Performance-based Seismic Risk Assessment of Urban Systems

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PERFORMANCE-BASED SEISMIC RISK ASSESSMENT OF URBAN SYSTEMS
(Running Head)

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ABSTRACT

Disaster risk mitigation has become a global urgent need. Similarly to other natural hazards, earthquakes may cause significant damage on a large scale. In Europe and in other regions with dense urbanization, seismic events can heavily impact historical city centres due to the several structural fragilities. These centers are often part of the worldwide cultural heritage and their preservation is considered a strategic issue. Furthermore, earthquakes may have severe negative short-term economic effects on the impacted communities and adverse longer-term consequences for economic growth. For this reason, the development of an efficient approach for urban seismic risk assessment becomes essential. An original approach is proposed, based on performance concepts and multidisciplinary perspectives. The procedure is applied for validation to the city center of Concordia Sulla Secchia (Italy), damaged by the 2012 Pianura Padana Earthquake (PPE), comparing predicted damage scenarios with the actual post-seismic survey data.

KEYWORDS: seismic risk, risk assessment, risk mitigation, performance-based assessment, cultural heritage protection, GIS applications

1. INTRODUCTION

With the approval of the “Sendai Framework 2015-2030 (UNISDR 2015)” the U.N. has declared disaster risk reduction one of the biggest global challenges the world deals with today, and has proposed unified guidelines for risk reduction and disaster management. In recent years, natural disasters have affected the world population in repeated and severe ways. Among all catastrophic events, strong earthquakes typically produce damage on a vast scale in areas of high hazard and poor construction techniques. They may cause a high number of casualties, severe economic losses and are a major threat to cultural heritage sites.

In Europe, historical city centres represent an essential part of the cultural heritage. Their dense urban structure, made of ancient masonry buildings, often built in aggregate, and pre-modern seismic code Reinforced Concrete (RC) constructions, make them highly vulnerable. This immeasurable cultural heritage is considered by the EU a “strategic resource for a sustainable Europe” that needs to be preserved (CotEU 2014). Among all European countries, Italy has the highest number of UNESCO listed heritage sites (source: UNESCO website). From 1968 to date, the Italian central government has spent more than 120 billion Euros for reconstruction costs in the aftermath of major seismic events (Di Mauro 2014), with a significant impact on the Nation’s economic budget. The development of practical seismic risk assessment tools could lead up to the preventive planning of retrofit works, aimed at minimizing casualties and damage.

In literature, many definitions of the seismic risk for a single element of the city (for example a building) can be found. One of the most complete definition is related to the PEER methodology (Porter 2003), leading to:

$$\lambda(DV) = \iiint G\langle DV|DM\rangle\, dG\langle DM|EDP\rangle\; dG\langle EDP|IM\rangle\, d\lambda(IM) \tag{1}$$

Where, from right to left, four different terms can be distinguished:

$d\lambda(IM)$ refers to the **hazard** characterization of the area under assessment, determining the probability of occurrence of seismic events and their expected Intensity Measure, IM. Among all possible intensity measures, the mainly used are: the peak ground acceleration, pga [unit measure: g], the spectral acceleration, S_a [g's], and the European Macroseismic Intensities, I_{EMS-98} [-] (Grünthal et. al. 1998);

$dG\langle EDP|IM\rangle$ refers to the **vulnerability** measure of the building under assessment given the hazard defined above (i.e. conditional probability). The vulnerability is the intrinsic predisposition to suffer structural damage after a seismic event, and the damage can be expressed using different Engineering-Demand Parameter, EDP (for example interstorey drift);

$dG\langle DM|EDP\rangle$ refers to the **damage** definition of the building under assessment given the vulnerability measure defined above (i.e. conditional probability). Damage parameter, DM, can be expressed using appropriate models , such as, for example, the interstorey drift ratios proposed by Ghobarah (2004) or the total displacement thresholds introduced by Lagomarsino and Giovinazzi (2006);

$G\langle DV|DM\rangle$ refers to the **loss** evaluation given the damage defined above (i.e. conditional probability). Losses are herein described as a Decision Variable, DV, because, depending on their entity, the evaluated risk level can be defined as *acceptable* or not.

The hazard characterization is usually performed using maps provided by Public Authorities. For example, the Italian National Institute of Geophysics and Volcanology (INGV) produces and updates an interactive hazard map of the Italian territory. More detailed assessment may include also specific data on site effects, like spectral amplification or liquefaction probability (Bramerini et al. 1995; McGuire 2004).

The vulnerability measure of buildings can be performed following different methods. The most accurate approach is based on structural response evaluation through Finite Element Modelling (FEM) analyses. This approach is referred to as **direct method**. It requires a highly detailed knowledge of the construction technique and may be time-consuming, depending on the FEM model complexity. Examples of this approach are the work of Lang and Bachmann (2003) and D'Ayala and Kishali (2012) that used non-linear analysis methods to study the in-plane and out-of-plane behaviour of unreinforced masonry (URM) buildings. A less accurate but more practical approach is represented by the so-called **indirect methods**. Their main advantage is they grant a swift evaluation and can be used when details regarding the construction technique are missing, for example when dealing with historical buildings. These methods attribute the vulnerability level by dividing constructions in *classes*, or by using *typological indicators.* An example of classes attribution is the classification proposed within the EMS-98 approach (Grünthal et al. 1998). Buildings are divided into 6 *Vulnerability Classes*, from A to F, where the most vulnerable constructions belong to Class A.

An example of typological indicators application is given by the *Vulnerability Index Method*, originally introduced by Benedetti and Petrini (1984) and then developed, among the others, by GNDT (GNDT-SSN 1994; CETE Méditerranée 2008) and Ferreira, Romeu and Varum (2014) for masonry buildings and Podestà and Romano (2014) for RC structures. This method uses standard forms, based on in-situ post-earthquake damage surveys, to evaluate the buildings' vulnerability level by considering 11 parameters (see Table I and Table II). Each parameter represents one of the main features that influence the buildings' response to a seismic event. Parameters are ranged into classes of increasing vulnerability level by means of assigned score, C_{vi}, and have an assigned weight, w_i. The weight denotes the different impact of parameters on the overall seismic vulnerability - a higher weight meaning a higher influence. Vulnerability classes of masonry buildings parameters are A-B-C-D. Vulnerability classes of RC buildings parameters are A-B-C, with the exception of the 11-th parameter with the additional class D. To assign a class and the related score to every parameter, buildings' inspection are required, considering both geometrical and structural aspects. Once all classes and scores are determined, the vulnerability index, I_V, is computed as a weighted sum of all the parameters' scores, normalized in the range $[0 - 100]$.

The choice between direct and indirect methods depends primarily on the number of buildings under assessment, see Fig. 1. In fact, direct methods have a high accuracy, but they can be extremely time-consuming. Therefore, when dealing with a large number of buildings (from the building's aggregate to the whole city), the use of indirect methods becomes essential even if it implies to accept a certain level of uncertainty of the results.

The damage definition is usually performed applying a probabilistic approach. For example, outputs of direct and indirect methods are used to derive *fragility curves* (Porter 2017). Fragility curves are cumulative distribution functions that express the probability of a building to exceed defined damage levels for increasing value of the PGA. First the American *Applied Technology Council* (ATC), introduced a fragility curve database (Anagnos, Rojahn and Kiremidjian 1995). Similarly, the European research projects RISK-UE (Mouroux et al. 2004; Lantada et al. 2010) and SYNER-G (2011) proposed a framework to produce earthquake scenarios and perform loss assessments. Then, the *Federal Emergency Management*, or FEMA, developed and has been constantly updating HAZUS (FEMA 2015), a tool to assess the seismic losses for both the built environment and population using *capacity curves* (Chopra and Goel 1999; Bertero 2000). A capacity curve, is the plot of a building's lateral load resistance as a function of a lateral displacement (i.e., a force-deflection plot), and values are usually expressed in terms of spectral acceleration, S_a, and spectral displacement, S_d.

Another approach to damage is given by the so-called *Macroseismic Method* (Giovinazzi and Lagomarsino 2004; Giovinazzi 2005; Lagomarsino and Giovinazzi, 2006), that derives by the introduction of the EMS-98 scale (Grünthal et. al. 1998). In fact, following the EMS-98 approach, a qualitative description of the expected damage level, $D_k = [0, 5]$ (0 = no damage, 5 = collapse) is used, for each vulnerability class and for increasing seismic intensities, I_{EMS-98}.

Within the macroseismic method, the expected damage level descriptions are used to define Damage Probability Matrixes (DPMs) that return the expected probability of undergoing a damage level for given vulnerability class and seismic intensity. Then, DMPs results are described using a single parameter: the Vulnerability, V. In this way, it is possible to associate a numerical value to each Vulnerability class, as reported in Bernardini et al. (2007).

Vulnerability, V, is used to evaluate the mean damage grade, $\mu_D = [0, 5]$ (0 = no damage, 5 = collapse) using the following Eqs. 2 and 3 (Lagomarsino and Giovinazzi 2006):

$$\mu_D = 2.5 \cdot \left[1 + tanh\left(\frac{I_{EMS-98} + 6.25 \cdot V - 13.1}{Q}\right)\right] \cdot f(I_{EMS-98}, V) \tag{2}$$

$$f(I_{EMS-98}, V) = \begin{cases} e^{\frac{V}{2}\cdot(I_{EMS-98}-7)} & I_{EMS-98} \leq 7 \\ 1 & I_{EMS-98} > 7 \end{cases} \tag{3}$$

Where:

- Q is a ductility factor, defined equal to 2.3 for masonry buildings and in the [2.3 ÷ 3.3] range for RC buildings depending the seismic code level and the regularity in height (Lagomarsino and Giovinazzi 2006)
- $f(I_{EMS-98}, V)$ is a corrective function to better describe the damage for lower intensities (Bernardini et al. 2007).

The buildings' damage distribution is subsequently defined through a probabilistic approach· In particular, Giovinazzi (2005) introduce the beta probability distribution function, $p_\beta(x)$, whose Probability Density Function (PDF) and Cumulative Density Function (CDF) are reported by Eqs. 4 and 5. The damage level x is assumed as a continuous variable and μ_x and σ_x^2 are its expected mean value and variance, respectively:

$$PDF: p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{(x-a)^{r-1}(b-x)^{t-r-1}}{(b-a)^{t-1}}; \quad a \leq x \leq b \tag{4}$$

$$CDF: p_\beta(x) = \int_a^x p_\beta(y)dy \tag{5}$$

Where $\Gamma(k)$ is the gamma function of the k-th variable and parameters a, b are assumed respectively equal to 0 and 6 (Giovinazzi 2005). Parameters t and r are evaluated using Eqs. 6 and 7 (Giovinazzi 2005):

$$t = \frac{\mu_x(a + b - \mu_x) - ab}{{\sigma_x}^2} - 1 \tag{6}$$

$$r = t\,\frac{\mu_x - a}{b - a} \tag{7}$$

But t is usually assumed constant and equal to 8 (see Bernardini et al. 2007).

The beta probability distribution function is used to obtain discrete probability distributions associated to every damage level, D_k, as shown by Eq. 8:

$$P(D_k) = \int_k^{k+1} p_\beta(x)dx \quad ; \quad k = 1 \div 5 \tag{8}$$

Where $P(D_k)$ the probability of the building to suffer a damage level D_k, with k in the [0 ÷ 5] range.

Expected losses are particularly relevant due to the high fragility of the built environment (D'Ayala et al., 1997). Their evaluation is performed considering both economic and human losses. Economic losses are usually divided between direct and indirect losses. For example, direct losses may refer to the physical damage undergone by a building, while indirect losses may refer to the income lost by the commercial activity carried on in the damaged building. Human losses are usually divided in casualties, injured and homelessness. To estimate expected losses, the exposure of the building, i.e. its social and economic value has to be assigned.

Due to the multiple factors that take part in the risk definition (see Eq. 1) seismic evaluations of single buildings can be extremely challenging and time consuming, but the evaluation complexity further increases when passing to the urban scale. In fact, to properly assess the risk of urban systems it is necessary to take into account additional factors, such as the buildings' functions and their interconnections. For this reason, prevention planning and urban management should consider at first that the overall vulnerability of a city is not the mere sum of the single buildings' vulnerabilities. Furthermore, the overall scope of risk management and reduction should be to increase resilience, defined as "the ability of social units to mitigate hazards, containing the effect of disasters when they occur and carry out recovery activities in the shortest time possible" (Bruneau et al. 2003).

The resilience definition is the result of socio-economic considerations, and can be framed in a more comprehensive approach to risk assessment and management, using performance concepts of modern structural design philosophies, such as the Performance Based Earthquake Engineering or PBEE (SEAOC 1995; Staniscia, Spacone and Fabietti 2017). PBEE is based on the definition of performance levels and is quite an effective approach in dealing with risk at the single structure level. For different hazard levels, minimum performance levels (or limit states) are defined for the structural system at hand. In analogy to what is done for structures, different performance levels or *limit conditions for urban settlements*, have been proposed (Olivieri et al. 2011). Table III shows five different performance levels, whose definition is based on the minimum response requested to the city's elements.

Among the different performance levels, the *Emergency Limit Condition* (ELC) is introduced as the settlement's extreme capacity, where full functionality is required of only those elements (buildings, connection routes and relative infrastructures) needed during the emergency phase. The ELC cannot be strictly considered as a "urban limit condition", given that the settlement safeguarding and recovery are not guaranteed. The ELC analysis for urban settlements was recently introduced by the Italian Civil Protection Department in an effort to enhance emergency preparedness in the case of an earthquake with catastrophic consequences (Bramerini et al. 2014). It represents a first step towards the definition of a complete performance-based approach to urban risk management.

These concepts have a great potential to give new impulse to urban risk management. However they have only been applied to a few case studies and their validity is yet to be fully shown. It is a main goal of this work to propose an effective procedure for the urban seismic risk assessment and management, based on performance concepts and on mechanically proper model of the urban system within reliability framework. Therefore, the “robustness” of the city is evaluated, identifying primarily those elements that have a higher or strategic role in the city life (hospitals, public buildings, fire stations, main connections, etc.). The seismic risk assessment at the urban scale is then performed using a semi-automated procedure, with the single buildings’ vulnerabilities as input data.

Section 2 of the present work introduces the proposed methodology and highlights the authors’ original contributions. Section 3 presents the implemented evaluation process, carried out with a MATLAB® script. For sake of clarity, the methodology steps are summarized in a flowchart. Section 4 presents the application of the proposed procedure to a case study, the ELC sub-system of Concordia sulla Secchia, Italy. This city was hit by the PPE in 2012, and it is used here as a case study to compare the observed post-seismic damages to the loss scenario predicted by the proposed methodology. Section 5 summarizes the paper’s key points, draws the conclusions and points to future research directions.

2. PROPOSED METHODOLOGY FOR THE SEISMIC RISK ASSESSMENT OF HISTORICAL CITY CENTERS

In this paper, a combined approach of the *Vulnerability Index* and the *Macroseismic method* is adopted. This approach has been recently applied in seismic risk assessments of historical city centres in Portugal (Vicente et al. 2011; Ferreira et al. 2013; Maio et al. 2016) even though it is limited to unreinforced masonry buildings (URMs). Following this approach, the definition of buildings vulnerability is performed using the Vulnerability Index method, by determining I_V values for each element under assessment. In the same way, the definition of buildings damage is performed using the Macroseismic method, by determining V values. For this reason, a correlation between parameters I_V and V is required. In this work, the formulation proposed by Ferreira et al. (2013) is assumed for vulnerability evaluation of masonry buildings, following Eq. 9:

$$V = 0.592 + 0.0057 \cdot I_V \tag{9}$$

Then, mean damage grade, μ_D, and discrete probability distributions, $P(D_k)$, for all buildings are evaluated using Eqs. 2 - 8.

In the current work, the abovementioned methodology is further developed proposing some original contributions. Specifically, a $I_V - V$ correlation to estimate the damage for RC buildings is derived, a tool for the city multidirectional assessment using the vulnerability ellipse approach is discussed, and the concept of the *urban system survival probability* is introduced and applied on a case study. The main aim is to introduce a performance-based approach to the seismic risk assessment, as well as to make the methodology usable also for other structural typologies. All contributions are described in detail in the following paragraphs.

2.1 Urban system survival probability

Assessing the seismic risk at the urban scale implies dealing with a large number of elements and their associated damage levels and probabilities. In a city, different constructions have different roles, making them more or less relevant for the city life. Roads, bridges, water supply, electric distribution and ICT networks are also part of the urban system and a complete damage scenario would have to include all of them along with their interdependencies to accurately assess the earthquake impact (see Pederson et al. 2006). However, because of the task complexity and the limitation of available data, the present pilot study considers only buildings and connections, letting to future developments the inclusion of other elements. Even with this limitation, the behaviour of the city can still be well represented, particularly by considering the ELC sub-system described in the previous chapter.

The city can be seen as a complex system of interconnected components. The easiest method to describe such a system is to model it making use of *series* or *parallel* elements configurations (Pinto, Giannini and Franchin 2007). In a *series* configuration of n elements, if the single *e-th* component fails, the entire system fails. It can be associated with the "weakest-link" concept. In a *parallel* configuration of n elements, if the single *e-th* component survives, the entire system survives. It can be associated with the "fail-safe" concept.

Given the failure probability of the *e-th* component, P_e, under the assumption that the elements' failures and survivals are independent, the probability of survival of the series systems, P_S, and parallel systems, P_P, can be expressed by the Eqs. 10 and 11, respectively (Pinto, Giannini and Franchin 2007):

$$P_S[survival] = 1 - P_S[failure] = \prod_{e=1}^{n}(1 - P_e) \tag{10}$$

$$P_P[survival] = 1 - P_P[failure] = 1 - \prod_{e=1}^{n} P_e \tag{11}$$

Series and parallel systems can be combined together in a *parallel-series system* configuration. In this configuration, m components are arranged in n parallel sub-systems that are connected in series. Given the failure probability of the $j - th$ element in the $e - th$ sub-system, P_{ej}, the probability of survival of the parallel-series systems, P_{PS}, can be expressed by Eq. 12:

$$P_{PS}[survival] = 1 - P_{PS}[failure] = \prod_{e=1}^{n}\left(1 - \prod_{j=1}^{m} P_{ej}\right) \tag{12}$$

The Macroseismic method (Lagomarsino and Giovinazzi, 2006) described in §1 returns the probability $P(D_k)$ that the *e-th* building suffers a given damage level, D_k. A specific damage threshold, D_{max}, can be defined for the *e-th* building, depending on its function in the city-life. In this way, if the *e-th* building under assessment suffers a damage level $D_k \geq D_{max}$, the building is considered to be failed. For this reason, the failure probability of the *e-th* building

$P_e = P(D_k \geq D_{max})$. Then, the overall urban system survival probability is computed by combining the failure probabilities P_e through Eqs. 10 - 12, depending on the selected system configurations of series-parallel systems, which represent different urban performance levels of Table III. The procedure is herein described in detail.

ELC – The *emergency sub-system* of the city is considered, formed by the essential elements for carrying out emergency operations. Very few strategic buildings are included, together with the main roads connecting them and the open spaces where people can gather. Strategic buildings and connection routes are identified by the Municipal Authorities and Civil Protection Departments, as the play a relevant role in the emergency phase. The emergency sub-system also includes *interfering* buildings, whose collapse can interrupt main communication roads and cause significant delays to emergency operations. Buildings not included in the ELC can undergo even severe damage. The ELC is well represented by a *series system* configuration (Fig. 2), where its E_e*-th* component belongs to the *emergency sub-system* of the city. As the ELC is the minimum performance level of the city (Olivieri et al., 2011) only the *main* strategic buildings are taken into account, leaving aside the *redundant* strategic buildings. In this framework, a strategic building is considered redundant when it is not essential in the emergency phase. The assumed definition of main and redundant strategic building is derived by Civil Protection Department Guidelines (Bramerini et al., 2014). The survival probability of the urban system is evaluated using Eq. 10. Failure probability P_e is a function of maximum admissible damage D_{max} , defined by Eq. 13:

$$\begin{gathered} strategic\ buildings \quad P_e = P(D \geq D_2) \\ interfering\ buildings \quad P_e = P(D \geq D_4) \end{gathered} \tag{13}$$

where D_4 and D_2 are maximum admissible damage levels corresponding to damage mean grades $\mu_D = 4$ and $\mu_D = 2$, respectively.

CLC – The ELC is considered along with redundancies. Similarly to the ELC, the city is assumed to undergo massive damage and interruption of the majority of functions. Still, the addition of redundant strategic buildings increase the robustness of the city towards the seismic event. In this case, the behavior of the city is well represented by a *parallel-series* system, as schematically shown in Fig. 2. The survival probability of the urban system is evaluated using Eq. 12. For strategic and interfering buildings, P_e and D_{max} are defined by Eq. 13.

LSLC – The CLC is considered along with *critical* constructions, whose function may have a relevant impact on the urban system. Main industrial and commercial facilities, chemical factories or high-density residential buildings are some examples of this category. Their collapse or even interruption of use can cause significant loss in terms of economy and population. The choice of critical buildings to be included in the LSLC is a social/economical/political choice that must be made at the political/administrative level. The behavior of the city is well represented by adding a parallel-series system of c_i elements to the CLC, as schematically represented in Fig. 2. The city is assumed to undergo only modest-to-long interruption of ordinary urban functions. The survival probability of the urban system is evaluated using Eq. 12. For strategic and interfering buildings, P_e and D_{max} are defined by Eq. 13. For critical buildings, P_e and D_{max} are defined by Eq. 14:

$$critical\ buildings \quad P_e = P(D \geq D_3) \tag{14}$$

Where D_3 is the maximum admissible damage level corresponding to damage mean grade $\mu_D = 3$.

DLC – The LSLC is considered along with *ordinary* constructions, which don't have a relevant role in the city-life. The city is assumed to undergo a limited level of damage so that it will be able to recover its original functionality in a short period of time. The majority of residential buildings are included in this category. Similarly to the LSLC, only short-to-modest or partial interruptions of ordinary urban functions are accepted. The behaviour of the city is well represented by adding a parallel-series system of o_k elements to the LSLC, as schematically represented in Fig. 2. The survival probability of the urban system is evaluated using Eq. 12. A lower maximum damage level D_{max} is requested for all buildings, including strategic and interfering elements, in order to guarantee the shortest recovery time for the city. For all buildings, P_e and D_{max} are defined by Eq. 15:

$$\begin{gathered} strategic\ buildings \quad P_e = P(D \geq D_1) \\ interfering\ buildings \quad P_e = P(D \geq D_3) \\ critical\ buildings \quad P_e = P(D \geq D_2) \\ ordinary\ buildings \quad P_e = P(D \geq D_3) \end{gathered} \tag{15}$$

Where D_3, D_2 and D_1 are the damage levels referred to the damage mean grade $\mu_D = 3$, $\mu_D = 2$ and $\mu_D = 1$, respectively.

OLC – Conceptually similar to the DLC, see Fig. 2, strategic and critical buildings do not have to undergo any interruption of use and only low damage of ordinary urban functions is accepted. This limit condition represent the ideal situation where the system is able to withstand the seismic event without losing its original functionality. The survival probability of the urban system is evaluated using Eq. 12. A lower maximum damage level D_{max} than the DLC is requested for all buildings. For all buildings, P_e and D_{max} are defined by Eq. 16:

$$\begin{gathered} strategic\ buildings \quad P_e = P(D \geq D_0) \\ interfering\ buildings \quad P_e = P(D \geq D_2) \\ critical\ buildings \quad P_e = P(D \geq D_1) \\ ordinary\ buildings \quad P_e = P(D \geq D_2) \end{gathered} \tag{16}$$

where D_2, D_1 and D_0 are the damage levels referred to the damage mean grade $\mu_D = 2$, $\mu_D = 1$ and $\mu_D = 0$, respectively.

Definitions reported above represent a first attempt to include urban planning concepts in seismic risk assessment. Of course, infrastructures such as transportation systems (roads, bridges, railways, etc.) or lifelines have to be included in future developments. A more comprehensive and life-like scenario can be evaluated using GIS-based software and modelling the interdependencies of such elements with appropriate models. An interesting example is represented by the *dependency matrix* of the SYNER-G (2011) approach.

2.2 Vulnerability Index extension for masonry aggregates

Masonry buildings in historical city centres are often built in aggregate sequence. It is generally challenging to understand if two contiguous buildings can be considered separately. In fact, seismic risk assessment requires to take into account possible interactions between adjacent buildings even if they are independent from the structural point of view. A simple methodological approach to account aggregate's effects has been proposed by Formisano et al. (2010), providing additional parameters P12-P16 to the vulnerability index, I_v, evaluation given in Table I. In this work, the aforementioned approach is adopted after a thoughtful parameters' recalibration. As a matter of fact, following the original approach, and considering moderate or low vulnerability buildings, the original parameters bring in some cases to negative I_v whereas, by definition, I_v has to be in the range [0-100]. For this reason, scores and weights have been adjusted in order to have non-negative values while keeping as much as possible a similarity with the original method. In the revised version, the additional parameters P12-P16 are modified as reported in Table IV.

The introduction of parameters P12-P16 results in a I_v variation of maximum ± 30% compared to the buildings considered as isolated, and the damage prediction is consequently influenced. The additional parameters have proved to provide better adhesion to the real damage observations of masonry structures.

2.3 $I_V - V$ correlation for RC buildings

The combined *Vulnerability Index - Macroseismic* approach (Vicente et al. 2011; Ferreira et al. 2013; Maio et al. 2016) considers at this stage masonry buildings only. Historical city centers, however, often present a heterogeneous mix of ancient masonry buildings and contemporary RC constructions, mainly due to post-war reconstruction. Vulnerability assessment of these RC buildings is necessary for a complete assessment of possible seismic damage scenarios. A mathematical correlation between the Vulnerability Index I_V and the Vulnerability Parameter V for RC buildings is herein proposed by Eq. 17:

$$V = 0.24 + 0.0165 \cdot I_V - 0.00003333 \cdot I_V^2 \tag{17}$$

This correlation represents an update of a previous formulation (Basaglia et al., 2016); specifically, the vulnerability definition of RC has changed, passing from the one defined by CETE Méditerranée (2008) to the original GNDT method (GNDT-SSN, 1994). The reason is due to the weight and scores of the vulnerability parameters that are considered to be overestimated by the first formulation. The above reported Eq. 17 has been derived following the analytical approach proposed by Vicente et al. (2011), and the main steps are briefly summarized below:

a) According to the classification proposed by Grünthal et al. (1998), RC buildings are most likely defined by vulnerability classes C, E and D;
b) For these classes, Bernardini et al. (2007) defined the Vulnerability Parameter, V, and the mean damage grade relation $\mu_D = \mu_D(V, I_{EMS-98})$, see Eq. 2;
c) Using the approach defined by Grimaz (1997) and then FEMA (2015), it is possible to define a mean damage grade relation $\mu_D = \mu_D(I_V, I_{EMS-98})$, where I_V is the vulnerability index;
d) Mean damage grade relations of steps (b) and (c) are used together to derive the V- I_V relationship given by Eq.14.

2.4 Multidirectional urban risk assessment

Ancient buildings often have an irregular in-plan layout and present different structural properties in different directions. Following the approach proposed by Grimaz (1993) for masonry buildings, structural vulnerability can be considered as the sum of *isotropic* and *anisotropic* factors. The isotropic factor considers all features unrelated to the input direction, such as the building materials' properties and age. The anisotropic factor includes all features dependant on the input direction, such as structural strength and stiffness as well as boundary conditions. It has been proved that directionality of incoming seismic waves along with the building orientation definitely affect the building seismic response. As a consequence, the overall urban vulnerability can be affected by the direction of incoming earthquakes.

Building's vulnerability typically assume its maximum value in one direction and its minimum value in the orthogonal direction, and can be effectively described by an elliptical function of the in-plan orientation. The *vulnerability ellipse concept* was firstly introduced by Grimaz (1993, 1997) and applied by Basaglia et al. (2016) to define the Vulnerability Index of buildings along their two principal directions (Fig. 3). This effect is accounted by modifying the Conventional Strength of the GNDT form (Parameter 3) according to Figs. 4a and 4b for masonry and RC buildings respectively.

The results obtained by Basaglia et al. (2016), however, have shown that seismic risk assessment results are not much affected by the adoption of the 2D formulation. In order to fully understand this evidence, some different aspects have to be considered. First of all, to date just one out of 11 parameters of the GNDT form (of 16 parameters if the aggregate sequence is taken into account) can be directly defined according to direction. Furthermore, constructions often present different structural deficiencies in both main directions, so that the resulting Vulnerability Indexes may be comparable. Finally, buildings of historical city centers are often arranged according to different orientations, due to the natural growth of the city through time (Fig. 1). For this reason, passing from the single element to the urban scale, the effect of vulnerability's ellipses in various directions may result attenuated.

Indeed, this aspect may be highly relevant when dealing with urban systems that have a regular buildings' disposition, where a higher difference in the overall seismic response is found depending on the earthquake's direction of propagation. Additional studies are required in order to properly assess the influence of the vulnerability ellipses on the seismic risk assessment.

3. COMPUTER-AIDED RISK ASSESSMENT

The proposed methodology for seismic risk assessment at the urban scale has been implemented in a MATLAB® environment. The main steps of the proposed numerical procedure are input data collection, numerical elaboration and GIS graphical visualization. The overall numerical procedure is summarized in the flowchart of Fig. 5.

The input data consists of information on buildings and site-effects of the area under consideration. More specifically, for each building, the following parameters are needed:

- Vulnerability Index I_V is evalulated in both principal directions (see § 1); for masonry and pre-code RC buildings I_V is evaluated by using Tables I and II respectively, for masonry aggregates using Table IV. It is reasonable to assume that all buildings designed according to new generation seismic codes present the lowest vulnerability level, $I_V = 0$.
- Structure Identifier is assigned to each building: ID = 0 for masonry buildings, ID = 1 for RC buildings and ID = 2 for buildings designed according to modern design codes;
- Local Soil Amplification Factor, F_a (Power, Borcherdt and Stewart 2004), is evaluated from geotechnical test of the considered site. In the case-study presented in §4, amplification factors are derived from tables of the Emilia Romagna region, published in the Public Act DAL 112/2007 (Emilia-Romagna Region 2007).

During the assessment, indexes I_V are converted into vulnerability values V according to Eqs. 9 and 17 for masonry (ID = 0) and RC buildings (ID = 1), respectively. For buildings designed according to modern seismic codes, $V = 0.24$ is assigned (Bernardini et al. 2007). Potential seismic site effects of the area under assessment are considered introducing an additional Vulnerability Modifier ΔV, see Eqs. 18 – 20, as proposed by Giovinazzi and Lagomarsino (2004):

$$\bar{V} = V + \Delta V \tag{18}$$

$$\Delta V = \frac{\Delta I}{6.25} \tag{19}$$

where:

$$\Delta I = \frac{\ln(F_a)}{0.602} \tag{20}$$

and F_a is the local soil amplification factor previously defined.

Mean damage grades μ_D are evaluated using Eqs. 2 and 3 for increasing intensities I_{EMS-98} in the $[5, 12]$ range. Lower intensities are not considered as they have negligible impact on buildings. For masonry and RC buildings of the Concordia sulla Secchia ELC, the ductility factor, Q, is assumed equal to 2.3 and 3, respectively. Using the mean damage grades, μ_D, damage probabilities $P(D_k)$ are defined using Eqs. 4 - 8. Finally, damage distributions are represented using fragility curves.

Damage probabilities $P(D_k)$ of all buildings are finally combined to determine the survival probability of the urban system, using models introduced in §2.1 for the considered limit condition (ELC, CLC, LSLC, DLC or OLC). The system survival probability is evaluated for increasing intensities I_{EMS-98} in the $[5, 12]$ range. In this way it is possible to predict the change in the city response towards moderate to strong earthquakes. Damage probabilities $P(D_k)$ can also be used to perform loss evaluations, predicting the number of damaged or unusable buildings as well as the number of casualties and severe injuries or homeless using the equations proposed by Vicente et al. (2011).

4. ELC RISK ASSESSMENT OF CONCORDIA SULLA SECCHIA. CASE STUDY

Comparing actual observed damage with predicted damage scenarios is the only way to improve the accuracy of seismic risk assessment methods. Italy represents a valuable asset in this regard, because of its considerable amount of post-seismic data collections, starting from the early years of the 20th century. For example D'Ayala and Paganoni (2010) have recently used damage data caused by the 2009 L'Aquila earthquake to test the reliability of the FaMIVE method. In that case however, the assessment focused mainly on old typical constructions of the L'Aquila's area, made of stones, bricks and rubbles, while RC buildings were excluded.

With a similar approach, in this work the case of the Italian city center of Concordia sulla Secchia has been considered to validate the proposed assessment methodology. Among all the cities hit by the Italian PPE in 2012, Concordia sulla Secchia has been selected due to its peculiar historical city center, made of a heterogeneous mix of masonry and RC buildings that date back to different periods of time and are typically built in aggregate sequence. After the PPE occurred, the Municipal authorities of Concordia commissioned a post-earthquake survey to the University of Ferrara (Regione Emilia-Romagna 2013), hanks to which geometrical and structural features of all buildings were gathered.

The PPE occurred on May 20, 2012 at 4:03 pm was classified of Magnitude Richter 5.9 (± 0.3) by the Italian National Institute of Geology and Volcanology (INGV). The epicentre was located at 8 km NW from Finale Emilia city with coordinates 44.89 ° N - 11.23 ° E and 6.3 km depth. The predominant incoming direction of PPE was WNW - ESE or 22° East. The municipalities closest to the epicentre were located on the border of Modena, Ferrara, Rovigo and Mantova provinces. Based on the National Seismic Network data, the shake map of the event was determined by INGV in an area of approximately 30x30 km^2 around the epicentre. Fig. 6 put in evidence that Concordia sulla Secchia experienced I_{EMS-98} in the [7, 8] range.

The ELC sub-system was defined by the Municipal Authorities of Concordia jointly with the Italian Civil Protection Department. Based on strategic buildings location and connecting main roads, the ELC sub-system is composed by a total of 42 elements: 4 strategic buildings (hosting a Day Care, a Kindergarten to Secondary School Institute, the City Hall and a Sports Centre) and 38 interfering buildings (hosting residential and commercial activities). From the structural point of view, 1 out of 4 strategic buildings is a pre-seismic code RC building, while 3 out of 4 are recent constructions, built following earthquake engineering design rules; 8 out of 38 interfering buildings are URM buildings built in aggregate sequence and 30 out of 38 are pre-seismic code RC buildings, whose 24 out of 30 are built in aggregate sequence. The ELC sub-system plan of Concordia sulla Secchia is reported in Fig. 7.

Thanks to available information, the risk assessment proposed methodology has been applied to the ELC sub-system of Concordia, damage scenarios and related μ_D have been obtained for the PPE event. Finally, the predicted damage scenarios have to be compared with the observed ones. Since the post-earthquake damage survey provides qualitative damage levels through a short description, in order to compare it with the numerical damage assessment, the following equivalence is assumed:

- *None* damage is related to μ_D in the [0, 1] range;
- *Very Light* to *Light* damage is related to μ_D in the [1, 2] range;
- *Moderate* to *Heavy* damage is related to μ_D in the [2, 4] range;
- *Very Heavy* damage is related to μ_D in the [4, 5] range;

The full comparison between observed and predicted damage levels is shown in Table V. Because the earthquake intensityI_{EMS-98} falls in the [7, 8] range, the predicted damage was computed for both intensity levels. For all the assessed buildings, Table V reports a feature identifier FID (used to identify buildings in the map), the vulnerability index I_V in the earthquake incoming direction, the construction period, the structural type, the predicted and observed damage levels. In particular, FID 113, 111, 110 and 112 refer to the 4 strategic buildings described above, respectively. The last columns report the difference $\Delta\mu_D$, between the predicted and the closest observed damage levels.

The comparison between damage levels reported in Table V shows that, for $I_{EMS-98} = 7$ the predicted damage matches the observed damage in 21 out of 42 buildings (highlighted in bold text and light grey background), with a positive feedback in 50% of cases. For $I_{EMS-98} = 8$, the predicted damage matches the observed damage in 26 of the 42 buildings (highlighted in bold text), with a positive feedback in about 62% of cases.

Figs. 8 show the frequency distributions of damage difference, $\Delta\mu_D$, where the and value "0" means the matching between predicted and observed post-earthquake damage scenario. For $I_{EMS-98} = 7$ (Fig. 8a) the risk assessment methodology generally underestimates damage, with a deviation of -0,8 μ_D that, related to the maximum damage grade ($\mu_{D,max} = 5$), means an error of -16%. For $I_{EMS-98} = 8$ (Fig. 8b) the risk assessment methodology generally overestimates damage, with a deviation of 0,6 μ_D and a maximum error of +12%.

The performed comparison shows that the damage prediction offered by the proposed methodology is quite reliable. In fact, the results obtained for I_{EMS-98} in the [7, 8] range are generally in good agreement with the post-earthquake survey data. In some cases the predicted and the observed damage are inconsistent (see for example FID 73 or FID 66 - 2). The deviation of the damage predictions may be due to imperfections of the proposed methodology and/or to approximations in the post-earthquake surveys, which were necessarily quick and coarse. This case study represents the first application of the proposed risk assessment methodology and, of course, further validation is deemed essential to test and increase its effectiveness.

The ELC sub-system survival probability is represented in Fig. 9. It is obtained by evaluating the probability of single buildings using Eq. 10 and then the overall survival probability using Eq. 7. In fact, by definition of the ELC, all elements are considered to be represented by a series system. It is observed that, for intensity $I_{EMS-98} \geq 7$ the survival probability drops to zero. This means that at least one strategic building or one interfering building has exceeded the considered damage thresholds of Eq. 13, consistently with the series system definition. As the 2012 PPE intensity I_{EMS-98} was in the [7, 8] range, the ELC of Concordia city needs definitely major improvements in order to survive future earthquakes.

Assessment output values can be depicted on a city map, as reported in Figs. 10, using the geospatial processing program ArcMap, of the Esri's ArcGIS suite (Chang 2006). Thanks to this suite it is possible to visualize the earthquake effects for different directions and increasing seismic intensities (Cova, 1999). A FID is assigned to each building in order to correctly reference the corresponding output results. Different colour maps can be used to represent the effects of increasing seismic intensities, and to identify the most vulnerable areas.

5. SUMMARY AND CONCLUSIONS

Seismic risk prevention is a urgent global goal that aims at reducing human casualties and economic losses and at preserving the inestimable cultural heritage of historical city centres. This paper proposes a general seismic risk assessment methodology at the urban scale, based on predefined performance level. It can be a useful tool to develop urban risk mitigation plans. The original contributions of the proposed methodology are:

- Performance-based approach has been applied to the urban settlement, resulting in the definition of the urban system survival probability. Thanks to this concept, predicted damages of many structures are used to define a single parameter representing the performance of the whole system, that is easier to understand;
- Masonry constructions built in aggregate sequence are taken into account by updating an existing method. Including this aspect leads to a better estimation of the damage that adheres more to real post-earthquake observations;

- RC buildings are included in the assessment evaluation. Existing formulations were available only for masonry structures. However, RC buildings constitute a significant part of historical city centres as well, and have to be included in the assessment in order to evaluate the seismic risk at the urban level;
- Vulnerability ellipse concept has been discussed and implemented in order to obtain the multi-directional assessment of the building performance. It is well know that structural response can be strongly dependent on earthquake direction. At global level, directional assessment is pivotal to produce reliable damage scenarios and related mitigation plans.

The proposed assessment method has been implemented in a computer-aided procedure using the MATLAB® software. The output results can be easily visualized by means of simple curves and GIS maps. The proposed automated procedure has been applied to a case study, the historical city centre of Concordia sulla Secchia (Italy), selected for its heterogeneous mix of masonry and RC structures, built in different periods, often in aggregate sequences. The settlement experienced the PPE in 2012, and was object of post-seismic damage survey. The proposed methodology has been carried out on the city ELC sub-system constituted by 42 buildings. From the comparison between predicted and observed damage, a matching rate of 50% ($I_{EMS-98} = 7$) and 62% ($I_{EMS-98} = 8$) has been found. This latter intensity may be considered as the most representative of the occurred seismic event. Recognizing the complexity of seismic risk assessment at the urban scale, the obtained results are considered promising. However, the procedure needs further validations on more case studies to be improved. Currently, the proposed methodology has been used to assess the expected earthquake damage on the historical Eixample district of Barcelona, Spain (Cara et al. 2018).

This paper is part of an ongoing research: the methodology used to estimate damage for the ELC sub-system of Concordia sulla Secchia is being used to assess the positive effects of mitigation strategies, including seismic retrofits. Indeed, expert committees instituted by the regional authorities of Emilia Romagna Region are actually processing post-earthquake reconstruction data in order to assess economic and social consequences produced by the aftermath of PPE in 2012. The application of the proposed methodology is proving to be essential helping the Decision-making Authorities in the task of increasing the resilience of historical city-centres.

Future work is expected to address the following issues, listed in order of priority:

- Definition of GNDT forms (parameters, scores and weights) for other structural types (for example precast, mixed structures and steel buildings);
- Integration of the GNDT forms with the aggregate effect and seismic retrofits;
- Simplification of the vulnerability assessment of huge urban systems. Large scale analyses require unacceptable time efforts to carry out the detailed survey needed to fill the GNDT (GNDT-SSN 1994) forms for all buildings. Following the Portuguese approach (Vicente et al. 2011; Ferreira et al. 2013; Maio et al. 2016) a "representative sample" should be defined to reasonably estimate the vulnerability of the remaining buildings.
- Inclusion of infrastructures like bridges, water supply, electric distribution and ICT networks in the urban risk assessment, as they represent the most critical facilities or "backbone" of the overall emergency response and post-event recovery;

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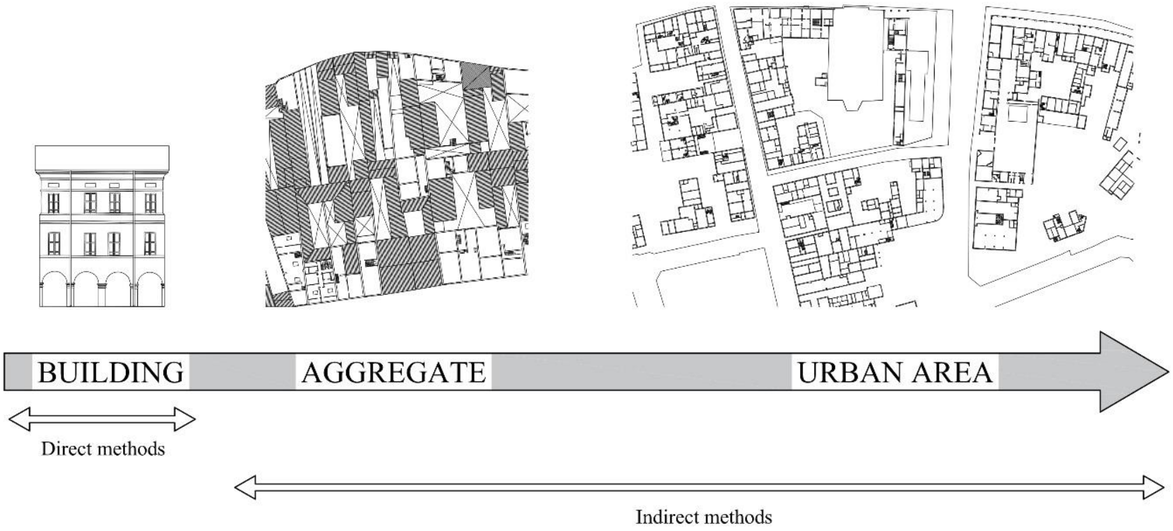

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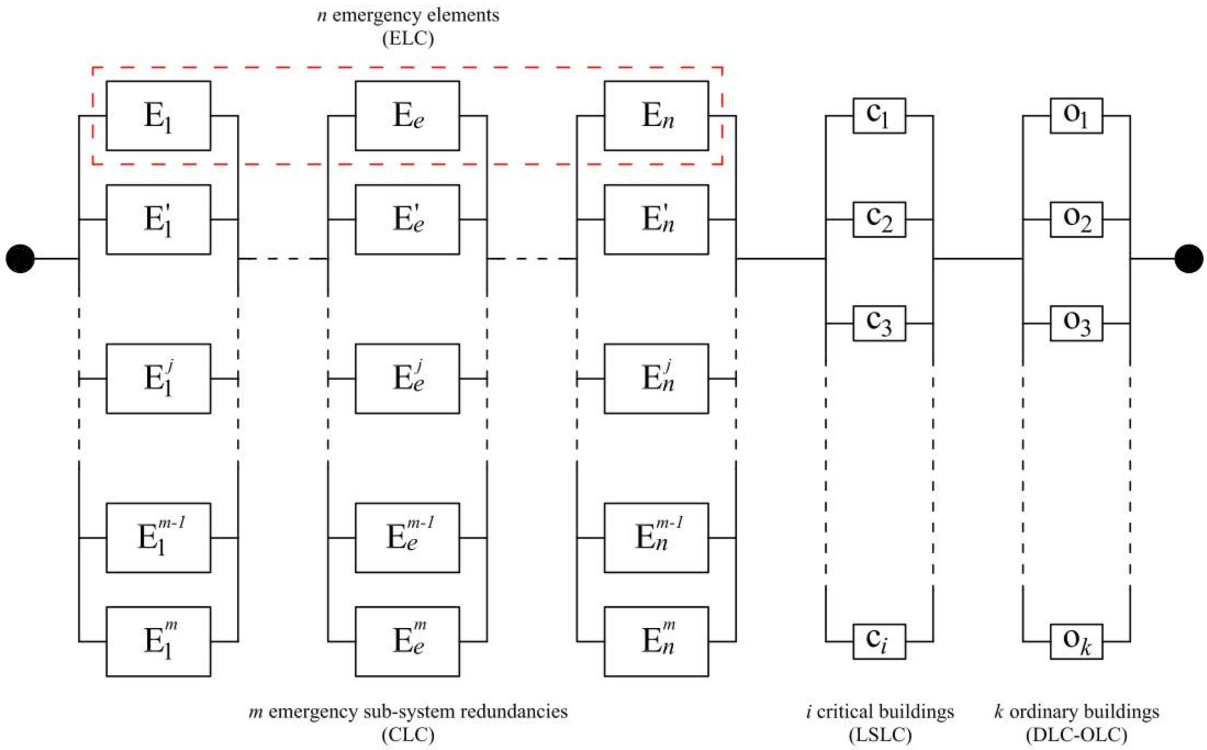

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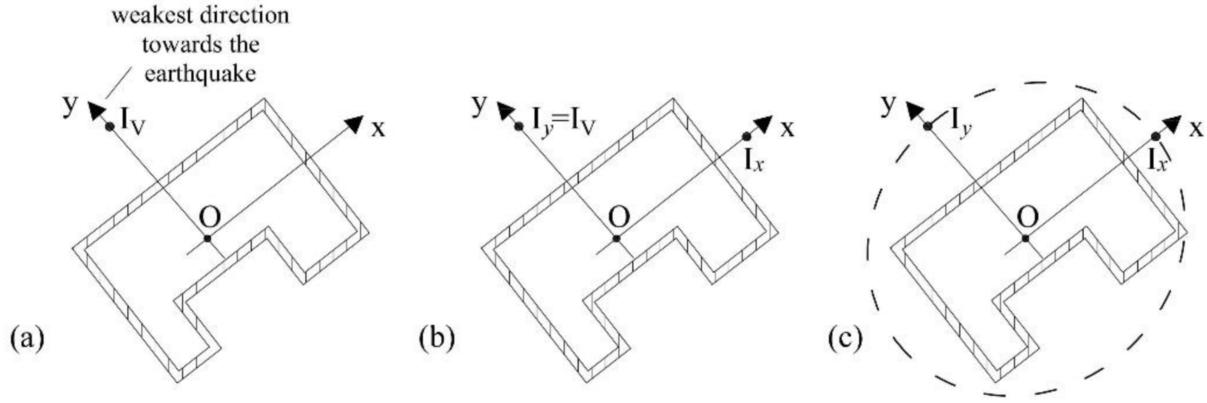


Fig. 3. Vulnerability ellipse concept.

PARAMETER 3 GNDT FORM (Conventional Strength)

MASONRY BUILDINGS

Building's no. of stories	N	[-]
Roof area	A_R	[m^2]
Resisting area in X-direction	A_X	[m^2]
Resisting area in Y-direction	A_y	[m^2]
Transversal strength reference	k	[t/m^2]
Average interstorey height	h	[m]
Unit weight of brick walls	p_m	[t/m^3]
Distributed load of ceilings	p_s	[t/m^2]
Evaluation in X-direction	$a_{0,X}$	[-]
	γ	[-]
	q	[t/m^2]
	C	[-]
	α_X	[-]
Evaluation in Y-direction	$a_{0,Y}$	[-]
	γ	[-]
	q	[t/m^2]
	C	[-]
	α_Y	[-]

R.C. BUILDINGS

	Building's no. of stories	N	[-]
	Average interstorey height	h	[m]
	Total height of building	H	[m]
	Fundamental vibration period	T_1	[s]
	Ground type	(S1 or S2)	
	Seismic coefficient	R	[-]
	Total seismic force (ΣF_i*)	FS	[t]
REINFORCED CONCRETE	No. of pillars	n_{pil}	[-]
	Average pillar side length	l_{pil}	[m]
	R.C. resistant area	$A_{R.C.}$	[m^2]
	Transv. strength reference	τ_k	[t/m^2]
	R.C. Young modulus	$E_{R.C.}$	[t/m^2]
	Toral resistant force ($A \cdot \tau$)	FR	[t]
	Alfa coefficient	α	[-]
	Main resistant direction	(X or Y or NONE)	
	Form coefficient	β	[-]
MASONRY (*infill walls*)	Masonry class	(A, high or B, low quality)	
	Masonry resistant area in X	$A_{M,X}$	[m^2]
	Masonry resistant area in Y	$A_{M,Y}$	[m^2]
	Transv. strength reference	τ_k	[t/m^2]
	Masonry Young modulus	E_M	[t/m^2]
	Modular ratio (E_M / $E_{R.C.}$)	n	[t]
	Pillars' no. in X-direction	$n_{pil,X}$	[-]
	Pillars' no. in Y-direction	$n_{pil,Y}$	[-]
	Evaluation in X-direction	α_X	[-]
	Evaluation in Y-direction	α_Y	[-]

MASONRY

$$a_0 = \frac{A}{A_{TOT}}$$

$$\gamma = \frac{B}{A}$$

$$q = (A_x + A_y) \cdot h \cdot \left(\frac{p_m}{A_{TOT}}\right) + p_s$$

$$C = \frac{a_0 \cdot \tau_k}{q \cdot N} \cdot 1 + \left[\frac{q \cdot N}{1.5 \cdot a_0 \cdot \tau_k \cdot (1+\gamma)}\right]^{0.5}$$

$$\alpha = \frac{C}{0.4}$$

X-direction: $A_X = A$; $A_y = B$

Y-direction: $A_y = A$; $A_X = B$

R.C.

	T_0	r	R_0
S1	0.35	2/3	2.6
S2	0.8	2/3	2.2

$0 < T < T_0$, $R = R_0$

$T_0 < 0$, $R = \frac{R_0}{(T-T_0)^r}$

$F_i = 0.4 \cdot R \cdot W_i \cdot h_i \cdot \frac{\Sigma W_i}{\Sigma W_i h_i}$, for the *i-th* floor

W_i, floor weight

$\alpha = A \cdot \tau / F_S$

X main res. dir.	Y main res. dir.	NO main res. dir.
$\beta = \frac{A_{RC,x} + n \cdot A_{M,x}}{A_{RC,y} + n \cdot A_{M,y}}$	$\beta = \frac{A_{RC,y} + n \cdot A_{M,y}}{A_{RC,x} + n \cdot A_{M,x}}$	$\beta = 1$
$\alpha_X = \beta \cdot \alpha$	$\alpha_X = \alpha$	$\alpha_X = \alpha$
$\alpha_y = \alpha$	$\alpha_y = \beta \cdot \alpha$	$\alpha_y = \alpha$

(a) **(b)**

Fig 4. Modified Conventional Strength (Parameter 3) of the GNDT form for **(a)** masonry buildings; **(b)** RC buildings.

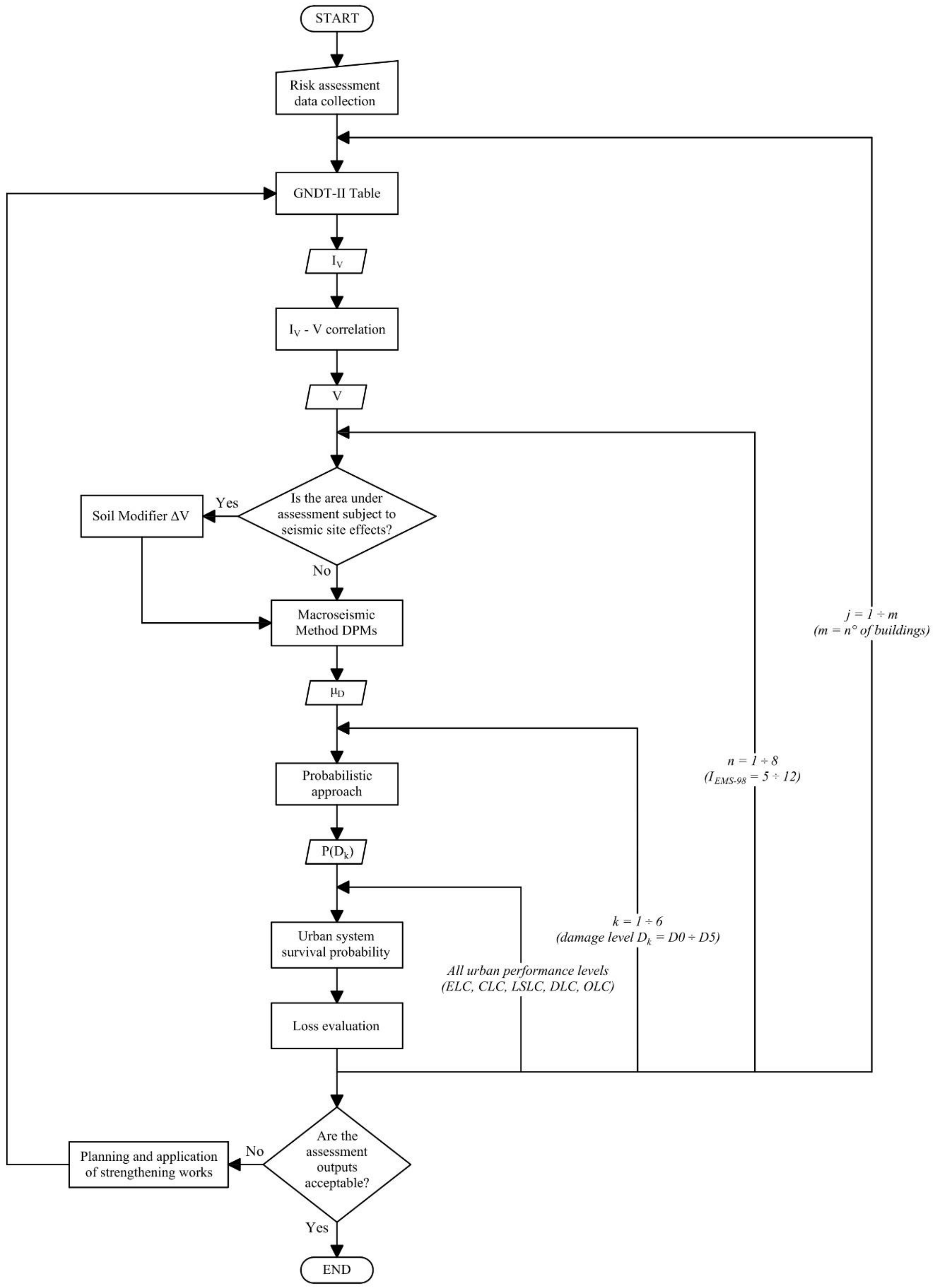
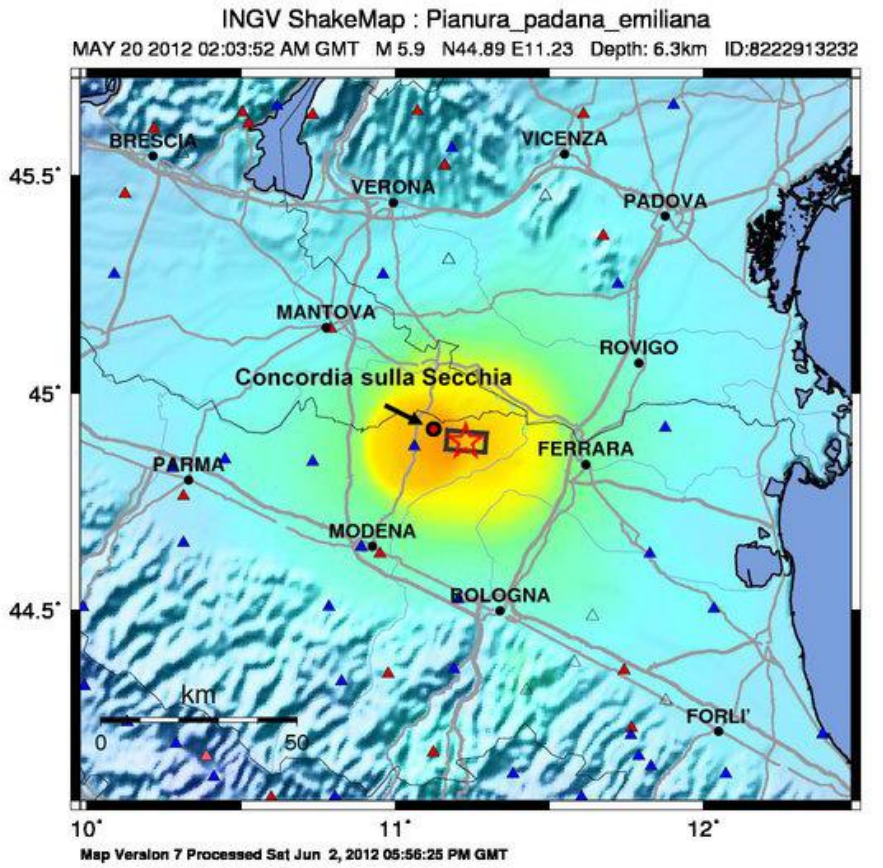


Fig. 5. Flowchart of the risk assessment procedure.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
PEAK VEL.(cm/s)	<0.07	0.4	1.9	5.8	11	22	43	83	>160
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Fig. 6. Italian PPE shake map (adapted by INGV) for the Pianura Padana Earthquake of May 20, 2012.

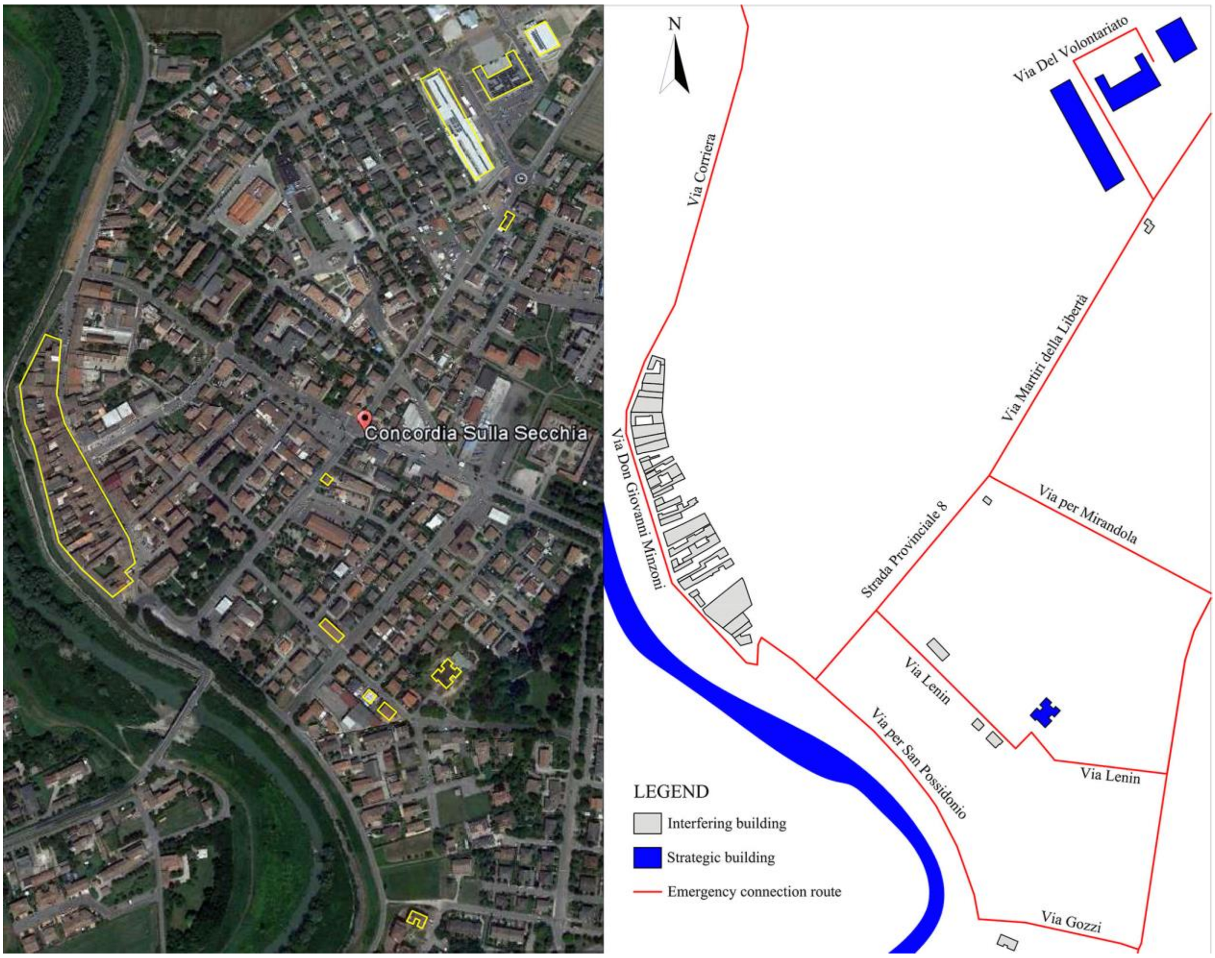
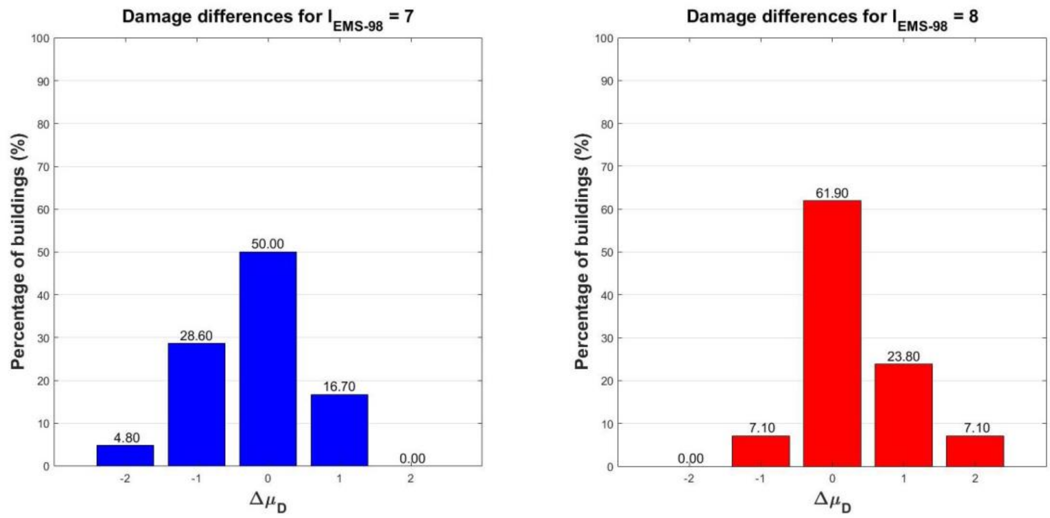


Fig. 7. ELC plan of Concordia sulla Secchia (aerial view and location of assessed buildings).



a) **b)**

Fig. 8. $\Delta\mu_D$ frequency distribution of the Concordia sulla Secchia ELC sub-system for **(a)** $I_{EMS-98} = 7$; **(b)** for $I_{EMS-98} = 8$.

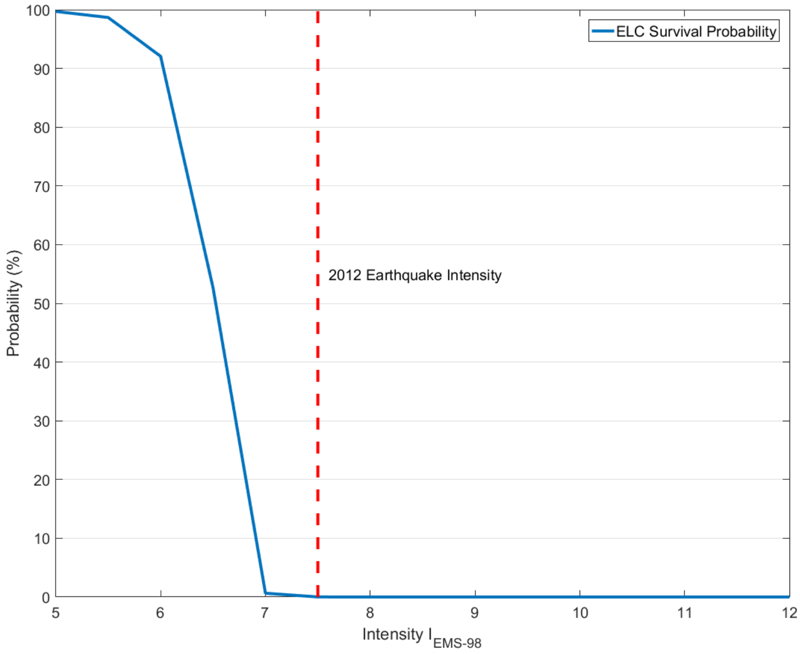
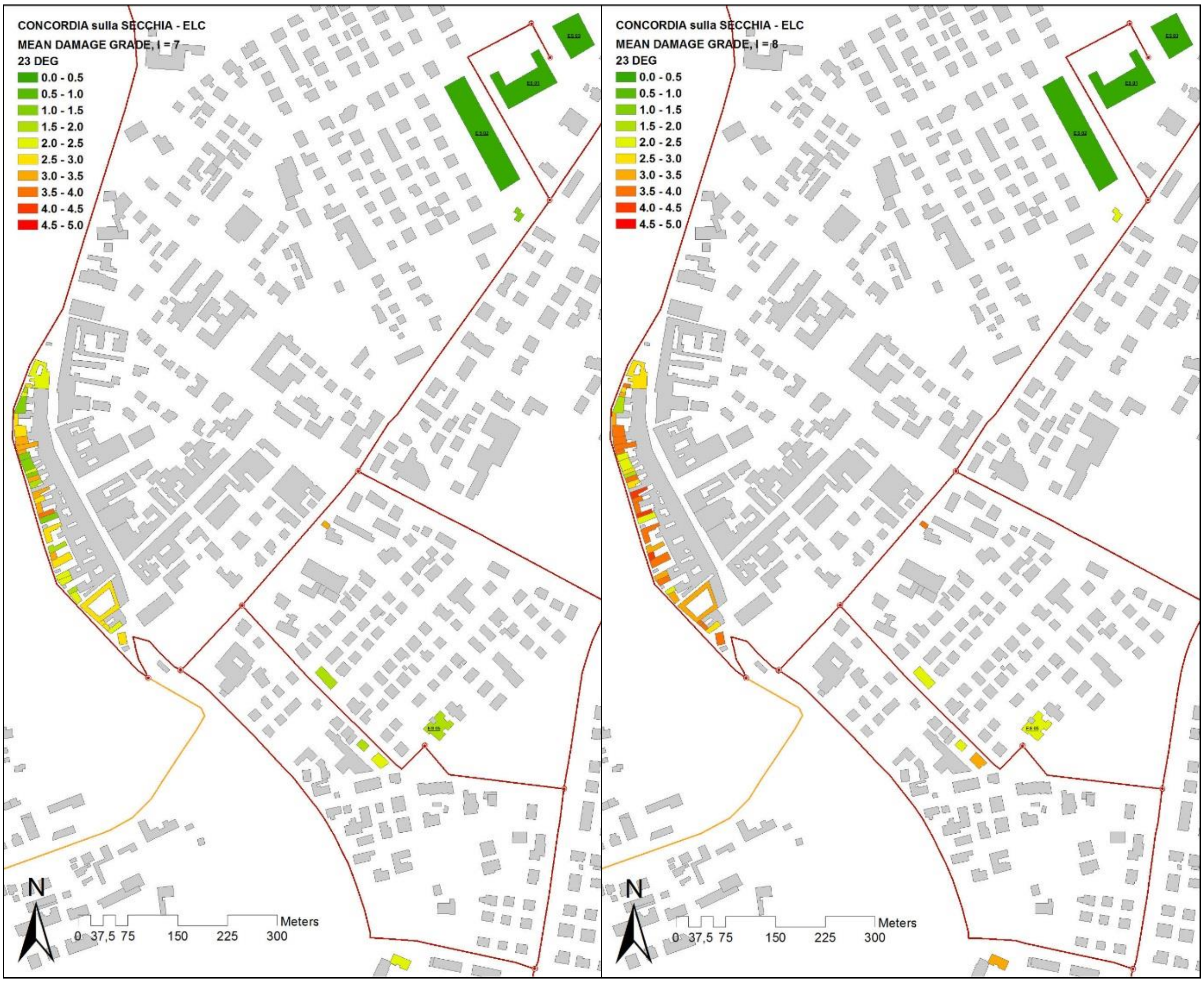


Fig. 9. Survival probability of the Concordia sulla Secchia ELC sub-system.



a) **b)**

Fig. 10. Damage grade maps of the Concordia sulla Secchia ELC sub-system for **(a)** $I_{EMS-98} = 7$; **(b)** for $I_{EMS-98} = 8$.

LIST OF TABLES

Table I. Vulnerability Index (I_V) for masonry buildings.

Parameters		**Class - C_{vi}**				**Weight**	**Vulnerability index**
		A	**B**	**C**	**D**	$\boldsymbol{w_i}$	
P1	Type and organization of resisting system	0	5	20	45	1.00	
P2	Quality of resisting system	0	5	25	45	0.25	$I_V^* = \sum_{i=1}^{11} C_{vi} \cdot w_i$
P3	Conventional strength	0	5	25	45	1.50	
P4	Building position and foundations	0	5	15	45	0.75	
P5	Horizontal diaphragms	0	5	25	45	variable *	
P6	Plan configuration	0	5	25	45	0.50	
P7	In height configuration	0	5	25	45	variable *	
P8	Maximum distance between walls	0	5	25	45	0.25	
P9	Roof	0	15	25	45	variable *	Normalization:
P10	Non structural elements	0	0	25	45	0.25	$0 \leq I_V \leq 100$
P11	General maintenance conditions	0	5	25	45	1.00	

* see GNDT-SSN, 1994 for the weight definition

Table II. Vulnerability index (I_V) for RC buildings.

Parameters		**Class C_{vi}**				**Vulnerability index**
		A	**B**	**C**	**D***	
P1	Type and organization of resisting system	0	-1	-2		
P2	Quality of resisting system	0	-0.25	-0.5		
P3	Conventional strength	0.25	0	-0.25		$I_V^* = \sum_{i=1}^{11} C_{vi}$
P4	Building position and foundations	0	-0.25	-0.5		
P5	Horizontal diaphragms	0	-0.25	-0.5		
P6	Plan configuration	0	-0.25	-0.5		Normalization:
P7	In height configuration	0	-0.5	-1.5		**a)** if $I_V^* > -6.5$,
P8	Connections and critical elements	0	-0.25	-0.5		$I_V = -10.07 \cdot I_V^* + 2.5175$
P9	Low ductility elements	0	-0.25	-0.5		**b)** if $I_V^* < -6.5$,
P10	Non-structural elements	0	-025	-0.5		$I_V = -1.731 \cdot I_V^* + 56.72$
P11	General maintenance conditions	0	-0.5	-1	-2.45	

* Class D is defined only for P11

Table III. Performance levels of urban functions in different limit conditions.

Limit state condition for urban settlement	**Strategic functions for emergency ***	**Strategic functions for urban recovery**	**Main and ordinary urban functions**	**Residence**
Operational Limit Condition (**OLC**)	FF	FF	FF *	FF *
Damage Limit Condition (**DLC**)	FF	FF	ML	ML
Life-safety Limit Condition (**LSLC**)	FF	FF	ML	ML
Collapse Limit Condition (**CLC**)	FF	ML	ML	RI
Emergency Limit Condition (**ELC**)	FF **	RI	RI	RI

FF: Fully Functional
ML: Marginal limitation (temporary or localized)
RI: Relevant Interruption (average-to-long term)

* accepted local losses not relevant at urban level
** most part

Table IV. Proposed update of the vulnerability Index (I_V) additional parameters for masonry buildings in aggregate sequence.

Parameters		Class C_{vi}				Weight
		A	**B**	**C**	**D**	p_i
P12	Presence of adjacent buildings with different height	0	15	25	45	1.25
P13	Position of the building in the aggregate	0	5	15	45	1.75
P14	Presence and number of staggered floors	0	25	35	45	0.75
P15	Effects of either structural or typological heterogeneity among adjacent structural unit	0	10	20	45	1.50
P16	Percentage difference of opening areas among adjacent facades	0	15	35	45	1.25

Table V. Risk assessment methodology validation. ELC sub-system of Concordia sulla Secchia, hit by the 2012 Pianura Padana Earthquake.

FID	I_V	CONSTRUCTION PERIOD (+ renovation if any)	STRUCTURAL TYPE	OBSERVED DAMAGE LEVEL INTERVAL	PREDICTED DAMAGE LEVEL		$\Delta\mu_D$	
					I = 7 (EMS-98)	**I = 8** (EMS-98)	**I = 7** (EMS-98)	**I = 8** (EMS-98)
79	32.73	82 - 91	RC	4 - 5	2	3	-2	-1
78	61.41	72 - 81	MASONRY	4 - 5	3	**4**	-1	-
77	30.21	72 - 81	RC	0 - 1	2	3	+1	+2
76	37.76	72 - 81	RC	2 - 4	**2**	**3**	-	-
75	20.14	92 - 01	RC	0 - 1	**1**	2	-	+1
74	42.80	82 - 91	RC	1 - 2	3	3	+1	+1
73	45.32	62 - 71	RC	1 - 2	3	4	+1	+2
72	50.35	72 - 81	RC	4 - 5	3	**4**	-1	-
71 - 70	50.35	72 - 81	RC	4 - 5	3	**4**	-1	-
69	22.66	92 - 01	RC	1 - 2	**1**	**2**	-	-
68	22.66	62 - 71	RC	2 - 4	1	**2**	-1	-
67 - 1	35.25	92 - 01	RC	1 - 2	**2**	3	-	+1
67 - 2	22.66	92 - 01	RC	1 - 2	**1**	**2**	-	-
66 - 1	52.87	< 1919 + 92 - 01	RC	4 - 5	3	**4**	-1	-
66 - 2	32.73	< 1919 + 92 - 01	RC	4 - 5	2	3	-2	-1
63	66.08	72 - 81	MASONRY	4 - 5	3	**4**	-1	-
64	57.14	92 - 01	MASONRY	4 - 5	3	**4**	-1	-
65	50.35	< 1919	RC	1 - 2	3	4	+1	+2
61	60.42	19 - 45	RC	4 - 5	**4**	**4**	-	-
60	25.18	72 - 81	RC	0 - 1	**1**	2	-	+1
59	50.35	72 - 81	RC	2 - 4	**3**	**4**	-	-
106	35.28	72 - 81	MASONRY	1 - 2	**2**	3	-	+1
105	61.82	72 - 81	MASONRY	4 - 5	3	**4**	-1	-
104	55.17	19 - 45	MASONRY	4 - 5	3	**4**	-1	-
58	47.07	< 1919	MASONRY	2 - 4	**2**	**3**	-	-
57	50.71	< 1919	MASONRY	2 - 4	**3**	**4**	-	-
56	25.18	92 - 01	RC	2 - 4	**2**	**2**	-	-
55	32.73	82 - 91	RC	2 - 4	**2**	**3**	-	-
54	40.28	92 - 01	RC	4 - 5	3	3	-1	-1
53 - 52	45.32	62 - 71	RC	2 - 4	**3**	**4**	-	-
51	37.76	62 - 71	RC	2 - 4	**2**	**3**	-	-
29	45.32	46 - 61 + 72 - 81	RC	4 - 5	3	**4**	-1	-
33	25.99	62 - 71	RC	0 - 1	2	2	+1	+1
32	27.23	19 - 45	RC	0 - 1	2	2	+1	+1
31	35.48	> 2002	RC	2 - 4	**2**	**3**	-	-
30	38.12	46 - 61 + 72 - 81	RC	1 - 2	**2**	3	-	+1
34	46.59	62 - 71	RC	4 - 5	3	**4**	-1	-
35	24.14	92 - 01 + > 2002	RC	0 - 1	**1**	2	-	+1
113	25.38	72 - 81	RC	0 - 1	2	2	+1	+1
111	0.1	> 2002 (2012)	STEEL	0 - 1	**0**	**1**	-	-
110	0.1	> 2002 (2012)	MIXED	0 - 1	**0**	**1**	-	-
112	0.1	> 2002 (2013)	STEEL	0 - 1	**0**	**1**	-	-