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Numerical assessment of the static and seismic behaviour of the basilica of Santa Maria all'Impruneta (Italy)

Michele Betti *, Andrea Vignoli [1]

Dept. of Civil and Environmental Engineering, University of Florence, I-50139 Florence, Italy

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ABSTRACT

The paper analyses the static behaviour and the seismic vulnerability of the Basilica of Santa Maria all'Impruneta near Florence (Italy). The static structural behaviour and the dynamic properties of the church have been evaluated using the finite element modelling technique, where the nonlinear behaviour of masonry has been taken into account by proper constitutive assumptions. A macro-modelling approach has been used based on the concepts of homogenised material and smeared cracking and crushing constitutive law. Seismic vulnerability has been evaluated using a pushover method, and the results obtained with the nonlinear numerical model have been compared with the simplified schemes of limit analysis. The capacity of the church to withstand lateral loads is evaluated together with the expected demands resulting from seismic actions. The comparison of seismic demand vs. capacity confirms the susceptibility of this type of buildings to extensive damage and collapse, as frequently observed in similar buildings. The paper's aim was to point out that advanced numerical analyses can offer significant information on the understanding of the actual structural behaviour of historic buildings. The methodology and the conclusions of this case study it is believed that are applicable to a wide variety of historic Basilica churches.

1. Introduction

The paper discusses the static behaviour and the seismic vulnerability of the Basilica of Santa Maria all'Impruneta, one of the major Basilica built around Florence (Italy). As church building represents a large portion of the Italian (and European) cultural heritage particularly susceptible to damage and prone to partial or total collapse under earthquake loads (as testified by the dramatic recent earthquakes in Italy [1,2]), it is both an economic and actual engineering concern. The high seismic vulnerability of this type of building is due to both the specific mechanical properties of masonry materials (characterized by a very small tensile strength) and the particular configuration of the buildings itself that are characterized by an open plan layout often with perimeter slender walls. Moreover the vulnerability of these historical masonry buildings is enhanced by the absence of adequate connections between the various parts that constitute the structural complex and the presence of thrusting horizontal structures (triumphal arches, etc.) as already discussed in several studies [1,3,4].

To complicate the problem, every ancient church building is characterized by its own history (the result of fusions, additions and replacements of structural elements that have led to its present configuration) so that each monumental building needs to be considered as a unique building: each ancient church requires, though the typological similarities, a specific approach. To demonstrate the interest of the scientific community toward the analysis of this constructive typology the inherent literature reports a plethora of illustrative case studies that cover a wide range of church applications around the European Community. Lourenço [5] discusses the case study of the Church of Saint Christ in Outeiro (Bragança, North of Portugal). The paper shows how sophisticated tools of structural analysis can offer significant information for the study of ancient structures with respect both to the understanding of existing damage and to the minimum and adequate design of strengthening. The Basilica of Pilar in Zaragoza, one of the most famous Spanish temples, has been analysed by Romera et al. [6,7]. In their research the authors identify the actual structural state of the church, its safety level and the relationship between structural behaviour and actual damages. A global numerical model of the church has been built and masonry material has been simulated as nonlinear (with brittle behaviour in tension and plastic behaviour in compression). Moreover the authors consider historical construction steps, including the reinforcement works added to the structure. The paper, approaching a significant case study, shows again how sophisticated numerical models could offer effective information in reproducing historical pathologies and check out the efficiency of historic restoration in cultural heritage. As

* Corresponding author. Tel.: +39 055 4796 326; fax: +39 055 495 333.
E-mail addresses: mbetti@dicea.unifi.it (M. Betti), avignoli@dicea.unifi.it (A. Vignoli).
[1] Tel.: +39 055 4796 214; fax: +39 055 495 433.

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an exemplary case study Lourenço et al. [8] approach the structural safety assessment the Monastery of Jeronimos in Lisbon (Portugal). Through the discussion of the case study the authors stress how the results obtained from advanced numerical simulations in historic structures are usually important for the understanding of the structural behaviour. The paper demonstrates that numerical models can also be used as a numerical laboratory where the sensitivity of the results to input material parameters, boundary conditions and actions can be efficiently analysed, offering invaluable information in the conception and understanding of *in situ* testing and structural monitoring. A Romanesque church, the abbey of Farneta near Cortona (Italy), has been analysed by Betti and Vignoli [9]. To assess the seismic vulnerability of the ancient building the authors built a 3D numerical model designed to develop linear and non linear analyses. The numerical model has been used to evaluate the seismic vulnerability of the Romanesque church and the efficiency of traditional strengthening techniques. Taliercio and Binda [10] analyse the Basilica of San Vitale in Ravenna (Italy), a Byzantine building which suffers diffused cracking and excessive deformation. The authors, taking into account the results of *in situ* topographical and mechanical investigation, built a complete finite element model of the Basilica that has been conceived as a first step toward the understanding of the structural behaviour of the fabrica. The ability of the finite element modelling technique to assess and to interpret the structural behaviour of historic constructions has been showed recently by Ivorra et al. [11]. The authors assess the seismic behaviour of the San Nicolas bell tower in Valencia (Spain). The numerical model was first calibrated by means of dynamic tests performed directly on the real structure and next used to obtain the seismic response and its relationship to the seismic Spanish standard. The numerical simulations showed a satisfactory performance of the tower. Discussing the cracking pattern in a historic Italian palace, Betti et al. [12] show a careful use of numerical analyses when dealing with practical engineering problems. Through the use of the finite element technique the authors provide an interpretation of the manifested damage in the palace, and the results of the numerical analyses have been used to design an extensive *in situ* investigation on the building. Ivorra et al. [13] report a study carried out on the bell tower of the Church of Santas Justa and Rufina in Orihuela in Alicante (Spain). After the model calibration, based on the dynamic characteristics of the tower in free vibration, the model has been used to predict the evolution of the dynamic behaviour of the bell tower taking into account the subsidence caused by variations in water table levels.

Within this field of research the present study discusses an even more illustrative case study. To analyse the structural behaviour of the Basilica of Santa Maria all'Impruneta a double approach has been proposed. Firstly a global analysis of the church has been made by using the finite element modelling technique. Specific assumptions on the material properties and on the non linear behaviour of masonry (nonlinear behaviour both in tension with low tensile capacity and consequent cracking phenomena and in compression) have been made to appraise the general properties of the building's structural response. In particular, static nonlinear analyses under vertical loads (dead and live loads) have been made, and pushover analyses to assess the seismic vulnerability of the Basilica have been considered. Secondly, the simplified scheme of limit analysis, considering several significant architectonical elements of the building, has been considered. With reference to the mechanisms activated on similar buildings during past earthquakes [1,14], some elementary macro-elements were

Fig. 1. Aerial view of the church case study.