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Seismic insurance model for the Italian residential building stock

Domenico Asprone [a,*], Fatemeh Jalayer [a], Saverio Simonelli [b], Antonio Acconcia [b], Andrea Prota [a], Gaetano Manfredi [a]

[a] Department of Structural Engineering, University of Naples "Federico II", Naples, Italy
[b] Department of Economics, University of Naples "Federico II", Naples, Italy

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A B S T R A C T

The expected life-cycle cost can be regarded as a benchmark variable in decision making problems involving insurance policy making for existing structures in seismic risk prone areas. The present study is a preliminary study aiming to calculate the expected insurance premium for Italian building stock subjected to seismic action in its service lifetime based on probabilistic seismic loss assessment. The proposed methodology leads to probabilistic assessment of the structural performance, expressed in terms of the discrete structural limit state exceedance probabilities, and the life cycle cost taking into account the Italian seismic zonation and the seismic vulnerability of the existing life stock. The expected insurance premium can then be evaluated based on the probabilities that the structure exceeds a set of discrete limit state thresholds and the average costs associated to them. The methodology is implemented in an illustrative numerical example which considers the Italian residential building stock discretized in 5 structural typologies and in 8088 areas, corresponding to the Italian municipalities. A monopoly market-based insurance model is built, assuming risk aversion of the property owners and risk neutrality of the insurance companies. The expected insurance premium is evaluated for each structural typology in each Italian municipality, taking into account also the maximum coverage and the insurance excess systems. Results are aggregated to compute the total annual expected loss for the entire Italian building stock, and the total income and profit margin for the insurance company assuming an insurance contract for all the property owners.

Introduction

The attention of scientific community investigating natural hazards and the effects of natural disasters is ever more shifting towards the resilience of urban environment. Resilience is coined as the ability of the society to cope with a strong unexpected event and the pace of its recovery. Insurance systems for the natural hazards can be considered as effective tools aimed at increasing the socio-economic resilience of the contemporary society. In this regard, the financial conditions of the central government represents a critical point for post-disaster resilience. The Disaster Deficit Index introduced by Cardona [1] measures the internal and external financial resources potentially available to the government in the aftermath of a disaster. The insurance systems enter this picture as providers of external resources which can potentially reduce the burden of reconstruction. However, proper implementation of the insurance systems for natural disasters can be subjected to the following challenges:

1. Insurance premium for private property owners can represent a prohibitive cost.
2. In the case of severe and rare events with wide-spread damages to the insured property, the insurance company system may encounter cash flow problems.

It should be mentioned that the above-mentioned challenges are particularly relevant in the case of seismic risk where the consequences in terms of loss per event can be extremely high.

In order to face the losses induced by seismic events and to facilitate the financial recovery of homeowners with damaged property, a variable range of seismic insurance systems are implemented in countries with high seismicity; such as, Japan, New Zealand, California and Turkey. In Japan and New Zealand, earthquake insurance is part of the fire insurance. Moreover, the national government provides a re-insurance program [2,3,4]. In Japan, the earthquake insurance also covers damages due to volcano and tsunami. Although in California the seismic insurance is provided by private companies, a state-run earthquake insurance company (CEA, formed after the Northridge earthquake in 1994) has been founded in order to overcome the potential financial difficulties encountered by the private companies [5]. In Turkey, the government has strived to introduce a compulsory insurance for homeowners, providing a public re-insurance support [3]. Although an earthquake insurance system for Italy has been often discussed, especially after significant seismic events, there are few

* Corresponding author. Tel.: +39 081 7683672; fax: +39 081 7685921.
E-mail address: d.asprone@unina.it (D. Asprone).

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Table 1
Number of residential buildings in Italy per construction time and structural typology [7].

Construction time	Structural typology Masonry	RC	Other	Total
Before 1919	2.026.538	–	123.721	2.150.259
From 1919 to 1945	1.183.869	83.413	116.533	1.383.815
From 1946 to 1961	1.166.107	288.784	204.938	1.659.829
From 1962 to 1971	1.056.383	591.702	319.872	1.967.957
From 1972 to 1981	823.523	789.163	370.52	1.983.206
From 1982 to 1991	418.914	620.698	250.89	1.290.502
From 1992 to 2001	228.648	394.445	167.934	791.027
Total	**6.903.982**	**2.768.205**	**1.554.408**	**11.226.595**

Table 2
Total square meters in residential buildings in Italy classified per construction time and structural typology.

Construction time	Structural typology Masonry	RC	Other	Total
Before 1919	452.461.897	–	27.622.990	480.084.887
From 1919 to 1945	264.320.537	18.623.487	26.018.136	308.962.161
From 1946 to 1961	260.354.844	64.476.342	45.756.179	370.587.365
From 1962 to 1971	235.856.942	132.108.359	71.417.310	439.382.611
From 1972 to 1981	183.866.663	176.195.160	82.725.408	442.787.230
From 1982 to 1991	93.530.259	138.582.249	56.015.809	288.128.317
From 1992 to 2001	51.049.873	88.067.104	37.494.355	176.611.333
Total	**1.541.441.015**	**618.052.701**	**347.050.187**	**2.506.543.903**

documented efforts on the implementation of a national seismic insurance system [6]. A proposal of law was elaborated in 1998, aiming at extending the (mandatory) fire insurance so that it covers also the seismic damage. However, this proposal has been never adopted and was eventually withdrawn.

The present paper characterizes a potential seismic insurance system in Italy that covers the whole private residential building stock. In particular, under a set of simplifying assumptions discussed hereafter, the annual insurance premium for the owners of residential property units and the expected annual losses, to be covered by insurance companies, are calculated. The proposed risk-based insurance model, is built up upon probabilistic loss assessments for a portfolio of buildings. The underlying assumptions and the governing equations for the seismic insurance model and the probabilistic loss assessment basis are presented in the following sections.

Furthermore, a back analysis of the losses to residential building stock incurred by 2009 L'Aquila and the 2002 Molise earthquakes is performed. This analysis consists in estimating the total loss caused by a seismic event to the building stock employing probabilistic loss assessment and comparing it to the actual losses.

Seismic loss estimation

Data from 2001 Italian census has been used to characterize the entire Italian building stock population [7]. To do this, Italy has been divided into 8088 areas, in correspondence Italian municipalities, assumed to belong to the same seismic zonation. For each municipality, the residential buildings have been divided based on structural typology and construction time, compatible with the building database classification, into following categories:

Structural typology:
- Masonry;
- RC (reinforced concrete);
- Other.

Construction time:
- Before 1919;
- From 1919 to 1945;
- From 1946 to 1961;
- From 1962 to 1971;
- From 1972 to 1981;
- From 1982 to 1991;
- From 1992 to 2001.

Table 1 reports the number of buildings belonging the each class for the whole Italian stock. It can be observed that most of the buildings belong to the "before 1919" class. Furthermore, it can be also observed that masonry buildings are more numerous than RC buildings up to 1981; whereas, buildings belonging to "other" category are much less numerous.

Instead of referring to the number of buildings per category, the total surface area in square meters is used in order to be compatible with available information on the repair cost (reported per square meters of area). However, the building category breakdown reported in Table 1 and normalized by unit area is available per province and not per municipality.[1] Hence, in order to obtain the disaggregated data per square meters per municipality, it has been assumed that the average square meters per building for each of the category identified by the disaggregation, is constant for all the municipalities within each province. Hence, multiplying the number of buildings belonging to each subcategory in each municipality by the assumed average square meters per building, the building disaggregation reported in terms of total the square meters per category per municipality was obtained. In Table 2, this disaggregation is reported for the whole Italian building stock.

Regarding the building category marked as "other", no information is provided on the structural typologies included in this class. It can be argued that it refers to other typical structural typologies, i.e., wood structures, steel structures and combined RC–masonry structures. However, in the opinion of the authors, combined RC–masonry structures could constitute a large majority in this category. Therefore, the "other" category has been approximated to be composed totally of combined RC–masonry structures. Arguably, given the relatively small amount of square meters associated

[1] In 2001, when the census was conducted, the 8088 municipalities were divided into 103 provinces.

with the "other" category in comparison with "RC" and "masonry" categories, the inaccuracy caused by the above approximation most likely is not going to be significant.

Seismic hazard

The seismic hazard has been characterized in terms of peak ground acceleration (PGA) and its annual probability of exceedance, in order to ensure independence on fundamental period of vibration of the buildings. The seismic hazard curve expressed in terms of the annual probability of exceeding various PGA values recorded at bedrock, has been extracted from the Italian Zonation by Istituto Nazionale di Geofisica e Vulcanologia [8] for the centroid of each municipality, and has been assumed constant within the municipality. In order to obtain PGA hazard curves reflecting the soil category at the building foundation, the PGA values at the bedrock have been multiplied by the stratigraphic amplification factor S_S and the topographic amplification factor S_T, as defined by Eurocode 8 [9], that have been assumed constant within each municipality. The values for the above-mentioned amplification factors have been derived by Colombi and coworkers [10] who estimated the average values for S_S and S_T, for each Italian municipality.

Seismic fragility

As the fragility models to be used in the seismic risk model, it has been chosen to use the fragility models available in literature and classified per structural category. An exhaustive literature survey has been conducted in order to indentify the fragility curves that could be potentially suitable for implementation in the seismic risk model. More than 70 works are identified, yielding fragility models derived both empirically (based on in-situ observations) and analytically (based on simplified mechanical models), for the 3 considered structural typologies, namely, RC structures, masonry structures and combined RC–masonry structures. According to the adopted representation of the seismic hazard, only the fragility curves depicted as a function of PGA (and not the spectral acceleration) as earthquake intensity measure (IM) have been selected. This has represented a major constraint for the choice of the fragility models and has significantly restricted the number of those that were effectively suitable for this study. This choice was adopted also because of the lack of data about the height/number of storeys of the buildings. As a result, estimating the structural fundamental vibration period was not possible.

Furthermore, it is observed that in many cases, for each structural typology, the fragility models are classified according to sub-categories that are not used in this study. For instance, in many cases, the fragility model parameters are distinguished per different height values of the buildings (or the number of storeys) and per seismic-designed structures and gravity load-designed structures.[2]

In this study, whenever possible, only fragility models not classified according to specific building height values were selected. In other cases, the fragility models referring to buildings with different height values have been collapsed in one fragility model, by computing the mean value of the different fragility curves.

As far as it regards the distinction between the seismic-designed structures and the gravity load-designed structures, the building stock database does not provide any direct information to be used for disaggregation purposes. However, a critical review of the evolution of the seismic provisions in the Italian codes reveals some relevant information. In particular, two consecutive versions of the Italian code, released in 1974 [11] and in 1984 [12], have mainly contributed to, updating the Italian seismic classification, establishing seismic design prescriptions for the new construction, and including new municipalities in the seismic zonation. Hence, for each municipality, all the structures built before the milestone date in which the municipality was classified as a risk-prone area (i.e., 1974 or 1984), were considered to be gravity load-designed; whereas, the structures built after that date were considered to be seismic load-designed.[3] In few cases, the municipalities have been included in the risk prone areas after 2001 (i.e., the date of the building census). In that case, the buildings in those municipalities were considered entirely gravity load-designed. Moreover, since the census data is classified per decade (i.e., in 1971, 1981 and 2001), a linear variation with time was assumed in order to bridge the gap between the milestone years marking the code evolution and the census ten-year classification.

It is noteworthy that the above-mentioned distinction (i.e., seismic- and gravity loading-design) was done only for RC structures and combined RC–masonry. In fact, it can be argued that the masonry building stock may reveal the presence of earthquake-resistant elements (e.g., RC ring beams, metallic chains) even if built before the seismic prescriptions became mandatory. Therefore, based on the above-mentioned analysis, the original three structural categories were further split into five categories, namely:

1. masonry structures,
2. gravity load-designed RC structures,
3. seismic load-designed RC structures,
4. gravity load-designed combined RC–masonry structures,
5. seismic load-designed combined RC–masonry structures.

Due to all the constraints in the choice of the fragility curves to be implemented, the final choice has been narrowed down to those works listed in Table 3. The table reports 5 models for masonry structures, 11 models for seismic load- and gravity load-designed RC structures (one of them only refers to gravity load-designed structures), and only 1 model for both seismic load- and gravity load-designed combined RC–masonry structures were considered. In Table 3, for each of the selected models, the number of limit states for which the fragility curves are available, the corresponding logarithmic mean μ and standard deviation σ values (characterizing analytic Lognormal fragility curves) are reported.

Exposed value

As it can be observed in Table 3, each of the featured models reports the fragility curves corresponding to a number of limit states, varying between 2 and 5. All these limit states are independently defined within each model, except for the last one that, for all the featured models, refers to structural collapse; that is, the structure needs to be rebuilt once beyond this limit state. The repair/reconstruction cost for each of the considered limit states, has been assumed to be deterministic and has been evaluated per square meter of the damaged property unit. A set of assumptions have been employed in order to define the unitary repair/reconstruction costs for different sets of limit states identified by each model featured. These set of assumptions have been explained in the following.

Let n be the number of limit states in a set of limit states, the reconstruction cost RC(LS) corresponding to the ultimate limit

[2] The choice of not distinguishing the fragility curves based on number of storeys/height in this study is due to the fact that the building inventory database available did not provide such a break-down. However, it is essential to keep in mind the break-down into number of storeys in updating the building inventory data.

[3] It is implicitly assumed that the building codes have been implemented immediately.

Table 3
Sets of fragility models used in the seismic risk model.

Structural typology	Authors	Number of limit states	Lognormal distribution mean value μ^*		Lognormal distribution standard deviation value σ^*	
Masonry structures	Rota et al. [18]	3		−2.03		0.36
				−1.65		0.27
				−1.35		0.22
	Ahmad et al. [19]	4		−1.13		0.35
				−1.03		0.35
				−0.85		0.26
				−0.77		0.23
	Erberik [20]	2		−0.47		0.35
				−0.33		0.35
	Lagomarsino and Giovinazzi [21]	3		−1.00		0.41
				−0.75		0.34
				−0.61		0.37
	Rota et al. [22]	3		−0.85		0.24
				−0.70		0.18
				−0.58		0.14
RC structures	Kappos et al. [23]	4	−1.78	−1.32	1.14	0.29
			−1.12	−0.95	0.80	0.27
			−0.70	−0.57	0.63	0.27
			−0.59	−0.24	0.57	0.28
	Spence et al. [24]	4	−1.01	−0.87	0.32	0.29
			−0.55	−0.46	0.32	0.28
			−0.28	−0.02	0.31	0.29
			−0.09	0.15	0.32	0.27
	Crowley et al. [25]	2	−0.77	−0.80	0.24	0.18
			−0.62	−0.61	0.26	0.22
	Ahmad et al. [19]	3	−1.07	−1.07	0.22	0.22
			−0.91	−0.91	0.29	0.29
			−0.59	−0.44	0.26	0.26
	Borzi et al. [26]	2	−0.74	−0.56	0.32	0.32
			−0.46	−0.37	0.34	0.33
	Borzi et al. [27]	2	−0.68	−0.41	0.45	0.35
			−0.41	−0.31	0.36	0.35
	Kostov et al. [28]	3	−0.48	−0.44	0.47	0.48
			−0.34	−0.28	0.48	0.49
			−0.29	−0.19	0.48	0.49
	Kwon and Elnashai [29]	2	−1.08	n.a.	0.22	n.a.
			−0.73	n.a.	0.22	n.a.
	Ozmen et al. [30]	2	−0.37	−0.36	0.35	0.30
			−0.17	−0.12	0.23	0.15
	Kappos et al. [31]	4	−1.57	−1.14	0.44	0.43
			−0.92	−0.57	0.44	0.43
			−0.67	−0.18	0.44	0.43
			−0.51	0.10	0.44	0.43
	Tsionis et al. [32]		−0.67	−0.64	0.27	0.28
			−0.22	0.18	0.38	0.79
Combined RC–masonry structures	Kostov et al. [28]		−0.62	−0.52	0.50	0.49
			−0.44	−0.34	0.49	0.49
			−0.35	−0.24	0.49	0.49

For RC and combined RC–masonry structures the first and the second row refer to gravity load and seismic load designed structures, respectively.

state (i.e., the collapse limit state) has been assumed to be equal to $RC_{final} = 1500$ €/m^2. This stems from the fact that average construction costs for new structures in Italy is estimated to be to nearly 1300 €/m^2 [13], nearly uniform for all the Italian territory. This value has been rounded up to 1500 €/m^2 in order to account also for damages to the building content. Moreover, it has been assumed that the repair cost corresponding to the i-th intermediate limit states can be calculated from the following relationship in terms of the reconstruction cost RC_{final}:

$$RC\,(LS) = \left(\frac{i}{n}\right)^{\alpha} RC_{final} \tag{1}$$

where α is a parameter that needs to be calibrated. It is evident that $\alpha = 1$ renders a linear dependence of the repair costs on the limit state; whereas, $\alpha > 1$ leads to a reduction of the costs for the intermediate limit states. In this study, α has been preliminarily set equal to unity. In order to check the validity of this assumption, a back-analysis on the losses caused by L'Aquila 2009 and Molise 2002 earthquakes has been conducted. The definition of the unitary loss for intermediate limits states based on Eq. (1) has the advantage of rendering the definition of the intermediate limit states invariant with respect to the assumptions and definitions made in each single model with regard to these limit states. The weakness of such assumption ($\alpha = 1$) is that the repair costs associated with the intermediate limit states are going to be approximate. Hence, Eq. (1) is only introduced to manage the relationship between repair/reconstruction costs and limit states, for all the featured fragility models and its validity, along with the value of α are verified through the back-analysis described in next section.

Loss estimation

Point estimates of the expected annual loss per square meter has been derived by integrating hazard, fragility and the exposed value, as described in the following. Within each municipality, seismic hazard has been computed in terms of the annual rate of exceeding a given PGA and denoted by λ(PGA), with PGA varying

Table 4
Expected annual loss per square meter.

	Maximum value of l_m (€/year/m^2)	Municipality where the maximum l_m takes place	Minimum value of l_m (€/year/m^2)	Municipality where the minimum l_m takes place	Mean value of l_m (€/year/m^2)
Masonry structures	29.99	Giarre (Catania)	0.026	Solonghello (Alessandria)	5.21
Gravity load designed RC structures	17.04	Giarre (Catania)	0.027	Cazzago Brabbia (Varese)	2.83
Seismic load designed RC structures	11.34	Navelli (L'Aquila)	0.001	Solonghello (Alessandria)	1.75
Gravity load designed combined RC–masonry structures	14.51	Giarre (Catania)	0.002	Solonghello (Alessandria)	2.39
Seismic load designed combined RC–masonry structures	11.71	Navelli (L'Aquila)	0.001	Solonghello (Alessandria)	1.88

Table 5
Expected annual loss per municipality.

	Maximum value of L_m (M€/year)	Municipality where the maximum L_m takes place	Total expected annual loss (M€/year)
Masonry structures	196.4	Roma	8661.8
Gravity load designed RC structures	51.5	Roma	1186.8
Seismic load designed RC structures	8.0	Reggio Calabria	489.9
Gravity load designed combined RC–masonry structures	25.1	Roma	667.2
Seismic load designed combined RC–masonry structures	2.4	Napoli	174.0
		Total	**11179.6**

between 0 and 2*g*. For each of the 5 structural typologies and for each of the works listed in Table 3, a set of fragility curves has been computed in terms of probability of exceeding a given limit state LS given the PGA value and denoted by $P(\mathrm{LS}|\mathrm{PGA})$. For each set of fragility curves composed of n limit states, the reconstruction cost vector RC(LS) has been computed according to Eq. (1). Finally, the expected annual loss l per square meter can be calculated according to the following equation:[4]

$$l = \sum_{\mathrm{LS}=1}^{n} \mathrm{RC}\,(\mathrm{LS}) \int [P\,(\mathrm{LS}|\mathrm{PGA}) - P\,(\mathrm{LS}+1|\mathrm{PGA})]|d\lambda(\mathrm{PGA})| \tag{2}$$

where for the last limit state, $P(n + 1|\mathrm{PGA}) = 0$. The expected annual loss per square meter l is computed for each municipality (characterized by uniform seismicity), each structural typology and each fragility model (i.e., set of fragility curves) featured in Table 3 (logarithmic mean and standard deviation values for each limit state). In each municipality, this leads to distinct values of expected annual loss per structural typology; namely, 11 values for both the seismic and gravity load designed RC structures, 5 values for the masonry structures and only 1 value for both the seismic and gravity load designed combined RC–masonry structures. Hence, for each structural typology and for each municipality, given the different values of l, one for each fragility model, the mean value l_m has been calculated. Table 4 reports the maximum, minimum and mean value for l_m over the 8088 Italian municipalities. Looking at the range of expected annual loss per square meter in Table 4, significant variability in the expected annual loss can be observed within each structural typology (except for the combined RC–masonry structures where only one value has been computed). Moreover, it can be observed, by comparing the mean values, that masonry structures are expected to suffer much more significant losses than the other structural typologies. On the other hand, the seismic load-designed RC structures can be identified as the less vulnerable structural category. By comparing the seismic load-designed RC structures with the gravity load-designed RC structures, about 40% of reduction in the l_m values can be observed. This allows to appreciate the effect of retrofit operations aimed at changing the structural behavior from that of the gravity load-designed structures towards that of the seismic load-designed structure. For each municipality, multiplying l_m by total square meters per each structural typology, the expected annual loss denoted by L_m is obtained for each structural category. The results for L_m are reported in Table 5. Since l_m values depend solely on the seismic hazard in each municipality (and not on the total square meters), the maximum values for l_m may occur also in small municipalities located in highly seismic areas. On the contrary, the maximum values for L_m occur in large cities, since these values also depend on total square meters in each municipality; that is, the exposed value to seismic risk. Finally, the annual expected loss for the residential building stock in the entire Italian territory is derived and is reported in Table 5, by summing all the L_m values over all the municipalities.

Back-analysis on L'Aquila 2009 and Molise 2002 earthquakes

In order to validate the loss estimation model, a back analysis of the L'Aquila 2009 earthquake and the Molise 2002 earthquake has been conducted. The 6.3 moment-magnitude L'Aquila earthquake occurred on 6th of April, in 2009 and caused significant damage to the built environment. The 5.8 moment magnitude Molise earthquake occurred on 31st of October, in 2002. It was less intense than the L'Aquila earthquake, especially in terms of damages to the built environment.

A discrete version of Eq. (2) reported below is used in order to calculate the specific loss values l for each municipality:

$$l = \sum_{\mathrm{LS}=1}^{n} \mathrm{RC}\,(\mathrm{LS})[P\,(\mathrm{LS}|\overline{\mathrm{PGA}}) - P\,(\mathrm{LS}+1|\overline{\mathrm{PGA}})] \tag{3}$$

where $\overline{\mathrm{PGA}}$ denotes the PGA value in the centroid of the municipality in question during the earthquake. Hence, the l values per square meter are treated as indicated in previous section in order to derive the total loss L in each municipality. It should be noted that in this case, the calculated loss values represent an average loss estimator over the entire municipality.

To derive the $\overline{\mathrm{PGA}}$ values, The ground motion prediction relations proposed by Sabetta and Pugliese [14] have been used, computing the PGA at the centroid of the municipalities, given the epicentral distance and magnitude. The PGA values at the bedrock, have been amplified by the soil amplification factors, as previously described. For each municipality and each structural typology

[4] Strictly speaking, Eq. (2) should be written in terms of the annual probability that a specific value of PGA is exceeded. However, the annual probabilities of exceedance are approximated with annual rates of exceedance. For rare events modeled by a homogenous Poisson process, this approximation is justified.

Table 6
Estimated loss caused by L'Aquila and Molise earthquakes.

	Loss caused by the L'Aquila earthquake (M€)	Loss caused by the Molise earthquake (M€)
Masonry structures	4550.2	1247.3
Gravity load designed RC structures	600.5	126.8
Seismic load designed RC structures	301.7	17.1
Gravity load designed combined RC–masonry structures	155.7	42.5
Seismic load designed combined RC–masonry structures	81.4	13.1
Total	**5689.5**	**1446.8**

(except for the combined RC–masonry structures), different values of loss per square meters have been obtained, one for each of the considered fragility models. The mean value l_m has been computed and integrated over the total amount of square meters per each structural typology, deriving the loss L_m. Table 6 reports the values for the total loss, obtained by summing L_m over all the municipalities hit by the earthquake, for both the L'Aquila and the Molise event.

In particular, the reconstruction/rehabilitation costs for each limit state RC(LS), in Eq. (3), have been computed, as previously illustrated, according to Eq. (1), assuming α equal to unity. This corresponds to a linear increase of the costs associated with each limit state, up to the reconstruction cost (i.e., 1500€ per square meter).

According to this model the total loss incurred to the residential building stock, caused by the L'Aquila earthquake, is equal to 5.7 billions of Euros, whereas, the total loss caused by the Molise earthquake is equal to 1.4. In both cases, the values appear to be plausible, if compared with available data on the damages; albeit, so far, it is not easy to make a precise estimation of the damages. For the Molise earthquake, according to the Molise region administration [15], the damage to the private building stock is about 1.8 billions of Euros, but this value includes also the non residential structures. Gaining total loss estimates becomes more complicated in the case of L'Aquila Earthquake. According to the reconstruction committee [16], the amount so far allocated for the private reconstruction is about 5.9 billions of Euros. However, this sum does not refer to residential buildings exclusively. In both L'Aquila and Molise earthquakes the total sum refers to structural and non-structural damages. Moreover, it should be also underlined that the reconstruction funds for private construction in L'Aquila may not strictly correspond to the suffered damages; that is, a part of such funds for sure have been allocated to strengthening the buildings beyond their original conditions. More detailed data on these two earthquakes, once available, and data related to other seismic events would allow to investigate further the reliability of the whole model and of all the assumptions in estimating the total loss over a large building portfolio.

Insurance model

The model presented herein is based on a monopoly market insurance system. It is built for the generic home-owner of a 1 square meter property unit. The probability that an earthquake hits the structure is calculated as $\Theta = P(\mathrm{PGA} > 0)$ or the annual probability that the peak ground acceleration is greater than zero. This value can be seen as a measure of the seismicity of the zone. For each level of ground-shaking expressed as $\mathrm{PGA_i}$, (e.g., $0 \le \mathrm{PGA}_i \le 2g$), the home owner is going to suffer an expected annual loss value equal to $L(\mathrm{PGA_i})$ which[5] is going to lead to a reduction in his house wealth denoted by W_0. $L(\mathrm{PGA_i})$ is evaluated, for each structural typology, over all the different fragility models considered and the structural limit states:

$$E[L_i|\mathrm{PGA_i}] = \frac{1}{N_f}\sum_{j=1}^{N_f}\left[\sum_{\mathrm{LS}=1}^{n}\mathrm{RC}(\mathrm{LS})[P_j(\mathrm{LS}|\mathrm{PGA_i}) - P_j(\mathrm{LS}+1|\mathrm{PGA_i})]\right] \tag{4}$$

where N_f denotes the total number of fragility models considered per building type and $P_j(\mathrm{LS}|\mathrm{PGA}_i)$ denotes the fragility model j for limit state LS and ground-shaking intensity $\mathrm{PGA_i}$.

Let $\lambda(0)$ denote the annual rate of events with PGA > 0, assuming Poisson arrivals, the probability of occurrence of at least one event with PGA > 0 in a year can be calculated as:

$$P(\mathrm{PGA} > 0) = 1 - e^{-\lambda(0)} = \Theta \tag{5}$$

However, the home-owner may decide to make an insurance contract providing him with a transfer x_i in case the loss occurs. The contract is made at a price equal p, which is the premium paid by the consumer to the insurance company. The house wealth W_0 can be assumed equal to the reconstruction cost (e.g., 1500€ for the case under study, as explained beforehand), since this is the maximum cost incurred in case of a seismic event in order to replace the property unit.

The insurance model can be expressed in terms of a utility function U which reflects the net profit gained by the property owner [17]. Assuming risk aversion of the home-owner, the utility U of the property owner can be expressed with a weaker than linear function of the wealth W, that is the utility U increases less than the wealth W. Therefore, the natural logarithm of W+1 is adopted, to have only positive values for U. Hence, in case the property owner does not make an insurance contract, the expected utility U can be calculated as the sum of two terms: one is related to the case in which no earthquake occurs (with probability $P(\mathrm{PGA} = 0) = 1 - \Theta$) and the value W_0 remains invariant; the second term is related to the case in which an earthquake with intensity PGA_i takes place (with probability π_i) and the value W_0 is reduced by the loss L_i. Thus, the expected utility U_n can be calculated as:

$$U = (1 - \Pi)\ln(W_0 + 1) + \sum\nolimits_i \pi_i \ln(W_0 - L(\mathrm{PGA_i}) + 1) \tag{6}$$

Alternatively, in case the property owner does make an insurance contract, the expected utility U can be still calculated as the sum of two terms: the first term is related to the case in which no earthquake occurs (with probability $P(\mathrm{PGA} = 0) = 1 - \Theta$) and the value W_0 is reduced by the premium p; the second term is related to the case in which an earthquake with intensity PGA_i takes place (with probability π_i) and the initial capital W_0 is reduced by both the premium p and the loss L_i and increased by the transfer $x(L_i)$, paid[6] by the insurance company. Therefore, the expected utility can be calculated as:

$$U = (1 - \Pi)\ln(W_0 - p + 1) + \sum\nolimits_i \pi_i \ln(W_0 - p - L_i + x(L_i) + 1) \tag{7}$$

It is assumed that the insurance company is risk neutral and that it makes a take-it-or-leave-it offer in a monopoly market in which it

[5] For the sake of simplicity, $L(\mathrm{PGA_i})$ is hereafter referred to as L_i in the text.

[6] For the sake of simplicity, $x(L_i)$ is hereafter referred to as x_i in the text.

makes a payment x_i (if the loss L_i occurs) to the home-owner. The consumer accepts the contract if the expected utility U is greater than or equal to the expected utility U_n. This condition can be written as:

$$\ln\left(\frac{W_0+1}{W_0-p+1}\right)^{(1-\Pi)} + \ln\left(\frac{\prod_i (W_0-L_i+1)^{\pi_i}}{\prod_i (W_0-p-L_i+x_i+1)^{\pi_i}}\right) \le 0 \quad (8)$$

where the loss L_i can not be greater than the house wealth W_0.

Generally, the transfer x_i, paid by the insurance company in case an event takes place, is fixed by the insurance contract and depends on L_i. It can be fixed as equal to L_i, that is the insurance company commits to cover all the occurred loss (i.e., full insurance), or a portion of it. In the latter case, a maximum coverage can be established, that is the transfer x_i can not go beyond a fixed value M:

$$\begin{aligned} x_i &= L_i; \quad \forall L_i \le M \\ x_i &= M; \quad \forall L_i > M \end{aligned} \quad (9)$$

Furthermore, also an insurance excess can be introduced, that is the transfer x_i is equal to L_i minus a certain amount E:

$$\begin{aligned} x_i &= 0; \quad \forall L_i \le E \\ x_i &= L_i - E; \quad \forall L_i > E \end{aligned} \quad (10)$$

Conditions 9 and 10 can be also applied together, with a maximum coverage and an insurance excess. Obviously, as the maximum coverage decreases and the excess increases the company insurance is going to pay less in case of an earthquake, but the premium p, to be paid yearly by the home owner, decreases.

Thus, the expected contribution to the profit of the company insurance provided by a specific home owner can be calculated by summing up the expenses incurred to the company in case an earthquake with ground-shaking intensity equal to PGA_i takes place:

$$P = p - \sum_i x_i \pi_i \quad (11)$$

where the expenses are represented by the transfer x_i, multiplied by the probability π_i that an earthquake with intensity PGA_i takes place, in a risk neutral formulation.

In a monopoly market, the insurance company fixes the premium in order to maximize its profit. The upper bound limit to the premium is represented by the inequality 8; that is, the home owner will consider it advantageous to enter into the insurance contract and pay the premium only if it is satisfied.

Hence, the premium p can be derived by solving the following optimization problem: maximize the profit P (defined in Eq. (11)), given that home owner utility in case of insurance contract, U, is greater than utility without insurance contract, U_n (defined in inequality 8). In this optimization problem, loss values L_i are known (Eq. (4)) as well as transfer values x_i (Eq. (9) and/or (10)).

Application to the Italian building stock

The loss estimation model and the insurance model have been applied to the Italian residential building stock. In particular, the insurance optimization problem (described in previous section) has been posed for a 1 square meter property owner, for each structural typology in each municipality, to derive the specific premium to be paid to buy an insurance contract. To do this, for each municipality, the vector of ground-shaking intensity probabilities π_i has been derived by discretizing the differential $d\lambda(\mathrm{PGA})$. For each structural typology, the loss values L_i, conditioned on the earthquake intensity i, have been derived from Eq. (4) as an average over all the loss values calculated for the various fragility models considered (except for the combined RC–masonry structures where only one set is available). The transfer values x_i have been calculated by considering a maximum coverage M and an insurance excess E, according to Eqs. (9) and (10), respectively. In particular, M has been assumed equal to [700; 800; 900; 1000; 1100; 1200; 1300; 1400; 1500] €/m^2 and E has been assumed equal to [0; 100; 200; 300; 400; 500] €/m^2. Table 7 refers to the full insurance case (i.e., M = 1500 €/m^2; E = 0 €/m^2) and reports the maximum and minimum value of the annual premium, together with the municipalities where these values occur, for all the considered structural typologies. The average value within all the municipalities is also reported. It can be observed that the maximum and minimum premium values occur in the same municipalities of the corresponding loss values. Furthermore, the premium values are about the 60% greater than the corresponding loss values. This increase is due to the risk aversion of the property owner, who prefers to pay more than the expected loss in order to avoid to directly face the actual loss, once an earthquake event would occur.

Fig. 1 reports the distribution of the yearly insurance premium per square meter in case of full insurance model for the seismic and gravity load designed RC structures. It can be observed that the premium per square meter has a distribution very similar to the seismic hazard, whose distribution is available in [8]. Fig. 2 reports the distribution of the total premium paid within each municipality, by all the property owners (that is the premium per square meter multiplied by the total amount of square meters within each municipality), in case of full insurance model. It represents the total income for the insurance company per municipality. It can be observed that the highest values are paid by the large municipalities, even if the hazard is moderate, as Rome and Naples.

The introduction of the maximum coverage and the insurance excess significantly reduces the premium values. The average p is reported in Table 8 for the masonry structural typology, for the considered values of M and E. It can be observed that the premium value, in case of full insurance contract, is equal to 8.62 €/m^2 and it significantly reduces as the maximum coverage reduces and the excess increases.

Multiplying the premium p in each municipality, the profit P and the expected expenses $\sum_i x_i \pi_i$ by the total amount of square meters per each structural typology, estimates of the total annual

Table 7
Yearly insurance premium per square meter in case of full insurance model.

	Maximum value of p (€/year/m^2)	Municipality where the maximum p takes place	Minimum value of p (€/year/m^2)	Municipality where the minimum p takes place	Mean value of p (€/year/m^2)
Masonry structures	50.50	Giarre (Catania)	0.026	Solonghello (Alessandria)	8.62
Gravity load designed RC structures	28.62	Giarre (Catania)	0.027	Cazzago Brabbia (Varese)	4.17
Seismic load designed RC structures	17.07	Navelli (L'Aquila)	0.001	Solonghello (Alessandria)	2.30
Gravity load designed combined RC–masonry structures	21.67	Giarre (Catania)	0.002	Solonghello (Alessandria)	3.23
Seismic load designed combined RC–masonry structures	17.37	Navelli (L'Aquila)	0.001	Solonghello (Alessandria)	2.44

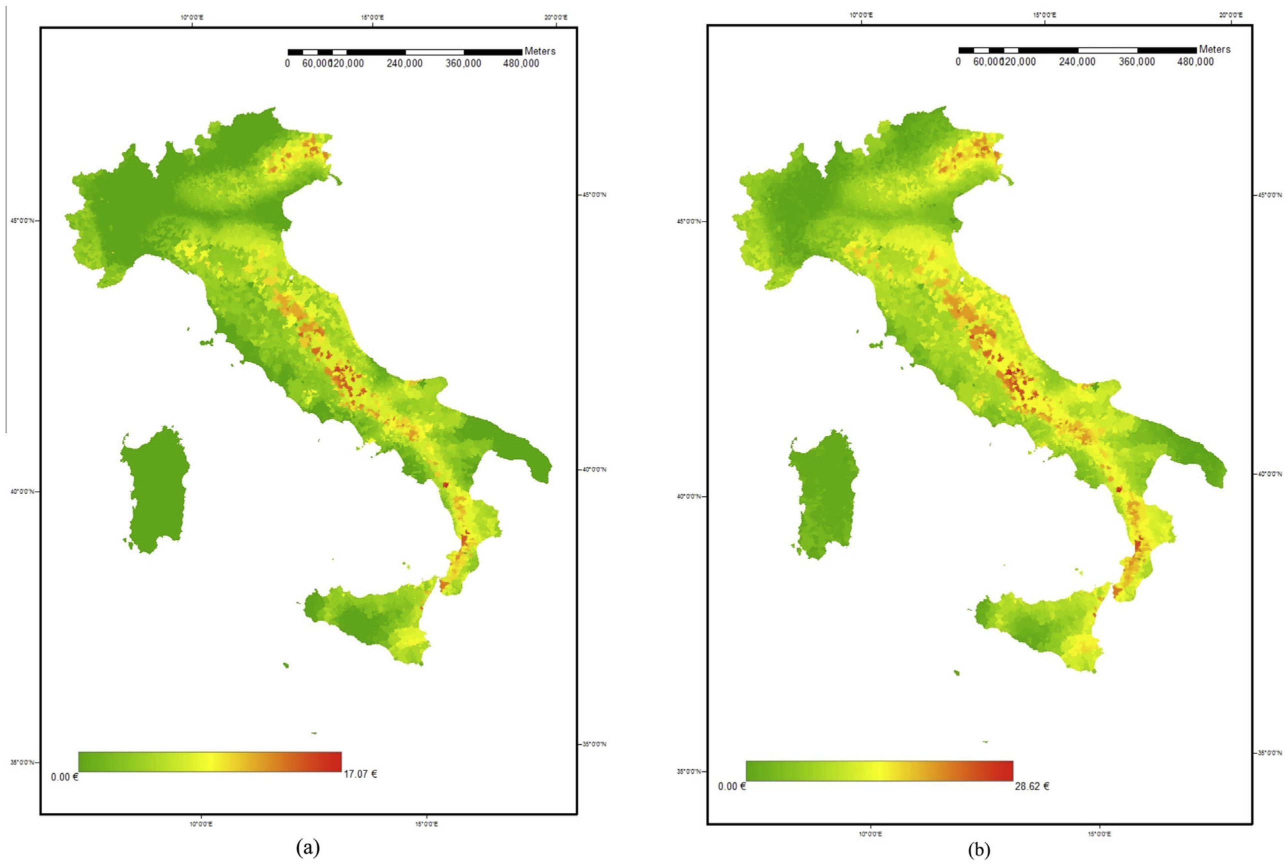

Fig. 1. Yearly insurance premium per square meter for seismic (a) and gravity (b) load designed RC structures in case of full insurance model.

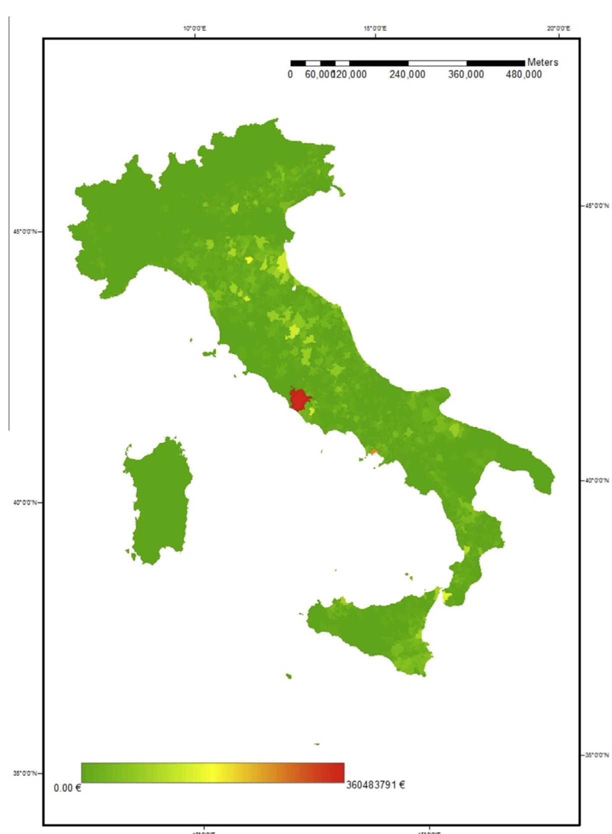

Fig. 2. Yearly total insurance premium per municipality in case of full insurance model.

income p_{tot}, the total annual profit P_{tot} and the total expected annual expenses x_{tot} are obtained for the insurance company. Tables 9–11 report these values for all the considered maximum coverage and insurance excess values. Also in this case, it can be observed that the insurance excess and the maximum coverage reduce the income, profit and expense values of the insurance company, as the risk is progressively moved from the insurance company to the home owner.

Conclusions

A seismic insurance model has been built for the Italian building stock, accounting for the site specific hazard in 8088 Italian municipalities and discretizing the building portfolio in 5 structural typologies. The insurance model builds itself upon a probabilistic loss estimation model resulting in the annual expected loss and in the annual insurance premium for the property owners in each Italian municipality. The obtained results showed high variations in the insurance premium among different Italian municipalities as a result of the variations in the seismic risk across the Italian territory. In each municipality, as a result of the variations in the seismic vulnerability per structural typology, a significant difference between the insurance premium calculated for various structural typologies was observed. It can be observed that the maximum insurance premium values occur in areas that are highly prone to seismic risk (Appennine area and East Sicily), whereas the minimum values are obtained in areas with relatively low seismic risk; such as, in Piemonte and Sardinia regions.

It is also interesting to compare the losses for the two companion categories, i.e., seismic- and gravity load-designed structures. It can be observed that the expected loss and insurance premium

Table 8
Average premium for masonry structures at different maximum coverage and insurance excess values.

Average premium for masonry structures (€/m^2)		Insurance excess				
		E = 0 €/m^2	E = 100 €/m^2	E = 200 €/m^2	E = 300 €/m^2	E = 400 €/m^2
Maximum coverage	M = 700 €/m^2	7.41	5.93	4.85	3.91	3.04
	M = 800 €/m^2	7.72	6.27	5.23	4.34	3.55
	M = 900 €/m^2	7.96	6.54	5.54	4.68	3.94
	M = 1000 €/m^2	8.17	6.76	5.78	4.95	4.25
	M = 1100 €/m^2	8.33	6.94	5.97	5.17	4.49
	M = 1200 €/m^2	8.46	7.07	6.12	5.33	4.67
	M = 1300 €/m^2	8.55	7.17	6.23	5.45	4.80
	M = 1400 €/m^2	8.60	7.23	6.30	5.52	4.88
	M = 1500 €/m^2	8.62	7.25	6.31	5.54	4.90

Table 9
Total annual income at different maximum coverage and insurance excess values.

Total annual income p_{tot} (M€)		Insurance excess				
		E = 0 €/m^2	E = 100 €/m^2	E = 200 €/m^2	E = 300 €/m^2	E = 400 €/m^2
Maximum coverage	M = 700 €/m^2	15,344	12,029	9732	7744	5946
	M = 800 €/m^2	15,959	12,708	10,490	8605	6947
	M = 900 €/m^2	16,450	13,247	11,088	9276	7713
	M = 1000 €/m^2	16,842	13,674	11,558	9800	8304
	M = 1100 €/m^2	17,147	14,005	11,920	10,199	8750
	M = 1200 €/m^2	17,372	14,249	12,186	10,491	9074
	M = 1300 €/m^2	17,530	14,419	12,370	10,693	9296
	M = 1400 €/m^2	17,618	14,513	12,472	10,803	9417
	M = 1500 €/m^2	17,636	14,533	12,493	10,827	9442

Table 10
Total annual profit at different maximum coverage and insurance excess values.

Total annual profit P_{tot} (M€)		Insurance excess				
		E = 0 €/m^2	E = 100 €/m^2	E = 200 €/m^2	E = 300 €/m^2	E = 400 €/m^2
Maximum coverage	M = 700 €/m^2	60,068	57,063	52,493	46,548	39,224
	M = 800 €/m^2	61,727	59,360	55,588	50,674	44,735
	M = 900 €/m^2	62,877	60,987	57,800	53,617	48,634
	M = 1000 €/m^2	63,643	62,110	59,353	55,703	51,390
	M = 1100 €/m^2	64,123	62,850	60,405	57,132	53,292
	M = 1200 €/m^2	64,396	63,305	61,078	58,069	54,546
	M = 1300 €/m^2	64,523	63,555	61,472	58,631	55,313
	M = 1400 €/m^2	64,564	63,661	61,653	58,903	55,690
	M = 1500 €/m^2	64,566	63,676	61,684	58,952	55,759

Table 11
Total annual expenses at different maximum coverage and insurance excess values.

Total annual expenses x_{tot} (M€)		Insurance excess				
		E = 0 €/m^2	E = 100 €/m^2	E = 200 €/m^2	E = 300 €/m^2	E = 400 €/m^2
Maximum coverage	M = 700 €/m^2	9337	6323	4482	3089	2024
	M = 800 €/m^2	9786	6772	4931	3538	2473
	M = 900 €/m^2	10,163	7148	5308	3914	2850
	M = 1000 €/m^2	10,478	7463	5623	4229	3165
	M = 1100 €/m^2	10,734	7720	5879	4486	3421
	M = 1200 €/m^2	10,933	7918	6078	4684	3620
	M = 1300 €/m^2	11,078	8063	6223	4829	3764
	M = 1400 €/m^2	11,161	8147	6306	4913	3848
	M = 1500 €/m^2	11,180[a]	8165	6325	4931	3866

[a] This value coincides with the total expected annual loss for the whole Italian building stock.

per square meter for the gravity load designed structures is almost 1.4 times that of the seismic load designed structures. This difference can be interpreted as the potential reduction, induced by seismic retrofit operations, of the expected loss and, as a consequence, of the insurance premium to be paid.

Finally, it is emphasized that this study represents an effort in analyzing the feasibility of a seismic insurance system, extended to all the Italian residential building stock. This kind of study would be helpful to analyze the premium distribution within the different regions of a seismic country, based on the building stock properties and on the seismic hazard, with different insurance seismic configurations. The results could be helpful for policy makers, with the purpose of verifying the feasibility of a seismic insurance system, as well as insurance companies, with the objective of analyzing potential markets. Further investigations need to be conducted in order to introduce more detailed hypothesis and in order to obtain a more sophisticated simulation. In particular:

- The Italian residential building stock was discretized in just 5 typologies. It is desirable to perform a more refined discretization accounting for building height, regularity/irregularity, age, retrofitting/maintenance operations, etc.
- The costs per square meter to be incurred in case of damage, per each limit state need to be modeled as dependent on both the location of the building and also on the structural typology.
- A full insurance-monopoly market was assumed; more complex cases such as private/public re-insurance mechanisms can be considered. Furthermore, different assumptions on risk attitude for home-owners and insurance companies could be investigated.
- The entire Italian residential building stock was assumed to be covered by an insurance policy. Moreover, the insurance model can also take into account the public incentive to contract the insurance policy.

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