Preliminary Italian Maps of the Expected Annual Losses of Residential Code-Conforming Buildings

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Abstract. The expected annual loss (*EAL*) is a metric often used to quantify the risk, including that related to seismic behavior of structures. It allows to combine the annual probability that the considered structure experiences any damage level, with the expected value of the consequences of such damages. In Italy, to promote seismic risk mitigation, a tax relief for retrofitting costs of existing buildings has been introduced. One of the two criteria adopted to demonstrate the improvement of the seismic performance of the structure after the retrofit is the comparison of (a simplified assessment of) the *EAL* before and after the retrofitting. In this context, it is interesting to quantify the *EAL* of code-conforming residential buildings of different structural typologies and supposed located in each Italian municipality. This kind of study descends from a recent Italian research project named RINTC – *Rischio implicito delle strutture progettate secondo le NTC* – that aims at the evaluation of the seismic reliability inherent to design according to the current Italian building code. Selecting some of the structures analyzed in the RINTC project, national maps of *EAL* for four code-conforming buildings are computed. Such structures are three- and six-storey reinforced concrete (RC) frame, infilled, buildings, and two- and three-storey unreinforced masonry (URM) buildings. The *EAL*s are obtained combing the results of probabilistic seismic hazard analyses, performed in accordance with an authoritative source model for Italy, with the fragility functions derived for two performance (i.e., damage) levels, namely *usability-preventing damage* and *global collapse*. Results, following those of the RINTC project, generally show that: (i) *EAL*s vary with the site and the considered structural typology; (ii) three-storey RC and two-storey URM are generally associated to the lowest *EAL* while the largest are often related to three-storey URM.

Keywords: Failure rate · Fragility functions · Probabilistic seismic hazard analysis · Seismic risk

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1 Introduction

In 2017 an Italian law enabled significant tax relief (up to the 85% of the total investment) for costs of structural seismic retrofitting of existing buildings [1, 2]. The amount of tax relief depends on the effectiveness of the seismic behavior improvement measured as a function of two parameters, computed with and without the retrofitting: (i) the ratio between the peak ground acceleration (*PGA*) causing the structure to exceed the *life-safety* limit state (as defined in [3]) and the design *PGA* adopted for the same limit state of a new-design building at the same site, (ii) the expected annual loss (*EAL*) computed combining the exceedance rates of six limit states, LSs, related to earthquakes, with the reconstruction costs associated to the exceedance of each LS. The LSs are defined for a range of damage states that goes from the onset of nonstructural damage to the conventional complete collapse of the building, namely: (i) onset and (ii) limitation of nonstructural damage, (iii) limitation of structural and nonstructural damage, (iv) life-safety, (v) collapse prevention, (vi) complete reconstruction. To the exceedance of each LS, a percentage of the complete reconstruction cost is associated (such costs vary between 0% to 100%). The mentioned law [1] provides a reference value of the *EAL* computed for a residential building conforming to the Italian code [3, 4], hereafter NTC08. Such a value is 1.13% assuming that each limit state is exceeded when the corresponding design seismic action (expressed in terms of *PGA*) is exceeded.

On the other hand, a large Italian research project, named *Rischio Implicito delle Strutture progettate secondo le NTC* or RINTC [5, 6], showed that, although the design seismic actions for a given limit state (i.e., design ground motion intensity) have the same exceedance return period over the country, the structural reliability of code-conforming buildings, measured as the failure rate with respect to two ad-hoc defined performance levels, that is, *usability-preventing damage*, UPD, and *global collapse,* GC, (although having similar names, they do not correspond with those of [1]) significantly changes across the Italian sites and structural typologies. The analyzed structures in the RINTC project were, among others, residential reinforced concrete (RC) buildings of three and six storeys (with infillings), and unreinforced masonry (URM) structures with two and three storeys. The structures were supposedly located in three Italian sites, Milan, Naples, and L'Aquila, chosen to be representative of different levels of design seismic hazard (low, medium, and high, respectively) according the probabilistic assessment for the country (e.g., [7]). Referring to each site, the structures were first designed according with NTC08 [3] (or its 2018 update [4]); then, the failure rates were computed with respect to UPD and GC.

The aim of the work described herein is to provide preliminary maps of conventional *EAL*s computed for each of the listed structure ideally located in each Italian municipality. To this end, the *EAL* is computed accounting for the seismic hazard of the sites evaluated by means of probabilistic seismic hazard analysis (PSHA) including the soil conditions, the seismic vulnerability of the structures with respect to UPD and GC, and the reconstruction costs defined in analogy with those indicated in [1]. However, due to several differences and limitations in the procedure (e.g., different number and definition of the considered performance/damage levels), the results of this study are not comparable with those obtained applying [1]; yet the maps shown here must be considered for comparison among different structural typologies over the country. It should also be noted that in a previous study, maps of failure rates of code-conforming buildings were developed at the municipality scale [8]. Such a paper shares most of the input models with the present work, yet results discuss seismic risk in a different perspective.

The remainder of this paper is structured such that the methodology for the computation of the *EAL* is presented first. Then, all the input models required for *EAL* assessment are described. Thus, results in terms of maps of *EAL* per structural typology are discussed. Some final remarks close the paper.

2 Methodology

PSHA allows computing the rate of earthquakes (i.e., mainshocks of seismic sequences) causing the ground motion intensity measure (IM) to exceed a threshold (im) at a site of interest characterized by a known soil class (θ), that is $\lambda_{im|\theta}$ [9]. The plot of $\lambda_{im|\theta}$ versus the possible im values is the so-called *hazard curve*. The probability that a building of a given structural typology reaches or exceeds a performance level (PL), that is, fails, given a known value of the IM, is defined as the fragility function, $P\big[PL \geq pl|IM = im\big]$. The latter can be used, together with the hazard curve, to compute the rate of mainshocks causing the failure of the building belonging to the considered structural typology and located on a soil class θ, $\lambda_{pl|\theta}$, Eq. (1):

$$\lambda_{pl|\theta} = \int_{im} P\big[PL \geq pl|IM = im\big] \cdot \left|d\lambda_{im|\theta}\right| \tag{1}$$

In the equation, $\left|d\lambda_{im|\theta}\right|$ is the absolute value of the differential of the hazard curve and it is assumed that the fragility is not dependent on the soil condition of the site [10].

Equation (1) can also be (approximately) applied to a given area (e.g., municipality) providing the rate of mainshocks causing a generic building of the structural typology to fail, indicated as λ_{pl}. This requires knowing the probability that the building is located on each possible soil condition, θ_i, that is, $P[\theta_i]$. Thus the total probability theorem results in Eq. (2) in which i varies between one and the number of soil classes considered by the ground motion prediction equation (GMPE) adopted for PSHA:

$$\lambda_{pl} = \sum_i \left\{ \int_{im} P\big[PL \geq pl|IM = im\big] \cdot \left|d\lambda_{im|\theta_i}\right| \right\} \cdot P[\theta_i] \tag{2}$$

Referring to the two performance levels defined in the RINTC project, that is, UPD and GC, Eq. (2) can be applied twice, computing λ_{UPD} and λ_{GC}. Thus, the *EAL* of the considered structural typology can be computed via Eq. (3), in which the annual probability of reaching or exceeding a generic performance level in one year is approximated by its annual rate and the expected value of the reconstruction cost given the performance level is $E[C_{\mathrm{UPD}}]$ and $E[C_{\mathrm{GC}}]$ for UPD and GC, respectively:

$$EAL = (\lambda_{\mathrm{UPD}} - \lambda_{\mathrm{GC}}) \cdot E[C_{\mathrm{UPD}}] + \lambda_{\mathrm{GC}} \cdot E[C_{\mathrm{GC}}] \tag{3}$$

3 Input Data for the *EAL* Computation

3.1 Probabilistic Seismic Hazard

The probabilistic hazard assessment at the basis of the design seismic actions in the current Italian building code considers thirty-six seismic source zones for the country (except Sardinia Island) as described in [11], and adopts a logic-tree constituted by sixteen branches [7]. Among them, the branch named 921 is the one adopted here. The seismic parameters of each seismic source zone are defined via the mean annual number of mainshocks per magnitude bins, that is, the so-called *activity rates* (e.g. [12]), and the GMPE is that of [13]. The *IM*s for which PSHA is carried out for the purposes of this study are the *PGA*, and the pseudo-spectral accelerations associated to two spectral periods (T) that are of interest for the considered structural typologies (to follow), that is $T = \{0.15\ \text{s},\ 0.5\ \text{s}\}$. Hazard analyses were performed, for each municipality, via the REASSESS software [14]. The hazard curves in terms of *PGA* on rock soil conditions, for all municipalities, are reported in Fig. 1a. In the same figure, the exceedance rate corresponding to a return period (T_r) equal to 475 years (yr) is presented together with the hazard curves computed for the sites of Milan, Naples, and L'Aquila; these sites (identified in Fig. 1b) are those considered in the RINTC project.

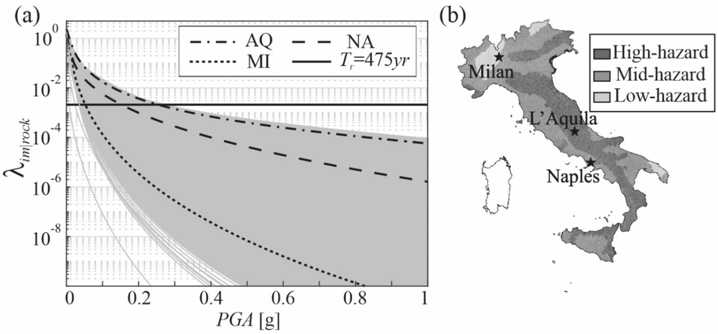

Fig. 1. (a) *PGA* hazard curves on rock computed via PSHA for all the Italian municipalities, (b) hazard classification according to PGA_{475} of each municipality.

To compute *EAL* maps, it is necessary to introduce some criteria to associate the RINTC structures to the Italian municipalities, other than those in which they were originally ideally located. To this aim, the values of *PGA* on rock corresponding to $T_r = 475yr$, that is PGA_{475}, computed for Naples (i.e., 0.15 g) and Milan (0.05 g) are (arbitrary) taken as bounds to define three hazard classes of the Italian municipalities. In other words, the sites characterized by a PGA_{475} lower than that associated to Milan were defined as low-hazard, sites with PGA_{475} lower than Naples (and larger than Milan) were considered mid-hazard and sites with PGA_{475} larger than Naples were high-hazard. The resulting classification is represented in Fig. 1b: the municipalities in low-hazard class are about 16% of the total, whereas those in mid- and high-hazard are about 47% and 36%, respectively (according to the source model, Sardinia is outside the definition range of the GMPE and is not considered hereafter).

Following such a classification, it is assumed that the RINTC buildings designed in L'Aquila, Naples, and Milan (see Sect. 3.3) are representative of buildings designed in any municipality belonging to the high-, mid- and low-hazard class, respectively.

3.2 Local Soil Classes at a Municipality Scale

According to Eq. (2), soil class probability is required for each considered municipality. Such an information can be retrieved profiting of the work of [12] that provides a database of local soil characterizations for a grid of about one million points covering the whole Italian territory. For each point, the soil class (from A to D) according to NTC08 is defined. Since the adopted GMPE accounts for the soil conditions referring to three categories, that is *rock*, *stiff* and *soft*, the soil classes from [12] were converted into these categories. More specifically, soil conditions that, according to NTC08, are identified as A correspond to rock, whereas soil conditions B correspond to stiff soil and soil conditions C and D correspond to the soft soil class of the GMPE.

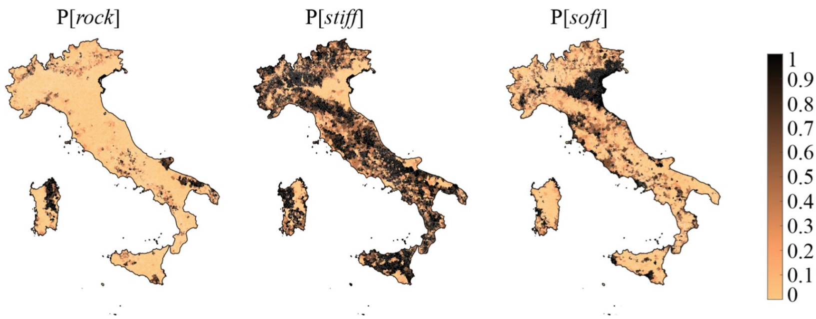

Fig. 2. Soil class probabilities in urbanized areas of Italian municipalities (adapted from [8]).

To quantify the probability that the building of a given municipality is located on a specific soil class, soil data can be combined with the data provided by the Italian *Istituto Nazionale di Statistica* (ISTAT) that identify the urbanized areas of each municipality (https://www.istat.it/it/archivio/222527, last accessed 21/12/2021). The computed percentages of soil categories in each urbanized area are treated as probabilities and are reported in Fig. 2. The largest percentages are associated to stiff soil in most of the municipalities; soft soil covers a non-negligible number of urbanized areas and is predominant in the north-eastern municipalities and along the coasts; finally, rock soil is a significant fraction only in a few areas.

3.3 Fragility Functions of Code-Conforming (RINTC) Buildings

In the RINTC project, a large set of residential buildings was designed, according to [3, 4], to be ideally located in a few Italian sites: L'Aquila, Naples, and Milan. Each structure was designed referring to *damage* and *life-safety* limit states as defined in NTC08. On the other hand, for reliability assessment, two different performance levels were defined:

UPD and GC. The former is reached if one of following conditions occurs (with some adjustments accounting for the peculiarities of specific structural typologies [10, 15]): (i) light damage in 50% of the main non-structural elements; (ii) at least one of the non-structural elements reaches a severe damage level leading to significant interruption of use; (iii) attainment of 95% of the maximum base-shear of the structure. GC, generally, corresponds to the deformation/displacement capacity associated to a 50% post-peak drop of the total base shear of the building.

Four different structural typologies are considered hereafter; they are characterized by the construction material and the number of storeys. The RC structures are moment resisting, infilled-frame buildings of three (RC3) and six storeys (RC6) [16], whereas the URM structures are two- and three-storey buildings (URM2 and URM3, respectively) made of perforated clay units with mortar joints [17]. All the structures are characterized by regularity in plan and elevation.

Lognormal fragility functions for each performance level and structure were defined in [18] as:

$$P\left[PL \geq pl|im\right] = \Phi\left[\frac{\ln(im) - \mu}{\sigma}\right] \tag{4}$$

where $\{\mu, \sigma\}$ are parameters. The adopted IM is the largest (between the two horizontal components) 5% damped pseudo-spectral acceleration at a vibration period close to that of the first mode of each model, indicated as $Sa(T)$: fragility functions for RC3, URM2 and URM3 refer to $Sa(0.15\text{ s})$, whereas $Sa(0.5\text{ s})$ is the chosen IM for RC6. The parameters of the fragility functions for both performance levels and for all the analyzed structures are provided by [8] and represented in Fig. 3.

Because the considered masonry structures are characterized by different architectural configurations, when URM buildings are of concern, Eq. (3) provides the expected annual loss per site, structural typology, and architectural configuration. Thus, the expected annual loss per site and structural typology can be computed by a weighted sum the EAL computed for each architectural configuration of the same typology. The weight associated to each architectural configuration is based, via expert judgement, on the representativeness of the architectural configuration with respect to the actual building portfolio (the sum of the weights for all the alternative architectural configurations of the same typology equals to one). The values of the weights are provided by [8].

3.4 Percentage Reconstruction Costs

The definition of the reconstruction cost for each performance level is a nontrivial task. It is herein assumed that the reconstruction costs of UPD and GC are the 50% and 100% of the reconstruction cost of the structure, respectively; thus, according to symbols in Eq. (3), $E[C_{\mathrm{UPD}}] = 50\%$ and $E[C_{\mathrm{GC}}] = 100\%$. These costs are those defined in [1] for life-safety (according to NTC08) and *complete reconstruction* limit states. However, the effect on results of the chosen reconstruction costs may be not negligible, as discussed in the following section.

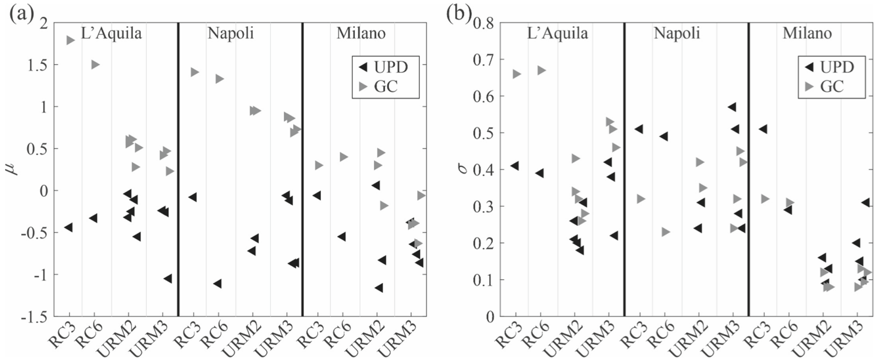

Fig. 3. Parameters of fragility functions: multiple values of μ and σ for URM2 and URM3 correspond to the different architectural configurations (parameters of RC6 refer to a different intensity measure expressing the fragility function than the other structural typologies).

4 Results and Discussions

As useful premise of this section, it should be noted that maps of the GC rates per structural typology, consistently computed with respect to this study, were reported in [19] showing that: (i) failure rates are different among different sites and structural typologies, (ii) in most of the municipalities, RC3 has the lowest failure rate that increases considering RC6 and URM2 and reaches the maximum for URM3. In this section, the analysis in terms of *EAL* allows to underline some additional issues.

The *EAL* computed for RC3, RC6, URM2, and URM3, supposed located in each Italian municipality (consistent with the hazard classes defined in Sect. 3.1), are shown in Fig. 4 from (a) to (d), respectively. It is to note first that, acknowledging the approach of [10], failure rates lower than 1E−05 are substituted by 1E−05 to avoid large extrapolations of hazard and fragility models. Thus, in some cases, the value of 1E−05 is associated to both λ_{UPD} and λ_{GC} resulting in an *EAL* equal to 1E−03%. This happens mostly for RC3 buildings located in northern or southern-east Italy (mild grey sites in the figure). Moreover, as shown in the figure, *EAL*s are different over the country and the considered structural typologies; this is in line with results of the RINTC project as well as the results of [8, 19].

The relative comparison of the maps in Fig. 4 shows that RC3 and URM2 are the buildings to which the lowest *EAL* is associated. RC3 buildings provide the lowest values in sites classified as low- and mid-hazard, whereas for high-hazard sites URM2 shows the lowest *EAL*s (i.e., best seismic performances). RC6 is generally comparable with RC3 over the country (in a few high-hazard sites RC6 has lower *EAL* than RC3). The largest *EAL*s are associated to URM3 in about 75% of the Italian municipalities; in the remaining sites, mostly belonging to the low- and mid-hazard classes, the largest *EAL*s are associated to RC6 and URM2. The mean value of the *EAL* computed for each map of the figure is 0.067%, 0.067%, 0.055%, and 0.113% for RC3, RC6, URM2 and URM3, respectively. The minimum value is equal to 1E-03 in each map. Finally, the maximum values are 0.38%, 0.33%, 0.21% and 0.58% for RC3, RC6, URM2 and URM3, respectively.

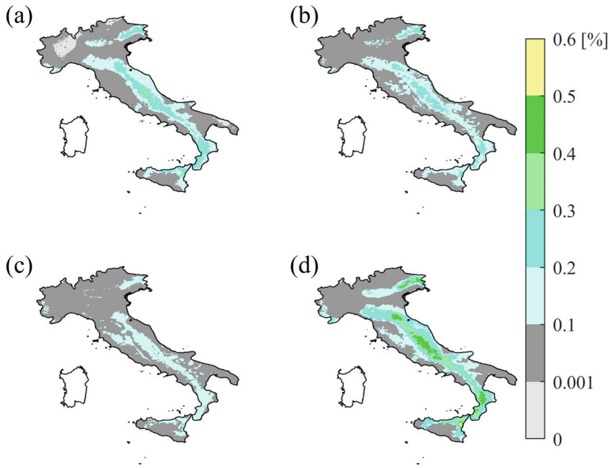

Fig. 4. *EAL* (percentage of the reconstruction cost) for (a) RC3, (b) RC6, (c) URM2 and (d) URM3.

The discussed comparison among the maps is partially in contrast with the conclusions of [19] being here URM2 (not RC3) the structure with the lowest *EAL* for several municipalities. This is motivated by the fact that, given the site, the values of the UPD rate for each structural typology do not have the same order as observed in the case of GC; i.e., referring to UPD, the failure rate for URM2 may be lower than RC3 and RC6, the failure rate for RC6 may be lower than RC3, and the URM3 failure rate may be lower than RC3 and RC6. This issue also means that, if different costs were associated to the considered performance levels, the results of maps' comparison may change.

5 Conclusions

This study evaluated the *EAL* associated to new code-conforming structures supposedly located in each Italian municipality. The considered structures were two- and three-storey unreinforced masonry and three- and six-storey reinforced concrete buildings that were designed, modelled, and analyzed in the RINTC project for three Italian sites (i.e., L'Aquila, Naples, and Milan). They were adopted to represent code-conforming buildings of the municipalities in high-, mid- and low-seismic hazard classes. These classes were identified according to the value of the PGA_{475} associated, via PSHA, to each (whole) Italian municipality. To compute the *EAL*, hazard curves resulting from PSHA (and accounting for soil conditions) were combined with the fragility functions of each structural typology considering two structural performances intended herein as damage levels: usability-preventing damage (UPD) and global collapse (GC). It was assumed that the repair costs associated to them is 50% and 100% of the total reconstruction cost of the building, respectively. Results, in terms of maps of *EAL*s per building typology, showed a clear dependency on the considered site and structural typology, confirming the findings of previous studies analyzing the seismic performance of code-conforming buildings with respect to a complementary point of view. It is also shown that RC3 is associated to the lowest *EAL* in low- and mid-hazard classes whereas URM2 has the lowest *EAL* in the high-hazard class; results for RC6 are comparable to RC3. In 75% of the sites, URM3 is the case with the highest *EAL*. However, in analyzing these preliminary results, their conventional nature and the effect of several limiting assumptions should be always considered.

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