Doctoral School on Engineering Sciences
Università Politecnica delle Marche

Extended summary

Historic masonry buildings: seismic vulnerability analysis from the urban to the building scale and intervention design. The case of the province of Ancona.

Curriculum: 'Architecture, Building and Structures'

Author

Sara Vallucci

Tutor

Prof. Enrico Quagliarini

Date: 30-01-2014

Abstract. Strong earthquakes that have hit the Italian Peninsula underlined the high seismic vulnerability of Italian Architectural Heritage, characterized by masonry buildings with high historic and artistic value. Architectural Heritage conservation is necessary in order to preserve the history of buildings and to ensure the safety of people towards natural disasters such as earthquakes. This work aim at recommending a well-defined consequential procedure for a correct prevention, using a process divided in three different phases. Firstly, identifying - within a statistical sample - the historic city centers mainly at risk (*phase 1: urban scale evaluation*); secondly, identifying - within the centers selected in phase 1 - the most vulnerable building aggregates in order to better analyze them (*phase 2: aggregate scale evaluation*). This operation allows the identification of critical areas within historic city centers, helping local administrations to focus their attention (using economical and logistical resources) on these areas with the aim of investigating the vulnerability of masonry buildings - through detailed structural analyses - either reducing or eliminating the vulnerabilities detected. Past experiences showed that historic masonry buildings exposed to the seismic action tend to discretize themselves into well-defined parts (macroelements). In this thesis it has been described the representation and analysis of the structural behavior of single buildings towards seismic actions through local mechanisms analyses. In the same way, this work has studied

solutions to problems concerning the sizing of interventions in order to achieve a better behavior and increase the safety of historic buildings (*phase 3: building scale evaluation*).
Finally, it has been implemented a method for the creation of risk maps of building aggregates, which shows an expected-damage scenario resulting from the seismic vulnerability of buildings and the local seismic dangerousness.

Keywords. Historic masonry, seismic risk prevention and reduction, seismic vulnerability.

1 Introduction

City centers of ancient establishment represent the historic building heritage that characterizes Italy. This heritage deserves to be protected in order to preserve its integrity and knowledge testimony, as well as to guarantee human safety under seismic events which are very frequent in this country (such as the more recent happened in 2009 – L'Aquila – and in 2012 – Emilia Romagna region). Italian architectural heritage, mainly constituted by masonry buildings with great historic and artistic value, in fact, is exposed to a huge risk if hit by earthquake.

Seismic risk should be reduced and it is determined by the following factors: (i) *Vulnerability*, (ii) *Dangerousness* and (iii) *Exposure*. In the case of existing buildings, in the aim of reducing seismic risk, nothing can be do about *Dangerousness* (that is site dependent), and almost nothing can be do about *Exposure*, therefore only *Vulnerability* should be reduced. This paper proposes a consequential process to obtain a correct prevention. The first step consists in developing an urban scale analysis, using a methodology that considers the historic city center as an urban system (*phase 1: urban scale evaluation*), with the purpose of identifying historic city centers more at risk [1, 2, 3].

After this phase, the next step is to identify, within these centers, mainly vulnerable building aggregates, the ones that deserve more attention (*phase 2: building aggregate scale evaluation*) [3, 4], by using detailed structural analyses as well as reducing or removing any vulnerabilities detected (*phase 3: building scale evaluation*). This thesis investigates building structural behavior under seismic action through local collapse mechanisms analyses. These analyses have been used for the intervention design in order to improve historic building seismic performance [5].

2 Historic center seismic vulnerability evaluation

2.1 Phase 1: Urban scale evaluation through the SAVE method

In this work it has been chosen to use the method developed within the SAVE project (*Strumenti Aggiornati per la Vulnerabilità sismica del patrimonio Edilizio e dei sistemi urbani – Updated Tools for the Seismic Vulnerability of heritage building and urban systems*) promoted by the National Group for the defense against earthquakes (GNDT - Gruppo Nazionale per la Difesa dai Terremoti) [1, 2]. The smallest unit that can be evaluated with this method is the city center, which is seen as a self-sufficient structure and boundary delimited by Non-Urbanized Areas or separated elements (like streets, city walls, etc.).

The objective of this evaluation is to create a list of historic centers according to the seismic risk (vulnerability maps at regional scale) in order to identify the ones that mainly need in-depth analysis.

This evaluation is developed taking into consideration six 'risk components': four of them concern *Vulnerability* (building vulnerability, urban layout vulnerability, public services and business activities vulnerability), one concerns seismic *Exposure* (human and goods exposure) and the last is represented by the historic center *Value*. Every component is described using factors which express potential losses, directly or indirectly caused by a seismic event [2, 3].

From the weighted sum of the above-mentioned components a *'global risk index'* can be obtained using the following formulation:

$$R = \sum_{i=1}^{4} V_i \times 1 + E \times 0.5 + Va \times 0.3 \quad (1)$$

Where V_i is the *Vulnerability* component, E is the *Exposure* component and V_a is the *Value* component. Notably that R is independent from *Dangerousness*.

2.2 Phase 2: Building aggregate scale evaluation through the SISMA method

In this case, the evaluation is based on 'building aggregate', analyzed using the 'aggregate sheet' developed by Le Marche region within the SISMA project (System Integrated for Security Management Activities) referred to the case of Offida, an historic center in the province of Ascoli Piceno [3, 4]. The sheet is composed of 10 parameters:

- non-homogeneity in building height;
- non compact shape of the plan;
- maximum difference between number of levels of each building and the average number of levels of the block;
- non-homogeneity in materials and structural typologies;
- non-homogeneity in time of construction or of last intervention;
- non-homogeneity in windows or floors lining;
- presence of building without 'boxed' behavior;
- shape of the plan;
- state of conservation;
- geomorphology and foundation line.

This method investigates the evaluation comparing the aggregate actual state to an 'ideal' condition about seismic vulnerability. The aggregate vulnerability (V_{An}) is calculated as the weighted sum of the 10 partial vulnerability (v_i) referred to the above-mentioned parameters:

$$V_{An} = \sum_{i=1}^{10} v_i \times p_i \quad (2)$$

The *Vulnerability Index* (I_{Vn}) is defined as the ratio between the nth aggregate vulnerability (V_{An}) and the maximum vulnerability value achievable from the procedure (V_{max}).

$$I_{Vn} = \frac{V_{An}}{V_{\max}} \times 100 \quad (3)$$

The outcomes can be used to create an 'iso-vulnerability' map of the historic center aggregate, useful for local administrations to concentrate their attention (economical and logistical resources) on the mainly critical areas.

2.3 Phase 3: Building scale evaluation

In the last step of the proposed procedure the worst building identified in the previous phase are analyzed from the structural point of view. According to the past earthquakes, it

is common knowledge that masonry buildings are considered as an assemblage of several masonry portions (called 'macro-elements') with self-contained behavior, that respond as single units to seismic action, and for which the main features of the collapse mechanisms are at least approximately known [6, 7, 8]. Therefore, structural behavior of masonry building can be analyzed through local collapse (in plane and out-of-plane) mechanism [9], using kinematic equilibrium limit analysis [5, 10, 11].

The same approach is used for the intervention design, with the aim of obtaining an improvement in terms of structural performances and safety under seismic events of masonry buildings: for every collapse mechanism that could be activated by earthquake, contrasting interventions have been proposed [5].

3 The case of historic centers in the province of Ancona

The case studies are four historic centers chosen in agreement with the Ancona Province: Senigallia, Loreto, Corinaldo and Camerano. They represent a heterogeneous sample of the different typology of historic centers that can be found in the province of Ancona.

In the four centers the SAVE method has been applied, by using data obtained from the Ancona Province database, the Italian National Institute of Statistics (ISTAT - Istituto nazionale di statistica), urban plans, technical units of local administrations as well as *in situ* measures and observations.

In the cases of Senigallia, Corinaldo and Camerano the SISMA method has been applied too, in order to better evaluate aggregates vulnerability and create 'iso-vulnerability' maps, from which more vulnerable aggregates deserving a deeper analysis can be identified.

4 Simplification of urban scale evaluation method

Due to the problems appeared in data research for SAVE method [1, 2] application, it arises the need of splitting data collected into two categories. The first is the one of *objective data*, acquired in univocal way from the Ancona Province database and ISTAT for the four case studies. The second is the one of *non-objective data,* (acquired from technical units of local administrations and from in situ measures). These data were defined also as *non-coherent data* because they are not always present or not always have the same degree of information.

As a consequence, a simplification of SAVE method has been proposed, supposing different scenarios for historic center seismic risk evaluation:

- Scenario 1: data from Ancona Province database + ISTAT + local administrations technical units + in situ measures (this is the scenario used for the determination of global *Risk Index*);
- Scenario 2: only *objective data* (Ancona Province database + ISTAT);
- Scenario 3: only data from local administrations technical units (to have a comparable results, only data available in all the four case studies were used);
- Scenario 4: data from *in situ* measures.

4.1 Results and discussion

Using the only *objective data* (Scenario 2) a *Risk Index* has been obtained, which ranges between 62% and 68% compared to the one obtained from Scenario 1, indicated as 100%. In all the four cases the error is almost constant (between 31 and 38%, Figure 1), therefore the result can be considered comparable, although the chosen centers were heterogeneous. On the other hand, the error connected to Scenario 3 and 4 is too high, therefore these data have been removed from evaluation method.

The *Risk Index* derived from Scenario 2 has been connected to the global one (Figure 2), using the following corrective coefficient:

$$corrective\ \ coefficien\ t = \frac{I_R\ (scenario\ 1)}{I_R\ (scenario\ 2)} \tag{4}$$

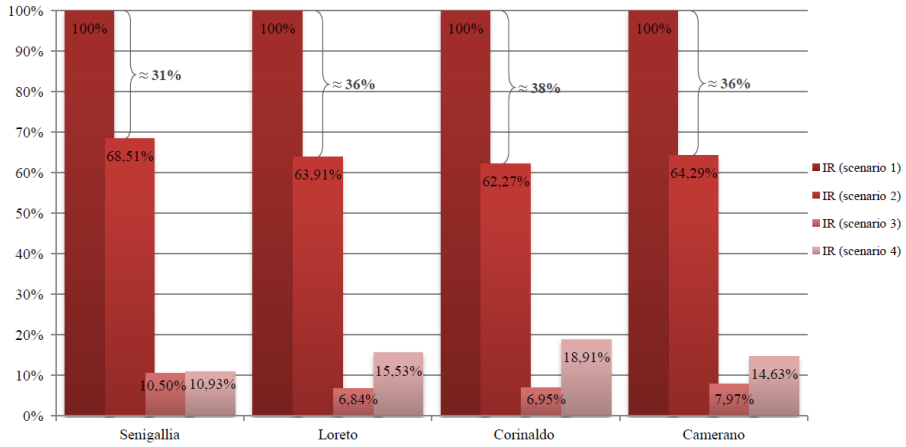

Figure 1. Comparison of committed error in determining the *Risk Index* for the analyzed historic centers.

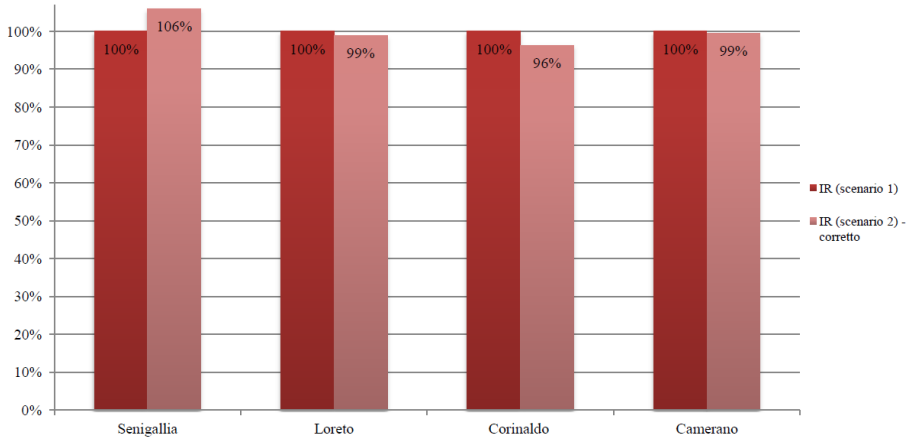

Figure 2. *Risk Index* obtained from Scenario 2 and adjusted using corrective coefficient.

5 A risk scenario through macroseismic method

Using a macroseismic method [12] that proposes to extrapolate vulnerability curves starting from the European macroseismic scale EMS-98, at the end of the research for the historic center of Senigallia it has been suggested a method for the creation of an 'iso-risk' map,

based on the expected damage which depends on the building vulnerability and local seismic dangerousness).

6 Conclusion

This thesis presents a study about masonry building seismic vulnerability with the aim of planning for prevention. The proposed procedure follows a process in three subsequent phases: identification of historic city centers mainly at risk (phase 1), within these identification of the most vulnerable building aggregates (phase 2), on which concentrate economical and logistical resources for detailed structural analyses at building scale (phase 3).

In phase 1 a method simplification has been proposed in order to make it more quickly and user-friendly. Objective data are available for all municipalities of the province of Ancona in univocal way. This first phase has a double value:

- It offers the possibility of determining local critical situation of the urban system identifying the level of *Vulnerability*, *Exposure* and *Value* that mainly affect the historic center *Risk Index*;
- It offers the possibility of mapping historic center seismic risk, useful for local administrations for intervention using planning and safeguard tools.

The proposed procedure has been confirmed for a sample of only four centers. To statistically validate the procedure, the study should be conducted on other centers as well.

The purpose of phase 2 has been the identification of worst building aggregate, from the seismic vulnerability point of view, within the centers detected in phase 1. This could be done through the creation of 'iso-vulnerability' maps. In the three centers studied in phase 2, it has been seen that the presence of irregular shapes and non-homogeneity of structural typology and technology mainly affect vulnerability.

According to the results obtained from these analyses, it is possible to detect the more critical buildings in order to evaluate - using detailed structural analyses (linear equilibrium limit analyses) - their vulnerability, and find the appropriate countermeasures to be adopted to enhance seismic safety.

The final aim of this work has been the implementation of a method able to create an 'iso-risk' map of the building aggregates of the Senigallia historic center, where it is possible to clearly see the expected damage scenario. This scenario depends both on the building vulnerability and local seismic dangerousness.

Following the comparison between the vulnerability index obtained from the 'aggregate sheet' (SISMA method) and other vulnerability indexes, it has been proposed to adapt macroseismic method to building aggregates. This allows the creation of 'vulnerability curves' (one for each aggregate) which link macroseismic intensity and expected damage level. The creation of these 'vulnerability curves' allows to modify the macroseismic intensity input (converted into PGA) using a seismic amplifier factor Fa=1.2 (obtained from seismic micro zoning executed on the Senigallia area).

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