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Damage assessment and partial failure mechanisms activation of historical masonry churches under seismic actions: Three case studies in Mantua

Marco Valente, Gabriele Milani*

Department of Architecture, Built Environment and Construction Engineering Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

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ABSTRACT

The structural safety and seismic performance assessment of historical masonry churches belonging to cultural heritage is currently a topic of increasing interest in Italy. Recent Italian seismic events have proved that severe damage or collapse can be caused to such typology of structures even by earthquakes of small-to-moderate magnitude. This paper describes the damage occurred in three important historical masonry churches of the outstanding cultural heritage in Mantua, Northern Italy, after the 2012 Emilia earthquake and presents the results of extensive numerical investigations carried out on detailed FE models with an elasto-plastic damage constitutive law for masonry. Historical and documentary research, on-site surveys and visual inspections were fundamental to identify the critical elements and obtain a thorough detailed knowledge of the churches for the development of accurate numerical models. The results of advanced FE analyses were used to investigate the causes of the crack patterns observed after the earthquake, indicating that the damage distribution detected in the churches can be simulated satisfactorily by the numerical approach adopted. Moreover, this study provides additional information on the seismic response of the three churches analyzed under higher PGA than those registered in Mantua during the 2012 Emilia earthquake. Comparisons among the seismic response of the churches are made in terms of predicted damage distribution, maximum normalized displacements and energy density dissipated by tensile damage.

1. Introduction

The conservation and preservation of historical and monumental constructions with cultural and artistic value are a prominent concern in our society, especially in earthquake prone countries such as Italy. Within this context, masonry churches are particularly vulnerable to seismic actions for their peculiar structural and architectonical features, such as high and slender perimeter walls, absence of adequate connections between the various parts, presence of large coverings or flexible wooden roofs [1, 2]. Recent seismic events have proved that extensive damage can be caused to this typology of structures even by earthquakes of small-to-moderate magnitudes [3–7].

In May–June 2012 a large part of the Po Valley between the cities of Ferrara, Modena and Mantua (Northern Italy) was struck by a damaging seismic sequence. The first major earthquake (magnitude 5.9) occurred on May 20 with epicenter between Finale Emilia and San Felice sul Panaro: two aftershocks of magnitude 5.2 followed and seven people were killed. The second major earthquake (magnitude 5.8) occurred on May 29 with epicenter in Medolla and caused extensive damages, particularly to buildings already

* Corresponding author.
E-mail address: gabriele.milani@polimi.it (G. Milani).

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weakened by the first seismic event. A great number of historical masonry constructions were seriously damaged by the seismic sequence in the south-east Lombardia. In particular, several masonry churches located in the southern part of the province of Mantua suffered extensive damage [8] and required important structural interventions. Significant damage was also observed in several historical buildings located in Mantua, recently declared an UNESCO World Heritage Site with the nearby city of Sabbioneta (2007).

This paper examines the major damage suffered by three monumental masonry churches located in Mantua and presents the results of advanced numerical investigations performed on detailed 3D finite element (FE) models considering different peak ground accelerations (PGA). The three churches are some of the most important symbols of the outstanding cultural heritage in Mantua: the damage observed after the earthquake provided strong motivations for deeply investigating the seismic vulnerability of the structures. In spite of the unquestionable importance of these case studies, before the present work the churches have never been studied with advanced numerical simulations.

The multi-disciplinary approach adopted to assess the structural safety and the seismic vulnerability of the churches involved different activities [9–11]. This paper summarizes mainly the information and the results provided by the execution of documentary research, visual inspection and, above all, advanced numerical simulations. Information regarding geometry, quality of materials, construction characteristics, damage and crack patterns was collected during on-site investigations and documentary research. The geometric and damage surveys were carried out to provide all the data necessary to complete the following numerical modelling stage. The development of the FE models of the structures under study was based on the work carried out by a group of students from Politecnico di Milano, Mantua Campus, starting from the data collected during several field surveys and valuable documentary research. The actual cracks patterns shown by the construction may provide an important indication of the seismic response of the building, highlighting the parts of the masonry structure with higher seismic vulnerability.

Extensive investigations on the seismic assessment of historical masonry constructions have been undertaken in recent years and many methods based on appropriate and advanced numerical tools have been proposed [12–21]. Considering the size and the complexity of the structures under study, the FE macro-modelling approach is the most suitable for this purpose, despite it needs many input data and requires a high computational effort [22–26]. In the literature, there are several significant examples of applications of the non-linear FE method to study the seismic response of historical masonry constructions [27–29].

The objectives of this study are: (1) to identify the most vulnerable elements of the churches under study and compare the results with the main findings of post-earthquake surveys; (2) to obtain important response parameters for different PGA levels; (3) to provide an indication of the seismic response and damage distribution for higher PGA than those registered in Mantua during the 2012 Emilia earthquake.

2. Description of the churches under study

The three churches analyzed in this study belong to the outstanding cultural heritage in Mantua: 1) Sant'Andrea church; (2) Santa Barbara church; (3) San Francesco church. Fig. 1 shows a general view of the three churches with details of the façade. In the following, a concise description of the main historical and geometrical features of the churches under study is provided.

2.1. Sant'Andrea church

Sant'Andrea church is the largest church in Mantua and one of the major examples of the 15th-century Renaissance architecture in Northern Italy: it is located in Piazza Mantegna, in the historical city center of Mantua. The construction of the church started in 1472 according to designs by Leon Battista Alberti on a site occupied by a Benedictine monastery, but the building was completed only in the XVIII century. In 1497 the vestibule, the major and minor chapels were erected and the central nave was partially covered by the large barrel vault. In 1597, the lateral arms were added and the crypt was finished. Between 1732 and 1765, the large late-Baroque dome, designed by Filippo Juvarra and covering the space between the nave and the transept, was erected.

The church presents a Latin cross plan with a single nave covered by a barrel vault and several side chapels: the overall dimensions of the plan are about 100 × 66 m. The main entrance of the church, overlooking Piazza Mantegna, is located along the longitudinal axis leading to the central nave, while the side one, overlooking Piazza Alberti, is placed along the transversal axis of the transept north arm. The façade, which was built near a pre-existing gothic bell tower erected in 1414, presents four large pilasters with Corinthian capitals supporting an entablature and a pediment: these elements recall the front of ancient temples. In the central part of the façade there is also a large arch that is supported by two shorter fluted pilasters: the arch extends deep into the facade,

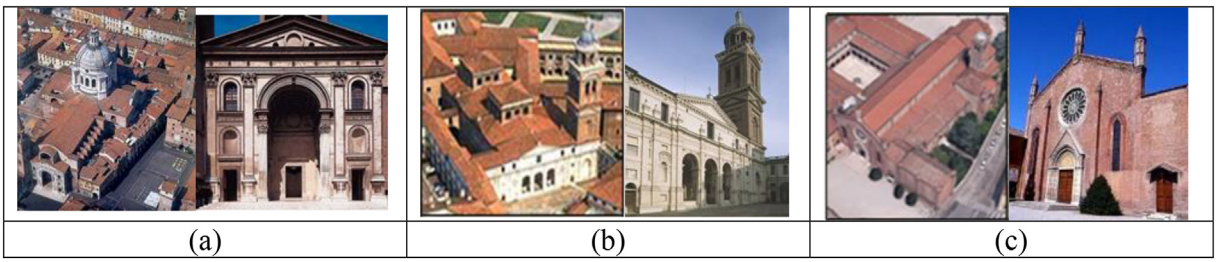

Fig. 1. General view and façade of the three churches under study: (a) Sant'Andrea church; (b) Santa Barbara church; (c) San Francesco church.

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