2025 IMEKO TC26 International Conference on
Metrology for Archaeology and Cultural Heritage
Bergamo, Italy, October 15-17, 2025

Experimental investigation of a masonry arch subjected to an asymmetric concentrated vertical load and validation via static and kinematic limit analysis

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***Abstract* – This paper presents an experimental study on the structural response of a 1500-mm span masonry arch subjected to self-weigh and an asymmetric concentrated vertical load increased up to failure. The arch is tested under controlled conditions, with steel plates installed at the springing to prevent parasitic sliding and ensure realistic boundary constraints. Displacement transducers (LVDTs) are strategically positioned to monitor vertical and horizontal displacements at selected points. The experiment allows for a direct observation of the evolution of the failure mechanism up to collapse, characterized classically by the formation of four plastic hinges. A simplified numerical validation is conducted using both static and kinematic limit analysis approaches, each based on Heyman's no-tension assumptions. The static analysis relies on the construction of a funicular polygon, while the kinematic one is developed according to the principle of virtual work pre-assigning the position of the four hinges. The analytical results, while not introducing novel methodologies, served to verify the consistency of the observed failure mechanism and the collapse load predicted experimentally. The study contributes to a better understanding of the experimental behavior of masonry arches under the application of non-symmetric point loading, providing a benchmark dataset to support future strengthening interventions with innovative reinforcement techniques and to validate numerical models for the structural assessment of heritage masonry.**

I. INTRODUCTION

Masonry arches and vaults represent some of the most iconic and structurally efficient forms in historical constructions, widely diffused throughout Europe and particularly in Italy. These elements have been employed for centuries in bridges, religious buildings, and civil architecture due to their capacity to span large rooms and carry considerable gravitational loads with relatively limited use of material [1]-[8]. According to Heyman's hypotheses for masonry, arches behave as an NTM (no-tension material) with infinite compressive strength and zero tensile resistance. In such circumstances, an arch does not collapse under the geometric requirement that the line of thrust must remain entirely within the masonry thickness [9].

However, despite the generally good structural performance of arches in carrying properly gravity loads, excessive or asymmetric point forces [5], foundation settlements [10], or horizontal actions such as earthquakes may lead easily to the triggering of collapse mechanisms, typically through the formation of four/five-hinges [1]-[3], [5], [8]-[10].

Although historical construction practice relied on the use of empirical rules of thumb and accumulated experience, recent research efforts have benefited from experimental investigations aimed at characterizing the failure modes and structural response of masonry arches under controlled conditions [2]. These tests, often conducted on small- or full-scale models, have revealed key insights into how masonry arches deform and collapse under various loading conditions, including eccentric and asymmetric forces that replicate more realistic scenarios.

The characterization of the unreinforced behavior of masonry arches is not only of historical and theoretical interest but also crucial for practical applications such as the structural assessment of heritage buildings and the validation of simplified and advanced numerical models. As noted in [11], the study of failure mechanisms in un-strengthened arches remains a necessary benchmark for interpreting the efficacy of both traditional and innovative interventions. Moreover, as shown in [12], the position and direction of applied loads significantly influence the collapse mechanism, underlining the importance of tailored experimental setups that mimic realistic conditions.

Several authors have contributed to the development of experimental protocols and analytical tools to determine the ultimate bearing capacity of masonry arches. In [1], numerical simulations based on a lower bound limit analysis approach and no-tension assumptions were used to evaluate the load-bearing capacity of curved masonry structures. Similarly, the FE (Finite Element) method proposed in [3] highlights the relevance of combining experimental observations with theoretical models based on simple approaches to put at the disposal of designers dealing with the assessment of such architectural elements.

Despite the wealth of literature on the retrofitting of arches and vaults with composite materials [1]-[3], there is still a need for dedicated investigations focusing solely on unreinforced configurations. Such studies serve as critical baselines for comparison, allowing researchers and practitioners to determine the residual capacity of masonry elements prior to any intervention. As stated in [11], a good understanding of the mechanical behavior of un-strengthened arches subjected to point loading conditions remains a key step for assessing both safety and the potential benefits of reinforcement.

In this context, the present work aims to contribute to the existing knowledge in the field, by presenting a preliminary result of a laboratory experiment conducted on a real-scale masonry arch subjected to an asymmetric concentrated vertical load. The experimental setup included the use of steel plates at the abutments to prevent parasitic sliding, and the application of several displacement transducers (LVDTs) strategically positioned to monitor vertical and horizontal displacements across the arch. The collapse mechanism observed was classically formed by four flexural hinges, and the ultimate load was compared with the results obtained via the application of both a static and a kinematic limit analysis, assuming for masonry Heyman's hypotheses. Although the numerical validation does not aim to introduce new methodologies, it confirms the reliability of the theoretical framework when compared with real experimental data.

The study is part of a broader effort to achieve a more comprehensive understanding of the behavior of masonry arches prior to the application of reinforcement and serves as a foundational step for future experimental campaigns aimed at evaluating the performance of innovative strengthening systems under common loading conditions.

II. EXPERIMENTAL SETUP AND RESULT

The experiment was conducted under controlled conditions in the laboratory of the University of Florence and involved a full-scale masonry arch. The arch, composed of 49 blocks, had a radius of 1500 mm and was constructed using standard Italian bricks (250 × 120 × 55 mm^3) arranged radially, as shown in Fig. 1.

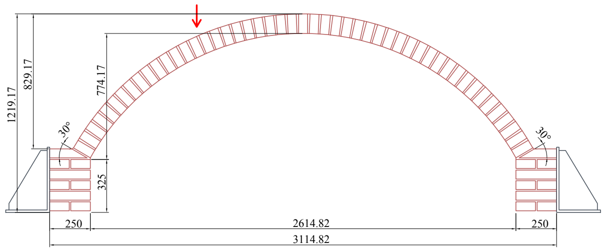

Fig. 1. Geometrical characteristics of the laboratory-tested arch.

The arch was supported by two masonry spandrels, which in turn rested on two steel plates anchored to the ground with steel bolts to prevent unintended sliding (see Fig. 1 and Fig. 2).

Fig. 2. Setup preparation.

The arch was loaded vertically in an asymmetric configuration, with a point load applied approximately at one-third of the span from the left side (as shown in Fig. 1 and Fig. 2). To measure vertical and horizontal displacements, seven LVDTs were installed on blocks 10, 15 (under the point of application of the concentrated force), 21, 29, and 40, as indicated by the crosses in Fig. 3. All sensors recorded vertical displacements, while those placed on blocks 10 and 40 also measured horizontal displacements.

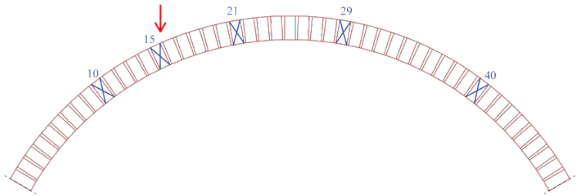

Fig. 3. LVDT positions (blue crosses) and applied load location (red arrow).

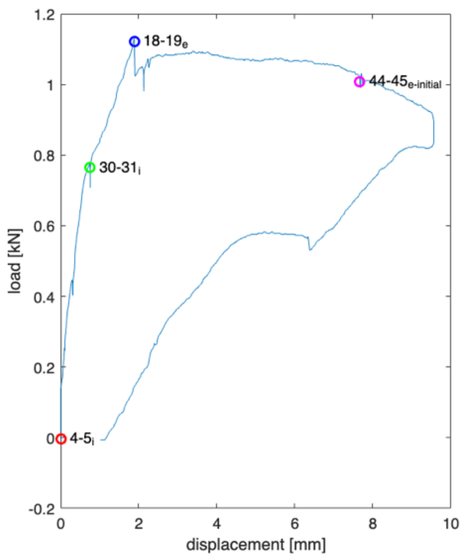

Fig. 4. Force–displacement curve, with the formation of plastic hinges marked at specific block interfaces.

The force-displacement curve obtained experimentally is shown in Fig. 4. The points at which plastic hinges formed are indicated on the curve, along with an indication of the involved mortar joint (e.g., between blocks 30 and 31). The letters *e* and *i* denote extrados and intrados, respectively. The maximum load reached during the test was 1.13 kN, while the ultimate load recorded was 1.01 kN.

For the sake of clarity, in Fig. 5 the hinge positions are depicted with the same colours used in Fig. 4.

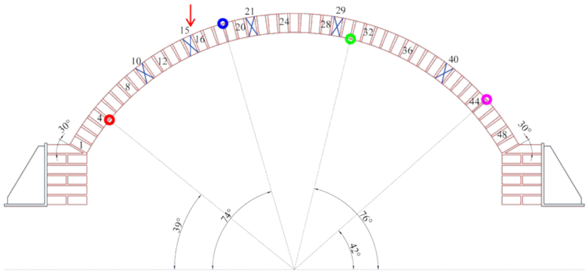

Fig. 5. Failure mechanism observed. Flexural hinge positions are indicated with coloured circles as per experimental data.

III. KINEMATIC LIMIT ANALYSIS

To provide a rapid but effective validation of the experimental test, two simplified computational tools were developed using GeoGebra. The first tool implements the static theorem of limit analysis and imposes equilibrium brick by brick through the construction of a funicular polygon (or line of thrust), allowing the user to check whether it is possible to identify, within the infinity family of equilibrated thrust lines, at least one that lies within the thickness of the arch, as illustrated in Fig. 6. This method is particularly useful to verify admissibility conditions under Heyman's assumptions, and provides in this case a collapse load of about 0.69 kN.

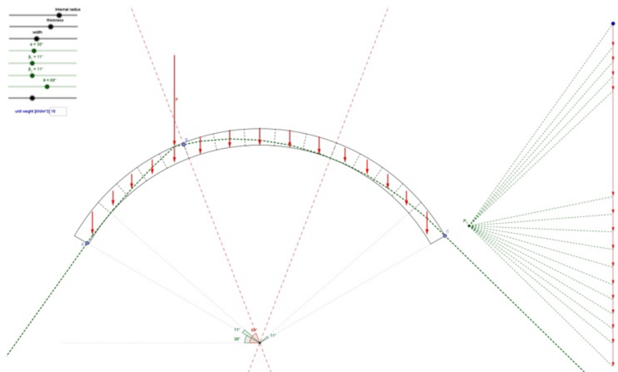

Fig. 6. Interface of the static approach implemented.

The second tool is based on the kinematic theorem of limit analysis and applies the principle of virtual work on mechanisms formed by four flexural hinges whose position is arbitrarily selected, to estimate the collapse load associated with the triggering of such failure mechanism. By discretizing the structure into three macroblocks and defining the position of the hinges, it is possible to graphically determine the displacement field. Then, applying the principle of the virtual works, it is possible to deduce the collapse load. With the position of the hinges found statically, see Fig. 6 and Fig. 7, the ultimate load found is again equal to 0.69 kN.

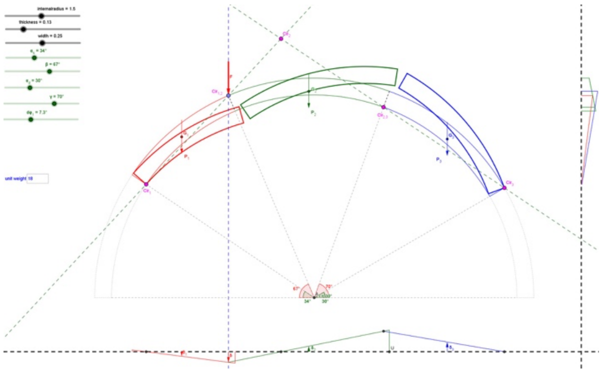

Fig. 7. Interface of the kinematic approach implemented.

The difference between the experimental result and the numerical predictions, which amounts to approximately 31%, can be attributed to the fact that the analytical procedure does not account for the tensile strength of the mortar, which is not negligible in this case. Future work will focus on developing more advanced numerical approaches capable of incorporating this tensile capacity, thereby improving the accuracy of the simulations.

These interactive models allow for parametric control over key variables – such as geometry, self-weight, and load position – and provide valuable insight into the structural behaviour of the arch. While they are not a substitute for detailed numerical simulations, they offer an accessible and visually intuitive means to support both the interpretation of experimental results and the preliminary reinforcement design or assessment of masonry arches.

IV. CONCLUSIONS

This study presented a combined experimental and analytical investigation of the behavior up to the failure of a full-scale masonry arch subjected to an asymmetric concentrated vertical load. The experimental campaign carried out under controlled laboratory conditions, allowed for a detailed observation of the structural response up to collapse, with particular attention to the formation of plastic hinges and the evolution of the failure mechanism.

The test confirmed the development of a four-hinge mechanism, in line with the classical collapse behavior predicted by Heyman's theory. The experimental evidence highlighted how the asymmetry of the applied load significantly affects the position of the hinges and the overall stability of the arch, causing early activation of concentrated inelastic phenomena on one side of the structure. The recorded displacement data – both vertical and horizontal – allowed for a precise identification of the sequence of formation and location of the flexural hinges, offering a clear insight into both the formed failure mechanism and the arch ultimate load-bearing capacity.

The force-displacement curve showed a peak load of 1.13 kN and a final collapse load of 1.01 kN, indicating the progressive development of a failure mechanism characterized by increasing deformation with limited load reduction. This behavior, often observed in unreinforced masonry systems, provides useful information for assessing safety margins and understanding warning signs prior to collapse.

The analytical validation through static and kinematic limit analysis, based on the assumption of rigid blocks connected by joints unable to withstand tensile stresses, showed good agreement with the experimental results. The collapse multipliers obtained by means of the theoretical models were consistent with that experimentally observed, confirming the reliability of Heyman's theory even when applied to real-scale arches in which the tensile strength is not negligible. The manual approaches served also as a valuable tool for interpreting the observed failure mode.

Overall, the integration of experimental data and simplified analytical modelling highlights the importance of a dual approach for the study of historic masonry structures. While numerical methods continue to evolve, analytical tools, such as those based on the static and kinematic theorems of limit analysis remain essential for rapid assessment and validation. Furthermore, the experimental results presented here serve as a benchmark for future investigations, including both numerical modeling and testing of reinforced configurations.

This work contributes to the broader effort of preserving masonry heritage by improving the understanding of the behavior of unreinforced masonry arches and by offering a reference for evaluating the efficacy of possible strengthening interventions. In this regard, future research will extend this work by developing advanced nonlinear numerical models and by testing the effectiveness of innovative strengthening with composite materials.

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