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Seismic vulnerability assessment of stone masonry façade walls: Calibration using fragility-based results and observed damage

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ABSTRACT

This paper is focused on the calibration of a simplified seismic vulnerability index method for masonry façade walls, through an innovative two-step calibration process based on two complementary approaches. The first one is based on a set of fragility curves constructed from out-of-plane damage limit states obtained from experimental data, which are used to calibrate the weights associated to the parameters of the vulnerability index method that rule the out-of-plane response of the masonry façade walls. The second approach, subsequently used to calibrate the weights of the remaining vulnerability parameters, is based on post-earthquake damage data collected after the seismic event that struck the Azores Archipelago in July 1998. The results obtained from such calibration are then presented and critically discussed taking into account not only the calibration itself, but also their reliability from the methodological point of view. Finally, the addition of three new evaluation parameters is further proposed and analysed. This two-step calibration process represents a valuable contribution for the current state-of-art of the simplified seismic vulnerability assessment methodologies which, up to the present, have been developed and calibrated only on the basis of empirical data.

1. Introduction and motivation

According to several past studies [1–5], the absolute seismic risk evaluation of built-up areas can be expressed as the probability of occurrence of a seismic event of certain intensity, for a specific site and during a determined period of time, and mathematically described by the convolution between hazard, vulnerability and exposure, Eq. (1).

$$R_{ie}|_T = |(H_i \otimes V_e) \otimes E|_T \quad (1)$$

where R is the probability of exceeding a certain level of loss for an exposed element e as a consequence of a seismic event of intensity i, H is the probability of exceeding a certain level of seismic activity with intensity i during a recurrence period T, V is the vulnerability, which is the intrinsic predisposition of an element e to suffer damage from a seismic event of intensity i, and E is the exposure of the elements at risk, reflecting the value of the exposed elements [6]. Within this holistic approach, the building stock vulnerability assessment of an urban centre is a key prerequisite for its seismic risk assessment, assuming great and particular importance, not only because of its obvious physical consequences, but also because it is the only factor that remains to be engineered.

When performing vulnerability assessment of a large number of buildings and over an urban centre or region, the resources and quantity of information to collect and deal with can be enormous and thus the use of more expedite approaches results more adequate and reasonable. Methodologies for vulnerability assessment either at the national and urban scale should be based on few parameters, of empirical nature, defined through the knowledge of the effects of past earthquakes, which can then be treated statistically [7]. The definition and nature of such approach (qualitative and quantitative) naturally limits the formulation of the methodologies and the level at which the evaluation is conducted, from the expedite evaluation of buildings based on visual observation to the most complex numerical modelling of single structures (see Fig. 1).

A most important criteria that distinguishes vulnerability approaches for old masonry buildings is whether the method is purely empirical, i.e., based on observation of damage of past-earthquakes, from which a correlation between building typologies and damage level given a known macroseismic intensity level can be derived, or analytical, where a model of a representative building for a typology is defined and a response of such model to expected shaking intensities is computed.

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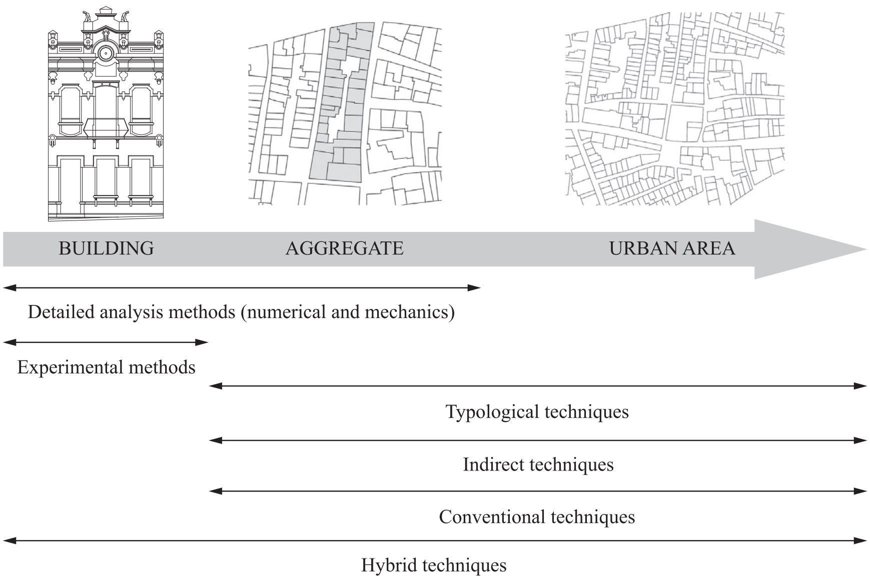

Fig. 1. Analytical techniques used at different evaluation scales [8].

The empirical methods are particularly suited to old city centres, where a record of past earthquakes is available and damage to buildings has been systematically collected over a significant number of events ([9–15] are examples of previous studies resorting to empirical approaches), while the analytical methods are suitable for the cases wherein construction details are recorded and well understood. Regarding the latter, this knowledge should be based on experimental work, to characterise the mechanical behaviour of the materials, and on observed damage data, to calibrate the procedure [16–19]. It is worth referring a third group of methods, the heuristic or expert opinion approaches, by which vulnerability is attributed to building typologies by a panel of experts elicited to perform an assessment based on a common set of information and their previous knowledge (see for example [20]). Finally, a forth group of methods, the hybrid approaches, combine features of the three previously described techniques. Examples of hybrid approaches can be found in [21–23].

This cumulated knowledge obtained from the extensive amount of work carried out in this field over the past 25 years, together with the broad damage data collected from recent earthquakes, opens a singular opportunity to develop and calibrate established vulnerability approaches, which can be truly valuable in the support of risk mitigation and management decisions at the urban scale. Thus, taking advantage of a wide set of collected damage data of traditional stone masonry buildings after the 1998 Azores earthquake [7], this paper presents and discusses the calibration of a seismic vulnerability assessment method for masonry façade walls. This methodology was originally proposed by Ferreira et al. [24] and can be considered as a blend of the typological and conventional methods (presented in Fig. 1 and to be reviewed in the following Section 2), being based on the computation of a vulnerability index, which results from a weighted sum of a set of ten parameters that evaluate the global seismic vulnerability of the masonry façade wall. Moreover, three new parameters are also proposed and calibrated in this paper, aiming at improving the overall methodology by including some new considerations and features that clearly contribute for the seismic vulnerability of the façade walls.

2. Literature review on empirical seismic vulnerability assessment methods

Following the presentation scheme of Fig. 1, the empirical methods described within the next subsections are categorised into four different groups of assessment techniques: typological, indirect, conventional and hybrid.

2.1. Typological techniques

According to Vicente et al. [6], typological methods classify buildings into classes depending on materials, construction techniques, structural features and other factors that influence the building response. According to these methods, vulnerability is defined as the probability of a structure to suffer a certain level of damage for a defined seismic intensity. The evaluation of damage probability is based both on observed and recorded damage from previous earthquakes and also on expert knowledge. Results obtained using this method must be considered in terms of their statistical accuracy, since they are based on simple field investigation and surveying. In effect, the results are only valid for that particular assessed area, or for other areas of similar building typology and equivalent level of seismic hazard. Examples of this method are the vulnerability functions or Damage Probability Matrices (DPM) developed by Whitman et al. [25], compiling DPMs for several building typologies according to the damaged sustained in over 1600 buildings after the 1971 San Fernando earthquake (Table 1).

Calvi et al. [26] stated that one of the first European versions of a DPM was produced by Braga et al. [27], based on damage data collected after the 1980 Irpinia earthquake, in Italy. These authors used a binomial distribution to describe the damage distributions of each class for different seismic intensities. Buildings were separated into three vulnerability classes (A, B and C) and a DPM based on the MSK scale was evaluated for each class [28]. According to Corsanego and Petrini [29], this type of method is also known as direct due to the direct relationship existing between the building typology and observed damage. The use of DPMs is still very popular, mainly in Italy, and several proposals have recently been made to update the above mentioned original DPM method [30]). One worth highlighting study was presented by Dolce et al. [31] wherein, as part of the ENSeRVES project (European Network on Seismic Risk, Vulnerability and Earthquake Scenarios), the original matrices were adapted for the Italian town of Potenza. An additional vulnerability class (D) was included by the authors in the formulation using the EMS-98 scale [32], in order to account for the buildings constructed after 1980, i.e., buildings that have been retrofitted and/or designed to comply with recent seismic codes [26].

2.2. Indirect techniques

Indirect methods initially involve the determination of a vulnerability index, followed by the establishment of the relationships