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Seismic-induced damage in historical masonry vaults: A case-study in the 2012 Emilia earthquake-stricken area

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ABSTRACT

The seismic analysis of historical masonry vaults is a challenging task for contemporary engineers, as vault behavior depends on a large number of factors. Among them, the vault's response is influenced by the seismic behavior of its bearing structures. This paper aims at investigating the capabilities and limitations of current finite element-based computational tools to analyze the seismic-induced damage in masonry vaulted structures. The case under study is the Giulio II vault, located in the main tower of the San Felice sul Panaro fortress (Italy), which has been severely damaged by the 2012 Emilia earthquake. Attention is focused on the interaction between the vault and its bearing tower. The developed finite element model includes the 3D geometry of the vault within the geometry of the tower, based on a before-quake survey. Nonlinear static and dynamic analyses are carried out by using a damage-plasticity constitutive law for masonry. Numerical results are compared to the vault's actual crack pattern, as well as to its actual-deformed geometry based on a post-quake laser scanning survey.

1. Introduction

The disasters caused by past and recent earthquakes on both monumental and ordinary historical masonry buildings have induced many researchers to investigate their seismic behavior. Most of the research works were focused on studying the seismic response of vertical masonry structures [1,2], or to analyze entire buildings also taking into account horizontal structural elements, generally constituted by timber floors or masonry vaults. In particular, these latter elements have been studied aiming at investigating their role in the seismic response of buildings. Indeed, working as horizontal diaphragms, their behavior significantly affects the overall response of the structure in terms of both strength and stiffness [3]. However, as their collapse may cause casualties and large artistic and cultural losses (e.g. the collapse of two frescoed vaults of the upper Basilica of St Francis of Assisi in 1997 [5]), deep investigations of their response under earthquake actions appear of primary importance. The seismic analysis of historical masonry vaults is a challenging task for contemporary engineers as their behavior depends on a very huge number of factors. Among them, the vaults response is also influenced by the seismic behavior of their bearing structures.

Another aspect which further makes challenging this topic derives from the complex geometries that characterize masonry vaulted structures. Recently, advanced surveying techniques, such as laser scanner, allow to rapidly capture the detailed geometry of complex objects. This technology has been successfully used for generating 3D models and monitoring the deformations of very complex masonry domes, see for instance [4].

Several studies have been dedicated to the analysis of masonry vaults under static vertical actions. Following [6] or [7], it can be affirmed that the modern theory of limit analysis of masonry structures, which has been developed mainly by Heyman [8,9], is the most reliable tool to understand and analyze masonry curved structures. However, classical manual methods of analysis [7] allow to find in a suitable way 1D equilibrium solutions for the different types of vaults. The first research works on the numerical assessment of the static behavior of masonry vaults date back to the early 90 s, see for instance the pioneering studies on the Brunelleschi Dome in [10]. As regards recently developed computational methods we can classify them into two broad categories [11]: (i) Thrust network methods, based on the Static Theorem of the limit analysis [12–16], and (ii) Finite and Discrete Element Methods, developed both for limit analysis and for nonlinear incremental analysis (see for instance FEM approaches in [17–24] and DEM approaches in [25–27]).

Concerning the studies published since 2000 it is possible to observe that a number of commercial software packages have been often used in

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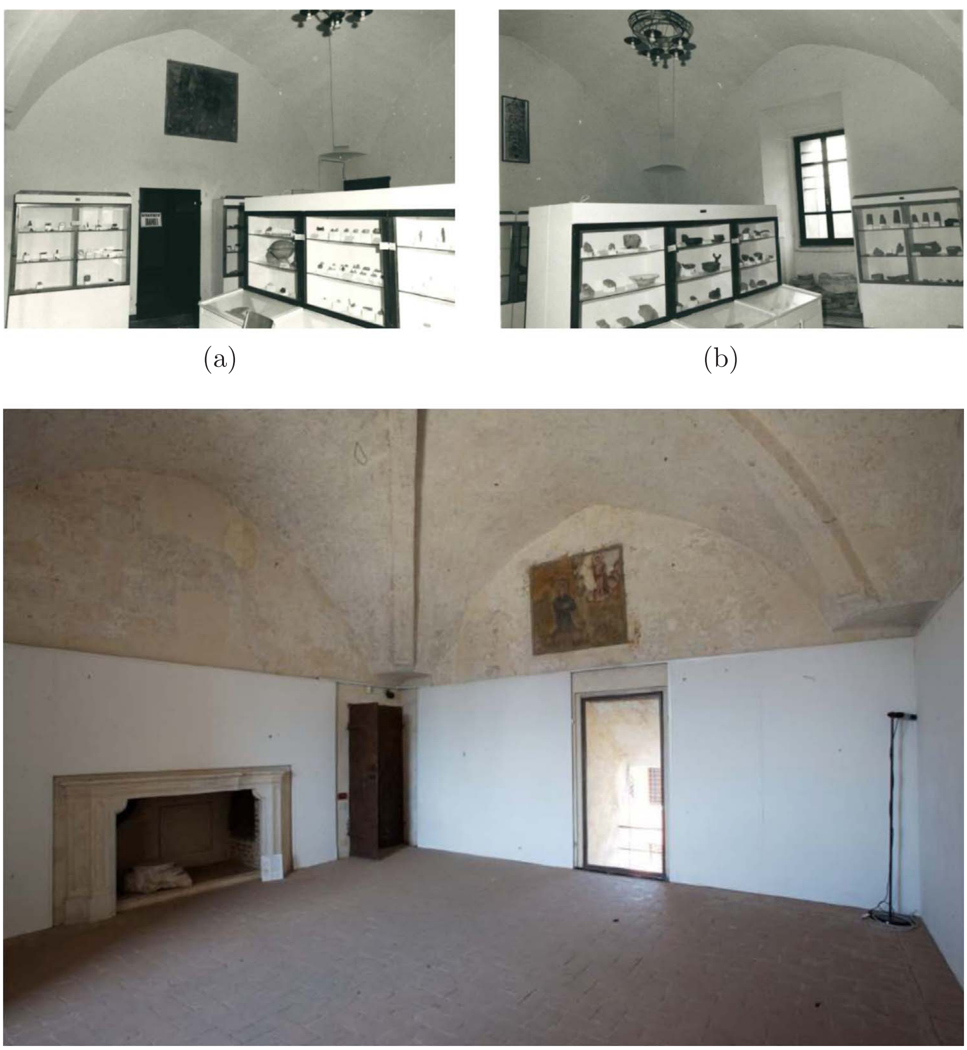
Fig. 1. San Felice sul Panaro fortress.

the scientific literature to model masonry vaults. These programs are mostly FE codes developed to study concrete structures employing complex plastic-damaging constitutive models: cracks are taken into account as a kind of smeared distortions. The heterogeneity of masonry is not accounted for and isotropic behavior either in the elastic field or at collapse is generally assumed. However, it is worth noting that these techniques of analysis turn out to be adequate if combined with proper engineering reasoning. However, there is still much work to do on the definition of constitutive equations for masonry in the dynamic field. For example, with no claim to be exhaustive, the authors mention that: DIANA TNO [23] and NOSA CNUCE [24] contain specific software developed for studying masonry shells; [17] used ANSYS by assuming for masonry elastic-plastic material models (either Drucker-Prager or Willam-Warnke with low tension strength); [15] used Algor V21 with contact elements; [21] employed Abaqus by adopting a damage-plasticity approach.

However, only few of the cited papers are specifically addressed to the seismic analysis of masonry vaults. Moreover, they seem efficient for laboratory samples only, while the seismic behavior of historical masonry vaults strictly relies on the seismic response of the bearing structure. Accordingly, the numerical modeling of a historical masonry vault under earthquake actions cannot disregard the modeling of the



(a) (b) (c)

Fig. 2. Giulio II Hall before the Emilia Earthquake.