimbalto stream 100m from the sea with a single span 14m long and 4 m wide, connects the old city of Loano (west bank) to the east bank and was built between 1690 and 1691. A statue (of S. Sebastian, of course) in the aedicule, figure 1, was placed only in 1934 even though the aedicule was built on the northern side simultaneously to the bridge.

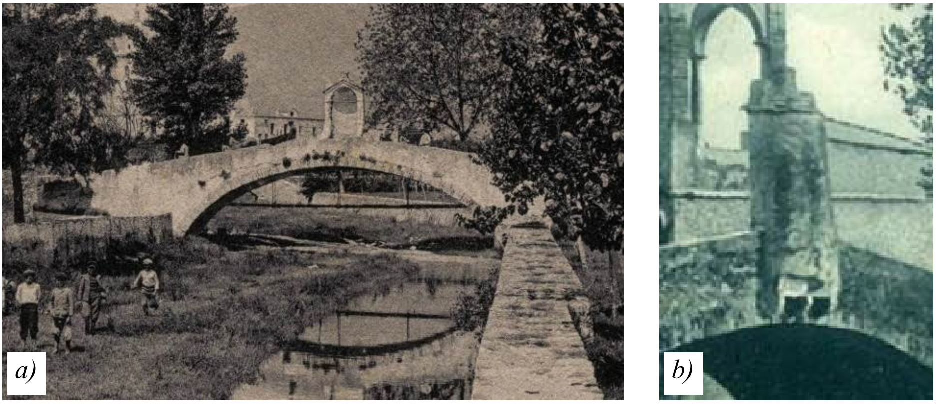

Fig. 1. *a) S. Sebastian bridge in a 1912 postcard. The black line below the bridge is the water pipe. b) rear view of the aedicula.*

Fig. 2. *Water pipe below the bridge – 2nd half of 19th century.*

Fig. 3. *a) Concrete pavement (1960 approx.). b) Original cobblestone on the right (after removal of the concrete layer). The southern side is on the left. On the right the „hole" in the spandrel due to the collapse of the aedicule.*

In the 2nd half ot the 19th century a water pipe, Fig. 1, was placed below the bridge through a couple of holes in the arch barrel, Fig. 2. Around 1930, a gas pipe was placed below the pavement on the sourthern side; close to 1960 a concrete pavement (10cm thick) was placed over the old cobblestone, Fig. 3.

The 4th of July 2013 at 7PM, apparently with no reason (no wind, no impact, no load), the aedicule collapsed along with part of the armilla. Fig. 4 shows its inclination few hours before the collapse. Fig. 5 shows the collapsed armilla and the texture of the arch barrel.

Fig. 4. *Few hours before the collapse.*

Fig. 5. *Collapsed armilla on the northern side.*

3. ASSESSMENT

3.1. Geometry and materials

The main geometric data of the bridge are: span 13.75 m, arch thickness 46 cm, rise 4.50 m, rise-to-span ratio 0.32 which identifies a shallow arch; polycentric arch. The spandrels are 70 cm high (in crown) and 26 cm thick, as much as the armilla. Almost no fill is present in crown and no internal spandrel has been detected.

As figure 1 shows, the aedicule was supported by 3 cantilevers fixed in the barrel brickwork. Fig. 6 shows the remains of the cantilevers after collapse outlining that the stones cracked but did not slide outside the arch, which means that no collapse of the cantilever restraints took place.

Fig. 6. *Frontal view of the cracked surface.*

***Fig.** 7. a) Spandrel on the south side: bad conditions and sliding (?) at the arch-spandrel interface; b) texture of the Finale Stone (rose type).*

The overall conditions of the bridge were very poor: the barrel, with no maintenance at all, presented large voids, due to water leaking, and was deformed (5 cm) due to the combined action of the water pipe and the flood (i.e. trees and other similar stuff) hitting the pipe. The concrete pavement had one longitudinal expansion joint filled with sand and other material and is doubtful whether it could still perform its task.

The spandrels were generally in bad conditions and sliding on the arch-spandrel interface appeared, Fig. 7a.

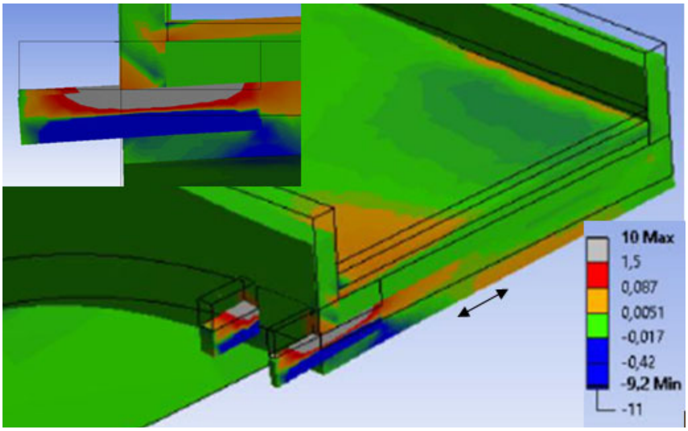

***Fig. 8.** Dead loads + wind loading (80km/h). Transversal stresses indicated by the arrow.*

The compressive strength of solid clay brickwork was assumed not lower than 5 MPa. The Finale stone of the cantilevers is a local stone, highly inhomogeneous, figure 7b, exhibiting low and highly variable mechanical properties: f_t = 3-8 MPa and f_c = 23-64 MPa.

3.2. Mechanics of the bridge

Being the arch a pedestrian bridge, the dead loads largely prevail over the live loads. A global analysis (not reported here) shows that the arch shape is somehow optimized, being the vault cross section fully compressed and the compressive stresses never exceeding 0.4 MPa.

The main loads are: i) dead loads; ii) wind; iii) temperature gradient between the pavement extrados and the brickwork arch ($\Delta T=40°$). Figures 8 and 9 show the main issue of structural analysis: the transversal stresses due to dead loads and wind loading (80km/h) on the aedicule (figure 8) and to thermal loads (figure 9). The concrete pavement is represented in the model with $\alpha_t=1.2*10^{-5}$ for concrete, $\alpha_t=0.6*10^{-5}$ for brickwork and $\alpha_t=0.8*10^{-5}$ for *Finale stone*. The analysis are non-linear with vanishing tensile stresses for brickwork; the cobblestone does not take part to the structure and the concrete pavement is in contact with the spandrels and separated from the barrel by a sand layer.

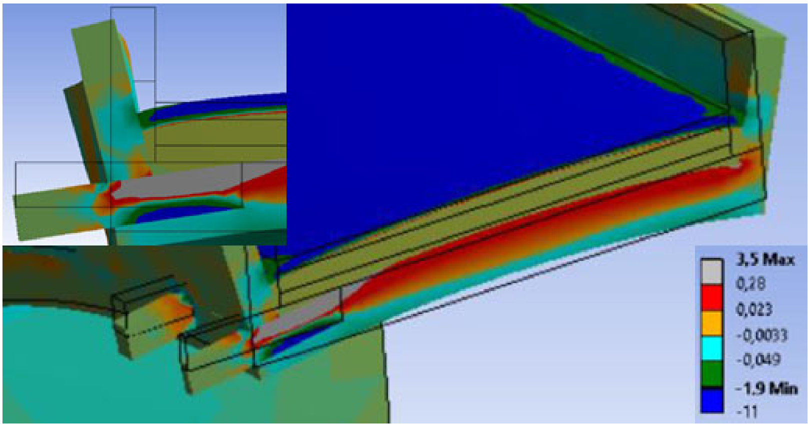

Fig. 9. *Thermal loads ($\Delta T=40°$ between bridge deck and arch barrel). Transversal stresses (arrow).*

Cantilevers and the surrounding zone are the crucial issue since cantilevers crushed slightly inside (30cm) the bridge surface, the maximum tensile stresses induced in the cantilever, 30cm deep in the arch barrel are:

dead loads: 1.7 MPa - wind loads: 8MPa - thermal loading: 3.5 MPa.

If we consider the summer frequent load combination (dead load + temperature) the max tensile stress in the cantilever is 5MPa. The typical winter load (dead load + wind) results in a peak stress (gust) close to 10MPa. Since the bridge survived more than 3 centuries, we have to conclude that also the 10MPa peak stress does not exceed the tensile strength of *Finale stone*. The following issues suggesst a wind- and thermal induced fatigue collapse: i) the peak tensile stresses are very close to the upper limit of the tensile strength for this material; ii) thermal loading may exceed the 40°C gradient and is, at least, a daily load; iii) in Loano, the wing gauge in the harbour (close to the bridge but more exposed) recorded gust peaks as large as 130 km/h. These issues show that the collapse can be attributed to fatigue of the cantilevers sustaining the aedicule.

4. RETROFITTING AND DISCUSSION

The authors proposed to retain the survived part of the cantilevers since they: i) proved to be well fixed in the arch barrel; ii) are compressed in the transverse direction (for the cantilevers) due to the arch barrel compression, figure 10.b. The external part of the cantilevers could be rebuilt by means of a reinforced concrete extension (also with FRP reinforcement on the extrados), figure 10.a, and armilla and spandrel rebuilt with solid clay brickwork. In this way: i) the restraints of the cantilevers were surely fixed in the arch through the mechanism of figure 6; ii) no damage was furtherly induced in the barrel; iii) the rebuilt part of the cantilevers could be recognized.

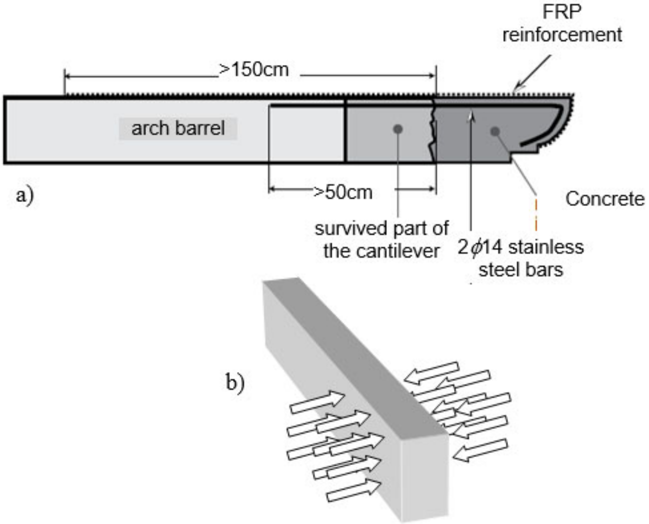

Fig. 10 *a) Proposed retrofitting strategy (authors); b) the restraint of the arch barrel to the cantilevers is due to the transversal compression of the arch.*

Two other proposals were suggested.

1) rebuild the armilla by means of a steel arch (H shaped section) embedded in massive concrete reinforced with ordinary bars. The spandrel and the aedicule could be rebuilt on the mixed steel-concrete armilla. Such a proposal was rejected by the authors and the Preservation authorities since it would introduce a severe stiffness mismatch in the bridge and would alter the monument and its historic value.
2) the cantilevers were simply "substituted": once removed the survived parts, figure 6, new cantilevers (same geometry of the ancient ones) were replaced in the arch barrel using expansive mortars to fix them in the arch. The armilla and the aedicule were later rebuilt using standard techniques. Such a procedure is uncertain since the removal of the survived parts of the cantilevers removes also the compressive stresses that guarantee the restraint to the cantilevers, figure 10.b. Besides, using the same material, the fatigue issue is not solved at all.

The S. Sebstian bridge in Loano is a prototype case study of a minor bridge with a significant historical value. The standard approach of common engineering practice does not take into account the bridge mechanics and does not look for the cause of the damage that needs to be retrofitted but simply look for modern technologies to be inserted in the bridge, thus destroying its monumental value. More careful investigations, such the simple ones discussed in this paper, show that a rational approach can save the value of the monument and economic resources at the same time.

REFERENCES

[1] ORBÁN Z., UIC project on assessment, inspection and maintenance of masonry arch railway bridges, *Proc. ARCH*, 2007, 7: 3-12.

[2] SUMON S. K., Innovative retrofitted reinforcement techniques for masonry arch bridges, *Proc. of the Inst. of Civil Eng.rs - Bridge Eng.ng.*, 2005, pp. 91-99.

[3] BORRI A. et al., Strengthening of brick masonry arches with externally bonded steel reinforced composites. *J. of Comp. for Constr.*, 2009, 13.6, pp. 468-475.

[4] TAO Y., STRATFORD T. J., CHEN J. F., Behaviour of a masonry arch bridge repaired using fibre-reinforced polymer composites. *Eng. Str.*, 2011, pp. 1594-1606.

[5] JURINA L., The reinforced arch method: a new technique in static consolidation of arches and vaults. *Proc. of the Eur. Conf. "Innovative Techn. and Mat.s for the Protection of Cult. Her.." Dec.*. 2003. pp. 2003.

[6] MODENA C., et al., Structural upgrading of a brick masonry arch bridge at the Lido (Venice). *Proc. ARCH04, Barcelona*. 2004. pp. 435-443.

[7] CAVICCHI A., GAMBAROTTA L., Collapse analysis of masonry bridges taking into account arch–fill interaction. *Eng. Str.*, 2005: 605-615

[8] GAGO A. S., ALFAIATE J., LAMAS A., The effect of the infill in arched tructures: Analytical and numerical modelling. *Eng. Str.*, 2011, pp. 1450-1458.

[9] MILANI G., LOURENÇO P.B., 3D non-linear behavior of masonry arch bridges. *Comp. & Str.*, 110, 2012, pp. 133-150.

[10] CALLAWAY P., GILBERT M., SMITH C.C., Influence of backfill on the capacity of masonry arch bridges. *Proc. of the Inst. of Civil Eng.rs: Bridge Eng,ng.*, 2012, pp. 147-157.