VAULT-FILL INTERACTION IN MASONRY BRIDGES: AN EXPERIMENTAL APPROACH - 1: STATICS

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SUMMARY

Masonry bridges are usually considered as an arch to which non-structural elements (spandrels, fill, etc.) are added. Experimental and theoretical evidences show, instead, that spandrels and fill take part in the load carrying mechanism accounting for a large part of the load carrying capacity. If this is neglected, the structural models may turn out to be unreliable and their outcomes strongly non-correlated with the real response of the bridge. In this paper, the arch-fil and arch-spanrel interaction is demonstrated and quantified by means of experimental tests on reduced scale models set on proper scaling rules. Woth deep and shallow arches are considered.

Keywords: *Masonry bridges, load carrying structure, arch-fill interaction; arch-spandrel interaction, deep arch, shallow arch.*

1. INTRODUCTION

Masonry bridges still play a fundamental role in the European Infrastructural System. Due to material degradation and new performances required (increased loads and speed) a rational assessment of masonry bridges is needed which usually makes use of simplifying assumptions, either in the load carrying mechanism and in the constitutive models for brickwork. The most common simplification is that fill and spandrels behave as dead loads only and do not take part in the load carrying mechanism. In spite of their apparent relevant computational performance, 3D FEM models overcome only few of these limitations for, at least, a couple of reasons: i) the information on the material response and on the inner geometry of the bridge is inadequate if compared to the code requirements; ii) the non-linear response of brickwork is still far from being modelled in a satisfactory way. For these reasons, the arch-filland arch-spandrel interaction is still not completely clear and a new interest of the scientific and technical community has been focused on masonry bridges as witnessed by the I/03/U/285 Research Project of the International Railway Union (UIC) and the E.U. Sustainable Bridges Project (6th Framework Program, project 1653).

The most popular procedures take into account a simplified load carrying structure consisteing of the arch only, which underestimates the bridge performance:

- the MEXE-MOT method [1-3] reduces a bridge, also a multi-span one, to a pinned-elastic single arch; on the basis of an elastic approach, the load carrying capacity turns out to be grounded on uncertain scientific bases;

- The Mechanism Approach [4], derived from the Kinematic Theorem, nowadays used for many commercial SWs, assumes a compressive rigid and no tensile resistant model for masonry. Collapse is attained when the number of point-like hinges in the arch is large enough to transform the arch itself into a mechanism [5-7].
- The Mery Method and the related developments [8], based on the static (safe) theorem, assumes either elastic and elasto-plastic models for masonry and defines the load carrying capacity as the load that makes the thrust line on the surface, or slightly inside, the arch;

In the last 30 years, tests on reduced scale bridge models have been performed to study some of the basic features of the collapse of masonry bridges [9, 10 among the others], apparently corroborating some approaches, mainly the Kinematic one. Unluckily, the tests were biased by unproper scaling rules that made the model-to-prototype similarity being lost. The few tests performed according to proper scaling rules showed significantly different results from what has been previously obtained and enlightened new aspects of the collapse of masonry bridges.

In this paper, tests on reduced scale models of single span masonry bridges are discussed showing that the contribution of the *non structural* elements of teh bridge may play a crucial role in the assessment of the structure.

2. EXPERIMENTAL EVIDENCES

2.1. Reduced scale testing

In order to retain the model-to-prototype similarity, proper scaling rules may be formulated on the basis of the Buckingam Theorem [11] assuming thet the load carrying capacity P_u of the bridge depends on: i) material compressive strength f_M; ii) arch span l; iii) material density ρ; iv) thickness s of the arch, width w of the arch, thickness t of the fill in crown and other geometrical parameters a_i:

$$P_u = g\,(f_M, l, \rho, s, t, w, a_i) \tag{1}$$

Assuming l and ρ as governing parameters, addressing the physical dimensions of the parameters in square brackets, the dimensional equation holds:

$$[f_M] = \frac{F}{L^2} = [l]^1 [\rho]^1 \,. \tag{2}$$

If we say α the geometric, β the compressive strength, γ the density model-to-prototype ratios, eq. (2) shows that the model-to-prototype similarity is maintained if:

$$\alpha\,\gamma\,/\beta = \text{const.} \tag{3}$$

There are two possible strategies to retain similarity via eq. (3): i) the material density has to be increased (i.e. in a centrifuge [12]); ii) reducing the material strength of the model by the same amount as the geometric ratio.

If the model is given a 1:α geometric ratio (say 1:4) and the materials are the same as for the real prototype (β =1 and γ =1) eq. (3) is not satisfied and the model-to-prototype similarity is lost, which is the basic bias affecting the vast majority of the reduced scale tests performed in the last 3 decades.

The classic approach (reduce only the geometry) retains the similarity with a hypothetical bridge which material has an increased strength of a factor α. Therefore, compressive crushing does not take place in the tests and the collapse of an arch is attributes to the activation of a collapse mechanism. The tests performed at Bolton Institute [10] used modern engineering bricks for solid clay brickwork obtaining a compressive strength of 26 MPa on the average. Since an average value for historical brickwork would be around 10 MPa [13], being the geometric ratio of the Bolton tests approximately 1:4, the self-similarity would be retained if the prototype brickwork had a compressive strength of 26MPa x 4 = 104 MPa, which is not typical of bridge brickwork. Similar conclusions can be derived also for other reduced scale tests [14].

In this paper eq. (3) is satisfied using a different material from brickwork with a compressive strength scaled by the same factor as the geometric ratio, so that the material density and overall mechanical behaviour should stay unchanged. Besides, when modelling the fill, only non-cohesive materials can be used being the friction coefficient a non-dimensional quantity not affecting eq. (3), thus neglecting the contribution to the l.c.c. of the fill cohesion. Under these assumptions, the models retain the similarity to the real bridges.

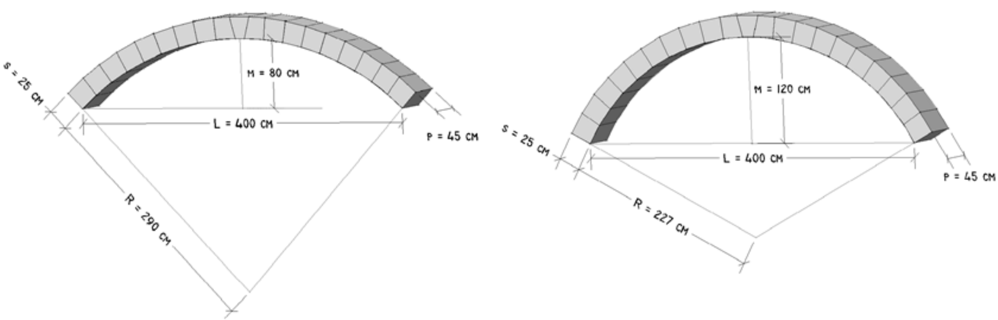

Fig. 1. *Shallow arch. r/s =0.2 and deep arch. r/s=0.3.*

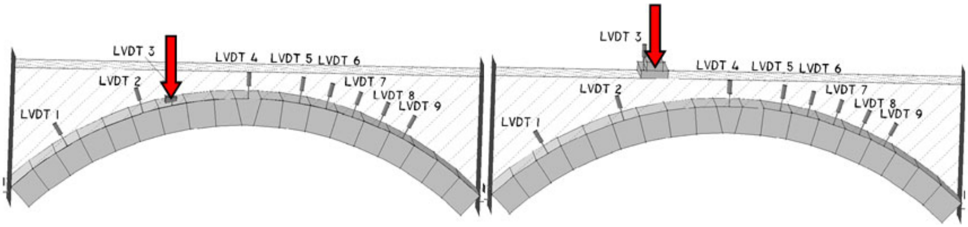

Fig. 2. *Load directly on the arch and load on the fill surface.*

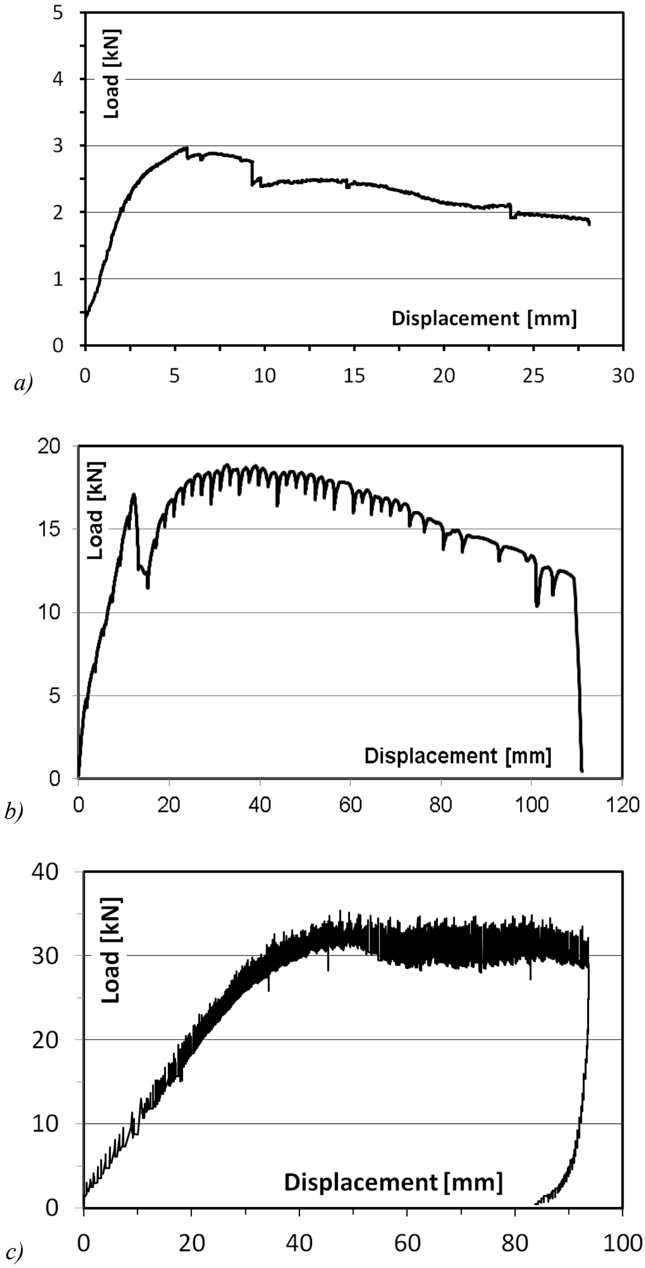

Fig. 3. *a) Shallow arch. r/s =0.2 – Bare arch,*
b) shallow arch. r/s =0.2 – Arch + Fill + <u>load on the arch</u>,
c) shallow arch. r/s =0.2 **-** *Arch+ Fill + <u>load on the fill</u>.*

Table 1. Material properties (aerated autoclaved concrete, brickwork, fill).

Property	Average	Model C.O.V.	Std. Dev.	Prototype	model/ /prototype
Compr. strength f_c [MPa]	<2.9>	12 %	0.35	11.6	1 / 4
Compr. elastic modulus E [Mpa]	<500 >	18 %	90	2000	1 / 4
Density ρ a.a. concrete [kN/m^3]	<6.4 >	4%	0.25	18	1/3.3 shallow
Density ρ fill [kN/m^3]	<17 >	3%	0.51	17	1/3 deep
Internal friction angle - fill	32°	8%	2.64	/	/

Two geometries were considered with rise-to-span ratio r/s = 0.2 and = 0.3, spanning 4m, 25cm thick and 45cm in depth, figure 1 (fill not represented). Three models were considered: i) arch only; ii) arch + fill + load applied directly on the arch, figure 2.a; iii) arch + fill + load applied on the fill surface, figure 2.b. The latter two models are aimed at identifying the net effect of the load distribution inside the fill. The material used for the models is aerated autoclaved concrete; its mechanical properties are compared to the average values for brickwork in table 1 [13]. The fill used in the tests consists of a non-cohesive granular material graded 8-10mm (internal friction angle: 32°). The arches were built assembling pre-cut blocks with no mortar so to represent a no-tensile-resistant material, ad brickwork is assumed to be. Steel chains were used to lock the springing of the arches.

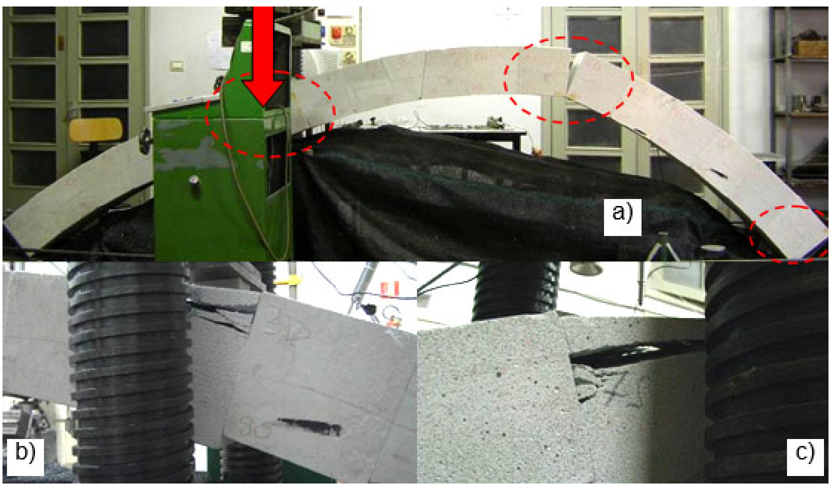

Fig. 4. Collapse mechanism of the SHALLOW (r/s =0.2) ARCH. a) global mechanism; b) and c): details of the "hinge" just below the load (final stage).

2.2. Test results

The scaling rule provided by eq. (3), taking into account a 4/3 ration in the arch mass and a 1/4 ratio in material strength leads to a geometric ratio of 1/3 and 1/3.3 for the deep and shallow arch respectively. This means that the results can be extrapolated to spans of 12 to 13.5 m, which is the average value of the standard European railway viaduct. The arches were loaded at 1/3rd of the span (the „weakest position") by means of a displacement-controlled procedure. A load cell with error ≤ 0.1% and LVDTs with precision of 1/1200mm were used; tests were performed at the DICCA Lab.s. The load has been applied on the fill by means of a 40cm wide device and directly on the arch on a 20cm wide strip for the other two models.

Figures 3.a-c show the load-displacement (loaded point) diagram for the bare shallow arch (Fig. 3a), and for the fill model with the load on the arch (Fig. 3b); the case with the load on fill (Fig. 3c). The collapse mechanisms and some details are showed in Fig. 4 and 5 for the two models of Fig. 3.

Figure 4.a shows apparently a typical four-hinges collapse mechanism. The details, Fig. 4b and 4c, show that the first hinge to be activated, just below the load, experiences compressive crushing, which happens when the 4 hinge mechanism is still far from activating (2 hinges out of 3 already active). Figure 5 shows a similar mechanism for the arch with the fill: the right hand side hinge exhibits compressive crushing at the intrados, which is different from the bare arch for which crushing takes place only in the hinge just below the load. Besides, Fig. 5b shows that compressive crushing is quite different as for the bare arch of Fig. 4b: in the first case the material crushes in thin slices, in the latter, a quite large compressed part, above the main crack, undergoes compression with no crushing, which can be probably attributed to the confinement effect of the fill.

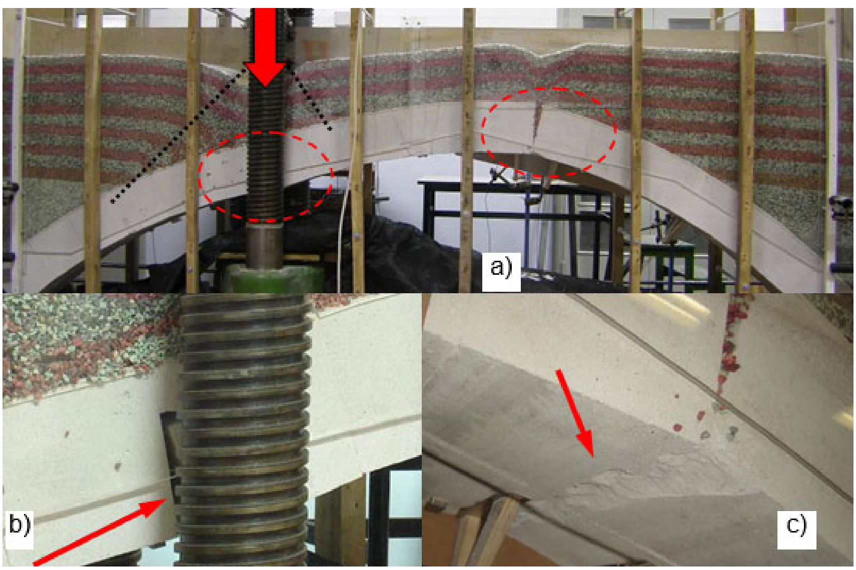

Fig. 5. *Collapse mechanism of the shallow (r/s =0.2) ARCH + FILL. a) global mechanism; b) left and c) right hinge (final stage).*

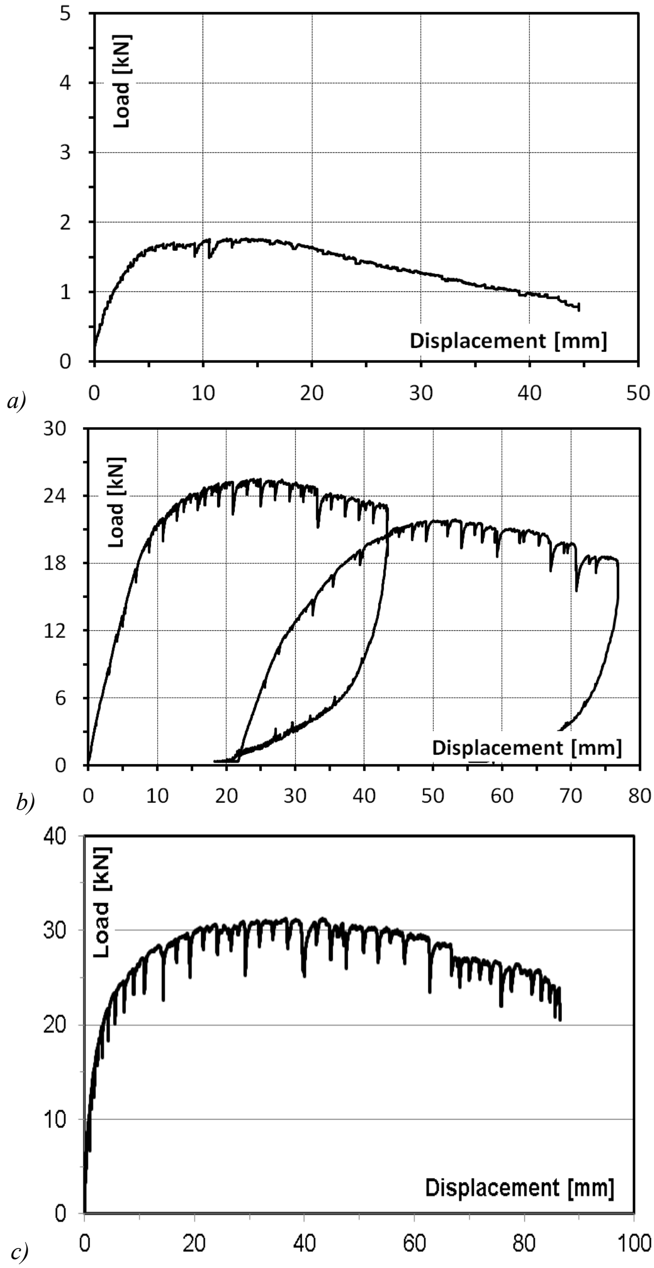

Fig. 6. *a) Deep arch. r/s =0.3 – Bare arch,*
b) Deep arch. r/s =0.3 – Arch+Fill + Load on the arch,
c) Deep arch. r/s =0.3 – Arch+Fill + Load on the fill.

Figures 6-8 are related to the deep arch. Apart from the different load carrying capacity of the deep arch, which is quite known, we can underline some issues: i) the contribution of the fill is approximately equivalent for the two models; ii) the collapse mechanism is rather close to what foreseen by the Kinematic approach for these bridges and the compressive crushing of the arch plays a minor role in the collapse of the arch, which can be explained as follows: i) shallow arches collapse due to compressive crushing of some sections and, therefore, greatly benefit from those elements distributing the load (fill);

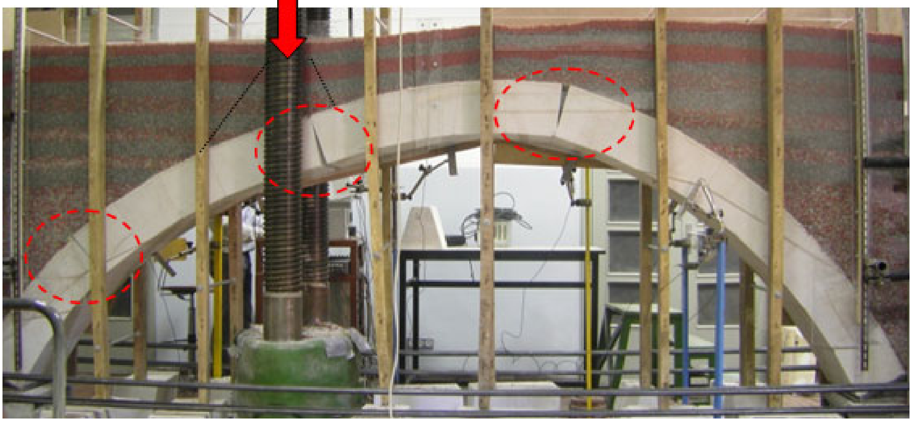

Fig. 7. Collapse mechanism of 1the deep (r/s =0.3) Arch + Fill.

ii) deep arches, on the contrary, collapse because of the activation of a mechanism and, therefore, benefit from all the devices that restrain some displacements of the arch.

Table 2 summarizes the tests, which are somehow similar to the results obtained by Royles and Hendry [14] on reduced scale models. Apart from relevant differences in the model geometry, in those tests the material of the models was solid clay brickwork, thus not respecting eq. (3): this could be the reasons for finding a contribution of the fill less relevant than what has been found in the present tests.

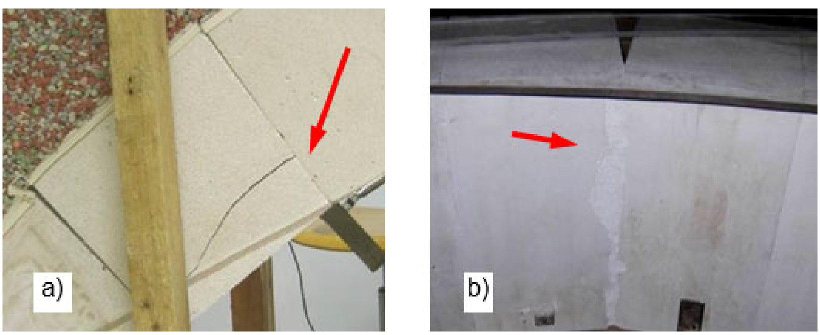

Fig. 8. *Deep (r/s =0.3) ARCH + FILL. a) left and b) right hinge (final stage).*

Table 2. *Load carrying capacity of the tested models.*

Load Carrying Capacity of (average of 2 tests) [kN]	Bare Arch	Arch + Fill Load on arch	Arch+Fill Load on Fill
Shallow Arch *r/s* = 0.2	3	11	33
Deep Arch *r/s* = 0.3	1.8	24	32

3. DISCUSSION AND CONCLUSIONS

The test results discussed show that masonry bridges are complex structures in which the load carrying capacity is due to the interaction of the bridge components. Therefore, the assumption of masonry bridges as "arch" bridges, i.e. the arch barrel as the load carrying structure and all the other elements as non-structural members, is only a lower order approximation to the actual response of the bridge. Proper structural and mechanical models should take into account all the bridge components.

Since the assumptions of Limit Analysis procedures, i.e. ductility of the materials, are not fulfilled by brickwork, the test results showed that, for shallow arches (rise-to-span ratio=0.2), collapse may take place far before the classical four-hinge mechanism is activated because of compressive crushing of the most stressed sections. The classical Mechanism Approach, in these cases, can therefore be conservative. On the contrary, Kinematic Limit Analysis seems to be more reliable for deep arches (rise-to-span ratio=0.3) for which material collapse seems to be of minor importance.

The research on this issue is still in progress and further information is provided in other papers presented in this conference.

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