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A parametric investigation of the seismic capacity for masonry arches and portals of different shapes

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ABSTRACT

Masonry arches are typical components of historic buildings throughout the world, and their damage or collapse is very often caused by earthquakes. The first-order seismic assessment of masonry structures can be represented by the equivalent static analysis method, which does not capture all of the dynamics, but provides a measure of the lateral loading that the structure can withstand before collapse. This study aims to understand the stability of unreinforced masonry arches and portals (i.e. buttressed arches) subjected to constant horizontal ground accelerations, combined with the vertical acceleration due to gravity. An analytical model based on limit analysis is developed to describe the relative stability of pointed and basket-handle arches and portals with respect to circular ones, for varying geometry parameters. The equivalent static analysis determines the value of the constant lateral acceleration needed to cause collapse of the structure, which coincides with the minimum peak ground acceleration needed to transform the vaulted system into a mechanism. Predictions of the analytical model are compared with results of numerical modelling by the Discrete Element Method (DEM). This numerical model considers masonry as an assemblage of rigid blocks with no-tension frictional joints, and is based on a time stepping integration of the equations of motion of the individual blocks. The satisfactory agreement between predictions of the two approaches validates the analytical model and verifies the potentials of the discrete element framework as a method of evaluating the quasi-static behavior of unreinforced masonry structures.

1. Introduction

Vaulted masonry structures are a large part of the world architectural heritage. These structures are particularly vulnerable to seismic events, as shown by the recent damage of invaluable monuments worldwide, which makes necessary to analyze their stability and safety to prevent possible collapse in hazardous conditions. For structural assessment purposes, it is necessary to elaborate models of the mechanical behavior of materials, which can vary widely from very accurate to very simplified ones. In this perspective, different aspects make the static or dynamic analysis of historical masonry constructions a complex task: the geometry data is usually scarse or missing; the constitution of the inner core of the structural elements is unknown, a complete mechanical characterization of the materials utilized is hardly possible, the existing damage of the structure is unknown, the sequence of construction is not documented and the building processes vary from one period to another as well as from one site to another.

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Analysis of masonry arches and vaulted structures in the framework of limit analysis investigates basic aspects of their behavior at collapse and matches modern analysis techniques with geometrical static principles rising from traditional theories. Three main hypotheses (i.e. no tensile strength, infinite compression strength, and no sliding failure) are clearly assumed by Heyman [1–4] on the mechanical behavior of masonry. This leads to simple computations and eliminates the possibility of failure due to material strength, but permits only failure due to instability, because of the formation of a sufficient number of hinges transforming the structure into a mechanism.

The application of limit analysis to the study of the collapse of structural elements like arches, vaults, and flying buttresses under vertical and/or horizontal static loadings seems to be very attractive, as demonstrated in the literature for many applications (e.g. [5–18], among others). Limit analysis is adopted in these works to treat simple masonry elements since complex buildings are an assemblage of elementary structural schemes, and their overall capacity can be somehow derived from the ones of the components. In addition to the collapse of masonry structures due to static loads, many works in the literature have explored the resistance of vaulted systems to lateral accelerations, such as those due to an earthquake. Most research conducted so far on arches and portals under horizontal accelerations has followed an equivalent static approach. With this approach the arch or portal is considered subjected to a constant horizontal acceleration and a vertical one due to gravity. The analysis computes the minimum work needed for the formation of a sufficient number of non-dissipative hinges transforming the structure into a mechanism.

Oppenheim [19] introduces an analytical model to describe a masonry arch as a single degree of freedom three-bar (four-hinge) mechanism under horizontal ground motion. Assuming that the hinges would only occur in some predefined locations, the governing collapse mechanism is derived with its corresponding minimum horizontal ground acceleration necessary to cause collapse through an iteration procedure. The same iterative approach is used by Clemente and Raithel [20] in order to compute the onset accelerations and the governing mechanisms of circular arches with an overhanging back-fill subjected to constant lateral accelerations. In their work, the authors assumed different models to simulate the structure-back-fill interaction, where the most suitable loading pattern for seismic actions is checked. The same problem is then studied by Ochsendorf [21] for a circular arch using the principle of virtual work to determine the ground surface tilt which causes collapse and the corresponding horizontal ground acceleration. The analysis is then extended to portals and triumphal arches by Baratta et al. [22], De Luca et al. [23], DeJong and Ochsendorf [24], analyzing the relative effect of each structural element (i.e. the circular arch and the buttress) on the global stability of the structure.

For more complex geometries, however, the limitations of analytical modelling have enhanced the usefulness of numerical modelling for the structural analysis of masonry structures [25–28]. Despite the wide use of FEM for structural analyses, this method is basically tailored toward continuous structures which remain relatively connected during elasto-plastic failure under quasi-static or dynamic loading. Masonry, on the other hand, is heterogeneous, and is separated by joints and fractures throughout, making it unreasonable to model as an elastic continuum. At the same time, the deformations in masonry structures are not due to elastic deformations of the masonry material, and cannot be predicted satisfactorily by an elastic analysis. Failure is brittle and individual units (e.g. stones, bricks) are often free to separate, especially during quasi-static or dynamic loading. Method primarily developed to predict strength failure can give an indication of possible collapse mechanisms, but often struggle to predict collapse. Moreover, the exact stress is sometimes incognizable in a masonry structure, due to the unknown loading history, boundary conditions, or material properties. For all these reasons, performing affordable non linear analyses with FEM still require high expertise.

An alternative and appealing approach is instead represented by the Discrete Element Method (DEM) where discrete bodies can move freely in space and interact with each other with contact forces, providing an automatic and efficient recognition of all contacts. For rigid bodies, the contact interaction law can be considered as the only constitutive law. Unlike FEM, in the DEM a compatible finite element mesh between the blocks and the joints is not required. Mortar joints are represented as zero thickness interfaces between the blocks. Representation of the contact between blocks is not based on joint elements, as occurs in the continuum FEM. Instead the contact is represented by a set of point contacts with no attempt to obtain a continuous stress distribution through the contact surface. Large displacements and rotations of the blocks are allowed with the sequential contact detection and update of tasks automatically. This differs from FEM where the method is not readily capable of updating the contact size or creating new contacts.

The numerical technique based on DEM has different advantages with respect to FEM, e.g. the low storage, simple to code, suitable for parallel processing, same algorithm for statics and dynamics. The DEM was initially developed by Cundall [29] to model blocky-rock systems and sliding along rock mass. The approach was later applied to evaluate the statics [14,15,30–34] or dynamics [24,35–42] of masonry structures including arches and buttresses with failure occurring along mortar joints. These studies demonstrated the suitability of DEM to perform analyses of masonry structures and to describe realistically the ultimate load and failure mechanisms.

However, the studies conducted thus far on masonry structures including arches were mainly focused on the structural behavior of semicircular geometries. On the contrary, there is a lack of information about the relative efficiency of different arch shapes, for any possible mechanism of collapse, such as pointed or basket-handle arches. Pointed arches are typical structural elements of the Gothic architecture. They allowed the Gothic cathedrals to reach larger heights than the Romanesque ones, while bearing lower thrusts for given loads and spans and reducing the weight on the lateral walls. Differently, the basket-handle arches generate a lower opening, for a given span. Their principal application was in bridges, though there are also examples of basket-handle arches in portals or ancient masonry buildings. It is well known however, as the ancient master builders were able to use geometrical rules, developed through centuries of trial and error, to build