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A parametric investigation on the seismic capacity of masonry cross vaults

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ABSTRACT

Considering the relevance and the artistic value of cross vaults in European seismic prone areas, a parametric study on the seismic capacity of this element is presented. In particular, the behaviour of the so-called groin vault is discussed, i.e. intersection at a right angle of two semi-circular barrel vaults. The influence of span, rise, thickness, infill, and masonry tensile strength is investigated with respect to two boundary conditions, representative of typical vault configurations within heritage buildings. The analyses were performed using an upper bound approach of standard limit analysis. For the sake of clarity, the adopted code framework is briefly reviewed.

With the aim of identifying the most frequent failure mechanisms, the outcomes of the parametric analysis have been visually inspected and sorted according to the input parameters. Aiming toward a simplified assessment criterion, the resulting list of parameters was subsequently processed through multiple linear regression analyses that can help practitioners in quick seismic evaluation.

1. Introduction

Masonry vaults represent one of the most important structural topologies within cultural heritage buildings. In Europe, they were mostly developed during the Roman Empire and in the period between High Middle Ages and Renaissance, achieving such a level of beauty and technological perfection that still amazes the modern observer. However, despite the relevance and the long-lasting history, being conceived to withstand only gravitational loads, masonry vaults are threatened by seismic events. This has been emphasized by the systematic damage surveys carried out in churches and historical centres after recent Italian earthquakes [8,21–23]. In this regard, considering the limited research in the field, the present paper aims to investigate the seismic behaviour of cross vaults. The study focused on the so-called groin vault, the simplest kind of cross vaults, obtained by the intersection at a right angle of two semi-circular barrel vaults.

In order to illustrate the most frequent damages for cross vaults due to seismic action, it is worth referring to the Italian National Civil Protection Service [8]. By means of a systematic observation of the damages occurred during the strongest Italian earthquakes of the last 30 years, researchers have individuated the most recurring crack patterns for several elements of a church, regardless age, technology and dimensions of the constructions. In this regard, Fig. 1 reports the crack patterns for cross vaults according to the location in the building.

The mechanism labelled as M7 regards the vaults of lateral aisles. The remarkable lower stiffness of the central nave colonnade with respect to the external wall produces a differential longitudinal displacement along the vault sides, i.e. an in-plane shear distortion, with the typical diagonal crack along the diagonal. On the other hand, mechanisms M8, M9, M12, M18, M24 regard the nave, lateral aisle, transept, apse (and presbytery) and chapels vaults, respectively. Support displacements (i.e. translation and rotation that can widen or narrow the vault span) and concentration of shear stresses are the main causes of damages. However, it is still not clear how geometrical and mechanical features influence the vault failure, representing a relevant issue for seismic assessment.

In general, the parameters that affect the seismic behaviour of the vault are numerous, such as geometrical quantities, presence of ribs, connections, overall weight (and mass), previous strengthening measures (e.g. the old-fashioned concrete cap) or

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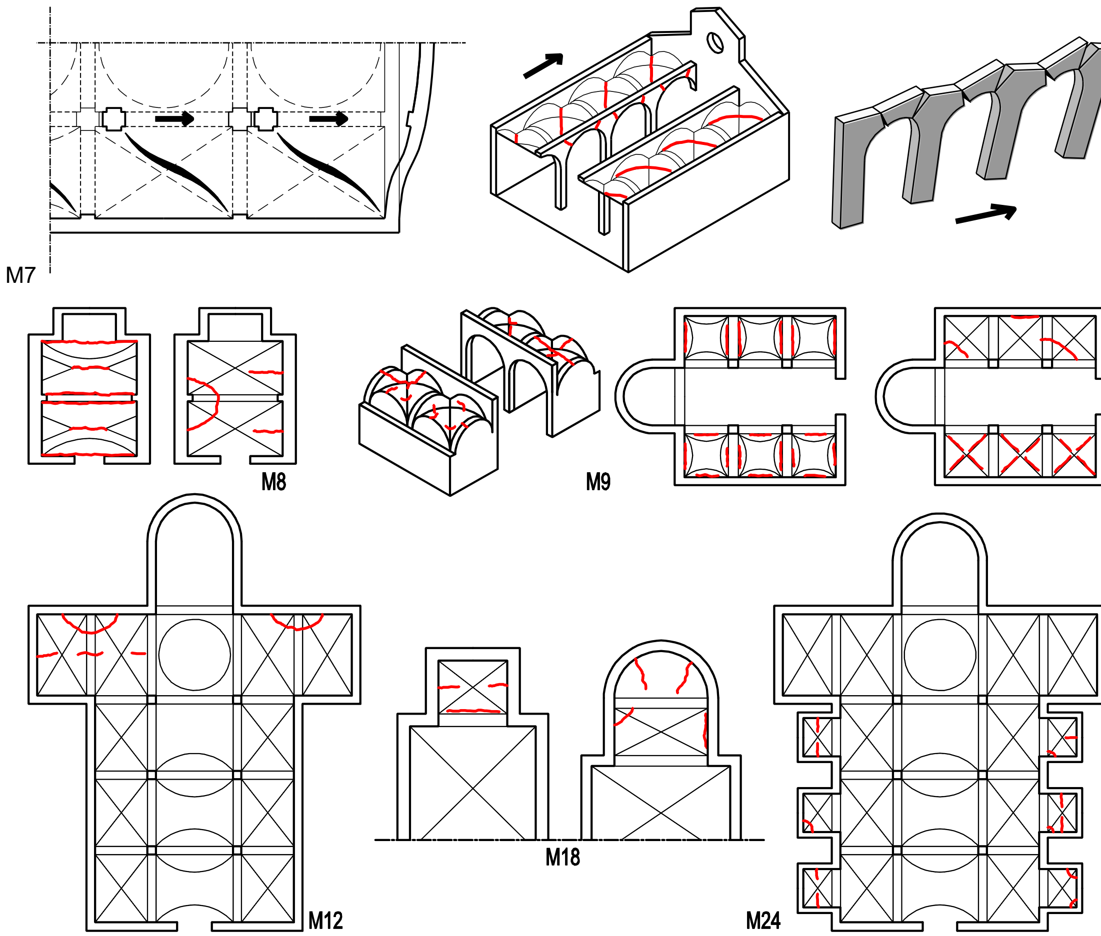

Fig. 1. Cross vault mechanisms in churches [8,22]: M7 (longitudinal response of central nave colonnade) and M8, M9, M12, M18, M24 (nave, lateral aisle, transept, apse/presbytery and chapels, respectively).

concentrated loads (e.g. roof truss resting on the extrados of the vault). The infill plays a crucial role too, as already pointed out for masonry arches [24–27], but also in the analysis of the two cross vaults of the Basilica of Assisi collapsed during the earthquake of Umbria and Marche in 1997 [28]. An excess of infill, in fact, may overload the vault and increment permanent vertical deformation, i.e. the vault reduces the original curvature, thus the bearing capacity.

In order to shed light on these aspects, this paper presents the results of a parametric analysis aimed at evaluating the influence of geometry, tensile strength and infill on the seismic behaviour of groin vaults. In particular, the ranges of vault dimensions (span, rise, thickness) were deduced from literature, from both historical [17] and experimental points of view [18–20]. The analyses basically focused on seismic capacity and failure mechanisms according to two different boundary conditions. The first regards fixed supports that induce an out-of-plane failure, in the fashion of a masonry arch undergoing horizontal action. This configuration is typical of supports with the same stiffness, e.g. vaults in the central naves. The second is aimed at modelling the in-plane shear distortion labelled as M7 in Fig. 1. The effect of support settlements, discussed in [10–13], are not considered in the present work, as it focuses on seismic action.

Regarding the infill, its influence on arched structure is a delicate and still open issue. In case limit analysis and gravitational loads are considered, the influence of the infill on the behaviour of the vault may be taken into account indirectly through the vertical load corresponding to its self-weight, with or without load dispersal, e.g. [14,15] (a more detailed discussion on this topic is reported in [16]). For the analyses of the present paper, the infill was modelled as distributed load and mass on the extrados of the vault. This approach neglects the proper distribution of vertical and horizontal pressure, the influence of its possible tensile strength (resulting from a loose material with low contents of some binding agent), and the nonlinear behaviour of the infill during motion (changes between active and passive pressure). Nonetheless, this approach is considered adequate for engineering applications.

The analyses were performed through a non-commercial code implemented by the last author. It is based on the kinematic theorem of standard limit analysis (with associated flow rule) and, although a concise review is reported next, the reader is referred to [4,29] for further details.

The results of the parametric analysis have been visually inspected and for each boundary condition it was possible to isolate a few main failure mechanisms, together with the relative range of input parameters. Relating this list of parameters to a multiple linear regression analysis provided a valuable tool for expedite seismic evaluation of groin vaults, which is a first step for addressing the lack of recommendations in current Codes of Practice, e.g. [5–7].

2. Review of the adopted numerical code

The FE discretization of the groin vault was represented by means of rigid flat six-noded wedge elements. The utilization of