Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 3127-3138

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

COMPLETION CRITERIA FOR DERIVATION OF MACROSEISMIC FRAGILITY CURVES OF EXISTING BUILDINGS

Audisio L.[1], **Tatangelo M.**[1], **D'Amato M.**[2], **Gigliotti R.**[1]

[1] DISG – Dept. of Structural and Geotechnics Engineering, Sapienza University of Rome,
Via Eudossiana 18, 00184 Rome, Italy
e-mail: lorenzo.audisio@uniroma1.it, mattero.tatangelo@uniroma1.it, rosario.gigliotti@uniroma1.it

[2] DIUSS – Dept. for Humanistic, Scientific and Social Innovation , University of Basilicata,
Via Lanera, 75100 Matera, Italy
e-mail: michele.damato@unibas.it

Abstract

The probabilistic assessment of seismic vulnerability in buildings through fragility curves plays a crucial role in seismic risk analysis, damage scenario prediction, and structural intervention planning. These curves are also fundamental for planning seismic risk in terms of economic losses, supporting a more effective allocation of resources. Through a macroseismic approach, it is possible to derive fragility curves for different structural types by processing observed damage data from existing buildings after seismic events. In this context, data completion criteria are particularly important, as their application can significantly influence the resulting fragility curves.

This study focuses on deriving fragility curves for reinforced concrete buildings, subdivided into different structural subtypes, and analyzing how the adoption of various completion criteria can modify these curves. A new completion criterion is also proposed, based on damage probability conditional to a macroseismic intensity measure and it is compared with existing criteria to assess its impact on seismic risk and damage scenarios. The analysis is based on the observed damage databases of L'Aquila (2009), Emilia (2012), and Central Italy (2016–2017) earthquakes.

The results highlight how the completion criterion chosen may influence the fragility curves and, consequently, the accuracy of seismic risk estimations.

Keywords: damage observed, empirical fragility curves, reinforced concrete buildings, seismic risk, expected annual loss.

doi: 10.7712/120125.12640.25162

1 INTRODUCTION

Macroseismic analysis is an approach used to assess the seismic vulnerability of existing buildings, based on the observation and analysis of damage sustained by structures following past seismic events [1, 2, 3]. Unlike analytical models, this method relies on empirical data derived from the actual behavior of buildings during earthquakes, providing insights into their ability to withstand seismic forces.

Empirical fragility curves are a key tool in macroseismic analysis, describing the conditional probability that a structure will reach or exceed a given damage level (DL) or limit state (LS) for a given seismic intensity measure (IM). Fragility curves are widely used in probabilistic assessments of seismic vulnerability and seismic risk, as they allow for the estimation of potential damage as well as the economic losses associated with future earthquakes [4, 5, 6, 7].

The derivation of empirical fragility curves is based on the statistical analysis of paired data obtained from direct observations of structural damage and the corresponding seismic intensity. These data are typically collected through post-earthquake surveys, such as the compilation of damage and usability assessment forms (AeDES) [8]. Seismic intensity can be expressed through macroseismic indicators [9] (e.g., the EMS-98 scale) or through engineering parameters representing seismic action [10] (such as Peak Ground Acceleration – PGA).

For the derivation of fragility curves, logistic regression models, such as probit or logit functions [11], are frequently adopted, and the Maximum Likelihood Estimation (MLE) method is applied to estimate their characteristic parameters [12].

This study focuses on the completion criterion for deriving fragility curves of existing buildings based on a macroseismic analysis. To this scope at first, a completion criterion is proposed. The it is applied for deriving fragility curves of Reinforced (RC) Concrete buildings, by considering several damage data of buildings suffered recent italian earthquakes. The fundamental parameters of the fragility curve (ϑ_i, β) are statistically estimated by partitioning the data into seismic intensity bins and selecting a lognormal cumulative distribution function as the fragility function [1].

2 DATABASE COMPLETION

A critical aspect in the derivation process of empirical fragility curves is database completion. In post-earthquake surveys, buildings are generally inspected more systematically in epicentral areas, while in more peripheral zones, sampling may be incomplete, with a prevalence of damaged buildings being recorded. This informational gap regarding undamaged (D0) and uninspected buildings can introduce a significant bias in the fragility curves, particularly for lower damage levels.

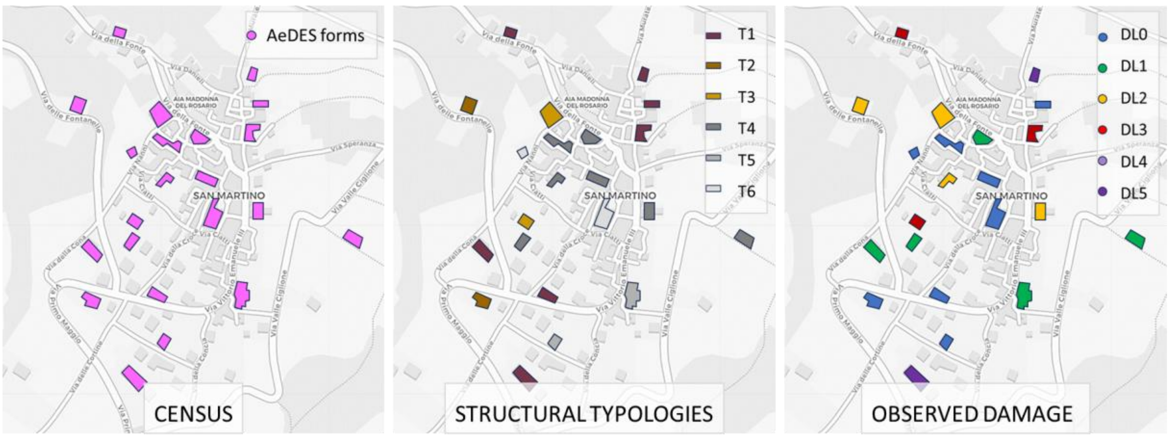

Figure 1: AeDES census of a generic municipality

The databases used for the derivation of fragility curves rely exclusively on buildings surveyed through the AeDES forms, which provide information on structural typology and observed damage levels. As example, Figure 1 highlights within a certain area, the buildings surveyed after a certain seismic event (Figure 1a), the corresponding structural typology Figure 1b), and the resulting seismic damage level Figure 1c), the later varying from D0 to D5 according to the EMS98 scale [9]. However, the number of surveyed buildings varies across municipalities, and a significant portion of buildings remains excluded from the census. For these unsurveyed buildings, no information is available regarding either their structural typology or the damage they sustained during the seismic event. It has been demonstrated that excluding these data leads to the development of fragility curves that are not fully representative, making the integration of missing data essential in the calculation process.

A fundamental parameter for the completion process is the completeness level of the survey campaign, which can be described and calculated through the Completeness Ratio (r_m). This ratio measures, for each municipality, the buildings number surveyed with an AeDES form ($N_{m,AeDES}$) to the existing buildings total number ($N_{m,TOT}$).

$$r_m = \frac{N_{m,AeDES}}{N_{m,TOT}} \tag{1}$$

To determine the total number of existing buildings in each municipality ($N_{m,TOT}$), data processed by the Italian National Institute of Statistics (ISTAT) was used [13].

In order to illustrate how the completion database may result significant on the buildings stock, Figure 2 illustrates the number of municipalities as function of the Completeness Ratio, for several Macroseismic Intensity Measures (MMIs). In this figure three buildings stocks are considered, suffering three distinct seismic events, that are: L'Aquila (2009), Emilia (2012), and Central Italy (2016/2017). In this Figure, shake maps provided by the National Institute of Geophysics and Volcanology (INGV) are used for defining the MMI.

The analysis shows that the MMI increases as the completeness ratio progressively increases, approaching unity and indicating larger survey coverage in municipalities where buildings suffered higher seismic damage. Conversely, in municipalities with lower MMI, the completeness ratio decreases significantly.

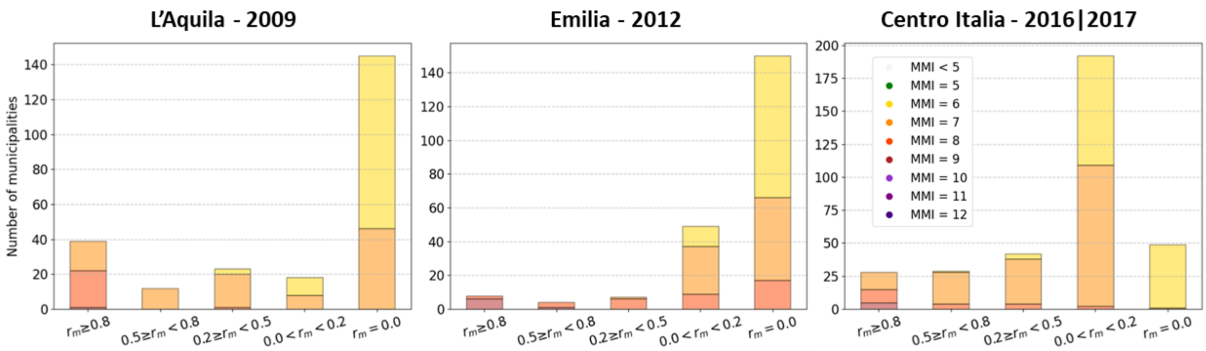

Figure 2: Municipalities completeness ratio by considering three building stocks.

This behavior reflects a well-known principle in damage survey campaigns using AeDES forms: the compilation of forms primarily occurred for buildings that suffered evident damage, while those with minor or no damage were ignored and not surveyed. As a consequence of this, the building stock data results incomplete, with regard to the buildings that were undamaged or with a low level of damage, but not surveyed. Consequently, this influences the overall building stock vulnerability analysis.

However, it is important to consider another issue. In a typical municipality, if a low completeness ratio is observed despite a high Macrosismic Intensity Measure (MMI), it is likely that the lack in the completion of AeDES forms for some buildings is not solely due to the presence of a negligible damage, but rather due to other reasons, such as logistical difficulties, limited access to the affected areas, or other problems in the survey process. In this context, automatically assigning a D0 damage level to not surveyed buildings may be inappropriate, leading to a biased representation of the damage distribution and of the overall vulnerability.

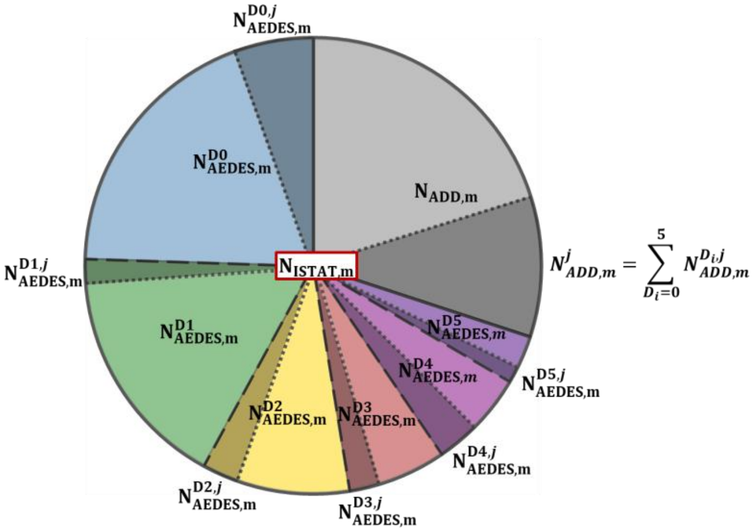

Figure 3: Completion problem statement.

Generalizing the problem, it is possible to calculate the buildings total number as the sum of the buildings surveyed through AeDES forms (N_{AEDES}) and the missing buildings (N_{ADD}):

$$N_{TOT} = N_{ISTAT} = N_{ADD} + N_{AEDES} \tag{2}$$

The total number of buildings can be expressed as the sum of the buildings in the m-th analyzed municipality:

$$N_{ISTAT} = \sum_{m} N_{ADD,m} + \sum_{m} N_{AEDES,m} \tag{3}$$

Introducing the subdivision for the different damage levels, we obtain:

$$N_{ISTAT} = \sum_{m} \sum_{Di=0}^{5} N^{Di}_{ADD,m} + \sum_{m} \sum_{Di=0}^{5} N^{Di}_{AEDES,m} \tag{4}$$

If the j-th structural typology is considered, the previous expression may be rewritten as follows:

$$N^{j}_{ISTAT} = \sum_{m} \sum_{Di=0}^{5} N^{Di,j}_{ADD,m} + \sum_{m} \sum_{Di=0}^{5} N^{Di,j}_{AEDES,m} \tag{5}$$

In the following, the Eq. (5) is rewritten for the m-th municipality:

$$N^{j}_{ISTAT,m} = \sum_{Di=0}^{5} N^{Di,j}_{ADD,m} + \sum_{Di=0}^{5} N^{Di,j}_{AEDES,m} \tag{6}$$

The completion problem is addressed by determining the number of missing buildings N_{ADD} for the j-th analyzed structural typology and for the different damage levels D_i.
Figure 3 presents a graphical representation of Equation 6, which generally describes the completion problem.

3 PROPOSED COMPLETION CRITERION

As described in the previous section, the missing data in the completion problem are certainly distributed across different structural typologies, and they can also be subdivided based on the level of damage intensity.

As for the structural typology distribution, to, it is proposed to use statistical analyses conducted on the known data to estimate the buildings percentage belonging to each j-th typology within the m-th municipality. This approach allows for a more accurate integration of the missing information, ensuring a distribution consistent with the observed reality. In this study a partition coefficient for the j-th typology is introduced, expressed as:

$$\bar{\lambda}^{j}_{m} = r_m \cdot \left(\lambda^{j}_{m} - \lambda^{j}_{tot}\right) + \lambda^{j}_{tot} \tag{7}$$

where:

Global partition coefficient by typology
$$\lambda^{j}_{tot} = \frac{N^{j}_{AEDES}}{N_{AEDES}} = \frac{\sum_m N^{j}_{AEDES,m}}{\sum_m N_{AEDES,m}}$$

Local distribution coefficient by typology
$$\lambda^{j}_{m} = \frac{N^{j}_{AEDES,m}}{N_{AEDES,m}} \tag{8}$$

The typology partition coefficient establishes a linear proportion between the global statistical data of the entire buildings stock and the local data of a single municipality, by means of the completeness ratio r_m. Thanks to this coefficient, it is possible to integrate the missing information preserving, as much as possible, the proportions of the different structural typologies present in each municipality. This approach allows for a more consistent and representative estimate of the actual distribution of buildings, improving the accuracy of the analysis.
By introducing the typology partition coefficient , the number of missing buildings can be calculated as follows:

$$N^{j}_{ADD,m} = \sum_{Di=0}^{5} \bar{\lambda}^{j}_{m} \cdot N^{Di}_{ADD,m} \tag{9}$$

Currently, it is common practice to assign a null damage level (D0) to the missing data. Additionally, a threshold of macrosismic intensity is established, above which the data does not need to be completed, regardless of the calculated Completeness Ratio r_m.

$$\begin{cases} N^{j}_{ADD,m} = N^{D0,j}_{ADD,m} = \bar{\lambda}^{j}_{m} \cdot N_{ADD,m} & per \quad MMI_m < \overline{MMI}_m \\ N^{j}_{ADD,m} = 0 & per \quad MMI_m \geq \overline{MMI}_m \end{cases} \tag{10}$$

Moreover, in this study a damage coefficient α^{j}_{Di} for the j-th typology and the D_i damage level is introduced, dividing the number of missing buildings according to the different damage level. Consequently, the Eq. 9 can be written as:

$$N^{j}_{ADD,m} = \sum_{Di=0}^{5} \bar{\lambda}^{j}_{m} \cdot N^{Di}_{ADD,m} = \sum_{Di=0}^{5} \alpha^{j}_{Di} \cdot \bar{\lambda}^{j}_{m} \cdot N_{ADD,m} \tag{11}$$

Using equation 11, it is possible to determine the number of missing buildings to be added for the j-th structural typology, distributed across the different damage levels, starting from the total number of missing buildings $N_{ADD,m}$ and applying the two proposed allocation coefficients.

The damage coefficient in the proposed method is expressed as a damage probability curve conditioned by the Macrosismic Intensity Measure (MMI) for each damage level:

$$\begin{cases} \alpha^{j}_{D_0} = P(D_0|MMI) = 1 - P(D \geq D_1|MMI) \\ \alpha^{j}_{D_i} = P(D_i|MMI) = P(D \geq D_i|MMI) - P(D \geq D_{i+1}|MMI) \qquad for\ i = 1 \div 4 \\ \alpha^{j}_{D_5} = P(D_5|MMI) = P(D \geq D_5|MMI) \end{cases} \tag{12}$$

where the fragility functions are derived starting from the qualitative information provided for each damage level by the EMS 98 [9].

As example, Figure 4 shows the completeness ratios r_m for a set of municipalities considered for the macro-seismic analysis. The figure also reports the fragility functions derived as described above, and the resulting coefficient damage coefficients α^{j}_{Di} for the j-th municipality.

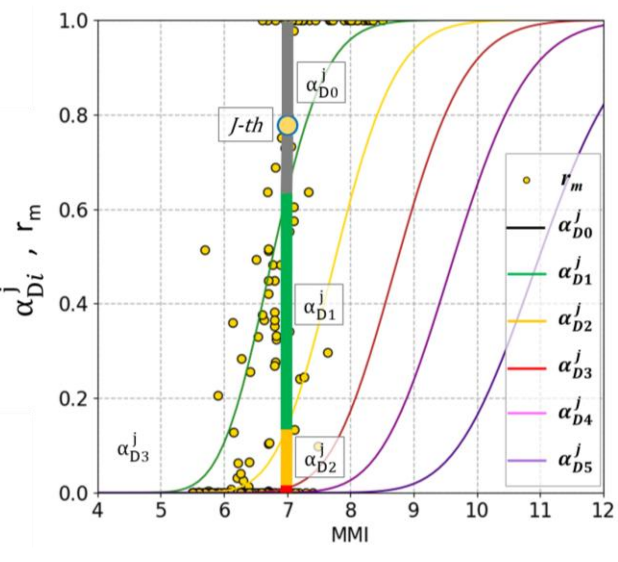

Figure 4: Damage coefficients - α^{j}_{Di}

The method can also be applied by assuming the hypothesis that buildings not surveyed are undamaged and, therefore, classified with a D_0 damage level . In this case, the damage coefficient is determined only for the damage level D_0:

$$\alpha^{j}_{D_0} = P(D_0|MMI) = 1 - P(D \geq D_1|MMI) \tag{13}$$

Consequently, the Eq. 11 can be rewritten as follows:

$$N^{j}_{ADD,m} = N^{D0,j}_{ADD,m} = \alpha^{j}_{D0} \cdot \bar{\lambda}^{j}_{m} \cdot N_{ADD,m} \tag{13}$$

For completeness, Figure 5 shows the completeness ratios r_m for the set of municipalities considered for the macro-seismic analysis, and the damage coefficient $\alpha^{j}_{D_0}$ obtained with the Eq. (13). For the j-th municipality it is also highlighted the corresponding damage coefficient α^{j}_{D0}

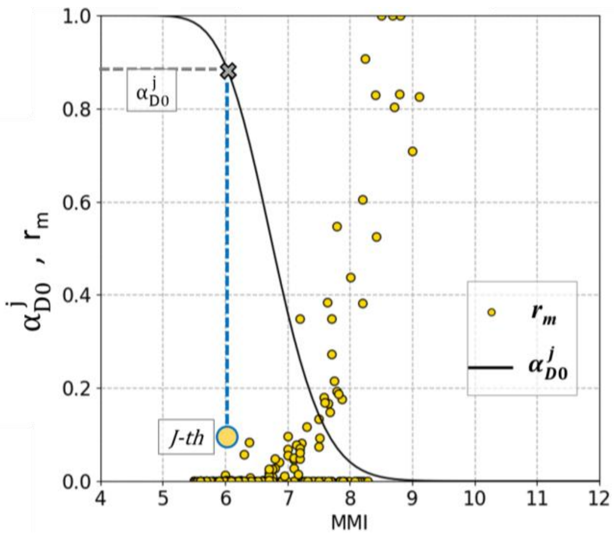

Figure 5: Damage coefficient - α^{j}_{D0}

4 RESULTS

In this section the empirical fragility curves for the j-th structural typology are derived and compared by applying different completion methods including the proposed one. The macro-seismic analysis is conducted by considering three databases archiving the seismic damage of three buildings stocks, surveyed after the seismic events of L'Aquila (2009), Emilia (2012), and Central Italy (2016-2017).

At first, the completeness ratio r_m for each municipality that was struck the seismic event is reported.

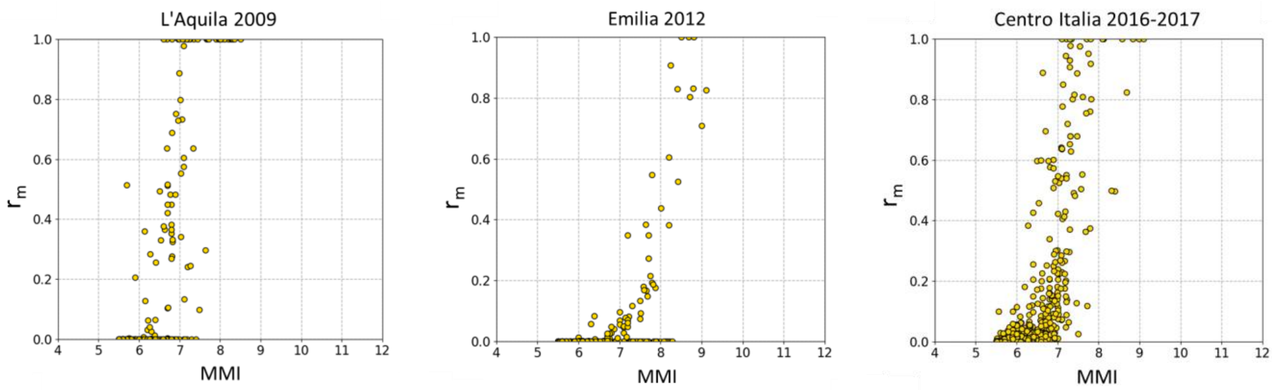

Figure 6: Completeness ratio for each municipality considered

The fragility curves obtained in this study refer to residential buildings made of RC frame structural system, without interventions, designed and constructed before the 1980s, and isolated from other buildings.

The completion criteria considered in this study are:

- Criterion 1: No completion to database is applied
- Criterion 2: Completion assigns to all not surveyed and undamaged buildings a D0 damage level for all MMI measures.
- Criterion 2*: Completion assigns to all not surveyed and undamaged buildings a D0 damage level for MMI measures lower than 7.5.
- Criterion 3: Database is completed with the damage coefficient α_{Di}^{j}.
- Criterion 4: Database is completed with the damage coefficient α_{D0}^{j}.

Table 1, 2, and 3 show the values of the fragility curve fundamental parameters, that are the median value θ and the logarithmic values standard deviation β. These tables report the values of θ and β obtained in according to the completion criteria considered, for the buildings stocks that suffered the seismic events of L'Aquila 2009, Emilia 2012, and Central Italy 2016-2017, respectively.

	Criterion					Criterion				
	1	2	2*	3	4	1	2	2*	3	4
Damage Level	θ					β				
D1	0.067	0.163	0.161	0.148	0.146					
D2	0.386	0.337	0.336	0.339	0.331					
D3	0.868	0.504	0.503	0.510	0.513	1.602	0.786	0.787	0.795	0.833
D4	2.369	0.837	0.837	0.848	0.884					
D5	8.923	1.635	1.637	1.667	1.800					

Table 1: Fundamental parameters derived for L’Aquila 2009 buildings stock

Referring to the results shown in Table 1, it is observed that the fundamental parameters obtained for the L'Aquila 2009 earthquake database do not significantly change with the completion criterion adopted. But the values are different only in the case of Criterion 1, when no completion criterion is adopted.

	Criterion					Criterion				
	1	2	2*	3	4	1	2	2*	3	4
Damage Level	θ					β				
D1	0.029	0.409	0.205	0.170	0.184					
D2	0.851	0.698	0.328	0.417	0.330					
D3	3.667	0.994	0.451	0.651	0.481	2.534	0.873	0.587	0.720	0.656
D4	12.596	1.401	0.611	0.904	0.680					
D5	63.415	2.240	0.900	1.376	1.049					

Table 2: Fundamental parameters derived for Emilia 2012 buildings stock

As for the Table 2, it is observed that the fundamental parameters obtained with the Criterion 1 and Criterion 2 differ significantly from those derived with the Criterion 2*, 3, and 4. This suggests that the buildings stock damage database related to the 2012 Emilia earthquake contains many municipalities with high MMI values but with a low completeness level. This result demonstrates that the criterion proposed in this work, adopted in the Criterion 3 and 4 may significantly vary the fragility curves and in particular when the database is incomplete, i.e. when a low number of AeDES forms is available in the case of high MMI measures.

	Criterion					Criterion				
	1	2	2*	3	4	1	2	2*	3	4
Damage Level	θ					β				
D1	0.001	0.181	0.166	0.153	0.118					
D2	0.339	0.317	0.284	0.295	0.213					
D3	37.010	0.746	0.646	0.660	0.513	4.479	0.999	0.936	0.917	0.874
D4	1639.2	1.196	1.019	1.030	0.834					
D5	812.1	2.612	2.174	2.158	1.832					

Table 3: Results fragility curves for Centro Italia 2016-2017

As far as the Centro Italia 2016-2017 results are concerned, , it is observed that the median values obtained through completion Criterion 2* and 3 are quite similar (Table 3). On the other hand, the values obtained with Criterion 1 and Criterion 2 differ significantly from the others, while those derived with the Criterion 4 tend to be slightly lower than those obtained with Criterion 2 and Criterion 3.

By comparing all the results obtained with the different completion criteria considered, it is observed that fragility curves derived from different databases and obtained through various completion criteria tend to converge to similar values of the fundamental parameters.

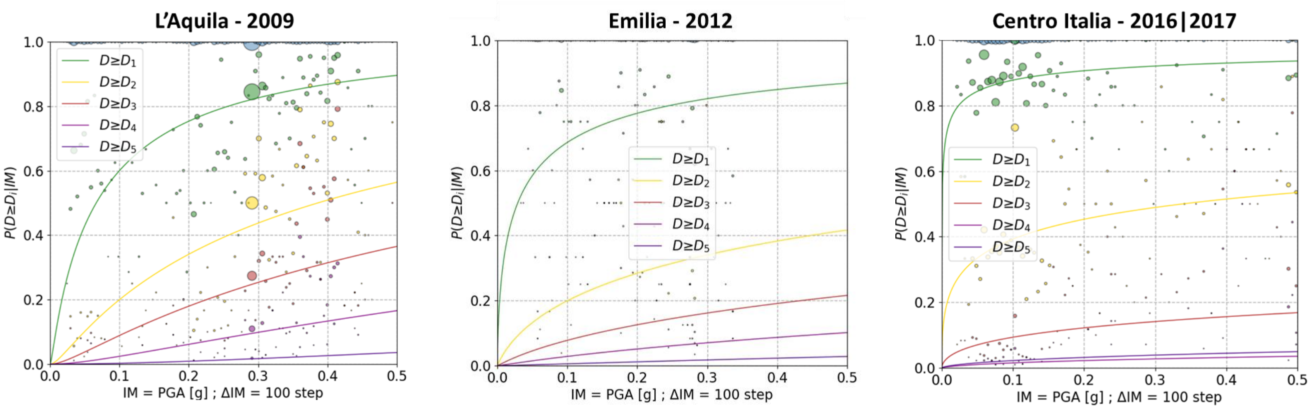

Figure 7: Incomplete fragility curves

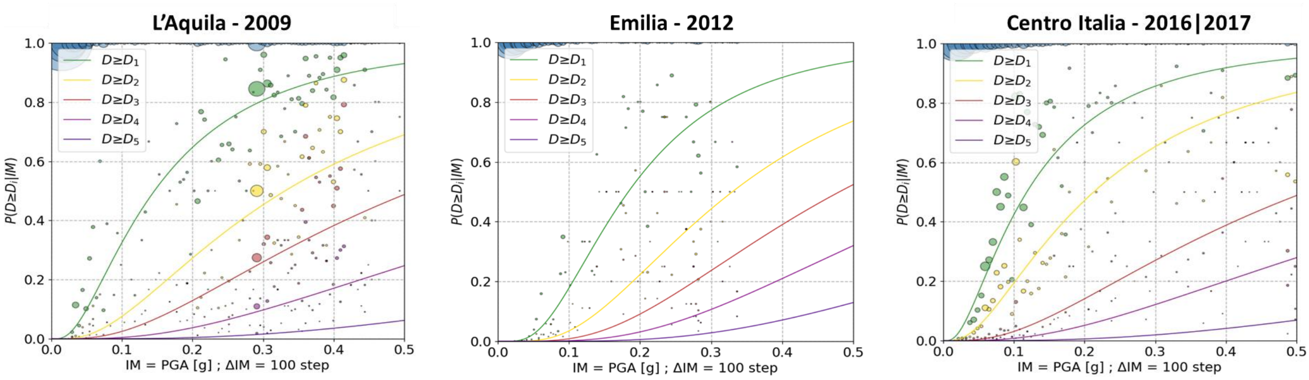

Figure 8: Completed fragility curves

For completeness Figure 7 Figure 8 plot the fragility curves derived for the three buildings stocks considered in this study without and with the completion criterion. In particular, the Criterion 4 is chosen. This comparison remarks that the empirical fragility curves derived from an incomplete database exhibit significantly different median values compared to those obtained from completed databases, as well as a higher dispersion.

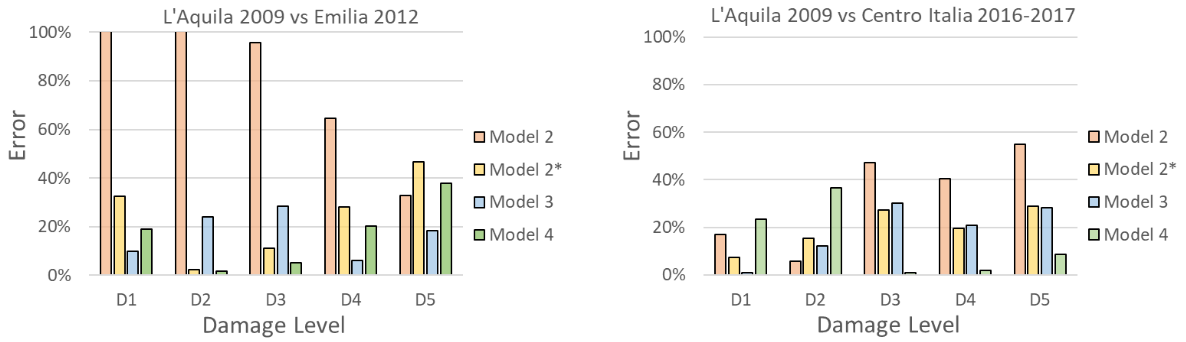

Figure 9: Comparison of median values

In Figure 9, the percentage differences between the fragility curves median values are plotted. In particular, the percentage differences are calculated for the Emilia and Central Italy fragility curves median values with respect to the ones derived for L'Aquila earthquake for all the damage levels. It is easy to observe that that the Criterion 2 differs significantly from the others. Furthermore, it is noted that the completion Criterion 3 and Criterion 4 yield the lowest percentage differences, making them the most representative.

5 CONCLUSIONS

In this study the influence of the completion criterion in evaluating the fragility curves by means of a macro-seismic analysis has been investigated.

In general, it has been observed that the empirical fragility curves derived from an incomplete database show median values that differ significantly from those obtained from completed databases, as well as much higher dispersions. Additionally, the fragility curves derived from different databases and obtained through various completion methods tend to converge towards similar values and exhibit lower dispersions once the data are completed, suggesting a higher representativeness for the analyzed structural typology.

When comparing the different completion models, it has been noted that assigning all missing data to damage level D0 leads to results differing significantly from the other methods., suggesting that a criterion based on the damage distribution coefficient results more appropriate. The reason why that many buildings remain unsurveyed after an earthquake is not solely because they appear undamaged. Also, survey complications can arise, preventing the completion of the AeDES form.

This study emphasizes the importance of a proper management of the post-earthquake damage database completion for the correct derivation of fragility curves. The adoption of appropriate completion criteria, such as those based on the probability of damage conditioned by the macroseismic intensity (MMI), may reveal more accurate and representative for estimating the seismic vulnerability and risk.

REFERENCES

[1] M. Tatangelo, L. Audisio, M. D. Amato, and R. Gigliotti, "Issues related to typological fragility curves derivation starting from observed seismic damage," *Eng Struct*, vol. 307, no. January, p. 117853, 2024, doi: 10.1016/j.engstruct.2024.117853.

[2] A. Rosti *et al.*, "Empirical fragility curves for Italian residential RC buildings," *Bulletin of Earthquake Engineering*, vol. 19, no. 8, pp. 3165–3183, 2021, doi: 10.1007/s10518-020-00971-4.

[3] C. Del Gaudio *et al.*, "Empirical fragility curves from damage data on RC buildings after the 2009 L'Aquila earthquake," *Bulletin of Earthquake Engineering*, vol. 15, pp. 1425–1450, 2017, doi: 10.1007/s10518-016-0026-1.

[4] M. Tatangelo, L. Audisio, M. D'Amato, and R. Gigliotti, "Seismic risk analysis on masonry buildings damaged by L ' Aquila Seismic risk analysis on masonry buildings damaged by L ' Aquila 2009 and Emilia 2012 earthquakes 2009 and Emilia 2012 earthquakes," *Procedia Structural Integrity*, vol. 44, no. 2022, pp. 990–997, 2023, doi: 10.1016/j.prostr.2023.01.128.

[5] M. Tatangelo, L. Audisio, M. D'Amato, and R. Gigliotti, "TYPOLOGICAL SEISMIC RISK MAPS BASED ON MASONRY BUILDINGS DAMAGED AFTER L'AQUILA 2009 EARTHQUAKE," in *18th World Conference on Earthquake Engineering (WCEE2024)*, Milan, 2024.

[6] L. Audisio, M. Tatangelo, M. D. Amato, and R. Gigliotti, "TYPOLOGICAL LOSSES ASSESSMENT FROM OBSERVED SEISMIC DAMAGE OF EXISTING ITALIAN RC BUILDINGS," in *18th World Conference on Earthquake Engineering (WCEE2024)*, Milan, 2024.

[7] M. Tatangelo, L. Audisio, M. D'Amato, and R. Gigliotti, "TYPOLOGICAL SEISMIC LOSSES ASSESSMENT BY DAMAGED MASONRY BUILDINGS AFTER L'AQUILA 2009 AND EMILIA 2012 EARTHQUAKES," in *In: Proceedings of the 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering - COMPDYN 2023*, 2023, pp. 1071–1083. doi: 10.7712/120123.10458.20639.

[8] M. Dolce *et al.*, "Observed damage database of past italian earthquakes: The da.D.O. WebGIS," *Bollettino di Geofisica Teorica ed Applicata*, vol. 60, no. 2, 2019, doi: 10.4430/bgta0254.

[9] Gottfried. Grünthal, R. M. W. Musson, J. Schwarz, and M. Stucchi, *Scala macrosismica europea 1998 : *EMS-98*. 2019.

[10] I. Oliveti, L. Faenza, and A. Michelini, "New reversible relationships between ground motion parameters and macroseismic intensity for Italy and their application in ShakeMap," *Geophys J Int*, vol. 231, no. 2, pp. 1117–1137, 2022, doi: 10.1093/gji/ggac245.

[11] F. Jalayer, H. Ebrahimian, K. Trevlopoulos, and B. Bradley, "Empirical tsunami fragility modelling for hierarchical damage levels : An application to damage data of the 2009 South Pacific tsunami," no. April, pp. 1–26, 2022.

[12] K. Porter, "A Beginner ' s Guide to Fragility, Vulnerability, and Risk," *University of Colorado Boulder*, p. 139, 2021, [Online]. Available: https://www.sparisk.com/pubs/Porter-beginners-guide.pdf.

[13] ISTAT. 15◦ Censimento generale della popolazione e delle abitazioni (Italian National Statistics Institute) Popul Hosing Census 2011. http://dati-censimentopo polazione.istat.it/Index.aspx