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REVIEW OF FRAGILITY CURVES FOR SEISMIC RISK ASSESSMENT OF BUILDINGS IN EUROPE

R. Maio(1), G. Tsionis(2), M.L. Sousa(3), S. Dimova(4)

(1) PhD student, Department of Civil Engineering of the University of Aveiro, Aveiro Research Centre of Risks and Sustainability in Construction, ruiamaio@ua.pt

(2) Scientific project officer, European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment, georgios.tsionis@jrc.ec.europa.eu

(3) Grantholder, European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment, luisa.sousa@jrc.ec.europa.eu

(4) Scientific project officer, European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory for Structural Assessment, silvia.dimova@jrc.ec.europa.eu

Abstract

Earthquakes represent a serious threat for several European countries, particularly for Mediterranean bordering countries, where seismic events have been triggering significant destruction and loss over the last decades. Since the early 1970's, when the first studies on seismic vulnerability assessment of buildings at large geographical areas were made, the scientific state-of-the-art of vulnerability assessment has undergone a notable development. However, initiatives for seismic risk assessment applied at a large scale still face significant challenges, such as the inventory of exposure data in very disparate databases and the selection of up-to-date vulnerability models compatible with the information available and with different construction practices.

Having the latter challenge in mind, the principal activity described in this paper is to investigate the practices and methodologies for assessing seismic vulnerability of the existing building stock in Europe, in areas of moderate to high seismicity. The study involves an extensive collection and review of analytical fragility curves available in the technical literature and their evaluation according to a set of qualitative criteria in order to select the most appropriate ones for each building class and geographic region.

The fragility curves assessed according to the above-mentioned criteria may be used for different seismic risk studies, namely: (i) the assessment of the seismic risk of buildings in Europe for decision-making on building renovation, (ii) the impact estimations after major earthquake disasters for emergency response, (iii) the seismic scenario simulation for emergency planning and disaster risk reduction and (iv) the definition of procedures for seismic risk assessment to be integrated in multi-risk approaches for different natural hazards in Europe.

The review revealed a number of issues that are not sufficiently addressed in the current literature, such as the use of more refined numerical models that capture better the response of structures, the effect of non-structural elements, shear failure modes of reinforced concrete elements, out-of-plane response and types of floors for masonry buildings and geometric irregularities.

Keywords: earthquake risk, fragility curves, analytical methods, European building stock

1. Introduction

Earthquakes represent a serious threat for several European countries, particularly for Mediterranean bordering countries, where seismic events have been triggering significant destruction and loss over the last decades. Since the early 1970's, when the first studies on seismic vulnerability assessment of buildings at large geographical areas were made, the scientific state-of-the-art of vulnerability assessment has undergone a notable development. Within this context, fragility curves are a valuable tool as they establish the link between the seismic hazard and the effects on the built environment. Fragility curves express the probabilities associated to a class of assets of reaching or exceeding predefined damage states for a range of ground motion intensities. They can be produced through empirical, analytical, expert judgment elicitation or hybrid approaches.

However, initiatives for seismic risk assessment applied at a large scale still face significant challenges, such as the inventory of exposure data in very disparate databases and the selection of up-to-date vulnerability models compatible with the information available and with different construction practices. Despite the considerable investment made by the scientific community in the field of vulnerability assessment, the disparity of assumptions, methods and approaches followed in each study hinder the creation of an integrated framework that could allow the evaluation and comparison of existing fragility curves. Recent relevant efforts in this direction include the systematic collection of existing and the development of new fragility curves for a wide range of exposed assets within the European collaborative research project SYNER-G [1] and the online platform developed by the Global Earthquake Model Foundation to store, visualize and treat fragility curves [2].

The objective of the work described in this paper is to collect the fragility curves developed for the European building stock and to perform a qualitative assessment, aiming to assist in the selection of the most appropriate ones for a given geographical area and building typology. 39 sets of fragility curves were collected in the literature, reviewed with focus on their most important features and assessed according to a series of qualitative criteria. The reviewed fragility curves were developed for the building stock of the countries shown in Fig. 1, which are characterised by medium or high seismicity. Some of these countries were recently struck by destructive earthquakes, such as the 2012 Emilia-Romagna earthquake in Italy and the 2011 Van earthquake in Turkey. Differences in construction techniques and detailing between different countries can be significant, even when buildings are designed to the same code, and such differences can substantially affect the fragility curves [3].

Fig. 1 – Number of existing fragility curves by country

2. Criteria for the assessment of analytical fragility curves

2.1 Overview

Structural, damage and fragility analysis are the main steps in the process of analytical fragility assessment, as illustrated in Fig. 2, each step involving mathematical models and associated uncertainties. Aspects related to capacity include the building's structural characteristics, the model used to compute the capacity and the numerical model used for the response analysis. Demand is mainly related to the ground motion to which the structure is subject and to its variability. Damage analysis comprises the definition of damage states and the choice of engineering demand parameters (and their threshold values, and intensity measures. Finally, the fragility analysis includes the choice of sample size and the probability distribution to express the fragility curves.

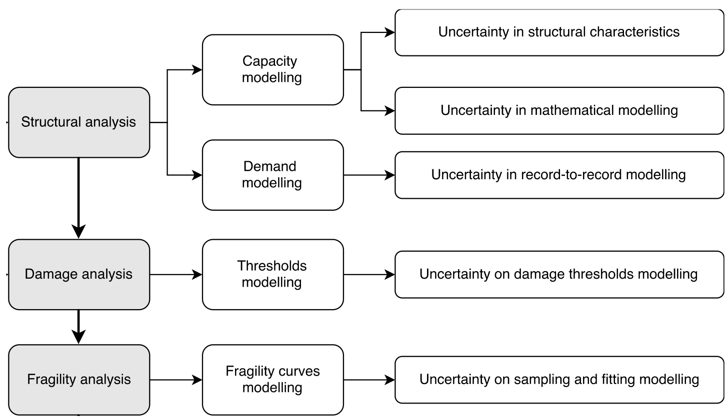

Fig. 2 – Process for analytical fragility assessment and associated uncertainties

The assessment criteria used in the following are based on the work reported in [16] that aimed to provide guidance to produce combined mean fragility curves. Similar principles are adopted herein to cover four fundamental aspects related to capacity, demand, methodology for fragility analysis and uncertainty. The goal of this paper is to provide a set of qualitative criteria to support the selection process of the most appropriate analytical fragility curves for the European building stock, consisting mainly of reinforced concrete (RC) and unreinforced masonry (URM) buildings. Low (L), medium (M) or high (H) rating is assigned to each criterion, as shown in Table 1.

2.2 Capacity

The importance of non-structural components for the structural response and fragility assessment is more relevant for reinforced concrete buildings than for masonry ones. Masonry infill walls have significant influence on the lateral stiffness and resistance of reinforced concrete frames; therefore, fragility curves for reinforced concrete buildings that have considered in the structural analysis the presence of non-structural components were given a high rating, while those that have only considered structural components were assigned a low rating.

The different seismic behaviour of low-, mid- and high-rise buildings, particularly masonry and reinforced concrete ones designed to old or no seismic code, is reflected in the fragility curves. Therefore, fragility curves that have considered buildings with a single number of storeys were given a low rating. Accordingly, fragility curves that have considered up to three and more than three different numbers of storeys were given a medium and high rating, respectively.

The reliability associated to the type of analysis is related to the level of detail of such analysis. Non-linear dynamic analysis (NLD) was assigned a high rating, non-linear static analysis (NLS) was given a medium rating, and non-linear static analysis with simplified mechanical models (NLS-SMM) or linear static analysis (LS) were assigned a low rating. Based on the same reasoning, the model types were evaluated as follows: multi degree of freedom (MDoF) models were given a high rating, reduced MDoF (stick) models were assigned a medium rating, and single degree of freedom (SDoF) models were given a low rating.

Table 1 – Qualitative assessment criteria and rating

Category	Evaluation criteria	Rating		
		Low (L)	Medium (M)	High (H)
Capacity	Non-structural elements (RC buildings)	No	-	Yes
	Number of classes of building height	1	2, 3	> 3
	Analysis type	NLS-SMM	NLS	NLD
	Model type	SDoF	Reduced MDoF	MDoF
	Shear failure (RC buildings)	No	-	Yes
	Out-of-plane mechanism (URM buildings)	No	-	Yes
	Horizontal diaphragms (URM buildings)	No	-	Yes
	Geometric irregularities	No	-	Yes
Demand	Seismic demand	Code-based spectra	< 7 accelerograms	≥ 7 accelerograms
	Site-specific	No	-	Yes
Methodology	Damage state thresholds definition	Pre-set	-	Custom
	Intensity measure	1	2, 3	> 3
	Sample size	One building	Few buildings	Several buildings
Uncertainty	Capacity	No	-	Yes
	Seismic demand	No	-	Yes
	Damage state thresholds	No	-	Yes

Shear failure of structural members can have important effect on fragility curves as it hastens the attainment of higher damage levels. However, it is normally not considered in the fragility analysis of reinforced concrete buildings. Therefore, fragility curves were assigned high rating if shear failure was considered in the analysis and low rating if it was not considered.

The out-of-plane response of masonry buildings is often neglected in numerical modelling, despite representing one of the dominant modes of failure. The fragility curves were given a high rating if they accounted for this failure mode and a low rating if they did not.

Given that the stiffness of different diaphragm typologies influences the global seismic response of masonry buildings, an additional criterion was defined based on whether the diaphragmatic behaviour of floors was considered in the analysis or not, assigning a high and a low rating to the fragility curves, respectively.

Geometric irregularities are capable of generating stress distributions significantly different from those expected in regular structures and therefore increase the vulnerability of structures. Hence, a high rating was assigned to the studies that have considered geometric irregularities and a low to those that did not.

2.3 Demand

The criterion for the description of the seismic demand was based on the recommendation of Eurocode 8 [5]. Thus, a high rating was assigned to the fragility curves where at least seven ground motion records were used to represent the seismic demand. Fragility curves that have considered less than seven records were assigned a medium rating and those that adopted code-based spectra were given a low rating. Furthermore, fragility curves were given a high rating when the seismic demand was related to the specific site and a low in the opposite case.

2.4 Methodology

The calculation of custom threshold values of engineering demand parameters between damage states for each specific building was assigned a high rating, while the use of pre-set values defined for a particular building typology was given a low rating. In addition, low, medium and high rating was assigned to those fragility curves that have considered one, two and three or more intensity measures, respectively. As regards the number of buildings that were analysed to produce the fragility curves, samples of several (hundreds) of buildings were assigned high rating, while those with few (dozens) buildings were assigned medium rating. Fragility curves where one building was analysed were given low rating.

2.5 Uncertainty

The treatment of uncertainty in capacity was assigned high rating if at least one of the following sources were accounted for: mechanical properties, geometric parameters, structural detailing and numerical modelling. If none of the previous sources of uncertainty were considered, low rating was given. The uncertainty in demand is associated to the natural variability of the ground motion characteristics related to the seismic source, attenuation path and site effects. The treatment of uncertainty in demand was given high rating, when record-to-record variability was considered, and low, when it was not addressed. Uncertainty in the definition of damage state thresholds is often neglected, but in a few cases, a probability distribution is used to describe damage state thresholds. Fragility curves where the uncertainty in damage state thresholds was considered were assigned high rating, and those that have not considered it were given low rating.

3. Review and qualitative assessment of analytical fragility curves

Table 2 presents a summary of the most important features of a number of fragility curves from literature. These features are grouped in four main categories related to general characteristics, structural capacity and demand, and the methodology for deriving the fragility curves. Because of space limitations, an indicative set of fragility curves for reinforced concrete buildings is examined in this paper, in order to illustrate the assessment procedure. A wider collection of fragility curves for European classes of reinforced concrete and masonry buildings is reviewed elsewhere [6].

The first category includes the geographic area for which the fragility curves were developed and the structural system typology. The structural systems examined in literature for reinforced concrete buildings include moment-resisting frames, wall-frame (dual) systems, infilled frames and precast concrete buildings.

The second category comprises the most important features related to the capacity of the buildings that are analysed to produce the fragility curves and in particular: non-structural elements, number of storeys, type of analysis, modelling, shear failure, geometric irregularities and engineering demand parameter. Checkmarks ✓ and × show whether non-structural elements (essentially masonry infills), shear failure of elements and geometric irregularities are taken into consideration in the analysis. The following engineering demand parameters (EDP) are used for the fragility curves reported in Table 2: inter-storey drift (d_r), chord rotation (θ), top displacement (d), global drift (d/h), shear force (V), plastic end rotation (θ_p) and floor acceleration (α_f). Important features of the analysis that may influence the fragility curves of masonry buildings, not examined here, include also the out-of-plane response and the diaphragmatic behaviour of different floor types.

The third category is related to the seismic demand. The majority of the fragility curves reported in Table 2 were produced by performing nonlinear dynamic analysis with real or artificial ground motion records. When the analysis is static or based on simplified mechanical methods, the seismic motion is normally represented by means of (code-compliant) response spectra. Checkmarks ✓ and × are used also here to identify if seismic input is related or not to the specific area where the buildings under assessment are located.

The last category includes a number of important features of the fragility curves and includes the definition of damage state thresholds, number of damage states, intensity measure and sample size. Damage state thresholds can be defined by means of either pre-set values from literature or custom ones that are defined from the analysis of the specific building under study. The intensity measures used in the studies reported in Table 2 include spectral displacement, velocity and acceleration (respectively $S_d(T)$, $S_v(T)$ and $S_a(T)$), peak ground acceleration (PGA), velocity (PGV) and displacement (PGD), cumulative absolute velocity (CAV) and Arias intensity (AI). Finally, as regards the number of buildings analysed for the development of fragility curves, the sample size may comprise one, few or several buildings.

Table 2 – Main features of analytical fragility curves for reinforced concrete buildings

	General		Capacity							Demand		Fragility curve methodology			
	Country	**Structural system**	**Non-structural components**	**Nb. of storeys**	**Analysis**	**Model**	**Shear failure**	**Geometric irregularities**	**EDP**	**Type**	**Site-specific**	**Damage state thresholds**	**Nb. of damage states**	**Intensity measure**	**Sample size**
[7]	TR	Dual	×	3	NLD	MDoF	×	✓	d_r	Ground motion records	✓	Custom	3	PGA, PGV, PGD, CAV	One
[8]	TR	Infilled frame	✓	2-5	NLD NLS	SDoF	×	×	d/h	Ground motion records	✓	Custom	4	PGV	Several
[9]	TR	Frame, dual	×	3-5	NLS	SDoF	✓	×	d_r	Ground motion records	✓	Custom	4	PGV	Several
[10]	IT	Frame	×	2-8	SMM	SDoF	✓	×	θ	Code-based spectra	✓	Custom	5	PGA	Several
[11]	IT	Infilled frame	✓	Multiple	SMM	SDoF	×	×	d	Code-based spectra	✓	Pre-set	6	PGA	Several
[12]	Europe	Infilled frame and dual	✓	2,5,8	NLS	SDoF	✓	×	θ, V	Code-based spectra	×	Custom	2	PGA	One
[13]	TR	Frame	×	5,10,15,20	NLD	MDoF	×	×	d_r, θ_p, α_f	Ground motion records	✓	Custom	12,11,15	$S_a(T)$, $S_v(T)$, $S_d(T)$, PGA, PGV, PGD, AI, CAV	Several
[14]	GR	Frame, dual	×	Low-, mid-, high-rise	NLD	Reduced MDoF	×	×	d/h	Ground motion records	✓	Pre-set	6	PGA	Several
[15]	TR	Frame	×	3,5,7,9	NLD	Reduced MDoF	×	×	d_r	Ground motion records	✓	Custom	4	PGV	Few
[16]	GR	Frame	×	3,49	NLD	MDoF	×	×	d_r	Ground motion records	✓	Custom	3	PGA	Few
[17]	IT	Frame	×	1-6,>7	NLS	SDoF	×	✓	d	Code-based spectra	✓	Pre-set	5	$S_d(T)$	Few
[18]	PT	Frame	×	1-5,>8	NLD	Reduced MDoF	×	✓	d/h, d_r	Ground motion records	✓	Pre-set	5	$S_a(T)$	Few
[19]	RO	Frame, dual	✓	11	NLS	SDoF	×	×	d	Code-based spectra	✓	Pre-set	5	$S_d(T)$	One

Table 3 – Qualitative assessment of analytical fragility curves for reinforced concrete buildings

	Capacity						Demand		Fragility curve methodology			Uncertainty		
	Non-structural components	Building height	Analysis	Model	Shear failure	Geometric irregularities	Ground motion representation	Site-specific	Damage state thresholds	Intensity measure	Sample size	Capacity	Demand	Damage thresholds
[7]	L	L	H	H	L	H	H	H	H	H	L	H	L	H
[8]	H	H	H	L	L	L	H	H	H	L	H	H	H	H
[9]	L	M	M	L	H	L	H	H	H	L	H	H	H	H
[10]	L	H	L	L	H	L	L	H	H	L	H	H	H	H
[11]	H	H	L	L	L	L	L	H	H	L	H	H	H	L
[12]	H	M	M	L	H	H	L	L	H	L	L	H	H	L
[13]	L	H	H	H	L	L	H	H	H	H	H	H	H	H
[14]	L	M	M	M	L	L	H	H	L	L	H	H	H	H
[15]	L	H	H	M	L	L	H	H	H	L	M	H	H	H
[16]	L	M	H	H	L	L	H	H	H	L	M	H	H	H
[17]	L	M	M	L	L	H	L	H	L	L	M	H	H	H
[18]	L	H	H	M	L	H	H	H	L	L	M	H	H	H
[19]	H	L	M	L	L	L	L	H	L	L	L	L	L	L

The assessment criteria described in the previous section are applied to the fragility curves and the results are reported in Table 3. The majority of the reviewed fragility curves are assigned a high rating as regards the treatment of uncertainty in capacity and seismic demand, as well as the use of site-specific seismic input. The criteria for which most of the fragility curves are assigned a low rating is related to the use of non-structural components in the analysis, the consideration of shear failure of members and of geometric irregularities.

For practical applications, the user should first sort out the fragility curves that refer to the structural type and geographic area of interest and then select, among them, the one that is assigned a higher rating. This implies that the user will need to identify which parameters are most important for the specific study. No guidance or consensus exist for the selection of the most important parameters.

4. Current trends in analytical fragility curves

In this section, the main trends that are possible to observe from the results of the qualitative evaluation performed on the larger set of fragility curves [6] are presented. This exercise provides additional support to perceive how the scientific community is approaching this topic in its main aspects and possibly to spot topics that should be further examined in the future development of fragility curves.

From Fig. 3 (*left*) one can observe that 62 % of the studies are developed for real existing buildings (EB), whose dimensions, materials and properties are known and used in the analyses, against 38 % developed for prototype buildings (PR). Even though unreinforced masonry buildings consist one of the most common and vulnerable building typologies worldwide, 62 % of the examined fragility curve studies were developed for reinforced concrete buildings, as shown in Fig. 3 (*right*). This might be explained by the severe damage and corresponding losses associated to the behaviour of this particular typology in recent earthquakes, often triggered by lack of adequate seismic designing or construction detailing.

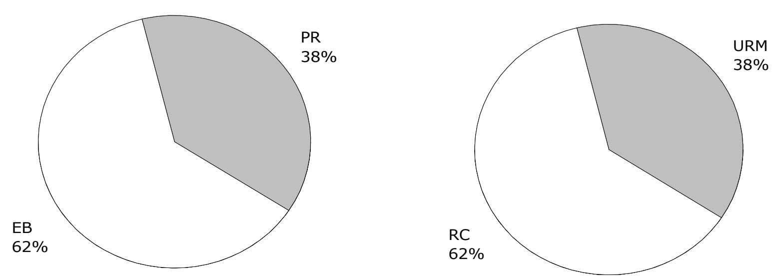

Fig. 3 – Percentage of fragility curves by building type (*left*) and structural material (*right*)

Fig. 4 presents the results of the evaluation carried out concerning the capacity aspects. In Fig. 4 (a) it is possible to observe that 75 % of the fragility curves for reinforced concrete buildings do not take into account the influence of non-structural components such as masonry infill walls. Fig. 4 (b) depicts the variability of the building height (or number of storeys) in the reviewed studies, with 38 % of the fragility curves considering more than three classes, 36 % considering two or three classes, and 26 % considering only one class of building height. The results regarding the analysis type adopted for the computation of the seismic response are presented in Fig. 4 (c), where it is shown that nonlinear dynamic analysis was performed in 33 % of the cases, against 38 % and 28 % of nonlinear static analysis and analysis with simplified mechanical models, respectively. In Fig. 4 (d) it is observed that most of the reviewed fragility curves were developed using single degree of freedom or stick models in the analysis, 62 % and 26 % respectively, and only 13 % have considered multi degree of freedom models. 65 % of the examined studies for reinforced concrete buildings have not considered the shear failure mechanism in the seismic response of structures, as illustrated in Fig. 4 (e). From Fig. 4 (f) one can observe that 69 % of the fragility curves for masonry buildings do not include out-of-plane collapse mechanisms in the analysis. Finally, Figs 4 (g) and (h) illustrate that the diaphragmatic behaviour of different floor types in masonry buildings and the geometric irregularities is not addressed in 62 % and 64 % of the examined cases, respectively.

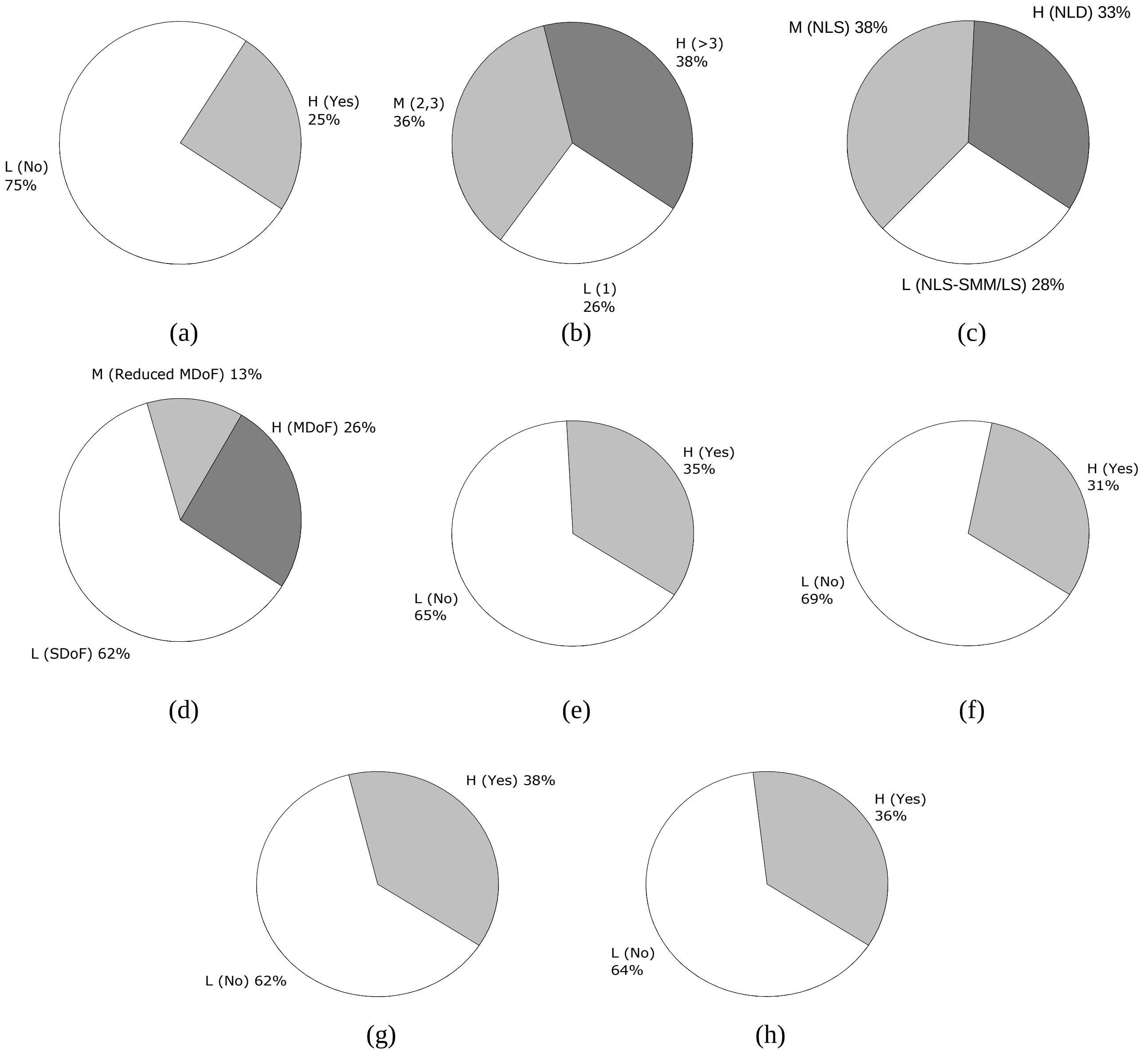

Fig. 4 – Percentage of fragility curves regarding capacity-related features: non-structural components (a), classes of building height (b), analysis type (c), model type (d), shear failure of reinforced concrete elements (e), out-of-plane mechanism in masonry buildings (f), horizontal diaphragms (g) and geometric irregularities (h)

Fig. 5 (*left*) depicts how seismic demand is represented. It is observed that around half (51 %) of the examined fragility curves have used more than seven real ground motion records and the remaining half (49 %) adopted code-based spectra. From Fig. 5 (*right*), it is possible to observe that in 85 % of the reviewed fragility curves, seismic demand is defined for the specific area where the studied structures are located. However, one should keep in mind that the remaining 15 % mainly concern methodologies that have adopted real ground motion records.

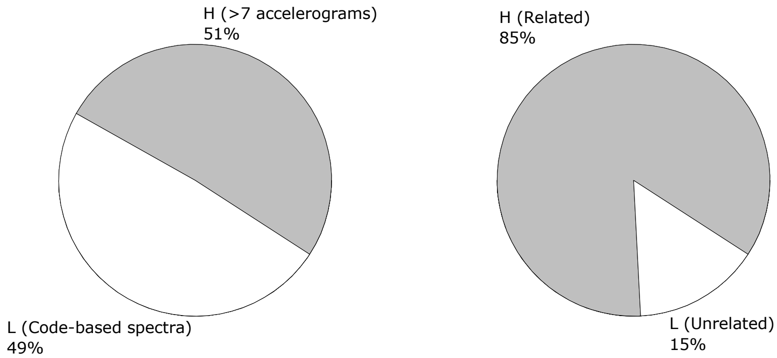

Fig. 5 – Percentage of fragility curves regarding demand-related features: representation of seismic demand (*left*) and of site-specific seismic demand (*right*)

With respect to the general features inherent to fragility curves, Fig. 6 (*left*) shows that 72 % of the examined studies adopted a custom definition of damage state thresholds for the construction of fragility curves, against 28 % that adopted pre-defined values. Moreover, from Fig. 6 (*centre*) it is observed that 90 % of the examined studies generated fragility curves based on a single intensity measure. Fig. 6 (*right*) refers to the sample size, from which it can be observed that 56 %, 23 %, and 21 % of the reviewed studies considered a sample with several, few, and only one building, respectively.

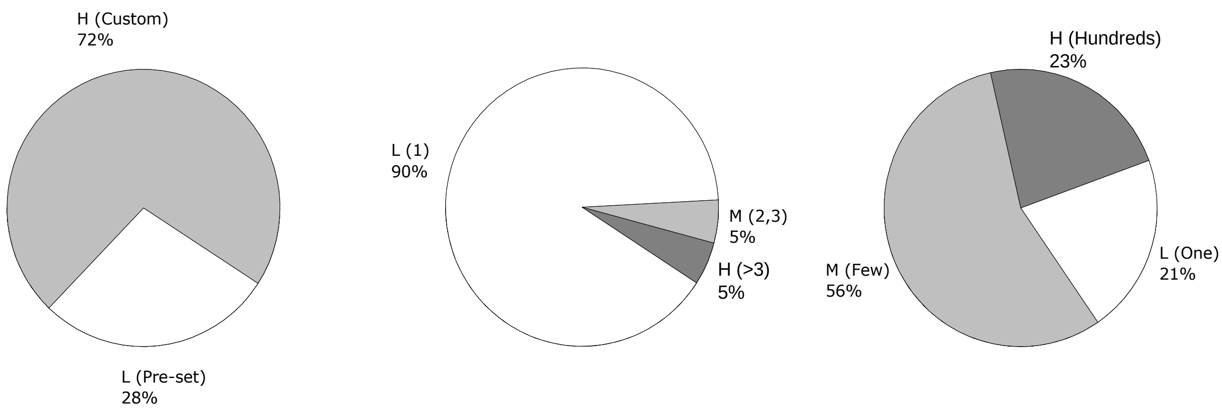

Fig. 6 – Percentage of fragility curves regarding the definition of damage states threshold values (*left*), number of intensity measures (*centre*) and sample size (*right*)

Fig. 7 depicts whether uncertainties related to capacity, demand and damage state thresholds were addressed in the literature. In Fig. 7 (*left*) it is shown that 82 % of the reviewed fragility curves have considered uncertainties in capacity. Similarly, uncertainty in demand and in the definition of damage state thresholds was included in 85 % and 69 % of the examined studies, as depicted in Fig. 7 (*centre*) and (*right*).

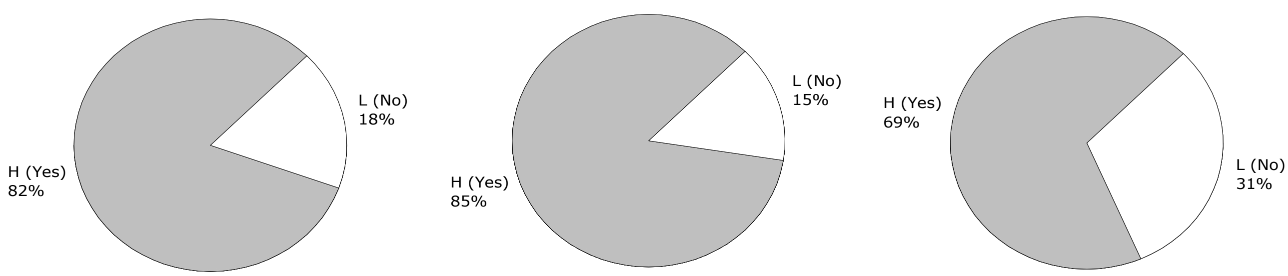

Fig. 7 – Percentage of fragility curves regarding the uncertainty in capacity (*left*), demand (*centre*) and damage state thresholds (*right*)

5. Final remarks

This paper aims to leverage upon the wealth of approaches for fragility assessment that have been developed in the last decades and to aid the selection of the most appropriate fragility curves for a given geographic area and structural typology of the European building stock. The literature review and the assessment of the most significant features of fragility curves according to a set of qualitative criteria provides a concise insight of the state-of-the-art on this topic and on aspects that need to be further examined.

The application of the qualitative assessment criteria to existing fragility curves resulted, mainly, in the assignment of a high rating to the treatment of uncertainty in capacity and in seismic demand and to the use of site-specific seismic input. On the other hand, most fragility curves were assigned a low rating with respect to the use of non-structural components in the analysis, to the consideration of shear failure of members and of geometric irregularities.

The summary of the aspects that stand out in most of the analysed fragility curves is as follows:

1. With regard to the building type and to the structural material, most fragility curves were developed for real existing reinforced concrete buildings and not for prototype buildings.
2. In relation to capacity-related features, most fragility curves for reinforced concrete buildings did not take into account the influence of non-structural components and of a shear failure mechanism. Most of the fragility curves developed for masonry buildings did not address out-of-plane collapse mechanisms and diaphragmatic behaviour of different floor types. In addition, most of the reviewed fragility curves were developed using single degree of freedom models and did not consider geometric irregularities.
3. With respect to the representation of seismic demand, most fragility curves took into consideration site-specific studies.
4. Finally, regarding general features, most fragility curves adopted a custom definition of damage state thresholds and are based on a single intensity measure.

The criteria and assessment of existing fragility curves are a useful guide for different seismic risk studies, namely: (i) the assessment of the seismic risk of buildings in Europe for decision-making on building renovation, (ii) the impact estimations after major earthquake disasters for emergency response, (iii) the seismic scenario simulation for emergency planning and disaster risk reduction and (iv) the definition of procedures for seismic risk assessment to be integrated in multi-risk approaches for different natural hazards in Europe.

The review of existing fragility curves revealed a number of issues that are not sufficiently addressed in the current literature, need to be further investigated and incorporated in future fragility assessment studies. These include the use of more refined numerical models to better capture the response of structures, particularly for the more severe damage states, the effect of non-structural elements, shear failure modes of reinforced concrete structural elements, out-of-plane response and types of floors for masonry buildings and geometric irregularities. The impact of aging and progressive deterioration of the material properties, the effect of soil-structure interaction and the validation of fragility curves with empirical and experimental data are additional challenges.

Given the disparities in the methodologies that have been developed for the derivation of fragility curves, agreed guidelines, for instance on taxonomy, intensity measures, definition and number of limit states, etc., will be useful to accomplish to the harmonisation of fragility curves.

It is noted that only analytical methodologies for deriving fragility curves are addressed in this paper. It would be interesting to extend this study to fragility curves produced with empirical, expert judgment elicitation and hybrid approaches. It would be equally interesting to extend this work beyond the European context.

6. Acknowledgements

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