International Journal of Bridge Engineering (IJBE), Special Issue 2016, pp. 23-37

ON THE EFFECT OF LIGHTENING THE SOLID FILL IN AN ANCIENT MASONRY BRIDGE

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ABSTRACT: In the paper the performance of ancient masonry vaulted bridges is investigated through the analysis of a study case which is referred to, in the region Campania, that is the Devil's bridge on Sele river in Capaccio. The proposed methodological approach is aimed at emphasizing a number of features, including the main vault/fill interaction, the overall cooperation of the structural and non-structural components.

KEY WORDS: Bridges, Masonry, No Tension material, Torsional effects.

1 INTRODUCTION

Historical masonry arched bridges represent a considerable part of the artistic and architectural heritage of railway and road constructions in Italy ([1]-[3]).

These infrastructures witness the high quality of their general conception resisting environmental and anthropological attacks during time, and showing a number of significant technical and technological features, which require proper investigations and deepening. Their preservation also requires to have at one's disposal a deep and detailed know-how about the materials, the conservation state, the hierarchical organization of the components in their reciprocal relationships, the structural interventions executed in their life, in order to proceed to the necessary subsequent analyses for check stability and general analysis of 2D and 3D response.

Typically proper analyses would require to be developed with reference to the No-Tension assumption (one may refer to the wide literature on masonry in [4]-[21]) about the basic masonry materials, thus implying to make recourse to the related tools from Incremental and Limit Analysis.

Actually, ought to the complexity of the bridge constructions, where even non-structural components play a fundamental role on the global response of the structure to existing loads a number of analyses should be integrated between each other in order to emphasize the multiple features characterizing the response of the constructions.

In the following, the study case of the Devil's bridge on the Sele river at

Barrizzo in the Campania Region is referred to; preliminary analyses refer to the application of the Kinematic Theorem of Limit Analysis for No- Tension structures in order to identify the most dangerous placement accidental loads; subsequent FEM analyses are then developed with reference to 2D and 3D modelling.

The executed investigation is aimed to highlight the real global behaviour of the study case, also checking about some features concerning the fill's contribution in the absorption of applied loads. In the specific case the fill is solid and made of masonry bricks with mechanical properties very close to those of the main structure, with some lightening realized through a number of cavities crossing the internal part of the bridge.

The structural response of the infrastructure is illustrated in terms of stress distribution, deformed configurations and torsional effects when referring to the spatial behaviour. Accidental loads referred to in the analysis are identified as concerns the Italian Instruction NTC2008 and they consist of the distributed crowd loads and the tandem load, with intensity respectively of 9 kN/m^2 and 300 kN.

2 THE STUDY CASE: GEOMETRICAL DATA AND MATERIALS

The study case considered in the paper is represented by the vaulted masonry bridge with one single span depicted in Capaccio, in the Campania Region, known as the Devil's bridge (*Fig. 1*).

The Devil's bridge was built in the IXX century with the purpose to allow the crossing of the Sele river, which, with its continued overflows, destroyed a number of bridges. Designed by the engineer Fiocca, it was similar to the Annibal's masonry bridge built in Capua dating back to the late IXX century as well, but, as regards to a number of different features also concerning the place and the river, some modifies were applied. The Devil's Bridge is integrally made of masonry blocks, both as regards the external and internal parts.

It presents a particular geometrical configuration because of the presence of the only big arcade with an elliptical shape with five focus points and with a variable thickness, identified as an "anse de panier". The adopted materials are local and consist of tuff and calcareous stone.

The fill is realized in stone blocks as well, and it is lightened through a number of the internal curved holes; bricks and squared stones compose the arcade, as shown in the *Fig.2*.

In the following *Fig. 3* and *Fig. 4* some section views of the Devil's bridge are depicted, that show its internal layout.

Figure 1. Devil's bridge on Sele river at the Barrizo in Capaccio (SA), Campania Region

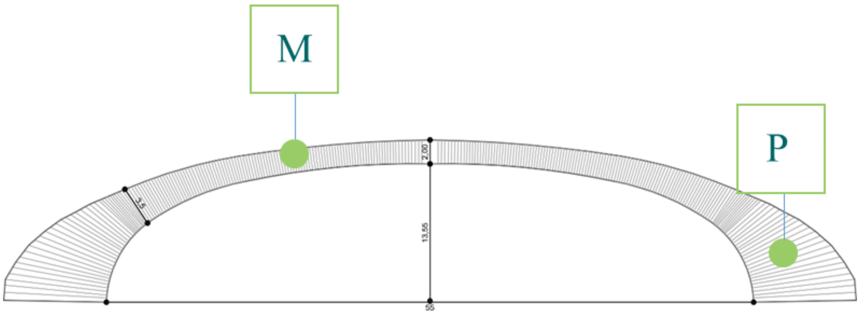

Figure 2. Longitudinal view of the main arcade and identification of materials where M denotes bricks and P denotes squared stones

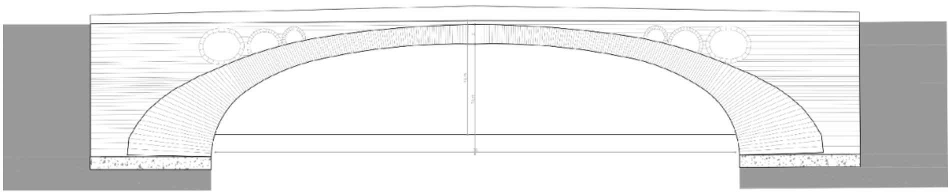

Figure 3. Longitudinal cross-section of the Devil's bridge on the Sele river with the internal geometrical layout

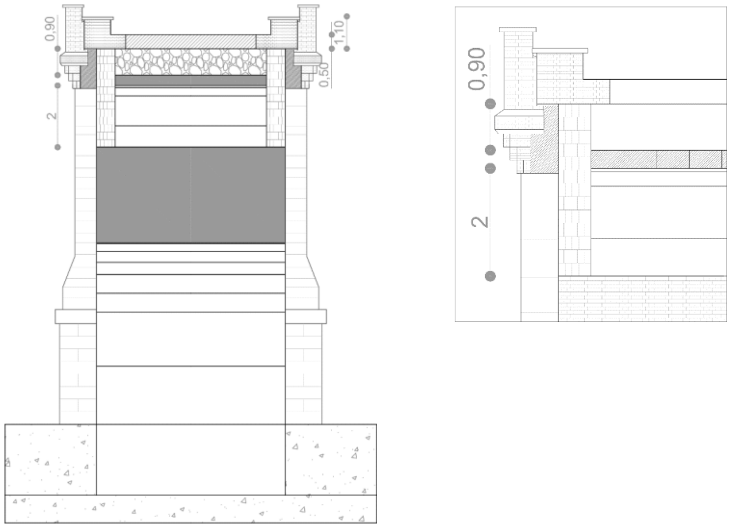

Figure 4. Cross- section of the Devil's Bridge on the Sele river on the main arcade and detail

3 PRELIMINARY ANALYSIS

3.1 Preliminary check of the vault stability

With reference to the considered study case, the preliminary phase has concerned the analysis of the stability of the main arcade under the hypothesis of NT material. Once identified the geometry, the materials and their mechanical properties, the scheme of the main vaulted span subject to the permanent loads of the self-weight of the vault and of all the additional components has been referred to, as shown in *Fig.5*.

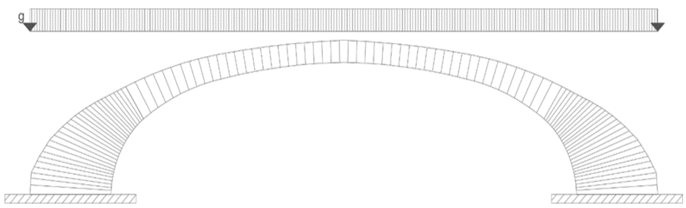

Figure 5. The model of the main vaulted span burdened by the permanent loads of the weight of the vault and of the superstructure

With reference to the permanent loads

$$F_i = P_i A_i p_i = P_i V_i \tag{1}$$

where:

F_i denotes the weight-force expressed in kN of the i -element

P_i denotes the specific weight of the i -element expressed in kN/m^2

A_i denotes the area of the i -element expressed in m^2

p_i denotes the depth of the i -element expressed in m

the identification of the funicular curve internal to the vault profile was performed for the stability check of the main arcade, as shown in Fig. 6 where the curve is reported laying in between the extrados and intrados profiles under the applied loads.

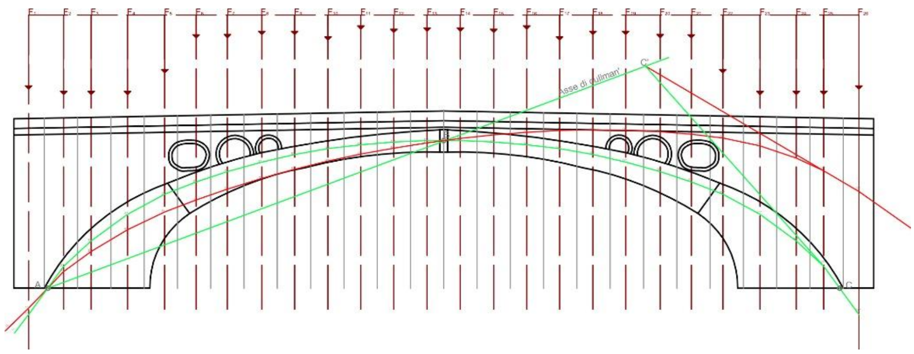

Figure 6. Identification of the funicular curve internal to the vault profile under the selected permanent loads

3.2 Limit analysis and the kinematic mechanisms

The development of cracks in masonry structures may be considered physiological, and, as well known, their appearance does not correspond to the achievement of the crisis in terms of functionality of the structure, whilst their formation remains related to the activation of possible collapse mechanisms depending on the number of redundancies of the structure.

In the following, as regards to the vault stability assessment of the considered study case, the identification of possible collapse mechanisms has been performed, according to the Kinematic Theorem of the Limit Analysis for NT structures, based on the search of the smallest kinematic load multiplier allowing to identify the collapse load. This approach has conducted to the identification of a number of possible collapse mechanisms and, consequently, of the relevant compatible deformed configurations, shown, as an example, in *Fig.7* and *Fig.8*. *Fig.9* and *Fig. 10* show the relevant kinematic mechanisms and their compatible deformed configurations.

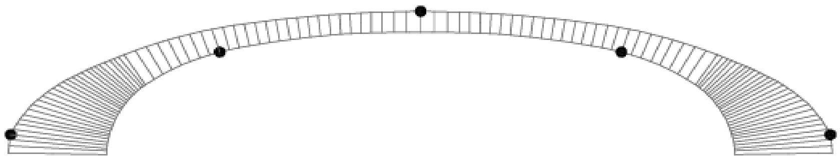

Figure 7. Symmetric mechanism with five unilateral hinges

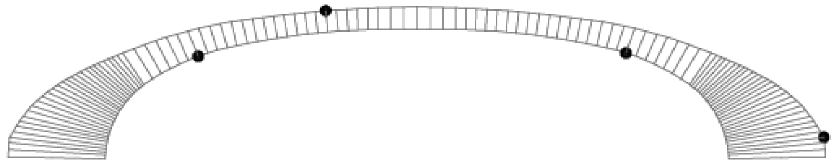

Figure 8. Asymmetric mechanisms with four unilateral hinges

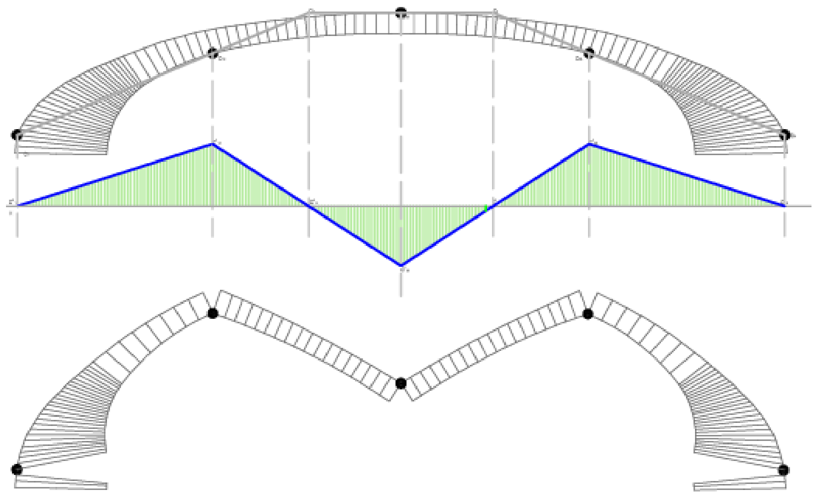

Figure 9. Symmetric kinematic mechanism with the relevant compatible deformed configuration

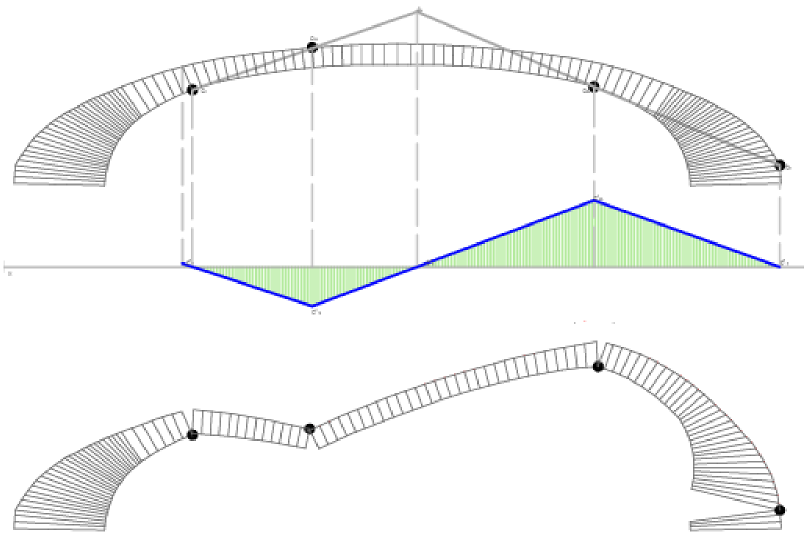

Figure 10. Asymmetric kinematic mechanism with the relevant compatible deformed configuration

The set of selected mechanisms does represent a collection of the most probable mechanisms and does not of course exhaust the infinity of possible mechanisms, thus allowing the identification of the worst situation within the selected class.

The most dangerous load condition within the set is identified by suitably placing the accidental loads for any single case, in such a way to maximize the disadvantageous work, as shown, for example in *Fig. 11* and *12*.

The accidental loads are selected with regards to Italian Instructions NTC2008, consisting of the segmented crowd load and the tandem load, and the load multiplier has been calculated as follows

$$\gamma_m = \frac{L_G^- - L_G^+}{L_a^+ - L_a^-} \tag{2}$$

where:

L_G denotes the work produced by the permanent loads

L_a denotes the work produced by the accidental loads

The index $(\cdot)^+$ and $(\cdot)^-$ denote the positive and negative contributions respectively.

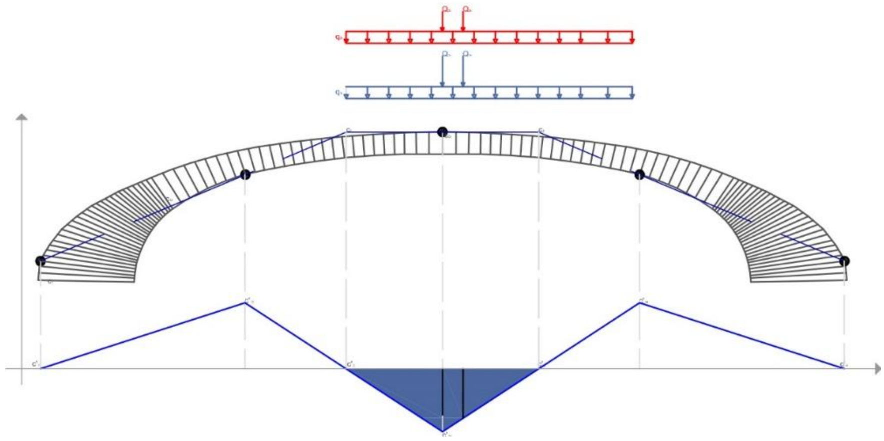

Figure 11. Placement of accidental loads for the given mechanism

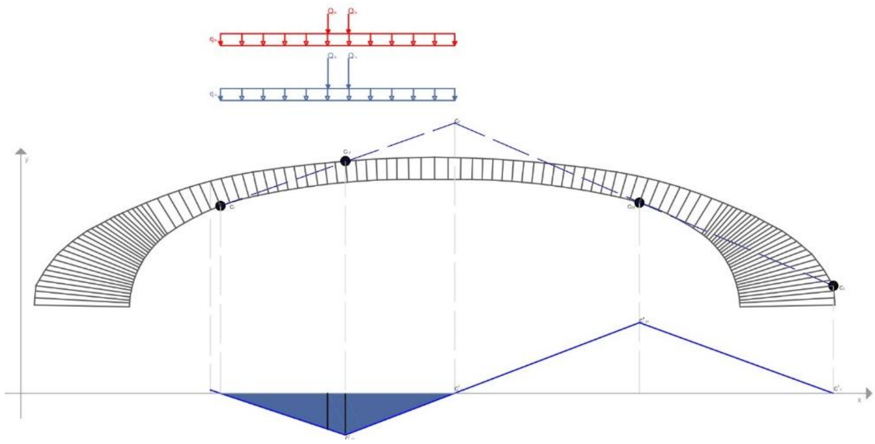

Figure 12. Placement of accidental loads for the given mechanism

In the following *Table 1* one reports some of the identified loads' conditions and their correspondent load multipliers, allowing to identify the collapse multiplier in the condition CdC5, which is depicted in *Fig. 13*.

Table 1. Load conditions and related multipliers

Load condition	*Multiplier*	*Load Multiplier*
CdC1	γ_1	*13,2*
CdC2	γ_2	*12,01*
CdC3	γ_3	*16,9*
CdC4	γ_4	*18,3*
CdC5	$\boldsymbol{\gamma_5}$	***9,1***
CdC6	γ_6	*19,5*
CdC7	γ_7	*24,9*
CdC8	γ_8	*19,3*
CdC9	γ_9	*13,2*
CdC10	γ_{10}	*25,8*

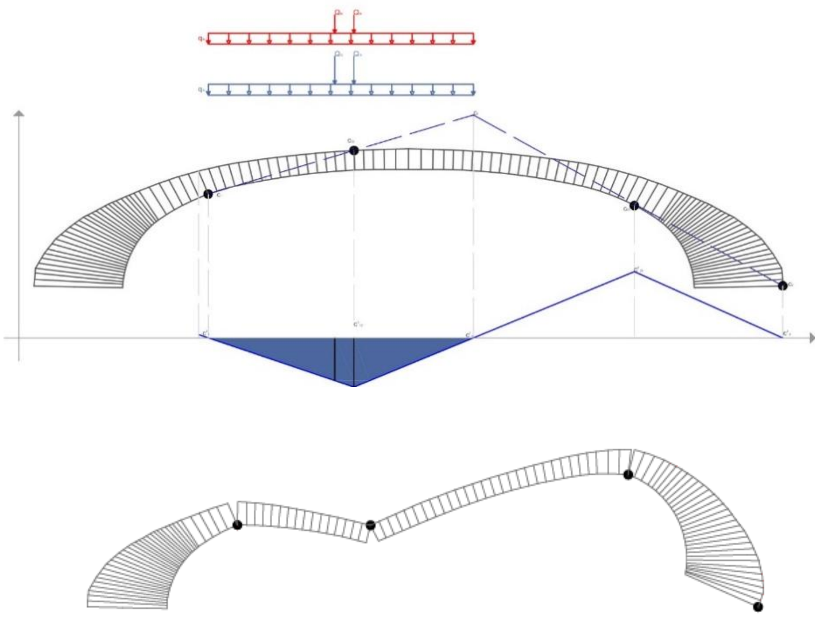

Figure 13. The most dangerous load's condition within the set of selected mechanisms and its compatible deformed configuration

4 THE FEM MODELLING

4.1 General layout

Subsequently to the preliminary analysis, a FEM modelling has been developed for the Devil's bridge aimed at emphasizing a number of effects, including the main vault-fill interaction in order to evaluate the contribution of fill to the global behaviour of the bridge.

To this purpose 2D and 3D analyses have been performed. The relevant models and meshes have been developed by considering a number of substructures that, thereafter, have been reassembled together, in order to describe the global behaviour of the bridge, and that one of the single component, as shown in the Fig.14.

Based on a preliminary historical and technological survey of the study case about its geometry, the employed materials and their mechanical, analyses have been performed in the 2D and 3D environments, by considering the self-weight of the structure and the variable crowd and tandem loads in their most dangerous positions, identified in the preliminary phase as explained in Sec. 3.2.

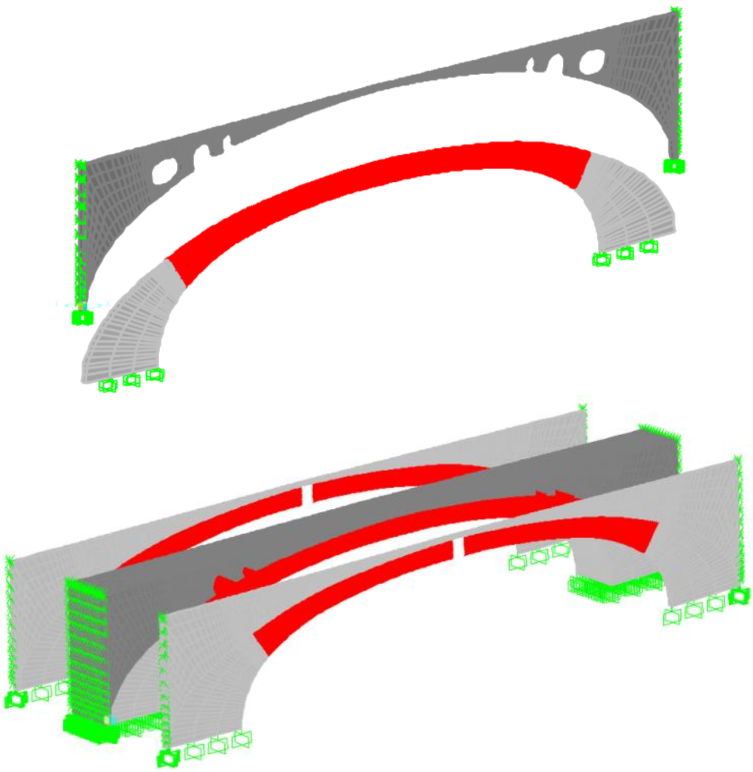

Figure 14. The hierarchical substructures and their assembling

Much attention has been paid to the selection of the mesh in such a way to reproduce as much as possible the real brick's layout for all the identified substructures, with reference to both the structural non-structural components. The adopted mesh is finally able to give back a sharp representation of the real tissue of the masonry in any part through the proper re-assembling of the sub-structures. Both the cases of fill with internal holes (corresponding to the real structure) and without internal holes are considered. Prismatic solid elements with eight or six nodes for fitting the geometry are selected inter-connected by internal constraints. Lateral boundary joints of the bridge are constrained by the unilateral horizontal supports in order to simulate the action of the soil.

The vault's mesh is realized as well in such a way to follow the real executive-technique of construction, by reproducing three overlapping brick's layers repeated in the vault's depth, and suitably interconnected between each-other through special elements.

4.2 Numerical investigation

In the following one reports some results concerning the 2D system under the coupled action of the permanent and accidental loads identified in Sec.3.4 .
In *Fig. 15* and *16* comparison in terms of deformed configuration is presented as regards the model with or without internal holes in the fill body, with the relevant stress spread depicted in *Fig.17* and *18* for the two cases respectively. Besides the attained stress intensities, which are quite close to each other for the two case, a different stress distribution may be noticed caused by the different inner geometry and the presence of lightening.

Figure 15. The deformed configuration of the bridge with fill with internal holes

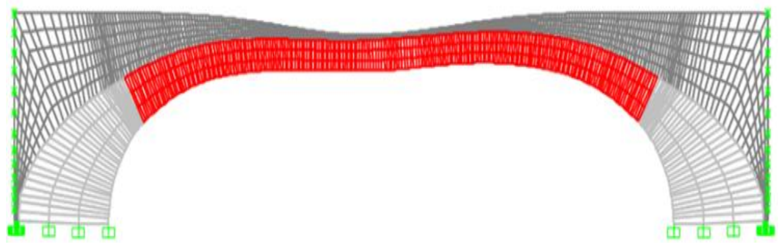

Figure 16. The deformed configuration of the bridge with fill without internal holes

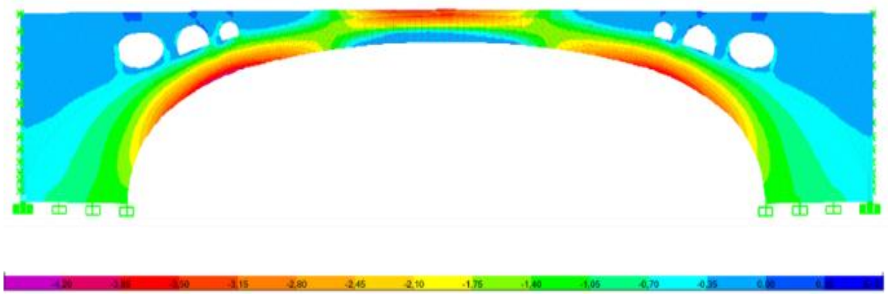

Figure 17. Spread of minimum principal stresses in the bridge with inner holes (kN/m^2, values to be amplified by the factor 10^3)

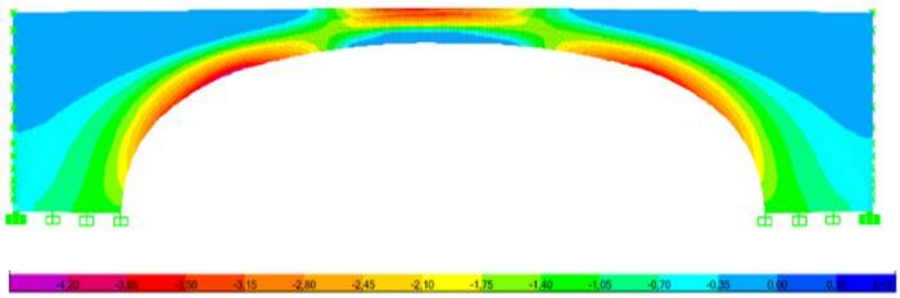

Figure 18. Spread of minimum principal stresses in the bridge without inner holes (kN/m^2, values to be amplified by the factor 10^3)

Results from 3D analyses allow to deepen the spatial behaviour of the bridge and to further highlight some effects, such as the torsional response, and the influence of lightening in the infill. To this purpose, placement of accidental loads along the bridge cross-section according to an asymmetric transversal distribution has been considered, following the Italian Instructions NTC2008.

The deformed configuration, amplified by a factor, of the cross-section between the left rein and the keystone of the bridge is reported in *Fig. 19*, showing torsional effects. The results show that as the particular configuration of the fill has influenced the global response of the bridge. Fig. 20 depicts the spatial deformed configuration, highlighting the global 3D response of the bridge under the applied loads.

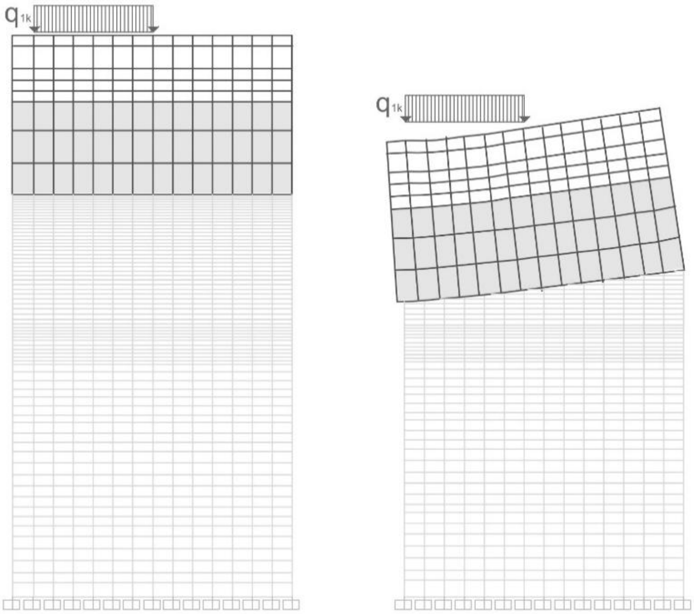

Figure 19. Deformed 3D configuration of the cross- section of the bridge under asymmetric variable loads

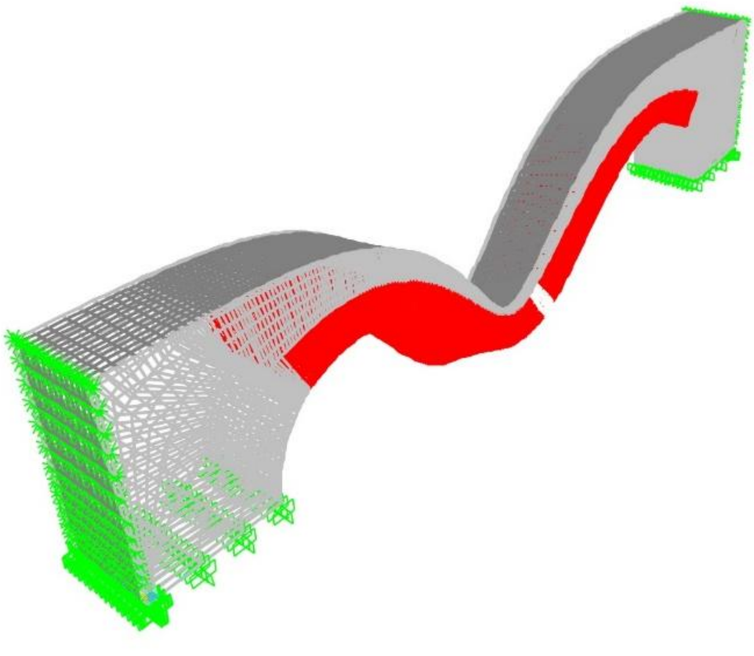

Figure 20. 3D view of deformed configuration under the application of asymmetric accidental loads

5 CONCLUSIONS

In the paper a methodological approach is proposed in order to examine the global behaviour of an existing ancient masonry vaulted bridge.

The selected study case is referred to the Devil's bridge on the Sele river in the Campania Region, which is integrally composed by masonry blocks, both in its external and internal structural and non-structural components.

The used approach refers, for preliminary analyses, to the application of Kinematic Theorem of Limit Analysis for No Tension structures, by selecting a finite number of collapse mechanisms within the infinite class of mechanisms, which allows the positioning of variable loads; thereafter FEM modelling is performed for evaluating the global 2D and 3D behaviour of the masonry bridge, also with attention to the interaction of the arch-fill.

The conducted analyses show the complete cooperation between the structural and non-structural component.

All the structural and non-structural members are re-produced in the models in their single layout as regards geometry, masonry tissue and materials, and, additionally, in their reciprocal hierarchical relationships.

The presence of the brick fill with internal lightening is considered and it is compared to the case when no cavity in its body is present. Moreover analyses developed on the asymmetric placement of the variable crowd's and tandem's loads allow to study the torsional spatial effects on the structural response.

ACKNOWLEDGEMENTS

The authors acknowledge the financial contribution of the Dept. Civil Protection through the ReLuis pool (convention signed 27/12/2013).

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