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Experimental and numerical investigation of the collapse of pointed masonry arches under quasi-static horizontal loading

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ABSTRACT

Pointed arches can exhibit a relevantly different behaviour from circular arches when subjected to horizontal actions. This paper considers the response of 11 reduced scale, dry-block pointed arches with varying geometry subjected to tilt tests. Crossed comparison between experimental and numerical results with variations in sharpness and thickness of models highlighted the sliding-governed response of a subset of samples. Thus, a novel, simplified, two-bar model, which assumes free sliding at the keystone interface and tackles the behaviour recorded during tests, is proposed. Moreover, the values of load multipliers obtained using limit analysis are compared to results from DEM modelling of the tilt tests. Finally, the sensitivity of the lateral response to the friction coefficient is carried out through DEM to define the sliding - hinging domain for possible geometric variations of pointed arches.

1. Introduction

Vulnerability of curved masonry structures has motivated the development of safety assessment methods - controlling equilibrium or stability, which have been used for centuries [1–6]. Recently, the response of masonry arches to horizontal loads has gained significant attention both due to an increased concern for protection of cultural heritage and to enhanced computational power.

For equivalent static loading, limit analysis as formulated by Heyman [7–9], is widely acknowledged as effective for the investigation of masonry arches. In this framework, the earthquake action is considered as a set of inertial forces proportional to self-weights and affected by a multiplier, whose value provides a reliable safety estimation as proposed in [10], where authors perform preliminary FEM analyses to fix the position of the hinges for the arch-pier system. In [11], the load multiplier and the related positions of hinges are simultaneously detected imposing stationarity of potential energy. Recently, in [12,13] the lateral capacity of an arch is determined through limit analysis with a lower bound approach taking into account possible geometrical uncertainties of the profile, and in [14] assuming a reduced ring-thickness caused by the damage level. With an upper bound approach, in [15], both buttressed and ring circular arches subjected to horizontal loads are examined; predictions of the minimization algorithm are compared to analytical and experimental results from other authors. Based on a similar iterative procedure, in [16] collapse load multipliers of pointed arches are investigated besides circular and basket-handle profiles including also the presence of a slender abutment.

For the response of circular arches to horizontal and time-varying acceleration inputs, this is addressed firstly by Oppenheim in [17] wisely applying the well-known dynamics of the four-bar linkage to the masonry arch and by Clemente and co-authors in [18] pivoting on the equation of virtual powers to gain a thorough sensitivity analysis. After [17,18], several studies that assume rigidity of masonry and exploit Limit Analysis, Discrete Element Modelling, Non-Smooth Contact Dynamics, Discontinuous Deformation Analysis or a combination of these, have been published. The dynamical system of a hinging arch, as proposed by Oppenheim [17], and which assumes a time-varying acceleration as input, is refined and enriched in [19–21], where a proper impact law, indispensable when considering a change in the direction of ground acceleration, is defined. Recently, it is shown in [22] that a non-uniform geometric profile sensibly affects the dynamic response of circular masonry arches even for basic inputs.

Pivoting on the assumptions of non-smooth contact dynamics, i.e. conceiving masonry arches as made of rigid blocks with unilateral constraints, in [23] an analytical model, previously applied to the rocking block problem, is proposed for the study of arches. In [24,25], exploiting the open-source code LMGC90, also based on NSCD, the dynamics of circular arches of stone masonry ruins belonging to cultural heritage and subjected to acceleration inputs is investigated.

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As regards non-circular arches, e.g. onion shaped, ogee, four-centred and semi-elliptical, these are investigated through FEM analyses in [26] focusing on the problem of in-plane buckling, and in [27] with the aim of evaluating the response for specific time histories. Only a few works address the analysis of pointed arches resulting from the composition of two circular arcs.

In [28], minimum ring thickness and extremal values of thrusts induced by vertical point loads at keystone or at haunches, or by relative displacements of abutments are investigated for a set of pointed arches with changing geometry. In [29], the response of a simplified model representing a pointed arch bearing a masonry wall is compared with similar systems but made of circular and elliptical arches. Strain and stress distributions at collapse are evaluated using 1-D non-linear elastic analysis under the assumption of a perfect elastic-plastic constitutive relation. Load bearing capacities are compared against those obtained through the graphical method of the stability area. According to [28,29], pointed arches withstand greater thrusts and abutment displacements than circular arches for a given span and ring thickness.

Regarding the response of pointed arches to horizontal actions, in [14] exploiting Limit Analysis with a lower bound approach, the horizontal load multiplier and the collapse mechanism are evaluated for a set of circular and pointed arches of varying geometry. Four nominal collapse modes are defined in [12] according to variations in thickness and in the embrace angle, i.e. angle subtended by the mechanism; although for embrace angles found in real architecture, the hinging collapse mode is unique. Results proposed are experimentally validated on a circular arch and a pointed one, finding good agreement between estimations and evidence. Estimations, in terms of collapse load multipliers of pointed arches, offered by the analytical model presented in [16] are compared to predictions of DEM. Results show that for real architectural shapes, i.e. embrace angle equal to 180°, pointed arches are more stable than circular arches with the same span and that an “optimal ratio” in ring thickness is recorded for a given sharpness ratio.

The model proposed in [30] by the authors for the pointed arch, differently from [12,16], is based on the closed form definition of the discontinuous curvature of the profile and an upper bound approach. Thus, no assumption on block discretization is made, and any iterative procedure is avoided, since a global non-linear optimization is carried out using virtual works to determine the minimum value of the load factor.

In this paper, the response of pointed arches under equivalent static loads is investigated with the aim of highlighting main differences between the predictions of the analytical model proposed in [30] and the outcomes of an extensive experimental campaign that addressed 11 geometrical variations of the profile. Given the outcomes of the experimental campaign, a novel kinematic model, capable of capturing the sliding-driven response recorded during tests for a subset of samples, is proposed and compared with estimations offered by DE models representing reduced scale arch models.

The rest of the paper is organised in five sections: a summary of the results of the experimental campaign are reported in Section 2; then, estimations of the minimization problem connected to the hinging response are presented in Section 3. Section 4 is dedicated to the analytical models employed to interpret test results. Finally, the results of DE modelling of tilt tests and conclusions are presented in Sections 5 respectively.

2. Experimental campaign

2.1. Specimens and tilt test apparatus

The experimental campaign considered 11 reduced scale (1:10 ratio) models of pointed arches that are showed in Fig. 1. Specimens were built in autoclaved aerated concrete (AAC), which can be easily cut into blocks with a circular saw, and the scaffolding, made from extruded polystyrene panels, was shaped with a hot wire XPS cutter table, Fig. 2a.

Arch models have a fixed mid-line span $s = 2R_c = 400$ mm, where R_c is the radius of a circular arch with the same span s, and varying rise and thickness, Fig. 3a. Models were shaped starting from two arcs of a circumference with centres placed symmetrically on the springing line. Eccentricity, e, which measures the distance between the symmetry axis and the centre of the circumference defining each semi-arch, Fig. 3a, was varied to create three classes of *Sharpness*, $Sh = e/R_c$. Thickness, t, was ranged into four classes of *Slenderness*, $Sd = t/R_p$, where $R_p = e + R_c$ is the radius of the pointed arch evaluated on the mid-line. Values assigned to Sh are 0.2, 0.6 and 1 and values chosen for Sd are 0.1, 0.15, 0.2, 0.25 (the specimen with $Sh = 0.2$ and $Sd = 0.1$ was not built).

Each model includes 17 blocks, i.e. 16 voussoirs and the crown block, Fig. 1, and for a given *Sharpness*, the width of the voussoir block and the rise of the model reduce increasing thickness, t, which ranges from 32 to 100 mm, according to the Sh and Sd classes.

Models shown in Fig. 1 have been accommodated so as to represent a stone pointed arch as represented in Fig. 3b, thus blocks adjacent to the key stone were glued together. Table 1 synthesizes block characteristics for each specimen.

Tilt test simulates the equivalent horizontal static force that a ground acceleration can cause to a structure. The test involves increasing the inclination of the base plane of the model up to collapse. Hence, during the test the specimen is subjected to both a vertical and horizontal action. The apparatus of the test, Fig. 2b, consists of two hinged wooden tables (0.8 m × 0.2 m × 0.02 m) on which the arch rest on. The tables are connected through a threaded rod that can spin on a hex nut fixed in the thickness of the upper wooden table, so that spinning the rod causes the upper table to tilt; a cup nut was screwed on the end of threaded rod, resting on lower table, to allow lateral sliding of the rod itself during the test. In addition, abrasive paper glued on the upper table prevented sliding at the springing level.

Each test was repeated three times and video recording at a sampling of 200 shots per second enabled the detection of the failure instant and the collapse mechanism, represented in Fig. 4. Results in terms of average collapse multiplier values and related coefficient of variation, are reported in Table 1 and Fig. 5.

To evaluate the experimental collapse multiplier, it was necessary to relate the inclination angle with its tangent; thus, a reference distance on the upper wooden table was marked, then, at test end, the inclination of the table was identified measuring abscissa and ordinate of the reference point with respect to the pivoting point, coincident with hinge axis.

2.2. Tilt test results

From screenshots of tests reported in Fig. 4, it is possible to highlight that two different collapse modes can be identified. The first is the hinging response, typical of shallower and slender specimens, i.e. those with lower values of Sh and Sd; this collapse layout is clear from Fig. 4a, b, c, d, e, g, h and i. The hinging response is the collapse mode associated with circular arches in which four alternate hinges form and a one degree of freedom four-bar mechanism can be defined. Specimens collapsed according to the hinging layout are identified with an H in Table 1.

Besides the hinging response, another distinct response was recorded, as shown in Fig. 4f and j. For these two specimens, i.e. Sh06Sd025 and Sh1Sd025, failure was triggered by the formation of minor hinges and a sliding interface, indicated by arrows in Fig. 4f and j. Sliding occurred mainly and visibly along the first interface free to move, while further hinging and sliding phenomena, although visible only comparing zoomed-in video frames, occurred along both macro-elements of the arches. The two specimens underwent sliding response are marked with an S in Table 1.

Table 1 also reports, for specimens marked H, the angular position