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DEM modeling and experimental analysis of the static behavior of a dry-joints masonry cross vaults

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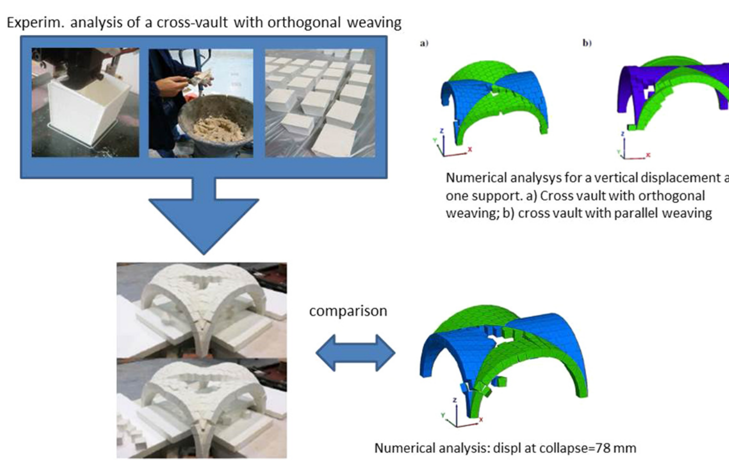
HIGHLIGHTS

- Study of the dynamic and static 3D behavior of a dry-assembled masonry cross vault.
- Numerical modeling by mean of Distinct Element Modeling.
- Comparison with laboratory tests' results on a physical model obtained by mean of 3D printing.
- Evaluation of the three-dimensional mechanism of the cross vault.
- Evaluation of the ability of computational methods to predict the experimental results.

GRAPHICAL ABSTRACT



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ABSTRACT

The purpose of this paper is to study the dynamic and static three-dimensional behavior of a dry-assembled masonry cross vault, through the comparison of Distinct Element Modeling results and laboratory tests' results on a physical model obtained by mean of 3D printing. The work consists of two phases: the first one compares two numerical models of a cross vault built with different masonry patterns (parallel, orthogonal); the second phase deals with a comparison between the static behavior of the computational and the real scaled models (1 m × 1 m) of the same cross vault, tested at one support collapse. The study focuses on three principal aspects: (i) to evaluate the three-dimensional mechanism of the cross vault, (ii) to determine the support displacement's magnitude that leads to its collapse and (iii) to evaluate the ability of computational methods to predict the experimental results. The results obtained from the numerical and the experimental tests have been compared in order to give general specifications on the behavior of these types of vaults.

1. Introduction

In recent years, considering the high percentage of historic-monumental buildings, their age of constructions and the damages due to the even more frequent earthquakes in Italy (i.e. L' Aquila 2009 earthquake, Amatrice 2016 and 2017 earthquakes), more

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and more attention is being paid to the vulnerability and structural safety of these kinds of buildings. To this goal, nowadays, there are many research activities aimed at identifying even more reliable modeling procedures, and durable and less invasive recovery techniques for historical buildings [1,2].

At the same time, however, most of these experimental researches are focused on structural analyses of the vertical components of buildings (walls) rather than on the study of the shell behavior (vaults). But given that vaults and domes are architectural elements necessary from a structural point of view to ensure the transfer of the forces to the supports their behavior significantly influences the overall building response in terms of strength and stiffness, both in the static and dynamic fields. The investigation of their dynamic behavior under earthquake excitation (stress and deformation states) is a fundamental issue for effective structural interventions [3].

Studies on masonry vaults developed over time are numerous and rely on different methodologies ranging from simplified methods, such as the non-interacting arched scheme, to the more complex methods that are based on the finite element analysis, or computational approach based on the well-known analogy between the equilibrium of arches and that of hanging strings or cables working in tension [4], up to the analysis of the distinct elements modeling and through a Differential Variational Inequalities (DVI) formulation specifically developed for the 3D discrete elements method [5].

Coming back to the XV century and before, when some geometric indications of the "rule of art" of vaults were first defined, the respect of the geometric proportions and the experience of building masters were the only tools available [6,7].

One of the first historical personalities interested in the behavior of arches was Leonardo da Vinci [8,9]. He defined, for the first time, an approach to the study of the static of an arch here considered as a system of two bars.

At the beginning of '700, Philippe De la Hire in his *Traité de Mecanique* [10], provided interesting elaborations on the staticity of masonry structures, tracing a sort of collapse calculus.

During the nineteenth century, starting from Luis Navier (1785–1836), the problem was faced in a different way, considering the material characteristics and their strengths rather than the geometry and the form.

Based on the studies of Navier, a first study on pressure curves was carried out by Eduard Henry Méry in 1840, who proposed a graphical method, still used nowadays for small arches [12]. The Méry's method consists in the construction of the pressure curve relative to the load system corresponding to the individual blocks of the arch (Fig. 1).

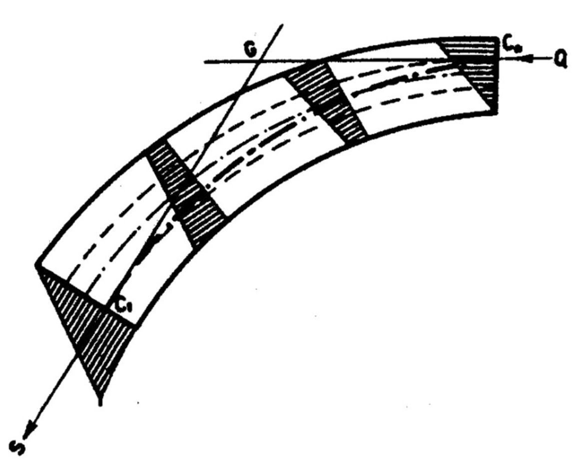

Fig. 1. Pressure Curve (Méry).

It was only later, with Luigi Menabrea (1808–1896) and Alberto Castigliano (1847–1884) that the modern theory of limit analysis came out. It still today represents one of the best mathematical tools to understand the mechanics of masonry arches and vaults. The limit analysis was best dealt with by Professor Heymann (1982) too [13]. In particular, the theorem of the uniqueness of the limit analysis leads to foreseeing pressure lines associated to the collapse mechanism, i.e. in each point where the funicular touches the extrados or intrados, a plastic hinge appears, and this means that the collapse of the structure can take place when the fourth plastic hinge first appears.

Beside the boundary analysis studies, the membrane theory of thin vaults was developed [14,15]; it allows to evaluate the stress state of a vault considered to be a flexural rigid membrane, subjected only to tangent membrane stresses in its plane. It can be considered a valid tool for studying the state of the previous cracking stress, but does not account for the scrolling effects between the blocks, which can only become negligible in the case of thin shells [16].

Until now, there are several methods of analysis available: the method of Heyman's pressure line in 1966 [14], and the membrane theory [15]. Another analytical tool is the finite element method (FEM), first utilized for civil structures in the 70s. This method is widely utilized for the numerical analysis of ancient masonry structures [17] and for arches and vaults too [18,19].

However, FEM presents some problems in masonry modeling; the main ones are described below:

- Definition of the type of elements for the modeling (monodimensional, two-dimensional or three-dimensional elements).
- Uncertainty in the mechanical characterization: in the choice of the constitutive law of the material (elastic-linear, elastic-plastic, elastomeric, resistance or non-traction resistance material), in the values of Young's Modulus, E, Poisson's Coefficient, υ, etc., in the evaluation of anisotropy and material inequality and, above all, in the impossibility to know the load history.
- The geometry is already deformed.
- Difficulty in taking into account the discontinuities (joints, cavities, rifts).

The difficulty of correctly detecting these values and their variability within the structure often makes it difficult the interpretation of the results. Application of the method to masonries requires "equivalent" modeling approaches, such as lowering the stiffness in order to simulate the nonlinear behavior of a masonry.

Also, it must be considered that the masonry is an anisotropic material, consisting of two materials, the blocks (ashlars) and the mortar. If one can define a regular block arrangement, a macroscopic approach, which involves homogenization, is a powerful tool for structural analysis. But when the homogenization process is approximate, for the heterogeneity of the materials and the behavior, this type of modeling is inadequate, especially for the estimation of the seismic vulnerability of historical buildings. In this case, a discontinuous modeling, in which distinctly blocks and joints are considered with their bond constraints is certainly a more rigorous approach that returns more accurate results, especially at a local level [20,21]. In the distinct elements modeling (DEM), in fact, the blocks and joints are considered distinctly with their respective constitutive laws, considering the actual arrangement of the components of the masonry, resulting in a more accurate approach that returns better results [22–25].

An application of the method for vaults was proposed by Lengyel and Bagi [26]. By comparing FEM and DEM modelings, it was studied the importance of ribs on the mechanical behavior of a cross vault. The efficacy of DEM applied to a masonry with respect to FEM analysis was also demonstrated. DEM approach