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Structural Analysis of the "3Ponti" of Comacchio (Ferrara, ITALY)

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Abstract The "3 Ponti of Comacchio" represents one of the most important architectural monuments in the Province of Ferrara and surely the most significant historical bridge in Emilia Romagna region. The masonry bridge was built in 1632 by the architect Luca Danese and the customer was the Cardinal Pallotta at that time governor of the town of Comacchio, therefore sometimes is denoted as Pallotta bridge. The shape of the bridge is very particular because it was built at the intersection of 5 canals and presents an internal vault composed by 5 groins of rampant barrel vaults. In 1690 two towers have been added and the bridge assumed the present form. Nowadays it is used as a pedestrian bridge. The interest for the structural behaviour of the masonry bridge is due to the rising up, in the last 2 years, of evident cracks interesting as well the internal vault as the staircases in the west side. The masonry structure was analyzed either by Diana program, using an elastic-plastic damaging model for the masonry, as well as by limit analysis algorithms recently developed by the University of Ferrara. One possible reason of the rising up of the cracks is the settlement of the 3 piers on the west side due to the lowering of the water level in the canals for hydraulic arrangement works. Furthermore, in this study, sinking of pillars foundation will be also taken into account.

Keywords: Treponti of Comacchio, non linear analysis, masonry bridge

Introduction

The masonry bridge called Treponti (Fig. 1), is located in Comacchio (FE) and represents the most significant historical bridge in Emilia Romagna region.

Figure 1: View of the west side bridge

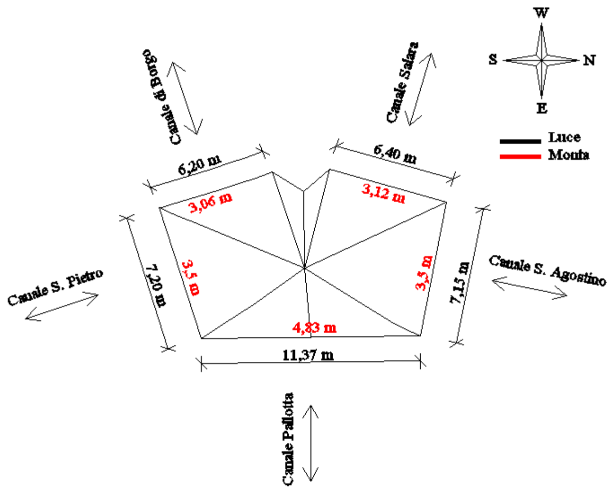


Figure 2: Geometry of the bridge's vault

Designer of the bridge, was the architect Luca Danese from Ravenna (1598-1672), among his works can be mentioned: the S. Romualdo's church, built in 1629 in Ravenna and the S. Maria della pietà dei Teatini church in Ferrara. The place where the bridge rises is the meeting point of five canals (Fig. 2): Pallotta Canal, S. Agostino Canal, Borgo's Canal, Salara Canal, S. Pietro Canal. This point is the fulcrum of the water network in Comacchio, travelling along the Pallotta canal is possible to reach the centre of the city. The bridge was built under the superintendence of Giovanni Piero from Lugano, capuchin friar who followed the various stages of the construction. Probably, due to the complexity of the work, some foreign skilled labour, not available in Comacchio, was hired. Works went on for two years: from 1632 to 1634. In the centuries, the bridge underwent several changes, the towers (Fig. 1) were built in 1690 and elevated in 1771. Today, in addition to the function of pedestrian bridge, is used as a space for theatrical performances and fashion shows. The interest for the structural behaviour of the masonry bridge is due to the rising up, in the last 2 years, of evident cracks interesting as well the internal vault as the staircases in the west side.

Structural Elements

The main structure of the bridge consists of a vault composed by 5 groins of rampant barrel vaults. The dimensions of the vault were obtained from a relief laser scan (Fig. 3). The bricks are arranged in order to achieve a thickness of 25 [cm]. On the intrados of the vault can be observed some signs of consolidation probably made at different times, in some places we can see replacements of bricks of the vault.

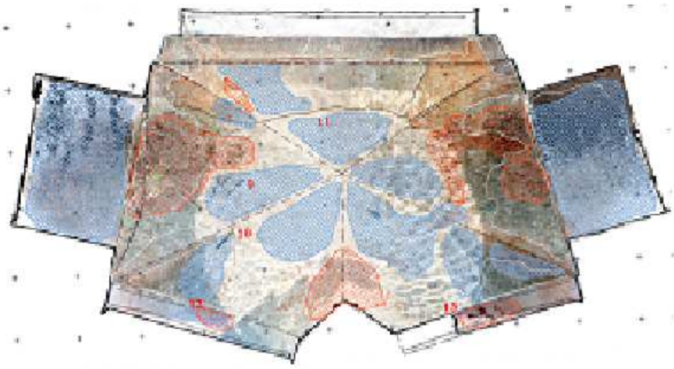


Figure 3: Relief laser scan of the vault

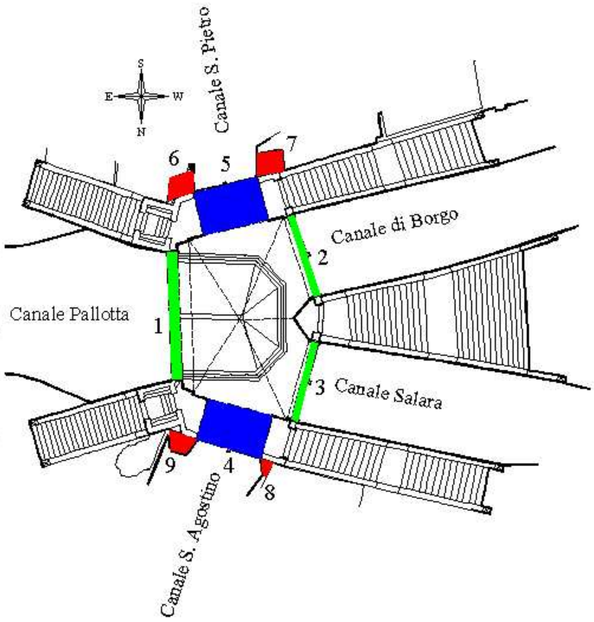


Figure 4: Plane view of the bridge

The vault is confined by three arches (Fig. 4, n°:1, 2, 3 green colour) and by two barrel vaults (Fig. 4, n° 4, 5 blue colour). The bridge also has five steps (Fig. 4) and in the corners of the bridge there are four spurs (Fig. 4, n° 6, 7, 8, 9) which are situated in correspondence of forces generated by the vault.

Foundations

An idea of the foundation of the bridge is given by the graphic table (Fig. 5) which is shown in the book titled *Genesi e morfologia di Comacchio* (Maestri 1977) about the Ponte Pio V's relief performed at its demolition. The wood used for the piles of the foundation was poplar or oak, the piles were tied in order to make a plane on which the bridge is based. The pillars and the piles are situated at the intersections of the five canals.

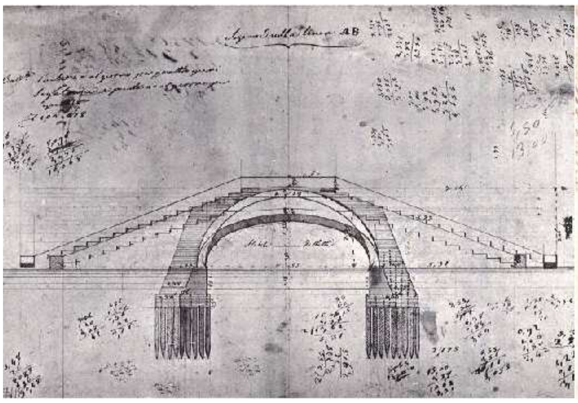


Figure 5: Longitudinal section of Pio V's bridge *Figure 6: View of the vault from Pallotta Canal*

Finite Element Model

For linear and non linear incremental analysis of the structure the program DIANA (release 9.2) has been employed. In particular, for some localized analysis on the possible collapse of the arches the interface model (Lourenco & Rots 1997) has been used, while for the analysis of the whole structure the elastic-plastic-damaging behaviour of the masonry has been simulated by means of the model denoted *Standard Smeared*. The following mechanical parameters have been adopted (Table 1). Let us note that therefore the dependence of these parameters on the masonry texture has not been taken into account.

Table 1: Mechanical parameters of masonry

Young' s Modul	*Poisson's ratio*	*Stress cut-off criterion*	*Compressive strength*	*Tensile strength*	*Tension softening*	*Ultimate strain*	*Shear retention*
3300[MPa]	0,15	Linear	3,3 [MPa]	0,1[MPa]	Linear	0,0035	1

In the end the fill (whose importance has been underlined in (Cavicchi & Gambarotta 2007) has been modelled by means of the Mohr-Coulomb criterion and the following mechanical parameters have been adopted (Table 2).

Table 2: Mechanical parameters of fill

Young' s Modul	*Poisson's ratio*	*Cohesion*	*Friction angle*	*Dilatancy angle*
550 [MPa]	0,1	0,02 [MPa]	30°	30°

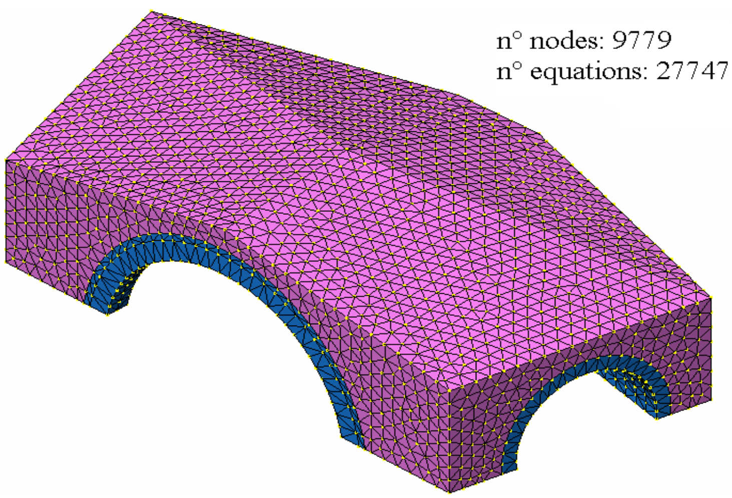


Figure 7: Finite element model of the masonry structure and of the vault-fill

Analysis under Service Loads

Firstly the analysis under the service loads defined by the Italian norms (NTC08) has been performed. Fig. 8 shows the colour map of normal stresses, whereas for each arch and section of barrel vaults the line thrust (Fig. 9) has been evaluated and the limit state (Heyman 1982) (Fig. 10) has been checked.

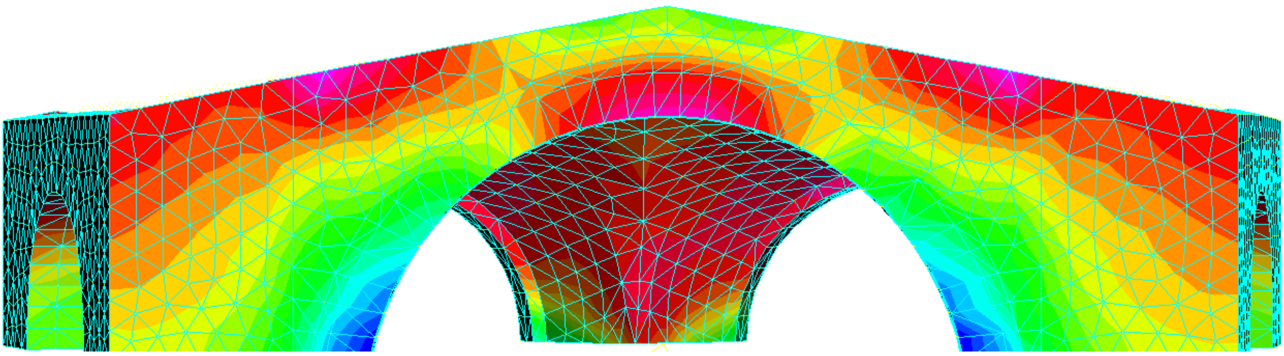
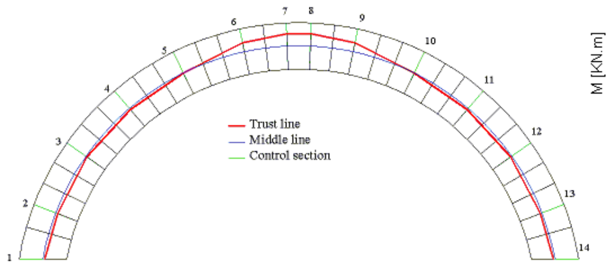


Figure 8: Colour map of normal stresses of the arch on Pallotta Canal



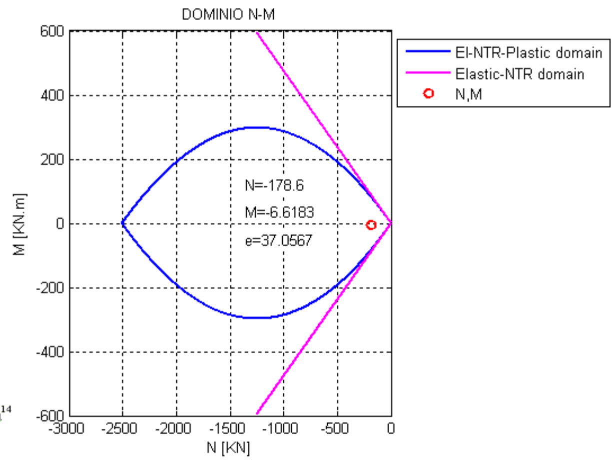


Figure 9: Thrust line of the arch on Pallotta Canal *Figure 10: Domain at a section of the arch*

The forces and the pressure distribution at the basis of the pillars are shown in Fig. 11 and Table 3.

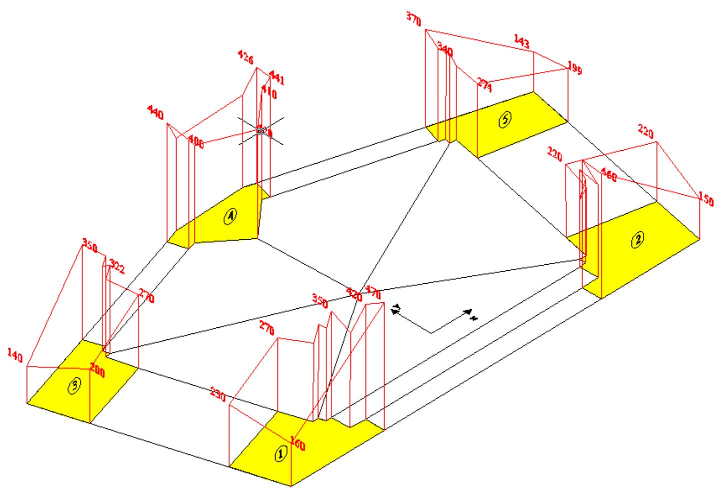


Table 3: Forces and pressure at the basis of pillars

Pillars	*N* [KN]	*A* [m²]	*σ* [KN/m²]
1	1995	9,76	204
2	1996	10,46	191
3	1377	7,66	180
4	1540	5,28	292
5	1388	7,50	185

Figure 11: Pressure distribution at the basis of pillars

The results provided by the analysis have shown that under service loads, the bridge doesn’t present structural problems.

Non Linear Collapse Analyses

Incremental non linear analyses of the structure under vertical and static seismic loads have been performed and satisfactory results have been obtained. Moreover a limit analysis of the 3 Ponti vault, taking into account the masonry texture by means of homogenisation techniques [Milani, Milani & Tralli 2008] has been performed. The analysis has provided a substantial confirmation of the aforementioned results. The decrease in water level (about 50 cm) and the consequent reduction in effective stresses are supposed to be the cause of the cracks pattern. In order to evaluate the reliability of this hypothesis a non linear analysis has been done applying a vertical shift (Fig. 12) at the basis of the three pillars on the west side of the bridge. The settlement of the pillars appears also responsible for the cracks on the steps on the west side of the bridge (Fig. 13).

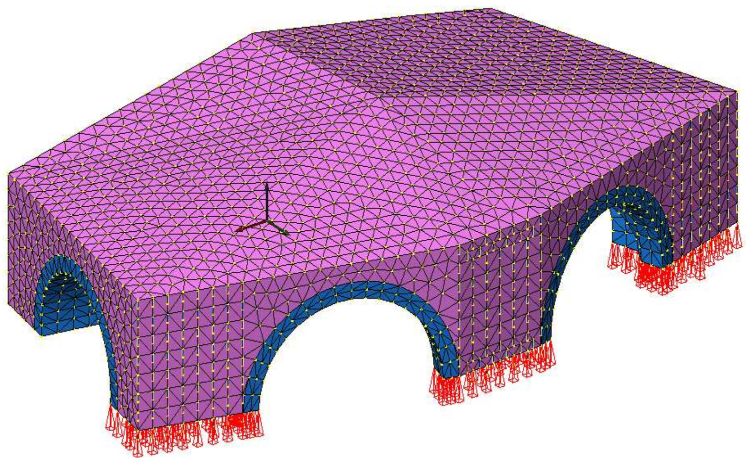


Figure 12: Finite element model employed for non linear analysis in presence of the foundation

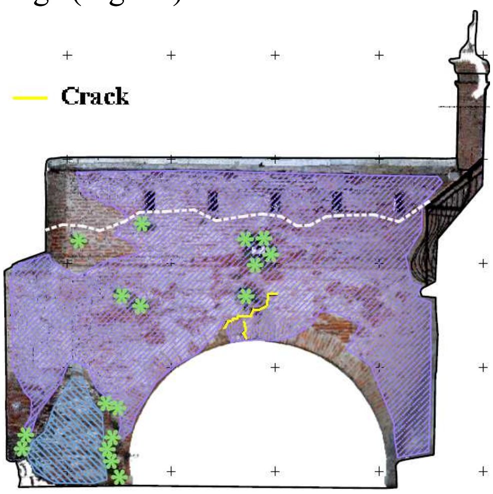


Figure 13: Cracks on the North side of the bridge

In Fig. 13 are shown one the crack pattern on the North side of the bridge, for which the results of the FEM provide a satisfactory explanation. For instance in Fig. 14 the colour map of the σ_{yy} stress obtained by non linear analysis, relative to a settlement of 70 [mm] is shown. Moreover, in Fig. 14 the stress evolution at the point A caused by the settlement is reported.

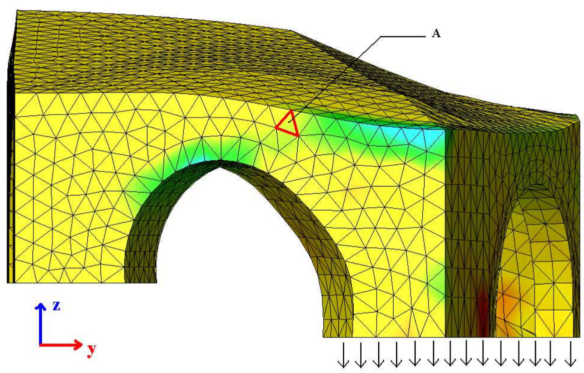


Figure 14: Colour map of the tension on the North side of the bridge FEM

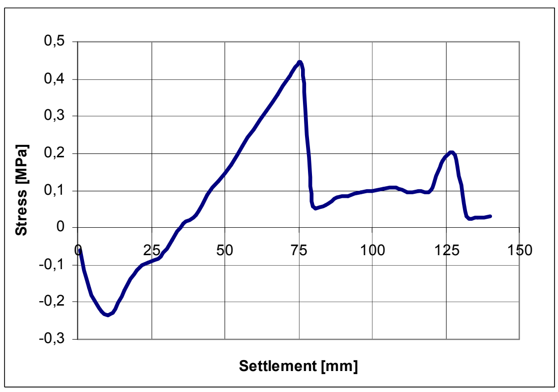


Figure 15: Stress evolution caused by the settlement

In the end in Fig. 16 and Fig. 17 it is shown the crack pattern in the staircases of the West side can also be justified.

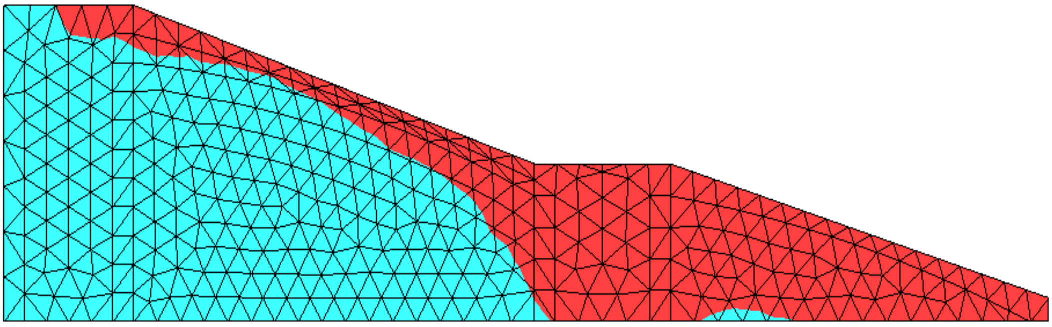


Figure 16: Colour map of normal stresses i σ_{zz} on North side of the central staircase

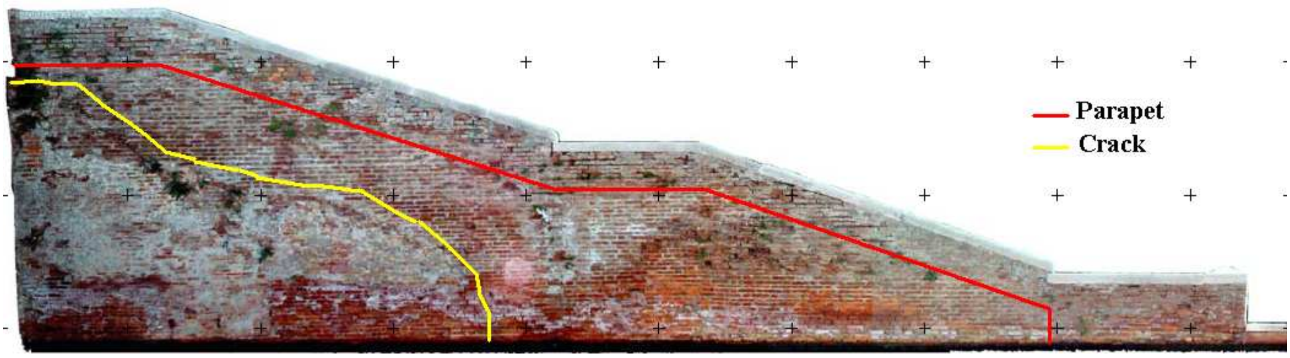


Figure 17:Main crack on North side of the central staircase

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