# Chapter 14
# Recommendations for Future Directions in Fragility Function Research

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**Abstract** This chapter outlines the main comments relevant to the compilation of fragility functions and highlights the main recommendations given in the different Chapters of this Book concerning the selection among existing fragility functions or the derivation of new ones for the most important elements at risk. Essential needs for future studies are also summarized.

## 14.1 Introduction

The objective of this Book, which also reflects a part of the work carried out in the SYNER-G project, is to present the state of the art on the fragility functions used in seismic risk assessment of buildings, lifelines, utility systems, transportation infrastructures and critical facilities, considering as much as possible the construction typologies in Europe. To this end, fragility curves from literature were collected, reviewed, harmonised and, where possible, validated against observed damage. In some cases, existing functions were modified and adapted, whereas in other cases, new fragility functions were developed.

Special attention is given to the methods used to derive the fragility curves and the various uncertainties associated with this topic. Different approaches can be used to compile fragility curves. Empirical curves, which are based on statistical damage data from past earthquakes, are more appropriate to the particular region and construction practice where the empirical data comes from and should be used with caution. They

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are also useful for the validation of functions based on other methods. Their main weaknesses are the lack of adequate and well documented data for all typologies of structures and the poor correlation of the observed damage with records of strong ground motion. Judgmental or expert elicitation methods depend on the experience of the individual experts consulted. They are approximate and highly subjective methods. Analytical methods, based on numerical models of structures subject to increasing level ground motion, and hybrid approaches which combine the results from different methods lead to reduced bias and are becoming more attractive, in particular due to the recent development of computing capabilities.

Whatever the approach is, crucial choices must be made regarding the definition of damage states and the associated damage indexes, together with their threshold values, as well as the intensity measure adequate to capture the seismic response of each element at risk. A wide range of options is available in the literature and only general recommendations may be put forward, based on effectiveness, efficiency, sufficiency, robustness and computability of the selected parameters. In principle, the use of a particular damage or intensity measure should be guided by the extent to which it corresponds and correlates to damage, but in practice it is often more related to the approach followed for the derivation of fragility curves.

The treatment of uncertainties is of major importance both in the derivation of fragility curves and in risk assessment in general. In Chap. 2 a comprehensive presentation of the way that the problem may be tackled has been provided. In the risk analyses that have been carried out within SYNER-G, aleatory and epistemic uncertainties are practically coexisting, and there is no conceptual difference between the two, except that the aleatory uncertainties are describable, in the majority of cases, by means of a continuous probability distributions, while on the other hand, the epistemic ones are often of the discrete type, and the associated probabilities are to be assigned subjectively, on the basis of experience.

There are several approximate techniques for dealing with this problem, starting from the simple but rather inadequate First Order Second Moment (FOSM) method, to the approach based on the use of a Response Surface in the space of the structural variables. In Chap. 2, Latin Hypercube Sampling is recommended for accuracy, however its practical limits, due to the demanding computational effort when modelling a large number of uncertain quantities, are underlined (P. E. Pinto in Chap. 2). In the different Chapters of this Book this issue is extensively discussed, providing the reader with a good overview of how uncertainties should be or have been modelled in the derivation of fragility functions.

The work performed within SYNER-G allows the identification of topics that require refinement and could be the subject of future research. In particular:

- Validation of existing fragility curves against observed damage will enable better rating of their quality and will potentially improve their reliability. However, such damage data is scarce for some elements at risk. The development of robust field measurement techniques that might help to better define the real condition of a building or a structure with regard to its vulnerability rating should be also an important improvement to the fragility analysis. Another essential step towards the improvement of damage estimation models is the establishment of a commonly accepted format for the systematic documentation and compilation of both damaged and undamaged structures as well as of nonstructural components. Moreover, advances in information technologies now permit rapid, cost-effective collection and analysis of virtually exhaustive data sets, which should be appropriately archived and made available to the engineering community.

- Fragility curves are not available and should be developed for several structures not included in the SYNER-G typologies, such as high-rise reinforced concrete frame buildings with infills, masonry buildings with seismic design, HDPE pipelines that are used in European cities, waterfront structures other than of gravity type, various components of EPN, industrial facilities and others.
- The uncertainty of the most important parameters that are introduced in the fragility curves (i.e. capacity and demand assessment of the element at risk and definition of damage states) needs to be further investigated so as to confirm the default values that describe the variability of these parameters that have been adopted in many studies, or to propose new ones.

In the following, an attempt is made to summarize essential comments relevant to the compilation of fragility functions and to highlight once more the main recommendations given in the different Chapters concerning the selection among existing fragility functions or the derivation of new ones. Important needs for future studies are also grouped for the most important elements at risk.

## 14.2 Fragility Functions for Reinforced Concrete Buildings

The review of existing fragility curves for reinforced concrete buildings shows a variety of methodologies, damage states, and intensity measures. It also becomes clear that existing taxonomies could leave out a large number of characteristics that could be used to distinguish the seismic performance of buildings. Hence, a modular classification scheme was developed. This collapsible and expandable scheme gives the flexibility to describe a building with as much information as can be collected, and allows one to expand the taxonomy when more detailed information is available, by adding new categories or sub-categories so as to describe all types of buildings, or by adding new sets of fragility curves considering other modelling hypothesis. For example in the frame of SYNER-G University of Patras in Greece (Fardis et al. 2012) has developed new fragility curves for RC frame and wall-frame buildings designed according to Eurocode 2 alone or for the three ductility classes of Eurocode 8. The curves were established point-by-point, from the probability that the (random variable) demand for given intensity measure exceeds the (random variable) capacity and consider shear failures, which are normally ignored in most of the existing analytical fragility studies.

The dynamic tool that has been developed and described in Chap. 13 provides a set of fragility functions for the most important RC building typologies in Europe, which are stored into the Fragility Function Manager. This dynamic tool was used for the harmonisation of the fragility curves and for the estimation of the associated epistemic uncertainty in the mean and standard deviation values for a set of curves, which was applied to buildings but could be used for other elements at risk. For simplicity, fragility curves were harmonised for the yielding and ultimate damage states, as it is difficult to compare the functions for the intermediate damage states.

The selection of the most appropriate fragility curves for the exposed assets is discussed in detail mainly for RC and masonry buildings in Chap. 3. On the basis of this discussion a rating system is proposed for empirical and analytical fragility functions and then a procedure is proposed for rationally selecting the most appropriate fragility curves from the literature for application in seismic risk assessment. Given that it is often very difficult to decide which existing fragility function is the "best" for a particular asset and location, within Chap. 3 possible methods for combining fragility functions, in cases where more than one set of suitable fragility curves exist, are explored.

### 14.2.1 Future Needs

Given the large number of approaches that have been applied in the past for developing fragility and vulnerability functions, especially within the branch of analytical methods, standard guidelines for the future development of these functions are needed. This important issue needs a coordinating effort at a global scale. To this respect the Global Earthquake Model provides one possible framework. It will release guidelines at the end of 2013 for empirical, analytical and expert-opinion development of physical vulnerability functions, which should be then reviewed and tested by the engineering community such that they may attain a general level of consensus. By having vulnerability functions that are developed using standard procedures accepted by the engineering community, the selection of functions by non-expert users will be easier, which should promote the use of seismic risk assessment in risk mitigation policy making.

Besides the permanent need to standardize procedures, to improve existing fragility functions and to validate them with empirical and experimental data, there are some specific challenges, which need further investigation. Among them are the following:

- Development of fragility curves for irregular RC buildings and buildings, which are not comprised in the taxonomy of SYNER-G, like for example prefabricated buildings of variable size and use.
- Traditionally, in seismic vulnerability assessment, it is implicitly assumed that structures are optimally maintained during their lifetime, thus neglecting any deterioration mechanism that may adversely affect their structural performance. On this basis, the impact of progressive deterioration of the material properties caused by aggressive environmental conditions, as for example the corrosion due to chloride penetration leading to the variation of the mechanical properties

of steel and concrete over time, is not accounted for. The safety and serviceability of RC structures may then be affected under the action of seismic loading, compromising the ability of the structures to withstand the loads they are designed for. Consequently, fragility functions are not constant in time and should account for aging effects introducing the time-variant vulnerability assessment. Among the recent efforts on this subject the reader is referred to the following: Ghosh and Padgett (2010), Choe et al. (2010), Fotopoulou et al. (2012), Karapetrou et al. (2013a, b, c) and Pitilakis et al. (2013).

- The effects of soil-foundation-structure interaction (SFSI) in the derivation of fragility functions for RC buildings are not explicitly taken into account so far in any of the currently available sets of fragility functions. In several cases these SFSI effects may modify considerably and sometimes in a detrimental way the analytical fragility functions (Pitilakis et al. 2013; Saez et al 2011).
- Development of damage-state-dependent fragility functions, which can be used to estimate the likelihood of a structure to suffer further damage in the event of an earthquake, while accounting for the increased vulnerability due to the fact that the building was previously damaged in a past earthquake. Cumulative damages from multiple seismic events on a building are actually a critical factor, which usually increase considerably the physical losses and the resulted casualty rate. In this context if the damaged building suffers further damage from aftershocks or/and new seismic events before repairs can take place, then its fragility is dependent on the accumulation of damage. A whole new set of fragility curves should be developed to account for this important issue (Luco et al. 2011; Iervolino et al. 2012; Réveillère et al. 2012).
- Development of fragility curves for reinforced concrete buildings in landslide prone areas triggered by earthquakes. An attempt to tackle this topic for few common building typologies is provided by Fotopoulou and Pitilakis (2012, 2013).

## 14.3 Fragility Functions for Masonry Buildings

In Chap. 5 a method for the vulnerability assessment of ordinary masonry buildings at territorial scale has been proposed in the framework of a probabilistic seismic risk assessment. The classification of the built environment is based on the SYNER-G taxonomy, which is dependent on the available data mainly from Europe. The general definition of fragility functions is recalled, through the use of static non-linear analysis for the evaluation of the capacity spectrum and the calculation of the response displacement using the demand spectrum. The selection of proper intensity measures for masonry buildings is treated, as well as the definition of damage and performance limit states. A detailed procedure for the propagation of uncertainties is proposed, which is able to single out the contribution of each independent component of uncertainty. Recommendations for deriving fragility functions with different approaches are given. In particular, it is shown how the macroseismic vulnerability method, derived from EMS98, can be used with expert elicitation or if empirical data are available. Moreover, the DBV-masonry

(Displacement Based Vulnerability) method is proposed as a powerful tool for the derivation of fragility function by an analytical approach. Finally, fragility functions are derived for ten different classes of masonry buildings, defined by a list of tags from the taxonomy, in order to show the capabilities of the proposed methods and their cross-validation.

### *14.3.1 Future Needs*

- Analytical models for masonry buildings are now reliable enough to be used for the development of fragility functions, provided that results are compared with empirical/experimental data and/or checked by experts.
- Analytical models can be very useful in the near future to distinguish the influence on vulnerability of single specific characteristics of buildings, moving from a macro-classification to a subdivision into sub-classes, through a proper taxonomy.
- The definition of a proper intensity measure for masonry buildings and the validation of the capacity spectrum method, currently frequently used for the development of fragility functions, would require an extensive use of incremental non-linear analysis (IDA).
- The mechanical models for masonry, the failure mechanisms and the dynamic properties, stiffness and strength of the masonry need further improvement and implementation in software tools to be used for the analytical derivation of fragility functions.
- There is a need to develop fragility curves for masonry buildings in landslide prone areas triggered by earthquakes, eventually combining this with hydrogeological hazards.

## 14.4 Fragility Functions for Electric Power Networks

A modern electric power network (EPN) is a complex interconnected system designed to generate, transform and transfer electric energy from generating units to various locations. Based on the review of the main recent works on fragility functions of EPN components, standard damage scales for micro- and macro-components were proposed together with the most appropriate fragility functions for the components that are of interest in SYNER-G. Several updates and improvements are needed especially in the European context, such as:

- Update of the taxonomy to include not only typologies for USA and Italy, but also those present to date in other European power networks.
- In case the fragility curves for these components are not available or not up to date, development of new fragility functions is needed.
- Since the SYNER-G methodology already accounts for the substation's internal logic, an update is needed of the typical layouts which are present to date in European power networks. The layouts are required not only for substations but

also for generation plants, for which today only the HAZUS curves (considering a power plant as a whole) are available.

## 14.5 Fragility Functions for Water Wastewater, Gas and Oil Systems

Water and wastewater systems are complex networks, prone to damage, which may result in extended direct and indirect losses and possibly in pollution of the environment. In this Book the most appropriate fragility functions for the main components and subcomponents have been collected, reviewed and, if possible, validated with empirical data. Fragility functions have been recommended mostly based on the validation of existing empirical curves from observed damage in different parts of the world; sometimes the recommended fragility functions have been compiled from numerical and fault tree analyses. The uncertainties are generally quite high, which is a determinant fact that should be taken into account in any risk assessment.

Fragility functions for gas and oil pipelines, storage tanks and support facilities are also collected and reviewed. It is recognized that existing fragility curves developed in the USA are mainly empirical, while those developed in Europe are based on numerical or fault-tree analysis. Appropriate functions were recommended in this Book based on their ability to cover all the important elements and typologies in Europe.

### *14.5.1 Future Needs*

- There is a serious lack of empirical data, especially in Europe, on damage to all kinds of pipes and pipelines for water, wastewater, gas and oil. As a result, empirical relations that have been derived from observational data in USA, Japan and recently in New Zealand are not always adequate for Europe. There is an urgent need in Europe, and elsewhere, to organize good documentation of the damage to utility and gas/oil systems following future earthquakes. A minimum requirement for this is the detailed survey and documentation in GIS of the existing networks, at least in the most vulnerable cities in seismic prone areas.
- It is often proposed to end-users to apply the same fragility functions for water and gas pipes; it is then necessary that the analogy between water and gas/oil network should be made more carefully, especially due to the differences in flow pressure and viscosity of the different fluids.
- More research should be engaged to assess the vulnerability of polyethylene (MDPE/HDPE) pipelines, which seem to behave well in earthquakes (O'Rourke et al. 2012).

- The use of generic fragility curves for gas/oil stations or reservoirs is probably irrelevant, mainly due to the large variability of the typologies and the construction materials. Large discrepancies are observed in the different typologies, based on the network type (high or low-pressure), or even from country to country. Further research on fragility curves for subcomponents (pumps, motors, electrical equipment, etc.) is advised, followed by fault-tree analyses to develop specific fragility functions whenever it is needed.

## 14.6 Fragility Functions for Bridges

The existing fragility curves for road and railway bridges were reviewed, stored in the Fragility Function Manager and used to identify the key parameters of a new taxonomy. It is noted that relatively few studies exist on the seismic fragility of European bridges, and for this reason, the fragility curves developed for bridges in other parts of the world are often adjusted for use in Europe. Except for few recent studies, shear failure of the piers is often disregarded in existing fragility studies. New fragility curves were produced in SYNER-G and have been described in this Book for road and railway bridges with continuous deck, monolithically connected to the piers or supported on elastomeric bearings, where the damage states are defined by the flexural and shear failure modes together with the deformation of the deck and the bearings.

### *14.6.1 Future Needs*

Among the most important needs for further improvement, refinement and development of the fragility analysis are the following:

- Validation of numerical fragility curves against earthquake damage data and experimental results.
- Development of fragility curves for irregular bridges and bridges beyond the SYNER-G typologies.
- Further study of the fragility of bridges designed with low-level seismic codes.
- Further development of parameterized fragility curves and eventually field noise measurements to easily obtain bridge-specific curves using only basic information.
- Consideration of particular structural characteristics and performance requirements for railway bridges.
- Better understanding of special issues, such as soil-structure interaction, asynchronous excitation, aging effects and cumulative damage and multiple hazards (i.e. earthquake, liquefaction, scour, corrosion), and incorporation in the standard procedures for fragility analysis.

## 14.7 Fragility Functions for Roadways and Railways

Experience from past earthquakes reveals that in roadway and railway systems, the most vulnerable components are usually the bridges. However, other components may also affect seriously the vulnerability of these important systems, vital in any modern society and economy. Their damage can be greatly disruptive for the whole urban or regional transportation network due to lack of redundancy, lengthy repair time or re-routing difficulties.

Road and railway elements, except bridges, such as tunnels, embankments, road pavements, slopes, trenches, railway tracks and bridge abutments, are basically "geotechnical" structures that need special attention in the fragility analysis. An extensive review is made in this Book on the available fragility functions for all these components. For several elements where the available fragility functions, mostly empirical or based on expert elicitation, were not considered reliable enough, new analytical curves have been proposed for a few common typologies; for example, for shallow tunnels in alluvial deposits, embankments, cuts/trenches and bridge abutments.

The existing fragility functions for railway elements are limited and are mainly based on data for road elements. New fragility curves were developed based on those for road elements and considering appropriate (lower) threshold values for the definition of the damage states.

### *14.7.1 Future Needs*

- Fragility functions are needed for several transportation network components (i.e. road and railway slopes, trenches, cuts, embankments, retaining/gravity walls, bridge abutments, tunnels) for earthquake-triggered landslides (eventually combined with hydrogeological hazards as well) and ground failures (i.e. liquefaction, lateral spreading, fault rupture).
- Further research is deemed necessary for tunnels of different geometries, and underground structures in the urban environment. It is also important that stakeholders/authorities are involved in the evaluation and verification of the fragility models, the definitions of damage states and serviceability thresholds for all components of the networks.
- More empirical data are needed as well as further validation of the present and future analytically derived fragility functions with experimental and empirical data.
- As for the above ground structures, aging effects for time dependent vulnerability assessment should also be considered, in particular for shallow tunnels in alluvial deposits with high water table and for bridge abutments.

## 14.8 Fragility Functions for Harbours

Damage to waterfront structures is usually attributed to ground failure and to a lesser degree to ground shaking alone, while damage to cargo handling and storage components is due to both ground shaking and permanent deformations. An extensive review of the existing fragility curves has been carried out for the most important elements of harbour systems based on the SYNER-G taxonomy. The available fragility functions are developed using all possible approaches i.e. use of empirical data from past earthquakes, expert judgement and analytical studies, while a fault-tree analysis is recommended for the complex components. Among them, the most appropriate for the European typologies were selected and recommended.

### *14.8.1 Future Needs*

- Development of fragility functions for different typologies of waterfront structures other than gravity walls for ground shaking and permanent ground displacements due to liquefaction.
- Development of fragility functions for different typologies of cargo handling facilities.

## 14.9 Fragility Functions for Hospitals

Hospital facilities are complex systems comprising several components (human, organizational, physical, environmental and medical services), each including a large variety of elements. Their behaviour has been studied, but capacity models and fragility curves are not available for all of them. A general methodology for the evaluation of the "probability of failure" of hospital systems has been proposed. It uses the fault-tree technique to establish the relationship between the state of the elements and the state of the system and a probabilistic approach to account for the large uncertainties characterising most of the quantities that contribute to the system response. Uncertainties are related, among others, to the external hazard, the evaluation of the structural response, the knowledge of system properties, the modelling of the capacities, and definition of damage levels. It is noted that each hospital needs to be modelled separately, as the layout is totally facility-dependent, and for this reason, a detailed analysis is necessary for each system.

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