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Collapse analysis of slender masonry barrel vaults

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ABSTRACT

Significant part of the world cultural heritage is represented by masonry buildings. Many of them are characterised by a complex architecture like as the religious buildings and need to be preserved, from a structural point of view, especially in high seismic risk areas. The recent earthquakes showed that the Historical and Monumental buildings are often characterised by high seismic vulnerability. The lowest seismic performances are associated with the presence of thrusting elements like as arches and vaults. In this background, the numerical analyses and experimental simulations provide important information about the structural behaviour of such elements. The structural behaviour of curved elements can be complex to simulate and to predict exclusively by numerical analyses. Indeed, the experimental tests can provide an efficient contribution to the calibration and interpretation of the numerical models.

The present work focuses on a particular typology of vaults generally used as roofs in religious buildings. These vaults typically do not include any backfill and are slender. These typologies of masonry vaults cannot be analysed with classical approaches where no-tension is assumed. In fact, the tensile strength must be included in order to assess the seismic capacity of these masonry elements. A simplified analytical model, which includes the tensile strength, was proposed. Validation of the analytical model is provided by comparing predictions of the load capacity and the failure mode with those obtained from previous shaking table test series on two full scale masonry vaults. The proposed method represents a useful modelling tool in order to design dynamic tests on masonry vaults and to assess their vulnerability.

1. Introduction

Masonry structures represent a significant part of international architectural heritage. Although they are among the oldest structures, their knowledge is still limited and it is usually difficult to investigate their structural behaviour. These difficulties are often due to the heterogeneity of the materials and of building techniques. Both the design techniques and building techniques from age to age greatly evolved. The design techniques were previously based on purely geometric rules. In the past the structural components were designed using a geometric approach without investigating the actual structural behaviour. This design approach, in some cases, has led to robust structures. Indeed, many of these structures: historic buildings, churches, railway bridges, etc. were subject to several seismic events without serious damage. However, this feature is typical of prestigious and strategic structures where same special structural measures were implemented. Instead, the geometrical rules applied on ordinary buildings, originated often poorly built structures and characterised by strong vulnerability. Only in recent decades designers become aware of how to analyse masonry structures.

The computing capacity of tools now available allows the development of complex numerical models that can be used to evaluate many structural aspects. The heterogeneity of the masonry often makes these numerical models very complex and unreliable when applied to structures different from those originally used to develop them. For these structures and their components (individual walls, vaults, etc.) the experimental support is necessary both to assess the mechanical behaviour and to validate models by means of numerical and experimental comparisons.

In this context, the development of simplified modelling approaches, manageable and convenient for seismic capacity assessment is certainly valuable. Particular attention should be paid to some structural components, typically found in the monumental buildings and churches, like as the vaults.

These structural elements, during the seismic event, often influence the behaviour of the entire building by means of the interactions which they have with the adjacent structural components.

The recent seismic events (L'Aquila, 2009 and Emilia Romagna, 2012 earthquakes) showed how the vaulted structures are vulner-

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Fig. 1. San Martino, Buonacompra and San Francesco D'Assisi respectively, Emilia Romagna (Italy), damages after 2012-Earthquake.

able. Fig. 1 shows some examples of the vaulted structures, as roofing, included in this study.

Knowledge of ultimate seismic capacity of these structural components and the collapse mechanism are key aspects both for the structural analysis and for the design of the strengthening interventions. The use of refined numerical FEM model can't be always adopted in practical structural problems without an experimental support [1]. For this reason, the application of simplified methods is interesting especially for ordinary engineering applications.

This work focuses on masonry vaults with significant slenderness ratio (span/thickness of the cross section ratio) typically used as roofs in the churches. For this type of structures the use of classical approaches (e.g. Heyman's theory [2]) to evaluate the seismic capacity could not be applicable or would produce inaccurate results. For particular geometrical values of span, rise and cross section, the tensile strength of the masonry can't be neglected as it will be clarified in the following.

In a first part the critical issues of the classical analysis methods are briefly analysed. Then the proposed method of analysis for masonry curved elements with great slenderness is explained in detail. The analytical method will be discussed accounting for various assumptions on the materials behaviour (linear-elastic, cracked and plastic with stress-block).

The proposed analytical method is validated by means of experimental and numerical comparisons. The experimental results have been obtained from several experimental tests conducted in the laboratory of Department of Structures for Engineering and Architecture of the University of Naples, Federico II. In these tests two masonry vaults in solid facing clay bricks were tested by means of uniaxial dynamic tests on the shaking table. The vaults are typical of churches built in Italy. The vaults were tested by using several increasing signals in order to obtain an increasing damage level. More details of the experimental program can be found in Giamundo et al. [3]. The focus of the present paper is on the analytical simulation of the collapse of slender masonry barrel vaults and the role of the tensile strength by means of a simplified model.

2. State of the art

An analysis of the principal analytical models and experimental tests on masonry vaults has been conducted, along with the design techniques used for many masonry arches in the past. A first purpose is to investigate the classical theoretical approaches which can be used to assess the seismic capacity of curved masonry's element and point out their limitations. After such analysis the novelties of the proposed method are introduced as improvements of the classical approaches, in particular accounting for the effect of tensile strength of masonry.

2.1. Design by geometrical rules

Structural analyses by using numerical models and prescriptions on technical codes have been applied to masonry buildings only recently. The first constructions were designed according to geometrical rules. The geometrical rules, in few cases (i.e. prestigious buildings), were coupled to other structural improvements like as steel ties, regular walls, elimination of thrust, etc. Such design rules were mainly based on past experiences, hence changed significantly during the years [4–6]. Generally, for a curved element, given the span and radius of the arch, its thickness could be easily evaluated.

In this work the focus is on curved elements made of masonry as arches and barrel vaults, yet including simple arch elements up to the major civil works as arch bridges, viaducts, etc. A deep awareness of their actual safety level is still lacking.

In Brencich et al. [7] the empirical rules were analysed according to modern structural principles. They showed that, in the majority of real cases designed through empiric rules, the structural performances are satisfactory. In fact, many of these structures are still in service although there are both a severe environmental degradation and inadequate maintenance. In De Santis et al. [8] a representative sample of 34 Italian railway arch bridges made of masonry has been assessed. The bridges date back to XIX and XX Centuries and differ both in terms of geographical position and geometrical properties. Surveying the geometrical characteristics of the historical bridges (referring to the vault thickness vs. span for deep arches and to pier top width vs. span and vault thickness for shallow arches), the majority of the existing scrutinised bridges were designed according to the empirical rules.

2.2. Classic theoretical approach

The basic assumptions refer to the material behaviour and the no-tension is the main assumption usually adopted in the engineering problems for masonry structures. No-tension means that material has no tensile strength, hence even if tensile strains arise for strain compatibility, corresponding tensile stresses are always zero, masonry cracks and the effective cross-section reduces; this assumption is on safe side and justified by the low tensile strength of typical masonries.

Different behaviours for material can be considered, namely linear-elastic, cracking and plastic. For each behaviour, it is well known how to evaluate the failure surfaces [9–14] and how they change accordingly.