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Predictive model for the seismic vulnerability assessment of small historic centres: Application to the inner Abruzzi Region in Italy

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ABSTRACT

The paper presents a predictive model for assessing the seismic vulnerability of small historic centres. The model, developed in the framing of other similar methods proposed in the past, needs a limited number of parameters and is based on information collected in the aftermath of the 2009 L'Aquila earthquake.

First, a damage survey carried out on two historic centres hit by L'Aquila earthquake is presented and the most recurrent failure types are classified in terms of severity and extension, leading to damage probability matrices (DPMs). Second, the proposed predictive model is calibrated on the basis of simple observations on the buildings' structural features. Finally, the model is validated through the application to a third historic centre characterized by the same features of the first two case studies. This application proves the generality of the proposed procedure by accurately reproducing the damage that was actually reported after the 2009 earthquake.

The model provides useful information on the most effective anti-seismic strategies that could be implemented at the urban scale for seismic risk reduction.

1. Introduction

The seismic activity that has recently rocked the Italian territory has once again highlighted the structural weaknesses of old historic centres, that typically consist of poor masonry buildings that are often characterized by significant fragilities. This statement is particularly true for small historic centres. These are tiny villages, developed in a poor economic contest and without stringent urban regulations, made up of buildings conceived according to a spontaneous "architecture without architects" style [40] and erected using rules that local builders applied for satisfying topography and climate needs rather than anti-seismic requirements [38].

Moreover, many historic centres are located in medium–high hazard seismic zones, such as the Alpine and the Apennine chains, with a high exposure, due to the architectural quality and/or historical value of the constructions, as well as to the financial, social and human losses that possible collapses could generate. Thus, according to well known definitions (i.e. [15,10], the seismic risk is relevant and needs to be mitigated in order to preserve the structural, cultural and functional assets that historical centres host.

The first step in this direction implies setting up reliable predictive tools for the evaluation of the seismic vulnerability of the historic centres' building stocks. These tools must properly account for the intrinsic peculiarities of the historic centres, which are frequently made of clustered buildings whose current aspect is the result of several additions in both plan and elevation, sometimes carried out using and superimposing different materials and local constructive techniques [19]. The global and local structural response of these complex clusters depends on several parameters [43,47], such as the type of inter-connection between the single structural units, the presence or absence of ring beams, effective iron ties, staggered reinforced concrete slabs, vaulted systems and strengthening interventions that took place over the building life. Moreover, the lack of Building Codes and Regulations has often lead to an irrational expansion of the single building aggregates and of the entire urban layout. As a result, an in depth on site investigation is often necessary to interpret the main construction practices and details used in the historic centres. This in depth survey represents the first and fundamental step for the definition of urban planning strategies for seismic risk mitigation of old historical city centres [53].

Nonetheless, when a vulnerability assessment is carried out at the urban level, a large number of buildings and a large amount of data need to be considered: detailed analyses of the single structures are unpractical and sophisticated models are of scarce interest. Viable vulnerability assessment procedures must be rather simple and can use data from similar buildings hit by past earthquakes. At the urban level,

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three alternative procedures are typically used for seismic vulnerability assessment [3]: (*i*) Damage Probability Matrices (*DPMs*), (*ii*) Vulnerability Indices (*VIs*), and (*iii*) Capacity Curves (*CCs*) based methods.

The above methods usually lead to plot proper fragility curves in a more practical, although more approximate, manner with respect to other numerical and heavy procedures, such as the ones based on the application of sophisticated numerical simulations [48,33,2], which are usually combined with VI methods [4].

The DPMs methodology divides the urban area in several building (for example old reinforced concrete buildings, new reinforced concrete buildings, older masonry buildings, new masonry buildings, etc.), grouped according to predefined qualitative descriptors. Each homogeneous group is assigned to a vulnerability class. Vulnerability classes are defined based on damage undergone in past seismic events. For each class, the conditional probability P $[D = j|IM]$ of experiencing a damage level j due to an earthquake of intensity IM is expressed, in a discrete form, as the frequency of buildings that, for that IM, presented that damage level in past earthquakes. An example of such matrices, related to the vulnerability class of steel and reinforced concrete buildings with five or more stories, was proposed by Whitman et al. [54] following to 1971 San Fernando earthquake: nine damage categories, identified by two qualitative damage descriptors and by a damage ratio (damage costs/building replacement costs), were proposed for five earthquake intensities.

VIs methods are based on the main vulnerability sources for the buildings of a given urban area (building position, lack of box behaviour, thrusting elements, material characteristics, large openings, etc.). A score is assigned to each vulnerability source, measuring its influence on the building structural response. The definition of the vulnerability sources and of their scores is a crucial operation that is carried out by trained experts that must provide consistent judgements during the evaluation process [39]. All structural data necessary for the definition of the scores are collected during extensive field surveys and are used to fill out a form (for example the GNDT forms, following [4] that yields a vulnerability index i_v. This index is then used to obtain, by means of suitable transformation functions (known as vulnerability functions), a mean damage grade, which, in turn, is related to the conditional probability P $[D > j|IM]$ by proper probabilistic functions [52].

The *CCs* methods broadly identify, during field inspections, the main buildings' geometrical and mechanical features and connect this information to analytical models used for calculating load factors through simplified nonlinear analyses. The determination of the performance points, obtained from push-over curves, leads to predict the damage levels that the structure could experience at different earthquake intensities. Meaningful applications of *CCs* methods were proposed by D'Ayala and Speranza [20] for applications of the FAMIVE procedure, and by Formisano [28], Formisano [29], Lang and Bachmann [35], Crowley et al. [18] and several other researches strongly involved in projects dealing with vulnerability assessment at the urban or regional scale, such as the European Risk-EU project [34].

In the above research framework, this paper presents an empirical method for the vulnerability assessment of ancient historic centres and develops it through the application to towns of the inner Abruzzi Region in Italy. The proposed method stems from the studies carried out by the University of Chieti-Pescara for the preparation of the reconstruction plans of fourteen small historic urban centres hit by the 2009 "L'Aquila" earthquake.

The proposed procedure was calibrated on the basis of the observed damage of two meaningful examples, Goriano Sicoli and Poggio Picenze, that experienced different seismic intensities and thus different damage levels. The gathered data helped draw damage scenarios for similar historic centres with the aim of providing a valid support for professionals and decision makers that must plan strengthening actions for reducing the seismic risk at the urban and territorial levels.

First, the paper provide a short description of the 2009 L'Aquila earthquake. Then, it describes the most recurrent failure modes observed in Goriano Sicoli and Poggio Picenze following the 2009 earthquake. Observed damage is classified in terms of severity and extension, leading to specific damage probability matrices (DPMs).

On the basis of the obtained outcomes, a predictive model, which can be used to forecast possible damage scenarios that can be expected in historic centres for earthquakes of increasing intensity, is presented. The model is then validated through its application to another historic centre, Bazzano. Finally, fragility curves for typical Abruzzi historic centres are derived.

The proposed model provides a useful tool for identifying the most effective mitigation strategies that could be implemented at the urban scale for effective seismic risk reduction actions.

2. The 2009 L'Aquila earthquake

The 6.3 M_w shallow earthquake that shook the centre-east part of Italy on April 6th 2009 had the epicentre two kilometres far from L'Aquila, the capital and second most populated city of Abruzzi. It caused 309 deaths, almost 1700 injuries and eighty thousand displaced persons.

The main event was a pure normal faulting mechanism, with a depth of about nine kilometres and a fault length of about 15 km in the SW direction.

The main shock was preceded, during the months before, by a long series of foreshocks that had a maximum peak on the 30th of March, when a M_L 4.1 earthquake was recorded. On the other hand, only four hours before the main shock, a M_L 3.9 event occurred.

Several aftershocks followed in the successive days, culminating in the 5.4 M_w event of April 9th [12]. Then a long sequence of aftershocks of decreasing magnitude was observed in the following months, as it is shown in Fig. 1, where the earthquake with $M_w \geq 3$ occurred since February to October 2009 are depicted.

As for the main event, the record of the station of the Italian Strong Motion Network (RAN) closest to the epicentre (about four kilometres far, on a soil type B), downloaded from the ITACA database [37] and processed according to [42], is shown in Fig. 2a.

At the same manner, in Fig. 2b the corresponding elastic −5% damped- spectrum is given. A maximum ground acceleration of *0.64 g* can be observed and resonance phenomena can be noticed for periods ranging from 0.1 to 0.9 s, which represents a domain of interest for the masonry buildings that are studied in this paper.

Several researches were carried out in order to investigate the particular features of L'Aquila earthquake. Among these, Bindi et al. [6] clarified some characteristic effects related to the source, the observed attenuation law and evidenced site effects.

Ameri et al. [1] studied, through suitable models, the spatial variability of the near-fault strong-ground motions recorded during the

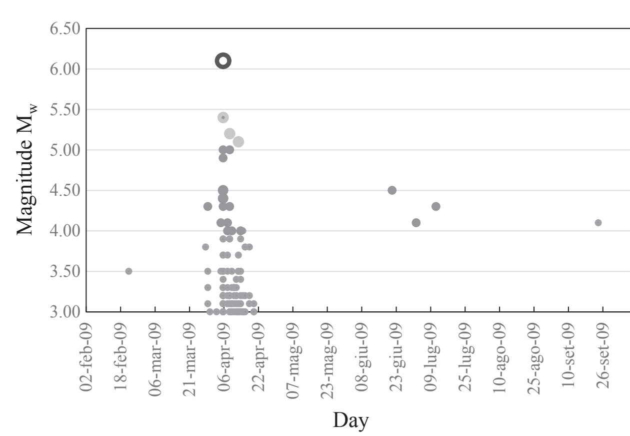

Fig. 1. The seismic sequence of L'Aquila Earthquake recorded between February and October 2009 (Earthquake with $M_w \geq 3$ only).

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