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EXPERIMENTAL AND NUMERICAL APPROACH TO THE ASSESSMENT OF THE DISSIPATIVE BEHAVIOUR OF A TUFF MASONRY ARCH SUBJECTED TO CYCLIC LOAD TESTS

Anna Castellano [1], Mariella Diaferio [2], Aguinaldo Fraddosio [1], Nataliia Pinchuk [1] and Francesco Salvatore Toscano [1]

[1] Department of Architecture, Construction and Design, Polytechnic University of Bari,
Via Orabona 4, 70125 Bari, Italy
e-mail: {anna.castellano, aguinaldo.fraddosio, nataliia.pinchuk}@poliba.it,
f.toscano1@studenti.poliba.it

[2] Department of Civil, Environmental, Land, Construction and Chemistry, Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy
e-mail: mariella.diaferio@poliba.it

Abstract

Masonry structures are the most widespread in southern European city centers, making seismic vulnerability reduction dependent on accurate prediction of their dynamic response. A major challenge in seismic analysis is understanding their structural capacity and dissipative behavior under cyclic loads, especially for curved elements like arches, vaults, and domes, which are common in historic buildings and frequently damaged by lateral forces during earthquakes. We propose an experimental study of a tuff masonry arch subjected to cyclic loading tests in order to evaluate the dissipative effects that occur during loading-unloading cycles. In particular, when the curved masonry structure begins the plasticization process, which involves the repeated opening and closing of cracks during cyclic loading, it does not collapse precisely because of its ability to dissipate energy. This dissipative behavior cannot be evaluated by commonly adopted static tests. Therefore, ad hoc cyclic tests have been performed to estimate dissipative effects of a curved masonry structure. We choose a cyclic test with vertical load which is effective for observing the dissipative effects produced by a horizontal dynamic load (such as an earthquake), which requires more complex and expensive experimental setup. The detailed and accurate nonlinear numerical model has been developed to describe the experimental behavior of the masonry arch and to model the reduction of the overall stiffness of the structure due to the activation of plasticization in arch joints.

Keywords: Tuff masonry, Arch structure, Cyclic tests, Dissipative effects.

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1 INTRODUCTION

Italy is a country steeped in ancient history and in architectural heritage, renowned for its remarkable collection of historic masonry structures, usually made from locally sourced materials. These materials not only contribute to the aesthetic and historical value of the buildings but also reflect the cultural and regional identity of the areas where they were sourced. In particular, the use of tuff, a porous volcanic stone, has played a significant role in the construction of numerous buildings particularly in the Apulian region. Tuff is highly valued for its workability, lightweight, and good thermal insulation properties, making it an ideal choice for the creation of buildings and structures for different purposes.

Some of the remarkable structural elements of the Italian masonry architecture are arches and vaults. One of the primary advantages of arches is their capacity to transfer compressive forces along the curve of the arch, which reduces the need for excessive material use and allows for the creation of larger openings without compromising structural integrity of the masonry constructions. Arches have proven to be a structural element capable of withstanding significant loads while maintaining a lightweight design (see the arches of Gothic cathedrals) and providing aesthetic appeal to arched structures.

The frequent occurrence of earthquakes in the Italian territory poses continuous challenges to the preservation and protection of masonry buildings [1-5] prompting research into an in-depth understanding of behavior under dynamic loading conditions. Masonry arches exhibit complex responses when subjected to cyclic loads, such as those caused by seismic events. The ability of arch and vaulted structures to dissipate energy during such loads plays a key role in determining their overall performance and stability. This dissipation of energy, known as dissipative behavior, helps prevent catastrophic failure by allowing the structure to gradually absorb and release the energy generated by external forces [6-8]. This characteristic is particularly important in seismic regions, as it allows masonry arches to withstand repeated dynamic forces without sustaining significant damage, thus extending the life span of these historic structures [9-10]. A dynamic behavior peculiar to multiblock masonry constructions is that of rocking. The study of the rocking dynamics of masonry columns, arches, and vaults can provide a better understanding of the dissipative capacity of these structural elements that have ensured the preservation over time of archaeological and architectural structures of considerable historical and artistic value.

The main focus of our research is to investigate the mechanical behavior of tuff masonry arches under cyclic loading, which is crucial for understanding their seismic performance [11-14]. In particular, the masonry arch was subjected to a vertical cyclic load test, useful for observing the same effects produced by a horizontal dynamic load (such as an earthquake), which is more difficult and onerous to simulate in the laboratory.

During loading cycles, energy dissipation occurs as the structure transitions from elastic to plastic behavior, manifesting in the opening and closing of cracks. This process cannot be captured in static tests, making cyclic loading an indispensable and effective method for assessing the energy dissipation capabilities of the arch and vault structures [15-22].

From the experimental data, a numerical approach was developed that could comprehensively study the dissipative behavior of the arch by implementing a damage model. Numerical results in terms of reduction of the overall stiffness of the structure as plastic deformations accumulate and in terms of hinge formation were compared with experimental results show the effectiveness of the developed approach.

2 EXPERIMENTAL CAMPAIGN

The experimental investigations were carried out at the Laboratorio Ufficiale Prove Materiali "M. Salvati" of the Polytechnic University of Bari. A full-scale circular arch was made of 15 trapezoidal blocks of Apulian tuff.

The mechanical properties of materials have been determined by mechanical tests in accordance with UNI standards. The compression tests were performed on six cubic tuff samples 430 mm x 240 mm x 150 mm and average mass density 1400 kg/m^3. Average compressive strength of the tuff bricks is f_{bm} = 2.25 MPa and the average Young modulus E_m = 637.39 MPa. Moreover, six prismatic samples of the mortar with nominal dimensions of 14 mm x 14 mm x 160 mm and average mass density 1883.98 kg/m^3 were prepared during the construction of the arch and were tested after 28 days of curing. As the results we have obtained the flexural strength f_{mf} = 1.91 MPa, the compressive strength f_{mc} = 8.94MPa and the average Young modulus E_m = 6902.27 MPa.

The internal radius of the arch is 80 cm, an external radius 104 cm, the thickness of the blocks orthogonally to the plane is 14 cm (Fig. 1). Twelve voussoirs, each cut from tuff blocks measuring 24 cm x 24 cm x 14 cm, were used to construct the arch, with two voussoirs shaped to serve as imposts. The keystone (voussoir 8), made at the near completion of the arch, had different dimensions to compensate for imperfections from the cut and mortar joint thickness.

The cyclic test was conducted in displacement control. Six displacement transducers (Fig. 1) were used:

- two on ashlar 10, where displacements will be induced;
- two on ashlar 6, in the direction symmetrical to the first, useful for measuring displacements in the horizontal and vertical planes;
- two at the two impost voussoirs of the arch, suitable for measuring displacements along the horizontal plane.

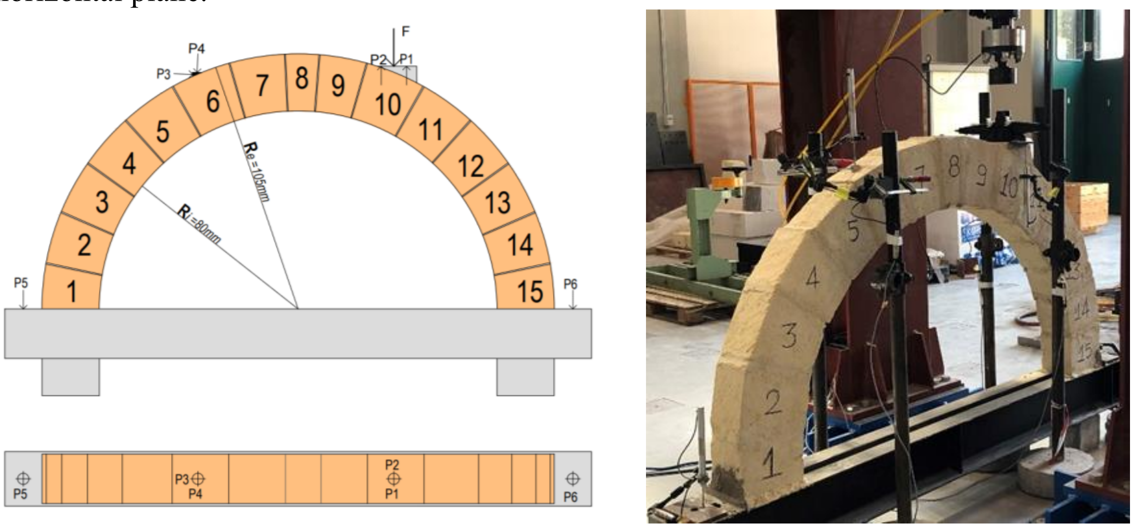

Figure 1: Geometric configuration of the arch and LVDT (P1 – P6) position.

A hydraulic jack and load cell with a capacity of 5 kN and a data acquisition system were used for load measurements, which enabled subsequent reprocessing of test data. A feedback system managed by LabView software was used to control the oil pressure in the hydraulic jack of the loading device, ensuring precise displacement control at a slow testing speed to minimize hydraulic instrument effects. For load distribution, a rectangular steel plate resting on a rectangular-section prism made of tuff, glued at the extrados of ashlar 10, was used.

The load was applied through 11 load-unload cycles with progressively increasing displacements, monitoring by visual inspection the formation of hinges, their opening and closing. The experimental test was conducted until the formation of four hinges, creating a collapse mechanism in the arch. The mechanism showed the classic behavior, with two hinges forming at the intrados and two at the extrados (Fig. 2). In the first five load-unload cycles, the arch exhibited elastic behavior; starting from the sixth load-unload cycle, the arch began to plasticize and crack at the joints due to hinge formation.

The first hinge (H1) appeared between voussoirs 9 and 10 at the intrados during the sixth cycle (C6), followed by a second hinge (H2) at the extrados between voussoirs 4 and 5. The formation of H2 led to a slight load reduction before the unloading phase began (Fig. 3). During the seventh load cycle (C7), the opening of joints corresponding to hinges H1 and H2 was observed again. At a load of approximately 1210 N, new fractures appeared between voussoirs 2-3 and 13-14, forming the remaining two hinges, H3 and H4, symmetrically. In the eighth cycle (C8), at a peak load of 1310 N, all four hinges fully opened. The failure load, calculated using the kinematic limit analysis theorem according to Heyman's assumptions, was 995.2 N, which closely corresponds to the load following the peak of the last cycle, indicating significant damage and significant reduction of the already limited tensile strength of the masonry. In the final load cycles (C9 to C11), the peak load progressively decreased. Additionally, residual displacements at full unloading continued to grow. In the last cycle (C11), the peak load reached about 1090 N at a displacement of 3.33 mm, but as the displacement increased to 6.2 mm, the load dropped to 940 N. The test was stopped as further displacement would have caused the arch to collapse.

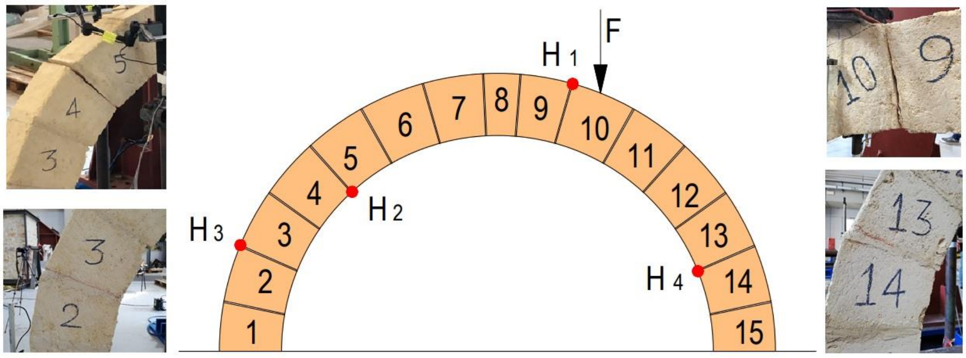

Figure 2: Hinge sequence.

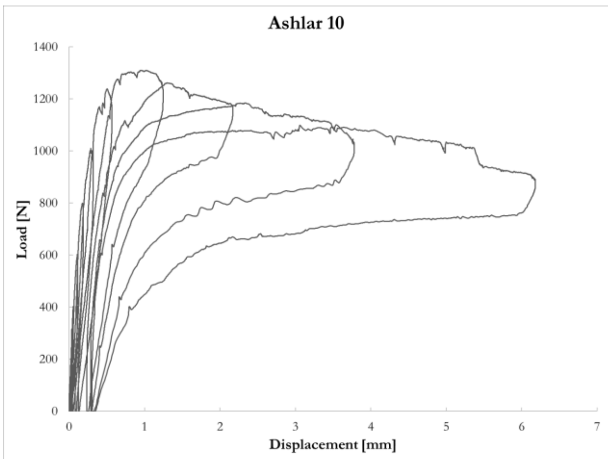

Figure 3: Load-displacement curves related to experimental data of the ashlar 10.

3 NUMERICAL MODEL

A numerical model aimed to study the dissipative behavior of masonry arch during the cyclic tests was developed by using ABAQUS software. The behavior of the arch was simulated using the discrete element modeling proposed in [23-25] where the arch was discretized into three elements: blocks, mortar and interfaces. The ashlars and mortar are modeled with continuous elements while the block-mortar or block-arch support interfaces are discontinuity surfaces. According to the characteristics of the experimental model, the numerical arch consists of 15 voussoirs and 14 mortar layers with the same dimensions of the real arch. Since the analysis time is directly dependent on the complexity of the geometry, the “2D Planar” modeling approach was chosen, using “Shell” elements.

As experimentally observed, since fractures (and hence hinges) are generated in the mortar joints, the ashlars have been modeled as elastic elements while the mortar was modeled as a nonlinear element described adopting an appropriate criterion called “Concrete Damaged Plasticity” (CDP model) which considers the reduction of the elastic stiffness induced by the plastic deformation during the cyclic tests [26]. The CDP model originally was developed to catch the non-linear behavior of brittle material as concrete but can also be effectively applied to describe the behavior of masonry structures. Here, the uniaxial constitutive relationships address a parabolic softening under compression, and a linear softening in tension (Fig. 4). The non-linear behavior in tension is described through the introduction of a reasonable fracture energy, in order to avoid mesh sensitivity peculiar to a stress-strain input [27].

A crucial role for the numerical study of the damage of the arch under the action of cyclic loads was assigned to the introduction of a damage parameter (d_t) that simulates the loss of stiffness of the mortar observed during the experimental program. In particular, according to the approach proposed in [26] it was possible to calibrate the variation of the mortar damage parameter as a function of the experimental displacement steps induced at the arch.

As suggested by the model [27], the adopted mesh consists of “Shell” elements with four nodes, where each node has two degrees of freedom and a defined dimension. The element shape is “Quad-dominated” (quadrilateral), and the technique is “Structured,” generating meshes following the geometry of the individual parts. A finer mesh was chosen for the mortar joints to obtain a more detailed solution, with a 1:2 ratio between the elements of the tuff blocks and the mortar. This decision also takes into account that the reliability of the solution is influenced by the number of elements at the block-mortar contact surfaces.

The final step involved defining the interface constraints to ensure that each block and each joint are properly constrained from one to another. The “Tie” constraint was used. Additionally, the discretization method Node-to-Surface was used, as it reduces the risk of element penetration during deformation. The Tie constraint was adopted from the model by [26].

The numerical analysis was performed by eight different steps until to experimental maximum load. This choice is justified by the observation during the experimental program that the stiffness showed a significant reduction once the peak load was reached [27]. Moreover, to simulate the application of displacements on block 10, a yielding was introduced at a node with a range of values obtained by the experimental testing.

It is emphasized that each analysis step starts from the previous condition, that is, from a deformed configuration of the arch due to the imposed loads and displacement.

At the end of the numerical simulations, the obtained results were compared with the experimental ones. For brevity, the numerically load-displacement graphs for each cycle are omitted, which show how the numerical model overestimates the maximum load. Instead, a comparison is made between the global stiffnesses of the arch obtained numerically at each load cycle and those obtained experimentally (Fig. 5). It can be observed that the stiffness values recorded for each cycle in the numerical model are higher than those obtained experimentally. This confirms the previous hypothesis, as the numerical model appears stiffer and thus capable of reaching a higher load value for the same deformation [28].

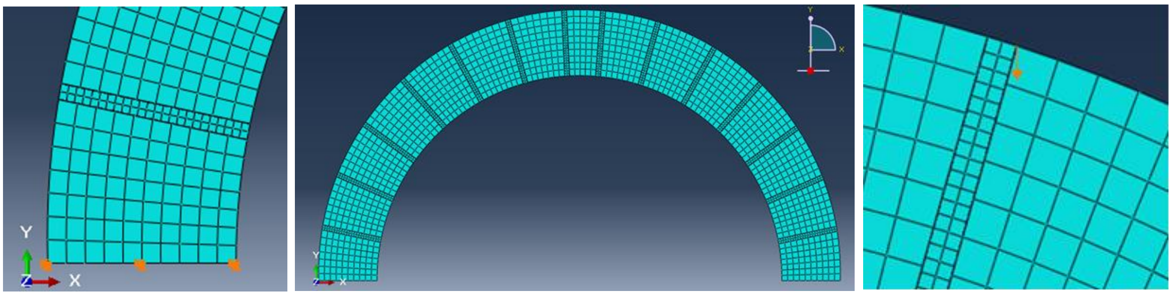

Figure 4: Details of the numerical model: geometry of the arch, displacements boundary conditions.

Furthermore, as shown in Fig. 6, the percentage of stiffness loss in the experimental model is greater than the loss observed in the numerical model, further confirming the higher stiffness of the numerical model. This suggests that the numerical model better retains its rigidity throughout the loading cycles compared to the experimental setup.

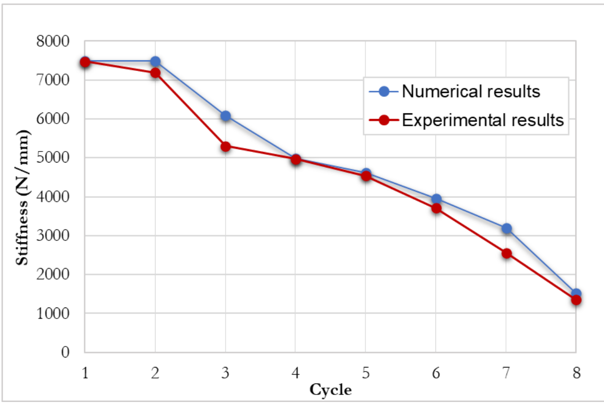

Figure 5: Comparison of stiffness value for each cycle obtained by the experimental tests and by the numerical model.

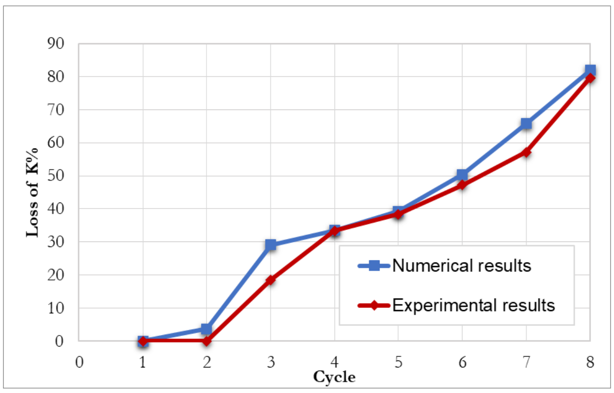

Figure 6: Comparison of stiffness loss percentage related to the experimental and the numerical results.

4 CONCLUSIONS

The proposed experimental and numerical approach allowed to evaluate the dissipative effects of a tuff masonry arch subjected to cyclic load tests. In particular, it was possible to experimentally observe this behaviour thanks to a vertical cyclic load test, more easily achievable in the laboratory compared to a test with horizontal cyclic load that would require a more complex setup. Despite the formation of cracks at the interface of the ashlars, the arched structure does not collapse precisely thanks to its ability to dissipate energy.

The numerical approach that uses the CDP model and the loss of stiffness induced by plastic deformations was able to reproduce the behavior observed experimentally although slightly overestimating both the maximum load and the global stiffness. We are proceeding to refine the conditions of the numerical model to better capture the experimental aspects.

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