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EMPIRICAL USABILITY FRAGILITY CURVES FOR UNREINFORCED MASONRY BUILDINGS AFFECTED BY THE 2009 L'AQUILA EARTHQUAKE

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Abstract. Recent earthquakes occurred in Italy highlighted the great vulnerability of the Italian building stoke that registered significant economic losses. In this context, many vulnerability models were developed in the literature to obtain a reliable loss assessment. They often focused on damage fragility curves definitions, intending to estimate the damage suffered by the buildings after the seismic events. Nevertheless, in the last years, the attention of different research groups is moved toward the prediction of the building usability, i.e. the condition of a building being habitable or occupiable after a seismic event. In fact, recent researches highlighted that usability is stronger correlated with direct and indirect costs than structural damage. Consequently, the prediction of usability performance represents a valid indicator for the economic funding distribution after an earthquake. From this perspective, this paper aims to develop typological usability fragility curves for Italian unreinforced-masonry buildings to be used for seismic risk assessment on a large scale. The proposed empirical model was calibrated from the observed data collected after the 2009 L'Aquila earthquake, including more than 56 000 unreinforced-masonry buildings. The database was increased to estimate the effective number of usable buildings in the study area. Then, the structural parameters affecting the usability assessment were investigated, and three parameters (construction timespan, number of stories, and state of repair), available both on the post-earthquake database and Italian census, were selected to define different typological classes. The usability fragility curves were defined as a function of peak ground acceleration for two building usability states strongly correlated to repair and population assistance costs: partially unusable and unusable. The curves represent a sound tool to be used as part of a risk model for assessing earthquake impact in terms of both economic and societal losses.

1 INTRODUCTION

Refined loss estimation involves the development of vulnerability models appropriate for damage scenario evaluation and risk assessment. The goal is to obtain tools to support the decision-making process to allocate the economic resources for earthquake risk prevention and emergency management activities [1,2]. Several empirical methods were developed worldwide in recent years based on field data. In particular, in Italy the National Department of Civil Protection made available the observed post-earthquake data through the Da.D.O. platform [3]. Different fragility curves were developed as a function of structural damage for typological classes characteristic of the Italian building stock, both for reinforced concrete (RC) buildings [4–6] and unreinforced masonry buildings [e.g. 7–11]. Once a robust estimate of structural damage is achieved [e.g. 12,13], consequence functions provide a correlation between structural damage and the estimated losses [14–16] that are expressed in either repair costs [17,18] or societal losses [19].

As an alternative to the above-mentioned methods, which are based on the damage suffered by a building after a seismic event, it is possible to consider the usability assessment of the buildings. The usability, defined as the fitness to use a building after a seismic event without an increased risk to human life, is a relevant indicator of the seismic performance [20–22]. The usability assessment needs detailed in situ investigations based on the damage sustained by the building after the earthquake [23].

In Italy, after the 2009 L'Aquila earthquake, at the start of the reconstruction process, funding for the structural repair was allocated based on the usability assessment [24,25]. Del Vecchio et al. [18] found a strong correlation between the usability judgment and repair costs related to different structural components of RC residential buildings. In addition, loss of serviceability was directly related to indirect costs associated to population’s time for assistance [26,27]. In addition, Zucconi et al. [28,29] showed a robust correlation between several structural parameters and the usability assessment.

This paper develops an empirical usability model for unreinforced masonry buildings starting from the observed data collected after the 2009 L’Aquila earthquake, including approximately 57 000 structures. The model aims to define fragility curves for two usability states, partially unusable and unusable, as a function of the peak ground acceleration. Twelve typological classes were defined identifying the relevant categories for the meaningful parameters, i.e., the construction timespan, the state of repair, and the number of stories above ground.

2 PROPOSED PROCEDURE FOR RISK ASSESSMENT

In the present work, a usability model for unreinforced masonry residential buildings is developed as part of a risk model for assessing earthquake impact in terms of both economic and societal losses. The developed model is based on the empirical data collected after the 2009 L'Aquila earthquake [30].

The developed procedure can be used as an alternative to vulnerability models based on post-earthquake damage estimates. The goal is to obtain a higher correlation between usability rating and repair costs, casualties, homelessness, and time of population assistance than traditional models based on structural damage prediction. The proposed model for risk assessment can be schematized by several steps, as summarized in Figure 1.

The first step requires access to the post-earthquake observation database, selecting the subset of data related to residential unreinforced masonry buildings, and discarding data if information, required in the next steps, are unavailable. The observed database is essential to calibrate the fragility curves in terms of usability. In Italy, the National Civil Protection Department made available the data collected in the post-earthquake phase starting from 1976. The proposed model is calibrated based on data collected after the 2009 L'Aquila earthquake, using the AeDES "Level 1 form for post-earthquake damage and usability assessment and emergency countermeasures in ordinary buildings", including 56 584 unreinforced masonry buildings.

The second step involves the Italian census for residential construction, the so-called ISTAT database, which provides information for all the national territory. This data allows the proposed methodology to be used in a different place where the post-earthquake data are unavailable.

Then, in the third step, the comparison between the number of buildings in the observed database and in census data makes it possible to estimate the actual number of buildings for each municipality, avoiding overestimation of the exceedance probability of a performance level at low values of the selected intensity measure, where the surveys are not systematic, but realized only on owners requests. In the Abruzzo region, a total of 318 468 not inspected unreinforced masonry buildings is estimated; consequently, the database is increased to 375 053 buildings, simulating the structural features by means of the Monte Carlo method following the parameter distributions of the observed database.

Step four requires the ground motion selection that must be evaluated for each building of the analyzed database [31]. In this work, the intensity measure is expressed in terms of peak ground acceleration (*PGA*) estimated from the shakemap made available by the Italian National Institute of Geophysics and Vulcanology (http://shakemap.rm.ingv.it/shake/1895389/products).

Step five establishes the typological structures characterized by a similar seismic response in terms of usability. The relevant parameters were identified considering the information available on both the observed database and the census one in order to use the proposed methodology elsewhere, resorting to census data. In step six, the fragility curves in terms of usability are calibrated starting from the observed points as a function of the *PGA* for two usability states, B partially unusable and E unusable buildings for the census-based typological structures selected in step five.

Then, step seven involves defining the consequence function that allows the probability of occurrence as a function of repair cost *Cr* for the selected usability states. The traditional loss functions allow relationships between the damage and losses and can be estimated from the data collected in the reconstruction process phase, as underlined by Di Ludovico et al [27]. The probability density functions of %*Cr* for masonry buildings as a function of usability rating shown in Figure 1 were deduced from [32].

Finally, the last step consists of the risk assessment in terms of societal impact and economic losses at a large scale, developing risk maps that allow to estimate the percentage of buildings that reach a usability state or a specific value of the economic losses in terms of *%Cr*. The map shown in step 8 of Figure 1 is intended to be representative of an example of maps that can be obtained with the proposed methodology, but it is not a result of the present work [16].

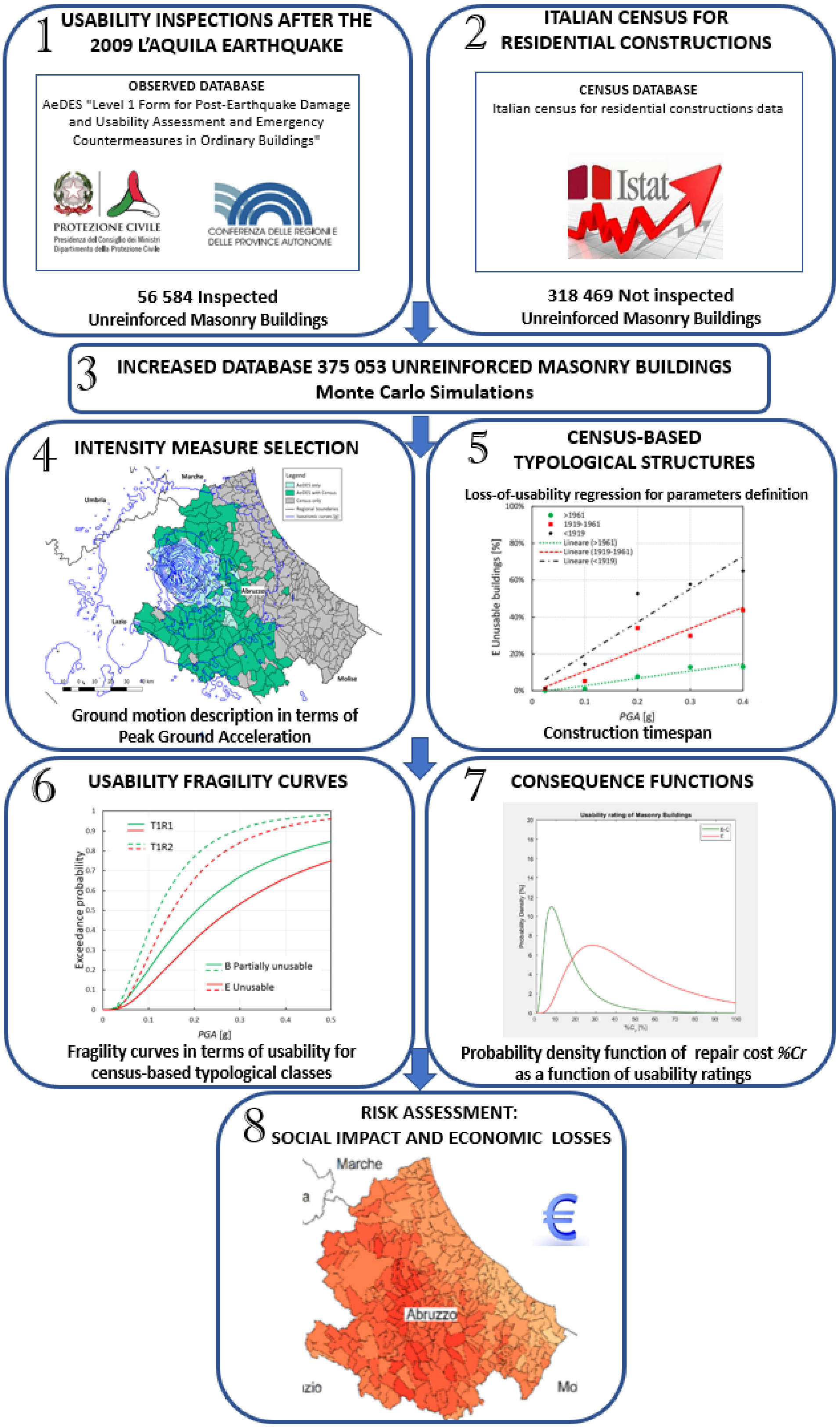
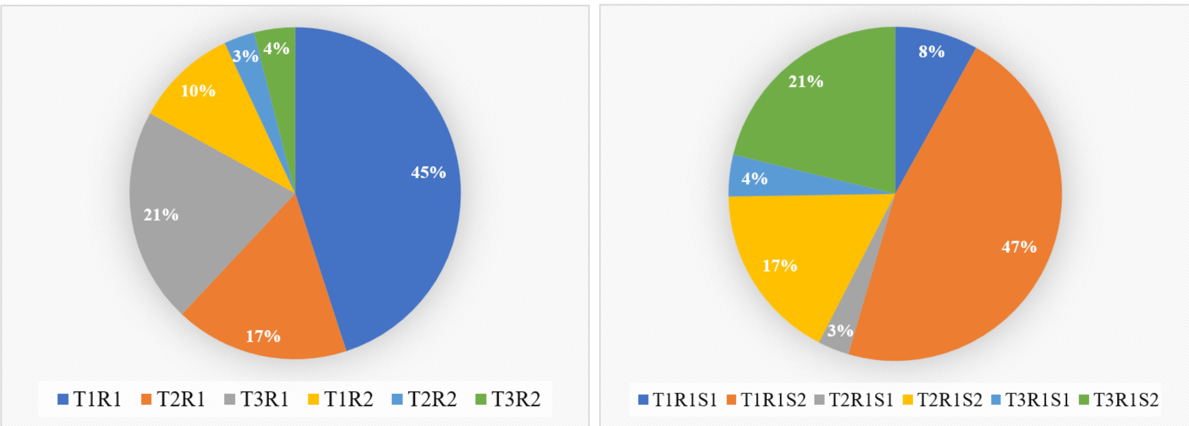


Figure 1: Proposed procedure for risk assessment in terms of societal impact and economic losses

The proposed procedure can be applied on other post – earthquake data in order to refine the calibration of suitable empirical fragility curves representative of the national building stock. Furthermore, starting from step 6, seismic scenarios in terms of usability and losses can be easily carried out by only knowing census based data.

3 CENSUS-BASED TYPOLOGICAL STRUCTURES AND LOSSES

The significant structural parameters influencing the performance were first determined by means of regressions of loss of usability, then the typological classes were established by including information available in both the AeDES database and the Italian census [33], with the aim of applying the proposed model to whatever municipality of the Italian territory. The parameters considered to define the typological classes were: the construction timespan, the state of repair, and the number of stories. For the construction timespan were defined three categories that go along with the main variations in Italian standards for unreinforced-masonry constructions: T1: < 1919, T2: 1919–1961, T3: > 1961 [34,35]. To define the state of repair parameters, an association between the pre-existing damage, compiled in the AeDES form, and the state of repairs categories reported in census data, was necessary [30] to define the two categories considered in this work: R1 for Excellent and Good, and R2 for Mean and Poor state of repair. Then, the number of stories parameter (1 story and more than 1 story) is significant only when the buildings show an excellent or good state of repairs R1. A total of twelve typological classes were thus defined combining the categories of the selected parameters: the relative frequency distribution of the census-based typological structures is shown in Figure 2 a) for typological structures based on construction timespan and state of repair only, and in Figure 2 b) construction timespan, state of repair R1 and number of stories.



a) b)

Figure 2: Relative frequency distribution of census-based typological classes accounting for: a) construction timespan and state of repair; b) construction timespan, state of repair R1 and number of stories

4 USABILITY FRAGILITY CURVES

The main aim of this work was to derive usability fragility curves as a function of peak ground acceleration for three usability states *US*: A rating: usable; B rating: partially unusable;

E rating: unusable.

Following other literature work that developed damage fragility curves [36–38], the lognormal distribution was chosen to fit the observed discrete cumulative frequency distribution according to the equation:

$$P[US \geq US_i | PGA] = \Phi\left(\frac{\ln(PGA) - \mu}{\beta}\right) \quad (1)$$

where $P[US \geq US_i|PGA]$ is the probability of reaching or exceeding a specific usability state US_i given a PGA value; $\Phi(\cdot)$ is the standard normal cumulative distribution function, μ is the logarithmic mean and β is the logarithmic standard deviation.

Then, the maximum likelihood estimation was used to evaluate the parameters μ and β, maximizing the likelihood function with the next equation:

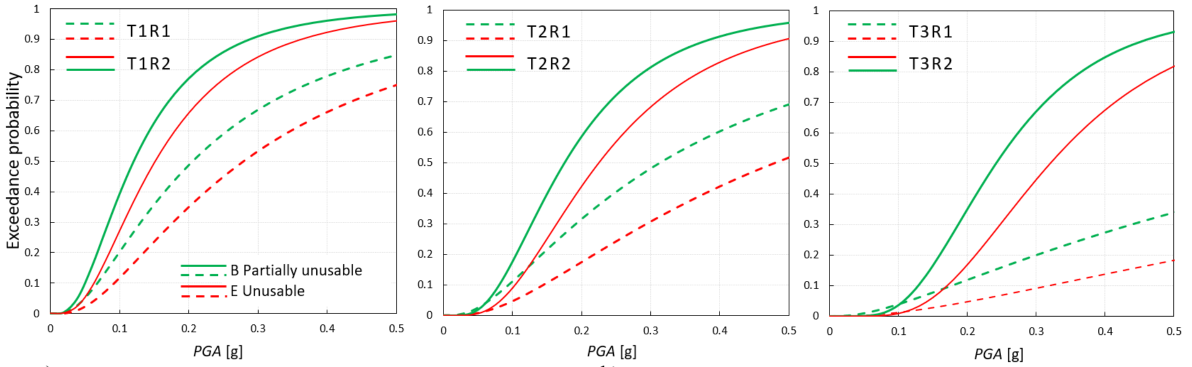
$$\hat{\mu}_{US_i}, \hat{\beta} = \underset{\hat{\mu}_{US_i}, \hat{\beta}}{\text{argmax}} \sum_{i=1}^{2} \sum_{j=1}^{m} \ln\left[\binom{n_j}{z_j}\left(\Phi\left(\frac{\ln(PGA_j) - \mu_{US_i}}{\beta}\right)\right)^{z_{i,j}} \left(1 - \Phi\left(\frac{\ln(PGA_j) - \mu_{US_i}}{\beta}\right)\right)^{n_j - z_{i,j}}\right] \quad (2)$$

where $\Sigma_{i=1}^{2}$ is the sum operator over values from 1 to 2 *US* (partially unusable and unusable) and $\Sigma_{j=1}^{m}$ is the sum operator over values from 1 to *m PGA* categories. The binomial distribution that is assumed to express the observed points $P_j^{z_j}$ that, for the j-th category, z_j buildings reach or exceed the usability state US_i, while $n_j - z_j$ buildings do not reach that usability state with a probability $(1 - P_j)^{n_j - z_j}$, with n_j the total number of buildings for the j-th *PGA* category. Then, $\binom{n_j}{z_j}$ is the binomial coefficient.

The parameter β was supposed the same for all US_i to prevent curves intersection as indicated by Porter [39].

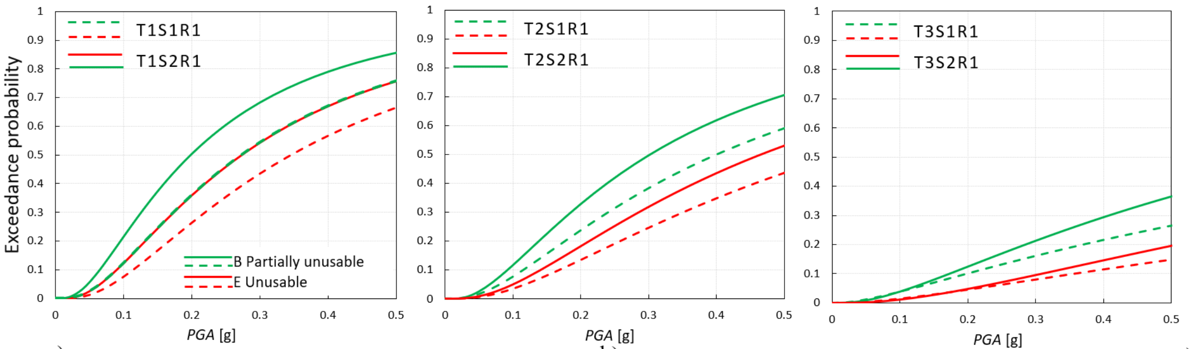
For the six typological classes defined according to construction timespan and state of repair, the fragility curves in terms of usability are shown in Figure 3. It can be noted that older buildings always have a greater loss of usability than newer ones, as can be observed by assessing the influence of the construction timespan, for which category T1 always shows a greater loss of usability than T2, which in turn is higher than T3. In addition, the state of repair R2 always results in a greater loss of usability than the state of repair R1, given the same construction timespan. Finally, median values increase with the *US*, so the partially unusable state always has a lower median than the unusable state; consequently, partially unusable buildings always have a higher probability of occurrence than unusable buildings for a given *PGA* value.

Fragility curves that also consider the number of stories above-ground lead to contradictory results in the case of the state of repair R2, with taller buildings being slightly less vulnerable than shorter ones at the same construction timespan. Therefore, fragility curves considering this parameter are presented exclusively for buildings with state of repair R1 in Figure 4: typological classes with 2 or more stories show a greater loss of usability than the building with 1 story, being equal all other parameters for both the usability states. In Figure 4 a) partially unusable fragility curve for typological class T1S1R1 is overlapped with the unusable fragility curve for typological class T1S2R1.



a) b) c)

Figure 3: Fragility curves in terms of usability for typological classes: a) T1R1, T1R2; b) T2R1, T2R2, c) T3R1, T3R2



a) b) c)

Figure 4: Fragility curves in terms of usability for typological classes: (a) T1S1R1, T1S2R1; (b) T1S1R1, T1S2R1; c) T1S1R1, T1S2R1

5 SEISMIC SCENARIO IN TERMS OF USABILITY AND LOSSES

In order to show how the proposed methodology can be applied, a seismic risk scenario is presented for Arischia, a hamlet of the municipality of L'Aquila, located at an altitude of 860 m above sea level and distant about 14 km northwest of the capital city. The settlement that registered a *PGA* = 0.4 g, was completely surveyed after the 2009 earthquake.

The historic center has 790 unreinforced masonry buildings, having the distribution in census based-typological categories shown in Table 1. Moreover, the comparison between the usability assessment observed after the seismic event and the predicted scenario obtained with the proposed methodology is also reported in the following table for the three usability states: A, usable; B, partially unusable; E, unusable.

Then, the same comparison of Table 1 is reported in terms of percentage of buildings in Table 2: the last three columns indicate the error carried out with the proposed methodology for each typological class and *US*, evaluated as the difference between the number of buildings in the observation database and in the prediction one, normalized on the observed data. A positive sign indicates an underestimation of the total number of buildings predicted with the proposed model, contrarily a negative sign implies an overestimation of the number by the model. The most significant errors are recorded for the typological classes T3R2 were the biggest error value is equal to 100%. Although this value may appear very large, only 4 buildings fall in this typological class, making this error assessment unreliable. If the T3R2 typological class is excluded, the mean error evaluated on the relative value of Table 2 is equal to 2% for *US* =A, 27% for *US* = B, and -6 for *US* = E.

Table 1: Census-based typological distribution (number of buildings) as a function of the usability assessment observed after the 2009 earthquake and predicted in the scenario with the proposed model

		Post EQ			Scenario		
Typological class	Tot	A, Usable	B, Partially Unusable	E, Unusable	A, Usable	B, Partially Unusable	E, Unusable
T1R1	326	100	48	178	72	38	216
T2R1	197	92	42	63	78	36	83
T3R1	178	115	26	37	129	24	25
T1R2	70	3	6	61	3	3	64
T2R2	15	1	2	12	1	1	13
T3R2	4	2	1	1	1	1	2

Table 2: Census-based typological distribution (% of buildings) as a function of the usability assessment registered in the observed database, the predicted scenario with the proposed model and the estimated

	Post EQ			Scenario			Error		
Typological class	A, Usable	B, Partially Unusable	C, Unusable	A, Usable	B, Partially Unusable	C, Unusable	A, Usable	B, Partially Unusable	E, Unusable
T1R1	30.7	14.7	54.6	22.1	11.7	66.1	28%	21%	-21%
T2R1	46.7	21.3	32.0	39.7	18.1	42.3	15%	15%	-32%
T3R1	64.6	14.6	20.8	72.7	13.6	13.8	-12%	7%	34%
T1R2	4.3	8.6	87.1	4.0	3.8	92.2	8%	56%	-6%
T2R2	6.7	13.3	80.0	8.6	8.5	82.9	-29%	36%	-4%
T3R2	50.0	25.0	25.0	15.3	17.2	67.6	69%	31%	-170%

Although computing the mean of relative values is usually wrong, and absolute or square values should be used, for an urban-scale scenario the data are required at municipality or settlement level is aggregated in nature, so that overestimations and underestimations compensate themselves indeed. In the estimation of economic and social losses in terms of repair costs and evacuees local mistakes are acceptable, provided that the overall assessment is sufficiently close to the mark.

Then, in order to complete the risk scenario, the results presented in Di Ludovico et al. [27] are used to estimate both direct and indirect losses. In particular, the authors present relationships between the usability rating and repair costs for unreinforced masonry and reinforced concrete buildings derived from data observed after the 2009 L'Aquila earthquake. The work refers to repair (%Cr) and population assistance costs (%Ca) evaluated in terms of percentage with respect to the reference unit cost of a new building. For unreinforced masonry buildings, the median values of %Cr are assumed equal to 0% for usable, 14% for partially unusable, and 42% for unusable buildings. The unit cost of a building, including all items (e.g., technical expenses, VAT, etc…), is set equal to 1350 €/m^2. The total surface of each building can be estimated starting from the information available in the observed database related to the number of stories and the average floor area or, alternatively, from the total floor area indicated in census data. Then, it is possible to determine for the buildings of each typological class the direct economic losses as a function of the usability rating, as shown in Table 3 in second and third columns. Overall, a loss of almost 40.5 M€ is estimated, of which about 3.5 M€ is related to partially unusable buildings and approximately 37 M€ to unusable ones.

Finally, the indirect costs can also be estimated by introducing the relationship between the %Cr and the %Ca proposed in [27] and shown in the first two rows of Table 4. In the third row of the same table the estimated values of the %Ca for Arischia is presented. Finally, in the last two columns of Table 3 the indirect losses assessed for each typological class as a function of the usability rating are reported: a loss of almost 23 M€ is expected, whose more than 2.5 M€ for partially unusable buildings and more than 20 M€ for unusable ones. In brief, a total loss of almost 63.5 M€ is estimated, including direct and indirect costs.

Table 3 Loss assessment in terms of repair (%Cr) and population assistance costs (%Ca) for Arischia.

	Cr		Ca	
Typological class	B, Partially Unusable	E, Unusable	B, Partially Unusable	E, Unusable
T1R1	1,088,843 €	18,461,996 €	838,409 €	10,101,349 €
T2R1	1,170,423 €	8,221,059 €	901,226 €	4,498,094 €
T3R1	1,096,851 €	3,332,690 €	844,575 €	1,823,457 €
T1R2	77,304 €	5,611,291 €	59,524 €	3,070,178 €
T2R2	38,347 €	1,123,676 €	29,527 €	614,811 €
T3R2	19,165 €	226,004 €	14,757 €	123,657 €
Tot	3,490,932 €	36,976,716 €	2,688,018 €	20,231,546 €

Table 4 Relationship between %Cr and %Ca [27]

%Cr [27]	%Cr ≤ 5	5 < %Cr ≤ 25	%Cr >25
%Ca [27]	0	0.77 Cr	0.19 Cr+0.15
%Ca (present study	0%	11%	23%

The proposed methodology can be further validated and enhanced with data collected after other earthquakes and can be extended to reinforced concrete buildings. Nevertheless, although the proposed fragility curves can be improved, the suggested procedure is suitable for risk scenarios, emergency management, and for reconstruction cost estimation by means of consequence functions.

5 CONCLUSIONS

The developed fragility curves, expressed in terms of partially unusable and unusable performance levels of buildings, can be a crucial tool for preventive seismic scenarios and risk assessment because usability is a suitable indicator for allocating economic funding after an earthquake. In fact, the usability strongly correlates with repair costs and time to the population assistance, which account for the most significant part of the direct and indirect seismic losses. Finally, the proposed fragility curves can be used for preliminary estimates in countries with similar constructions until further specific studies and calibrations based on local earthquake data will be available. When a systematic census of buildings is lacking, the minimal number of parameters defining the proposed model is faster to collect than those required by more detailed alternative models. In fact, in most cases, they can be identified from online tools such as Google Street View and historical maps without needing an on-site survey. Finally, a similar model can be developed for residential RC buildings.

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