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Generalized Extreme Value-Based Fragility Curves †

Zahra Haqi *, Matteo Dalmasso and Marco Civera

Department of Structural, Geotechnical, and Building Engineering (DISEG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Turin, Italy; matteo.dalmasso@polito.it (M.D.); marco.civera@polito.it (M.C.)

* Correspondence: zahra.haqi@studenti.polito.it

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Abstract

Fragility curves are essential for assessing the vulnerability of buildings to earthquake-induced damage, representing the probability of exceeding various damage states as a function of seismic intensity. They enable rapid pre-screening of large building stocks, guiding focused analyses, monitoring, and mitigation strategies. This study introduces an empirical approach using the Generalized Extreme Value (GEV) distribution to model fragility curves, offering greater flexibility than the conventional lognormal method. In this work, GEV-based curves were derived from empirical data retrieved from the Italian Da.D.O. platform using Python 3.10.1 tool. The approach provides a practical framework for accurate, large-scale seismic risk assessment.

Keywords: seismic hazard; fragility curves; GEV distribution; Da.D.O. platform; risk assessment

1. Introduction

Earthquake events highlight the vulnerability of our built environment, making it essential to quantify the probability of structural damage. Fragility curves estimate the likelihood that a structure reaches or exceeds a given damage state as a function of seismic intensity, forming a cornerstone of seismic risk assessment and performance-based earthquake engineering, including the Hazards U.S. (HAZUS) methodology developed by the Federal Emergency Management Agency (FEMA) and National Institute of Building Sciences (NIBS) [1]. They provide a simplified yet effective tool linking seismic hazard to expected structural damage at both building and territorial scales.

Fragility curves can be developed empirically from post-earthquake damage observations, often classified by macroseismic intensity scales such as EMS-98 [2], or analytically using nonlinear structural analyses and probabilistic performance assessment frameworks [3,4]. Porter et al. [4] proposed a widely adopted formulation for performance-based earthquake engineering. At the same time, recent studies leverage detailed damage and exposure datasets to refine empirical models for specific building types and regions [5–7]. Most applications represent fragility curves using lognormal distributions, due to their simplicity and ability to capture a smooth increase in damage probability with seismic intensity [3,4]. This approach underpins standard methodologies such as HAZUS [1] and has been widely applied to reinforced concrete (RC) and unreinforced masonry (URM) buildings, including the empirical models by Rosti et al. [6,7]. However, lognormal assumptions may not fully capture abrupt damage transitions observed under strong or extreme seismic events, which are critical for assessing rare but high-consequence outcomes [8].

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To address this limitation, the present study introduces the Generalized Extreme Value (GEV) distribution as an alternative. The GEV explicitly models extreme behavior, providing a more realistic representation of the upper tail of the damage probability distribution. The methodology is applied to Italy's predominant residential building types—URM and RC—and systematically compared with established empirical models, particularly those by Rosti et al. [6,7], to evaluate the benefits and limitations of extreme-value-based distributions in seismic fragility assessment.

2. Materials and Methods

2.1. Fragility Curves and Damage States

Building fragility curves, typically modeled with lognormal functions, estimate the probability that a structure will experience varying levels of damage during an earthquake. By accounting for uncertainties in building strength, damage definitions, and earthquake intensity, they provide a probabilistic framework for assessing structural vulnerability.

Figure 1 presents fragility curves for four distinct damage states defined by FEMA/NIBS methodology. Each curve shows the probability of reaching a specific damage state across different levels of spectral response [1,5]. The accompanying figure illustrates the relationship between seismic intensity (IM) and the probability of exceeding various damage states [3]. Along the curve, seismic intensity increases, and with it, the likelihood of damage, in terms of damage states (DSs). Each curve shows the increasing probability that a structure will exceed a given damage level [4].

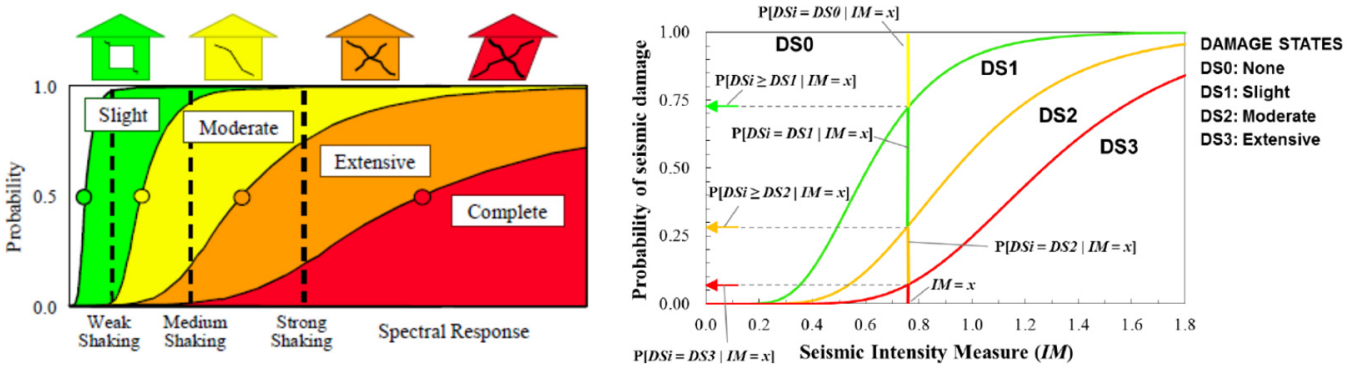


Figure 1. (**Left**): Fragility curves depicting the probability of reaching four damage states under varying seismic intensities, based on FEMA/NIBS methodology. (**Right**): Cumulative fragility curves showing the probability of exceeding each damage state with increasing seismic intensity.

The European Macroseismic Scale 1998 (EMS-98, [2]) classifies building damage into five grades, ranging from slight damage to total structural collapse. This standardized system provides a clear framework for post-earthquake field surveys. It underpins the development of fragility curves by ensuring consistent damage-state definitions across building types [2], and it can be applied to both URM (left side of Figure 2) and RC buildings (right side).

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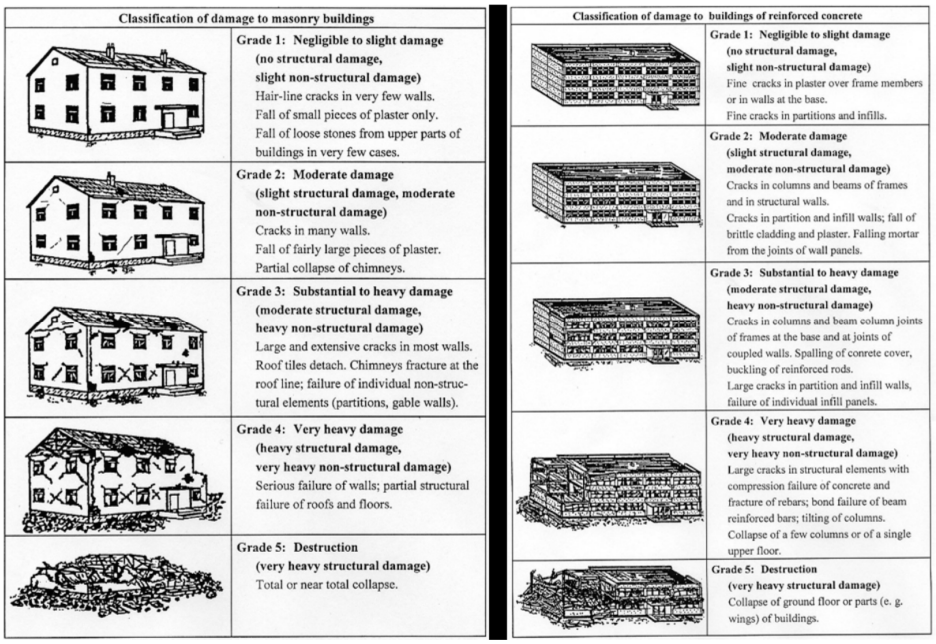


Figure 2. Classification of building damage according to the European Macroseismic Scale 1998 (EMS-98) [2], detailing five damage grades.

2.2. Generalized Extreme Value and Lognormal Distributions

In seismic fragility analysis, the lognormal distribution is commonly used to model the probability of building damage as seismic intensity increases. Its advantages include mathematical simplicity, alignment with the multiplicative nature of structural failure, and good fit to typical earthquake response. However, its fixed shape can underestimate rare, extreme events, limiting its usefulness for high-consequence scenarios.

In contrast, the Generalized Extreme Value (GEV) distribution is designed to model extremes, offering greater flexibility in the upper tail to represent low-probability, high-impact seismic demands realistically. Depending on its shape parameter (ξ), the GEV can assume Fréchet ($\xi > 0$), Weibull ($\xi < 0$), or Gumbel ($\xi = 0$) forms, making it especially suitable for rare-event modeling. This flexibility supports risk assessments focused on extreme seismic scenarios, aligning with the research objective of capturing the full spectrum of structural vulnerability.

In this classic framework, the Probability Density Function (PDF) can be defined as:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right)} \quad (1)$$

And the corresponding Cumulative Distribution Function (CDF) as:

$$f(x) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{lnx-\mu}{\sigma\sqrt{2}}\right)\right] \quad (2)$$

In the case of the Generalized Extreme Value approach for rare-event modeling, the Probability Density Function (PDF) becomes:

$$f(x) = \frac{1}{\sigma}\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\left(1+\frac{1}{\xi}\right)} \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \quad (3)$$

While the Cumulative Distribution Function (CDF) is as follows:

$$f(x) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \quad (4)$$

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2.3. Benchmark Fragility Curves

This study builds on the well-established fragility curves of Rosti et al. [6,7], replacing their lognormal fit with a Generalized Extreme Value (GEV) distribution. Specifically, the fitting was applied to Rosti et al.'s [6,7] curves directly, rather than recreating the figures from fitting the Da.D.O. data, because the original filtering process was not fully transparent, and attempts to reproduce it did not exactly match the histograms and results reported in Rosti et al. [6,7].

In particular, Rosti et al. [6] categorize RC buildings by height and seismic design class. Similarly, Rosti et al. [7] classifies URM buildings again based on height and six classes of construction, to account for building code evolution, plus some other categories [7]. For this work, both the RC and URM classifications were kept unaltered for direct comparability, using the EMS-98 damage states (as in [6,7]).

3. Results

This study tested multiple distributions beyond lognormal and GEV, including Exponential, Gaussian, Generalized Logistic, Weibull, Fréchet, and Gumbel, aiming to model all fragility curves without overparameterization. Weibull, Fréchet, and Gumbel are special cases of the GEV distribution, depending on the shape parameter ξ.

Datasets of 5000 points from Rosti et al. [6,7] for RC and URM buildings were converted to MATLAB R2022b files, and curve fitting was performed using non-linear least-squares and maximum likelihood estimation. Scripts automated analysis, and generated parameter estimates, CSV outputs, and error structures, providing a complete framework for evaluating fragility. Figure 3 illustrates the comparison of lognormal curves from this procedure with Rosti et al. [6].

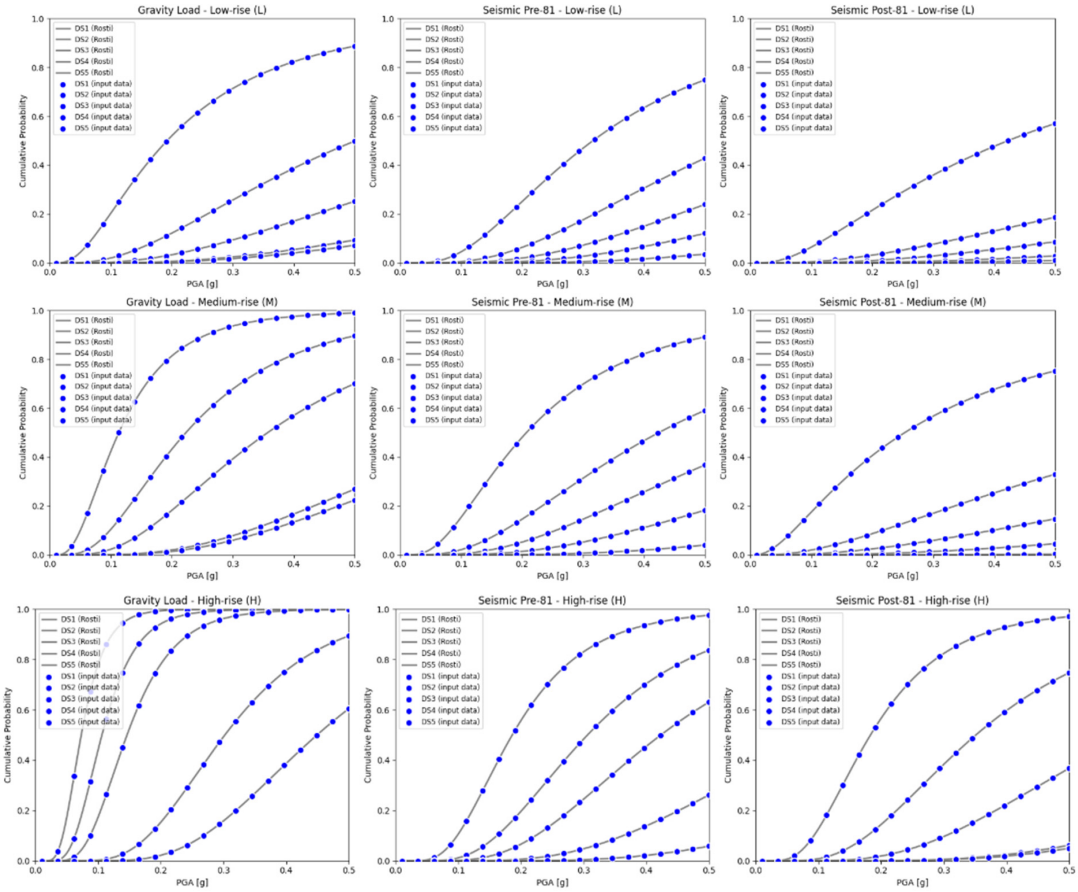


Figure 3. Comparison of the fragility curves resulting from the fitting procedure and Rosti et al.'s [6].

3.1. Error Metrics

Mean Squared Error (*MSE*) measures the average squared difference between predicted and observed values [8].

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \quad (5)$$

MSE was calculated for each curve and damage state, with select results shown in Table 1 (darker = higher error, brighter = lower). The lowest errors were generally found for lognormal, GEV, and Fréchet, with GEV typically converging to the Fréchet form after fitting.

Table 1. *MSE* for DS1 curves fitting over all cases and all distributions. Cells shaded in pale blue indicate lower Mean Squared Error (*MSE*) values, while cells shaded in dark blue indicate higher MSE values, highlighting the relative fitting performance of the distributions for each building class.

CATEGORISE	EXPONENTIAL	NORMAL	LOGNORMAL	GENERALIZED LOGISTIC	GEV	WEIBULL	FRECHET (INVERSE WEIBULL)	GUMBEL
RC LOWRISE PRE 1981	0.007679	0.001521	2.00×10^{-6}	0.0003881	8.37×10^{-5}	0.0003109	8.37×10^{-6}	0.0003701
RC LOWRISE POST 1981	0.001774	0.001128	9.69×10^{-6}	0.000484	2.90×10^{-6}	9.73×10^{-5}	2.90×10^{-6}	4.70×10^{-4}
RC MIDRISE GRAVITY LOAD	0.00642	0.001834	4.42×10^{-6}	0.0003746	1.69×10^{-6}	0.0005212	1.69×10^{-5}	0.0003743
RC MIDRISE PRE 1981	0.006384	0.002868	2.77×10^{-6}	0.0007102	1.68×10^{-5}	0.0005111	1.68×10^{-5}	0.00071
RC MIDRISE POST 1981	0.001102	0.003037	2.44×10^{-6}	0.001407	6.72×10^{-6}	0.0003004	6.72×10^{-6}	0.001379
RC HIGHRISE GRAVITY LOAD	0.01002	0.0003091	2.22×10^{-5}	1.74×10^{-5}	1.49×10^{-5}	0.000208	1.49×10^{-5}	1.73×10^{-5}
RC HIGHRISE PRE 1981	0.01723	0.001509	2.69×10^{-6}	0.0001305	4.70×10^{-6}	0.0006611	4.70×10^{-6}	0.0001302
RC HIGHRISE POST 1981	0.01491	0.001745	2.96×10^{-6}	0.0002023	3.20×10^{-6}	0.0006881	3.20×10^{-6}	0.0001981
URM LOWRISE PRE 1919	0.001878	0.003958	8.39×10^{-6}	0.001388	2.87×10^{-5}	0.0004714	2.87×10^{-5}	0.001387
URM LOWRISE 1919-1945	0.001943	0.003757	2.78×10^{-6}	0.001438	1.32×10^{-5}	0.0004445	1.32×10^{-5}	0.001438
URM LOWRISE1946-1961	0.001002	0.002701	4.76×10^{-6}	0.001285	4.65×10^{-6}	0.0002532	4.65×10^{-6}	0.001256
URM LOWRISE 1962-1971	0.0005477	0.001476	1.93×10^{-6}	0.0008046	2.67×10^{-6}	0.0001156	2.67×10^{-6}	0.000794
URM LOWRISE 1972-1981	0.0007048	0.0009032	2.49×10^{-6}	0.0004753	1.86×10^{-6}	6.74×10^{-5}	1.86×10^{6}	0.0004741
URM LOWRISE POST 1982	0.0005329	0.0007908	1.43×10^{-6}	0.0004541	1.68×10^{-6}	6.429×10^{-5}	1.68×10^{-6}	0.0004469
URM MID-HIGHRISE PRE1919	0.002176	0.00353	1.25×10^{-5}	0.001156	2.90×10^{-5}	0.0004907	2.90×10^{-5}	0.001156
URM MID-HIGHRISE 1945-1961	0.001995	0.003887	1.38×10^{-5}	0.001341	2.54×10^{-5}	0.0004537	2.54×10^{-5}	0.00134
URM MID-HIGHRISE 1919-1946	0.001833	0.003341	9.42×10^{-6}	0.001287	1.74×10^{-5}	0.0003515	1.74×10^{-5}	0.00128
URM MID-HIGHRISE 1962-1971	0.0009924	0.002231	4.34×10^{-6}	0.001092	7.68×10^{-6}	0.0002147	7.68×10^{-6}	0.001086
URM MID-HIGHRISE 1972-1981	0.0009099	0.001212	1.61×10^{-6}	0.0006279	2.67×10^{-6}	0.0001056	2.67×10^{-6}	0.000618
URM MIDRISE POST 1982	0.000857	0.001144	2.31×10^{-6}	0.0006032	2.43×10^{-6}	0.0001063	2.43×10^{-6}	0.0005986

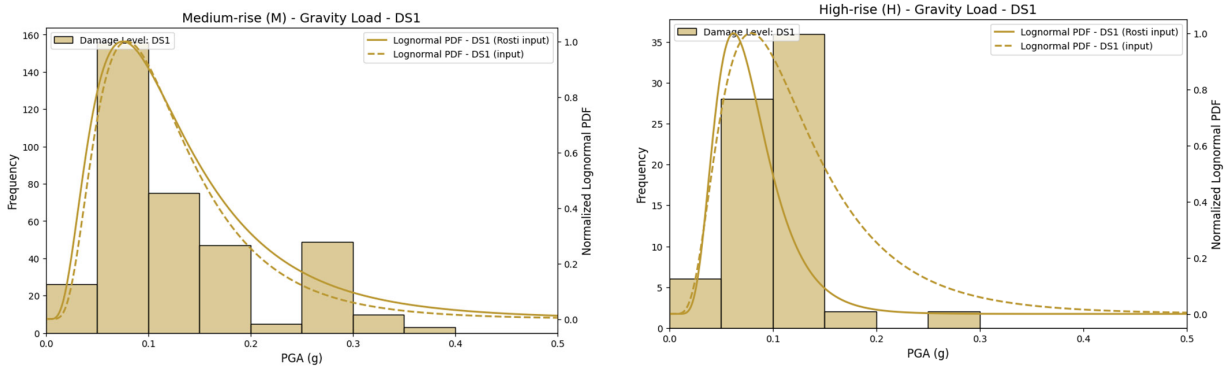
Table 2 lists the GEV fragility parameters for each building class. θ indicates the seismic intensity at which a damage state is reached (higher θ = greater resistance), and β represents the response variability (lower β = more predictable behavior).

Table 2. GEV fragility curves parameters.

Curve	θ_{DS1}	θ_{DS2}	θ_{DS3}	θ_{DS4}	θ_{DS5}	β
RC_LOWRISE_GRAVITYLOADS	0.193355	0.5029	0.815089	1.41209	1.537243	0.522237
RC_LOWRISE_PRE1981	0.315332	0.566891	0.801661	1.116553	2.795463	0.472771
RC_LOWRISE_POST1981	0.420146	1.059549	1.905898	3.745728	23.118614	0.526098
RC_MIDRISE_GRAVITYLOADS	0.114498	0.224342	0.35801	0.730144	0.803064	0.517133
RC_MIDRISE_PRE1981	0.206305	0.423057	0.630304	0.95919	2.350266	0.515366
RC_MIDRISE_POST1981	0.252636	0.746047	1.258867	2.728176	109.21187	0.587645
RC_HIGHRISE_GRAVITYLOADS	0.073069	0.107343	0.145678	0.302755	0.449734	0.396585
RC_HIGHRISE_PRE1981	0.187085	0.306632	0.425902	0.694207	1.43351	0.429145
RC_HIGHRISE_POST1981	0.181971	0.348326	0.591881	1.519646	1.731426	0.44599
URM_LOWRISE_PRE1919	0.150805	0.225006	0.271972	0.372379	0.644212	0.747848
URM_LOWRISE_1919_1945	0.195288	0.313276	0.375145	0.558469	0.934835	0.696127
URM_LOWRISE_1946_1961	0.277942	0.515702	0.665459	0.945949	1.638185	0.613205
URM_LOWRISE_1962_1971	0.436388	0.883369	1.078509	1.540505	2.466089	0.54699
URM_LOWRISE_1972_1981	0.546604	1.158421	1.542489	2.064957	5.659942	0.516544
URM_LOWRISE_POST1981	0.624525	1.114523	1.271029	1.600089	2.783944	0.512863
URM_MIDHIGHRISE_PRE1919	0.128941	0.186684	0.224769	0.304973	0.571405	0.753045
URM_MIDHIGHRISE_1919_1945	0.160426	0.275102	0.35204	0.525826	0.836192	0.687177
URM_MIDHIGHRISE_1946_1961	0.213908	0.393193	0.516623	0.713427	1.058736	0.634596
URM_MIDHIGHRISE_1962_1971	0.322944	0.709511	0.917403	1.344281	1.731869	0.567159
URM_MIDHIGHRISE_1972_1981	0.467513	1.05832	1.280005	1.779964	3.656293	0.530431
URM_MIDHIGHRISE_POST1981	0.494728	0.949989	1.133006	1.440627	2.415125	0.529102

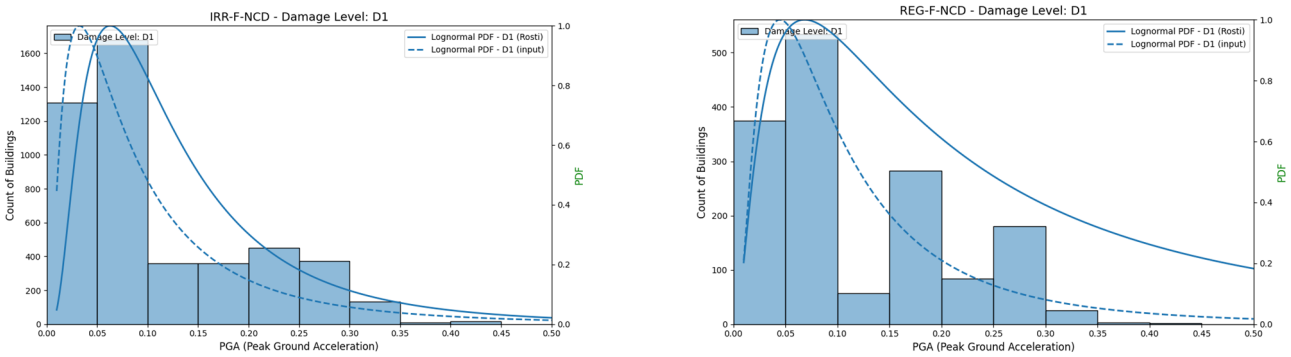
3.2. Comparison with Retrieved Data from the DaDO Platform

The fitting procedure targets the published fragility curves from Rosti et al. [6,7], rather than the original raw data from the Da.D.O. platform. Although attempts were made to reproduce their filtering steps, the specific parameters remain undisclosed. However, the obtained histograms seem to indicate an overall good match, as the PDFs obtained here by the authors match them well (Figures 4 and 5 report Rosti et al.'s lognormal PDFs, according to the parameters reported in their papers, superimposed on the lognormal PDF estimated here by the authors).



(**a**) (**b**)

Figure 4. Comparison between histograms and PDF distributions resulting from the authors' fitting of Da.D.O data (dashed line) and Rosti et al.'s [6] (solid line) in RC buildings: (**a**) for the MEDIUM-RISE-Gravity Load-DS1 category, and (**b**) for HIGH-RISE-Gravity Load-DS1.



(**a**) (**b**)

Figure 5. Comparison between histograms and PDF distributions resulting from the authors' fitting of Da.D.O data (dashed line) and Rosti et al.'s (solid line) in URM buildings [7]: (**a**) for the IRR-F-NCD DS1 category, and (**b**) for the REG-F-CD DS1 category.

Table 3 shows the *MSE* between the input fragility data and the PDFs from Rosti et al. [6,7] for selected RC and URM building classes, assessing how well the reference PDFs capture observed fragility behavior.

Table 3. Mean Squared Error (*MSE*) table between input data and Rosti et al.'s [6,7] PDFs for some cases of masonry and RC buildings. Cells shaded in pale blue indicate lower Mean Square Error (MSE) values, while cells shaded in dark blue indicate higher MSE values, highlighting the relative fitting performance of the distributions for each building class.

Load Type	Damage Level	MSE	Building Class	Load Type	Damage Level	MSE
IRR-F-NCD	D1	0.047524	Low-rise (L)	Gravity Load	DS1	0.008207
IRR-F-NCD	D2	0.111412	Low-rise (L)	Gravity Load	DS3	0.025769
IRR-F-NCD	D3	0.146891	Low-rise (L)	Gravity Load	DS2	0.01726

3.3. Fragility Curves

Figure 6 for RC buildings and Figure 7 for URM buildings compare lognormal and GEV fragility curves across different building types and classes. Both models are similar at lower damage levels, but at higher levels, the GEV shows a steeper increase in damage probability, capturing extreme events more effectively than lognormal.

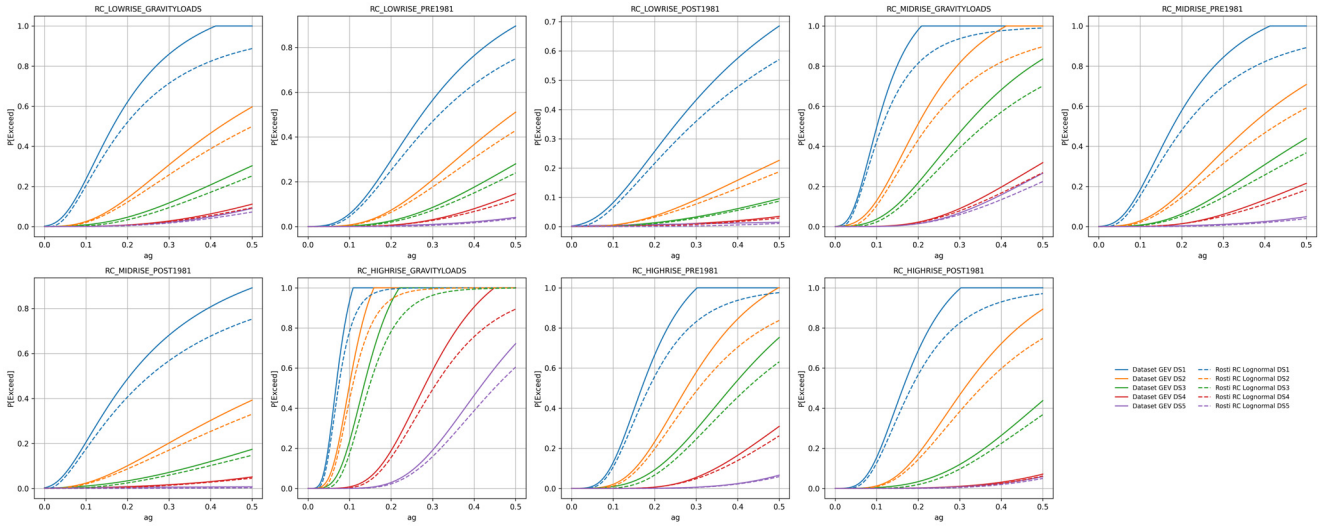


Figure 6. Comparison between GEV and lognormal CDF distributions in RC buildings.

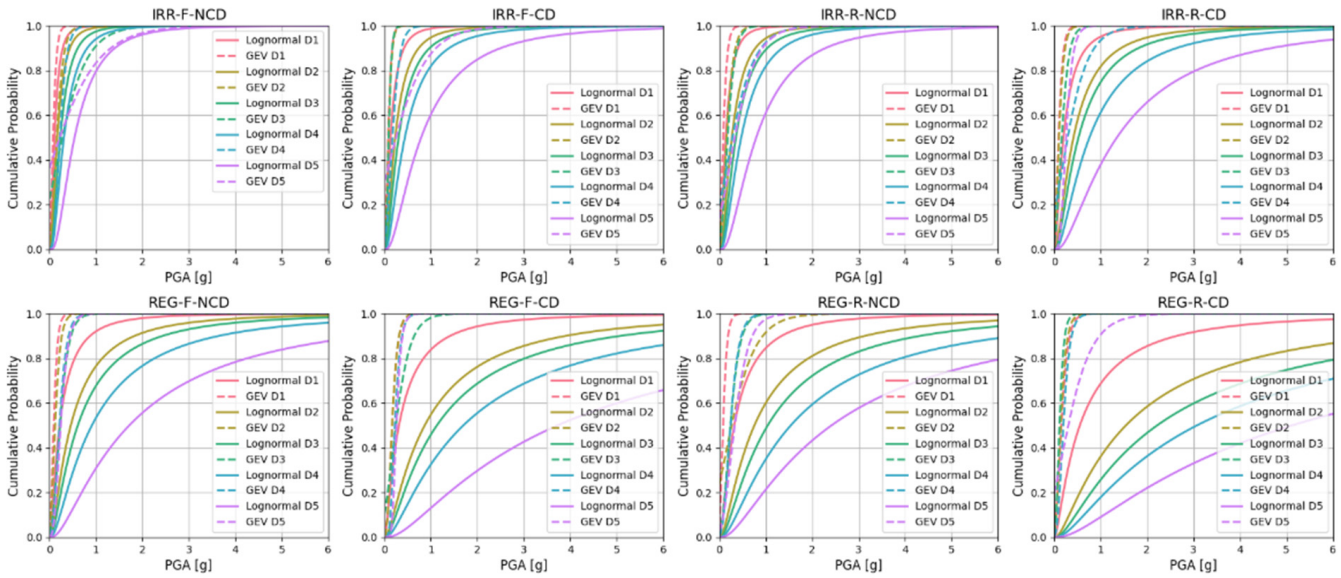


Figure 7. Comparison between GEV and lognormal CDF distributions in URM buildings.

The GEV approach performs well for both Reinforced Concrete (RC) and Unreinforced Masonry (URM) structures. For RC buildings, it captures both gradual damage progression and rare extremes, while for URM buildings, it realistically reflects their higher vulnerability to sudden, severe damage. This versatility makes the GEV model suitable for informed risk assessment, retrofitting, and urban resilience planning.

A fragility model is statistically robust if it reliably represents damage probabilities across typical and extreme seismic events. The GEV-based curves were evaluated using goodness-of-fit metrics, parameter confidence intervals, and sensitivity analyses, confirming accurate representation of both central tendencies and upper tails. This demonstrates that the GEV approach provides reliable and actionable insights for RC and URM structures.

4. Conclusions

The GEV distribution provides a statistically robust alternative to the lognormal model by explicitly modeling the tails of seismic fragility. Its adoption improves the reliability of risk estimates, particularly for high-intensity events, and strengthens the proposed simplified assessment protocol. Future work will expand datasets and incorporate site-specific seismic parameters to refine fragility assessments further and support effective earthquake mitigation strategies.

While the GEV approach performs well for both RC and URM structures, its application is limited by the scarcity of URM data, due to fewer inspections, variable construction, and incomplete records. Future research can expand URM datasets and incorporate site-specific seismic parameters to improve fragility assessments and mitigation strategies.

Author Contributions: Conceptualization, M.C.; methodology, M.C., M.D. and Z.H.; software, M.C., M.D. and Z.H.; validation, Z.H.; formal analysis, M.C. and Z.H.; investigation, M.C. and Z.H.; resources, M.C.; data curation, Z.H.; writing—original draft preparation, Z.H.; writing—review and editing, M.C.; visualization, Z.H. and M.C.; supervision, M.C. and M.D.; project administration, M.C.; funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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