Engineering Failure Analysis 79 (2017) 773–802

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

# Seismic assessment of two masonry Baroque churches damaged by the 2012 Emilia earthquake

Marco Valente*, Gaia Barbieri, Luigi Biolzi

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

ARTICLE INFO

*Keywords:*
Masonry Baroque church
Survey
Experimental tests
FE model
Non-linear dynamic analysis

ABSTRACT

The structural assessment of historical buildings is a complex and articulated problem based on different activities. This paper describes the different phases of an integrated approach to obtain an accurate knowledge of the structural damage and seismic performance of two masonry Baroque churches located in Northern Italy and hit by the 2012 Emilia earthquake. The activities involved historical research, laser scanning survey, diagnostic investigation and structural analysis. The historical research, based on the analysis of written documents and historical maps, aimed at understanding previous structural problems and major changes in the structure over the centuries. The geometrical survey of the churches was performed by means of a laser scanner technique in order to very precisely determine the geometry of the two churches. Experimental tests and visual inspections allowed identifying location and extent of cracks, construction techniques, presence of voids and defects in structural masonry walls, as well as some characteristics of masonry. Based on this information, detailed three-dimensional finite element models of the two churches were developed and non-linear dynamic analyses were performed. The numerical simulations led to the determination of damage distribution and the identification of the most vulnerable elements, highlighting the main structural deficiencies of the churches when subjected to different levels of seismic actions.

## 1. Introduction

The seismic sequence that occurred in Northern Italy in May–June 2012 caused extensive structural damage and several collapses of precast and masonry structures [1–8]. It involved a wide area including the provinces of Modena, Ferrara and Bologna in the Emilia-Romagna region, the Southern portion of the province of Mantua in Lombardia and some municipalities of the province of Rovigo in Veneto. Buildings belonging to the cultural heritage are mostly constituted by unreinforced masonry structures. Even if the sound structural design used by the ancient architects and builders allowed many historical structures to be preserved till nowadays [8] - even in particular conditions [9] - exceptional events involving significant horizontal actions may seriously jeopardize these structures [10]. The high seismic vulnerability of the historical heritage was clearly evident after the 2012 earthquake and the extensive damage found on the monumental buildings - such as churches, fortresses, palaces - was one of the most dramatic effects occurred, as documented, among the others, by [11–13]. In particular, churches were especially damaged for their intrinsic vulnerability to seismic actions, mainly related to particular features, such as large halls, single and double curvature structures such as arches, vaults and domes, high bell towers, presence of annexes [14–17]. For this reason, they have been extensively analyzed over time [18–24] and their preservation and strengthening against earthquakes is of relevant importance for historical, social and artistic

* Corresponding author.
*E-mail address:* marco.valente@polimi.it (M. Valente).

http://dx.doi.org/10.1016/j.engfailanal.2017.05.026
Received 6 September 2016; Received in revised form 2 May 2017; Accepted 3 May 2017
Available online 04 May 2017
1350-6307/ 


**Fig. 1.** General view of the two churches under study: (a) Sant'Antonio Abate church in Villa Pasquali; (b) San Erasmo and Agostino church in Governolo.

reasons [25–26].

The structural assessment of historical masonry churches is an articulated problem due to the complexity of the structures and requires a deep knowledge of the history, geometry, materials and structure [27–31]. This paper highlights the importance of an integrated approach in the evaluation of the seismic vulnerability of historical masonry churches damaged by earthquakes. The main purpose of the integrated use of the different methodologies was the improvement of the knowledge of the churches for recognizing structural problems, identifying vulnerable elements and defining future appropriate retrofitting solutions.

Two masonry Baroque churches located in the province of Mantua are analyzed in this study: 1) Sant'Antonio Abate church in Villa Pasquali; 2) San Erasmo and Agostino church in Governolo. The two churches suffered a significant and different damage after the seismic events of May–June 2012. Fig. 1 shows a general view of the two churches under study. These buildings have been selected because they can be considered valuable examples of Baroque architecture in the province of Mantua. In particular, the importance of Sant'Antonio Abate church is due to the prestige of its architect, Antonio Galli da Bibiena, and to the peculiar system of masonry perforated vaults, which is an unicum in architectural history, as underlined also in a previous study presented by the Authors [32]. Nevertheless, until now the two churches have not been studied and one of the aims of this study is to give a valuable contribution to fill the gap of knowledge about these two churches.

The two churches have been investigated according to a research plan consisting of different phases: (i) documentary and historical research; (ii) geometric survey; (iii) on-site investigations and experimental campaign; (iv) evaluation of crack patterns; (v) structural analysis. The careful application of complementary activities provides the most reliable information for a thorough knowledge of the structural damage and seismic vulnerability of the two churches.

The historical research was devoted to the examination of old written documents, by focusing on the history of the churches and on their transformations over the centuries, which could be usefully combined with the data provided by architectural analysis.

The geometric survey of the churches was performed by means of a Terrestrial Laser Scanner (TLS) technique and traditional methods. All the data collected during the on-site laser scanning technique were processed to obtain a three-dimensional model by assembling the point clouds surveyed from different station points. This part was fundamental to create a precise reconstruction of the geometry of the two churches.

Experimental tests were carried out on masonry structures to qualify the masonry and to locate and quantify degraded or deteriorated areas. This experimental campaign was focused on the acquisition of the data needed for evaluating the structural safety of the two churches.

During the field investigations carried out after the 2012 earthquake, the presence of extensive cracks and damage was evaluated for the two churches. The crack patterns and the masonry discontinuities were accurately classified and documented by pictures and schematic drawings. Moreover, the visual inspections led to the identification of materials and to the preliminary evaluation of the state of conservation and decay of the structures.

Based on this available information, detailed three-dimensional finite element (FE) models of the two churches have been developed. An isotropic softening model has been adopted for masonry and the main mechanical properties of the materials have been reasonably defined through the results of the experimental tests. The results of the numerical simulations could help in the damage interpretation, highlighting the main structural deficiencies of the churches when subjected to different levels of seismic actions.

In what follows, the main results and outcomes of the different phases are presented with the aim of providing useful information about the structural damage and the seismic performance of the two churches.