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Tilting plane tests on a small-scale masonry cross vault: Experimental results and numerical simulations through a heterogeneous approach

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ABSTRACT

The seismic response of masonry vaults is discussed by presenting the results of an experimental campaign on a small-scale model and their numerical simulation though a heterogeneous full 3D non-linear Finite Element (FE) approach. The model relies into a discretization of the blocks by means of few rigid-infinitely resistant parallelepiped elements interacting by means of planar four-noded interfaces, where all the deformation (elastic and inelastic) occurs. In the framework of a heterogeneous approach, two typologies of interfaces are present, namely internal brick–brick interfaces, here assumed elastic, and mortar joints with zero thickness, behaving as a frictional (Mohr–Coulomb) material with infinite strength in compression and almost vanishing tensile strength. The model is incremental, non-linear elasto-plastic and exhibits softening at mortar interfaces. Each load step is solved by means of mathematical programming, i.e. through the formulation of a suitable constrained minimization problem where the objective function is represented by the energy of the mechanical system. The experimental and numerical results are compared and discussed in terms of both collapse mechanisms and force/displacement capacity.

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1. Introduction

The disasters caused by past and recent earthquakes on both monumental and ordinary buildings of historical centers have induced the researchers to investigate their seismic behavior. Most of the research works were focused on studying the seismic response of masonry vertical structures, while less efforts were addressed to the analysis of horizontal structural elements, generally constituted by timber floors or masonry vaults. These latter elements, in particular, have been little studied, especially in the context of historical buildings [1,2]. However, they have a relevant role in the seismic preservation of heritage buildings. On the one hand, working as horizontal diaphragms, their behavior significantly affect the overall response of the building in terms of strength and stiffness; on the other hand, their collapse may cause casualties and cultural losses (related to the presence of frescos or attached decorative elements).

Despite the importance of the problem, at present there is still a lack of knowledge in understanding the 3D behavior of vaults because of its complexity. In published literature, many studies on different modeling strategies for masonry vaults were done. Most of them have been oriented to the analysis of vaults under static forces, either by extending the classic theory of limit analysis of arches to spatial structures [3–9] or adopting non-linear continuum [10–14] or discrete models developed in the framework of the Finite Element method [12–17]. However, only few of them are specifically addressed to the seismic analysis, and still less are focused on understanding vaults behavior in the context of the seismic response of the whole building [18,19]. A further effective tool of analysis consists in experimental investigations that aim to better understand the three-dimensional behavior of vaults and to provide suitable data to verify the reliability of theoretical models to simulate their response, e.g. [20–22]. An extensive literature review and classification of analytical and numerical modeling techniques, as well as experimental evidences, is given in [23].

In this paper, the attention is focused on the investigation of a heterogeneous non-linear FE code, developed by the first author of this paper, in predicting the seismic behavior of vaults. In particular, the response of the vault when subjected to horizontal forces proportional to their mass and to differential displacements at the abutments is analysed. Its capability is verified based on the results of a new set of experimental tests on a 1:5 small scale model of a cross vault carried out by the other three authors and described in Section 2. The numerical model, fully described in Section 3, relies into a discretization of masonry material in rigid infinitely resistant eight-node elements, while mortar joints are lumped into

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interfaces with elasto-plastic behavior, softening and very low tensile strength. The approach proposed has been already applied in a variety of static non-linear problems including in-plane loaded panels [24] and vaults [25], but always in the framework of the homogenization theory, i.e. for models where masonry is substituted at a structural level with an orthotropic non-linear material with softening. In this work, for the first time, the FE code is adapted to a direct heterogeneous discretization at a structural level. In Section 4, both the force/displacement resulted curve and the pattern of the damage mechanisms obtained from numerical analysis and experimental tests are compared.

2. Experimental campaign and test results

2.1. Aims of the experimental tests

The main aim of the experimental research was to investigate the seismic response of masonry cross vaults under two different types of loading conditions:

(a) Direct Seismic Action (DSA), where vaults are subjected to horizontal forces proportional to their mass. In this case, the seismic acceleration directly excites the mass of the vault, the abutments being fixed.
(b) Indirect Seismic Action tests (ISA), where vaults are subjected to differential horizontal displacements at their abutments. In this case, the seismic acceleration excites the supporting structures (the walls, piers, and pillars of the building) and the vault is only indirectly loaded by the differential acceleration/displacements produced on its supports.

With DSA testing, the main goal was the evaluation of the collapse multipliers for different directions of seismic action. ISA tests, whose results have been already published in [23], were instead oriented to evaluate the strength and displacement capacity of vaults under different displacement patterns. In both cases, 3D damage mechanisms of the structure were identified.

2.2. Physical model

The physical model represents a single-leaf cross vault with a square base. It was made by plastic blocks produced by means of the 3D printing technology and assembled with dry joints. The model had a span l of 0.620 m, a rise r of 0.225 m and a thickness t of 0.024 m. Geometry, masonry pattern and stereometry (especially of blocks at webs intersection, see Fig. 1) referred to a real vault of span 3.1 m made of typical Italian clay bricks with dimensions $0.06 \times 0.12 \times 0.24$ m.

The mean friction coefficient μ between blocks was measured by means of direct shear tests (12 replicates) on masonry couples and estimated equal to 0.56. Masonry elastic modulus E was equal to 120 MPa; it was obtained by compression tests on masonry pillars constituted by 6 blocks. The density of the plastic material was $\rho = 0.55$ g/cm^3. Since this quite low value would have compromised the model stability under accidental actions, the weight of the model was increased by inserting a steel plate within each block, as illustrated in Fig. 1. This technical measure allowed obtaining an equivalent density of about 2.70 g/cm^3, measured with an electronic scale loaded with several blocks. The mass of the whole structure was thus roughly equal to 35.6 kg.

2.3. Tests set-up and results

2.3.1. DSA tests

DSA were simulated by adopting the tilting plane test. In this static testing technique, the specimen is set on a plane that is progressively inclined of an angle α (Fig. 2a), producing horizontal

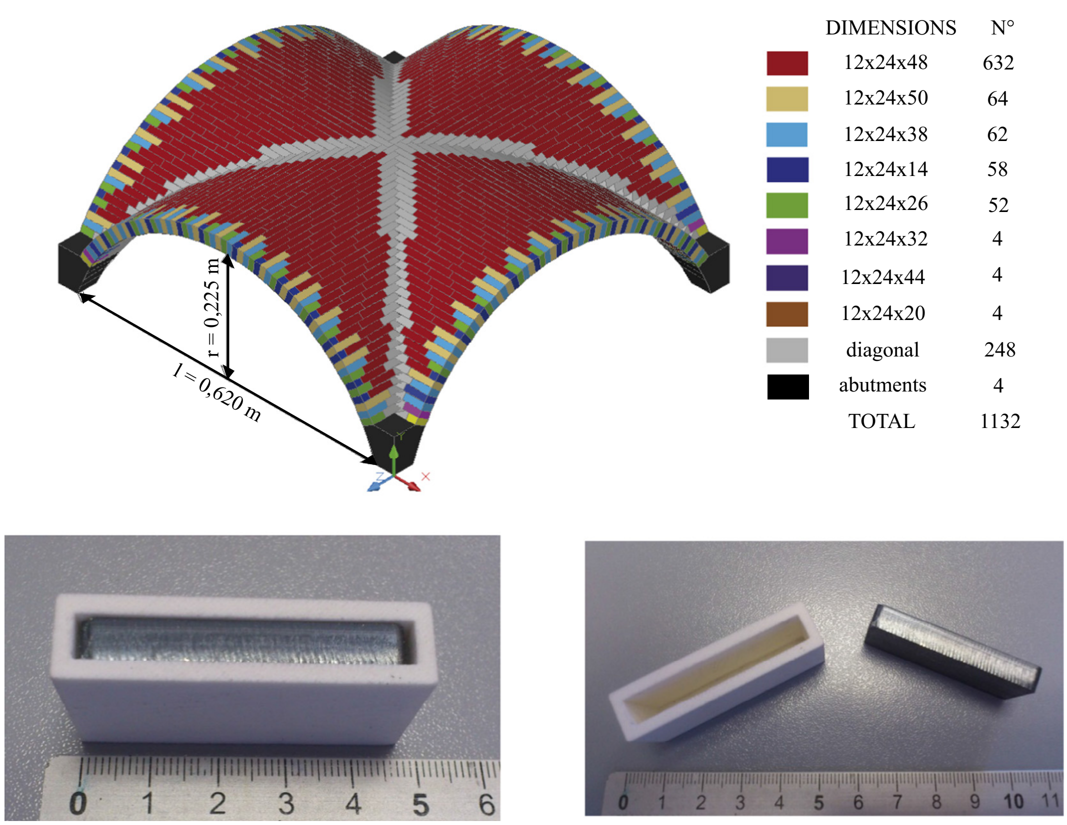

Fig. 1. Geometry of the vault model (top) and view of a single block with the steel plate inserted (bottom).

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