Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Simplified analysis on multiring masonry arch bridges

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ABSTRACT: Multi-ring brickwork masonry arch bridges in service in the European railway and roadway network represents a typology of masonry bridges that generally have lower load carrying capacity with respect to masonry arch bridges with different arch texture. These bridges differ from the single-ring arches for their peculiar mechanical behaviors and collapse modality. This paper presents the evaluation of the load carrying capacity of multi-ring masonry arches by means of a simplified numerical strategy, that permits to investigate the in-plane failure mechanism of the element. In the simplified approach the arch geometry is subdivided in rigid elements, interacting along their rigid edges through non-linear bidimensional links in which the stiffness and the material nonlinearities are concentrated. The numerical results obtained with the proposed approach are compared with experimental outcomes.

1 INTRODUCTION

The multi-ring brickwork masonry arch bridge is a bridge category diffuse all around the world. The majority of them were built over a century ago and the increasing of the traffic loads demand and the deterioration of the materials bring the necessity of the static and seismic assessment of these structures. The peculiarity of this category is the presence of the rings joints that can be potential surfaces of weakness for the arch (Melbourne & Gilbert 1995). For this reasons, several different numerical approaches have been developed to perform the structural safety assessment of this type of bridge. Among them, the Finite Element Method (FEM), the Rigid Block analysis Method and the Discrete element method are most diffuse.

The FEM models, despite the high computational cost and the problems with the convergence of the solution, can reaches accurate prediction of the response of the bridge (Zampieri & Tetougueni & Pellegrino 2021). One among the FEM models, is the mesoscale approach (Zhang & Macorini & Izzuddin 2018) that reproduces the geometry subdividing the bricks into 3D solid elastic elements and the mortar joints into 2D non linear interface elements in which the nonlinearities are concentrated obtaining good prediction of the results.

The Rigid block analysis considers the geometry of the arch as a mesh of rigid block, investigate the structural equilibrium and collapse model through limit analysis obtaining with less computational cost good results(Melbourne & Gilbert 1995).

The discrete element method has the possibility of using deformable or rigid element and nonlinear interfaces recreating the arch geometry (Kassotakis & Sarhosis & Forgàcs & Bagi 2017).

The aim of this paper is to present a simplify numerical method for the evaluation of the capacity of multi-ring masonry arches, capable of simulate the failure modes typical of this category, for example the detachment between rings, using less computational cost than another sophisticated methods.

2 DESCRIPTION OF THE NUMERICAL STRATEGY

The approach considered in this paper simulates the geometry of the original arch by means of rigid panels connected through a distribution of 2D nonlinear links capable of simulating

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the flexural and shear-sliding masonry behaviors and coupling between them(Zampieri & Piazzon & Pantò & Pellegrino 2022, Caddemi & Caliò & Cannizzaro & D'Urso & Pantò & Rapicavoli & Occhipinti 2019, Cannizzaro & Pantò & Caddemi & Caliò 2018) (Figure 1).

The interface link is composed by two in series mono-dimensional springs, the normal spring is disposed perpendicularly to the edge meanwhile the tangential spring is parallel to it (Figure 2). The mechanical coupling is obtained according to the Mohr-Coulomb yield criterion, based on the friction coefficient (μ) and the cohesion (c). The links are capable of simulate the material cracking that leads to the formation of the hinges, typical mechanism of the masonry arches.

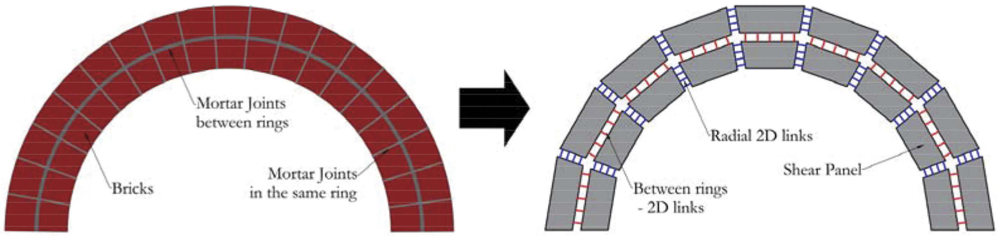

Figure 1. Real masonry arch (left); numerical representation of the geometry with discrete elements (right).

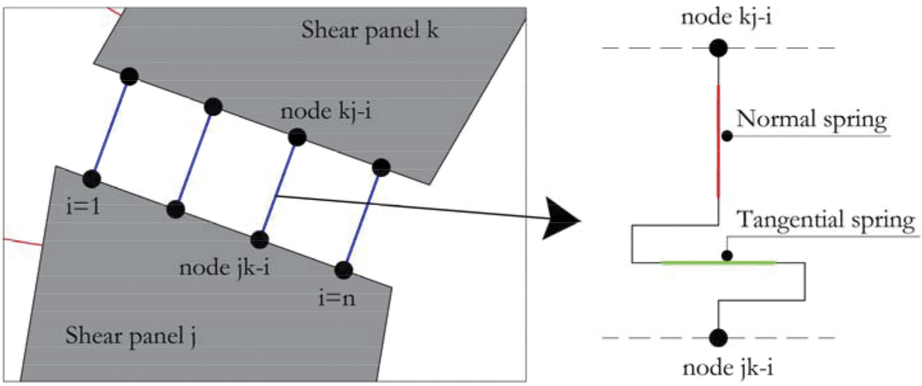

Figure 2. Discrete element interface with nodes connected with links (left) and numerical representation of the 2D link(right).

3 MODEL CALIBRATION

The normal springs reproduces the joint and brick compressive behaviour by means of a parabolic relationship reaching the peak-strength, followed by a linear softening and a residual strength. The tensile behavior is simulated with a linear elastic law with linear softening after the peak-value. The linear softening ends with a zero force residual, that corresponds to the cracking of the material. The link that simulates cracked masonry maintains the original behavior in compression but, if tensile displacement occur, it is considered detached and it doesn't contribute in the normal and tangential directions. The initial normal stiffness $K_{N,0}$, the peak force in tension and the peak force in compression are modelled considering the potential mortar joint and unit failure modes. The tangential spring describes the sliding behavior with an linear elasto-plastic constitutive law with linear softening, controlled by a damage function that reduces cohesion, friction coefficient and tangential stiffness. Considering the Mohr-Coulomb yielding surface, the peak force value $F_{T,lim}$ is calculated as:

$$F_{T,lim} = \mu \cdot F_N + F_0 \tag{1}$$

Where the μ is the friction coefficient, F_N the normal force acting in the link, $F_0 = c \cdot \lambda \cdot s$, c the cohesion, λ is the influence length in the direction parallel to the edge, and s is the thickness of the arch represented.

The shear stiffness is calibrated in function of the shear moduli of the brick and the mortar, and the actual thickness of the joint.

4 NUMERICAL SIMULATIONS OF TESTS ON MASONRY ARCHES

To evaluate the effectiveness of the proposed method, two experimental tests, one executed on a two-rings masonry arch with 3m span and one on a three-rings arch with 5m span, are numerically simulated (Melbourne & Wang & Tomor 2007). Both arches has the span-rise ratio of 4:1.The arches, built using high quality bricks and cement mortar, were pre-loaded using hydraulic jacks at ¼ and ¾ of the arch, each of which applies 10 kN for the 3m-span arch and 22.5 kN for the 5m-span arch. In the experimental tests the live vertical load is applied monotonically with load control at ¼ of the span and the vertical and horizontal displacement at the previously reported points are recorded. In the numerical simulation, permanent non-structural loads(G2) are implemented as concentrated forces meanwhile the live load (Q) is applied as imposed displacement to a single control point positioned at ¼ of the span considering displacement control, condition that permits to analyzing the post-peak behavior as resumed in the Figure 3. The meshes reproduce the actual number of rings and number of bricks utilized in the experimental tests. The numerical mechanical properties are calibrated on the materials properties obtained from previously citated work.

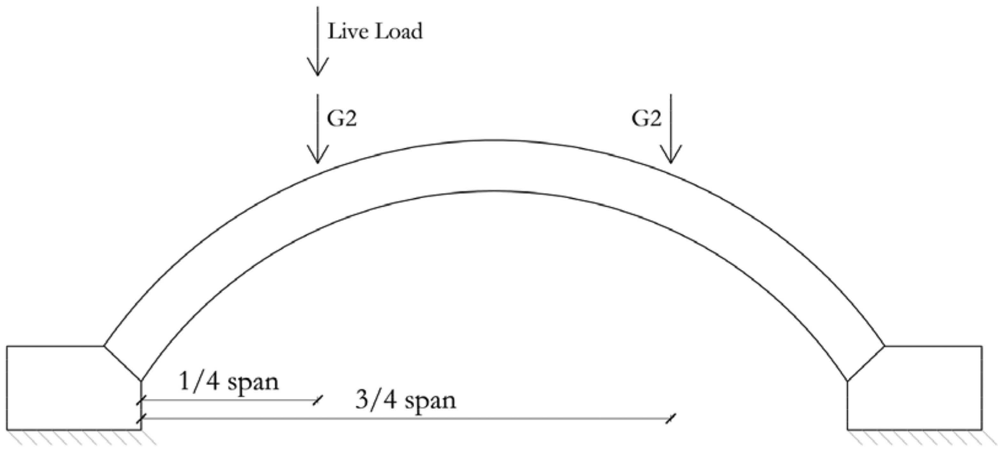

Figure 3. Test set-up.

The results are reported in Figure 4 and Figure 5, compared to the experimental findings, in terms of load-displacement curves, considering the vertical displacement of a point in the intrados in correspondence of ¾ of the span for the 2-rings arch and ¼ of the span for the 3-rings span.

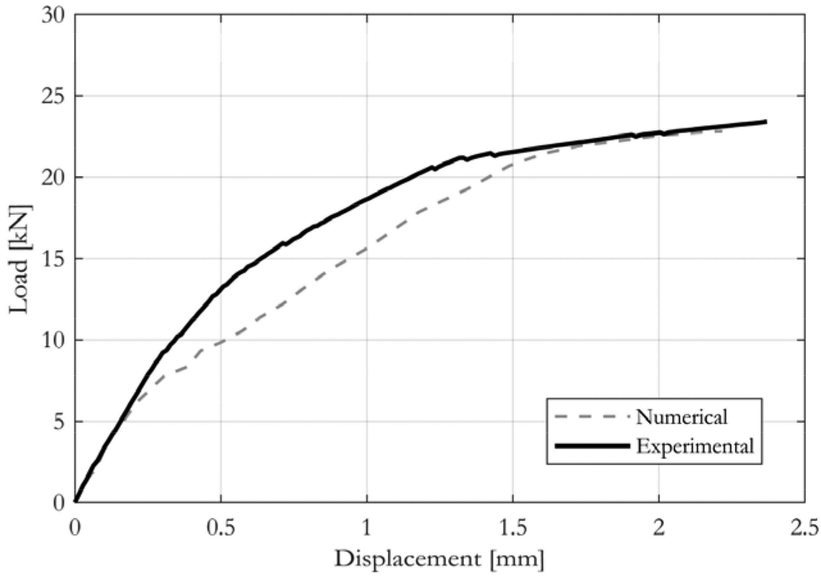

Figure 4. Comparison between the experimental and numerical results for the 2-rings arch.

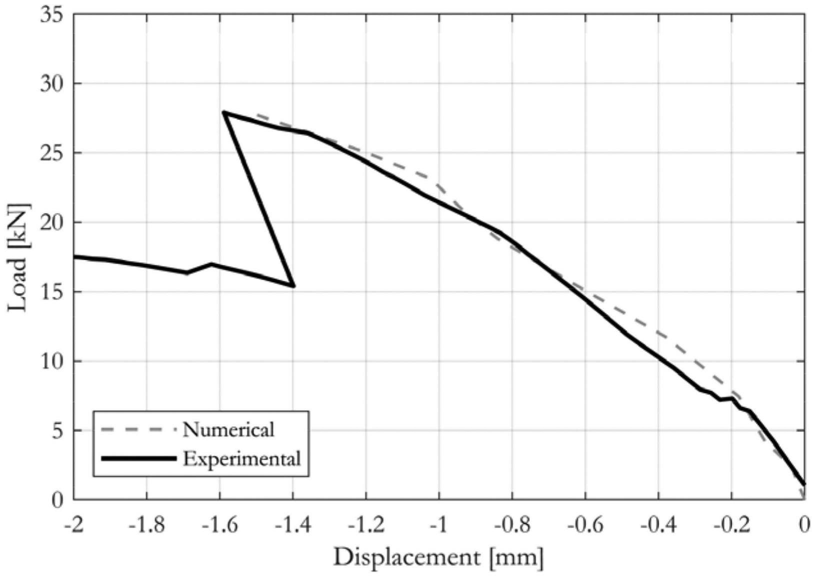

Figure 5. Comparison between the experimental and numerical results for the 3-rings arch.

5 DISCUSSION OF THE RESULTS

In the Figure 6 and Figure 7, the numerical deformed shapes are reported, in comparison with the experimental deformed shape for the 2-ring arch and a representation of the position of the 4 hinges for the 3-rings arch. The results highlight good correspondence between the numerical and the experimental tests in terms of peak load, initial stiffness and failure mode. In particular the first arch, with two brick rings, exhibit the typical 4-hinges mechanism, even in the highest hinge is diffuse and it is not assimilable to an unique crack. Neither the experimental and the numerical model present between-rings separation. The numerical capacity curve (Figure 4) approximates the experimental one especially in the initial and final part, reproducing the effective initial stiffness of the arch. The numerical test ends because of convergence limits. The 3-rings arch's exhibits a first phase in which it manifests the 4-hinges mechanism meanwhile the failure mode is governed by the shear/sliding mechanism between rings and between elements of the same ring. As presented in the deformed shape, the sliding between rings is the primary failure mode, at which result the sliding in the opposite direction. In the Figure 5 can be observed the well prediction of the model in terms of initial stiffness and degradation of the stiffness before the failure point. The peak load corresponds to the rings separation/sliding and the activation of the mechanism presented in the Figure 7, after which the load registered decreases in value.

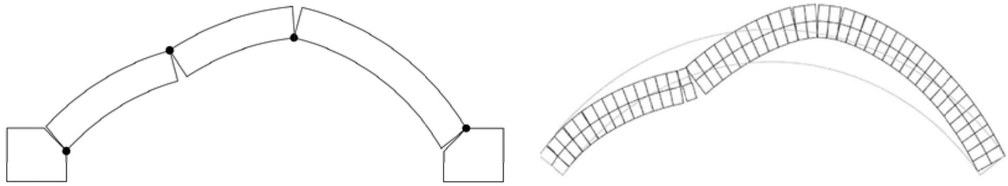

Figure 6. Failure mechanism of the experimental test for the 2-rings arch (left) and deformed shape obtained from the numerical model, considering an amplification factor of 50 (right).

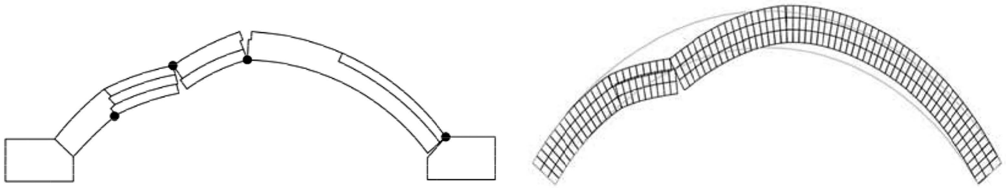

Figure 7. Failure mechanism of the experimental test for the 3-rings arch (left) and deformed shape obtained from the numerical model, considering an amplification factor of 50 (right).

6 CONCLUSIONS

This paper introduces a simplified numerical strategy for the simulation of the nonlinear in-plane response of masonry multi-rings arches. The geometry of the masonry is represented by a mesh of discrete elements, connected with links able to simulate the flexural and shear-sliding collapse modes typical of masonry material. The case studies present two typical failure mode of masonry arches, well reproduced in the numerical tests. In particular, the proposed model is able to reproduce the sliding between rings, failure mode not visible in the single-ring arches.

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