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Failure modes prediction of masonry voussoir arches on moving supports

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ABSTRACT

This paper reports numerical and experimental investigations carried out to analyse vulnerability of masonry voussoir arches when subjected to soil settlement. A novel numerical procedure aimed at predicting collapse layout and limit settlement is here presented. To identify the location of the three hinges that open when the settlement triggers, a procedure based on combinatorial analysis is exploited together with both static and kinematic analysis. In the framework of finite displacements, the limit settlement of an arch is also found checking equilibrium at every step increase of the settlement.

Good agreement is found between experiment results provided by reduced scale arch models, made of blocks of PVC and subjected to a horizontal or vertical settlement of the left support, and numerical predictions.

Furthermore, a sensitivity analysis has been carried out in order to assess the trend of the limit settlement in relation with ring thickness and number of blocks. Results show that the limit settlement for spreading supports is independent from the number of blocks for a given angle of embrace.

1. Introduction

Conservation of historical masonry buildings belonging to the cultural heritage is a crucial challenge for the scientific community, deeply committed to refining proper safety assessment methods. The most severe hazards threatening these buildings are often sudden and catastrophic (earthquakes, floods, landslide). However, differential settlement of foundations is as worrying given the frequent occurrence and the natural development of this hazard, which can induce significant displacements and the opening of deep cracks over time.

Such a response can be effectively modelled in the framework of limit analysis assuming a no tension material, as firstly proposed in [1,2] and widely exploited in recent years [3–30] as a valid and acknowledged tool alternative to those assuming an elastic response of masonry structures, [31]. In particular, in the framework of limit analysis, the response of arches subjected to different static loading conditions [3–12] and to inertial actions exerted during seismic events [13–21,32] have been broadly considered.

The response of arched structures, schematized as systems constituted by rigid blocks, has been investigated with particular attention to minimum ring thickness necessary to bear inertial loads in [13]. In recent years, significant research efforts have been put on investigations related to arched structures. For example, specifically designed investigation tools [33–39] as well as effective strengthening strategies, such as those making use of composite materials [22–28,40–43], are the object of extensive research.

As regards to investigations on the response of arches on moving supports, fewer works exist in the literature. Supports settlement of block arches is considered in the experimental campaigns reported in [9,26,31,44–46]. Both experimental campaigns, [44–47], and observations on real case studies, [48,49], permitted the identification of the phenomenological response of arches subjected to settlement of supports. In particular, if one or both supports settle three fractures at block interfaces open abruptly. The increase in the amplitude of settlement causes collapse when the thrust line becomes tangent to the profile of the arch in a further section.

In [45–47], in addition to a wide experimental investigation on reduced scale models, a novel computing procedure, based on the thrust line analysis, has been proposed to evaluate the minimum horizontal displacement necessary to cause the failure of circular arches composed of rigid blocks. Major results report that hinges can also change their positions if significant geometrical deformations are considered.

To identify the position of the three hinges that occur when an infinitesimal settlement triggers, methodologies based on the static theorem or on the kinematic theorem of limit analysis can be applied, [48,49]. In particular, among all statically admissible arches, i.e. structures equilibrated because the thrust line lies within the profile of the arch, the static theorem of limit analysis has been demonstrated to be capable of identifying the structure with the lowest value of the horizontal reaction of the moving support (i.e. lowest value of thrust).

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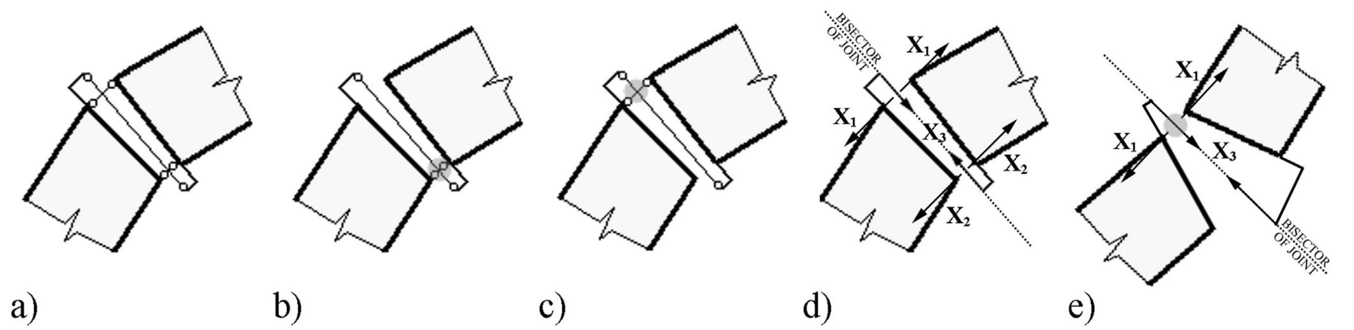

Fig. 1. (a) Interface type 1, uncracked; interface type 2: (b) cracked with intrados hinge and (c) extrados hinge; (d) axial and tangential forces transmitted at interfaces (bisectors of joints) in the undeformed configuration and (e) in the deformed configuration in correspondence to a hinged joint.

Vice-versa, among all kinematic compatible arches, the kinematic theorem has been demonstrated to be capable of identifying the structure with the highest value of the horizontal reaction of the moving support (i.e. highest value of thrust). Thus, according to both theorems, the only limit solution must satisfy both admissible equilibrium and compatibility of constraints.

In [50], circular arches on elastic supports subjected to both vertical and horizontal loads are analysed to compute their minimum thickness. In [51], with a kinematic approach, finite horizontal displacements and related maximum thrust value that bring an arch to collapse are the focus of a numerical investigation carried out on circular arches, represented through a continuous model and subjected to self-weight. In [52] with a similar approach, different layouts for settled constraints are considered and estimations offered by limit analysis are compared to FEM and experimental results. In [53], standard plane masonry structures are analysed along with the case of an arch on spreading supports in the framework of large displacements.

Software tools to handle limit analysis of arch bridges focusing on moving loads, [54,55], or interactive tools [56–58], have also been developed, combining static and kinematic analysis.

In this paper, the proposed numerical procedure, which refers to the analysis of rigid-block arches, is proved to be suitable to analyse the behaviour of arches subjected to displacements of supports. The arch model is assumed to be composed of rigid blocks connected by rigid-cracking interfaces, so that hinges can occur only on the actual joints, consistently with the actual damage process of masonry arches. Moreover, this discrete block model permits the geometrical simulation of any arched structures, e.g. pointed, segmental, polycentric etc., including arch-buttress systems, where the support settlement can be applied.

The aim of the proposed procedure is to identify, for arches subjected to any load condition and having any geometric shape, the three positions of hinges that occur when the settlement triggers, to evaluate the limit support settlement and the corresponding displaced geometrical configuration. The procedure allows to model any kind of settlements as well, e.g. horizontal settlements moving apart or approaching one support to the other, vertical, rotational and combined settlements. Herein, the specific case of circular arches subjected to asymmetric loads and horizontal and vertical settlements of supports is taken as an example to present the procedure.

The procedure for detecting the position of three hinges couples combinatorial analysis with static and kinematic procedures. In this first phase, the un-deformed configuration of the arch is taken as the reference configuration for both the static and kinematic analysis because the settlement is assumed to be infinitesimal. In the second phase, to detect the collapse settlement, the reference configuration of the structure is deformed due to finite displacement at the supports.

Results obtained with the proposed procedure have been validated through comparisons with outcomes of the experimental campaign carried out by the authors as well as with data available in the literature from both experimental [45] and numerical [45,51] investigations. Moreover, a sensitivity analysis permitted further validation of the procedure checking the stability of the solution with respect to the number of blocks considered and arch thickness.

The rest of the paper comprises six sections. The rigid block model adopted and the related numerical procedure are described in Section 2 and 3 respectively. Then, Sections 4 and 5 focus on the comparison between experimental and numerical outcomes of this study and other studies available in the literature. Finally, Section 6 shows results of sensitivity analyses and Section 7 is dedicated to concluding remarks.

2. The rigid block model

The arch is regarded as a system of n rigid blocks and $n + 1$ interfaces. Interfaces between blocks coincide with the bisectors of the joints and are represented through a set of three links, two are orthogonal to the interface at the intrados and extrados boundaries and the third is along the interface (Fig. 1). Links are characterized by a rigid-cracking behaviour with respect to axial forces and perfectly rigid behaviour with respect to shear forces [29,59,60]. The constitutive model that characterizes contact joints is thus based on Heyman's assumptions, i.e. no tensile strength and infinite strength with respects to both compression and shear forces, [61].

In correspondence to uncracked joints (interface type 1, Fig. 1a), the interface is composed of three links, which prevent all possible displacements between two adjacent blocks. For cracked joints (Fig. 1b and c), the interface is composed of two links: the tangential link and the link orthogonal to the interface in correspondence to the intrados or to the extrados, Fig. 1b and c respectively.

Tensile forces in links orthogonal to an interface are considered inadmissible because, in such a case, the thrust line would lie outside the profile of the arch and therefore the structure would not be in admissible equilibrium.

3. Numerical procedure

The proposed procedure is grounded on evidence from both experimental [44] and analytical [46,48,49,51] investigations, which showed how for a settlement of one or both supports of an arch, three hinges at block interfaces suddenly occur causing the development of a mechanism that can lead the arch to fail.

The procedure identifies for any assigned settlement the only structure kinematically compatible and in equilibrium with its load condition, avoiding any optimization technique exploited in limit analysis. In particular, by means of combinatorial analysis, the set of three hinges opened in the structure due to a settled support is identified; then, each structure undergoes a kinematic test, and only those that are compatible, are successively statically analysed to check for equilibrium. In so doing, only one structure is found, which is the structure at collapse in a condition of admissible equilibrium.