Measurement 131 (2019) 183–192

Contents lists available at ScienceDirect

Measurement

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

Structural vulnerability assessment of masonry churches supported by user-reported data and modern Internet of Things (IoT)

Giuseppina Uva *, Valentino Sangiorgio, Sergio Ruggieri, Fabio Fatiguso

DICATECh Department, Via Orabona 4 Bari 70128 Polytechnic of Bari, Bari, Italy

ARTICLE INFO

Article history:
Received 31 March 2018
Received in revised form 7 August 2018
Accepted 8 August 2018
Available online 11 August 2018

Keywords:
Building vulnerability
Distributed measurement system
Heritage masonry buildings
Analytic Hierarchy Process
Macro-element approach

ABSTRACT

The seismic vulnerability and damage assessment of heritage buildings at the regional scale can be considered a complex measurement problem that has suggested the development of specific multi-level procedures based on the inventory and classification of typological, constructive features, vulnerability parameters, potential or existing damage. Ancient masonry churches represent a particularly vulnerable architectural typology and the experience progressively acquired during post–earthquake observations have pointed out that recurrent damage patterns and main failure mechanisms can be identified by separately looking at the different architectural "macro–elements", through on-site surveys. In the last few years, the macro-element approach has been extensively and fruitfully applied to perform preliminary vulnerability assessments, by recognizing the correspondence between each structural macro-element and the most recurrent collapse mechanisms associated. This paper deals with the measurement problem of damages to evaluate seismic vulnerability of historical masonry buildings. To this aim an information system is proposed consisting of a computer platform (named Quality Detection Platform - QDP) and a mobile device dedicated for data acquisition supported by Internet of Things (IoT) technology. The QDP evaluates a vulnerability index by using the macro-element approach and the Analytic Hierarchy Process (AHP) is used to improve the interpretations of the obtained measures and calibrate the relative importance of the kinematic and static criteria and automatically assign the weight to each mechanism.

1. Introduction

The protection of historical and cultural architectural heritage against seismic hazard is a topic that has deserved a major attention in Italy in the last decades. The recent post-earthquake observations in Italy (i.e. Umbria and Marche, 1997; L'Aquila, 2009; Emilia, 2012; Central Italy, 2016) show that the question is still open [1] and there is the need of further developing research studies aimed at the assessment of the existing building stock at the regional scale [2,3] but also of improving methods and effective computational tools for the assessment of single monuments by properly accounting for the complex nonlinear behaviour of masonry monuments under seismic events [5–6].

This paper focuses on the problem of measuring the damages of historical masonry churches, which represent a particularly vulnerable architectural typology. The experience progressively acquired during post-earthquakes surveys and the consequent research studies have revealed that recurrent damage patterns and failure mechanisms can be identified, leading to the idea that it is possible to separately investigate the different architectural "macro–elements": façade, nave, aisle, transept, lateral chapel, dome, bell tower, ... [7,8], as sketched in Fig. 1. Thus, it has become an accepted practice to evaluate the seismic response of limited structural parts and macro-elements instead of considering the complete building at one time. This type of approach, which is incorporated in the Italian Guidelines for the Seismic Risk Assessment of the Architectural Heritage [9], has been usefully applied to perform preliminary vulnerability assessment, by recognizing the association between each structural macro-element typology and the most recurrent collapse mechanisms, based on a relatively large amount of available data [10,11], and also for performing more detailed vulnerability assessment individual buildings [12,13,14]. In addition, several authors have studied methods for integrating the analysis of damage patterns and failure mechanisms in the information systems of management and monitoring [15], in order to provide a priority scale to public or private administrators, who have limited resources to allocate to this problem. Furthermore, these systems should be useful for surveyors, which collect data for defining a vulnerability index of churches, using the well-known methodology based on 28 damage mechanisms [16].

* Corresponding author.
E-mail address: giuseppina.uva@poliba.it (G. Uva).

https://doi.org/10.1016/j.measurement.2018.08.014
0263-2241/

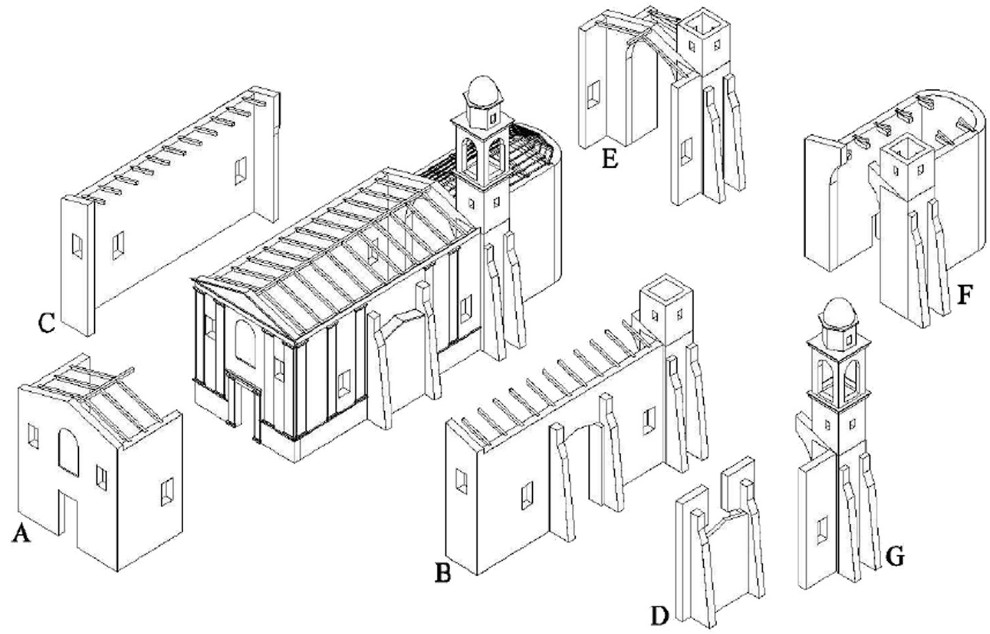

Fig. 1. Schematic representation of the macro–elements of a typical historical church [7].

This paper proposes a novel estimation and distributed measurement approach based on both Information and Communication Technologies (ICT) to acquire data, and mathematical formulations to improve the interpretations of the obtained measures. To this aim an Information System (IS) is specified that includes a Quality Detection Platform (QDP) and a mobile application (APP) devoted to the assessment of structural and safety conditions of large number of churches. The innovation of the proposed measuring strategy is twofold: i) the IS combines a QDP, a smart phone application, which can be connected by Bluetooth to a smart set of devices suitably positioned on the building components [17] in support to surveyors; ii) an improved version of the classical method of the Vulnerability Index for Churches (based on 1st and 2nd level vulnerability forms developed in Italy since 1987 [9,16,18]) is applied. In particular, the measurement method is improved by applying the Analytic Hierarchy Process (AHP) that is able to calibrate the relative importance of the kinematic and static criteria and automatically assign the weight to each mechanism. The outcome of the resulting methodology is a modern distributed ICT tool that is suitable to give calibrated measures of the damages and vulnerability of the masonry churches in large scale.

1.1. Overview about simplified methods for the vulnerability assessment of churches

In order to quantify the vulnerability of churches at a regional scale and provide a rational basis for risk mitigation plans, it is fundamental to define simplified methods able to provide extensive information on a large portfolio of buildings and, at the same time, reduce the cost and time of field investigation. In Italy, the first simplified method provided for the vulnerability analysis of churches was the "GNDT – S3 Model" sheet (1987), based on subdivision of structure in macro-elements [7]. In the following years, after the experience gained after many Italian Earthquakes the sheet was modified and updated to the latest version, in which the vulnerability evaluation is based on 28 damage mechanisms that can be activated on specific macro-elements. According to this simplified approach, which can be classified within the framework of indirect vulnerability methods, the building performance is expressed via a *Vulnerability Index* i_v [4,9,10,11,16,18,19] that summarizes the constructive characteristics and quality (considering also anti-seismic devices) that can directly influence the collapse mechanisms of the building, contrasting or favouring their activation. It is defined as a weighted average of the vulnerability of each macro-element:

$$i_v = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k(v_{ki} - v_{kp})}{\sum_{k=1}^{28}\rho_k} + \frac{1}{2} \qquad (1)$$

For the generic mechanism k $(1 \le k \le 28)$, ρ_k is the weight assigned to the mechanism and represents the influence of each mechanism in the global behaviour of structure and is variable from 0.5 to 1 according to predefined ranges. In particular, in order to fix the predefined variation range of ρ_k Lagomarsino and Podesta [10] employed knowledge acquired during the vast amount of post-earthquake investigations by considering the macro-element importance in relation with the damage mechanisms. Hence, among the defined ranges, the value of ρ_k used in (1) is selected directly on the base of the surveyor's personal appraisal referring to the importance of the surveyed damage and mechanism. Furthermore, v_{ki} and v_{kp} are respectively the vulnerability score and the a-seismic score of the macro-element and are variable from 1 to 3. All these values are evaluated on the base of the experience of the surveyors. The maximum vulnerability level corresponds to $i_v = 1$.

The application of the procedure on a portfolio of church in a specific geographic area allows to determine a mean vulnerability index $i_{v,m}$, which is a significant synthetic indicator of the mean vulnerability of a representative sample and can provide useful indications for damage scenarios and mitigation strategies [10,11].

Although Eq. (1) is very widespread and widely accepted in the study of churches' vulnerability, it is worth noting that it is strongly affected by a few uncertainty factors related to the subjective opinion of surveyors, who autonomously assign a score to each mechanism (both about the vulnerability score and the a-seismic score of each mechanism) basing on their personal judgement and experience. The definition of ρ_k is an additional uncertainty factor, which can provide an unrealistic vulnerability index.