LOAD BEARING STRUCTURE OF MASONRY BRIDGES

A. Brencich, G. Cassini, D. Pera

University of Genoa, Department of Civil, Chemical and Environmental Engineering, Genoa, ITALY.

e-mails: brencich@dicca.unige.it, cassini@dicca.unige.it, davide.pera@edu.unige.it

SUMMARY

Masonry bridges are often considered arches to which the fill, retained by the spandrels, contributes as a stabilizing dead load. Recent research demonstrated that the arch-fill interaction is a fundamental contribution to the load carrying capacity of these bridges. To highlight this aspect, several tests on reduced scale models were performed but improper scaling rules introduced a bias on the results making them often unreliable. In this paper, test results on reduced scale models, according to proper scaling rules, are discussed providing an estimation of the amount of load carrying capacity increase due to the arch-fill interaction. Up to now, only a deep arch model has been tested, showing also that the classic assumption of hinge-mechanism is not fulfilled, being anticipated by compressive crushing of the materials. This raises some questions on the standard procedures for the bridge assessment.

Keywords: *Masonry bridges, load carrying structure, arch-fill interaction, deep arch, material strength, mechanism collapse.*

1. INTRODUCTION

Masonry bridges are almost unknown to academic courses, being a structural type no longer used in Bridge Engineering. As a consequence of such a foggy knowledge, they are considered arches to which the fill contributes as a stabilizing dead load and as a load-distributing device. The contribution of the fill to the load carrying mechanism is quite complex, involving either the spandrels and the fill, and usually accounts for at least 2/3rd of the l.c.c. of the bridge.

The research of the last two decades showed that the main contribution to the load carrying capacity of the bridge originates from the arch/fill interaction due to: i) the stabilizing effect of the fill; ii) the distribution of the load through the fill; iii) the contribution of the fill as a geotechnical structure that restrains and often locks the activation of a four-hinge mechanism [1-3]. To gain deeper insight, both theoretical and experimental research were carried out. For the latter, the vast majority of the tests, due to practical and economic reasons, has been performed on reduced scale models [4-6] obtained scaling the bridge geometry but disregarding other scaling rules. This issue, based on the Buckingham Theorem, is deeply discussed. The consequence or improper scaling is that a bias has been introduced in the results, reducing their significance. Since the material used for the models is ordinary solid clay brickwork, the model is similar to a prototype with an exceptionally over-strong material. This enlightened some aspects of the collapse mechanism but did not look into the effects of material crushing, assuming – with no actual proof- that it is of minor importance.

Also in this paper the arch/fill interaction is studied on the basis of a series of tests on reduced scale models. The criteria for proper scaling of the models, to preserve the model-to-prototype similarity, show that the model needs to be built using a material with compressive strength reduced as much as its geometry. Conversely, the other possibility is that of increasing the loads, as performed by another research group [7], which is much more complicate.

Deep arches only are considered in three different setups: i) bare arch; ii) arch+fill with the load applied on the arch; iii) arch+fill with the load applied on the fill to address the effect of load distribution on the arch by comparison with the results with the previous model and also directly measured by means of pressure cells have been located at the arch-fill interface.

2. EXPERIMENTAL EVIDENCES

2.1. Reduced scale testing

For masonry arch bridges we can assume that the load carrying capacity depends on the bridge geometry and load position, on the bridge dead load (i.e. on the masses) and on the material compressive strength. Under these assumptions, it can be proved that the model-to-prototype similarity is retained if the following equation is satisfied, being α the geometric, β the compressive strength, γ the density model-to-prototype ratios:

$$\alpha\,\gamma/\beta = \text{const.} \tag{1}$$

If the model is given a α geometric ratio (say 1:4) and the materials are the same as for the real prototype (β = 1 and γ = 1) eq. (1) 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. Two options allow the similarity to be retained: i) increase the gravity loads (parameter γ) by the opposite of α; ii) decrease the material strength by α.

The basic parameters of the Italian railway bridges are: i) typical strength of solid clay brickwork around 10-15 MPa; ii) the arch accounts for 1/4th of the global weight of the bridge, a mass density of 16.5 kN/m^3 and 18 kN/m^3 for the brickwork and for the fill respectively, we get an average weighted mass of the bridge of 17.6 kN/m^3; iii) average span length in-between 12-to-18 m. In this paper we assume: a) aerated autoclaved concrete as the material for the arch, which has an average compressive strength of 2.4MPa and a density of 4.7kN/m^3; b) gravel for the fill with density of 14 kN/m^3 that lead to an average weighted density of 11.7 kN/m^3. Therefore, we have β =2.4/15÷2.4/10 ≅ 1/6÷1/4 as material strength scaling ratio and γ = 11.7/17.6 ≅ 2/3 as scaling ratio of the masses. Eq. (1) shows that the geometric ratio for prototype similarity is $\alpha = \beta/\gamma$ ∈[5/24; 5/16] ≅ [1/4 ; 3/8]. This means that the tested models represent real bridges with span 2.7-to-4 times larger than the models, i.s. in-between 11-to-16m, which is the span of a medium-to-large bridge.

2.2. Model geometry and test procedure

Since we assume for solid clay brickwork a non-tensile-resistant response, the model has been assembled with aerated autoclaved concrete (a.a.c.) blocks without any mortar in the joints. The voussoir dimension is not aimed at reproducing the vertical joints of brickwork but at reproducing the material response on the average. Besides, the compressive response of a.a.c. follows a Kent&Park shape, as solid clay brickwork does, Fig. 1 [8].

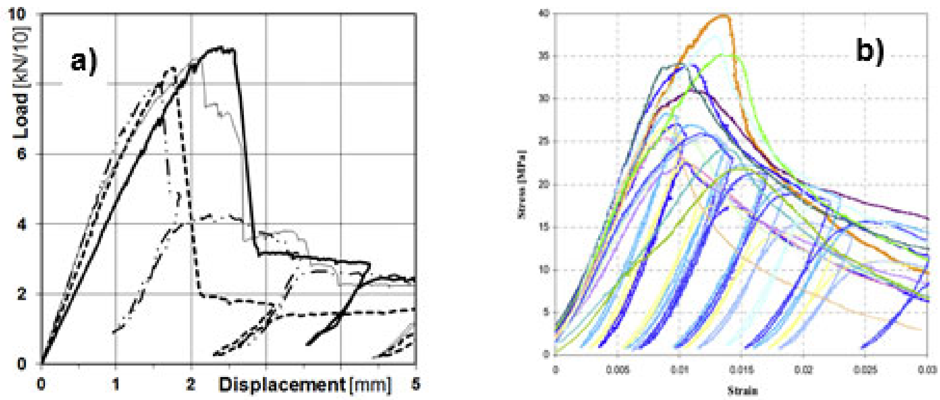

Fig. 1. *Compressive response of a) aerated autoclaved concrete; b) solid clay brickwork [9] (note that the specimens were prisms with different dimensions⇒ different loads).*

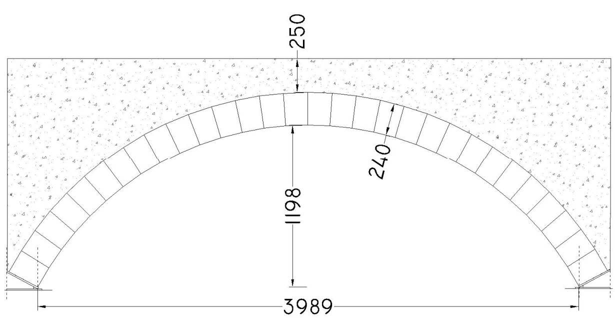

Fig. 2. *Arch geometry. The arch thickness (third dimension) is 450mm.*

Figures 2 to 4 show the geometry of the model and the two loading conditions, i.e. load directly on the arch and load on the surface of the fill. These two models are aimed at identifying the net contribution of the fill as a load distributing device as separated from its contribution as a stabilizing dead load and a geotechnical component of the arch structure. Table 1 summarizes the main geometric parameters of the model and the geometry of the prototype bridges that are represented by these tests. The loading procedure was displacement-controlled with displacements imposed at 1/3rd of the span and the resulting load has been measured by means of a class 1 (error $\leq 0.1\%$) load cell.

The displacements have been recorded by means of both LVDTs (precision: 1/100mm) located in several position along the arch and a laser scanning.

One of the open issues on masonry bridges is the amount, if any, of the load distribution through the fill. In the technical and scientific literature there are several assumptions (45°, 30°, 2:1 or 3:1 slope) but no experimental data can be found.

Table 1. *Geometric properties of the prototype and model.*

Property	Model	Prot.	Property	Model	Prot.
Span [m]	4.00	11÷16	Arch thickness [m]	0.24	0.65÷0.96
Rise [m]	1.30	3.3÷4.8	Arch width [m]	0.45	1.2÷1.8
Rise/Span ratio	0.33	0.33			

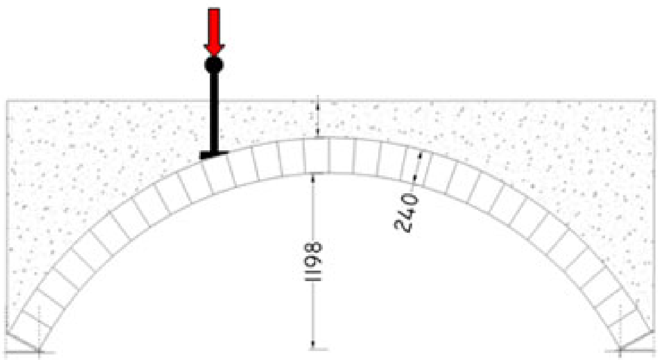

Fig. 3. *Loading directly on the arch (tests 1 and 2).*

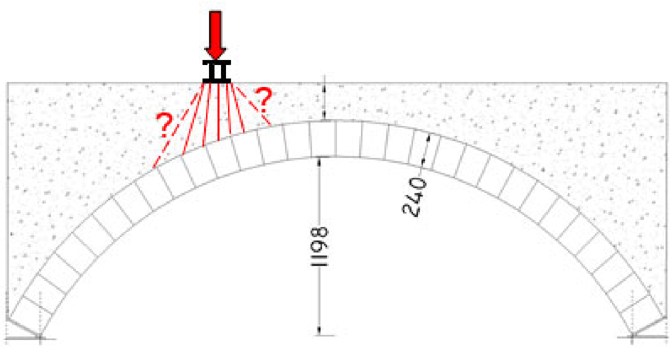

Fig. 4. *Loading on the fill surface (test n. 3).*

Since the l.c.c. of such a kind of models (i.e. blocks without mortar in the vertical joints) strongly depends on the contact surface in-between adjacent blocks, also digitally cut blocks do not produce exactly equal arches. For this reason, each arch has been first tested as a bare arch (LT_1 to LT_3 tests, thin lower lines of Fig. 5) and later on tested with fill and load on the arch (Load Tests 1 and 2) and load on the fill surface (Load Test 3), bold upper lines of Fig. 5.

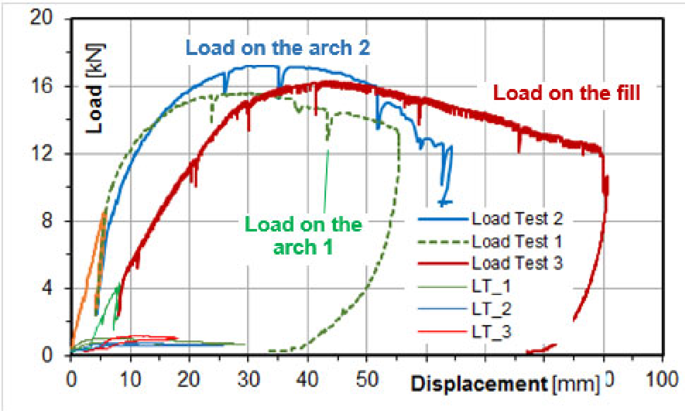

Fig. 5. Load-Displacement diagrams for the three tests. Thin lines: bare arches. Bold lines: arches + fill. Tests 1 and 2: load applied on the arch extrados; test 3: load applied on the fill surface.

3. TESTS RESULTS

Figure 5 shows the load-displacement (below the load) diagram for the 3 tested models; 6 load tests have been performed, 2 for each arch: the first one on the bare arch, the second on the arch+fill model; Table 2 summarizes the outcomes. Figure 6 shows the arch model (n. 3) at the beginning (unloaded) and at the end (maximum displacement, 90mm approx) of the load history, while Fig. 7 shows the results of the laser scanning compared to the original (undeformed) shape of the arch.

The final collapse mechanism showed at least 3 hinges to be activated, the fourth being uncertain. Hinges n. 1 and 2, the first 2 to be activated, experienced compressive crushing, Fig. 8. This means that even though the collapse mechanism was activated, the crushing of some hinge alters the classical mechanism approach.

4. DISCUSSION AND CONCLUSIONS

Figure 5 and table 2 point out some issues: i) the contribution of the fill to the l.c.c. of the arch is the major part of the l.c.c. itself (15 times or more); ii) l.c.c. of the models with the fill are similar (16-to-17 kN), which shows that the contribution of the fill as a load distributing device seems to play a minor role, if no role at all. This suggests that the load distribution due to the fill may be significant only for lower load levels (i.e. Boussinesq type) but, when the ultimate load is approached, the distribution of the load through the fill is much reduced and the load is transferred substantially through a vertical path to the arch. Similar assumptions, not based on experimental data, have been already conjectured by other authors [10, 11]. This opens an issue in the assessment of masonry bridges: when the assessment looks at the service conditions, the load could perhaps be considered distributed on the arch upper surface, but when the load carrying capacity is considered the load distribution should be considered quite limited.

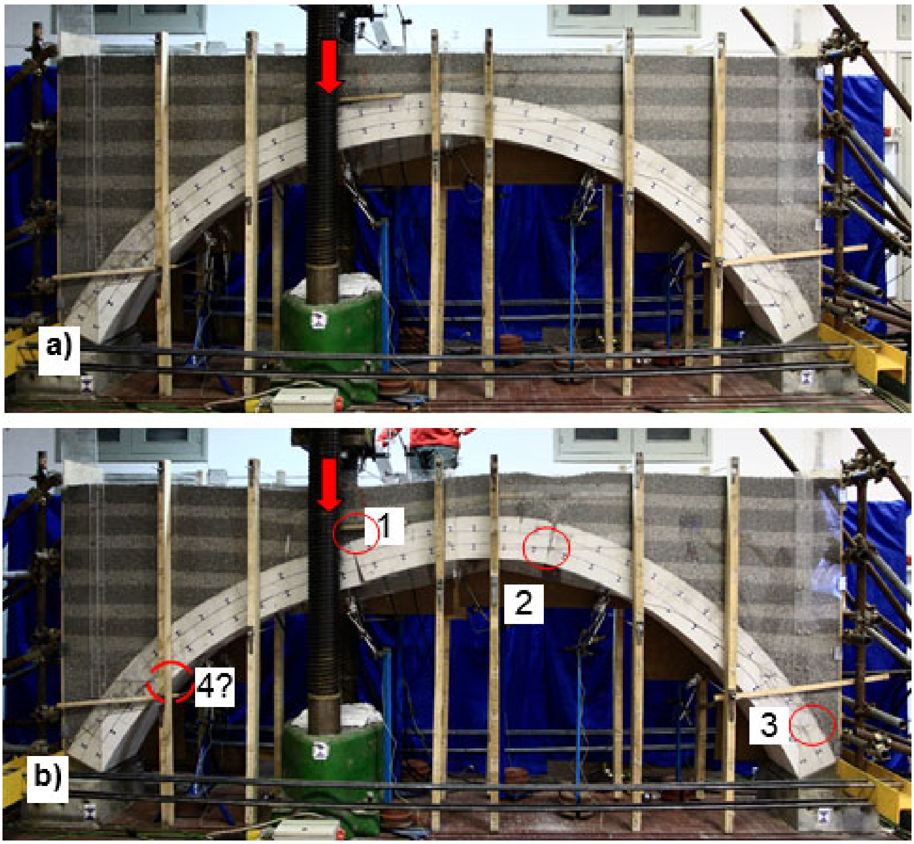

Fig. 6*.Model 3. a) unloaded; b) at maximum displacement (90 mm). Red circles stand for the detected hinges.*

Figure 8 shows that the hinge below the load, the first to be activated, undergoes quite extensive crushing. Besides, Fig. 7 shows that the location of the fourth hinge is not clear; actually it is not clear whether the 4th hinge is activated at all. Whatever the case, it is clear that the collapse mechanism involves also material crushing. Crushing has been detected also in the other hinges, such as location 2 of Fig. 6.

Table 2. *Summary of the tests - Load Carrying Capacity.*

Model no.	Bare arch [kN] *(RING)*	Arch + Fill [kN]	Arch + Fill Load position
1	0.98 *(1.38)*	15.4 *(22.8)*	Arch
2	0.76 *(1.36)*	17.2 *(23.2)*	Arch
3	1.15 *(1.10)*	16.2 *(20.2)*	Fill

These observation open serious objections on all the assessment methods that rely on the classical No-Tensile-Resistant mechanism method [13-15].

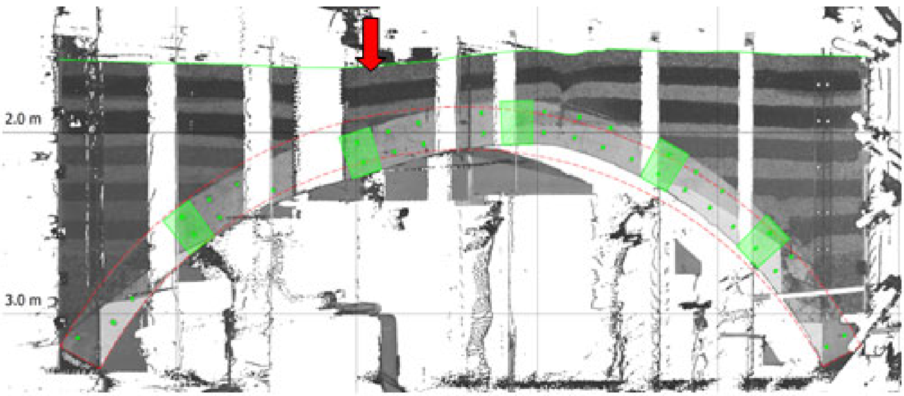

Fig. 7. *Deformed shape of the arch at the maximum displacement (90mm) compared to the undeformed shape.*

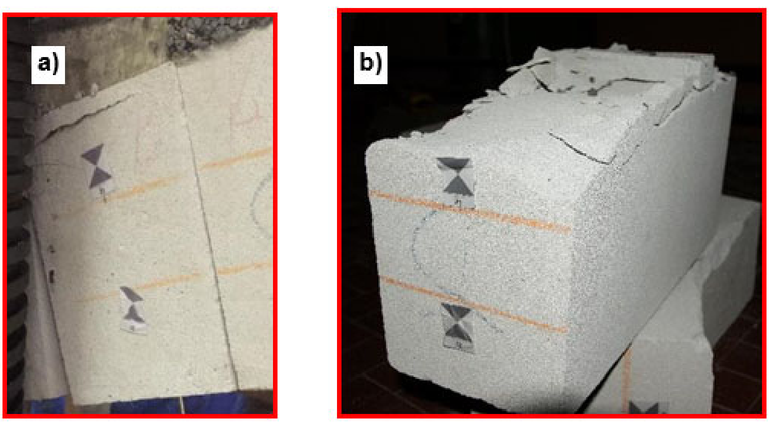

Fig. 8. *Plastic hinge located just below the load (fig.s 6 and 7): a) in the arch; b) after dismounting the model.*

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