

## STRUCTURAL UPGRADING OF A BRICK MASONRY ARCH BRIDGE AT THE LIDO (VENICE)

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**Abstract.** *In the framework of some maintenance works for the improvement of about 1 km of bank sides at the Lido (Venice), some repairs on the pedestrian and the vehicular bridges on the Excelsior canal were carried out. In particular, the upgrading of the brick masonry arch bridge “Sandro Gallo” is presented in this contribution. The S. Gallo bridge was built in the XIX century and is currently used as vehicular bridge. The repairs carried out on the bridge were mainly aimed at upgrading the bridge to the first category, according to the Italian code. The intervention consisted in the combination of traditional and innovative strengthening techniques. Some local repairs were made on the masonry arch. Its thickness was increased using a new layer of brick masonry, with bricks inserted as shear connectors between the old and new masonry, and its extrados was regularized for the application of CFRP laminates. For the upgrading, a reinforcement of the foundation by means of reinforced concrete beams resting on inclined and vertical micro-piles was designed. The beams, that are external with respect to the old foundations, were designed to be connected to both the new layer of masonry and the CFRP laminates. The main phases related to the design of the intervention and its realization are discussed.*

## 1 INTRODUCTION

The Sandro Gallo bridge was built in two subsequent phases, in the XIX and in the first decades of the XX century, with a substantially homogeneous structural arrangement. The bridge consists in a masonry arch, with a thickness of about 0,36 m (three brick layers) in the central part, and of 0,55 m (four brick layers) from the springing to the connection with the abutments. The abutments are composed by brick/stone masonry in the older part and mainly by concrete in the more recent part. In the inspection phase it was not possible to evaluate the presence of reinforcement bars inside the concrete.

The Venice administration decided to increase the load bearing capacity of the bridge, at the moment able to carry relatively light traffic (cars, buses), and to upgrade it to the rank of 1<sup>st</sup> category bridges, as defined by the Italian standards (maximum load equal to 600 kN on three axles).



Figure 1: View of the bridge from the canal

## 2 INVESTIGATIONS ON THE STRUCTURE

The structural investigation, by means of destructive and slightly destructive tests, consisted in three core samples, three single and one double flat jack tests, performed on the structure of the masonry arch. Other two core samples were performed vertically in correspondence of the abutments of the bridge, on both sides, in order to characterize the foundation structures and to determine a probable use of different materials and techniques, as a result of the subsequent widening of the bridge.

Results obtained by the preliminary tests defined the morphology of the masonry arch: the core samples allowed to determine the thickness of the masonry arch at the crown (0,37 m) and at a distance of 1,27 and 0,53 m from the abutment (thickness of 0,47 and 0,55 m, respectively).

Also the flat jack tests were performed on different points of the masonry arch (at 1,00, 1,70 and 1,90 m from the abutment). The results revealed a moderate state of stress in all of the points tested (0,25, 0,24 and 0,25 MPa respectively) and the masonry structure shown a

fair good response in terms of compressive strength (2,00 MPa).

The core samples on the two abutments of the bridge were performed to determine the morphology of the underlying structures and the soil stratigraphy. The samples shown, under the road surface, the presence of a 1,00-1,60 m layer of a gravel, sand and cobblestones filling, then a difference in terms of foundations characteristics was found.

The first core sample, under the filling, indicated the presence of a brick/trachyte masonry with a poor quality mortar, from -1,00 m below the road surface to -5,90 m, where the lowest level of the foundations was found.

The second sample was carried out on the structures of the probable widening of the bridge; it showed, on the contrary, a 0,40 m thick concrete slab and a 0,90 m thick underlying brick masonry in poor condition. The related abutment was then composed by a massive concrete structure (thickness of 2,70 m) in fair condition.

The soil was finally investigated as far as 15,00 m below the starting level of the foundations: the core sample determined a sequence of silty sand and clayey silt. Finally, between the depths of -6,00 and -7,50 m, a timber pile was found.

### 3 THE REPAIR INTERVENTION

The aim of the intervention is the substantial conservation of the structure of the bridge and the increasing of the actual load bearing capacity; the upgrading foresees the utilization of the existing structure, strengthened by using innovative and traditional materials and possible removable or substitutable intervention techniques.

The central part of the arch span (thickness of three brick whytes) is widened by the insertion of one more layer of bricks. The thrust inside the vault is transferred from the new elements to the older structure in correspondence of the thickening of the arch (from three to four bricks, at the springers); locally, the connection between the new and the old masonry is improved by means of brick units and metallic dowels glued with epoxy resin to the older part, used as shear connectors (see figures 2a, 2b, 3a, 3b).



Figure 2 a),b): the extrados of the masonry arch after the filling removal

At the level of the abutments, a new foundation structure, positioned on micro-piles aimed

to bear the extra load arising from the increased traffic loads, is constructed. The new foundation is made by reinforced concrete and it is positioned aside the existing abutments, externally respect to the canal. It is designed to bear the increase of the horizontal and vertical loads transmitted by lateral friction from the existing foundations. This is on purpose molded with a saw-tooth shape, to better transmit the thrusts to the new structure.

The assessment of the so strengthened arch bridge, re-designed with its new geometry, performed analytically using the limit analysis, gives a safety factor of 2,24. A further increase of the safety factor, to reach the requirements of the Italian standards, is found in the application, at the extrados of the masonry arch, of strips of uni-directional high resistance CFRP (Carbon Fiber Reinforced Polymer), having a Young modulus  $E_{\text{cfRP}} = 2,3E+11$  MPa, a tensile strength  $f_{t, \text{cfRP}} = 3430$  MPa and a ultimate tensile strain  $\varepsilon_{\text{cfRP}} = 1,5\%$ . The ends of the Carbon strips are connected by epoxy-based adhesive to the new reinforced concrete abutments, previously smoothed with an anti-shrink, thixotropic, high mechanical characteristics mortar. Fibers are also glued with epoxy resin to the arch structure, whose surface is regularized by the presence of the new layer of bricks and the application of a hydraulic-lime based mortar layer ( $f_{\text{cm}} = 18$  MPa,  $f_{\text{bm}} = 7,8$  MPa).

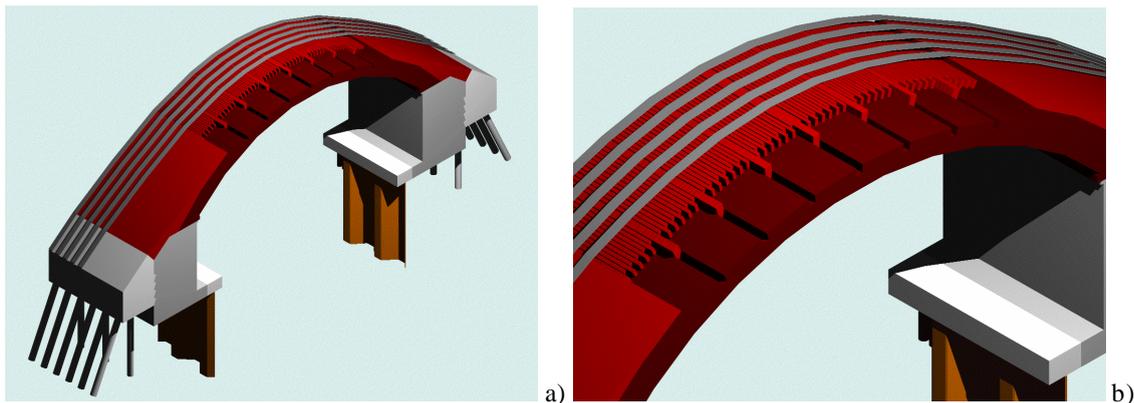


Figure 3: a) rendered images of the new structural arrangement of the bridge, b) detail of the extrados

The obtained structural configuration may hence present two possible successive behaviors: in a first condition, a complete connection between the new/old masonry structure and the CFRP is considered; in a second, being the safety of the structure in any case guaranteed, it is allowed the total detachment of the carbon fibers from both the masonry arch and the new reinforced concrete structure.

### 3.1 Description of the intervention phases

The repair intervention comprises different phases, both at the intrados and the extrados of the arch bridge, and is currently being executed.

The works to be carried out on the lower structure of the bridge (in the canal, below the sea level, and at the intrados of the masonry arch) regard the insertion, at the level of the abutments, of timber piles 2,00 m long, connected at their upper end with a reinforced

concrete beam, to avoid the possible damage on the submerged structures. Moreover, the intrados of the masonry arch will be restored in a “traditional” way (cleaning of the surface, removal of the plaster, substitution of the most damaged bricks with new ones, excavation of the deteriorated part of the mortar joints and repointing with proper hydraulic-lime based mortar -  $f_{cm} = 18 \text{ MPa}$ ,  $f_{bm} = 7,8 \text{ MPa}$ , and final repositioning of the plaster). Figure 4 shows the actual front view of the bridge.

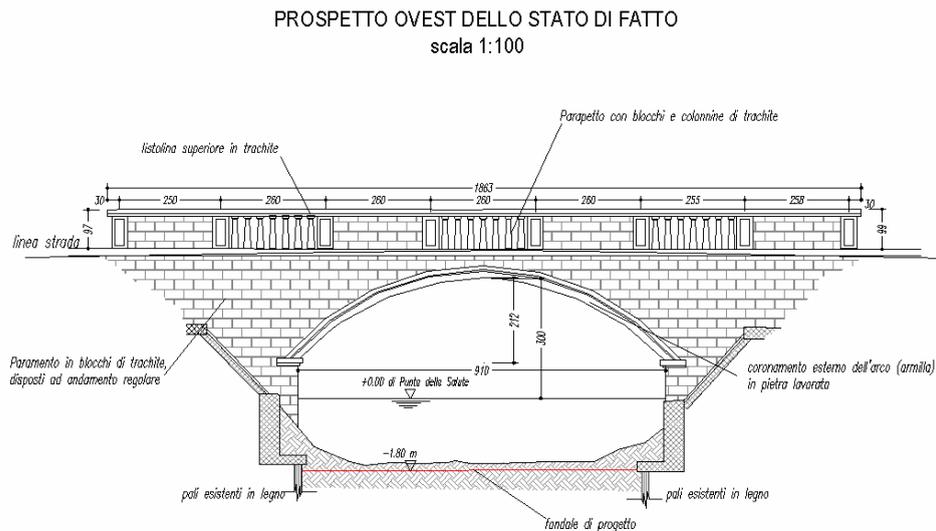


Figure 4: front view

The repair interventions to be performed at the extrados will be subdivided in subsequent phases:

- removal of the internal filling of the arch;
- preparation of the horizontal level for the positioning of the concrete foundation beam;
- execution of the sub foundation micro-piles (diameter 200 mm) with an internal reinforcement composed by a steel hollow bar (external diameter 101,6 mm, thickness 10 mm);
- Casting of the horizontal reinforced concrete beam, inclusion of the micro-piles upper ends inside the beam;
- Construction, close by the springing, of a new masonry arch layer, regularizing the extrados structure and being connected to the old masonry;
- Thickening of the existing masonry structure in the central part of the span, positioning of brick units orthogonal to the axial line of the arch used as connectors between the old and the new masonry, positioning of steel rods, diameter 20 mm, with the same function, glued to the old structure with epoxy resins (see figure 5,6);
- Preparation of the upper surface of the arch and placing of the CFRP: removal of the damaged bricks and substitution with new ones, excavation of the deteriorated parts of the mortar joints and repointing with the same hydraulic-lime based mortar used at the intrados, application of a hydraulic-lime based mortar layer and smoothing of the



## 4 STRUCTURAL ASSESSMENT

The verification concerns the structure of the bridge subjected to the increased traffic loads. Live loads are indicated in the Italian relative standard (D.M. 04/05/90)<sup>i</sup>. In the calculations a three point load of 200 kN (a conventional truck of 600 kN on three axles, wheel-base of 1,5 m) is taken into account, distributed on the structure; due to the load diffusion through the filling, a reductive factor of 0,5 is considered. The dynamic amplifying factor is equal to 1,2.

A first step consists in analyzing the simple masonry structures, completed with the insertion of new brick units, in the central part of the span and at the springers.

The second level of analysis considers the connection of the CFRP fibers to the bridge structure.

### 4.1 Arch structure without carbon fibers reinforcement

As calculation method, the limit plastic analysis is considered, as the collapse of the structure can be due to the formation of four/five hinges (in case of asymmetric/symmetric loads). This analysis allows to predict the minimum thickness of the arch, under a given load configuration, as a limit corresponding to the activation of a mechanism (Factor of Safety = 1).

Two load cases are examined: the first presenting the three point load at quarter span, being the worst load condition from the theory of limit plastic analysis<sup>ii</sup>; the second presenting the three point load in central position.

The load combination with the traffic load at quarter span gives a lower horizontal thrust but also requires an increased thickness of the masonry vault respect to the combination with the live load in the centered position. The Safety Factor is 2,24, being the minimum thickness required by the calculations and the one of the restored arch respectively 0,214 and 0,48 m.

### 4.2 Arch structure with carbon fibers reinforcement

For the evaluation of the safety conditions of the structure, the load combination presenting the three point load at one fourth of the span is considered; a safety domain is determined and the force/moments combinations on the structures of the bridge are inserted in the same diagram. Assuming a rectangular stress-block diagram for the ultimate stresses on the masonry and an elastic behavior for the CFRP, an ultimate strain of 0.006 and a compressive strength of 2,50 MPa, evaluated on the basis of the flat jack test results, are considered for the masonry. The live and dead loads are amplified with the coefficient 1,50, both for the masonry and the CFRP.

The safety domain is defined by the following equations, arising from relations of equilibrium<sup>iii,iv,v</sup>:

$$\frac{M_{Rd}}{lt^2 f_{M,k}} = \frac{1}{2} w \frac{\left(1 - \frac{x}{t}\right)}{\frac{x}{t}} + \frac{0,4}{g_M} \frac{x}{t} \left(1 - 0,8 \frac{x}{t}\right) \quad (1)$$

$$\frac{x}{t} = \frac{g_M}{1.6} \left[ \frac{N_{Rd}}{l f_{M,k}} - w + \sqrt{\left( w - \frac{N_{Rd}}{l f_{M,k}} \right)^2 + \frac{3.2}{g_M} \cdot w} \right] \quad (2)$$

where  $t$  and  $l$  = height and width of the section, respectively;  $f_{M,k}$  = compressive strength of the masonry;  $x$  = neutral axis depth);  $M_{Rd}$  and  $N_{Rd}$  = bending moment and axial load defining the safety domain;  $\gamma_M$  = partial safety factor for the masonry.

The parameters  $\omega$ ,  $\rho$  and the ratio between the CFRP and the masonry ultimate strains are defined as follows:

$$r = \frac{A_{cfRP}}{lt}, \quad (\text{CFRP area fraction}) \quad (3)$$

$$w = \frac{e_{M,u} E_{cfRP}}{f_{M,k}} r, \quad (\text{CFRP normalized area fraction}) \quad (4)$$

$$\frac{e_{cfRP,u}}{e_{Mu}} = \frac{\left(1 - \frac{x}{t}\right)}{\frac{x}{t}}, \quad (\text{ultimate strains ratio}) \quad (5)$$

where  $A_{cfRP}$  = CFRP cross-sectional area;  $E_{cfRP}$  = Young's Modulus of the fibers;  $\epsilon_{cfRP,u}$  and  $\epsilon_{M,u}$  = ultimate tensile and compressive strains for the fibers and the masonry, respectively.

The structural assessment is completed by the verification of the inclusion in the safety domain (see diagram, figure 7), of the points corresponding to the couples of design axial forces/bending moment, evaluated in the cross sections of the arch.

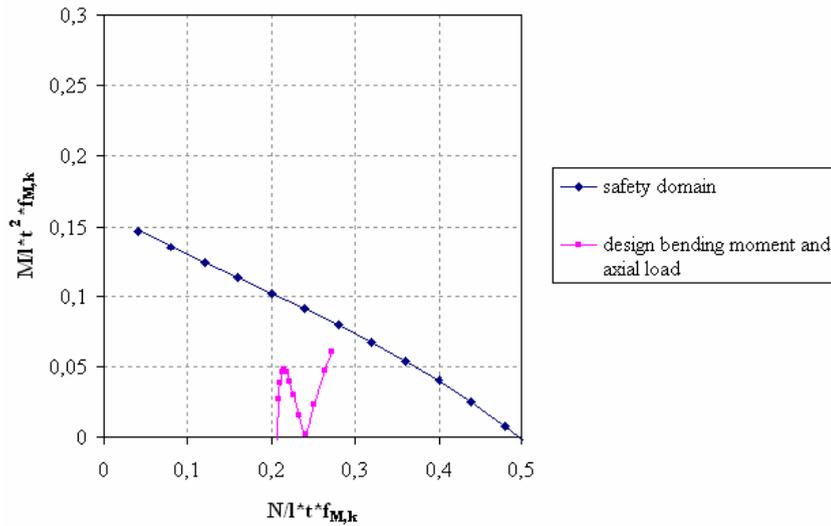


Figure 7: Moment capacity versus axial load

## 5 CONCLUSIONS

- A case study was presented, outlining a methodological approach to the structural upgrading of an existing masonry arch bridge, unable in its current state to bear in safe conditions the increased traffic live load that are take into account when designing a new bridge structure. The restructuring intervention is in course of execution at the present moment.
- The solution proposed respects the structural role of the old arch masonry structure, making it constitutive part of the new structural lay-out. Moreover, the strength of new materials, namely the CFRP, is considered when assessing the safety of the structure to reach the standard requirements; in parallel to this, it is also considered a total ineffectiveness of the new material in the future, presenting the upgraded masonry structure itself the possibility to bear with “minimum acceptable” safety level the increased traffic loads.
- The strengthening intervention at the level of the foundations is not substitutive to the existing structural arrangement. The existing abutments share part of the loads coming from the masonry arch with the new reinforced concrete beams by friction. The bearing capacity of the existing structure is preserved and is increased, in case of extra thrusts, by the interaction with the parallel new foundation system.
- Analytical models, calibrated on the basis of experimental tests, were used in assessing the safety state of the structure reinforced at the extrados with CFRP. The evaluation of the safety factor is nevertheless based on the limit plastic analysis, individuating the collapse of the arch when a sufficient number of hinges force the structure into a mechanism.

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