Chapter 4
Epistemic Uncertainty in Fragility Functions for European RC Buildings

Helen Crowley, Miriam Colombi, and Vitor Silva

Abstract This chapter briefly summarises the work carried out under the auspices of the SYNER-G project to collect, harmonize and compare fragility functions for European RC buildings. All of these functions have been stored in the Fragility Function Manager described in Chap. 13. Examples of a methodology for estimating the epistemic uncertainty across a collection of fragility functions is presented, which, as discussed herein, should first be carefully reviewed for reliability, for example following the methodology presented in Chap. 3.

4.1 Introduction

The identification of the seismic fragility functions for common buildings types is a fundamental component of a seismic risk loss assessment model and, for this reason, many research studies have addressed this topic in the recent past.

In the context of the SYNER-G Project, the main typologies of reinforced concrete buildings in Europe have been identified and the existing fragility functions have been reviewed with the objective of homogenizing the existing model building types (through a new taxonomy, called the SYNER-G taxonomy), and comparing these functions amongst themselves. The main output is method to identify a set of fragility functions (with associated uncertainties) for the main reinforced concrete typologies present in Europe. For further details, the reader is referred to Crowley et al. (2011a, b).

H. Crowley (✉) • M. Colombi • V. Silva
European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata 1, 27100 Pavia, Italy
e-mail: helen.crowley@eucentre.it; miriam.colombi@eucentre.it; vitor.silva@eucentre.it

K. Pitilakis et al. (eds.), *SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk*, Geotechnical, Geological and Earthquake Engineering 27,
DOI 10.1007/978-94-007-7872-6_4,

4.2 Review of Fragility Functions for European Buildings

In the European continent, most of the buildings are constructed with masonry or reinforced concrete, and for this reason, the majority of the existing fragility functions in the academic literature treat these two types of structures. Fragility functions describe the probability of exceeding different limit states (such as damage levels) given a level of ground shaking. A “fragility function set”, as referred to herein, represents a group of functions for a given building typology for a number of different limit states of damage. A large number of fragility function sets have been collected in the context of the SYNER-G project and they have been stored into a dynamic tool, the SYNER-G Fragility Function Manager, which is described in Chap. 13 of this book.

About 50 studies/publications have been reviewed as part of the project and for each study, usually more than one building typology is investigated and different fragility function sets are identified. For example, Polese et al. (2008) considered three different types of reinforced concrete buildings and developed three different fragility function sets. Therefore, in total, 415 fragility function sets for buildings have been collected in the project. The review of fragility functions is not claimed to be comprehensive, but it was carried out to develop the Fragility Function Manager, and additionally investigate the epistemic uncertainty of fragility functions, using the methodology described in Chap. 13.

As discussed in Chap. 1, different methodologies can be used for deriving fragility functions and it is possible to classify them into four generic groups: empirical (based on observed data), expert opinion-based, analytical (based on numerical models) and hybrid (typically a combination of empirical and analytical methods). An “unknown” class has been added in this study due to the fact that it could be unclear from the reference material which method has been used. In the pie charts below, the percentages of the different methodologies used in the 50 studies reviewed are shown for reinforced concrete buildings. Figure 4.1 shows the popularity of analytical methods for the derivation of fragility functions for European buildings, which is also an outcome of the fact that two recent European projects – RISK-UE (Mouroux and Le Brun 2006) and LESSLOSS (Calvi and Pinho 2004), both promoted the use of analytical methodologies for deriving fragility functions.

Another key element which is significant in the development of the fragility curves, is the Intensity Measure Type (IMT) that represents the reference ground motion parameter against which the probability of exceedance of a given limit state is plotted. The vulnerable conditions of a structure are defined for a certain level of ground shaking. An intensity measure describes the severity of earthquake shaking.

In the reviewed papers, different IMTs have been used to define the level of ground shaking. It is possible to group these IMTs into two main classes: observational intensity measure types and instrumental intensity measure types.

With regards to the observational IMTs, different macroseismic intensity scales could be used to identify the observed effects of ground shaking over a limited area.

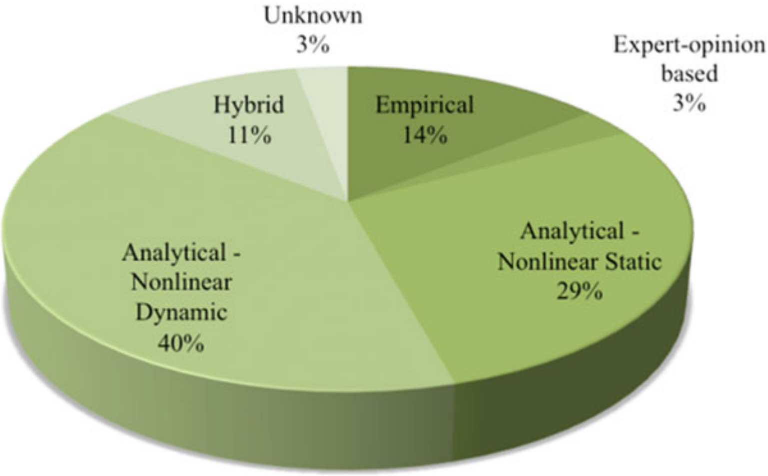

Fig. 4.1 Pie chart presenting the percentages of different methodologies used to develop fragility function for reinforced concrete buildings

In the reviewed papers, fragility functions have been estimated using the following different types of macroseismic intensity:

- MCS: Mercalli-Cancani-Sieberg Intensity Scale;
- MMI: Modified Mercalli Intensity Scale;
- MSK81: Medvedev-Sponheuer-Karnik Intensity Scale;
- EMS98: European Macroseismic Scale.

The instrumental IMTs (obtained from accelerograms), have the advantage that the severity of the earthquake is no longer subjective. In the reviewed papers, several instrumental IMTs are used to link the probability of exceeding different limit states to the ground shaking:

- PGA: peak ground acceleration;
- PGV: peak ground velocity;
- RMS: root mean square of the acceleration;
- $S_a(T_y)$: spectral acceleration at the elastic natural period T_y of the structure;
- $S_d(T_y)$ and $S_d(T_{LS})$: spectral displacement at the elastic natural period (T_y) of the structure or at the inelastic period (T_{LS}) corresponding to a specific limit state, respectively;
- Roof Drift Ratio: represents the ratio of the maximum displacement response at the roof and the height of the building.

The latter three intensity measures in the list above might be referred to as structure-dependent intensity measures as they are based on response parameters, and thus require structural information regarding the building typology in order to be used (Fig. 4.2).

In the pie charts above, the percentages concerning the different IMTs used in the studies are shown and as can be noted, peak ground acceleration has been the most commonly used intensity measure type in the studied literature.

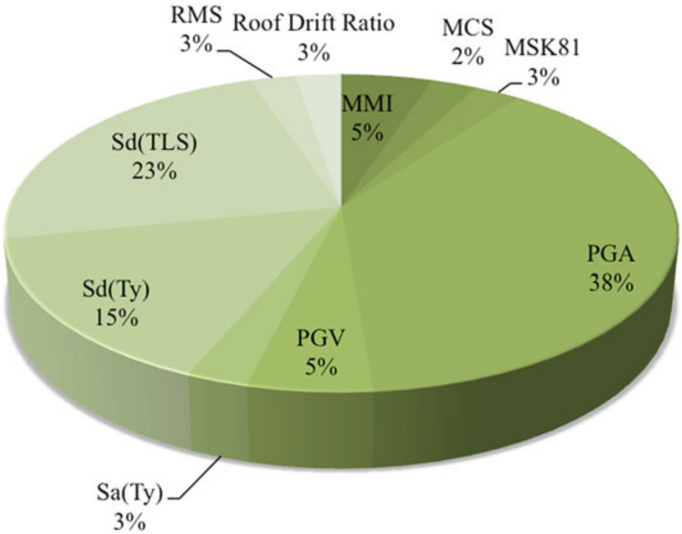

Fig. 4.2 Pie chart presenting the different percentages of intensity measure types used to develop fragility function for reinforced concrete buildings

4.3 Taxonomy of European Building Typologies

Fragility functions are developed for classes of buildings that have similar characteristics in terms of the attributes that affect seismic vulnerability. The classification of buildings based on their structural characteristics can be carried out with a "taxonomy".

A number of building taxonomies have been proposed over the past 30 years although many actually provide a list of building typologies rather than a scheme with which the main attributes of buildings can be classified. From the extensive study of fragility functions carried out in this work it became clear that existing taxonomies could leave out a large number of characteristics that could be used to distinguish the seismic performance of buildings, and in many cases it was not clear how these taxonomies should be simply expanded to include such information. Hence, a classification scheme for buildings was developed within the SYNER-G project. The main categories of this classification scheme proposed for buildings within SYNER-G are: force resisting mechanism (FRM), force resisting mechanism material (FRMM), plan regularity (P), elevation regularity (E), cladding (C), detailing (D), floor system (FS), roof system (RS), height level (H), and code level (CL). The attributes of the taxonomy that are most relevant for RC buildings are presented in Table 4.1. Readers are referred to Chap. 5 for a discussion of the attributes of the SYNER-G taxonomy used to describe masonry buildings.

Table 4.1 SYNER-G building taxonomy: attributes of importance for RC buildings

	Category	Sub-category
FRM	Moment resisting frame (MRF) Structural wall (W) Flat slab (FS) Precast (P)	Embedded beams (EB); Emergent beams (EGB)
FRMM	Concrete (C)	Reinforced concrete (RC); High strength concrete (>50 MPa) (HSC); Average strength concrete (20–50 MPa) (ASC); Low strength concrete (<20 MPa) (LSC) High yield strength reinforcing bars (>300 MPa) (HY); Low yield strength reinforcing bars (<300 MPa) (LY); Classification of reinforcing bars based on EC2 (A,B,C); Smooth rebars (SB); Non-smooth rebars (NSB)
P	Regular (R) Irregular (IR)	
E	Regular geometry (R) Irregular geometry (IR)	
C	Regular infill vertically (RI) Irregular infill vertically (IRI) Bare (B)	Fired brick masonry (FB); High % voids (H%); Low % voids (L%); Autoclaved Aerated Concrete (AAC); Precast concrete (PC); Glazing (G); Single layer of cladding (SL); Double layer of cladding (DL); Open first floor (Pilotis) (P); Open upper floor (U).
D	Ductile (D) Non-ductile (ND)	
FS	Rigid (R) Flexible (F)	Reinforced concrete (RC); Steel (S); Timber (T).
HL	Low-rise (1–3) (L) Mid-rise (4–7) (M) High-rise (8–19) (H) Tall (20+) (Ta)	Number of stories (indicate the number)
CL	None (NC) Low (<0.1 g) (LC) Moderate (0.1–0.3 g) (MC) High (>0.3 g) (HC)	

FRM force resisting mechanism, *FRMM* force resisting mechanism material, *P* plan, *E* elevation, *C* cladding, *D* detailing, *FS* floor system, *HL* height level, *CL* code level

The building typology is defined using the label put in the brackets for each parameter within a given category. For example:

FRM1-FRM2/FRMM1-FRMM2/P/E/C-CM/D/FS-FSM/RS-RSM/HL-NS/CL

More than one label can be used per category separated by a dash. For example, a building with moment resisting frames and walls (dual system) would be MRF-W, a building with mixed construction of reinforced concrete and masonry would be RC-M. Not all categories need to be defined due to the fact that there might be lack of information about the structure. In this case, where information is unknown, it can be left by an X. In the following, two examples are shown:

- MRF/C-RC/X/X/RI-FB-H%/ND/R-RC/X/L-2/NC: moment resisting frame, in reinforced concrete with regular external infill panels in brick with a high percentages of voids, with non-ductile design details, with rigid reinforced concrete floor, low-rise, two storeys, not designed to a seismic code;
- BW/M/X/X/X/X/X/X/L/X: low-rise masonry bearing wall structure.

The proposed taxonomy is constructed with a modular structure. In this way, other categories and sub-categories can easily be added and all the different kind of European buildings can be taken into account. Subsequently, additional categories for describing the non-structural elements might be added.

This modular structure represents a new and a different approach in categorizing and classifying buildings. It has a flexible structure and it can be used to describe a considerable amount of different buildings. It can be updated at any time with new categories being added and different features can be added to existing categories. The SYNER-G taxonomy was defined by Charleson (2011) as having the most potential amongst all taxonomies reviewed and subsequently formed the basis of the Global Earthquake Model (GEM) Building Taxonomy (Brzev et al. 2012). It is proposed that in future European studies the GEM Building Taxonomy is used, as it has built upon and further improved the SYNER-G taxonomy.

4.4 Fragility Functions for RC Buildings

Following the review of fragility functions in Europe, and their classification using the SYNER-G building taxonomy, a tool was developed to store all of the functions, and allow users to harmonize and compare the functions. This tool is the Fragility Function Manager, described further in Chap. 13 of this book.

As described in Sect. 4.3, a taxonomy for European buildings has been derived in this project. This taxonomy has been assigned to all of the fragility functions collected (which can be found in Crowley et al. 2011a). The fragility functions for a given taxonomical description can then be filtered using the SYNER-G Fragility Function Manager.

One main class of reinforced concrete structures has been selected herein for the comparison of fragility functions: reinforced concrete buildings with moment

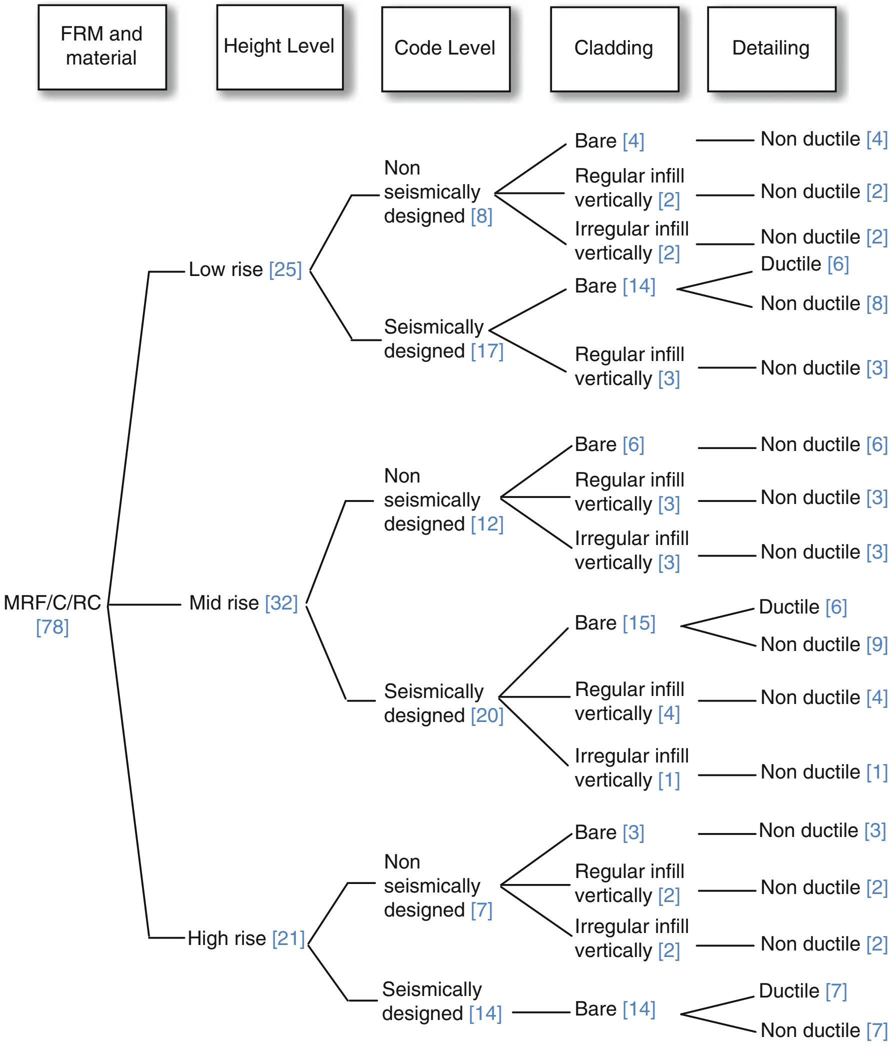

Fig. 4.3 Flow chart for a reinforced concrete with moment resisting frame building class. The number in *blue brackets* reports the available number of fragility function sets

resisting frames. A project has been created with the aforementioned tool to consider this main class and sub-projects have been developed to group the structures taking into account the height level, the code level, the cladding and the detailing (Fig. 4.3). Each column represents a different level of detail. In this way, the user can choose to compare fragility functions taking into account different levels of information. For instance, it should be possible to compare all the available fragility functions sets concerning reinforced concrete with moment resisting frame building that are low rise or all the available fragility functions

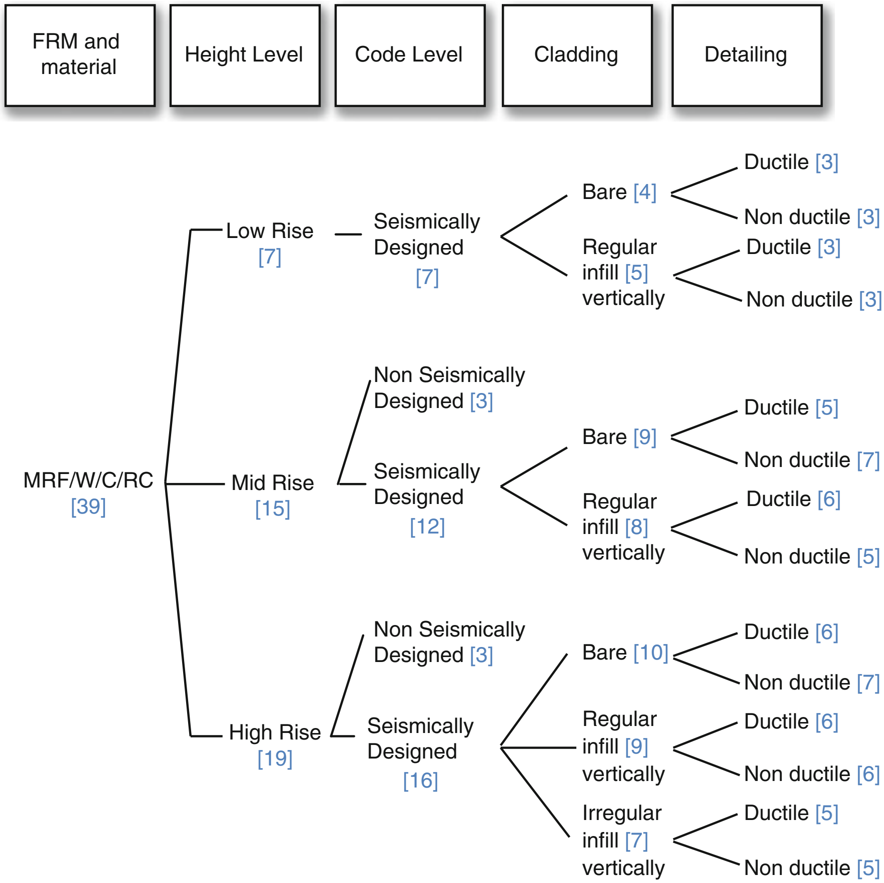

Fig. 4.4 Flow chart for a reinforced concrete with dual system building class. The number in *blue brackets* reports the available number of fragility function sets

sets concerning reinforced concrete with moment resisting frame building that are low rise, seismically designed, bare and ductile. In Fig. 4.4, the chart produced using the same exercise for reinforced concrete buildings with dual systems is also provided.

By observing Figs. 4.3 and 4.4 it is apparent which building types need to be analysed in future research developments. In fact, there are some classes that are represented by very few fragility curves (sometimes just one fragility function) and for this reason it is not possible to conduct a critical review and an exhaustive study of the epistemic uncertainties across the fragility functions of this typology.

A collection of fragility functions for a given RC building type has been produced, and then harmonized (in terms of the intensity measure type and limit

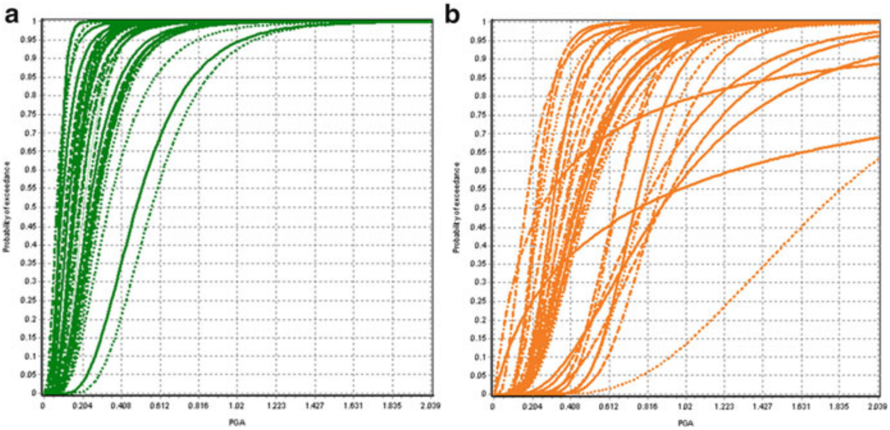

Fig. 4.5 Yield limit state (**a**) and collapse limit state (**b**) harmonised fragility functions for a reinforced concrete mid-rise building with moment resisting frame: MRF/C/RC/X/X/X/X/X/X/MR/X

states) and compared. In the following, four examples are described to show in detail the capability of the tool and the comparison between different literature studies. Readers that are interested in more guidance regarding the selection of fragility functions from a wide range of choices are referred to Chap. 3, where a methodology for selecting reliable fragility functions is presented. Such a method has not been applied herein, which is one reason for the very large epistemic uncertainty that can be seen across the fragility functions. The main reason for presenting the functions herein has been to demonstrate one possible methodology for estimating epistemic uncertainty, which has been implemented in the SYNER-G systemic vulnerability framework, which is described further in the companion Book (Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Lifeline Systems and Infrastructures: The SYNER-G Methodology and Applications).

The selected examples in Figs. 4.5, 4.6, 4.7 and 4.8 go from a lower level of detail (reinforced concrete building, mid rise, moment resisting frame) to a higher level of detail (reinforced concrete building, mid rise, moment resisting frame, seismically designed, bare and non ductile). Somewhat surprisingly, increasing the level of detail of the taxonomic description of the building typology does not necessarily reduce the epistemic uncertainty in the fragility functions. There are a wide range of reasons for the variability in the curves which include the methodology used to derive the functions (and the treatment of uncertainties within that method), the region of applicability, the limit state criteria applied, the intensity measure type employed (and the uncertainties associated with converting to a common intensity measure type). As discussed in Chap. 3, and as highlighted by the following results, an evaluation of these criteria should first be made, before fragility functions can be selected and compared.

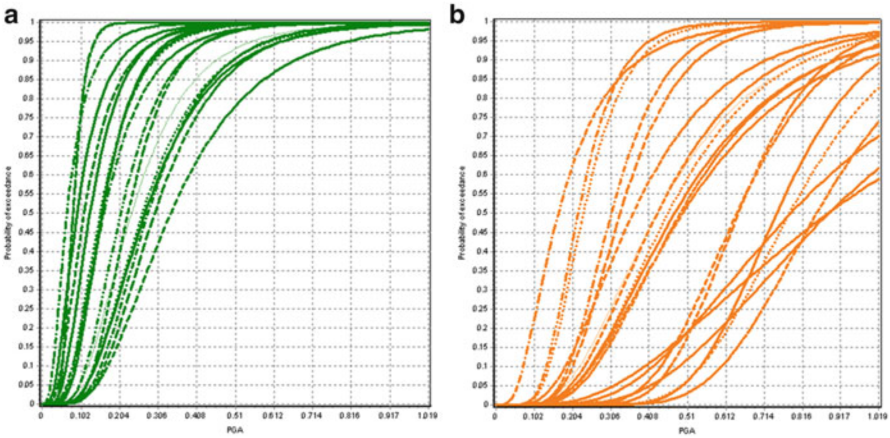

Fig. 4.6 Yield limit state (**a**) and collapse limit state (**b**) harmonised fragility functions for a reinforced concrete mid-rise building with moment resisting frame with lateral load design: MRF/C/RC/X/X/X/X/X/X/MR/C

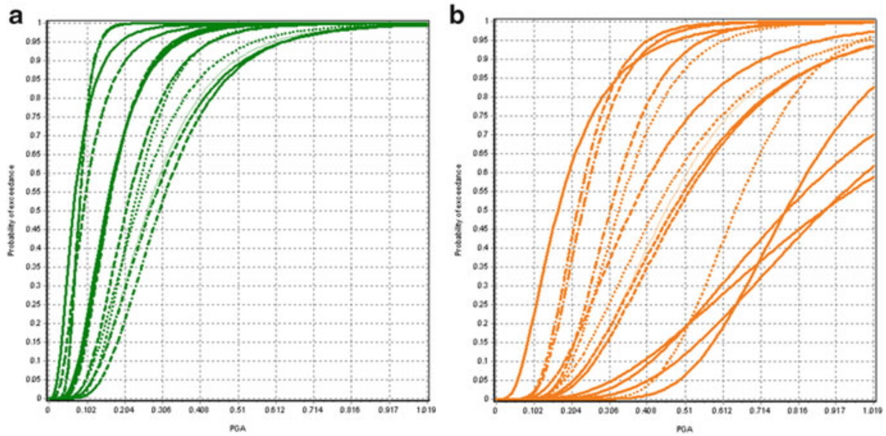

Fig. 4.7 Yield limit state (**a**) and collapse limit state (**b**) harmonised fragility functions for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design: MRF/C/RC/X/X/B/X/X/X/MR/C

For each reinforced concrete buildings class, in the Figs. 4.9, 4.10, 4.11 and 4.12 below are shown the mean curve and the individual fragility functions, whilst in the following Tables 4.2, 4.3, 4.3, 4.4, 4.5, 4.6, 4.7 and 4.8 are reported the mean and coefficient of variation (cv) of the lognormal parameters of the fragility functions (i.e. logarithmic mean and logarithmic standard deviation), as well as the corresponding correlation coefficient matrix. The methodology for estimating these parameters is presented in Chap. 13.

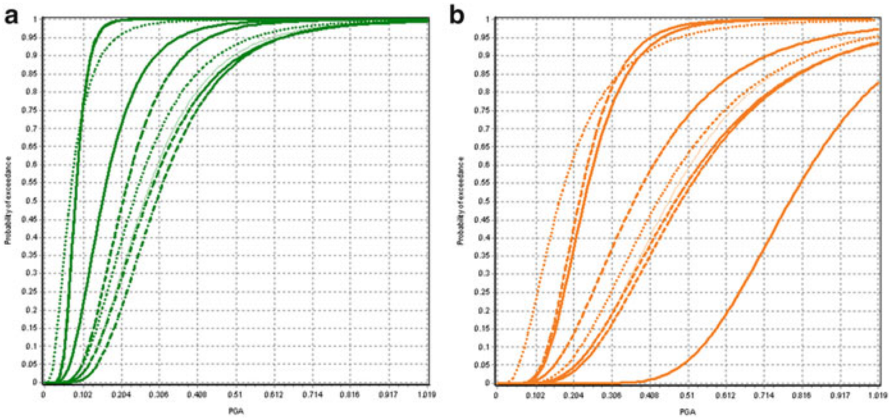

Fig. 4.8 Yield limit state (**a**) and collapse limit state (**b**) harmonised fragility functions for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design: MRF/C/RC/X/X/B/ND/X/X/MR/C

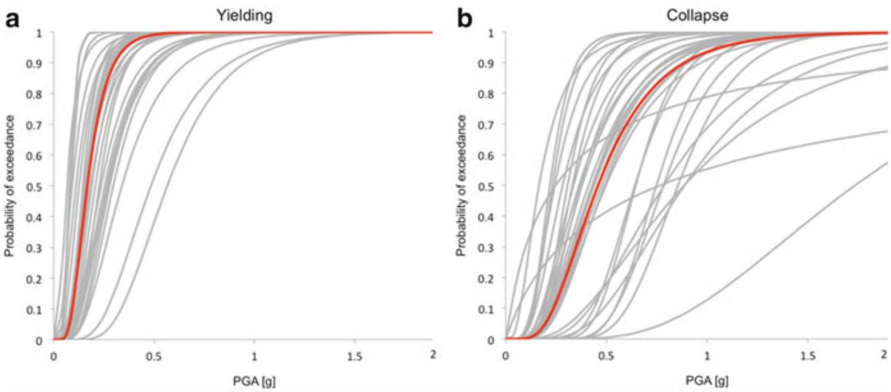

Fig. 4.9 Mean curve for yielding limit state (**a**) and collapse limit state (**b**) for a reinforced concrete mid-rise building with moment resisting frame

4.5 Concluding Remarks

As part of the study on existing fragility functions in Europe carried out within the SYNER-G project, a number of issues have been tackled from which the following recommendations can be extracted:

- A classification scheme (taxonomy) for European buildings has been proposed. The SYNER-G taxonomy has formed the basis of the GEM building taxonomy (Brzev et al. 2012), which if used in future research and risk assessment applications, will simplify the comparison of fragility functions across various studies.

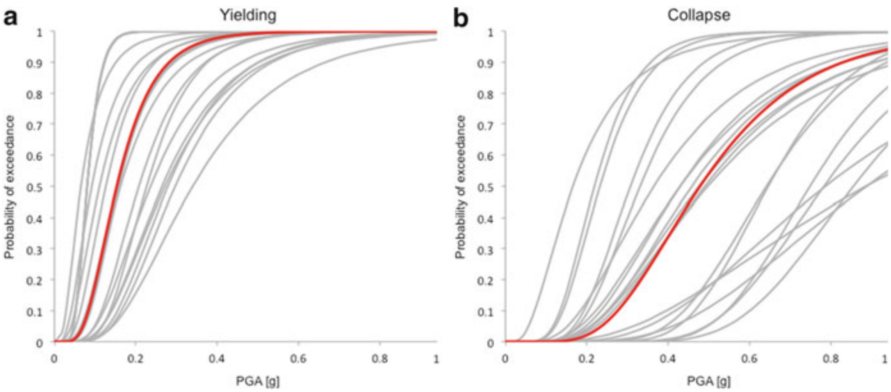

Fig. 4.10 Mean curve for yielding limit state (**a**) and collapse limit state (**b**) for reinforced concrete mid-rise building with bare moment resisting frame with lateral load design

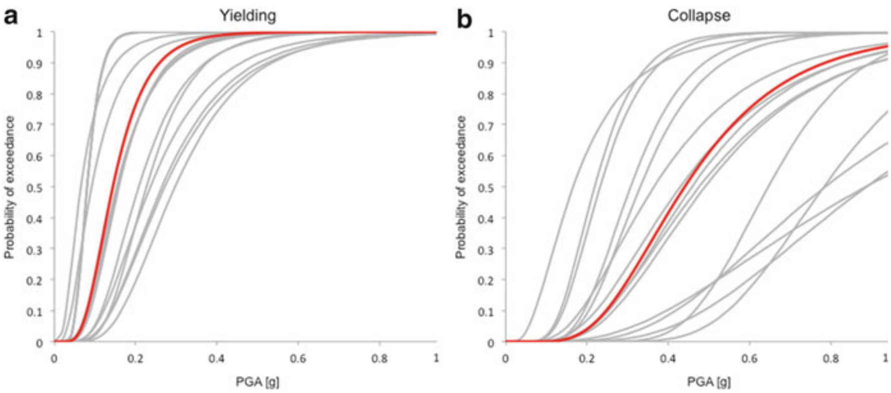

Fig. 4.11 Mean curve for yielding limit state (**a**) and collapse limit state (**b**) for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design

- A tool for those working on seismic risk assessment has been developed which allows fragility functions, that have until now been confined to the pages of academic literature, to be shared and compared. A recommendation for the future development of the Fragility Function Manager will be for the fragility functions to first be quality rated before a methodology to estimate the epistemic uncertainty is applied. Chapter 3 proposes that the reliability of a fragility function can be described in terms of a number of factors including the data quality, class definition and sampling method/size and derivation method. Such evaluations of fragility functions will aid users in selecting functions for risk assessment.
- It is recommended that future research into fragility functions in Europe takes into account the gaps that have been identified through the review carried out in this project. In particular, fragility functions for high rise moment resisting

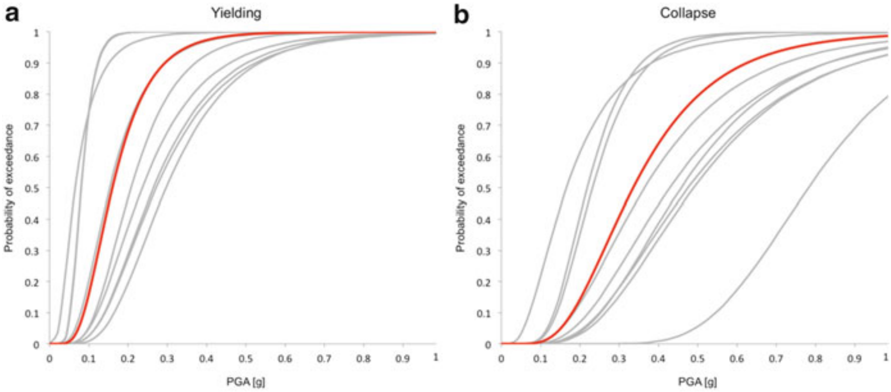

Fig. 4.12 Mean curve for yielding limit state (**a**) and collapse limit state (**b**) for a reinforced concrete mid-rise building with bare non-ductile moment resisting frame with lateral load design

Table 4.2 Mean and c_v of the lognormal fragility parameters for a reinforced concrete mid-rise building with moment resisting frame

	Yielding		Collapse	
	Logarithmic mean	Logarithmic standard deviation	Logarithmic mean	Logarithmic standard deviation
Mean	−1.853	0.481	−0.879	0.452
c_v (%)	26	19	48	23

Table 4.3 Correlation coefficient matrix for a reinforced concrete mid-rise building with moment resisting frame

	Median (yield)	Dispersion (yield)	Median (collapse)	Dispersion (collapse)
Median (yield)	1	0.116	0.537	0.272
Dispersion (yield)		1	0.278	0.008
Median (collapse)	Symmetric		1	−0.109
Dispersion (collapse)				1

Table 4.4 Mean and c_v of the lognormal fragility parameters for a reinforced concrete mid-rise building with moment resisting frame with lateral load design

	Yielding		Collapse	
	Logarithmic mean	Logarithmic standard deviation	Logarithmic mean	Logarithmic standard deviation
Mean	−1.876	0.476	−0.738	0.430
c_v (%)	28	21	67	28

Table 4.5 Correlation coefficient matrix for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design

	Median (yield)	Dispersion (yield)	Median (collapse)	Dispersion (collapse)
Median (yield)	1	0.152	0.386	0.094
Dispersion (yield)		1	0.371	0.354
Median (collapse)	Symmetric		1	−0.279
Dispersion (collapse)				1

Table 4.6 Mean and c_v of the lognormal fragility parameters for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design

	Yielding		Collapse	
	Logarithmic mean	Logarithmic standard Deviation	Logarithmic mean	Logarithmic standard deviation
Mean	−1.939	0.458	−0.821	0.452
c_v (%)	28	23	64	25

Table 4.7 Correlation coefficient matrix for a reinforced concrete mid-rise building with bare moment resisting frame with lateral load design

	Median (yield)	Dispersion (yield)	Median (collapse)	Dispersion (collapse)
Median (yield)	1	0.189	0.504	−0.041
Dispersion (yield)		1	0.276	0.723
Median (collapse)	Symmetric		1	−0.089
Dispersion (collapse)				1

Table 4.8 Mean and c_v of the lognormal fragility parameters for a reinforced concrete mid-rise building with bare non-ductile moment resisting frame with lateral load design

	Yielding		Collapse	
	Logarithmic mean	Logarithmic standard deviation	Logarithmic mean	Logarithmic standard deviation
Mean	−1.832	0.474	−1.091	0.485
c_v (%)	33	21	48	24

frames with seismic design and infills panels were not identified in the review, and frame-wall structures without seismic design were much less common than their seismically designed counterparts. The reason for the reduced number of studies is likely to be related to the lower frequency of these building typologies in Europe, but it is nevertheless suggested that the research herein could provide some guidance on where to focus fragility function efforts for RC buildings in

Table 4.9 Correlation coefficient matrix for a reinforced concrete mid-rise building with bare non-ductile moment resisting frame with lateral load design

	Median (yield)	Dispersion (yield)	Median (collapse)	Dispersion (collapse)
Median (yield)	1	0.158	0.783	0.033
Dispersion (yield)		1	0.118	0.614
Median (collapse)	Symmetric		1	−0.453
Dispersion (collapse)				1

the future. In the meantime, as mentioned previously, users of existing fragility functions are recommended to apply methodologies such as those described in Chap. 3 for evaluating and selecting robust fragility functions, and a methodology such as the one described in Chap. 13 for parameterizing the uncertainty across a number of functions.

References

Brzev S, Scawthorn C, Charleson AW, Jaiswal K (2012) Interim overview of GEM building taxonomy V2.0, GEM Foundation, December 2012. Available from URL: http://www.nexus.globalquakemodel.org/gem-building-taxonomy/posts/testing-and-evaluation-of-the-gem-building-taxonomy-v-2.0/at_download/attachment

Calvi GM, Pinho R (2004) LESSLOSS, a European integrated project on risk mitigation for earthquakes and landslides. Research report ROSE 2004/02. IUSS Press, 178 pp. ISBN: 88-7358-020-3

Charleson A (2011) Review of existing structural taxonomies. Available from URL: http://www.nexus.globalquakemodel.org/gem-building-taxonomy/posts/review-of-existing-structural-taxonomies

Crowley H, Colombi M, Silva V, Ahmad N, Fardis M, Tsionis G, Papailia A, Taucer F, Hancilar U, Yakut A, Erberik MA (2011a) D3.1 Fragility functions for common RC building types in Europe, SYNER-G Deliverable 3.1. Available from URL: http://www.vce.at/SYNER-G/files/dissemination/deliverables.html

Crowley H, Colombi M, Silva V, Ahmad N, Fardis M, Tsionis G, Karatoni T, Lyrantazaki F, Taucer F, Hancilar U, Yakut A, Erberik MA (2011b) D3.2 Fragility functions for common masonry building types in Europe, SYNER-G Deliverable 3.2. Available from URL: http://www.vce.at/SYNER-G/files/dissemination/deliverables.html

Mouroux P, Le Brun B (2006) Presentation of RISK-UE project. Bull Earthq Eng 4:323–339

Polese M, Verderame GM, Mariniello C, Iervolino I, Manfredi G (2008) Vulnerability analysis for gravity load designed RC buildings in Naples – Italy. J Earthq Eng 12(S2):234–245