Seismic risk assessment at territorial scale for Southern Lazio: a preliminary application to Cassino

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ABSTRACT

The evaluation of seismic risk is a complex task that combine data coming from different field of expertise. The most diffused products of those studies are maps that are a graphical representation of the potential adverse outcomes that a seismic event can have over the territory at study, typically focusing on urban areas where the human activities are concentrated. Main source of concern is indeed the existing building stock, mostly composed by structures not compliant with modern seismic design criteria.

The assemblage of a building inventory is pivotal for the evaluation of seismic risk. Building inventory represents how building typologies are distributed at the territorial scale and are necessarily coupled with a seismic vulnerability assessment of each class of buildings. Census-based data are usually employed as primary source for building inventory. A recent advancement is provided by the Cartis project, implemented in Italy within "Territorial themes" of Reluis consortium, financed by the Italian Civil Protection Department. This paper proposes a preliminary evaluation of the seismic risk of the town of Cassino in Southern Lazio using Census data (ISTAT) and already available fragility curves calibrated at national level. This is intended as a Level 0 approach to be used as comparison for the ongoing CARTIS programme, when more refined data will be available.

1 INTRODUCTION

As demonstrated by some of the most recent Italian earthquakes (Molise 2002, L'Aquila 2009, Emilia Romagna 2012, Central Italy 2016), existing buildings may have an inadequate structural performance against seismic actions (Decanini et al. 2004; Rasulo et al. 2004, Lavorato et al. 2019, Marino et al. 2019). People expectation is that modern standards of living should avoid the harm that a moderate to strong earthquake can induce to a community in terms of loss of lives and damages.

It is a matter of fact that the techniques about how the building would be constructed in order to reduce damages and prevent the collapses have evolved at a highly faster speed than the renovation of the building stock. Furthermore it is believed that the increase of the structural safety of existing buildings and infrastructures in seismic prone areas can be extremely expensive. Therefore any decision about mitigation measures to be undertaken is necessarily a trade-off between the cost-effectiveness of preparing for risks and that of coping with their consequences.

By this point of view, the assessment of seismic risk at large-scale is a pivotal point for any measure aimed at safeguarding people and undertaking possible mitigation plans. Generally an useful tool is represented by seismic risk maps, that represent the expected loss an earthquake can produce over a territory. Since those maps deal with events that would occur in the near future, their development must take into account the uncertainty that are involved into the forecast. Usually the developing of such a map is a complex task that involves many disciplines including geophysics and geology (in order to take in account past seismicity, seismo-tectonic framework, wave propagation as well as soil effects), survey (in order to collect data about the building stock), structural analysis (in order to assess the building response under seismic loads) and social and economic sciences (in order to evaluate socio-economic consequences of an earthquake). The standard definition of seismic risk is the probability or likelihood of a damage, due to an earthquake, and consequent loss to a specified class of elements at risk over a specified period of time. In order to keep the problem of computing the risk tractable, it is tackled initially decomposing the task in specialized (simpler) components, conditionally independent. Those components are essentially three, conventionally referred as hazard (devoted to assess the likelihood of the seismic shaking on ground), vulnerability (devoted to study the susceptibility to damage of the built environment) and exposition (devoted to evaluate the socio-economic consequences of the damages).

Once the single components have been evaluated, the risk is obtained, finally, applying recursively the total probability theorem to aggregate together the separate components. Hence the risk can be symbolically expressed in the form of a convolution integral (Cornell and Krawinkler 2000):

$$G_{L,\Delta T}(z) = \int_y G_{L|LS}(z\,|\,y)\cdot\ldots$$

$$\ldots\cdot\int_x f_{LS|IM}(y\,|\,x)\cdot\left|\frac{dG_{IM,\Delta T}(x)}{dx}\right| dx\; dy \qquad (1)$$

where:

$G_{L,\Delta T}(z)$	is the probability of exceeding a loss, L, equal to z ($L \geq z$) in a period of time ΔT;
$G_{IM,\Delta T}(x)$	is the probability of exceeding a seismic intensity measure, IM, equal to x ($IM \geq x$) in a period of time ΔT;
$f_{LS\|IM}(y\|x)$	is the conditional probability of strictly attaining a damage state, LS, equal to y ($LS=y$), given the attainment of a seismic intensity measure, IM, equal to x ($IM=x$);
$G_{L\|LS}(z\|y)$	is the conditional probability of exceeding a loss, L, equal to z ($L \geq z$), given the attainment of a damage state, LS, equal to y ($LS=y$).

In Equation (1) the seismic intensity measure, *IM*, is one of the different parameters used to represent the severity of the ground shaking at site (e.g., macro-seismic Intensity, peak ground acceleration or spectral acceleration at a selected natural period).

The loss, *L*, summarizes the consequences of the seismic damage and is measured in socio-economic terms (e.g., casualties, monetary losses, duration of downtime).

The damage state is represented here by the technically conventional concept of Limit State, *LS*, which is commonly understood by structural engineers and is defined in modern seismic design codes. Since the Limit States are discrete quantities, the integration over y becomes more reasonably a summation over a finite number of Limit States, LS_y; $y=[1,\ldots,n_{LS}]$, as explicitly done in the application calculations in equation (4).

Absolute value is used on the hazard component, since the differential is negative.

Sometimes the integral in equation (1) is calculated using annual frequencies, $\lambda(u) = \Pr[U \geq u; \Delta T = 1\ \text{year}]$, rather than probabilities over a generic time interval ΔT, $G_{U,\Delta T}(u)=\Pr[U \geq u;\Delta T]$, since hazard curves are routinely defined as such, but the outcomes are consequently very small probabilities, less effective to be presented to general public which is more impressed by the risk of an adverse outcome projected in a lifetime (usually 30 or 50 years).

Since the seismic process in time is Poissonian the two quantities are correlated as follows:

$$G_{\Delta T}(u) = 1 - e^{-\lambda(u)\Delta T} \qquad (2)$$

Some examples of seismic risk analysis on engineering structures and infrastructures can be found in (Faccioli and Pessina 2000; Dolce et al. 2003; Nuti et al. 2007; Nuti et al. 2010; Rasulo 2015, Rasulo 2017).

2 SEISMIC HAZARD

Seismic Hazard analysis is aimed at estimating a measure of the intensity of the ground motion at a site considering the characteristics of surrounding seismic sources. This kind of study is restricted to the shaking felt at the ground level and does not consider the action on the built environment. Therefore in hazard analysis the core aspects investigated are the source modelling (i.e. mechanism at the epicenter that produces the shaking), the wave attenuation (along the path between the source and the site of interest) and the local ground amplification (through the ground layers around the site).

The probabilistic assessment of seismic hazard involves determining either the probability of exceeding a specified ground motion, or the ground motion that has a specified probability of being exceeded over a particular time period. Accordingly, output of the hazard analysis is either a curve showing the exceedance probabilities of various ground motions at a site, or a hazard map that shows the estimated magnitude distribution of ground motion that has a specific exceedance probability over a specified time period within a region.

Despite the fact that several studies on seismic hazard were undertaken in Italy before, only after 2004 this kind of analysis assumed official recognition in technical community, since the seismic classification was compulsory associated with the likelihood of reaching some levels of seismic accelerations at site. Therefore the probabilistic hazard analysis conducted by the INGV (Meletti and Montaldo 2007), has become the Italian national reference in engineering applications.

3 SEISMIC VULNERABILITY

Seismic Vulnerability represents the susceptibility to damage of the object at study, given a measure of the seismic input. Methods applied in representing the vulnerability analysis vary greatly depending on the complexity of the approach and the available data about exposure (see next section). Generally when in a vulnerability analysis it is considered a single item (like a specific building) the study can reach a very fine level of detail, defying the modality of damage and/or the number and type of components damaged (Grande and Rasulo 2013; Grande and Rasulo 2015); on the other hand when it is under scrutiny a bulk of items, like a building stock, the vulnerability may necessarily been defined in looser terms as the damage potential of a class of similar structures, using as classification a broad identification (as for example the same structural type, number of floors, age, technique of construction …). Vulnerability of structures to ground motion effects is often expressed in terms of fragility curves (or damage functions) that take into account the uncertainties in the seismic demand and capacity.

In the present study the fragility curves have been built according to the SP-BELA approach (Borzi et al. 2008a; Borzi et al. 2008b). According to this methodology the displacement capacity of the buildings at different damage levels (limit states) is produced, relating the displacement capacity to the material and geometrical properties. Three limit state conditions have been taken into account: slight damage (LS1), significant damage (LS2) and collapse (LS3). The slight damage limit condition refers to the situation where the building can be used after the earthquake without the need for repair and/or strengthening. If a building deforms beyond the significant damage limit state it cannot be used after the earthquake without retrofitting. Furthermore, at this level of damage it might not be economically advantageous to repair the building. If the collapse limit condition is achieved, the building becomes unsafe for its occupants as it is no longer capable of sustaining any further lateral force nor the gravity loads for which it has been designed. The aforementioned limit states can be assumed equivalent to the definitions contained in Eurocode 8, as follows: LS1: Damage Limitation (DL), LS2: Significant Damage (SD) and LS3: Near Collapse (NC).

In order to fit fragility functions to exposure data, in the case of masonry buildings, four separate building classes have been defined as a function of the number of storeys (from 1 to 4), whilst for reinforced concrete the building classes have been defined considering the number of storeys (from 1 to 4) and the period of construction. The year of seismic classification of each municipality has then been used so that the non-seismically designed and seismically designed buildings could be separated. In this way, the evolution of seismic design in Italy and the ensuing changes to the lateral resistance and the response mechanism of the building stock could be considered.

4 EXPOSURE

Exposure is a representation of the population of items object of the study and their relevant aspects in relation to the risk analysis (this kind of information has necessarily to interact with hazard and vulnerability components of the study). Depending on the extension of the scope of the analysis, exposure may include a single building with its occupants and contents, or may include the entire constructed environment in a specified area, inclusive of buildings and lifelines (infrastructural systems forming networks and delivering services and goods to a community). The characterization of building typologies is intended to investigate the whole local panorama, identifying under the qualitative profile the presence of peculiar constructive characteristics. In fact, throughout the country, construction techniques have differentiated over the centuries due to local cultures and conditioning, and this may have significantly affected the characteristics and quality of the construction, determining substantial differences also in terms of seismic response. In order to facilitate information collection about the existing facilities in a region, a standardization of the inventory has been attempted, providing a systematic classification of the structures according to their type, occupancy and function, by the CARTIS project (Zuccaro 1999) developed by the PLINIVS research centre of the University of Naples "Federico II" within the within "Territorial themes" of ReLUIS consortium, in collaboration with the Department of Italian Civil Protection (DPC). The scope of the CARTIS project is to improve the knowledge of building taxonomies, commonly found in Italian urban centres, and their territorial distribution at national scale. At this aim a form has been developed to collect the relevant information about ordinary buildings over municipal or sub-municipal areas, called urban sectors. The buildings studied are the most recurrent ones: multi-story buildings, with masonry or concrete structure, framed or with bearing walls, used for residential or service functions. Are therefore excluded all the typologies that fall outside the definition of ordinary building like monuments (churches, historical buildings, …), strategic institutions (hospital, schools, governmental buildings, …), or special structures (industrial building, …). The urban sectors are characterized by typological and structural homogeneity, in terms of texture, age of construction, bearing structure and construction technique. The form is divided into four sections: Section 0 for the identification of the municipality and the sectors identified therein; Section 1 for the identification of each of the predominant typologies characterizing the generic sub-sector of the assigned municipality; Section 2 for the identification of general characteristics of each typology of the constructions; Section 3 for the characterization of the structural elements of all individuated construction typologies.

Since an exhaustive survey has not yet been accomplished, this study relies on the data made available by the Census, providing the general characteristics of the building stock. The data utilized in the present study are obtained from the 14th General Census of the Population and Dwellings (ISTAT 2001). The Census data are collected and aggregated at different levels: the basic unit for data collection is the single household and dwelling, but each dwelling is classified as being located within a building, of a given construction type (RC, Masonry, Other), with a given number of storeys (1, 2, 3, 4+) and age of construction (≤1919, 1919/1945, 1946/1961, 1962/1971, 1972/1981, 1982/1991, ≥ 1991). In order to protect privacy, the collected data are disclosed only in aggregated format whose minimum territorial extension is the Census tract (a small, relatively permanent statistical subdivision of a geographical region, designed to be relatively homogeneous with respect to population characteristics, economic status and living conditions). In highly urbanized areas, like the Cassino town centre, a census tract has the dimensions of a building block. Further details about the elaboration of the exposure data are discussed in the next section.

5 APPLICATION RESULTS

The case analyzed in this paper is represented by Cassino, a small sized town (35'000 inhabitants) located in southern Lazio. The main feature of the built environment of Cassino, that differentiates this town from similar Italian municipalities, is the fact that the town was almost completely destroyed at the end of World War II during the so called 'Battles of Monte Cassino' (January-May 1944) (Herbert 1973, Caddick-Adams 2013) and then rebuilt, at the end of the war, in a relatively short time.

It is of great interest for the aims of this study that the building stock of Cassino is relatively younger then the Italian average and that reconstruction began when the municipality was already classified in seismic zone after the Avezzano earth-quake (January 13, 1915, Mw=7.0), so that the first structures built during the reconstruction are supposed to be designed according with the seismic principles commonly applied at the time (elastic design relying over the allowable stress principle and using horizontal forces about 7% of the weight). Cassino was subsequently declassified in the 20 years span period since 1962 until 1982, when the economic boom was associated with the maximum rate of the building activity. It was, indeed, felt that the enforcement of seismic rules was an impediment to economic activities and urban development and therefore it was not so uncommon that municipalities, after some time since the last seismic event that justified their insertion in seismic zone list, petitioned to be removed. In the case of Cassino, the cancellation was 'de facto', since it was sufficient not to be included in the new list prepared in 1962, while in the case of the nearby Pontecorvo town an ‘at hoc’ decree was issued in 1959 to selectively declassify the periphery (to be urbanized) whilst the already constructed urban centre was kept seismic. Cassino was then reclassified in 1983, after the Irpinia earthquake (November 23, 1980, Mw=6.9). In Italy only after the Molise earthquake (October 31/November 2, 2002, Mw=6.0), a fundamental revision of the seismic classification as well as of the seismic design rules was undergone, redefining the seismic classification on the basis of a probabilistic hazard analysis rather than on an historical basis and incorporating in the new recommendations the limit state approach, with load and resistance safety factors and capacity design principles.

The information about the geotechnical setting has been obtained by a recent study on microzonation (Regione Lazio 2012; Saroli et al. 2014), from which emerges that the town of Cassino is settled in an alluvial plain, characterized by the presence of soft soils.

For privacy purposes the relevant data about buildings contained in census tracts (Cassino municipality is subdivided in 780 tracts) are made available through their marginal frequency, without disclosing the underlying joint distribution (this kind of data is available in aggregate format only for provinces and big cities).

The seismic risk analysis has been carried initially performing the calculations over the 84 classes of buildings and then combining the results on tracts (in order to keep the output format consistent with the one provided by the Census) considering the effective composition of each tract through a weighted average. The results of the analysis are shown in Figures 1 through 4.

The computations have been carried using essentially equation (3) and (4) (Rasulo et al. 2015, Rasulo et al. 2016) as explained in the following.

Figures 1 through 3 report, both on the entire municipality and on a significant quadrant of the town center, an index built on the probability of exceedance in a 50 years period of the three limit states considered, $P_{ex,50}(LS_i)$ (where LS1: slight damage, LS2: significant damage and LS3: collapse):

$$P_{ex,50}(LS_i) = \int_x F_{LS|IM}(y \geq LS_i|x) \cdot \left|\frac{dG_{IM,\Delta T=50y}(x)}{dx}\right| dx \quad (3)$$

The three limit states have been considered separately since their concept is quite familiar to structural engineers and the outcomes can be easily compared with known threshold parameters. Indeed, in order to have a term of comparison, the probability of exceedance calculated on the existing buildings, $P_{ex,50}(LS_i)$ ($i = 1,2,3$), has been divided by the probability of occurrence of the seismic action used in the design of new residential buildings, $P_{new,50}(LS_i)$. According to Italian seismic rules NTC-08 (Decree of the Ministry of Infrastructures 2008) this probability is given for the three limit states as follows:

$P_{new,50}(LS_1) = 0.63$. $P_{new,50}(LS_2) = 0.10$
$P_{new,50}(LS_3) = 0.05$

It is worth noticing that the aforementioned threshold parameters are also intended for the assessment of the existing buildings, even if a recently drafted revision of the Italian seismic rules suggests considering as time span of reference in the calculations the residual service life of the existing building rather than the fixed term of 50 years.

The index $I_1 = P_{ex,50}(LS_i)/P_{new,50}(LS_i)$ obtained represents a comparative measure between the expected capacity (numerator) and the expected demand (denominator) in terms of probability of exceedance (the highest is the index, the less safe is the structure). Obviously the new structures, which have at least to comply with the indicated demand, are designed with additional conservative measures (represented by load and resistance safety factors, capacity design rules, minimum design requirements), so that the few cases where is $I_1 < 1$, do not necessarily imply that an existing structure is safer than a new one.

As shown in Figures 1-3, while the differential between capacity and demand is acceptable for LS1, it deepens as the level of damage increases (for LS2 or LS3).

This kind of result was somehow expected, since the slight damage (LS1) is conditioned mostly by the quality of the details of non-structural components (whose design is controlled by architectural or climatic rather than seismic or structural considerations), while the occurrence of significant damage (LS2) and collapse (LS3) is conditioned by the presence in the design of seismic provisions and the expected mechanism of collapse.

Finally figure 4 represents $I_2 = E(L)/R$, a comparison between the expected monetary losses due to an earthquake, $E(L)$ and the cost for the retrofit of the structure, R.

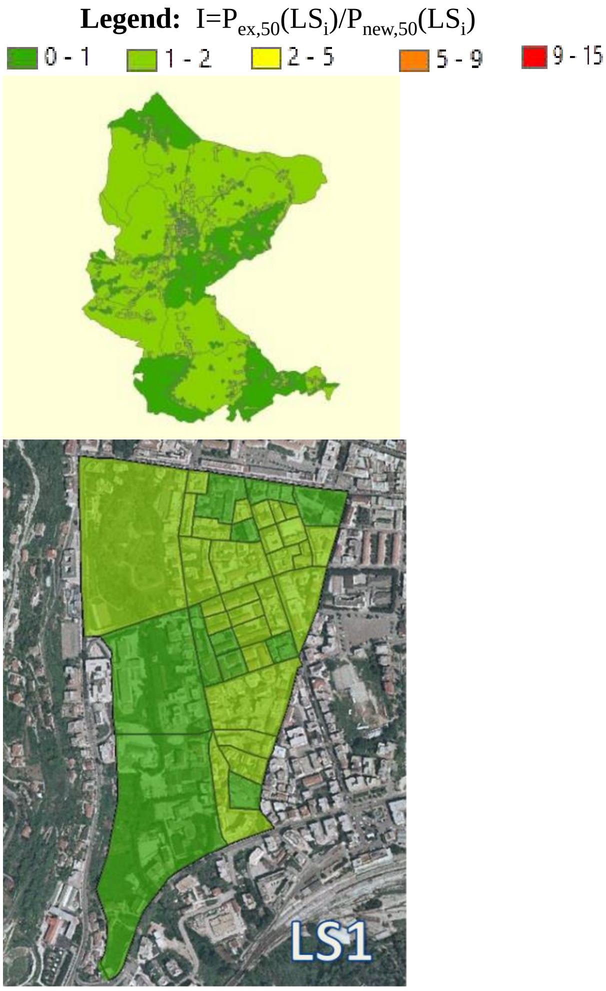

Figure 1. Risk map for LS! (damage limitation) Limit state

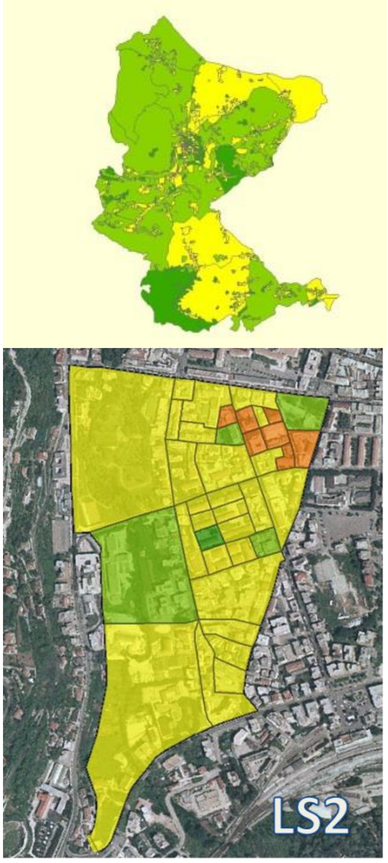

Figure 2. Risk map for LS2 (significant damage) Limit state

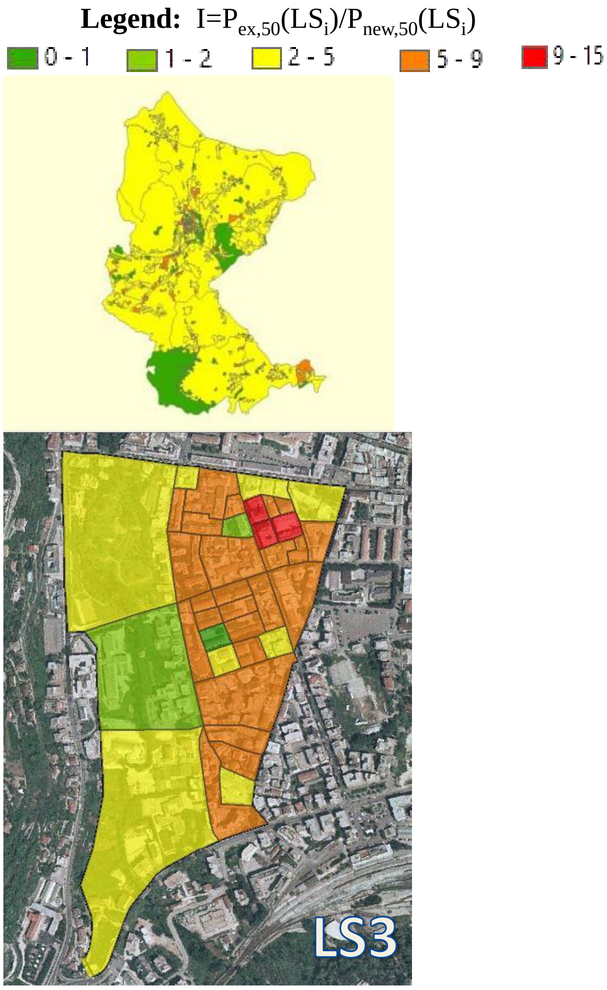

Figure 3. Risk map for LS3 (near collapse) Limit state

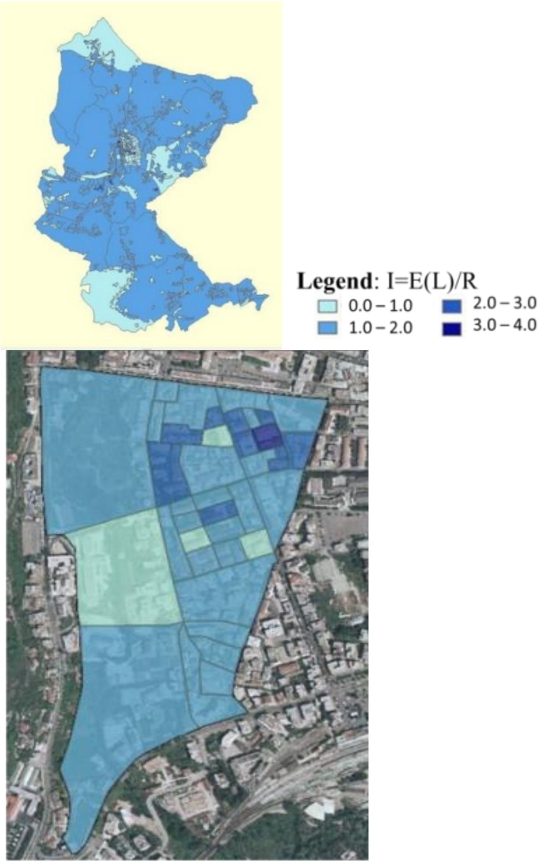

Figure 4. Expected monetary loss and retrofit cost ratio

The expected loss, $E(L)$, has been defined considering the probability of attaining strictly each limit state, $f_{LS|IM}(LS_i)$ is the conditional probability of strictly attaining a damage state,LS, equal to y $(LS = y)$, given the attainment of a seismic intensity measure, IM equal to x $(IM = x)$; and the corresponding cost for repair or rebuilding, L_i , associated with the damage suffered at the i-th Limit State (the more severe is the damage, the higher are the costs):

$$E(L) = \sum_{i=1}^{3} L_i \cdot \int_x \left[G_{LM|IM}(y \geq LS_i|x) - G_{LS|IM}(y \geq LS_{i+1}|x)\right] \cdot \left|\frac{d_{G_{IM|\Delta T}}(x)}{dx}\right| dx \qquad (4)$$

In equation (4) the term $f_{LS|IM}(y = LS_i|x)$ is required in order to avoid (in the summation) to count several times the damages suffered at higher limit states, but for operative reasons (the fragility functions are traditionally calculated for the probability of exceeding rather than strictly attaining a specified limit state) it has been substituted by the term:
$f_{LS|IM}(y = LS_i|x) = [G_{LS|IM}(y \geq LS_i|x) - G_{LS|IM}(y \geq LS_{i+1}|x)]$
Obviously for i=3, $f_{LS|IM}(y = LS_3|x) = G_{LS|IM}(y \geq LS_3|x)$, since no higher Limit State has been considered.

On the other hand the retrofit cost, R, has been assumed as a deterministic value and independent of the existing structural conditions (in a traditional retrofit, the demolition and reconstruction works of finishing and implants that are needed to access the structural components are fixed terms and usually cost much more than the structural enhancement *per se*). In R the indirect costs due to service interruption of the dwelling or building (rent to be spent for temporally relocating the inhabitants, …) are not included since those cost were not considered for $E(L)$

The monetary values assumed in this study, consistently with international (Smyth 2003, Liel and Deierlein 2013) and national literature (ANCE Catania 2012, Comune de L'Aquila 2013), have been selected considering that the cost of construction of a new building approximates 1'200 €/m^2, whilst the one for retrofit is around 500 €/m^2.

Obviously the index graphed in Figure 2 wants to represent the order of convenience of undertaking measures of reduction of seismic risk even if do not considers the possible utility associated with the change in the market value of the real estate.

6 CONCLUSION

The work presented herein consisted in the assessment of the seismic risk map of the town of Cassino using a state-of-the-art evaluation procedure. The study, even if focused on a particular case for demonstration purposes, can be usefully extended to any other Italian urban agglomerate since the basic ingredients used in the analysis are already made available at national scale and the procedure can be easily standardized using modern computing tools like GIS. The study permitted to evaluate the level of affordability of the input ingredients and thus to evidence the aspects requiring a better refinement.

It is important to point out that when tackling a small town, like Cassino, an extensive verification of the quality of the information utilized in the analysis was possible and reasonably not onerous. On the contrary, at national level, the availability of a very large amount of data, coming from different institutions and not necessarily collected for the scopes of a seismic risk analysis, poses the problem of harmonization of the pieces of information.

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