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SEISMIC RISK ASSESSMENT OF MASONRY BUILDINGS: INFLUENCE OF STRUCTURAL KNOWLEDGE ON FRAGILITY CURVES

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Abstract

In this paper, a seismic risk analysis of masonry buildings is presented, using fragility curves derived through a Macro-Seismic Approach. The structural typologies considered are based on the model provided in Sections 2 and 3 of the Italian AeDES forms, with information collected in the Observed Damage Database (D.a.D.O.). This study examines the influence of building knowledge on seismic risk assessment, analyzing how the amount of information used to identify structural typologies affects this evaluation. The impact evaluation is performed by comparing a "complete" model, which incorporates all available information (consistent with the typological definitions of the AeDES forms), with "incomplete" models, which progressively reduce the data considered.

Keywords: Damage observed, Empirical fragility curves, Masonry buildings, Seismic risk, Expected annual loss.

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1 INTRODUCTION

Seismic risk analysis quantifies the potential economic losses from earthquakes at a specific location over a given time period. It enables the estimation of building repair costs before an earthquake occurs, based on the probability of various damage levels.

Seismic risk analysis requires the use of fragility curves to assess the damage and losses resulting from seismic events. These curves have become an indispensable tool for calculating and preventing economic and social losses [1], within a probabilistic framework that accounts for both epistemic uncertainty (due to lack of knowledge) and aleatory uncertainty (typically reflecting record-to-record variability).

For this study, typological fragility curves, which are derived from the analysis of observed damage to buildings following a seismic event, will be used. These fragility curves are categorized into five distinct damage levels, ranging from D_1 (minor damage) to D_5 (collapse), in accordance with the European Macroseismic Scale EMS-98 [2]. The curves represent structural typologies as defined by the model outlined in Sections 1 and 2 of the AeDES forms [1]. To assess the impact of available knowledge on seismic risk evaluations, a comparison is made between a "complete" model, which includes all available information (consistent with the typological classifications in the AeDES forms), and "incomplete" models that progressively reduce the amount of data.

2 SEISMIC RISK METHODOLOGY

The Expected Annualized Loss (EAL) is a crucial parameter for quantifying seismic loss. It represents the average annual financial loss, accounting for both the frequency and severity of different seismic events. The EAL is determined by the area under the loss curve [1]. Typically, for a given structural typology, where losses are assumed to be limited to direct costs, the seismic risk assessment can be expressed in the standard form shown in equation (1) ([1], [4]):

$$P[L] = \sum_{d \quad edp \quad im} P[L_d|D] \cdot P[D|EDP] \cdot P[EDP|IM] \cdot P[IM] \tag{1}$$

P[L] represents the probability of loss associated with a specific structural typology (i.e., EAL), resulting from earthquakes at a given reference seismic site within a specified time period. This probability is calculated by convolving key parameters that characterize seismic hazard, structural vulnerability, and exposure. Specifically, P[IM] denotes the average annual exceedance probability of a seismic event with a certain Intensity Measure (IM) at the reference site. P[EDP|IM] represents the conditional probability of an Engineering Demand Parameter (EDP), such as drift ratios, displacements, or accelerations, occurring due to the annual exceedance of IM. Additionally, P[D|EDP] defines the probability of reaching a specific damage level D, given the EDP. The IM-EDP relationship is typically determined through numerical analyses or simulations, which help correlate damage levels with observed test data.

However, when structural behavior is assessed based on observed damage analysis, defining EDPs becomes challenging. In such cases, the terms are condensed into P[D|IM], where the probability of a certain damage level D is directly conditioned by IM. Finally, $P[L_d|D]$ expresses the probability of incurring a specific loss L_d due to the occurrence of damage level D.

In this study, the uncertainty in the damage-to-loss function $P[L_d|D]$ is disregarded, and therefore, the procedure outlined in Tatangelo et al. ([5], [6]) is adopted to derive the loss curves and EALs. Specifically, once the fragility curves are determined, damage probability curves P[D=d|IM] are established for all considered damage states. Each damage probability curve is then associated with an economic consequence, expressed as a percentage of the Reconstruction Cost (%RC), to generate typological economic loss curves. By incorporating a hazard law λ(IM) specific to the reference site, the economic loss curves can be derived, and integrating these curves yields the value of the EAL.

3 FRAGILITY CURVES

A fragility curve expresses the conditional probability that a structure or system will experience damage at a given IM value, reaching or surpassing a certain threshold. Typically, fragility curves are modeled using the log-normal cumulative distribution function (2)., which effectively captures the variability and uncertainty associated with structural performance under different loading conditions.

$$P(D \geq D_i \lfloor IM) = \Phi \left[\frac{ln(IM/\theta_i)}{\sigma_{ln,i}} \right] \tag{2}$$

where Φ represents the cumulative distribution function of a standard normal distribution, while ϑ and σ_{ln} correspond, respectively, to the median value of the IM and the standard deviation of its logarithmic values. These key parameters (ϑ, σ_{ln}) are estimated using the Maximum Likelihood Estimation (MLE) method, which maximizes the probability of observing the given damage data [7]. In practice, the available data is divided into several sub-samples with equal amplitude to facilitate this estimation process. It is important to note that the way the sample is partitioned is critical, as the choice of the number of intervals and, consequently, their amplitude directly affects the estimation of these fundamental parameters. Therefore, in line with the study by Tatangelo et al. [8], the values of ϑ and σ_{ln} are derived by considering sub-samples containing 100 data points each.

With this number of intervals, the values of ϑ and σ_{ln} remain stable, unaffected by the selection of sub-samples. Additionally, σ_{ln} is assigned individually to each curve, ensuring that no curve intersections occur. This approach avoids the potential inaccuracies that could arise from using a single σ_{ln} value, which might lead to suboptimal data fitting in certain cases.

4 L'AQUILA 2009 DATABASE

Following the L'Aquila 2009 earthquake, the Da.D.O. database [9] collected AeDES forms [1] for 74049 buildings across 129 municipalities. Among these, 68556 buildings, located in 95 of the 129 municipalities, were identified as having a declared residential use and were affected by the earthquake swarm under consideration. Figure 1.a presents the number of buildings (larger histograms), the corresponding percentage (inner, narrower histograms), and the cumulative percentage (dashed line) for both residential buildings and those with other uses. Residential buildings account for approximately 93% of the surveyed building stock, with their distribution by construction material detailed in Figure 1.a. Notably, masonry structures dominate, representing 81% of the total.

An insightful result emerges when the sub-stock of masonry residential buildings (56338) is categorized into isolated (IS) and aggregate structures. Aggregate buildings are further classified based on their position within a block: internal (IN), external (EX), or corner (CO). Figure 1.c illustrates this distribution, highlighting that the majority of the sample consists of aggregate buildings.

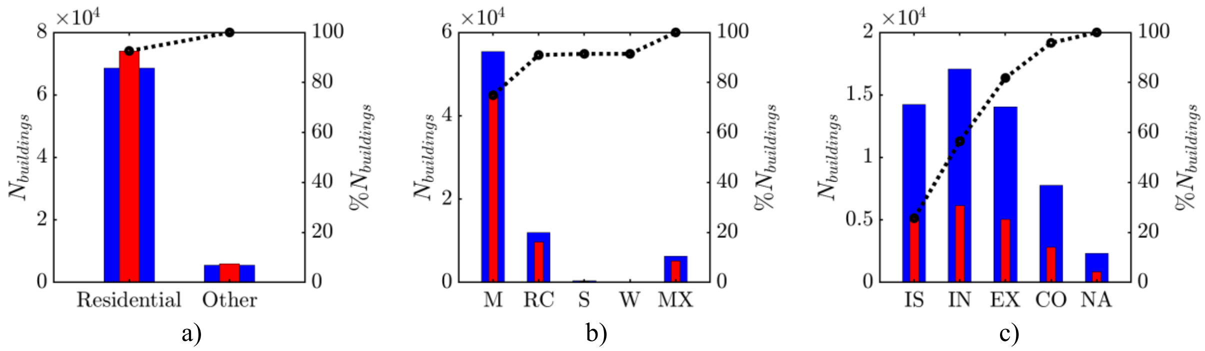

Figure 1: Number and percentage of surveyed residential buildings after the L'Aquila 2009 earthquake: a) residential buildings and others; b) material; c) isolated and aggregate

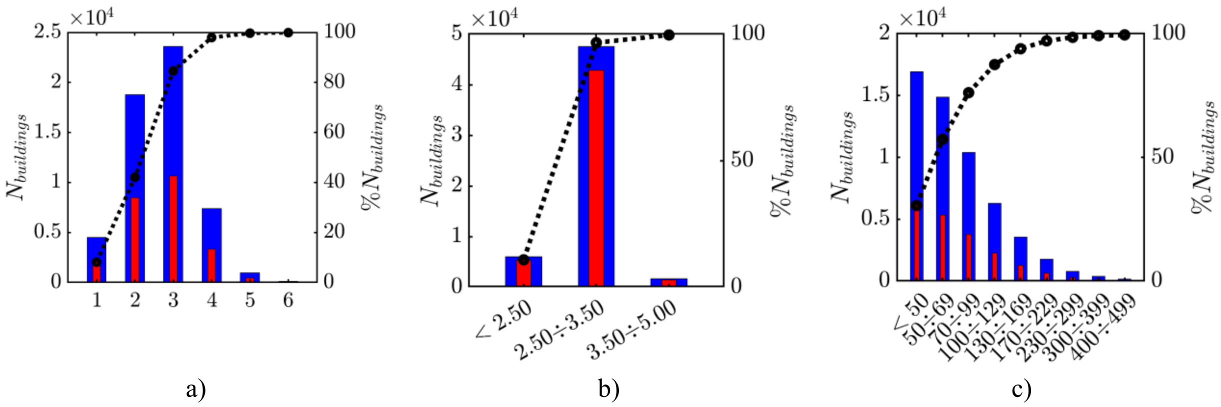

Figure 2: Number and percentage of surveyed residential buildings after the L'Aquila 2009 earthquake: a) floors total numbers; b) average floor height; c) average floor area

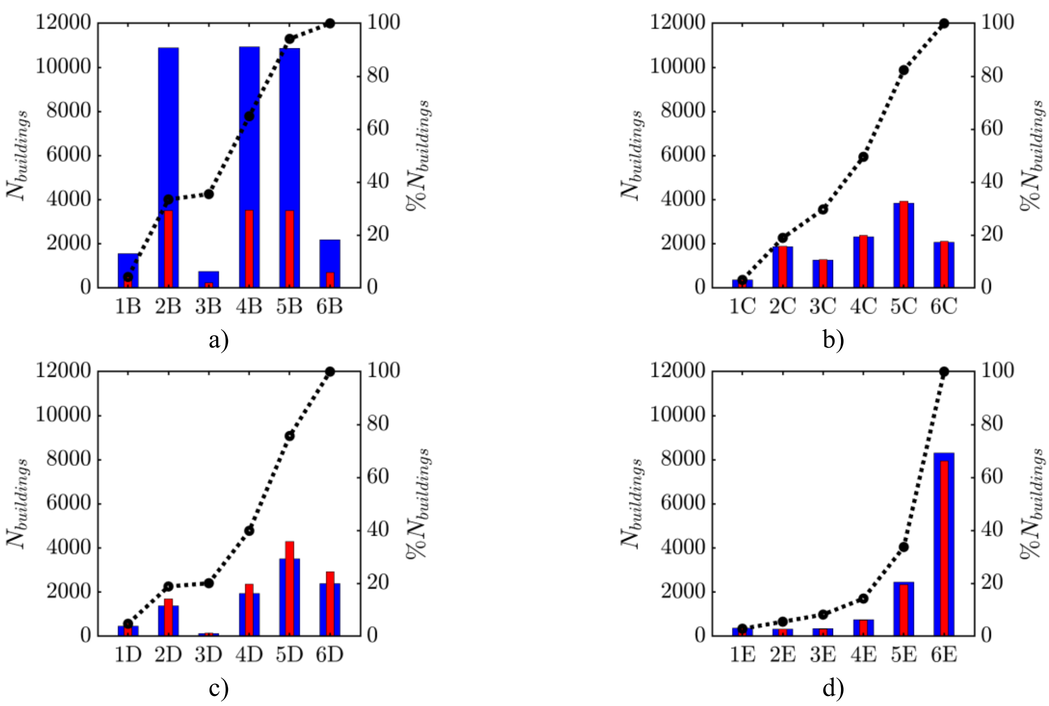

Figure 3: Number and percentage of surveyed residential buildings after the L'Aquila 2009 earthquake: a) type B; b) type C; c) type C; d) type D

Figure 2 illustrates the distribution of key dimensional characteristics within the analyzed sample. These distributions are represented as histograms, with the cumulative percentage shown as a dashed line for each observed parameter. Specifically, the examined building data include the total number of floors (Figure 2.a), the average floor height (Figure 2.b), and the average floor area (Figure 2.c). Observing these distributions, it is evident that the majority of the sample approximately 80% consists of buildings with 2 to 4 floors and an average floor area of less than 50 m² (Figure 2.c). Regarding the average floor height (Figure 2.b), most surveyed buildings have values ranging between 2.5 m and 3.5 m.

Each histogram in Figure 3 presents the number of buildings (wide bars) along with the corresponding percentage (narrow bars), while a dashed line represents the cumulative percentage. From the analysis of the surveyed building stock, it is evident that masonry of poor quality (type B in Figure 3.a) is the predominant vertical structural element. This structural type is commonly associated with vaults, beams with deformable slabs, and beams with semi-rigid slabs.

5 KNOWLEDGE IMPACT ASSESSMENT ON SEISMIC RISK

In order to enable a comparison between structural typologies that accounts for all available information (following AeDES form typological definitions) and those with incomplete data, fragility curves need to be developed for the typologies specified in Table 1, using a data reduction method.

Type	Masonry	VS	HS	Ties	Position	n. Floor	h. Floor	Area
T-1	yes	-	-	-	-	-	-	-
T-2	yes	B	-	-	-	-	-	-
T-3	yes	-	4	-	-	-	-	-
T-4	yes	-	-	yes	-	-	-	-
T-5	yes	-	-	-	aggregate	-	-	-
T-6	yes	-	-	-	-	3	-	-
T-7	yes	-	-	-	-	-	2.5-3.5 m	-
T-8	yes	-	-	-	-	-	-	<50 m^2
T-9	yes	B	4	yes	-	-	-	-
T-10	yes	B	4	-	aggregate	3	2.5-3.5 m	-
T-11	yes	B	4	yes	aggregate	3	2.5-3.5 m	<50 m^2

Table 1: Typologies analyzed.

The T-11 typology represents the complete information scenario. Conversely, T-1 is the most uncertain typology, where only the material (i.e., masonry) is known. Typologies T-2 through T-8 progressively incorporate the specific characteristics of T-11, adding details step-by-step from T-1. Typology T-9 accounts for the knowledge of the vertical (VS) and horizontal (HS) structural elements. Meanwhile, T-10 considers the information that a surveyor could obtain by inspecting the building only from the outside.

Figure 4 shows the fragility curves for the various typologies outlined in Table 1. Figures 4.a to 4.e compare these typologies across each damage level. The complete typology (T-11) is represented by a solid line, the most dissimilar typology by a dotted line, and the most similar typology by a dashed line.

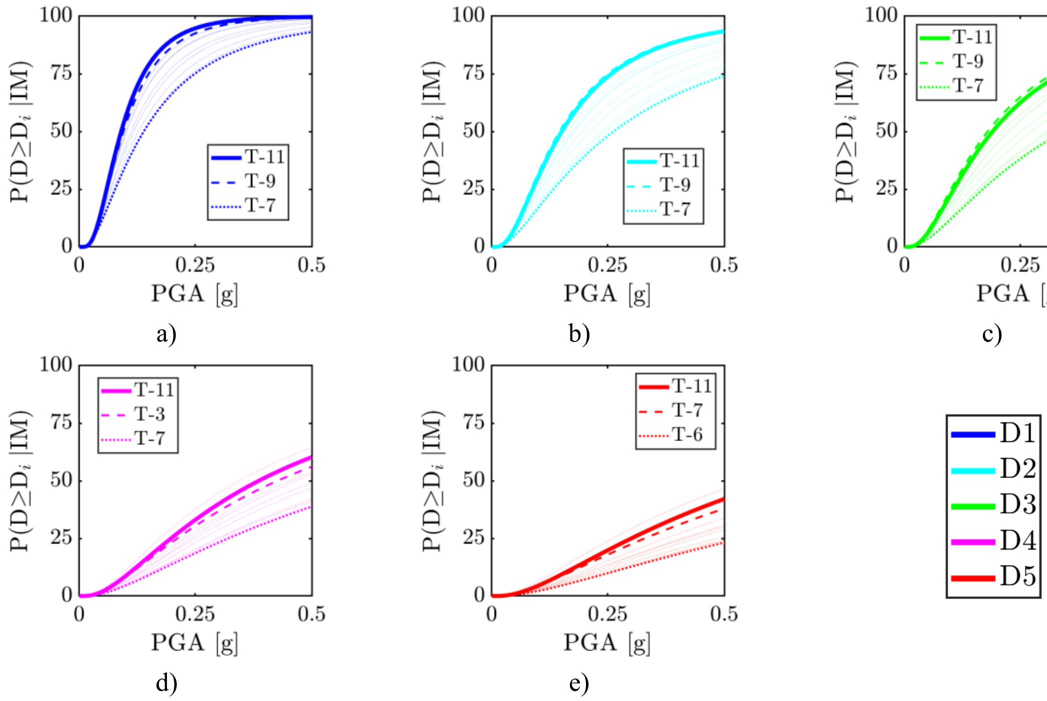

Figure 4: Comparison among fragility curves of the typologies of Table 1

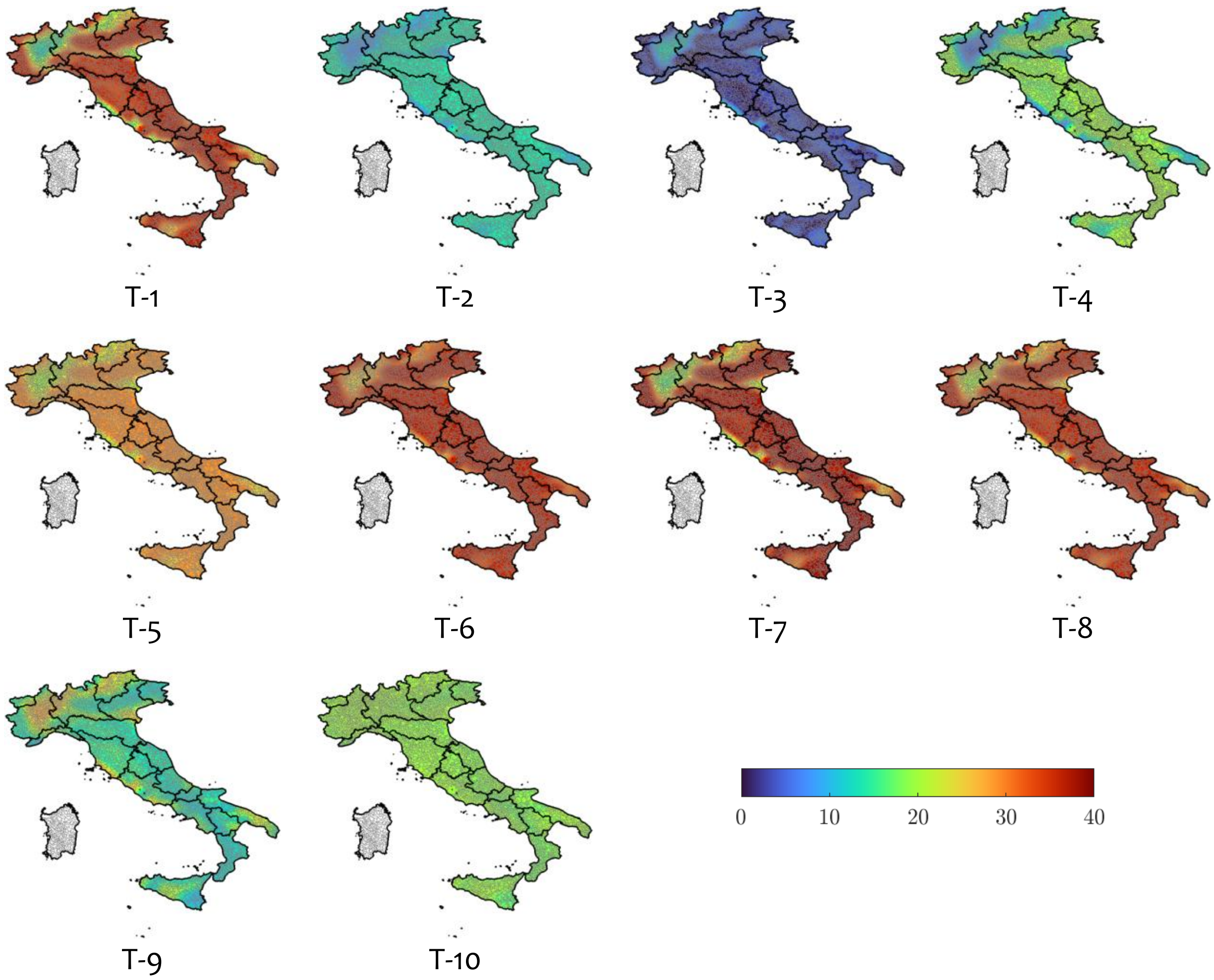

Figure 5: Maps of errors of seismic risk of the typologies from T-1 to T-10 compared to T-11

Figure 5 presents maps comparing the seismic risk across Italy between typology T-11 and the other typologies (T-1 to T-10), specifically highlighting the percentage error.

Analysis of Figure 5 reveals that typology T-3, which includes information on both the material and horizontal structural elements, exhibits a very low error. Conversely, typology T-6 shows the greatest deviation from the seismic risk assessment provided by most accurate typology T-11.

6 CONCLUSIONS

In this study, a seismic risk analysis of masonry buildings was conducted using fragility curves derived through a MSA. The investigation highlighted how the level of structural knowledge significantly influences the assessment of seismic vulnerability and, consequently, the estimation of expected losses.

The analysis confirmed that integrating more detailed information, consistent with the typological definitions of the AeDES forms, leads to a more accurate characterization of the seismic behavior of buildings. Conversely, using incomplete models, with a progressive reduction of available data, introduces increasing levels of uncertainty in risk assessment. In particular, it was observed that the loss of information regarding vertical and horizontal structural elements has a significant impact on fragility curves and economic loss estimates.

The proposed approach allows for the identification and quantification of the effect of knowledge on seismic risk assessment, providing a useful framework for improving risk mitigation strategies and optimizing data collection in post-earthquake studies. Additionally, the results suggest that applying methods to complete missing information could be an effective solution for reducing uncertainties in seismic vulnerability models.

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