A NEW RETROFITTING TECHNIQUE FOR MASONRY BRIDGES

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SUMMARY

Retrofitting of masonry bridges usually applies the basic concepts of r.c. to this kind of masonry structure. The results are that often that the retrofitting works are almost ineffective and, always, the historical value of the bridge is largely lost. A series of tests on reduced properly scaled models (see other papers in this Conference) show that the actual load carrying structure is an arch with reduced span in comparison with its geometric appearance. The actual span depends on the fill material (stiffness and strength) at the springing. Besides, the fill does not distribute the load, applied on its surface, on the arch extrados close to the ultimate load. Based on these two issues, a new retrofitting technique is discussed: selective injection of the fill, limited to the part close to the springing, may reduce the effective arch span, thus increasing the l.c.c. of the bridge as a whole. This issue is discussed through a test on a 4m-span model.

Keywords: *Masonry bridges, load carrying structure, retrofitting, load carrying capacity.*

1. INTRODUCTION

Masonry bridges are a specific class of masonry-vaulted structures for many reasons: i) they are and need to be kept in service; ii) spandrels limit the vaults transversally; iii) the thickness-to-span ratio is much lower than for ordinary vaults and arches (massive arches); iv) clearing the fill is not an easy task as it could be for masonry vaults. For these reasons, retrofitting of masonry bridges asks for specific techniques and procedures.

In the last 20–25 years several methods for strengthening arch bridges have been developed: i) concrete saddling/overlaying [1-3]; ii) near-surface reinforcement by means of stainless steel bars [4, 5] or FRP reinforcements [6-8]; iii) transversal and through-the-thickness reinforcement [9]; iv) transversal steel ties [10]; v) mixed strategies [11]. Most of these techniques consider the collapse mechanism of an arch with 4 hinges, figure 1, and makes use of surface reinforcement to lock the activation of some of the hinges [12 among the others]: overlaying the arch with tensile-resistant material locks the hinges located at the arch intrados while the near-the-surface reinforcement locks the hinges just below the load. Such a procedure comes from the collapse model first introduced by Heymann [13] and later on apparently confirmed by a series of reduced scale tests [14 and 15 among the others].

As discussed in other papers in this conference by the same authors, the reduced scale tests need proper scaling rules to be defined in order to retain the model-to-prototype similarity. All the tests performed so far simply reduce the arch geometry and use the same materials used in the prototypes. It can be demonstrated, by a direct and quite simple application of the Buckingham Theorem [16], that scaling only the geometry makes the model to loose similarity with the prototype. Actually, the models obtained scaling just the geometry, would be similar to real bridges with an overstrong brickwork with compressive strength higher than 30-35 MPa. This introduces a bias in the research: the collapse mechanism is activated only because the model, representing an overstrong material, is unable of representing any effect originated by material crushing.

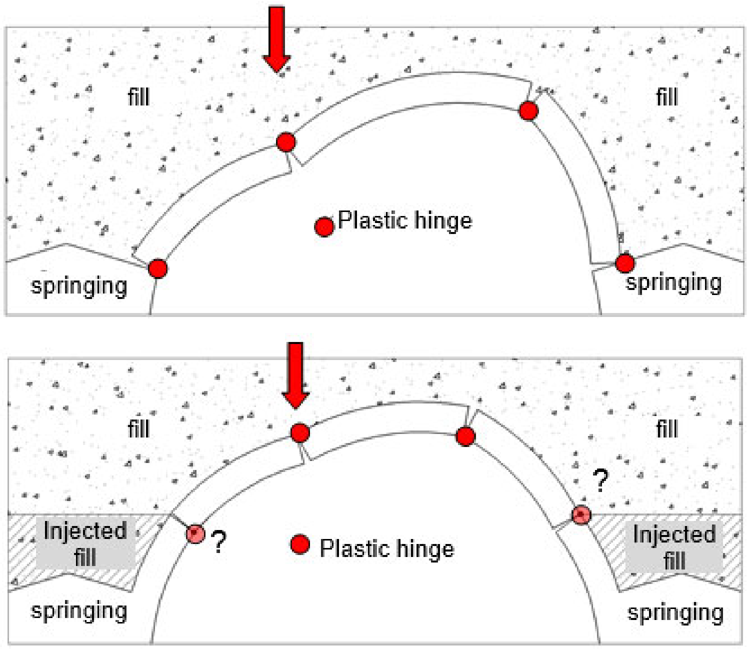

Fig. 1. *Basic idea for arch bridge strengthening. Collapse mechanism of a) original geometry; b) the bridge once the fill over the springings has been injected.*

Proper scaling rules ask also the material strength to be scaled [16]. If the models follow such an approach, the collapse mechanism of the arch bridge may significantly differ from what is commonly assumed: the four hinge mechanism is activated only for deep arches with rise-to-span ratio higher than 0.30-0.35, which is quite uncommon for railway and road bridges. For shallow and intermediate arches, the collapse is attained due to crushing of the most compressed sections, when only three, and often only two of the hinges have been activated [17]. This means that the strengthening techniques used for vaults may fail in increasing the load carrying capacity since the hinge to be locked would activate far before the material will crush.

In this paper a new and low-invasive technique is discussed and corroborated by means of experimental data. If the fill just above the springing is injected with a liquid cement grout, the increase in strength and stiffness of that part of the fill makes the actual springing to be lifted up and load carrying arch results in a reduced span and, consequently, in a higher load carrying capacity, figure 1. Figure 1.b shows the classical collapse mechanism considered in many approaches. The aforementioned tests, scaling only the geometry of the bridge, outlined such a collapse due to the lost in model-to-prototype similarity. If compressive crushing is taken into account, the activation of the four-hinge mechanism of figure 1 is simply an assumption since the collapse could be attained far before the mechanism is activated due to compressive crushing of the material.

2. MODEL GEOMETRY AND MATERIALS

As discussed in detail in another paper by the same authors in this Conference [16], the model bridge consists of a dry assemblage (no mortar in the joints) of aerated autoclaved concrete (a.a.c.) blocks. The voussoir dimension is not aimed at reproducing the vertical joints of brickwork but at reproducing the material response on the average. This choice is aimed at retaining the model-to-prototype similarity by reducing the material strength; to this aim, a.c.c. exhibits a post-peak response (Kent&Park type) similar to that of solid clay brickwork, with compressive strength reduced by a factor 4 approx. Further details can be found in [16].

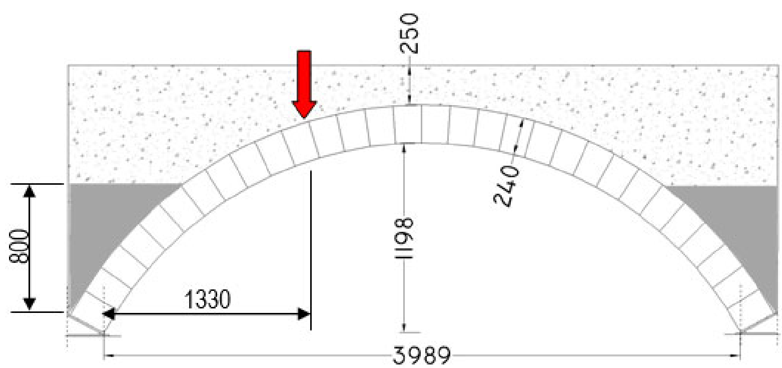

Fig. 2. *Geometry of the model. The thickness (third dimension) is 450mm. Grey areas represent the injected zones.*

Figure 2 shows the geometry of the model; the side areas, dark grey in figure 1, represent the part of the fill assumed to be injected. It was not in jected in reality but made of poor concrete (compressive strength of 2.0 MPa when the arch was tested) to represent the injected area. Even though its height is significant with respect to the arch rise, its quantity is limited if compared to the whole mass of the fill (approx 16% of the fill). For other details, see [16].

3. TESTS RESULTS

Figure 3 shows the load-displacement response of the arch; the displacement is that of the loaded point. Figure 4 shows the deformed shape at the maximum displacement, while figure 5 outlines the position of the detected plastic hinges and the crushed material. Fig. 3 shows a relevant plastic plateau just after the peak load; at this moment, the first hinge (hinge A o figures 4 and 5) underwent compressive crushing. Hinge B (Fig. 4 and 5) crushes when the displacement is approx. twice the „elastic" limit. It is not clear whether a third hinge activated in position 3 (Fig. 4 and 5); when the model was dismountled no compressive crushing was detected in the blocks located close hinge C.

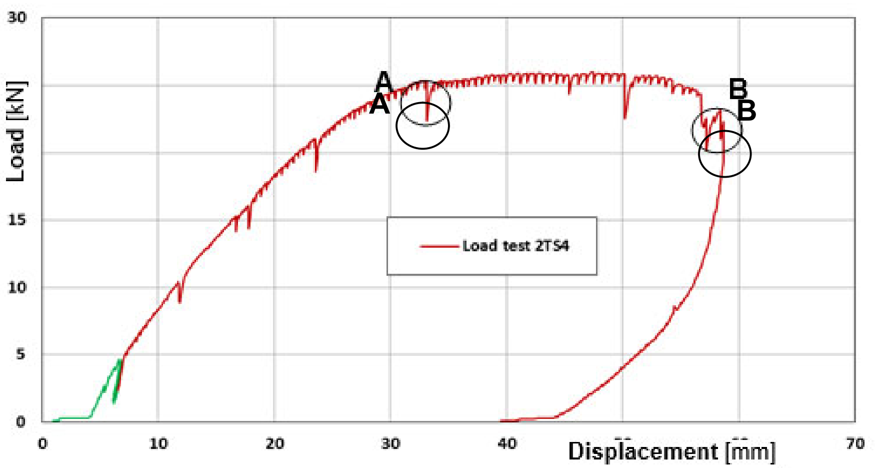

Fig. 3. *Load-displacement response of the strengthened arch of figure 2.*

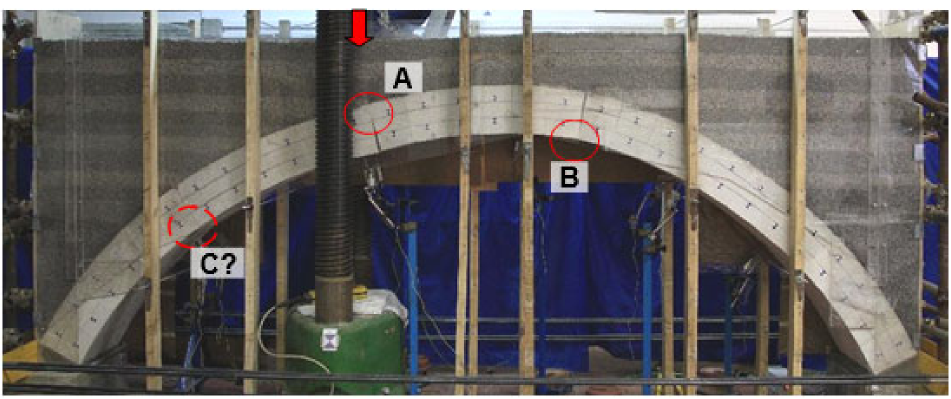

Fig. 4*. Deformed shape of the model at maximum displacement.*

The same geometry has been tested naked (with no fill) and with the fill, either loaded directly on the arch and on the fill surface [16]. These different setups and loading conditions are aimed at identifying the effect on the l.c.c. of the arch of: i) the fill as a geotechnical structure; ii) the fill as a geotechnical structure and a load distributing device so as to estimate the l.c.c. increase due to the selective injection technique. Figure 6 shows the load-displacement diagrams for these four models.

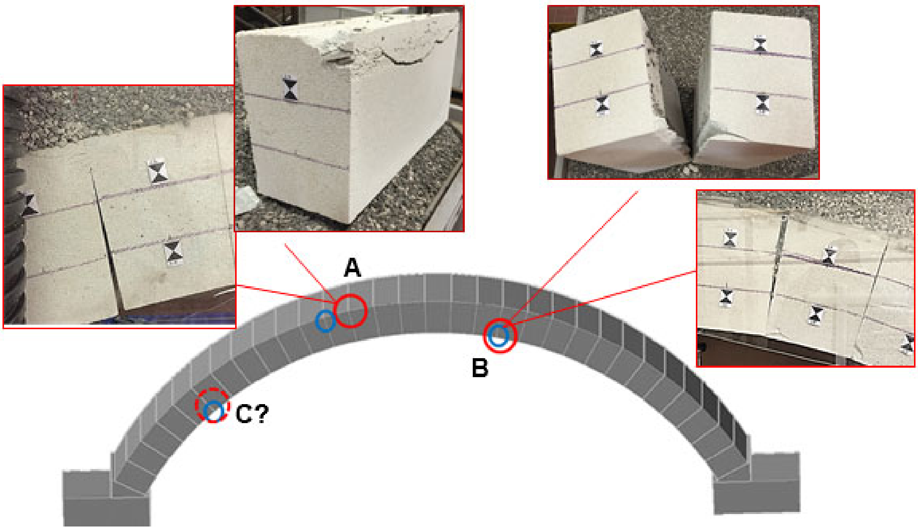

Fig. 5. Red circles indicate the plastic hinges detected; blu circles indicate the position of the hinges foreseen by RING sw.

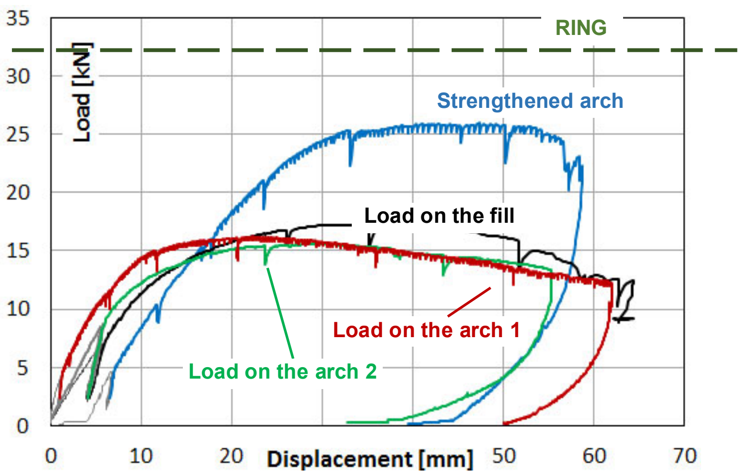

Fig. 6. Load-displacement diagrams for the other models [16] and for the RING model.

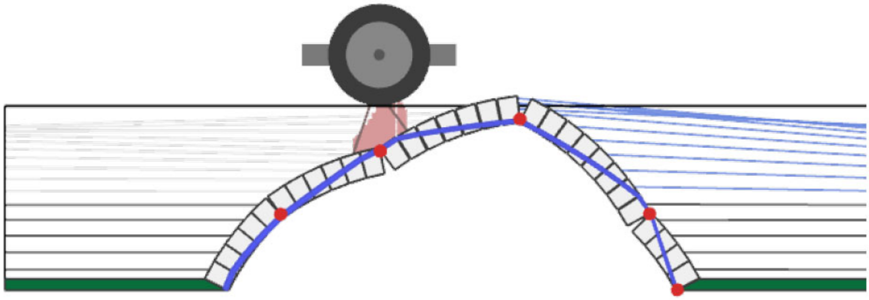

Fig. 7. Collapse mechanism foreseen by RING.

4. DISCUSSION AND CONCLUSIONS

Figures 4 and 5 show that collapse has been attained when only 2 hinges were active; both of the hinges crushed. It is not clear whether a third hinge was active in position C of figure 4 and 5; whatever the case, no crushing took place in that location.

Such an outcome is quite new: the collapse mechanism is not activated and is preceded by compressive crushing, which opens serious discussion on the Heymann approach on arch assessment. If the arch is a deep arch, the mechanism activates and compressive crushing plays a minor role on the arch l.c.c. If the arch is shallow, or if selective injections rises up the springings of an arch, that becomes a shallow arch even though it was originally a deep one, than it happens that collapse is driven by compressive crushing of the most stressed sections (or hinges, according to the classical approach).

Table 2 shows the comparison between the models discussed in [16] and the value foreseen by a well-established and scientifically grounded code, RING [17]. Since RING code assumes hinges to be activated in the collapse mechanism, figure 7, even though it takes into account, in some way, the material compressive strength, and the injected areas (by increasing the mechanical properties of those parts of the fill) it falls in the path of Kinematic Limit Analysis. Therefore, it provides an overestimation of the actual collapse load, as figure 6 shows.

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

Model no.	Bare arch [kN]	Arch + Fill [kN]	Arch + Fill Load position
1	0.98	15.4	Arch
2	0.76	17.2	Arch
3	1.15	16.2	Fill
4	1.38	25.9	Fill+Injection
RING	1.36	31.6	Fill+Injection

Table 2 shows that selective injection can increase the l.c.c. of an arch bridge some 50% or more, which is a relevant increase that may avoid more invasive and often uncertain retrofitting works. Since selective injection may change a deep arch into a shallow one, as it almost always is expected to achieve, the l.c.c. of the bridge turns out to be no more driven by the activation of a mechanism but by compressive crushing of the most stressed sections. This asks more detailed models to be used to assess the bridge in order to avoid overestimation of the l.c.c. of the structure.

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