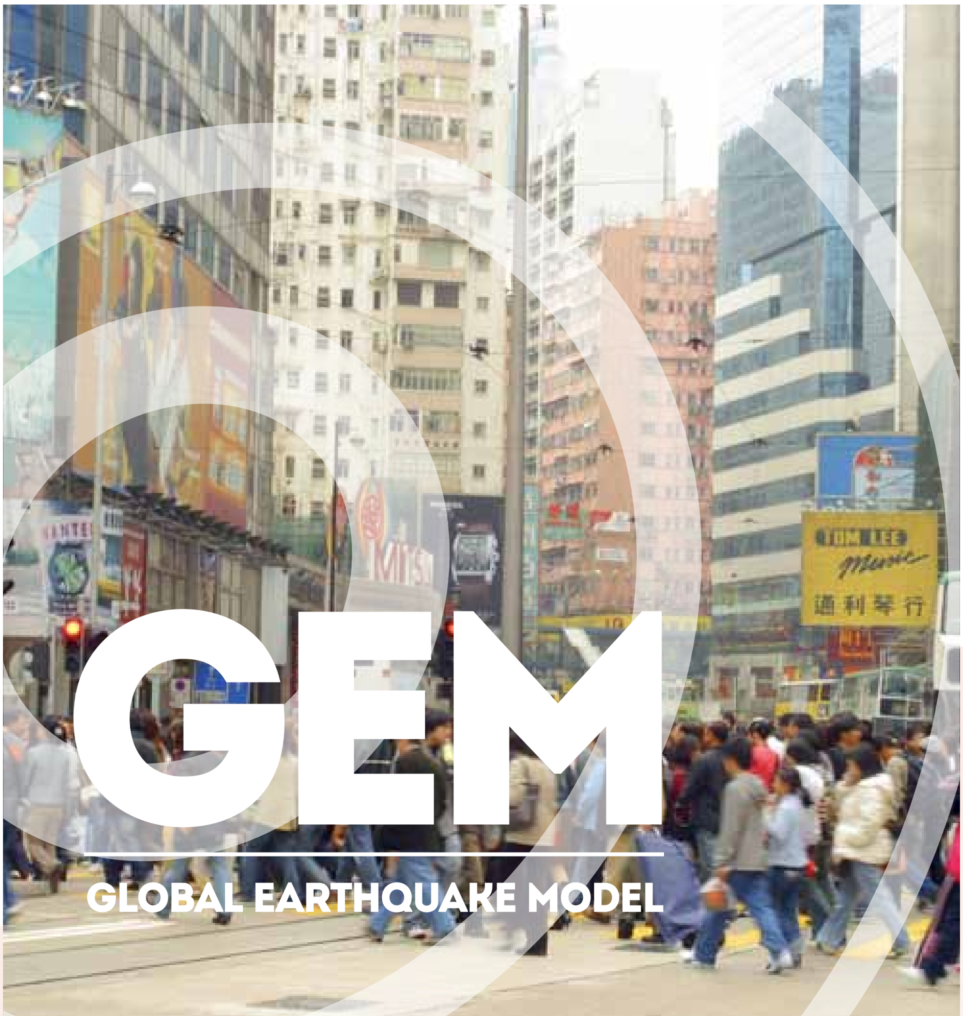
VULNERABILITY AND LOSS MODELLING

GEM TECHNICAL REPORT 2015-01 V1.0.0

Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection

T. Rossetto, I. Ioannou, D. N. Grant



Existing Empirical Vulnerability and Fragility Functions: Compendium and Guide for Selection

Vulnerability Global Component Project

Version: 1.0

Author(s): T. Rossetto, I. Ioannou, D.N. Grant

Date: July, 2015

Citation: Rossetto, T., Ioannou, I., Grant, D.N. (2015) Existing Empirical Fragility and Vulnerability Functions: Compendium and Guide for Selection, GEM Technical Report 2015-1, 10.13117/GEM.VULN-MOD.TR2015.01.

www.globalquakemodel.org

ABSTRACT

This document reviews existing empirical vulnerability and fragility functions worldwide collected until April 2014 in terms of their characteristics, data sources, and statistical modelling techniques. A qualitative rating system is described and applied to all reviewed functions to aid users to choose between existing functions for use in seismic risk assessments. The MS Access database developed by GEM VEM of all reviewed empirical functions and associated ratings is also described in this document. The database may be freely downloaded and includes all existing empirical vulnerability and fragility functions.

Keywords: empirical; fragility functions; vulnerability functions; rating system

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Introduction

In seismic risk assessment, vulnerability functions express the likelihood that assets at risk (e.g. buildings, people) will sustain varying degrees of loss over a range of earthquake ground motion intensities. In the GEM Vulnerability Estimation Methods (GEM VEM) working group, the seismic loss is expressed in terms of the cost of the direct damage, casualties, and downtime. In addition, ground shaking is considered the only source of seismic damage to the building inventory. Vulnerability functions are based on the statistical analysis of loss values recorded, simulated, or assumed over a range of ground motion severities. The loss statistics can be obtained from past earthquake observations, analytical or numerical studies, expert judgement, or a combination of these. This document focuses on the review and rating of existing empirical vulnerability functions developed from post-earthquake observations. Other GEM VEM reports review and rate existing vulnerability functions developed by analytical methods and engineering judgement (D'Ayala et al, 2015; Jaiswal et al, 2012). A recent study instead (Rossetto et al, 2014) attempts to harmonise the ranking system for the selection of the best fragility functions from available analytical and empirical functions.

Post-earthquake surveys of the performance of asset classes are commonly regarded to be the most realistic source of loss statistics, since all aspects of an earthquake source as well as the wide variety of path, site, foundation, exposure, structural and non-structural components are, at least in theory, represented in the sample. These observations collected after one or more seismic events are effectively considered capable to predict the vulnerability of specified assets for ground motion intensities occurring in future events. However, empirical vulnerability curves may not yield reliable predictions given the typically poor quality and (often) quantity of available observations and the often questionable procedures adopted to capture the uncertainty in the observations. Furthermore, empirical vulnerability curves constructed from data obtained from a single event may not appropriately account for the variability in structural response due to aleatory uncertainty in the characteristics of the ground shaking (e.g. number of cycles, duration or frequency content of the ground motion) at any given intensity. This perhaps makes them unable to reliably predict the vulnerability of this building class affected by a future event. By contrast, databases corresponding to multiple seismic events from diverse tectonic environments might be associated with observations from buildings having considerably diverse structural characteristics, resulting in functions with very large uncertainties and questionable applicability (Rossetto and Elnashai, 2003).

Empirical vulnerability functions can be constructed directly from past earthquake observations of losses collected over sites affected by different intensities of strong ground motion. If an intensity measure level (IML) has not been recorded at each site, one can be assigned using an appropriate ground-motion prediction equation. A model is typically fit to the data so as to minimise hindcasting errors. Commonly this is done through regression analysis, which aims to estimate the parameters of a chosen functional form. Such "direct" vulnerability curves are often developed for the estimation of casualties or economic losses at a national or regional level and may or may not distinguish between casualties associated with different building classes (Jaiswal and Wald 2010; 2013).

An alternative "indirect" procedure involves constructing empirical vulnerability functions through the coupling of the empirical fragility of given building class located in the affected area, with appropriate damage-to-loss functions, which convert the damage estimates to loss estimates. In this case, the empirical fragility functions express the likelihood of differing levels of damage sustained by a structure class estimated from post-earthquake building damage survey data. Similar to the direct functions, an IML is typically assigned in each site using an appropriate ground-motion prediction equation due to the scarcity of ground motion recordings. The damage-to-loss functions may be empirical in nature if based on field observations and specific surveys, or they can be based on expert judgement. A detailed review of these functions can be found in the GEM report by Rossetto et al (2015).

Both direct and indirect empirical vulnerability assessment procedures require the quantification and modelling of substantial uncertainty from a number of sources. Depending on the model, aleatory (inherent in the model) and epistemic (due to lack of knowledge or modelling capabilities) components of this uncertainty can be identified. This classification of uncertainty may assist the user to make informed decisions on how to improve the model. In empirical vulnerability functions, aleatory uncertainty is introduced by the natural variation in earthquakes and their resulting ground shaking, or the variation of the seismic response of the buildings of a given class. Epistemic uncertainty is introduced mainly by the low quantity and/or quality of the damage/loss databases and the inability to account for the complete characteristics of the ground shaking in the selection of measures of the ground motion intensity. Not every source of uncertainty is modelled in existing studies, which typically do not appropriately communicate the overall uncertainty in the vulnerability or fragility functions and are often incapable to distinguish the effect of the two components, i.e. aleatory and epistemic.

This document presents a review of existing empirical vulnerability functions for buildings constructed using "direct" and "indirect" approaches and published until April 2014. As part of the latter, it also reviews existing empirical fragility functions which have (or not) been used for vulnerability assessment. This is because more research has been done to date on fragility than vulnerability, and lessons learned from the former can be applied to the latter. The review highlights issues related to: the functional form of the relationships, quality issues regarding the loss/damage databases and the ground motion intensity as well as empirical vulnerability or fragility assessment and validation procedures. A qualitative rating system is also proposed and applied to the reviewed functions to aid users to assess the quality of existing empirical functions for use in future seismic risk studies. Finally, the content of the MS Access 2010 database (here called "Compendium") of empirical fragility and vulnerability functions is described. This compendium has been compiled specifically for GEM and is freely available to download from the GEM Nexus site and the EPICentre website (http://www.epicentreonline.com/).

2 Existing Empirical Vulnerability and Fragility Functions

A number of empirical vulnerability and fragility functions have been developed from post-earthquake data mostly by individual researchers or small research groups rather than a united research community. Consequently, there is a large variation in the empirical vulnerability or fragility assessment procedures presented in the literature. These result from differences in the selected functional form of the relationship, in the quality of the adopted loss or damage observation databases and the selected ground motion intensity, as well as the statistical modelling techniques and validation methods.

This chapter presents a review of existing methodologies for constructing empirical vulnerability and fragility functions. The review is organised in terms of the aspects of the fragility or vulnerability functions deemed important, which are listed in the first column of Table 2.1. As many of these aspects relate both to vulnerability and fragility functions these are treated together in the following sections. The main characteristics of the individual functions mentioned can be found in Table A.3 to Table A.**6** in Appendix A.

Table 2.1. Important aspects of reviewed vulnerability and fragility assessment methodologies.

Form of Relationship:		Discrete.
		Continuous function.
Damage or Loss Database Quality:	**Damage Characterisation:**	Damage scale.
		Consideration of non-structural damage.
	Loss Characterisation:	Measures of economic loss, casualty and downtime.
	Building Classification:	Single or multiple building classes.
	Data Quality:	Post-earthquake survey method.
		Coverage error in surveys.
		Response error in the surveys.
		Measurement error in surveys.
		Degree of refinement in building class definition.
		Number of damage states (DS).
	Data Quantity:	Country/Countries of data origin.
		Number of seismic events.
		Structural unit.
		Quantity of data in each isoseismic unit (e.g. number of buildings or loss observations).
		Range of IM and DS covered by data.
		Total number of data.
Quality of Ground Motion Intensity:		Intensity Measure (IM).
		Isoseismic unit (e.g. zip-code area, town etc.).
		IM estimation method (e.g. GMPE or recorded).
Statistical Modelling Techniques:		Data manipulation or combination.
		Relationship model.
		Optimisation method.
		Method of conversion of damage to loss in “indirect” vulnerability curves.
		Treatment and communication of uncertainty in the vulnerability or fragility curves.
Validation Procedures:		With independent data.
		With other existing functions/methods.

2.1 Form of Functions

Vulnerability and fragility functions correlate loss and damage, respectively, to ground motion intensity and their form is found to be either discrete or continuous. This section discusses the general forms of vulnerability and fragility functions found in the literature, with a detailed discussion of the functional shapes and parameters of the functions provided in Section 2.4.3.

In the case of empirical fragility assessment, the vast majority of existing functions are expressed either in terms of damage probability matrices (e.g. Whitman et al, 1973; Yang et al, 1989; Gulkan et al, 1992; Decanini et al, 2004; Eleftheriadou and Karampinis, 2008) or fragility curves (Rossetto and Elnashai, 2003; Colombi et al, 2008; Rota et al, 2008; Liel and Lynch, 2009). Damage probability matrices (DPM) are composed of sets of values defining the probability of a level of damage being reached in a given building class at specified intensity measure levels. By contrast, fragility curves express the probability of a level of damage being reached or exceeded given a range of intensity measure levels. The two outcomes are linked as follows:

$$P(DS = ds_i|IM) = \begin{cases} 1 - P(DS \geq ds_i|IM) & i = 0 \\ P(DS \geq ds_i|IM) - P(DS \geq ds_{i+1}|IM) & 0 < i \leq n-1 \\ P(DS \geq ds_i|IM) & i = n \end{cases} \quad (2.1)$$

where $P(DS \geq ds_i|IM)$ is the probability of a level of damage, ds_i , being reached or exceeded given seismic intensity measure *IM* (fragility curves); $P(DS = ds_i|IM)$ is the probability of the buildings being within ds_i for *IM* (DPM); and ds_n is the highest state of damage. The relationship between these two expressions of fragility is also illustrated in Figure 2.1b, where the fragility curves corresponding to three damage states ($ds_{1\text{-}3}$) are depicted. For a given intensity measure level *im*, the probability of being in one damage state is represented by the distance between one fragility curve and the one below it.

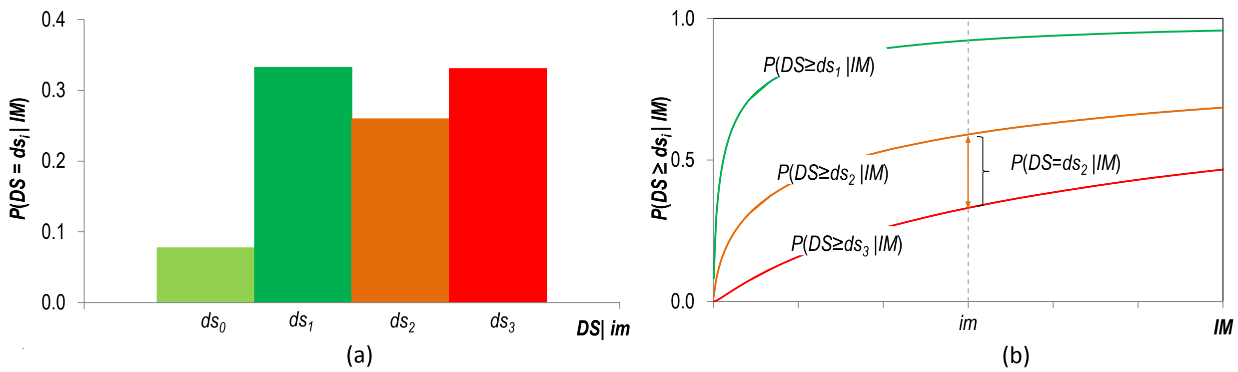


Figure 2.1. Illustration of a) a column of a DPM for intensity im, b) fragility curves corresponding to *n=3* damage states for the same building class.

A variant of the traditional definition of fragility relationship above can also be found in the literature (e.g Scawthorn et al, 1981; Petrovski and Milutovic, 1990) where instead of the exceedence probability, the probability of a building class sustaining a given level of damage as a continuous function of ground motion intensity is used. In the case of empirical fragility functions, this variation has a subtle disadvantage over the traditional definition, i.e. as each damage state curve is regressed for separately, the sum of the probabilities obtained from each damage state curve for a given level of ground intensity does not always equate to one.

DPMs and fragility curves have been used in some studies for the construction of vulnerability functions through an indirect approach. In its generic form, the indirect approach constructs the intensity-to-loss relationship by coupling damage probabilities for building classes at specified intensities to damage-to-loss functions (for more details on the latter functions see Rossetto et al, 2014) using the total probability theorem:

$$P\left(L>l\middle|IM\right)=\sum_{i=0}^{n}P\left(L>l\middle|ds_i\right)P\left(DS=ds_i\middle|IM\right) \quad (2.2)$$

where $P(L>l|IM)$ is the complementary cumulative distribution of the loss given intensity IM; $P(L>l|ds_i)$ is the complementary cumulative distribution of loss given a damage state ds_i; $P(DS=ds_i|IM)$ is the damage probability matrix. In practice, most indirect empirical vulnerability assessment methods (Benedetti et al, 1988; Yang et al, 1989; Spence et al, 2003; Eleftheriadou and Karabinis, 2011) ignore the uncertainty in the damage-to-loss functions and focus on the estimation of the average loss at discrete IMLs, i.e.:

$$E\left(L\middle|IM\right)=\sum_{i=0}^{n}E\left(L\middle|ds_i\right)P\left(DS=ds_i\middle|IM\right) \quad (2.3)$$

where $E\left(L\middle|ds_i\right)$ is the mean loss L suffered by a class of structures for a given damage state; $E\left(L\middle|IM\right)$ is the mean loss for intensity IM.

To date, few direct vulnerability functions have been constructed due to the scarce availability of good quality empirical loss data. The majority of these existing functions correlate a measure of the cost of the direct damage to an intensity measure type. A small minority correlate a measure of casualty with intensity and only Comerio (2006) are found to correlate downtime with ground motion intensity. With regard to the form of these functions, discrete functions of loss are proposed by Scholl (1974) and Cochrane and Schaad (1992) in terms of average economic loss and by Comerio (2006) in terms of downtime. These are represented in similar matrix formats to DPMs with mean losses presented for each intensity level. Continuous functions have also been proposed to correlate the economic loss of the direct damage (Scawthorn et al. 1981; Petrovski et al. 1984) or fatality ratio (i.e. the deaths divided by the total exposed population of an area) (Jaiswal and Wald 2010) with a range of IM parameters. These take a range of forms, further discussed in Section 2.4.3.

An alternative representation of vulnerability or fragility is applied by Yang et al (1989), Sabetta et al (1998) and Wesson et al (2004). These studies fit probability distributions to the loss or damage data for each isoseismic unit, i.e. an area associated with a specific level of ground motion intensity whose spatial distribution across the municipality is considered negligible. Then, they use a continuous relationship to correlate the parameters of the latter distribution to a range of intensities. This approach, however, may lead to wider confidence intervals around the parameters since it does not accounts for the overall number of data, but rather concentrates on the number of isoseismic units available.

2.2 Quality of Loss or Damage Database

The level of quality of the loss or damage databases strongly affects the accuracy of the vulnerability or fragility functions. Ideally, empirical functions should be based on a high quality database, i.e. one that includes detailed damage and loss data from all the structural units (e.g. buildings), or at least a statistically significant representative sample, located in the area affected by a strong event. However, this is rarely the case. Instead, epistemic uncertainty is introduced in the vulnerability or fragility assessment by the lower quality of databases, typically adopted in the reviewed studies, which are associated with errors or low degree of refinement in the definitions of damage scales, loss measures, building classes or the location of the structural units as outlined in Table 2.2.

The errors affecting existing databases used for the construction of vulnerability or fragility curves can be classified as sampling or non-sampling errors (UN, 1964):

- *Sampling errors* occur because a subset of the population of buildings, located in the affected area, has been selected (surveyed) instead of the total affected population. The subset is selected to be representative of the target population of buildings, with the required number of buildings for a given level of error typically being calculated from standardised procedures based on the adopted sampling technique (see Levy and Lemeshow, 2008).
- *Non-sampling errors* represent the remaining sources of error occurring in the survey design, as well as errors in the collection and processing of the data. Three main sources of non-sampling error have been identified in the empirical vulnerability or fragility literature (United Nations, 1982):
    - Coverage errors are unobservable errors that occur in cases where the database of damage or loss observations does not accurately reflect the target population of the considered asset, e.g. total number of structural units in the affected area.
    - Response errors occur when incomplete or no data for some structural units are collected during the survey due to rapid assessment, an inexperienced team, poor supervision or problems with questionnaire (e.g. lengthy and/or unclear).
    - Measurement errors describe the deviance of the observed value of a variable from its 'true', but unobserved value.

In what follows, a critical review of the definitions of damage scales, loss measures and building classes is presented, together with a discussion of the common sources of error found in seismic loss/damage databases due to the survey design and data collection (non-sampling errors). Section 2.2.6 specifically reviews how common non-sampling errors are dealt with in the literature. As sampling errors are typically reduced by aggregating data from different classes or combining loss or damage databases, they are instead further discussed in Section 2.4.2 where data combination is reviewed.

Table 2.2. Database typologies and their main characteristics.

Type	Survey Method	Typical	Typical Building	Typical No.	Reliability	Typical issues

		Sample Sizes	Classes	of Damage States	of observations	
Damage	Rapid Surveys	Large	All buildings	2-3	Low	Safety not damage evaluations.
	Detailed “Engineering” Surveys	Large to Small	Detailed Classes	5-6	High	Possibility of unrepresentative samples.
	Surveys by Reconnaissance Teams	Very Small	Detailed classes	5-6	High	Possibility of unrepresentative samples.
	Remotely sensed	Very Large	All buildings	3-5	Low	Only collapse or very heavy damage states may be reliable. Misclassification errors.
Economic Loss	Tax assessor data	Very large	All buildings/ Detailed classes	-	High	Often focus on damaged buildings only.
	Claims data	Very large	All buildings	-	High	Often focus on damaged and/or insured buildings only.
Casualties	Government Surveys	Very large	All buildings	1-2	Low	Unlikely association with building damage and causes of injuries.
	Surveys by NGOs/ hospitals	Varies	All buildings	1-5	Low	
	Detailed Casualty Surveys	Very Small	Detailed classes	3-5	High	Possibility of unrepresentative samples.

2.2.1 Damage

The quality of a damage database compiled from post-earthquake observation depends on the adopted measure of damage and the errors in the design and execution of the survey. In existing fragility functions, damage is characterised via descriptive damage states associated with a discrete damage scale. The choice of a damage scale for the assessment of buildings is therefore fundamental to the definition of fragility functions and resulting indirect vulnerability functions. As discussed in Hill and Rossetto (2008), for post-earthquake damage observations to be useful in the development of empirical fragility functions they must clearly and unambiguously define the damage states in terms of visually observable structural and non-structural damage characteristics for different structural classes, ideally using both text and figures. The inclusion of non-structural damage in the damage scale is particularly important for loss evaluation. The survey should also be carried out by engineers trained in the identification of building damage using the damage scale. All these measures reduce potential misclassification errors.

In reviewing the empirical fragility and vulnerability literature, a wide variety of damage scales is seen to have been used. These scales vary in the number of damage states and the level of detail in the description of damage for each state according to the purpose of the survey. With very few exceptions (e.g. Liel and Lynch, 2009) building damage statistics are not collected from the field for the purpose of constructing fragility or vulnerability functions. Rather, they have become available from surveys carried out to assess structural safety or evaluate cost of repair for insurance, tax reductions, or government aid distribution purposes or for reconnaissance purposes. Hence, care must be taken when adopting these for fragility analysis.

Post-earthquake surveys commissioned by state authorities as part of their disaster response are the most commonly used source of data for vulnerability or fragility relationship construction, e.g. Greek authorities (Eleftheriadou and Karabinis, 2008; Karababa and Pomonis, 2010), Italian authorities (e.g. Braga et al, 1982; Benedetti et al, 1988; Yang et al, 1989; Goretti and Di Pasquale, 2004; Decanini et al, 2004), Japanese authorities (e.g. Yamazaki and Murao, 2000). These databases tend to be the most extensive in terms of the size of the affected area surveyed and number of buildings. The survey area is seen in the literature to vary in geographical scale according to the earthquake size and attenuation/amplification characteristics of the affected area. According to the availability of the survey data, the reviewed studies select a target area for the empirical vulnerability or fragility curve generation, which can range in geographical extent from the entire earthquake affected area (e.g. Braga et al, 1982; Petrovski et al, 1984; Goretti and Di Pasquale, 2004; Karababa and Pomonis, 2010), a city within the affected area (e.g. Scholl, 1974; Benedetti, 1988; Sengezer and Ansal, 2007; Eleftheriadou and Karabinis, 2008), or smaller political units such as a ward (e.g. Yamazaki and Muraio, 2000). The smaller the chosen target area the smaller the sample sizes (number of buildings) for the building classes that can be used for vulnerability or fragility assessment. This target area is typically subdivided into smaller, units, which are considered isoseismic. As stated in Section 2.3.1, the chosen isoseismic units are seen to vary substantially in geographical size and population of buildings, even within the same study. In some surveys, all units within the target area have been surveyed (e.g. Benedetti et al, 1988; Goretti and Di Pasquale, 2004; Eleftheriadou and Karabinis, 2008; Karababa and Pomonis, 2010). In others, only a fraction of these units has been surveyed (Braga et al, 1982; Petrovski et al, 1984; Sengezer and Ansal, 2007). Nonetheless, with the exception of Scholl (1974), who selected two sites with similar number of buildings but different soil conditions, the reviewed studies did not provide the unit selection criteria. This raises questions on whether the effects of the examined earthquake are appropriately represented in the survey. For example, what is the proportion of less affected versus severely affected units? Are all the sites close to the epicentre and few located far away? Are buildings randomly selected? This level of detail regarding the survey design is missing from most empirical studies.

It is not uncommon that successive surveys with increasingly detailed structural evaluations, and potentially different damage scales, are carried out in earthquake-affected areas, as shown in **Figure 2.2**. Initially, a rapid survey is conducted in order to assess the safety of the building inventory affected by the earthquake. These surveys commonly adopt damage scales consisting of three limit states (such as in the Greek level 1 approach, OASP 1997 (Dandoulaki et al, 1998) or ATC-20 1989 in the USA) but some may only consist of two broad damage states (i.e. damaged and undamaged, or safe and unsafe), grouping together a wide range of seismic damage levels, e.g. buildings that suffered collapse or severe damage are grouped together. For those buildings identified as being damaged, this first stage of evaluation is commonly followed a second more detailed assessment: the “detailed damage evaluation” or “engineering evaluation” (see Figure 2.2). The damage scales used for the latter evaluations commonly comprise between three and eight discrete and mutually exclusive states. Damage evaluation forms are used to record damage to the structural and non-structural components (see for example the Italian AeDES forms, Baggio et al, 2000). The procedures and forms adopted for damage data collection vary for different countries and have changed over time, (see Goretti and Di Pasquale, 2002 for a summary of the evolution of damage data collection procedures and tools in Italy).

The aforementioned surveys commonly suffer from a number of significant non-sampling errors. For example, rapid damage evaluations commonly adopt damage scales with two or three damage states. No distinction is often made between different structural classes. In addition, these surveys are carried out through an external inspection of the structure only, potentially introducing a significant misclassification error in the assignment of the damage. For all these reasons, the resulting vulnerability or fragility functions are of limited usefulness and reliability. Whilst rapid surveys can cover the entire affected region, detailed damage evaluations are typically carried out over a subset of the affected regions (usually the worst affected regions) and cover a sample of total number of buildings (e.g. buildings that are heavily damaged, or buildings for which a specific request for detailed damage evaluation has been made by the owner). For example in the 2002 Molise earthquake in Italy, Goretti and Di Pasquale (2004) report that for areas away from the epicentre, where damage was less, engineering surveys were only carried out on the building owner's request. This may result in significant coverage error in the database due to the practical exclusion of the majority of the undamaged buildings from the sample. This error, if untreated, could lead to a bias in the damage statistics (see Section 2.2.6).

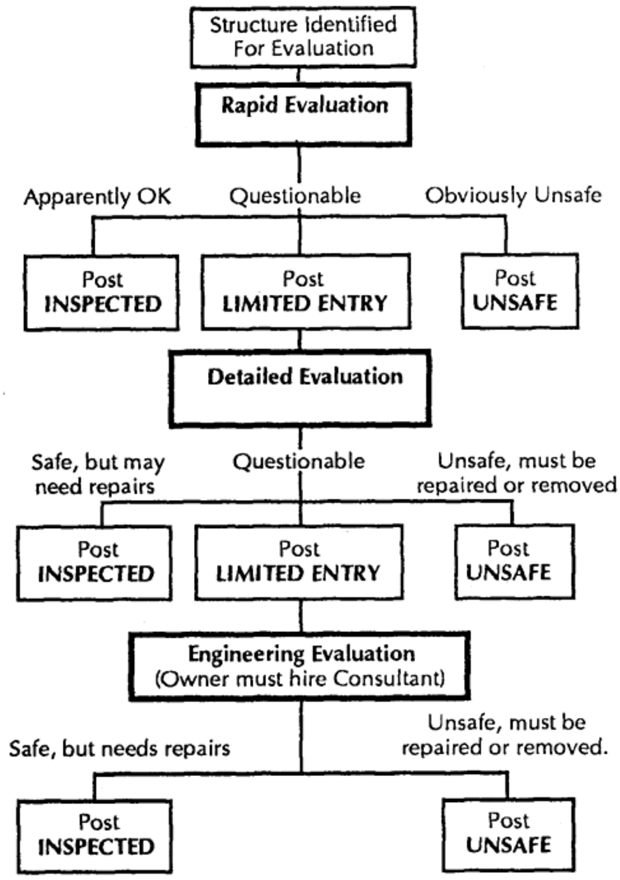


Figure 2.2. ATC-20 (1989) flowchart for normal building safety evaluation and posting.

Partial non-response errors can also be introduced when information regarding the building typology, level of damage, building's location or repair cost is omitted from the survey forms. This is seen to be a significant problem in Eleftheriadou and Karabinis (2008), who, due to incomplete reporting, only used data from 73,468, out of 180,945 surveyed reinforced concrete buildings in the 117 municipalities of Athens affected by the 1999 earthquake to build their DPMs. It is unclear what influence this has on the final result bias, especially as it is unclear whether the spatial distribution of these buildings is taken into account. The proportion of unreliable data due to incomplete survey forms or claims were also found to be substantial (ranging from 27% to 66%) in other damage databases (i.e. Colombi et al, 2008) but insignificant in others (i.e. Rota et al, 2008 and Wesson et al, 2004).

Measurement errors are also commonly found in survey forms/claims. These errors occur when inexperienced engineers carry out the surveys, when the survey form is not sufficiently detailed or appropriate training has not been provided to reduce the surveyors' bias. Measurement errors in a database also occur from inclusion of the combined losses or damage caused by successive large aftershocks or other main events (e.g. Goretti and Di Pasquale, 2004; Karababa and Pomonis, 2010) and/or secondary hazards (e.g liquefaction in Scawthorn et al, 1981) with those caused by ground shaking in the main event. Such errors limit the application of functions based on these databases to other locations. The importance of these errors is not clear given that existing studies did not (and in some cases could not) independently check their damage data.

An alternative source of building damage statistics are databases compiled by institutions or specialist reconnaissance teams, such as those of the UK Earthquake Engineering Field Investigation Team (EEFIT) and the US Earthquake Engineering Research Institute (EERI). Such databases are smaller in geographical scale than those carried out by government authorities. They mostly consist of damage surveys carried out through external building inspection and over small areas (at road or block level). Such surveys commonly use damage scales linked to macroseismic intensity scales (such as those in EMS-98, (Grunthal,1998)), as part of the remit of the teams may be to evaluate the macroseismic intensity distribution caused by the event. Most such databases are associated with low measurement errors as they are carried out by experts but high sampling errors due to the small sample sizes (of the order of 10-50) of surveyed buildings. Data collected by reconnaissance teams have been used in combination with other larger databases for the construction of fragility functions (e.g. Coburn and Spence, 2002; Rossetto and Elnashai, 2003; Liel and Lynch, 2009). For example, Liel and Lynch (2009) examined the vulnerability of Italian RC buildings by inspecting a sample of 483 out of the total population of 14,088 RC buildings located in the municipality of L'Aquila in the aftermath of the 2009 event. Despite the high reliability of the observations (i.e. low damage misclassification error), the samples can often biased with under-coverage error due to the traditional focus of the reconnaissance teams on the severely damaged buildings/areas. However, recently reconnaissance teams have been targeting locations close to ground motion recording stations (e.g. Sarabandi et al, 2004 and Rossetto et al, 2010). These data could, in theory at least, improve the reliability of the fragility functions by minimising the uncertainty in the value of ground motion intensity. Such a sampling technique was used by King et al (2005) who adopted a database of 500 inspected buildings affected by the 1994 Northridge earthquake, which were located within 1000 feet from 30 ground motion stations.

Following recent events, large databases of building damage data have been obtained using remote sensing. These damage assessments have been made by visual interpretation or change analysis of satellite images taken after, or before and after, an earthquake event, respectively. Such sources are becoming more viable as the number of satellites and availability and resolution of satellite images increases, and the cost of these images decreases. The satellite images can be used alone or adopted together with aerial reconnaissance images. Of note is the recent establishment of the Virtual Disaster Viewer (Bevington et al. 2010), supported by several international institutions which provides images and a forum for experts to interpret damage from satellite images. The subsequent GEO-CAN initiative (Ghosh et al. 2006) also brought together experts from all over the world to interpret damage in the 2010 Haiti and 2011 Christchurch, New Zealand earthquakes. Three major issues have been identified with the use of remotely sensed damage data (Booth et al. 2011, Saito and Spence 2004 and Clasen et al (2010) :

- Difficulty in recognising soft-storey type collapses from vertical satellite images of rooftops,
- Inability to reliably identify damage states lighter than collapse,
- Difficulties with automating the change analysis procedure for damage detection.

Some of these difficulties may be overcome with time as more "angled" satellite or aerial images become available and as technologies develop. To date, remotely sensed damage data has only recently been used for the construction of empirical fragility functions for earthquakes (Hancilar et al. 2011) and tsunami (e.g. Koshimura et al 2009).

In order to reduce epistemic uncertainty, empirical fragility assessment studies should adopt the same damage scale as used by the damage surveys. However, in the literature it is seen that damage statistics are sometimes interpreted in terms of a different damage scale (e.g. the 8 damage states of the Irpinia 1980 damage statistics converted to the 6 damage states of the MSK scale in Braga et al, 1982). This may be in order to use a damage scale more closely related to the IM used, if the latter is expressed in terms of a macroseismic intensity. The mapping of damage states between different damage scales is instead necessary when damage data from surveys for the same earthquake (e.g. Karababa and Pomonis, 2010, Yamaguchi and Yamazaki, 2001), or different earthquake events from the same country (e.g. Colombi et al, 2008; Rota et al, 2008, Sabetta et al, 1998) or different countries (e.g. Spence et al 1992, Rossetto and Elnashai, 2003) are to be combined. This is discussed further in Section 2.4.2.

2.2.2 Economic Loss from Direct Damage

Vulnerability functions that correlate the economic loss with levels of ground motion intensity have been obtained with direct as well as indirect vulnerability assessment procedures. Existing studies have been limited to the estimation of economic loss from direct damage to structural and non-structural elements of buildings, and have ignored the indirect loss of revenue or the rent paid by the owners during the repairs of their dwelling or business.

Jara et al (1992) measured vulnerability in terms of monetary cost of repairing the damaged RC buildings in dollars. However, the adoption of such a measure of economic loss is strongly location- and time- specific. A more useful measure of economic loss is the damage factor (DF) estimated in terms of repair to replacement cost ratio for the examined building class. Damage factors are assumed to vary much less over time for any location and structure type, and not to vary greatly for similar structures in different locations, thus allowing comparisons between existing functions to be made. However, the validity of these assumptions is questionable and is not explored in the literature. Moreover, there is not a wide consensus on the definition of 'repair' or 'replacement' cost. For example, repair cost is usually assumed to be the cost of repairing the structural elements of the building to their original state without any strengthening, and may or may not include the cost of replacing non-structural elements. Similarly, replacement cost is typically estimated as the average cost of constructing a building of a given class without specifying whether the cost of site clearance or the provision of a new structure with design compliant with current seismic code is taken into account. By contrast, Dowrick and Rhoades (1990) use the property value instead of the replacement cost, and Wesson et al (2004) consider the replacement cost to be equal to the fire-insured value of the examined buildings.

Detailed post-earthquake economic loss databases have been compiled from claims submitted by building owners to the authorities (Dowrick and Rhoades, 1990) and/or the private insurance industry (Dowrick and Rhoades, 1990; Cochrane and Shah, 1992; Wesson et al, 2004). An acknowledged bias in the latter databases is the under-coverage error occurring due to the lack of data regarding losses below the deductible, i.e. a threshold of economic loss below which the policyholder, rather than the insurance company, is expected to pay for the repair cost. Another source of under-coverage error can be introduced by the potentially large proportion of uninsured buildings present in the building inventory, which may lead to the sample (insured buildings) misrepresenting the distribution of damage in the exposed inventory. Some studies have ignored this issue (Cochrane and Shah; 1992; Wesson et al, 2004). Others (Dowrick, 1991; Dowrick and Rhoades, 1990) have instead shown that for their data, the number of uninsured data although notable (15%) did not lead to substantial errors. Questionnaires have also been used in the past to collect loss data after earthquake events. Whitman et al (1973) identified an area affected by the 1973 San Fernando earthquake where approximately 1,600 mid- and high-rise buildings were located. They collected loss data from a sample of 370 buildings by sending questionnaires to the building owners. In general, the latter databases can be considered unbiased and of high quality, with their level of epistemic uncertainty depending on the sample size.

Post-earthquake cost data, (like building damage state data), can also be obtained from detailed or engineering surveys (see Section 2.2.1), where engineers are asked to provide estimates of repair or replacement costs from the observed degree of building damage. However, such data is rare, may be inconsistent, and is dependent on the experience and training given to the engineers carrying out the assessment. Such cost data can be used directly for generating vulnerability functions but, in recognition of its high variability, should only really be used to define average Damage Factors (or DF distributions) for specified building classes, which can then be adopted in indirect vulnerability curve generation. More information on DFs can be found in Rossetto et al (2015).

2.2.3 Downtime

Downtime is defined as the time (i.e. in years or months) necessary to plan, finance and complete the repairs of damaged buildings (Comerio, 2006). Interestingly, the time for the replacement of severely damaged or collapsed buildings is not included in this definition. Although downtime is a measure of loss necessary for the estimation of business disruption and the overall impact of an earthquake on society, it is largely ignored in the empirical vulnerability literature. This may be due to the lack of systematically collected observations on downtime caused by the significant span of time required to complete repairs (which can extend to several years). It may also be due to the extremely large expected variation in downtime estimates for buildings with different usage in different locations. Such variations are often influenced by socio-economic and governance factors (e.g. availability of funds for repair/rebuilding) as well as the size of the earthquake affected area. Furthermore, building-owners and/or state-authorities often play an important role in prioritising and determining works, which influence the time of repair.

2.2.4 Casualties

In direct vulnerability functions, casualties are usually characterised by fatality counts (the number of people who have died in an event) or by fatality rates (the number of deaths as a proportion of the exposed population considered). Fatality rate is a more useful parameter than fatality counts for use in comparing vulnerabilities in different locations. Indirect methods for casualty estimation usually involve combining building damage or collapse estimates from fragility analyses with lethality rates defined for the considered building class. Lethality ratio is defined by Coburn and Spence (2002) as the ratio of number of people killed to the number of occupants present in the collapsed buildings of a particular class. The lethality ratio can be affected by a number of factors including: building type and function, failure mechanism, occupant behaviour, time of the event, ground motion characteristics, and search and rescue effectiveness (Coburn and Spence, 2002).

The empirical evaluation of fatality counts, fatality and lethality rates depend on the availability of reliable casualty data from past earthquake events. However, earthquake casualty data are reported to be scarce and associated with significant quality issues (Lagorio, 1990; Petal, 2011). A number of sources of casualty data have been used for the development of vulnerability functions. These include official statistics published by government agencies, hospital admissions data, coroner and medical records, and specific surveys carried out by casualty researchers (e.g. De Bruycker et al 1985; Petal 2009). Methods used for the data collection vary and are commonly only specified in the case of researcher-led surveys. Hence, fatality counts, fatality ratios, and lethality are plagued by inconsistencies in definitions and data collection methods.

Also, Li et al (2011) show that the reported fatality count changes as a function of time following the earthquake event, however, there is no apparent guidance or consensus in the literature as to how long after the event deaths should stop being attributed to the earthquake. Furthermore, in highly fatal earthquakes, the number of deaths is seen to be highly unreliable and to vary widely, with official figures sometimes being incorrect, e.g. aggregating different causes of death, (e.g. cardiac arrest, deaths from secondary hazards or from epidemics following earthquakes), to deaths directly from structural and non-structural earthquake damage. Petal (2011) also states that in some cases official death counts can be deliberately exaggerated or understated for political reasons. In some casualty studies, official statistics are replaced or supplemented with data from hospital admissions (e.g. Pomonis et al, 1992) or specific field studies conducted after earthquakes in order to determine the number of deaths and their causes, (associating them, for example, demographic characteristics or with mechanisms of structural damage). Such studies provide data of higher quality, but the geographical scale of areas covered is a small subset of the entire affected area, resulting in an insufficient range of ground motion intensities for the determination of direct vulnerability functions. Hence, the casualty data are used mainly to calibrate damage-to-casualty functions used in indirect vulnerability estimation. Different approaches are followed to collect casualty data in field surveys. For example, De Bruyker et al. (1985), collect casualty data from a random sample of one-third of villagers in a selected area affected by the 1980 Southern Italy earthquake, and Petal (2009) carry out geo-stratified random sampling of families affected by the 1999 Kocaeli (Turkey) earthquake. Although small in sample size, such data can be considered unbiased and complete for the target area if significant migration of people out of the affected area has not taken place. However, in many other instances, (e.g. So, 2011), convenience sampling is carried out, whereby only easily accessible groups or locations are sampled. This may result in biases if the sample is not representative of the demographics of the affected population, or if the full range building types and failure mechanisms within a selected building class are not represented. Such biases result in estimates of fatality rates and lethality rates, respectively, that cannot be projected to the affected population.

2.2.5 Building Classification

Buildings have unique structural and non-structural characteristics that are (partially) responsible to the wide differences in their performance under similar seismic excitation. Nonetheless, in empirical vulnerability studies building classes with similar earthquake response characteristics need to be defined in order to obtain the basic damage statistics required to construct the vulnerability functions. In theory, the more detailed the building class the more homogenous the group of buildings and the smaller the variation in seismic response. However, in practice a narrowly defined building class often results in small sample sizes. A careful balance is therefore struck between level of detail in the building class definition and sample size.

The structural (and non-structural) characteristics mostly affecting seismic response depend on which loss parameter is being assessed. For example, the structure's deformation affects the state of damage and consequently cost, downtime, and human casualties. The structural characteristics influencing this deformation are well documented (e.g. FEMA 547, 2007 and include (but are not limited to):

- Lateral load resisting system (e.g. MRF, Shear wall etc)
- Construction materials
- Layout in plan and elevation
- Presence of irregularities
- Seismic design code used (i.e. capacity design, level of structural detailing)
- Height of structure
- Weight of structure
- Redundancy of structure
- Type and amount of strengthening intervention

A building classification system that accounts for all these influencing factors allows a high-degree of differentiation in fragility studies. However, in the case of cost, downtime and casualty evaluation, the presence of non-structural elements and occupancy/use of the structure also have a strong influence on the accuracy of the vulnerability evaluation, and hence should also be considered as part of the building classification system. Furthermore, in the case of human casualty the lethality of the building materials, floor and roof system should be considered in addition to their contribution to the structure dynamic response. However, the latter is not commonly done, a primary relationship often being assumed between material or roof type and the vertical elements of the structure (Shiono et al, 1991).

In the case of empirical vulnerability functions, the building class definition used can be dictated by the level of detail present in the loss or damage data. In particular, rapid post-earthquake survey data often do not distinguish between damage/losses observed in structures of different types, and vulnerability or fragility functions developed from these data are highly specific to a particular built environment (e.g. Tavakoli and Tavakoli, 1993). Different degrees of refinement are seen in the building classification systems adopted by existing studies according to their data. For example, Gulkan et al (1992) classify buildings by construction material only, Colombi et al (2008) by construction material and height, Karababa and Pomonis (2010) by construction material, lateral load resisting system and age (representative of seismic code level), and Spence et al (2003) classify reinforced concrete buildings in terms of their design code, height and quality of construction. Dolce et al (2006) is the only study seen to account explicitly for the presence of seismic strengthening measures, and none of the reviewed empirical functions takes explicit account of structures with irregularities that may precipitate their damage/failure under earthquake loading.

Despite the existence of various building classification systems (e.g. adopted by HAZUS99 (FEMA, 1999) or PAGER (Porter et al, 2008), these are not commonly adhered to by existing studies; rather, bespoke building classes are defined. For example, there is no agreement as to how many storeys are included in different height categories. Low-rise structures are fairly uniformly defined as being between 1-3 storeys, but definitions of mid-rise and high-rise categories differ significantly. For example, Scawthorn et al (1981) define mid-rise as containing buildings with between 3 and 12 storeys, whereas Rossetto and Elnashai (2003) adopt 5-8 storeys. Seismic code classes depend on the location being assessed, and on the year of the study. Care must be taken when adopting studies carried out long ago, as the rapid evolution of seismic codes in recent years may mean that the classes of structure they regard as “modern” may be considered “low-code” by current standards.

Instead of using strictly typological building classes, some existing studies have adopted the approach of assigning structures to vulnerability classes. These vulnerability classes are either described through bespoke vulnerability indices that are evaluated from the characteristics of the structure (e.g. in Benedetti et al. 1988) or are taken from earthquake macroseismic intensity scales. An example of the latter is Goretti and Di Pasquale (2004), who assign the MSK vulnerability classes to the masonry buildings in their datasets through consideration of their layout, the flexibility of their floors as well as the presence of tie beams.

2.2.6 Non-Sampling Errors

Several sources of non-sampling errors have been mentioned in Sections 2.2.1-2.2.5. Here, specific examples of non-sampling errors found in the literature are discussed together with the procedures that have been followed to reduce or deal with them.

Large under-coverage errors in existing damage databases have been acknowledged in the literature as major sources of bias. In the case of government led surveys, this bias commonly occurs from procedures that require the building owner to request their building to be inspected (Goretti and Di Pasquale, 2004; Eleftheriadou and Karabinis, 2008; Karababa and Pomonis, 2010) resulting in a database mainly comprising damaged buildings. Such a bias is likely to be larger for areas least affected by the ground shaking (typically more distant from the earthquake fault). This bias, which occurs due to the incomplete surveying of buildings, is addressed in two different ways by existing studies. In the first approach, a minimum proportion of surveyed buildings within a geographical unit (of assumed uniform ground motion intensity) is defined as the “threshold of completeness”. If a smaller proportion of the building stock in the geographical unit is surveyed, then the unit is discarded. The value of the ”threshold of completeness” is, however, seen to vary arbitrarily. For example, Gorreti and Di Pasquale (2004) selected a level of completeness ≥ 80%. This threshold was reduced to 75% for Sabetta et al (1998) and 60% for Rota et al (2008) who used larger proportion of their database but with lower reliability. Whatever the threshold, this approach results in a (potentially significant) reduction in the number of suitable data, especially for less populated building typologies. By contrast, in the second approach non-surveyed buildings are assumed undamaged and the surveys are “completed” using census data (e.g. Karababa and Pomonis, 2010; Colombi et al, 2008). In some studies (Karababa and Pomonis, 2010; Eleftheriadou and Karabinis, 2011), the census dates to a time close to that of the earthquake event. However, other studies (Yang et al, 1989; Colombi et al, 2008) are seen to use census data compiled up to 11 years before or after the examined event. This introduces a bias due to the likely substantial differences in the built environment, e.g. old buildings could be demolished, and new buildings, especially the ones built after the census year, are misrepresented. The lack of a contemporary census led Tavakoli and Tavakoli (1993) to estimate the number of buildings located in the affected area by projecting the population recorded in the 1976 census to 1986. Undoubtedly, this is associated with large uncertainties and raises questions about the validity of their curves. The completion process can also be complicated if the census is reported in structural units that are not consistent with that of the survey, with further uncertainties introduced by the harmonization of the structural units in the two databases (e.g. the census used by Colombi et al. (2008) uses dwellings rather than buildings).

Response errors may also occur in a single earthquake damage/loss database due to a large number of incomplete survey forms. To date, existing empirical vulnerability and fragility studies consider that this error is random, and as such can be addressed by simply ignoring the incomplete forms and constructing vulnerability or fragility functions using only the complete forms. This assumption, however, is not appropriately validated, and considering the survey process, it is likely not to be random. It is possible that the same set of surveyors consistently does not complete forms and that there may be a geographical bias, if these surveyors are assigned to particular sites. If the error is not random, ignoring incomplete forms would introduce bias in the results especially in cases where the proportion of the eliminated data is significant; e.g. Colombi et al (2008) eliminated 50% of the available data.

Measurement errors are also found to contaminate existing databases mainly due to the inclusion of loss or damage data associated with secondary hazards. In existing studies, such errors are seen to be removed from the databases where the survey data are available in sufficient detail (e.g. Yamazaki and Murao, 2000, removed buildings damaged due to liquefaction from their database), or where the areas affected by the secondary hazard were geographically constrained (with damage data from these areas excluded). However, this is not always possible (e.g. Scawthorn et al, 1981). By contrast, measurement errors occurring due to the inclusion of loss or damage data from successive strong aftershocks or other large earthquakes (e.g. Goretti and Di Pasquale, 2004; Karababa and Pominis, 2011) cannot be removed from the database. In the latter cases, this bias is acknowledged by the studies, and should be considered in interpreting the results from these vulnerability or fragility studies, which may over-predict the damage/loss, (especially if applied to estimate risk from small magnitude events).

2.3 Quality of Ground Motion Intensity

The construction of empirical vulnerability or fragility functions requires reliable loss and/or damage statistics from the typically large area/s affected by strong ground shaking. In practice, the affected area is subdivided into smaller units over which the seismic demand is considered uniform (isoseismic units). Ideally, these isoseismic units should be areas of uniform soil conditions, in close proximity to ground motion recording stations. These are necessary conditions for an accurate and uniform seismic demand to be assumed across the building population, which minimises the uncertainty in the ground motion and results in damage/loss statistics that reflect only the uncertainty in buildings resistance (Rossetto and Elnashai 2005).

In practice, the size of the isoseismic unit can be dictated by the minimum building sample size, survey method used or way in which the damage data is reported. Scarcity of ground motion recording instruments means that ground-motion prediction equations are used to assign IMLs to the isoseismic units. Moreover, a range of different intensity measures has been used in the derivation of fragility and vulnerability functions. In this section, existing fragility and vulnerability studies are critically reviewed with respect to these three aspects of ground motion intensity estimation and implications on epistemic uncertainty are discussed.

2.3.1 Isoseismic Unit

In the literature, a multitude of sizes of isoseismic units is assumed (see Appendix A). Most existing post-earthquake surveys report observed building damage over very large areas (e.g. a town in the case of Murakami, 1992), which are unlikely to have uniform soil types or sustain a uniform level of ground shaking. This is especially true when government led survey data is used as the empirical source, or when a measure of macroseismic intensity is used as the measure of the seismic hazard. However, no existing empirical study is seen to evaluate the uncertainty associated with the representation of the ground motion intensity across an area by a single (average) parameter value.

2.3.2 Measures of Ground Motion Intensity

The epistemic uncertainty in the vulnerability or fragility assessment due to ground motion intensity partly depends on the ability of the parameter chosen for its representation, IM, to describe the damage potential (and consequent loss potential) of strong ground shaking, This reasoning has led to the widespread use of macroseismic intensity as the measure of ground motion intensity in existing fragility and vulnerability functions, (see Appendix A). Many different macroseismic intensity scales have been used for this in the empirical literature, and the majority of existing DPMs use measures of macroseismic intensity as their IM. Those most frequently adopted are the Modified Mercalli Intensity (MMI), Japan Meteorological Agency (JMA), Mercalli-Cancani-Sieberg (MCS), Medvedev-Sponheuer-Karnik (MSK) and its successor the European Magnitude Scale (EMS98). Different criteria are adopted in the definition of the macroseismic intensity levels within each scale. Consequently, vulnerability or fragility functions obtained for different macroseismic intensity scales are not directly comparable.

Despite the good correlation reportedly observed between macroseismic intensity and observed damage and loss, their use in vulnerability or fragility assessment is not without disadvantages. Macroseismic intensities are subjective measures, and large discrepancies have been noted in their evaluation at the same sites by different reconnaissance teams (e.g. Rossetto et al, 2007). Macroseismic intensity scales are discrete measures associated with intervals between unit values which are not necessarily equal, and intermediate decimal or fractional values have no meaning. Furthermore, few ground motion prediction functions for macroseismic intensity exist, and conversion equations between macroseismic intensity and other ground motion intensity measures introduce additional uncertainty. This is a severe limitation in terms of the application of macroseismic intensity-based fragility and vulnerability functions in risk assessments. Despite these drawbacks macroseismic intensities have been extensively used in existing empirical vulnerability studies (e.g. Samaradjieva and Badal (2002), Thráinsson (1992)). One appeal of macroseismic intensity is that empirical loss and damage data pre-dating the widespread use of earthquake measurement devices can be used. A further appeal is that macroseismic intensity values form natural “bins” of IM within which a large number of observations of loss and damage can be obtained, due to the large spatial coverage of any given macroseismic intensity value (e.g. Eleftheriadou and Karambinis, 2011). This helps provide statistically significant samples of buildings in each IM value. However, in the case of data from more than one event, a very large scatter in the vulnerability data associated with each macroseismic intensity value will be observed, which results in considerably larger error distributions than present in the original single event data (Spence et al, 1991).

In recognition of the disadvantages posed by the discrete nature of macroseismic intensity Spence et al (1992), devised a continuous parameterless intensity measure, termed PSI or Ψ. PSI can be evaluated for a site based on the distribution of damage observed in unreinforced masonry constructions. This parameter has been adopted by Orsini (1999) and Karababa and Pomonis (2010) for their fragility curves. Functions between PSI and peak ground acceleration (PGA) are proposed by Pomonis et al (2002) for use together with existing ground motion prediction equations, which allows the PSI vulnerability curves to be used in predictive earthquake risk assessments. However, these PSI-PGA functions are based on a limited number of field observations and corresponding ground motion recordings. Therefore, they are associated with large scatter and require additional verification before they can be deemed reliable.

Regardless of the scale continuity, the use of macroseismic intensity, including PSI, to characterise ground motion in vulnerability or fragility functions can introduce inter-dependence between the predicted vulnerability or fragility and the IM. This is because macroseismic intensity is evaluated directly from observed earthquake effects and, hence, its value is partly dictated by the building stock fragility. In the case of single earthquake events use of macroseismic intensity as the IM results in a reduced data scatter, as damageability of an earthquake is better correlated with its observed damage than with direct measures of ground shaking. Intuitively, one could assume that this would be offset by higher uncertainty on the prediction of the IM, since it shifts the main predictive responsibility to GMPEs that estimate macroseismic intensity (i.e. Intensity Prediction Equations, which include both damage observations and felt effects) from seismological features such as magnitude, hypocentral location, and style of faulting. On the other hand, limited evidence on this topic (e.g. Allen et al, 2011) suggests that there is actually a lower uncertainty on predictions of macroseismic intensity than peak motions. This results from the fact that macroseismic intensity estimates involve a spatial average over a study area, while peak motions are point measurements. The authors are not aware of any studies that have compared uncertainty on loss estimates, propagated through from the estimation of the IM and vulnerability, but such a study would be valuable for the assessment of the relative merits of each approach.

A few studies propose continuous functions correlating the economic loss (Thráinsson and Sigbjörnsson 1994) or death rate (Samardjieva and Badal, 2002; Nichols and Beavers, 2003) to earthquake magnitude and epicentral distance, due to a limited amount of available data. However, earthquake magnitude is seen to be a very poor predictor of fatalities by Ferreira et al (2011). This is because earthquake magnitude is not representative of the strong ground shaking caused by the earthquake, and hence the applicability of functions using this parameter as their IM is severely limited.

A different approach for the selection of ground motion intensity measures has been promoted by the current seismic risk assessment framework, where it is important to decouple the uncertainties associated with the seismic demand from their counterparts introduced by the structural fragility. This can be achieved by selecting a measure of seismic demand capable of representing the influence of source, path, and site on the strong ground motion. This measure should characterize the ground shaking at each isoseismic unit and ideally its level should be determined from earthquake ground motion records. However, due to the scarcity of strong ground motion recording stations, in practice ground motion parameter values are obtained from ground motion prediction equations, whose availability determines the applicability of the measure of intensity. For the latter reason, and due to its traditional use in the definition of design loads for structures and seismic hazard maps, peak ground acceleration (PGA) is the main parameter used to represent ground motion intensity in empirical fragility studies (e.g. Sabetta et al, 1998; Rota et al, 2008). However, it is well known (e.g. Rossetto and Elnashai, 2003) that PGA does not correlate well with observed damage (especially for ductile structures or large damage states). In engineering terms, PGA is related to the dynamic loads imposed on very stiff structures and, therefore, may not be adequate for the characterisation of seismic demand in medium or high rise building populations. Peak ground velocity (PGV) is more representative of the seismic demand on structures of intermediate natural period of vibration than PGA. PGV is generally calculated through direct integration of accelerograms and may be sensitive to both the record noise content and filtering process. Fewer ground motion prediction equations for PGV exist than for PGA, but PGV seems to be the preferred IM in empirical fragility studies from Japan (e.g. Yamazaki and Murao 2000). Few empirical vulnerability or fragility studies (e.g. King et al, 2005) currently exist that adopt peak ground displacement (PGD) as their IM. Few attenuation functions exist for the prediction of PGD, due to its high sensitivity to noise in accelerograms and to filtering techniques adopted in the elimination of unwanted frequencies from raw records. The PGD attenuation functions that do exist, (e.g. Sadigh and Egan 1998), are based on few digital records and cover limited areas and fault mechanisms. Rossetto (2004) observes a better correlation of PGD than PGA with her database of reinforced concrete building damage statistics, however notes that in both cases the overall correlation is poor. Sarabandi et al (2004) also notes poor general correlation of all the ground motion indices they studied with a limited set of damage data for reinforced concrete structures (60 buildings maximum sized database), but also notes slightly better correlation of PGD than PGV and PGA with their data.

Parameters such as PGA, PGV, and PGD are unable to capture features of the earthquake record, such as frequency content, duration, or number of cycles, which affect the response of a structure and its consequent damage and loss. Hence, in an attempt to better capture the influence of accelerogram frequency content, more recent empirical fragility and vulnerability studies have favoured the use of response spectrum based parameters as measures of ground motion intensity.

Acceleration spectra are representative of the imposed seismic forces on the structure over a wide range of frequencies, and are used by most modern design codes in the determination of structure loads. In view of this, ground motion prediction equations for elastic spectral acceleration at 5% damping ($S_{a5\%}(T)$) have been proposed by various authors (e.g. Ambraseys et al 1996) and $S_{a5\%}(T)$ is commonly used in seismic hazard maps. $S_{a5\%}(T)$ has been adopted in several recent empirical fragility and vulnerability studies (e.g. Wesson et al 2004; Colombi et al, 2008). Spence et al (1992), Singhal and Kiremidjian (1997) and Rossetto (2004) noted that $S_{a5\%}(T)$ provided a better correlation with their empirical damage data than PGA. However, damage is more closely related to the seismic energy imparted to the structure and imposed relative displacements than to imposed forces.

Spectral velocity, $S_v(T)$, is indicative of the peak (not total) earthquake energy, and although ground motion prediction equations exist for the parameter evaluation, $S_v(T)$ is rarely used in the development of empirical vulnerability curves (e.g. King et al, 2005; Scholl 1974). A few empirical fragility studies have adopted spectral displacement ($S_d(T)$) as their IM (e.g. Rossetto and Elnashai, 2003; Sarabandi et al, 2004; Colombi et al, 2008). $S_d(T)$ has gained importance in seismic risk assessment due to the development of displacement-based methods of seismic design and assessment (e.g. Priestley et al, 2007). Furthermore, the installation of digital strong-motion measuring instruments in countries worldwide has eliminated the uncertainty in the spectral displacement determination from accelerograms, associated with noise contamination and record frequency filtering procedures. Consequently, ground motion prediction functions for $S_d(T)$ have been derived (e.g. Akkar and Bommer 2007). Rossetto (2004) judges $S_d(T)$ to correlate better with the observational damage statistics in her database, compared to $S_a(T)$ and PGA, and this is also observed for limited data by Sarabandi et al (2004).

One of the main difficulties associated with the use of elastic spectral values are the determination of equivalent vibration periods and damping coefficients for the characterisation of buildings as single degree of freedom systems (SDOF). Consideration must be given to the likely structural failure mode and its strength and stiffness degradation during ground excitation. It may be possible to identify the likely failure mode from the structural configuration and seismic code used in construction. However, estimation of the probable degradation is extremely difficult as this depends not only on the structure, but also on the ground motion characteristics. However, Rossetto (2004) sustains that in the case of empirical damage/loss data, the effects of inelasticity in both the seismic demand and structural response are implicitly included in the observations. Consequently, inelasticity and period elongation during ground shaking is taken into account in the determination of the exceedence probabilities. The inclusion of inelasticity in the IM is, probably unnecessary and the structure elastic period of vibration can be used to characterise the ground motion demand for all damage state curves.

This however does not solve the question as to which elastic period of vibration should be used to characterise a given building class, which will naturally be composed of structures with a range of geometrical and material characteristics. Empirical functions relating building height to fundamental period of vibration have been used by several empirical studies, (e.g. Scawthorn et al, 1981 for mid-rise building fragility curves). Seismic building codes typically include such empirical relationships (e.g. Rossetto and Elnashai, 2003 used those in Eurocode 8), however, they tend to provide conservatively low values of the structural elastic period as this results in higher spectral acceleration values, and consequently higher design forces. This conservatism is not appropriate for use vulnerability studies. Crowley et al. (2004) instead present empirical relationships for the cracked elastic period of different structures, which provide a more appropriate estimate of fundamental period for use in empirical fragility studies but have not yet been applied in this context. All, these relationships for estimating the structure fundamental period assume that the building height is known or that an average height for a building class can be adopted. Another solution is to derive the structural period that results in the best fit of the damage data to a regression curve. This is done by Scawthorn et al (1981) who adopt spectral acceleration evaluated at a fundamental period of 0.75s in deriving fragility curves for their low-rise wooden building class. However, when considering the height of structures in the building class (1-2 storeys), it is questionable whether this value of fundamental period value is representative of the elastic response of the buildings. In order to overcome the issue of fundamental period evaluation for a population of buildings, and in recognition of the variation of fundamental period in a building class, some reviewed studies adopt spectral response parameters averaged over a range of structural periods (relevant to their building class) for their IMs (e.g. Scholl 1974).

Colombi et al (2008) are the only authors to derive empirical fragility curves using inelastic spectral displacement for their IM. They assume each building class to have achieved a given ductility level at each damage state in their fragility relationship and use this to calculate the effective period and inelastic (overdamped) spectral displacement at this structural period. Use of inelastic spectral values presents a problem when interpreting and/or applying the resulting fragility functions. In the first case, the IM values associated with one structure at different damage states is different which means that the proportion of buildings in each damage state (which should sum to 1) cannot be determined directly from a single IM value. In addition, determination of the ductility values corresponding to the damage states implies carrying out a pushover analysis of the building being assessed if the fragility curves are to be applied to a structure type that differs from those in the study (for which ductility values have been proposed). The plastic deformation associated with a damage state for buildings within a structural class will differ significantly and this source of uncertainty should be quantified and included in the fragility calculation, but is not.

Finally, it is worth noting that there exist different definitions for peak ground motion and spectral parameters, depending on the treatment of the two measured horizontal components of ground acceleration. For engineering applications, Baker and Cornell (2006) noted that it is important that seismologists and engineers use a consistent measure when estimating seismic hazard and structural response, and this applies similarly for loss assessment. GMPEs are available for the geometric mean of two measured components, the maximum of two measured components, and other mean or maximum definitions. Existing studies on fragility and vulnerability relationships are not explicit on which definition has been used; when instrumental intensity measures have been estimated from GMPEs, the original GMPE reference would need to be consulted to determine which definition was used. Demand estimates based on a maximum measure are likely to be better correlated with damage than geometric mean measures (Grant, 2011), but intensity estimates of the latter are more stable, as extreme values are averaged out (Baker and Cornell, 2006).

2.3.3 Evaluation of Ground Motion Intensity

When evaluating an existing empirical fragility or vulnerability relationship care must be taken to assess the method used to determine the IM values at the damage/loss sites. Ideally, ground motion recordings would be available across the affected area. In practice, such instruments are scarce and may not cover the entire affected area. Two exceptions are found from the literature. Yamaguchi and Yamazaki (2001) propose fragility curves that are developed using data from 346,078 low-rise wood frame buildings surveyed after the 1995 Kobe earthquake in areas close to 17 accelerometers. For areas of low ground shaking (roughly half the points), the isoseismic units used in order to get a non-zero value of damage are however so large they are unlikely to represent areas of uniform ground shaking. Sarabandi et al (2004) use damage data collected near recording stations during the Northridge 1994 (USA) and Chi Chi 1999 (Taiwan) earthquakes to develop fragility functions for several structural classes. However, the constraints imposed by similar soil conditions and proximity to a recording station, result in small numbers of datasets, containing small numbers of buildings for each building class considered (e.g. 69 steel buildings in total). Hence, there exists a practical trade-off between the uncertainties introduced into the fragility/vulnerability relationship from the use of small samples versus that introduced from error in the ground motion determination.

In the majority of cases, IM values are determined from ground motion prediction equations (GMPE). In these cases, the adequacy of the chosen GMPE for the earthquake event and site should be assessed. Modern GMPEs are based on numerous ground motion recordings and account for differences in focal mechanisms and soil types. However, modern GMPEs may not be available for the particular country assessed and adopted from regions with similar tectonic environments, or the study may pre-date the derivation of reliable GMPEs for the particular intensity measure and site. For example, in the fragility curves of Rossetto and Elnashai (2003), a very limited set of GMPEs for spectral acceleration and displacement IM evaluation are used to represent damage data from different tectonic settings. A better approach would have been to take country or region specific GMPEs. Soil type should always be accounted for in the determination of IMs. However, this is not always done; for example, in Rota et al (2008) all municipalities in Italy for which they have damage data are assumed to be founded on rock. Rota et al (2008) do carry out a sensitivity analysis to see the effect of randomly varying the PGA at their sites by up to 50%. They report little differences in the resulting mean fragility curves. Despite this assertion, it is possible to observe from produced figures differences of up to 10% in the exceedence probabilities of the larger damage states. Furthermore, since Rota et al (2008) “bin” their PGA values for regression, this “binning” process may result in less observed variability than if a direct regression were carried out.

In empirical fragility and vulnerability studies, macroseismic intensities are usually evaluated from field observations of damage, which, results in a dependence of the x-axis of the derived fragility curve on the y-axis. Although strong ground motion based IM values are usually derived from accelerogram readings or GMPE, in a few cases in the literature observed damage distributions have been used to update and modify such IM values. For example, Yamazaki and Murao (2000) adopt an iterative derivation methodology for their fragility curves wherein the peak ground velocity (PGV) distribution derived by Yamaguchi and Yamazaki (1999) for the Nada Ward after the Kobe (Japan, 1995) earthquake, is modified using preliminary fragility functions. The resulting PGV distribution is then re-applied in the derivation of new fragility curves. The process of PGV re-estimation and fragility curve updating is repeated several times and the final PGV distribution obtained differs significantly from the original. Such processes are not recommended as the axes of these fragility curves are effectively inter-dependent and the horizontal axis can no longer be regarded as representative of the observed strong ground motion.

Care must be taken in adopting fragility or vulnerability curves from older studies that use spectral ordinates as IMs. In past studies based on relatively limited computing power, standard spectral shapes (such as Trifunac 1977 by Scawthorn et al 1981) or pseudo spectral values may have been used (e,g, pseudo spectral displacement in Scawthorn et al 1981). The use of pseudo spectral values was investigated by Colombi et al (2008) who considered two methods for deriving spectral displacement with 5% damping in their fragility study of Italian buildings: (1) the pseudo-spectral velocity GMPE of Sabetta and Pugliese (1996), transformed to spectral displacement via the pseudo-spectral functions; and (2) the use of a GMPE for spectral displacement $S_d(T)$ by Faccioli et al (2007). They report that the epistemic uncertainty in the GMPE has a large influence on the fragility curves generated, as they predict widely different $S_d(T)$ values for the same building classes.

2.4 Vulnerability or Fragility Assessment Procedures

This section aims to critically review existing procedures used for the construction of empirical fragility and vulnerability functions. In particular, the focus is on issues regarding the treatment of uncertainty, especially the manipulation or combination of damage and loss data in databases, the selection of a model to express the functions, the adopted optimisation processes, and procedures and tests used to establish confidence of the chosen relationship to the data and to communicate the overall uncertainty in the relationship.

2.4.1 Sample Size

The sample size of a high quality database determines the reliability of the mean vulnerability or fragility functions. The sample size depends on the type of post-earthquake survey, i.e. surveys undertaken by reconnaissance teams contain small samples, whilst surveys conducted by state authorities produce large databases. Existing empirical functions are based on a wide range of sample sizes varying from 20 (Sarabandi et al. 2004) to 346,078 (Yamaguchi and Yamazaki, 2001). It should be mentioned that most existing functions are based on samples of 200 buildings or above, which can be, theoretically at least, considered an acceptable sample size. However, loss or damage observations often do not encompass a range of ground motions sufficient for the reliable determination of vulnerability or fragility functions for all damage states over a wide IM range (e.g. Karababa and Pomonis, 2010 acknowledged the lack of data for most building classes to construct partial collapse and collapse damage state fragility curves for some of their building classes). This is particularly true for the damage statistics based on data collected in the aftermath of small magnitude events, e.g. in Dolce et al (2006), the M_L 5.2 Potenza earthquake of 1990 had a maximum-recorded MCS intensity of VII.

2.4.2 Data Manipulation and Combination

Section 2.2 highlighted the serious issues with data quality of available post-earthquake damage and loss surveys. This means that data from post-earthquake surveys, even from single events, is almost never adopted for constructing fragility and vulnerability relationship without some level of data manipulation or database combination aiming at reducing the sampling errors (note: non-sampling errors are discussed in Section 2.2.6). Data manipulation is also required for transforming each database into a form suitable for combination with other databases. In what follows, the main procedures for data manipulation and combination found in empirical vulnerability or fragility assessment literature are discussed.

Some studies address high sampling errors by aggregating data from various detailed building classes into more general ones. For example, Braga et al (1982) combine the detailed building typologies used by the 1980 Irpinia database into three vulnerability classes in line with the requirements of the MSK-76 macroseismic scale. However, as buildings with different geometries and structural systems are grouped together, uncertainty in the resulting vulnerability or fragility increases. Moreover, the ability of the obtained general functions based on heterogeneous data to represent subclasses of buildings with very small contribution to the overall sample size of the class is questionable (e.g. Rossetto and Elnashai, 2003).

Some of the reviewed studies combine loss or damage databases from multiple events. Several empirical vulnerability or fragility studies combine loss or damage data from several earthquakes in the same country in an attempt to overcome data scarcity, e.g. Colombi et al (2008) and Rota et al (2008) for Italy, Gulkan et al (1992) for Turkey and Amiri et al (2007) for Iran, Jaiswal and Wald (2010) for casualty data in Italy, India and Iraq. These studies largely retain the advantage of consistently assembled damage survey data for similar asset classes (if post-earthquake survey procedures have not substantially changed over the considered time frame), but significant differences may be found in adopted methods for casualty and economic loss data collection. Although functions derived from multiple earthquake databases tend to include data over a wider range of IMs than single event functions, due to the infrequency of large earthquake events near urban areas, the datasets are still seen to be highly clustered in the low-damage/loss, low-IM range. In areas of medium and low seismicity, this may be acceptable if the IM values covered by the data sufficiently represent the ground shaking that can be generated by locally feasible events. A few studies are seen to combine empirical loss or damage data for similar asset types from multiple events and countries worldwide in order to obtain data over a wider range of IM values, or simply a larger quantity of data from which to construct the functions. However, even in these cases the number of datasets available for high-damage states and high-IM values are few (e.g. Rossetto and Elnashai, 2003). Implicit in the studies is the assumption that the uncertainty in the seismic performance of individual buildings is larger than the uncertainty in the performance of buildings in different earthquake. This assumption has not been addressed anywhere in the literature. In addition, none of the aforementioned studies provided a thorough discussion on the criteria for selecting the seismic events. Existing loss estimation methods (e.g. Coburn and Spence, 2002) and some fragility functions (e.g. Rossetto and Elnashai, 2003) are seen to combine databases from different tectonic environments and/or significantly different fault systems. These methods assume that the variability in IM and resulting damage are sufficiently accounted for by the ground motion prediction equations (GMPEs) used to estimate the IMs. However, few use GMPEs that appropriately distinguish between different faulting mechanisms. In addition, the combined databases are associated with different degrees of reliability. This is typically not taken into account in the curve fitting procedures used (but should be). Finally, it is well known that fatality rates are affected by a number of factors that are specific to the event and location (such as time of day of the event, working practices and local customs, effectiveness of response teams, etc.). Hence, the combination of multiple event data from diverse environments into simple fatality ratio estimation models that do not explicitly take such factors into account can add significant uncertainty to the loss estimate. For example, this is true of the empirical fatality vulnerability functions proposed by Jaiswal and Wald (2010), who combine casualty data for multiple earthquake events at a national level, without accounting for the influence of population demographic characteristics, season or time of day.

Most empirical fragility and vulnerability studies aggregate the damage or loss data into isoseismic units, which assumes that the buildings in the isoseismic unit are subjected to the same ground motion intensity.

The number of isoseismic units (and hence data points) that have been used to construct individual vulnerability or fragility curves of this type range from 3 (e.g. Karababa and Pomonis, 2010) to approximately 79 (Yang et al 1989). In larger databases, individual datapoints are also seen to be aggregated into “bins” of similar ground motion intensity values, resulting in a smaller number of datapoints for regression (e.g. Rossetto and Elnashai, 2004; Rota et al. 2008). This tendency for aggregation might be traced to two main reasons. The first reason is the general lack of very detailed building-by-building databases. The data are often only available in an aggregated form. The second reason stems from the common use of least squares methods of regression for model fitting. In the unweighted form of the least squares method the reliability of the fitted model is based on the number of data points, which in the case of fragility, is the number of points expressing the probability of a building reaching or exceeding a damage state given various levels of ground motion intensity, and not the total number of buildings in the database. This means that a data point based on 5 buildings is as important as a data point based on 1000 buildings. To avoid datapoints deriving from small numbers of observations strongly influencing the model fit, some studies specify a minimum threshold number of buildings for data points, below which the data points are considered unreliable and ignored (e.g. 20 buildings for Spence et al, 1992 and Karababa and Pomonis, 2010). In the reviewed empirical fragility and vulnerability literature, the effect of different aggregation assumptions (e.g. chosen minimum thresholds of buildings in a datapoint, size of bins, bin ranges) is not fully understood and has not been systematically studied.

Finally, manipulation of damage and loss data in a database to prepare it for combination with other databases usually involves the interpretation or mapping of the damage states of the data onto a different damage scale. Direct mapping of data discretised according to a large number of damage states to scales with fewer (or equal number of) damage states (e.g. in Braga et al, 1982, and assumed in Spence et al 1992) introduces uncertainties. However, it is assumed in the literature that these are small and are never seen to be explicitly quantified. Mapping from a small number to large number of damage states must assume some distribution of the damage data within the larger damage state classes. This should not be done unless the original damage survey forms are available and are detailed enough to allow for a larger number of damage states to be defined (as is the case in Rota et al, 2008). Despite this, Sarabandi et al (2004) and Rossetto and Elnashai (2003) have carried out such damage state mapping, both following a similar procedure. In the former, a mean damage factor value is assigned to the damage scales within each damage scale used, according to the damage scale definition. In the latter a maximum interstorey drift (ISD) value is assigned to the damage states of all damage scales used in their database, through comparison of the damage state descriptions with those of their proposed and experimentally calibrated damage scale. These DF/ISD values are used to fit lognormal/beta distributions to each reported damage frequency plot for a given IM and site. These fitted distributions are then used to derive the proportion of buildings in damage states defined by their damage scale DF/ISD thresholds. Neither study explicitly quantifies the uncertainty introduced by damage scale mapping.

2.4.3 Shape of Vulnerability or Fragility Functions

Vulnerability and fragility of the examined assets have been characterised as discrete or continuous functions (see Section 2.1). In this section, the shape and parameters of the functions selected by the reviewed studies to represent loss or damage data at one or more isoseismic units are discussed.

Post-earthquake survey damage data for buildings is most commonly represented as histograms, expressing the probability of being in the predefined damage states for a specified level of intensity. Some empirical studies are seen to transform these discrete damage functions into parametric probability distributions.

Braga et al (1982), Sabetta et al (1998), Di Pasquale et al (2005) and Roca et al (2006) all fit discrete binomial distributions to their histograms of damage. This distribution is fully described by a single parameter, which Sabetta et al (1998) correlated through a third degree polynomial with the ground motion intensity in order to develop their representation of fragility. Instead, Rossetto and Elnashai (2003) adopt continuous beta distributions, which are fully described by two parameters. In theory, using a model with more parameters may improve the fit. However, the use of a continuous distribution in this case requires the correlation of each discrete qualitative damage state with a threshold of a loss or response parameter. Such functions are mainly judgement based, and rarely validated with experimental or observational data, thus this can introduce additional, and perhaps substantial, uncertainty in the model.

Where continuous functions expressing the probability of buildings being in a damage state versus ground motion intensity are proposed, these functions are seen to be either linear (e.g. Scholl 1974, and Scawthorn et al, 1981) or exponential (e.g. Petrovski and Milutovic, 1990).

Another continuous representation of the fragility is the fragility curve. In this representation, the majority of empirical studies adopt lognormal cumulative distribution functions (LN_CDF). The popularity of LN_CDF can be attributed to three properties. Firstly, this function is constrained in the y-axis between [0, 1], which is ideal for fitting data points expressing aggregated probabilities. Secondly, with regard to the x-axis, the values are constrained in (0, +∞). This agrees with the range of almost all the ground motion intensity measures. Thirdly, this distribution appears to be skewed to the left, and can thus, theoretically at least, better reflect the frequency of the observations which are mostly clustered at low ground motion intensities. The normal cumulative distribution function (N_CDF) is the second most popular regression curve in the empirical fragility assessment literature. It is mostly preferred by studies (e.g. Spence et al, 1992; Orsini, 1999; Karababa and Pomonis, 2010) that use intensity measures that range from (-∞, +∞), e.g. PSI. Nonetheless, Yamaguchi and Yamazaki (2000) express their fragility curves in terms of this distribution despite their intensity measure being discrete and positive.

Instead of using a cumulative probability distribution, an exponential function, which is unconstrained in both x- and y-axis has been adopted by Rossetto and Elnashai (2003) and Amiri et al (2007). The use of a non-probability distribution function to express the fragility curves may have implications in the risk assessment, which requires its coupling with a hazard curve to produce the annual probability of reaching or exceeding a damage state.

In the reviewed vulnerability functions, Jaiswal and Wald (2010) adopt the lognormal distribution to express death rate in terms of the ground motion intensity, in line with most fragility assessment methodologies. By contrast, many other casualty vulnerability functions correlate the total death rate with earthquake magnitude due to the lack of more refined data. The use of magnitude ignores a number of significant contributors to loss such as the source-to-site distance, the soil conditions, and the tectonic environment, thus increasing the uncertainty in the model. In such studies, linear functions are often used to correlate death rates and magnitudes. Similar functions are proposed for economic loss by Thráinsson and Sigbjörnsson (1994), who correlate loss to earthquake magnitude and source-to-site distance. In the reviewed literature, economic loss is directly correlated to other IMs through a number of different function forms, such as linear (e.g. Petrovski et al, 1984) and power functions (e.g. Scawthorn, 1981). A different approach is proposed by Wesson et al (2004) who fit a gamma distribution to insurance economic loss data in each isoseismic unit, and then correlated the two parameter of this distribution with the intensity through the use of continuous exponential and polynomial functions. Yang et al (1989) follow a similar approach to Wesson et al (2004) in their indirect vulnerability assessment method. They fit normal distributions truncated in [0,1] to the data in each IM value (in this case MMI Intensity), and then correlate the two parameters of this distribution (i.e. the mean and standard deviation) to the IM through the use of linear functions. With regard to the remaining indirect vulnerability functions, the mean economic loss given discrete levels of intensity is obtained in most studies with the exception of Elefteriadou and Karabinis (2011), who obtain multi-linear piecewise vulnerability functions from the aforementioned discrete values. The general forms of relationship here described are all presented in Appendix A.

2.4.4 Statistical Modelling Techniques

Most empirical fragility and vulnerability studies reviewed focus on fitting a parametric function to post-earthquake building damage and loss observations, respectively. This is effectively treated as an optimisation problem by the reviewed studies, who thus assume that the damage/loss data is of high quality and that the intensity measure levels can be determined with negligible uncertainty. Through these assumptions an objective function can be formulated, which correlates the loss/damage (considered the dependent variable) to the ground motion intensity (considered the explanatory variable). Values of the 'true' but unknown parameters of the selected function (e.g. LN_CDF or N_CDF) have mainly been estimated by minimising the objective function, and rarely by its maximisation. A discussion of the two approaches follows.

According to the minimisation approach, used almost exclusively in the reviewed empirical literature, the objective function has been expressed in terms of the sum of least squares errors (i.e. observed - predicted values):

$$\boldsymbol{\theta}^{opt} = \arg\min\left[\sum_{j=1}^{m}\varepsilon_j^2\right] = \arg\min\left[\sum_{j=1}^{m}\left[w_j\left(y_j - f\left(\boldsymbol{\theta}, im_j\right)\right)\right]^2\right] \tag{2.4}$$

where yj is data point j based on loss or damage observations (a data point can express the damage ratio sustained by an isoseismic unit with intensity IM=imj or the probability of buildings sustaining or exceeding a specified damage state in this isoseismic unit); m is the number of data points; wj is the weight for data point j; m is the number of data points; f(θ,imj) is the predicted value based on a predetermined function f(.) with parameters θ=[θ1, θ2, …,θN]; εj is the error at point j which is considered independent and normally distributed for each j with mean zero and constant standard deviation.

In most direct vulnerability assessment studies, the parameters, θ, are linearly combined in the proposed functions, therefore their values are estimated by a closed form solution through the linear least squares method. This method is also overwhelmingly adopted in the fragility assessment studies to fit cumulative lognormal or normal distributions to the damage data. The application of this method for the estimation of parameters nonlinearly combined in the fragility functions requires the linearisation of the fragility functions (e.g. Yamazaki and Murao, 2000; Yamaguchi and Yamazaki, 2000; Beneddetti et al. 1998) in the form:

$$f^{-1}\left(y_j\right) = \theta_1 im_j + \theta_2 + \varepsilon_j \tag{2.5}$$

Also required is the transformation of the data points into the form: (ln(im_j), $\Phi^{-1}(y_j)$) or (im_j, $\Phi^{-1}(y_j)$) for the cumulative lognormal and normal distributions, respectively. However, this transformation may introduce bias to the estimation of the mean fragility curves. This bias is more evident when y_j is very close to the extreme values of 0 and 1, as the transformation is not feasible for these values, limiting the applicability of this approach. Procedures (e.g. Porter et al, 2007) that have attempted to deal with the transformation of y_j=0 seem questionable (Baker, 2011). However, the transformation of the selected model does not lead to bias in cases where an exponential function (e.g. Eq.(A.6)) is fitted.

A handful of fragility assessment studies avoid this bias (Rossetto and Elnashai, 2003; Amiri et al. 2007; Rota et al. 2008) through the numerical estimation of the parameters by the use of the nonlinear least square method. However, the nature of damage data typically is seen to violate the assumptions of this approach with regard to error normality and error homoscedasticity (i.e. constant error for each level of IM). For example, the normality of the error is clearly violated by the fact that exceedence probability is a variable bounded between 0 and 1. In addition, the homoscedasticity assumption is violated given that the uncertainty in seismic performance for extreme levels of intensity is considered lower than for the intermediate intensity measure levels. Some studies attempt to address the heteroskedasticity requirement by using weighing techniques. Sabetta et al. (1998) weight the least squares by the number of buildings in each isoseismic unit. The use of buildings by the latter study, however, implies sample sizes that vary from few tens to few thousands, and this difference is unlikely to reduce the heteroskedasticity. A different weighting technique is adopted by Rota et al (2008), where datasets falling within an IM bin are grouped into one data point for the regression. The bootstrap technique is adopted to find the variance values to represent the scatter in the mean data point in each bin. The inverse of this variance is used to weight the least squares in Eq. (2.4) in order to reduce the impact of bins with small numbers of data points. Nonetheless, the effect of these schemes on heteroskedasticity is questionable. Instead of weighting techniques Jaiswal and Wald (2010) address the heteroskedastic error by use of a different objective function. The level of bias introduced in the generated mean fragility curves by fitting models using a nonlinear least squares method with violated assumptions is an issue of ongoing research (e.g. Ioannou et al. 2012). There are indications, however, that the differences compared to more realistic models (e.g. the generalized least squares model) are evident in the tails of the distributions (e.g. Lallemant and Kiremidjian 2012).

Few existing studies adopt the maximum likelihood method in order to estimate the parameters of statistical models used in the vulnerability or fragility assessment. Such studies maximise the likelihood function, which has the form:

$$\boldsymbol{\theta}^{opt} = \arg\max\left[\prod_{j=1}^{m} f\left(y_j;\boldsymbol{\theta},x_j\right)\right] \tag{2.6}$$

where $f(.)$ is the probability density function of a variable with parameters $\boldsymbol{\theta}$;. This approach was used by Yang et al (1989) and Wesson et al (2004) to fit truncated normal and gamma distributions, respectively, to their isoseismic unit loss data. Ioannou et al. (2012) also adopt this method in order to fit a generalised linear model to damage data. According to the latter study, individual fragility curves were constructed from data points having the form (x_j,(y_j, m_j-y_j)), which express the intensity level im_j that affect an isoseismic unit j causing y_j buildings to suffer damage $DS\geq ds_i$ and causing m_j-y_j buildings to suffer damage $DS<ds_i$. A generalized linear model is then constructed, which considers that the counts of data with $DS<ds_i$ and $DS\geq ds_i$ for each unit j follow a binomial distribution, having a likelihood function in the form:

$$L(\boldsymbol{\theta}) = \prod_{j=1}^{M} \binom{m_j}{y_j} \mu\left(im_j;\boldsymbol{\theta}\right)^{y_j} \left[1-\mu\left(im_j;\boldsymbol{\theta}\right)\right]^{m_j-y_j} = \\ = \prod_{j=1}^{M} \binom{m_j}{y_j} \Phi\left(\theta_1 \ln\left(im_j\right)+\theta_2\right)^{y_j} \left[1-\Phi\left(\theta_1 \ln\left(im_j\right)+\theta_2\right)\right]^{m_j-y_j} \tag{2.7}$$

The mean $\mu(im_j;\boldsymbol{\theta})$, which fully defines the binomial distribution, is assumed to follow the probit function with log(*IM*), which is essentially equivalent to the lognormal cumulative distribution function as presented in the right side of Eq.(2.7). The parameters of this statistical model are estimated by maximizing the likelihood function. Contrary to the model expressed in Eq.(2.4), this model provides a better, in theory at least, representation of the damage data given that (i) it recognizes that the fragility curves are bounded in [0,1], (ii). it successfully relaxes the assumption of constant variance of residuals by accommodating for smaller uncertainty in the tails of the mean μ, and higher in the middle, and (iii). It takes into account that some points have a larger overall number of buildings than others.

Determination of the goodness of fit of the selected models to the adopted data involves procedures for assessing the validity of the assumptions on which the fitted statistical model fitted is based, and on ways to identify the best model amongst acceptable models. Despite the importance of these procedures in determining the reliability of proposed models, only Ioannou et al. (2012) provide any detail on goodness of fit checks carried out, and recognize, in their case, the need for more detailed damage data and perhaps more sophisticated statistical models. A small number of existing fragility and vulnerability studies provide an incomplete goodness-of-fit assessment by accompanying their curves with the coefficient of determination (R^2) in the case that linear least squares regression is used or the sum of the least squares if nonlinear regression analysis is adopted. However, these measures cannot highlight potential violation of the assumptions on which the statistical models are based. In two studies (King et al. 2005; Frolova et al. 2011), the Smirnov-Kolmogorov goodness-of-fit test was used to assess the suitability of the selected probability distribution.

Existing empirical vulnerability and fragility studies overwhelmingly fail to provide a deeper insight on the goodness of fit of the selected model by quantifying the uncertainty in the estimated parameters and constructing confidence intervals around the mean fragility curves, which can illustrate the uncertainty introduced by the often limited number of data. Notable exceptions in the fragility literature are Braga et al (1982), Orsini (1999) and Amiri et al (2007). Braga et al (1982) propose upper and lower bounds for the parameter of their discrete damage probability matrices but do not associate these bounds with a confidence level. Similarly, Orsini (1999) estimates upper and lower bounds for their damage probability matrices for given levels of MSK, corresponding to the upper and lower bound of PSI for this intensity measure. Amiri et al (2007) also estimate the 90% confidence intervals of the parameters of their fragility curves. However, the envelope of the fragility curves obtained from the four combinations of the upper and lower bound of the parameters often takes negative values, perhaps due to the small number of data points in combination with the inappropriate statistical model selected. With regard to vulnerability assessment studies, Wesson et al (2004) estimate confidence intervals for the parameters of the gamma distribution for each isoseismic unit for which loss data is available by using the bootstrap technique. Only two studies are instead seen to construct prediction intervals for their fragility curves, which account for the above uncertainty as well as the typically large scatter in the data points from different isoseismic units. In particular, Rossetto and Elnashai (2003) attempt to estimate the 90% prediction intervals by taking into account the non-constant error noted in their analysis. It is noted that these prediction intervals could be biased given that the non-constant error violates one of the assumptions on which their regression is based. Ioannou et al (2012) use a bootstrap in order to construct point wise prediction intervals corresponding to their data points and highlight the difficulties in projecting these intervals for future groups of buildings and the need for further research.

2.4.5 Method of Conversion of Damage to Loss in "Indirect" Vulnerability Curves

The estimation of indirect vulnerability from fragility functions requires the use of damage-to-loss conversion functions. The treatment of uncertainty in these functions by the reviewed studies is discussed here.

In the case of economic losses, damage factors are commonly correlated to the discrete qualitative damage states by the use of field data, insurance claims, engineering judgement, or combination of the aforementioned sources. With the exception of Yang et al (1989) and Spence et al (2003) who adopt different damage factors for each building class, overwhelmingly the damage factors adopted are assumed independent of the building typology in existing vulnerability studies. This is counterintuitive, as different building types damaged to the same level are unlikely to have the same cost of repair.

Damage-to-loss functions are commonly expressed deterministically in terms of a best estimate level of the damage factor given a damage state. The only exception is noted in the study of Dolce et al (2006) who introduce the aleatory uncertainty in these functions by adopting beta distributions of the damage factor for each damage state. It should be mentioned that the epistemic uncertainty of these functions, expressed in terms of a family of probability distributions of the loss given a damage state, is not explicitly treated anywhere in the reviewed studies.

Indirect vulnerability approaches to casualty estimation typically only include fragility functions for the damage state of collapse in their calculation of fatalities (e.g. Murakami, 1992). The estimated number of collapsed (and sometimes heavily damaged) buildings is converted to number of fatalities by considering that a defined proportion of the people likely to be in the building type are killed (lethality ratio). Quite complex models are seen to exist for determining both the stated proportion and level of building occupancy. Such models (e.g. Coburn and Spence, 2002; Nichols and Beavers, 2003) combine a number of parameters that are supposed to represent the proportion of occupants directly killed, those trapped, and the proportion of those trapped that are then rescued. The numerical values of the parameters and the parameter distributions change according to building type, and are based on data but undoubtedly contain some level of judgement. In existing casualty studies, the level of occupancy of buildings is often estimated from census data. These values of occupancy can be used directly, or modified through empirical or judgement-based factors to take into account the influence on occupancy of tourism, occupant behaviour, season and time of day of earthquake, (amongst others). Very complex models for converting building damage into fatalities are not currently justified by the data used for their calibration, as this is rarely very detailed, plentiful or reliable (see also Section 2.2.4).

2.5 Validation Procedures

Ideally, the validity of vulnerability or fragility functions should be determined through comparison with independent post-earthquake observations. However, in the reviewed literature only two studies are seen to do this. Orsini (1999) compare the overall loss obtained indirectly from their fragility curves (which are constructed from the 1980 Irpinia damage database) with the overall loss caused by the 1997 Umbria-Marche earthquake. Spence et al (2003) compare their DPMs (developed from observations from several Turkish earthquakes) with the damage frequencies in two sites affected by the Kocaeli 1999 (Turkey) earthquake. However, it is unclear from the study whether or not the damage data from Kocaeli used for the validation was also included in the construction of their DPMs. The lack of interest in this type of validation can perhaps be attributed to the common practice of using all available datasets for the construction of vulnerability or fragility functions in order to get adequate sample sizes.

The main procedure adopted for validation of the vulnerability or fragility functions in existing empirical studies is the comparison with other functions constructed for similar asset types by the same or other authors. Orsini (1999) compares the upper and lower bound of his DPMs for each level of intensity with their counterparts obtained for the Umbria-Marche 1997 earthquake. Yamaguchi and Yamazaki (2001) compare their fragility curves with their counterparts obtained for similar building types by Miyakoshi et al (1998) using the same database. Colombi et al (2008) and Rossetto (2004) validate their empirical fragility functions with the analytical vulnerability curves they developed. Rota et al (2008) use the judgement-based approach proposed by Giovinazzi and Lagomarsimo (2006) to validate their fragility curves. Eleftheriadou and Karabinis (2011) compare the multi-linear piecewise loss curves obtained indirectly from their DPMs with their counterparts estimated by hybrid and empirical methods for similar Greek building types. In all these cases, the comparisons made are visual only, and no systematic comparison of quantitative values is carried out.

3 Rating System for Empirical Fragility and Vulnerability Functions

The here proposed rating system, is a modification and extension of the rating system for all vulnerability functions proposed by Porter (2012). The rating system here is specific to empirical fragility and vulnerability relationships and consists of two components, namely the overall quality of the fragility/vulnerability curves and their relevance to the needs of a future application as depicted in **Figure 3.1**. The description of the four main attributes to these two components, also presented in **Figure 3.1**, is briefly outlined in what follows.

Data quality: An overall rating of data quantity, constrained categories, excitation observations, and loss observations.

- *Damage/Loss observations:* Each estimate of loss or damage state is reasonably accurate, verified by some quantitative measure.
- *Excitation observations:* The estimates of excitation (shaking, deformation, ground failure, etc.) to which the specimens were subjected are reasonably accurate. In addition, the observed levels of excitation span up to the highest level that most assets are likely to experience in their design life.
- *Data quantity:* The number of observations is sufficient to draw statistically useful conclusions. *The number of observations for each considered asset and damage/loss state represented are sufficient to reasonably model the uncertainty in the damage/loss at given IM values.*

- *Constrained categories:* The observations are clearly made from specimens of the asset category in question, and the category is clearly defined (passing the so-called clarity test).

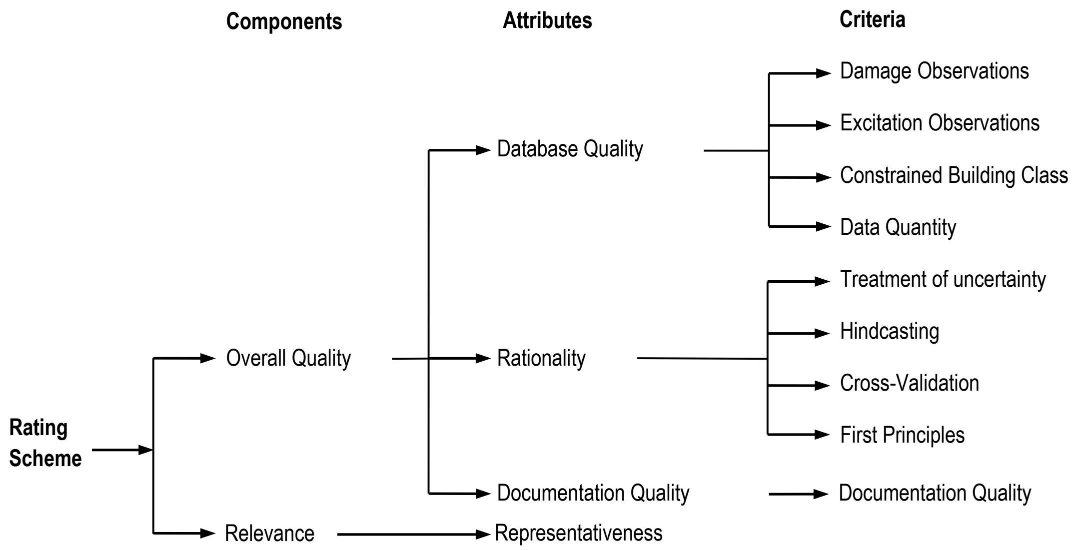


Figure 3.1. Components, attributes and criteria of the proposed rating system.

Representativeness: The specimens observed are broadly representative of the diversity of assets in the category, considering material properties, building configuration, detailing, geographic extent, and variety of failure modes.

Note: This criterion refers here to the representativeness of the vulnerability or fragility curves for the needs of a particular future project. For example, the indirect empirical vulnerability assessment of casualties is based on the presence of reliable fragility functions corresponding to the collapse and heavy damage. However, the rating of this criterion for the functions presented in the compendium (Appendix B) is not presented. Instead, future users are encouraged to rate the representativeness of existing studies according to the specific needs of their project.

Rationality: An overall rating of hindcasting, cross validation, first principles, and treat uncertainty:

- *Treat uncertainty:* The author identifies and treats the major sources of uncertainty in asset category and value, excitation, and loss or damage. By “uncertainty in asset category,” the question is how well constrained the observations are as to the membership of the observed assets in the asset category. If replacement value or construction cost is a parameter of the model, how well established are those values? Unless specimens were instrumented or very near instrumentation, the excitation to which specimens were subjected can be highly uncertain, especially if estimated using ground-motion prediction equations or in terms of macroseismic intensity. Is the excitation so crisply defined that there can be no ambiguity? For example, spectral acceleration response at some specified damping ratio and period can be ambiguous unless direction is specified. Damage is more certain if it is defined in terms of measurable quantities, less if qualitative and highly subject to interpretation. Loss is more certain if the repair costs (or other loss measures) were actually recorded and distinct from modifications or other costs unrelated to damage, less if loss were estimated, or otherwise subject to different interpretation by different observers.

- *First principles:* The vulnerability function or fragility function seems reasonable in light of engineering principles of hazard analysis, structural analysis, damage analysis, and loss analysis. The rationality of analytically derived structural vulnerability and fragility should reflect the degree to which the structural analysis follows current, peer-reviewed procedures.

- *Hindcasting:* The vulnerability function or fragility function reasonably hindcasts loss or damages in some significant past event, especially if the data source and events being hindcast are independent.

- *Cross validation:* The vulnerability function at least roughly agrees with some prior accepted model. If it disagrees, the disagreement seems reasonable in light of shortcomings in the past model, or differences between the asset classes of the past model and the one in question.

Documentation quality: All the necessary inputs, outputs, and analytical steps are clearly documented to a level that will allow the study to be reproduced by others. The documentation is readily available to future users. The documentation has been independently peer reviewed.

The proposed system allows for four possible values to be assigned to each criterion:

- **'H':** Superior, meaning little, if anything, could have been done better.
- **'M':** Average, meaning the work is of acceptable quality, though there are areas for improvement or further research.
- **'L':** Marginal, means that the work is acceptable for use but only if there are no practical alternatives; and much improvement or further research is needed.
- **'N/A':** Not applicable means that the rating measure cannot be applied.

The above rates are assigned to each criterion when the details conditions presented in **Table 3.1**-**Table 3.2** are met for a given empirical function. It is acknowledged that the rating exercise is prone to subjectivity, and that interpretations of the general criteria may change according to intended use and understanding of the reviewer.

Table 3.1. Rating the overall quality of existing empirical fragility functions.

Attribute	Criterion	Rate	Assigned when:
Data quality	Loss or Damage Observations	H	Damage scales or loss measures are clearly defined. Negligible non-sampling errors. Significant non-sampling errors have been acknowledged and reduced using adequate methods.
		M	Damage scales or loss measures are clearly defined but some significant non-sampling errors have been treated by relying on assumptions which are not checked.
		L	Damage scales or loss measures are defined with ambiguity. Significant non-sampling errors have not been reduced or reduced with questionable procedures.
	Excitation Observations	H	The IMLs have been determined from ground motion recording stations or GMPEs, and more than one intensity measure has been used in order to identify the one that fits the data best. The influence of the uncertainty in the ground motion in the fragility or vulnerability functions has been investigated.
		M	The uncertainty in IM has been partially investigated or if more than one IMs has been used for the vulnerability or fragility
		L	IMLs are interdependent with the observed damage data. If they used a single intensity measure and did not explore any other
	Constrained Building Class	H	Building classes are defined in terms of building material, lateral-load resisting system, height and seismic code (age).
		M	Building classes are defined in terms of building material, lateral-load resisting system or in terms of vulnerability class, e.g.
		L	Crude building classes are defined, e.g. RC buildings, RC frames, adobe buildings from worldwide databases.
	Data Quantity	H	For continuous functions: Sample sizes ≥200 damage or loss observations. For aggregated damage data, a minimum of 20 observations per bin of IM is used for a minimum of 10 bins. For discrete functions: Sample sizes ≥200 observations with a minimum of 20 structural units per bin of IM.
		M	For continuous functions: sample sizes between 20 and 200. For aggregated damage data, number of bins of IM between 5 and 10 are used with a minimum of 20 observations per bin. For discrete functions: A minimum of 20 observations per bin, for most bins of IM.
		L	For continuous functions: Sample sizes <20 units or units aggregated in <5 bins of IM. For discrete functions: Less than 20 observations per bin, for most bins of IM.
Rationality	First Principles	H	Obtained curves follow expected trends and they do not cross.
		M	Not applicable.
		L	Obtained curves violate the first principles, e.g. fragility curves cross.
	Treatment of uncertainty	H	Acceptable assumptions regarding data manipulation. Appropriate statistical models are selected and diagnostic tools
		M	Acceptable assumptions regarding data manipulation. Appropriate statistical models are selected, but diagnostic tools fail to demonstrate their goodness of fit.
		L	Unacceptable assumptions regarding data manipulations. Inappropriate statistical models are selected.
	Hindcasting	H	Independent damage or loss data are predicted by the fragility or vulnerability function, respectively.
		M	The overall damage or loss of an independent event is well predicted by the available functions. However, a more detailed of damage or loss hindcasting has not been done.

Table 3.1. Rating the overall quality of existing empirical fragility functions (continued…).

Attribute	Criterion	R	Assigned when:
Rationality	Hindcasting	L	Independent data are not reasonably predicted by the fragility or vulnerability function. Independent data has not been used to assess the predictive capacity of the functions.
	Cross-Validation	H	Obtained functions are compared with existing functions and the agreement or disagreement of the results is thoroughly and reasonably justified.
		M	Obtained functions are compared with existing functions and the agreement or disagreement is not accompanied by reasonable
		L	Obtained functions are not compared with existing functions.
	Documentation quality	H	All the necessary inputs, outputs, and analytical steps are clearly documented and the work is reproducible.
		M	Only partial information regarding the aforementioned issues has been addressed in the work.
		L	Insufficient information is provided to the fragility or vulnerability function or the methodology.

Table 3.2. Rating the relevance of existing empirical fragility functions to the needs of future application.

Attribute	Criterion	Rate	Assigned when:
Representativeness		H	The range of IMs (for which the functions have been obtained) includes the required levels or range of IM. The building class and region for which the function has been obtained is exactly the same as with the required class. The description of the damage scale (or state) is appropriate for the needs of the user's study.
		M	The required intensity measure level is 20% greater or smaller than the min or max value of the IM range for which loss or damage data are available. The building class of the function is a subset or includes the required class. The same applied to region.
		L	The range of IMs (for which the functions have been obtained) is very different than the levels or range of required IMs. When the building class is not a subset or does not include the required class or region. The description of the damage scale is too crude for the needs of the user's study.

3.1 Application

The rating exercise has been carried out by the authors for empirical fragility and vulnerability functions found in the literature and the results are presented in Tables 3.3-3.6. The resulting qualitative scores are included as fields in the compendium of empirical functions described in Section 4. The ratings are based on the documentation easily available to the authors and might change if further information is made available. Where the same reference proposes multiple functions, each is rated separately in the compendium with Table B.1 and Table B.**2** only presenting a general overall rating. Examples of how the rating system is applied are presented in detail in Tables **Table 3.3** to **Table 3.6** for four functions: the single event DPMs of Braga et al. (1982), the multiple event fragility curves of Rota et al (2008b), the indirect economic vulnerability relationship of Yang et al. (1989), which are all for Italian earthquake events, and the indirect fatality vulnerability functions of Murakami et al. (1992) for Armenia.

Table 3.3. Rating for the damage probability matrices proposed by Braga et al. (1982).

Attribute	**Criterion**	**Rate**	**Comments**
Data Quality	Data Quantity	H	41 datasets are used for each of the three vulnerability classes of structures considered. These span the three MSK Intensity levels considered.
	Constrained Building Class	M	The 13 building classes of the survey data are combined into three vulnerability classes, judged to show similar earthquake response characteristics and defined to be consistent with MSK-76 vulnerability classes.
	Excitation	L	Macroseismic intensity (MSK-76) is used as the IM, which has an interdependence with the damage data, especially as, in this study, its values are determined from the damage data directly rather than from field observation.
	Damage Observations	H	The surveys are very detailed and evaluate damage to both the vertical and horizontal elements of the structure. The surveys are carried out by military engineers and architects. No large aftershocks are reported.
Rationality	Hindcasting	L	The proposed DPMs represent the data used but are not verified with independent data.
	Cross validation	L	No cross-validation is carried out with other studies.
	First principles	H	The proposed method and data is reproducible and the results do not invalidate engineering principles.
	Treatment of uncertainty	M	Uncertainty is taken into account to an extent in the proposal of binomial distributions for the DPM entries and the provision of upper and lower limits. However, these limits are not associated confidence levels. Also bias in sampling the municipalities is not addressed.
Documentation	Documentation quality	H	Well-documented procedure and data collection survey method.

Table 3.4. Rating for the fragility curves proposed by Rota et al. (2008b).

Attribute	Criterion	Rate	Comments
Data Quality	Data Quantity	H	For most of the fragility curves for the 23 building classes specified, more than 10 datasets are available for each damage state curve. However, in the compendium, an 'M' rating is given to the fragility curves associated with some of the building classes where data was insufficient for the definition of collapse state curves.
	Constrained Building Class	H	Masonry building categories account for structural system, floor system, presence of tie rods and irregularities. RC building classes include structural systems, seismic code, and height categories.
	Excitation	M	PGA is used as the main IM and is evaluated using a GMPE. Housner Intensity is also used for the IM. However, rock conditions are assumed for all affected locations.
	Damage Observations	M	The surveys from the five Italian earthquakes considered use a detailed and approximately consistent survey methodology and damage scale. Where the damage scale differs, the original survey data has been consulted in order to correctly map damage states.
Rationality	Hindcasting	NA	The study results are not verified with independent data but represent well their used data.
	Cross validation	H	The PGA-based fragility curves are cross-validated with the judgement-based curves proposed by Giovinazzi and Lagomarsino (2007). They do not show a good agreement due to differences in relationship form, the use of macroseismic intensity to PGA conversion by the latter, etc.
	First principles	H	The proposed method and data is reproducible and the results do not invalidate engineering principles.
	Treatment of uncertainty	L	An inappropriate statistical model is fitted.
Documentation	Documentation quality	H	Well-documented and reproducible procedures.

Table 3.5. Rating for the indirect economic vulnerability relationship proposed by Yang et al. (1989).

Attribute	Criterion	Rate	Comments
Data Quality	Data Quantity	H	76 datasets are used which report damage to rooms in 76 municipalities affected by the 1976 Friuli, Italy, earthquake.
	Constrained Building Class	L	Rooms are used rather than buildings as the structural unit. The rooms are grouped by age of construction; however all are built prior to 1975 when the first seismic code was introduced in Italy. However, the age classes are used to better estimate the DFs.
	Excitation	L	Macroseismic intensity (MSK) is used as the IM, which has been evaluated from field observation. There are insufficient observations for intensities VI and X, for which data is extrapolated.
	Loss Observations	L	Details of the survey are not given in detail but a government-led reconnaissance based report is referenced. Average replacement costs for the rooms are taken from the survey report. The authors estimate the number of undamaged rooms from census data collected in 1971.
Rationality	Hindcasting	L	The proposed matrix of average damage factors when used by the authors to recalculate losses in municipalities does not give a good estimate of the observed losses.
	Cross validation	L	No cross-validation is carried out with other studies.
	First principles	H	The proposed procedure does not violate any first principles.
	Treatment of uncertainty	L	Sources of uncertainty in the damage and loss data are not taken into account explicitly or quantified. These are insufficient to determine the vulnerability (mean damage factor) values at MSK intensities VI and X (the limits of their vulnerability matrix).
Documentation	Documentation quality	M	Moderately well documented procedure.

Table 3.6. Rating for the indirect economic vulnerability relationship proposed by Murakami et al. (1992).

Attribute	Criterion	Rate	Comments
Data Quality	Data Quantity	L	Adopts damage data from 10 towns surveyed by EERI after the 1988 Spitak, Armenia, earthquake. The town surveys are associated with three MSK intensity levels. However, in the case of pre-cast concrete panel structures and precast concrete frame structures, only two observations are available for deriving the DPMs. Also, in the case of stone masonry and composite stone masonry buildings, respectively 3 and 6 of the 10 observations have sample sizes less than 20 buildings. The damage survey concerns only damaged buildings.
	Constrained Building Class	L	Multistorey residential buildings are used that belong to four categories of construction material.
	Excitation	L	Macroseismic intensity (MSK) is used as the IM, estimated from observed data.
	Loss Observations	L	The damage surveys are carried out by experts following a sound and unbiased damage survey method. Occupancy level is assumed from another empirical study. Lethality ratios are determined for the different building types from casualty data collected for five areas by another author, who does not state the building class where the deaths occurred. Predominant building classes are assigned to each area from background knowledge, in order to estimate the lethality ratios. There is bias in the collected data towards damaged buildings.
Rationality	Hindcasting	L	No hindcasting using independent data is available.
	Cross validation	L	No cross-validation is carried out with other studies
	First principles	H	The proposed method is reproducible.
	Treatment of uncertainty	L	Sources of uncertainty in the damage and loss data are not taken into account explicitly or quantified.
Documentation	Documentation quality	H	Well documented procedure.

4 Compendium of Existing Vulnerability or Fragility Functions

4.1 Basic Information

A compendium of existing vulnerability or fragility functions has been compiled in MS Access (2010), wherein each row of information is termed “record” and each column “field”. For the constructed compendium, the fields are classified into 10 general categories as presented in **Table 4.1**. Each record provides information regarding the vulnerability or fragility functions obtained for a specified building class by an existing study. Each vulnerability or fragility relationship is also rated according to the rating system described in Section 3, and each entry is accompanied by a brief commentary. The continuous functions are all included in the compendium, illustrated in the appropriate field in terms of their parameters (see Table 4.2) and/or shape (see **Figure 4.1**). With respect to the discrete functions, only those providing values of the levels of loss or damage corresponding to two levels of intensity or more are included in the compendium. In the case of indirect vulnerability functions, only those that adopt empirically constructed fragility functions are included in the compendium, irrespective of the nature of the damage-to-loss functions used. The latter damage-to-loss functions are also reported in the compendium.

Table 4.1. Basic information provided in the compendium of existing vulnerability or fragility functions.

General category	Field	Description	Properties	Example
Existing Study	**Reference**	Reference based on the author-date reference system used by GEM.	PText	Karababa and Pomonis (2010)
	Type of assessment	Type of assessment followed by study, e.g. fragility, direct or indirect vulnerability.	PText	Fragility
Damage and Loss measures	**Damage scale**	The main damage scale adopted by the study.	PText	EMS-98
	No of DS	Number of damage states used by the main damage scale.	Number	6
	Other DS?	Did the study adopt more damage scales? (Yes-No)	Y-N	No
	Other DS	The alternative damage scales used by the examined study.	PText	
	No of other DS	Number of damage states used by the alternative damage scale.	Number	
	Loss Parameter	Definition of the loss adopted by a vulnerability assessment study, e.g. fatality rate.	PText	
Building Classification	**GEM Building Class**	The building class according to GEM taxonomy system.	PText	
	Construction material?	Does the building class account for the construction material of the buildings? (Yes-No)	Y-N	Y
	Structural System?	Does the building class account for the structural system? (Yes-No)	Y-N	Y
	Age?	Does the building class account for the age? (Yes-No)	Y-N	N
	Height?	Does the building class account for the design code? (Yes-No)	Y-N	Y
	Design Code?	Does the building class account for the construction material of the buildings? (Yes-No)	Y-N	Y
	Irregularity?	Does the building class account for the irregularity? (Yes-No)	Y-N	N
	Vertical Material	The material of the vertical structure of a building class, e.g. RC, M.	Ptext	RC
	Infill?	Do the buildings of each class have infill walls? (Yes-No-Unknown)	Y-N-NA	Yes
	Infill Material	Material of the infill walls, RC.	PText	Hollow clay masonry
	Structural System	Description of the structural system.	PText	Non-ductile frames
	Horizontal Material	The material of the horizontal structure of a building class.	PText	RC
	Flooring system	The structural system of the floors, e.g. rigid, flexible.	PText	
	Irregularity	Horizontal or vertical irregularity of the building class, e.g. PYLOTIS.	PText*	
	GEM Height	General description of the height of a building class, e.g. low-rise.	PText	Low-Rise

Table 4.1. Basic information provided in the compendium of existing vulnerability or fragility functions (continued).

General category	Field	Description	Properties	Example
Building Classification	**Occupancy**	Use of the buildings	PText	
Ground Motion Intensity	**Type of IM**	Type of IMs, e.g. macroseismic intensity (MI), ground motion parameters (GMP).	PText	MI
	IM	The main ground motion intensity measure used by each study, e.g. PGA.	PText	PSI
	Range of IM	Range of IM values of the data, e.g. 0g-1g.	FText	
	Main IM Estimation Method	The main way of determining the levels of IM, e.g. observed data.		
	Other Methods IM?	Did the study adopt alternative ways to determine levels of IM?	Y-N	
	Other Methods IM	Alternative methods used to estimate levels of IM, e.g. recorded ground motions.	PText	
	GMPE_TE	The ground motion prediction equation and or transformation equation used.	PText*	
	Other IM?	Did the study adopt alternative intensity measures? (Yes-No)	Y-N	No
	Other IM_1(-N)	Alternative IM adopted by a study, e.g. Arias Intensity.	PText	
	Other Methods_IM_1(-N)	Methods used to estimate the level of the alternative IM.	PText	
	Other GMPE_TE_1(-N)	The equation that has been used to estimate the IM (if available).	PText	
Damage-to-Loss functions	**Source of D-L Relationship**	The methodology used to obtain these functions, e.g. empirical, expert judgement.	PText	
	D-L Relationship	The D-L Relationship, e.g. parameters, shape of the probability distribution of loss for each damage state.	File.xcl	
	D-L Uncertainty	Whether deterministic D_L function, or whether the aleatory and/or epistemic uncertainty are taken into account	PText	
Data quality/quantity (used for the construction of vulnerability or fragility functions)	**Country/ies**	Name of the country of each database used, e.g. Greece.	PText	Greece
	Source	Source/s of data, e.g. 1973 San Fernando database.	PText*	2003 Leukada
	Mechanism	The focal mechanism of each event.	PText	Strike-slip
	Depth	The focal depth of each event, e.g. 15km.	Number	12km
	No Event	Number of events, e.g. single event.	FText	Single
	No Assets	Number of suitable assets (e.g. buildings, casualties) used for the construction of the examined relationship, e.g. 1000 buildings.	Number	3079
	Non-sampling Errors?	Is the damage/loss databases contaminated with non-sampling errors? (Yes-No-NA(Unknown))	Y-N-NA	Yes
	Non-sampling errors	The non-sampling errors	PTest	
	Addressed non-sampling errors	The errors which were addressed by the use of a rigorous procedure.	PTest	
	Isoseismic Unit	The isoseismic units adopted for the regression, e.g. municipality.	PTest	District
	No of Data Points	Number of data points used for the construction of the regression analysis, e.g. 10 data points.	Number	33

Table 4.1. Basic information provided in the compendium of existing vulnerability or fragility functions (continued).

General category	Field	Description	Propeties	Example
Data quality/quantity (used for the construction of vulnerability or fragility functions)	**Min No of Assets Data Point**	Minimum number of assets, e.g. a minimum of 20 buildings is used in each data point.	Number	20
	Min No of non-zero Data Points per DS	Minimum number of non-zero data points used for the construction of each fragility curve.	Number	6 for DS4
Method for constructing the vulnerability or fragility functions.	**Type of analysis**	The analysis used by the examined study, e.g. regression, univariate distribution fitting.	PText	Regression
	Method	Methods used to manipulate the data, e.g. maximum likelihood or least squares.	PText	Non-linear least squares
	Algorithm	The algorithm used.	PText	Newton-Raphson
	Other Analysis?	Did they use additional analysis to construct vulnerability or fragility functions? (Yes-No)	Y-N	No
	Other Analysis	Additional analysis used to manipulate the data in order to correlate them with IM, e.g. regression.	PText	
	Other Method	Methods used to manipulate the data, e.g. maximum likelihood or least squares.	PText	
	Other Algorithm	Algorithm used to perform the additional methods.	PText*	
	Type of relationship	Type of relationship adopted by a study, e.g. DPMs, Fragility Curves, Loss Curves.	PText	Fragility Curves
	Form of relationship	Functional form of the relationship, e.g. linear, discrete.	PText	Normal CDF
	Relationship	Contains the plot of vulnerability or fragility functions and where available the corresponding parameters.	File.xcl or File.png	**Error! Reference source not found.**, **Error! Reference source not found.**
	Goodness of fit?	Does the study comment on the goodness of fit of the relationship to the data? (Yes-No)	Y-N	No
	Goodness of fit	The method of goodness of fit test adopted for testing the fit of a relationship.	PText	
	Measurement Error in X axis?	Was the epistemic uncertainty in the X axis of the examined relationship taken into account? (Yes-No)	Y-N	No
	Type of Confidence	The measure of confidence provided by the study, e.g. 90% confidence intervals	PText	
	Val. Raw Data?	Are the functions validated with independent data? (Yes-No)	Y-N	No
	Source of Raw data	Source of independent data, e.g. 2003 Leukada.	PText	
	Val. Existing Study?	Are the functions validated by comparing them with existing functions? (Yes-No)	Y-N	No

	Val. Existing study	The existing study adopted for the validation.	PText	M

Table 4.1. Basic information provided in the compendium of existing vulnerability or fragility functions (continued).

General category	Field	Description	Properties	Example
Ranking system	**Data Quantity**	Check section 3.1 for definition.	PText	H
	Constrained Categories		PText	L
	Excitation		PText	H
	Loss Observations		PText	H
	Representativeness		PText	M
	Hind Casting		PText	H
	Cross Validation		PText	L
	First Principles		PText	L
	Documentation Quality		PText	H
	Overall Rating Score		PText	
General Comments	**General Comments**	General comments regarding the ranking of the examined study.	FText	Well reported survey. Survey focussed on damaged structures, undamaged determined from 2000 census. Damage data contains buildings damaged from a major aftershock as well as the mainshock. Constant standard deviation assumed for all fragility curves and mean regressed for. Curves for high damage states (D4 and D5), “borrowed” from Coburn and Spence (2002), where no/insufficient statistics to construct curve. Curves adopt PSI as IM and are compared to curves by Coburn and Spence (2002). No measurement error accounted for in IM or loss values. No confidence or prediction intervals defined.
Notation	**PText: Text with predefined options.** **PText* Text with predefined options, which allows for multiple entries.** **N-Y(-NA): Yes-No(-Unknown) options.** **FText: Free text.** **_1(-N): This implies that N fields are included which account for the alternative IM measures.**			

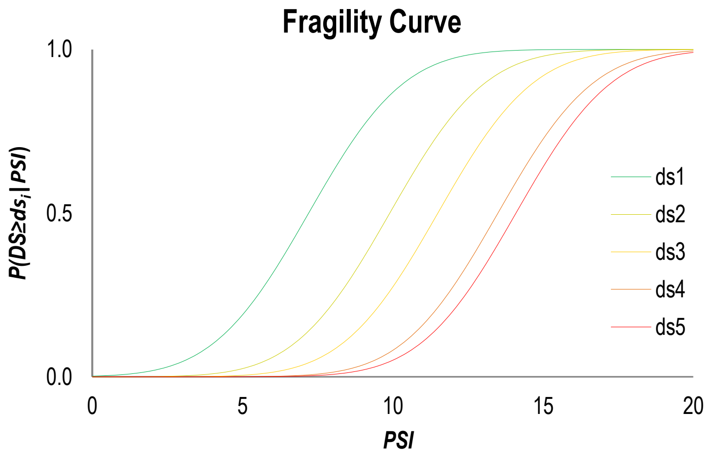


Figure 4.1. Fragility curves constructed by Karababa and Pomonis (2010).

Table 4.2. Parameters of the fragility curves (mean μ and standard deviation σ) constructed by Karababa and Pomonis (2010).

DS	*M*	σ
ds_1	7.2	2.5
ds_2	9.9	2.5
ds_3	11.5	2.5
ds_4	13.5	2.5
ds_5	14.1	2.5

4.2 Global Coverage of Existing Empirical Vulnerability and Fragility Functions

The compendium includes existing empirical vulnerability and fragility functions, which provide loss or damage for at least two intensity measure levels. The compendium contains 245 empirical functions (see Appendix A). Fragility functions constitute approximately 80% of these functions. Of the included 55 empirical vulnerability functions, 65% are obtained directly from loss data. 80% of the reviewed existing vulnerability functions express loss as the economic loss due to direct damage sustained by affected buildings, whilst the remaining 20% as casualties in both cases using varying definitions of loss. There is a single function that correlated the downtime with a single level of ground motion intensity and for this reason, it is not included in the compendium.

Vulnerability and fragility functions have been constructed for only a few seismic-prone countries as depicted in **Figure 4.2**. In particular, **Figure 4.2**a shows that vulnerability functions have been constructed mainly from data from earthquakes in the USA or by combining data worldwide. A very different picture is presented in **Figure 4.2**b for fragility functions, which have mainly been developed from data obtained from events in Southern Europe and Japan.

The fragility curves have overwhelmingly been constructed for building classes defined predominantly via construction material, followed by structural system (which in some cases includes structural irregularities), and height, in line with the first layer taxonomy used in the GEM project. With regard to construction material, more than half of the fragility functions included in the compendium correspond to reinforced concrete (RC) or masonry buildings. By contrast, the distribution of the construction material is approximately uniform for the vulnerability functions.

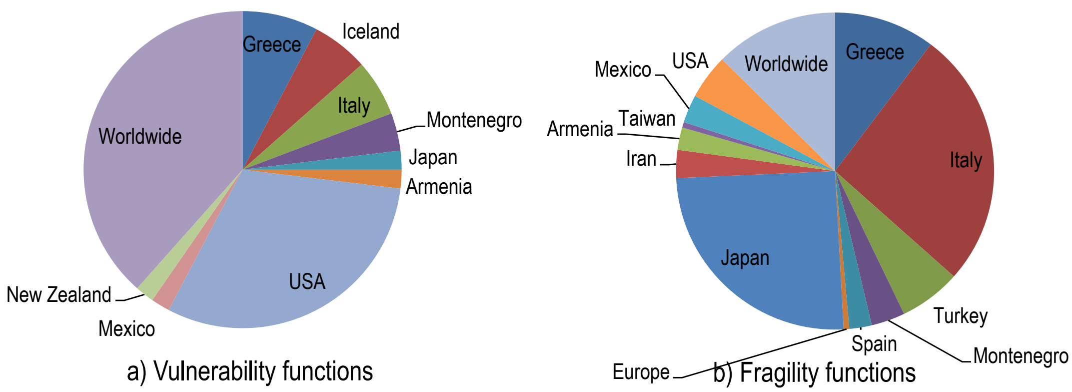


Figure 4.2. Distribution of reviewed a) vulnerability and b) fragility functions according to the country/countries of data origin.

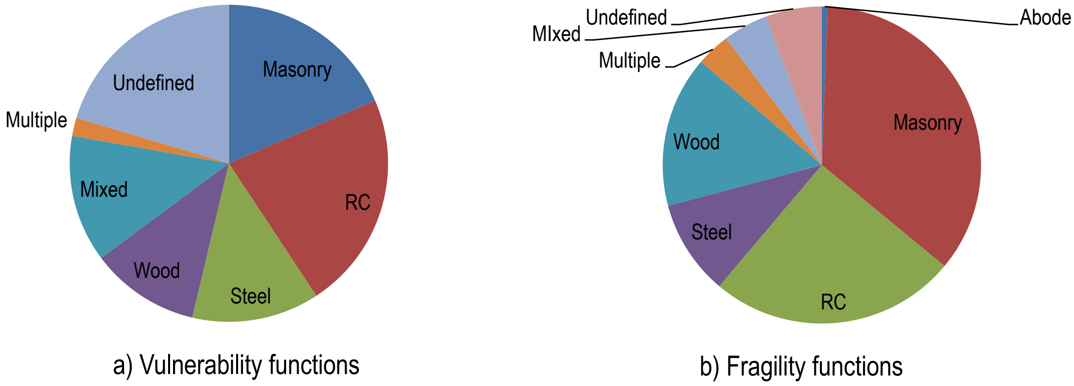


Figure 4.3. Frequency of construction material used in the reviewed a) vulnerability and b) fragility functions.

Most (over 60%) of the reviewed vulnerability functions have been based on multiple databases as depicted in **Figure 4.4**a. By contrast, most empirical fragility functions are based on data from a single earthquake, as depicted in **Figure 4.3**b. As mentioned in Section 2.6, single event damage/loss data often covers a small range of IM levels and typically contains few observations for high levels of loss or damage.

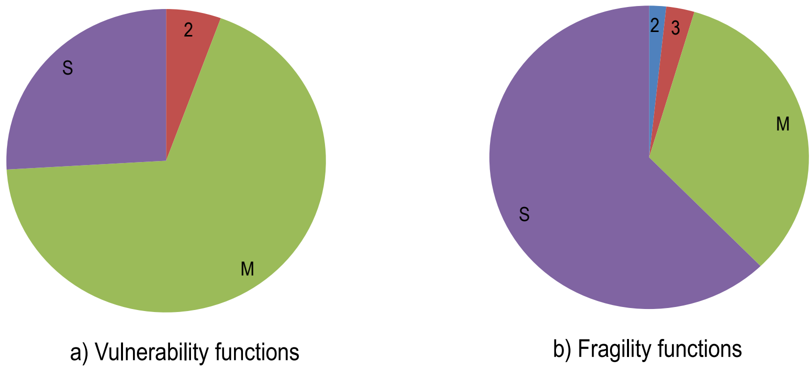


Figure 4.4. Distribution of reviewed a) vulnerability b) fragility functions according to whether they use one or more database.

The adopted intensity measure type is also a significant factor for the future application of a vulnerability or fragility relationship (see Section 2.3). **Figure 4.4**a depicts the distribution of measures of intensity in the vulnerability studies. It is observed that macroseismic intensity types, (mostly MMI followed by MSK), are predominant in the reviewed vulnerability studies, with peak ground acceleration (PGA) also being a popular choice. Earthquake magnitude has been used for the construction of vulnerability functions, which functions show high levels of uncertainty. A greater variety of intensity measure types have been used in the fragility literature as illustrated in **Figure 4.4**b. Macroseismic intensities are still the most frequently observed when all the literature is considered together, but are seen to appear less frequently in recent fragility functions. Peak and spectral ordinates of strong ground motion are also popular with PGA and PGV dominating the recent literature. The use of other measures (e.g. Housner Intensity in Rota et al. 2008b), also appears to be significant. However, most such functions derive from a single study, King et al, (2000) who constructed fragility curves for the same database for over 20 intensity measure types.

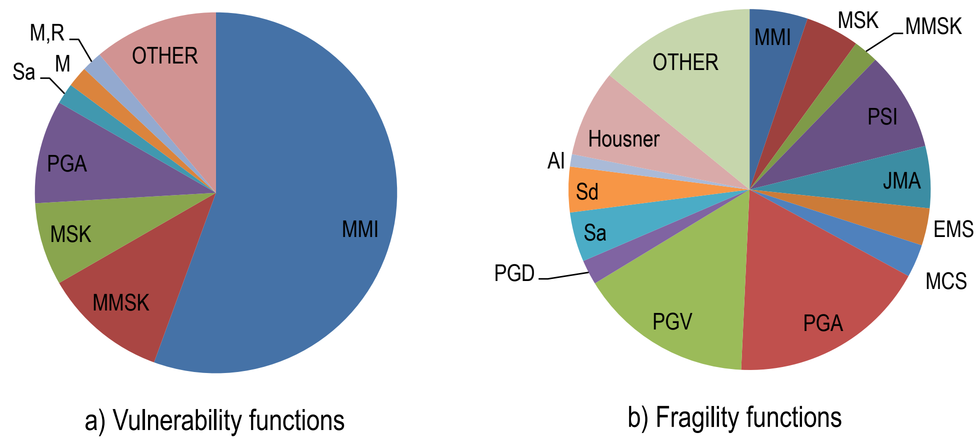


Figure 4.5. Frequency of ground motion intensity measures used in the reviewed a) vulnerability and b) fragility functions.

4.3 Harmonisation of Damage and Intensity Measures for Comparison of Existing Functions

Comparison of existing vulnerability or fragility functions may be desirable for validation purposes, sensitivity checking or to help choose a relationship for use in seismic risk assessment. This is straightforward if two functions for identical building classes exist with the same IM and loss parameter/damage scale. However, this is not usual, as multiple taxonomies are seen to exist in the empirical functions even for the same geographic area. Structures of different heights, seismic codes, materials, and lateral load resisting systems can be grouped in different ways, and their damage expressed through different damage scales. Casualties, downtime, and cost can also be defined in different ways. This makes it difficult to compare existing fragility and vulnerability functions. The same differences can also be seen in the data itself, when collected by different authorities or for different earthquakes. This hinders data comparison and combination (e.g. for the development of fragility and vulnerability functions from multiple events). Vulnerability or fragility functions are also seen to vary in terms of intensity measure (IM) used, which again hinders comparison of existing functions.

Converting or mapping of damage states and intensity measures will introduce large uncertainties (e.g. see Hill, 2011) and is not recommended for quantitative comparisons. However, for qualitative comparisons, the damage state conversion tables proposed in Rossetto et al (2013) and IM conversions suggested by Cua et al (2010) could be used.

4.4 Overview of Quality Ratings of Existing Functions

In Section 3, a new rating system is proposed for empirical fragility and vulnerability relationships. The summary results of the application of this rating system to the relationships present in the compendium are presented in Appendix B. From Table B.1 and Table B.**2**, it is evident that no fragility or vulnerability relationship obtains a “High” rating in all criteria. The rating exercise highlights the profusion of data quality and quantity issues (discussed in Sections 2.2 and 2.4) in existing empirical studies. It is also clear that data quantity alone cannot be taken as a measure of relationship reliability, as some vulnerability or fragility functions that rate highly for data quantity may not have good ratings in constrained categories and excitation parameters/observations (e.g. Yang et al. 1992), which counterbalance the advantages posed by large quantities of data.

It is a real concern that there is a failure in most existing functions to appropriately treat uncertainty. Very few studies are also seen to cross-validate their proposed functions with the results of other studies, and fewer still compare their functions with independent data. Difficulties were experienced by the authors in carrying out the rating exercise caused by poor documentation regarding the survey data, almost universal lack of explanation of the rationale for selection of survey sites, unclear definition of parameters used, and lack of detail on the exact methodology followed for manipulation, combining data and generating the relationship. It is recommended that all these observations be taken into account in the development of the GEM VEM guidelines for empirical vulnerability functions.

5 Final Comments

This report provides an overview of the state of art in empirical fragility and vulnerability relationships, and presents a database of all existing such functions found by the authors in the literature. A rating system is also proposed that can be used to qualitatively assess which empirical fragility or vulnerability functions are most reliable for use in future seismic risk assessments.

Overall, it is noted that a number of authors have developed empirical seismic fragility and vulnerability functions but that the quality and geographic scope of these functions vary. Existing empirical fragility and vulnerability functions are seen to typically be based on databases associated with important quality issues, which include low levels of refinements on the building class, damage states, and often substantial non-sampling errors. Paucity of observations at high shaking intensities and damage states is common and very few detailed loss databases are available for direct vulnerability evaluation. There is no consensus in the literature concerning the functional form of empirical vulnerability and fragility functions or on best-practice methodologies for the treatment of the non-sampling and sampling errors. Instead, a variety of methods for manipulating, combining data, and curve-fitting procedures has been noted. Finally, existing studies are severely limited in their modelling and communication of uncertainty in the vulnerability or fragility assessment.

These observations highlight the need for improved protocols for the collection of loss and damage data in post-earthquake scenarios, in order to provide a sound base for the derivation of future empirical fragility and vulnerability functions. There is also an urgent need for a rational, statistically correct, widely accepted approach to be developed for the construction of empirical fragility and vulnerability, which explicitly quantifies and models the uncertainty in the data and clearly communicates the uncertainty in the vulnerability or fragility functions. To provide such guidance is the aim of the GEM vulnerability estimation methods working group.

REFERENCES

Access, M. [2010] MS Access.

Akkar S., Bommer J. [2007] "Prediction of elastic displacement responce spectra in Europe and the Middle East", Earthquake Engineering & Structural Dynamics, Vol. 36, No. 10, pp. 1275-1301.

Allen T.I., Wald D.J., Worden C.B. [2011] "Prediction of macroseismic intensities for global active crustal earthquakes", Journal of Seismology, Vol. 16, No. 3, pp. 409-433.

Amiri G.G., Jalalian M., Amrei S.A.R. [2007] ''Derivation of vulnerability functions based on observational data for Iran'', Proceedings of International Symposium on Innovation & Sustainability of Structures in Civil Engineering, Tongji University, China.

ATC-20 [1989] ''Procedures for post-earthquake safety evaluation of buildings'', Report, Applied Technology Council, 555 Twin Dolphin Drive, Suite 550, Redwood City, California 94065.

Baggio C., B. A., Colozza R., Corazza L., Della Bella M., Di Pasquale G., Dolce M., Goretti A., Martinelli A., Orsini G., Papa F., Zuccaro G. [2000] ''Field manual for the 1 level post-earthquake damage, usability and emergency measures form'', Report.

Baker J. [2011] Fitting fragility functions to structural analysis data using maximum likelihood estimation Working Paper -PEER.

Baker J.W., Cornell C.A. [2006] "Which spectral acceleration are you using?", Earthquake Spectra, Vol. 22, No. 2, pp. 293-312.

Benedetti D., Benzoni G., Parisi M.A. [1988] "Seismic vulnerability and risk evaluation for old urban nuclei", Earthquake Enginnering & Structural Dynamics, Vol. 16, No. 2, pp. 183-201.

Bevington J., Adams B., Verrucci E., Rossetto T., Evans R., Amyx P., H. M. [2010] ''The Virtual Disaster Viewer: Understanding disasters through shared knowledge. The story so far...'', Proceedings of 7th International Workshop on Remote Sensing for Disaster Management University of Texas at Austin, MCEER.

Booth E., S. K., Spence R., Madhabushi G., Eguchi R.T. [2011] "Validating assessments of seismic damage made from remote sensing", Earthquake Spectra, Vol. 27, No. S1, pp. S157-S177.

Braga F., Dolce M., Liberatore D. [1982] ''Southern Italy November 23, 1980 earthquake: a statistical study of damaged buildings and an ensuing review of the M.S.K.-76 scale'', Report, Rome, Italy.

Clasen C. [2010] '' A comparative study of the 2010 Haiti earthquake damage using a proposed semi-automated methodology and community remote sensing method'', Report, MSc Thesis for MSc Remote Sensing, University College London.

Coburn A.W., Spence R.J.S. [2002] ''Earthquake protection'', John Wiley and Sons, Chichester, UK.

Cochrane S.W., Schaad W.H. [1992] ''Assessment of earthquake vulnerability of buildings'', Proceedings of 10th World Conference on Earthquake Engineering, Madrid, Spain.

Colombi M., Borzi B., Crowley H., Onida M., Meroni F., Pinho R. [2008] "Deriving vulnerability curves using Italian earthquake damage data", Bulletin of Earthquake Engineering, Vol. 6, No. 3, pp. 485-504.

Comerio M.C. [2006] "Estimating Downtime in Loss Modeling", Earthquake Spectra, Vol. 22, No. 2, pp. 349-365.

Crowley H., Pinho R., Bommer J. [2004] "A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation ", Bulletin of Earthquake Engineering, Vol. 2, No. 2, pp. 173-219.

Cua G., Wald D. J., Allen T. I., Garcia D., Worden C.B, Gerstenberger M., Lin K., Marano K. [2010] '' „Best Practices” for using macroseismic intensity and ground motion intensity conversion equations for hazard and loss models in GEM'', Report, GEM Foundation, Pavia, Italy.

D'Ayala D., Meslem A. [2015] ''Guide for selection of existing analytical fragility curves and compilation of the database'', Report, GEM Foundation, Pavia, Italy.

Dandoulaki M., Panoutsopoulou M., Ioannides K. [1998] ''An overview of post-earthquake building inspection practices in Greece and the introduction of a rapid building usability evaluation procedure after the 1996 Konitsa earthquake'', Proceedings of 11th European Conference on Earthquake Engineering, Paris, France.

De Bruycker M, Greco D, L. M.F. [1985] "The 1980 earthquake in Southern Italy: mortality and morbidity", International Journal of Epidemiology, Vol. 14, pp. 113-117.

Decanini L.D., De Sortis A., Goretti A., Liberatore L., Mollaioli F., Bazzurro P. [2004] "Performance of Reinforced Concrete Buildings During the 2002 Molise, Italy, Earthquake", Earthquake Spectra, Vol. 20, No. S1, pp. S221-S255.

Di Pasquale G., Orsini G., Romeo R.W. [2005] "New developments in seismic risk assessment in Italy", Bulletin of Earthquake Engineering, Vol. 3, No. 1, pp. 101-128.

Dias W. P. S., Yapa H. D., Peiris L. M. N. [2009] "Tsunami vulnerability functions from field surveys and Monte Carlo simulation", Civil Engineering and Environmental Systems, Vol. 26, No. 2, pp. 181-194.

Dolce M., Kappos A., Masi A., Penelis G., Vona M. [2006] "Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies", Engineering Structures, Vol. 28, No. 3, pp. 357-371.

Dolce M., Masi A., Goretti A. [1998] ''Damage to buildings due to 1997 Umbria-Marche earthquake'', Proceedings of International Workshop on Measures of Seismic Damage to Masonry Buildings, Monselice, Padova, Italy.

Dowrick D.J. [1991] "Damage costs for houses and farms as a function of intensity in the 1987 Edgecumbe earthquake", Earthquake Engineering & Structural Dynamics, Vol. 20, No. 5, pp. 455-469.

Dowrick D.J., Rhoades D.A. [1990] "Damage costs for domestic buildings in the 1987 Edgecumbe earthquake", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 23, No. 2, pp. 137-149.

Earthquake Planning and Protection Organisation [1997] ''Guidelines and forms for immediate post-earthquake screening of reinforced concrete buildings (in Greek)'', Report, Athens, Greece.

Eleftheriadou A.K., Karabinis A.I. [2008] ''Damage probability matrices derived from earthquake statistical data'', Proceedings of 14th World Conference on Earthquake Engineering, Beijing, China.

Eleftheriadou A.K., Karabinis A.I. [2011] "Development of damage probability matrices based on Greek earthquake damage data", Earthquake Engineering and Engineering Vibration, Vol. 10, No. 1, pp. 129-141.

Faccioli E., Cauzzi C., Paolucci R., Vanini M., Villani M., D. Finazzi [2007] ''Long period strong ground motion and its use as input to displacement based design'', Earthquake Geotechnical Engineering: 4th International Conference on Earthquake Geotechnical Engineering - Invited lectures'', Pililakis K.D., Springer, Netherlands.

FEMA 547 [2007] ''Techniques for the seismic rehabilitation of existing buildings'', Report, Federal Emergency Management Agency.

FEMA [1999] ''HAZUS: Earthquake loss estimation methodology, Technical manual SR2'', Report, Federal Emergency Management Agency through aggreements with National Institude of Buildings Science, Washington D.C., USA.

Ferreira M.A., Oliveira C.S., M. d. S. F. [2011] ''Estimating human losses in earthquake models: A discussion'', Human Casualties in Earthquakes: Progress in Modelling and Mitigation'', Spence R., S. E.K.M and S. C., Springer, London.

Florova N., Larionov V., Bonnin J. [2011] ''Earthquake casualties estimation in emergency mode'', Human Casualties in Earthquakes: Progress in Modelling and Mitigation'', Spence R., So E.K.M and Scawthorn C., Springer, London, UK.

Giovinazzi S., Lagomarsimo S. [2006] "Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings", Bulletin of Earthquake Engineering, Vol. 4, No. 4, pp. 415-443.

Goretti A., Di Pasquale G. [2002] ''An overview of post-earthquake damage assessment in Italy'', Proceedings of EERI invitational workshop: An action plan to develop earthquake dmage and loss data protocols, Pasadena, California, Earthquake Engineering Research institute.

Goretti A., Di Pasquale G. [2004] "Building inspection and damage data for the 2002 Molise, Italy earthquake", Earthquake Spectra, Vol. 20, No. S1, pp. 167-190.

Grant D.N. [2011] "Response spectral matching of two horizontal ground-motion components", Journal of Structural Engineering, Vol. 137, No. 3, pp. 289-297.

Grünthal G. [1998] ''European macroseismic scale 1998'', Report, Vol. 15, Cahiers du Centre Européen de Géodynamique et de Séismologie, Luxembourg.

Gűlkan P., Sucuoğlu H., Ergűnay O. [1992] ''Earthquke vulnerability, loss and risk assessment in Turkey'', Proceedings of 1th World Conference on Earthquake Engineering Madrid, Spain.

Hancilar U., Taucer F., Corbane C. [2011] ''Empirical fragility assessment after the January 12, 2010 Haiti earthquake'', Risk Analysis VIII'', B. C.A., WIT Press, Southampton, UK.

Hill M., Rossetto T. [2008] "Comparison of building damage scales and damage descriptions for use in earthquake loss modelling in Europe", Bulletin of Earthquake Engineering, Vol. 6, No. 2, pp. 335-365.

Hill M.P. [2011]. ''A framework for the seismic risk assessment of existing buildings in Europe'', PhD Thesis, University College London, London.

Ioannou I., Rossetto T., Grant D.N. [2012] ''Use of regression analysis for the construction of empirical fragility curves'', Proceedings of 15th World Conference on Earthquake Engineering, Lisbon, Portugal.

Jaiswal K., Aspinal W.P., Perkins D, Wald D., Porter K.A. [2012] ''Use of expert judgement to estimate seismic vulnerability of selected building types'', Proceedings of 15th World Conference on Earthqueak Engineering, Lisbon, Portugal.

Jaiswal K., Wald D. [2010] "An empirical model for global earthquake fatality estimation", Earthquake Spectra, Vol. 26, No. 4, pp. 1017-1037.

Jaiswal K., Wald D. [2013] "Estimating economic losses from earthquakes using an empirical approach", Earthquake Spectra, Vol. 29, No. 1, pp. 309-324.

Jaiswal K.S., Wald D.J., Hearne M. [2009] ''Estimating casualties for large worldwide earthquakes using an empirical approach'', Report, U.S.G.S. .

Jara M., Guerrero J.J., Aguilar J. [1992] ''Seismic vulnerability of Mexico City buildings'', Proceedings of 10th World COnference on Earthquake Engineering, Madrid, Spain.

Karababa F.S., Pomonis A. [2010] "Damage data analysis and vulnerability estimation following the August 14, 2003 Lefkada Island, Greece, Earthquake", Bulletin of Earthquake Engineering, Vol. online.

King S., Kiremidjian A., Sarabandi P., Pachakis D. [2005] ''Correlation of observed building performance with measured ground motion'', Report, Department of Civil and Environmental Engineering, Stanford University USA.

Koshimura S., O. T., Yanagisawa H., Imamura F. [2009] "Developing fragility functions for tsunami damage estimation using numerical model and post-tusnami data from Banda Aceh, Indonesia", Coastal Engineering Journal, Vol. 51, No. 3.

Lagorio H.J. [1990] ''Status of medical inputs to vulnerability studies conducted by the U.S. Federal and State agencies'', Proceedings of International Workshop on Earthquake Injury Epidemiology: Implications for Mitigations and Response, Reston VA/Baltimore MD, U.S. Geological Survey.

Lallemant D., Kiremidjian A.S. [2012] ''Fitting fragility curves to empirical data'', Report, GEM foundation, Pavia, Italy.

Levy P.S., Lemeshow S. [2008] ''Sampling of Populations: Methods and Applications, 4th edition'', John Wiley & Sons, New Jersey, USA.

Li Y, Wu Z., Zhao Y. [2011] "Estimating the number of casualties in earthquakes from early field reports and improving the estimate with time", Natural Hazards, Vol. 56, No. 3, pp. 699-708.

Liel A.B., Lynch K.P. [2009] "Vulnerability of reinforced concrete frame buildings and their occupants in the 2009 L'Aquila", Natural Hazards Review, Vol. In press.

Miyakoshi J., Hayashi Y., Tamura K., Fukuwa N. [1998] ''Damage ratio functions of buildings using damage data of the 1995 Hyogo-Ken Nambu earthquake'', Proceedings of 7th International Conference on Structural Safety and Reliability, Kyoto, Japan.

Murakami H.O. [1992] ''A simulation model to estimate loss for occupants of collapsed buildings in an earthquake'', Proceedings of 10th World Conference on Earthquake Engineering, Madrid, Spain.

Nations, U. [1964] ''Recommendations for the Preparation of Sample Survey Reports (Provisional Issue)'', Report, Statistical Papers, Series C, ST/STAT/SER.C/1/Rev.2, New York, USA.

Nichols J.M., Beavers J.E. [2003] "Development and calibration of an earthquake fatality function", Earthquake Spectra, Vol. 19, No. 3, pp. 605-633.

Orsini G. [1999] "A model for buildings' vulnerability assessment using the parameterless scale of seismic intensity (PSI)", Earthquake Spectra, Vol. 15, No. 3, pp. 463-483.

Petal M. [2011] ''Earthquake casualties research and public education'', Human casualties in earthquakes: Progress in modelling and mitigation'', Spence R., So E. and S. C., Springer, London.

Petrovski J., Milutinovic Z. [1990] ''Development of Vulnerability Functions Based on Empirical Data from September 19, 1985 Michoacan, Mexico Earthquake'', Proceedings of 9th European Conference on Earthquake Engineering, Moscow, USSR.

Petrovski J., Stankovic V., Nocevski N., Ristic D. [1984] ''Development of Empirical and Theoretical Vulnerability and Seismic Risk Models'', Proceedings of 8th World Conference on Earthquake Engineering San Francisco, California, USA.

Pomonis A., Coburn A.W., et al. [1992] ''Part three: casualty estimation in the collapse of reinforced concrete buildings, human casualties in building collapse - second year report'', Report, Cambridge, U.K.

Porter K., Jaiswal K., Wald D.J., Greene M., Comartin C. [2008] ''WHE-PAGER Project: A new initiative in estimation global building inventory and its seismic vulnerability'', Proceedings of 14th World Conference on Earthquake Engineering, Beiijing, China.

Porter K., Kennedy R., B. R.. [2007] "Creating fragility functions for performance-based earthquake engineering", Earthquake Spectra, Vol. 32, No. 2, pp. 471-489.

Porter K.A., Farokhnia K., Cho I.H., Rossetto T., Ioannou I., Grant D., Jaiswal K., Wald D., D' Ayala D., Meslem A., So E., Kiremidjian A.S., Noh H-Y. [2012] ''Global vulnerability estimation methods for the global earthquake model'', Proceedings of 15th World Conference on Earthquake Engineering.

Priestley M.J.N., Calvi G.M., Kowalsky M.J. [2007] ''Displacement-based seismic design of structures'', IUSS, Pavia, Italy.

Roca A., Goula X., Susagna T., Chávez J., González M., Reinoso E. [2006] "A simplified method for vulnerability assessment of dwelling buildings and estimation of damage scenarios in Catalonia, Spain", Bulletin of Earthquake Engineering, Vol. 4, No. 2, pp. 141-158.

Rossetto T. [2004]. ''Vulnerability curves for the seismic assessment of reinforced concrete structure populations '', PhD Thesis, Imperial College, London, UK.

Rossetto T., D' Ayala D., Ioannou I., Meslem A [2014] ''Evaluation of Existing Fragility Curves'', SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk'', C. H. Pitilakis K., Kaynia A.M.,, Springer.

Rossetto T., Elnashai A. [2003] "Derivation of vulnerbaility functions for European-type RC structures based on observational data", Engineering Structures, Vol. 25, No. 10, pp. 1241-1263.

Rossetto T., Elnashai A. [2005] "A new analytical procedure for the derivation of displacement-based vulnerability curves for populations of RC structures", Engineering Structures, Vol. 27, No. 3, pp. 397-409.

Rossetto T., Free M., Hill M. [2007] "Report on building damage from the 28th April 2007 Kent (Folkestone): Earthquake and intensity evaluation", The Society for Earthquake and Civil Engineering Dynamics (SECED) Newsletter, Vol. 20, No. 3, pp. 6-10.

Rossetto T., Ioannou I., Grant D.N., Maqsood T. [2014] ''Guidelines for empirical vulnerability assessment '', Report, GEM Foundation, Pavia, Italy.

Rossetto T., Novelli V., Porter K. [2015] ''The conversion of damage and loss in GEM-VEM indirect vulnerability curve derivation'', Report, GEM Foundation, Pavia, Italy (under review).

Rossetto T., Peiris N., Alarcon J.E., So E., Sargeant S., Free M., Sword-Daniels V., Del |Re D., Libberton C., Verrucci E., Sammonds P., Faure Walker J. [2010] "Field observations from the Aquila, Italy earthquake of April 6, 2009 ", Bulletin of Earthquake Engineering, Vol. 9, No. 1, pp. 11-37.

Rota M., Penna A., Strobbia C.L. [2008] "Processing Italian damage data to derive typological fragility curves ", Soil Dynamics and Earthquake Engineering, Vol. 28, No. 10-11, pp. 933-947.

Rota M., Penna A., Strobbia C.L., Magenes G. [2008b] ''Derivation of empirical fragility curves from Italian damage data'', IUSS Press, Pavia, Italy.

Sabetta F., Goretti A., Lucantoni A. [1998] ''Empirical fragility curves from damage surveys and estimated strong ground motion'', Proceedings of 11th European Conference on Earthquake Engineering Paris, France.

Sabetta F., Pugliese A. [1996] "Estimation of response spectra and simulation of nonstationary earthquake ground motions", Bulletin of the Seismological Society of America, Vol. 86, No. 2, pp. 337-352.

Sadigh R.K., Egan J.A. [1998] ''Updated relationships for horizontal peak ground velocity and peak ground displacement for shallow crustal earthquakes. '', Proceedings of 6th US National Conference on Earthquake Engineering, Seattle, USA.

Saito K., Spence R. [2004] ''Rapid damage mapping using post-earthquake satellite images'', Proceedings of International Geoscience and Remote Sensing Symposium, IEEE International.

Samardjieva E., Badal J. [2002] "Estimation of the expected number of casualties caused by strong earthquakes", Bulletin of Seismological Society of America, Vol. 92, No. 6, pp. 2310-2322.

Sarabandi P., Pachakis D., King S., Kiremidjian A. [2004] ''Empirical fragility functions from recent earthquakes'', Proceedings of 13th World Conference on Earthquake Engineering, Vancouver, Canada.

Scawthorn C., Iemura H., Yamada Y. [1981] "Seismic damage estimation for low- and mid-rise buildings in Japan", Earthquake Engineering & Structural Dynamics, Vol. 9, No. 2, pp. 93-115.

Scholl R.E. [1974] "Statistical analysis of low-rise building damage caused by the San Fernando earthquake", Bulletin of Seismological Society of America, Vol. 64, No. 1, pp. 1-23.

Scholl R.E., Kustu O., Perry C.L., Zanetti J.M. [1982] ''Seismic damage assessment for high-rise buildings'', Report, URS/JAB 8020, URS/John A. Blume & Associates, Engineers, San Francisco, USA.

Şengezer B., Ansal A. [2007] "Probabilistic evaluation of observed earthquake damage data in Turkey", Natural Hazards, Vol. 40, No. 2, pp. 305-326.

Shiono K., Krimgold F., Ohta M. [1991] "Post-event rapid estimation of earthquake fatalities for the management of rescue activity", Comprehensive Urban Studies, Vol. 44, pp. 61-104.

So E.K.M. [2011] ''Challenges in collating earthquake casualty field data'', Human Casualties in Earthquakes: Progress in Modelling and Mitigation'', Spence R., So E.K.M. and Scawthorn C., Springer, London, UK.

Spence et al, So E. [2008] ''Estimating shaking-induced casualties and building damage for global earthquake events '', Report, Cambrige Architectural Research Ltd, Cambridge, UK.

Spence R., Bommer J., del |Re D., Bird J., Aydinoğlu N., Tabuschi S. [2003] "Comparing loss estimation with observed damage: a study of the 1999 Kocaeli earthquake in Turkey", Bulletin of Earthquake Engineering, Vol. 1, No. 1, pp. 183-113.

Spence R., So E., Jenkins S., Coburn A., Ruffle S. [2011] ''A global earthquake building damage and casualty database'', Human CAsualties in Earthquakes: Progress in Modelling and Mitigation'', S. E. K. M. Spence R., Scathorn C.,, Springer London, UK.

Spence R.J.S., Coburn A.W., Pomonis A. [1992] ''Correlation of ground motion with building damage: The definition of a new damage-based seismic intensity scale'', Proceedings of 10th World Conference on Earthquake Engineering, Balkema, Rotterdam.

Spence R.J.S., Coburn A.W., Sakai S., Pomonis A. [1991] ''A parameterless scale of seismic intensity for use in seismic risk analysis and vulnerability assessment'', Proceedings of Earthquake, Blast and Impact: Measurement and Effects of Viration, Manchester, UK, Elsevier.

Steinbrugge K.V. [1982] ''Earthquake, Volcanoes and Tsunamis: An anatomy of hazards'', Skandia America Group, New York, USA.

Tavakoli B., Tavakoli S. [1993] "Estimating the vulnerability and loss functions of residential buildings", Natural Hazards, Vol. 7, No. 2, pp. 155-171.

Thiel C.C., Zsutty T.C. [1987] "Earthquake characteristics and damage statistics", Earthquake Spectra, Vol. 3, No. 4, pp. 747-792.

Thráinsson H. [1992] ''Damage assessment ofor two Icelandic earthquakes'', Proceedings of 10th World Conference on Earthquake Engineering, Madrid, Spain.

Thráinsson H., Sigbjörnsson R. [1994] ''Seismic vulnerability of Icelandic URC shear wall buildings'', Proceedings of 10th European Conference on Earthquake Engineering, Vienna, Austria.

Trifunac M. D. [1977] ''Forecasting the spectral amplitudes of strong earthquake ground motion'', Proceedings of Sixth World Conference on Earthquake Engineering, New Delhi, India.

United Nations [1982] ''National household survey capability programme. Non-sampling errors in household survyes: sources, assessment and control'', Report, Department of Technical Co-Operation for Development and Statistical Office, New York, USA.

Wesson R.L., Perkins D.M., Leyendecker E.V., Roth R.J., Petersen M.D. [2004] "Losses to single-family housing from ground motions in the 1994 Northridge, California, earthquake", Earthquake Spectra, Vol. 20, No. 3, pp. 1021-1045.

Whitman R.V., Reed U.W., Hong S.T. [1973] ''Earthquake damage probability matrices'', Proceedings of 5th World Conference on Earthquake Engineering, Rome, Italy.

Yamaguchi N., Yamazaki F. [2000] ''Fragility curves for buildings in Japan based on damage surveys after the 1995 Kobe earthquake '', Proceedings of 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Yamaguchi N., Yamazaki F. [2001] "Estimation of strong motion distribution in the 1995 Kobe earthquake based on building damage data", Earthquake Engineering and Structural Dynamics, Vol. 30, No. 6, pp. 787-801.

Yamazaki F., Murao O. [2000] ''Vulnerability functions for Japanese buildings based on damage data due to the 1995 Kobe earthquake'', Implication of Recent Earthquakes on Seismic Risk, Series on Innovation and Construction, Imperial College Press 2, London, UK.

Yang W.S., Slejko D., Viezzoli D. [1989] "Seismic risk in Friuli- Venezia Giulia: an approach", Soil Dynamics and Earthquake Engineering, Vol. 8, No. 2, pp. 96-105.

APPENDIX A Tabulated Data for Compendium

Table A.1. Glossary

General category	Category	Options
Source of Statistics	Country/Countries of data origin	Standard two letter abbreviations for countries (e.g. AM for Armenia, GR for Greece, IT for Italy).
	Sample size	-: The total number of buildings of all types in the dataset is not mentioned.
	No of events	S: single seismic event.
		M: ≥4 events.
		M*: Italian events only.
		M**: Events affected mainly the USA.
		M***: Mainly European events.
Quality of Surveys	Source	The name of the event on which the dataset is based.
		C: Census.
		FS: Field Study data.
	Completeness: A database is complete if all the buildings in an isoseismic unit has been surveyed.	Y: The survey is complete.
		N: Only some buildings from each isoseismic unit have been considered.
		N*: A census is used to estimate the number of undamaged buildings.
		N**: High levels of completeness have been considered.
		-: The level of completeness is not available.
	Other biases	B1: Damaged buildings from aftershocks or other main events are included.
		B2: Burnt buildings have been included in the database.
		B3: Buildings damaged by liquefaction have been included in the database.
		B4: Size of building stock estimated from projecting the size of population.
		B5: The Census and field surveys used different structural units.
		B6: Errors in compilation of the survey forms.
		B7: Data from tsunami included.
		B8: Damage was not concentrated in the vertical elements. Undamaged buildings >10 storeys. The weakest storey according to the method was not the most damaged.
		B9: The exposed population has been estimated.
		B10: Misclassification error due to remote sensing data.
		-: Biases are not mentioned.
Building classification	Structural Unit	B: Building.
		A: Apartment.
		R: Room.
		S: Structural elements.

Table A.1. Glossary (continued).

General category	Category	Options
Building classification	Material	M: Masonry.
		M: Masonry
		RC: Reinforced Concrete.
		URM: unreinforced masonry.
		S: steel.
Loss parameter	Loss	FR: fatality rate.
		FC: fatality count.
		DF: Damage factor.
Intensity Measure	Isoseismic Unit	A: Isoseismic Contour (Areas with a given intensity level).
		Co: Communities.
		D: District.
		GBB: groups of building blocks.
		IC:
		M: Municipality.
		S: sites.
		Se: Settlement.
		T: Town.
		-: the type of isoseismic unit is not available.
	Other (if other ground motion intensity measures have been adopted)	<BLANK>: No additional measures were used.
		AI: Arias Intensity.
		EPA: effective peak acceleration.
		HI: Housner Intenstiy.
		k: base shear coefficient.
		M: Magnitude of the seismic event (unspecified type).
		Ms: Surface magnitude of a seismic event.
		R: Source to site distance.
	Source of IMs	GMPE: ground motion prediction equations.
		RGM: recorded ground motion.
		TE: Empirical transformation equation from one measure to another.
Analysis		CFS: Closed Form of Solution.
		LS: Least Squares
		LLS: Linear Least Square.
		ML: Maximum Likelihood.
		NLS: Nonlinear Least Square.
		_GN: Gauss-Newton Algorithm.
		_LM: Levenberg- Marquardt Algorithm.
		_NR: Newton-Raphson Algorithm.
		_W: Weighted Least Squares.
		PP: Probability Paper.
		<Blank>: No optimisation technique was adopted.
		-: The type of optimisation technique is not mentioned.
Confidence refer to methods or ways the confidence or the quality of fit is taken into account in the literature		CI: Confidence intervals.
		I: Upper and lower intervals without levels of confidence associated with them.
		I*: intervals produced with fuzzy logic.
		K-S: Kolmogorov-Smirvov test.
		R^2: coefficient of determination.

Table A.2. Notation for the vulnerability or fragility functions

General category	Options
Vulnerability or fragility Functions	Be: Beta distribution. Bi: Binomial distribution with parameter *p*. D: Discrete values of loss given im. H: Histogram. G_PDF: Gamma Probability Density Function: $P(L=l)=\frac{1}{b^a\Gamma(a)}l^{a-1}\exp\left(-\frac{1}{b}\right)$, with parameters a, b estimated from Eq.(A.7), Eq.(A.8). LN_CDF: Lognormal Cumulative Distribution Function, $\Phi\left(\frac{\ln(im)-\lambda}{\zeta}\right)$, λ and ζ the log mean and log standard deviation. MLP: Multi-Linear Piecewise Curve. ModBe: Modified Beta distribution. ModBi: Modified Binomial distribution. N_CDF: Normal Cumulative Distribution Function, $\Phi\left(\frac{im-\mu}{\sigma}\right)$, μ and σ the mean and standard deviation. TR_N_PDF: Truncated in [0,1] Normal Probability Density Function with parameters μ, σ estimated from Eq.(A.9), Eq.(A.10). Eq.(A.1): $P(DS\geq ds_i\|IM)=\alpha IM^b$ or $P(DS=ds_i\|IM)=\alpha IM^b$ where *α*, *b* parameters. Eq.(A.2): $P(DS=ds_i\|IM)=e^{\alpha IM}e^{bIM^2}$ where *α*,*b* parameters. Eq.(A.3): $p=\alpha_0+\alpha_1 IM+\alpha_2 IM^2+\alpha_3 IM^3$ where α_0, α_1, α_2, α_3. Eq.(A.4): $P(DS\geq ds_i\|IM)=1-\exp(-\alpha IM^b)$ where *α*, *b* parameters. Eq.(A.5): $\ln(L)=\alpha+\beta M-\ln(R)+bR$ where *α*, *β*, *b* parameters. Eq.(A.6): Log(N)=a+bM Eq.(A.7): $a=\alpha\exp\left[-\left(1+\frac{1}{\beta IM^\delta}\right)\right]$ where *α*, *β*, *δ* parameters. Eq.(A.8): $b=\alpha_0+\alpha_1 IM+\alpha_2 IM^2$ where α_0, α_1, α_2 parameters. Eq.(A.9): $\ln(\mu)=\alpha+bIM$ where *α*, *b* parameters. Eq.(A.10): $\sigma=\alpha+b\ln(IM)$ where *α*, *b* parameters. Eq.(A.11): log(fatality counts)=$-\alpha M^2+\beta M+c$

Reference	Country(ies) o data origin	Sample size	No of events	Source	Completeness	Other biases	Structural uni	Material	Structural syst	Height	Age/Design co	Isoseismic Uni	Main	Other
Whitman et al (1973)	USA	-	S	1973 San-Fernando	-	-	B		High-rise RC (-'33; 47'-) Medium-rise RC (-'47) High-rise S (-'33; 47'-) Medium-rise S (-'47)			A	MMI	
Scholl et al (1982)	Worldwide	5,676	M	FS	-	-	B		High rise RC High-rise S			A	EI	MM
Yang et al (1989)	IT	-	S	1979 Friuli,1981C	N*	-	R		Rooms built -'45 '46-'60 '61-'75			79 M	MSK	
Gűlkan et al (1992)	TR	30,000	M	FS	-	-	B		Brick M Wood RC Stone M Adobe			A	MSK	
Dolce et al (1998)	IT	4,745	S	1998 Umbria-Marche	-	-	B		M			5 M	MCS	
Spence et al (2003)	TR	-	M	FS	-	-	B		URM Low-rise RC frame (good, poor design) Mid-rise RC frame (good, poor design) C (MSK)			-	EMS-98	
Goretti and Di Pasquale (2004)	IT	23,300	S	2002 Molise	N**	B1	B		A,B,C (MSK) for masonry RC S			13 M	MCS	
Eleftheriadou and Karampinis (2008)	GR	73,468	S	1999 Athens,2001C	N*	B6	B		Non-ductile MRFs, dual frames or mixed masonry and RC load bearing systEMS-98 ('59-'85;'85-'95;'95) M with RC, S , W floors			117 M	MMI	
Braga et al (1982)	IT	29,157	S	1980 Irpinia	Y	-	B		A,B,C (MSK)			41 M	MSK	
Sabetta et al (1998)	IT	47,677	2	1980 Irpinia 1984 Abruzzo	-	-	B		A, B, C (MSK)			68 M	PGA	EPA AI
Di Pasquale et al (2005)	IT	50,000	M*	FS, 1991C	-	-	A		A, B, C1, C2 (MSK)			(>41)M	MCS	
Roca et al (2006)	ES	29,157	S	1980 Irpinia	Y	-	B		A, B, C1, C2 (MSK)			41 M	EMS-98	
Thiel and Zsutty (1987)	Mainly USA	10,971	M**	FS	-	-	B		URM (mainly) Wood Adobe RC			A	MMI	

Reference	Country(ies) of data origin	Sample size	No of events	Source	Completeness	Other biases	Structural unit	Material	Structural syst	Height	Age/Design co	Isoseismic Unit	Main	Other
Murakami (1992)	AM	2,175	S	1988 Spitak	N	-	A B		9 storey precast RC 4-5 storey composite stone 1-5 storey stone URM 1-2 storey stone URM			10T	MSK	
Spence and So (2008)	Worldwide	53,446	M	Wordwide	-		B		A-E according to EMS98			5 IC	MMI	
Pomonis et al (2011)	GR	2,950	S	1986 Kalamata		Incomplete	B		Masonry Mixed Masonry			7 Iso-seis-mal Areas	MMI	
Frolova et al (2011)	Russian, Uzbekistan, Turkmenistan Romania, Moldova, Armenia, Georgia	-	M	-			B		A,B,C,D,E7-9			-	MMSK-86	

Table A.4. Main characteristics of existing indirect methodologies developed for the construction of vulnerability functions.

Reference	Damage-to-Loss functions			Definition of loss	Confidence	Vulnerability curves
	Analysis	Form	Source			
Yang et al (1989)	CFS	BE	FD for a room	DF (dependent on class)	-	TR_N_PDF, Eq.(A.9
Spence et al (2003)	CFS	BE	FD+ Insurance Data	DF (dependent on class)	-	D (expected scenario los sites)
Spence et al (2008)	CFS	Discrete	Martin Centre	Death rate, injury rate	-	Discrete
Frolova et al (2011)	CFS	Discrete	Observed data	Fatality rate	-	Discrete
Eleftheriadou and Karabinis (2011)	CFS	BE	EJ	DF (independent of class)	-	MLP (E(*L*/*IM*)

Reference	Country(ies) c data origin	Sample size	No of events	Source	Completenes	Other biases	Structural un	Material	Structural sys	Height	Age/Design co	Isoseismic Un	Main	Other	Source of IM
Scholl (1974)	USA	1,043	S	1972 San-Fernando	-	-	S	>80% low rise wood frames >40 years old				2 S	S_a		RGM
Tavakoli and Tavakoli (1993)	IR	314,000	S	1990 Manjil	N	B4	B	Residential Hospitals Education buildings				-	PGA		TE
Scawthorn et al (1981)	JNP	60,755	S	1975 Miyagikenoki	-	-	B	Low-rise wooden frames Mid to High rise RC+SRC (3-12 storeys)				13 S	S_a(T=0.75s) S_d(T)		
Petrovksi et al (1984)	ME	40,000	S	-	-	-	B	Strengthened masonry RC frames				7Co, 700 Se	Equi-valent PGA		Recorded PGA
Petrovski and MIlutovic (1990)	MX	2,100	S	1985 Mexico City	-	-	B	5 ranges according to fundamental periods				44 S	S_a		RGM and Soil conditions
Benedetti et al (1988)	IT	500	S	1979 Friuli	-	-	B	Masonry details accounted for by the vulnerability index (VI)				M	MSK		Observed data

Reference	Country/Coun s of data origi	Sample size of surveyed buildings	No of events	Source	Completeness	Other biases	Structural uni	Material	Structural syst	Height	Age/Design cc	Isoseismic Uni	Main	Other	Source of IM
Jara et al (1992)	MX	429/200	S	1985 Mexico City FS	-	B8	B	RC up to 13 storeys.				1 Area subdivided into 2 zones	k		Surveye building drawing
Spence et al (1992)	Worldwide	70,000	M (13)	Martin Centre FS	-	-	B	Brick with ringbeam or diaphragm Unreinforced brick M Non-ductile RC frame Rubble stone M Adobe Concrete block M Dressed stone M Reinforced unit M				-	Ψ	MSK	Observe data
Orsini (1999)	IT	53,774	S	1980 Irpinia FS	Y	B6	A	A, B, C1, C2 (MSK)				41 M	Ψ	-	Observe data
Karababa and Pomonis (2010)	GR	43,353	S	2003 Leukada FS,2001C	N*	B1	B	Low-rise with: RC non-ductile frame infill (no code; code 1959;code 1984; >’95) Stone M with lime mortar, W floors (nocode,’19-’45, 46-’60, >’60) Post beam, W floors European style wood frames, W floors Non-ductile stone of brick M and RC bearing system, RC or W floors (no code; >’60)				3-33 D	Ψ	-	Interpreta of URM damage statistic
Miyakoshi et al (1998)	JNP	-	S	1995 Kobe FS1	-	B2	B	Wood frame (-’50;’51-‘60;’61-’70;’71-’80;’81-‘94) RC (-’71;’72-’81;’82-‘94) S (-’81;’82-‘94) Light Gauge S				GBB	PGV	-	RGM, overturn tombston observed c
Yamaguchi and Yamazaki (2000)	JPN	96,261	S	1995 Kobe FS2	-	-	B	Low-rise wood frames				GBB	PGV	S_a,JMA	RGM, observed c
Yamazaki and Murao (2000)	JPN	30,544	S	1995 Kobe FS3	-	B3	B	Wood frame (-’51;’52-‘61;’62-’71;’72-’81;’82-‘94) RC (>’71;’72-’81;’82-‘94) S (’71;’72-’81;’82-‘94) Light Gauge S (’71;’72-’81;’82-‘94)				GBB	PGV		RGM, observed c
Yamaguchi and Yamazaki (2000)	JPN	346,078	S	1995 Kobe FS4	-	-	B	Low-rise residential wood frames				GBB	PGV	S_a,JMA	RGM, observed c
Sabetta et al (1998)	IT	47,677	2	1980 Irpinia 1984 Abruzzo	N**	-	B	A, B, C (MSK)				68 M	PGA	-	GMPE
Sarabandi et al (2004)	USA, TWN	83	2	1994 Northridge 1999 Chi-Chi	-	B5	B	C1,C2				30 S (<1000 ft from a station)	S_d	MMI, S_a, PGA, PGV etc	RGM
Rossetto and Elnashai (2003)	Europe*	340,000	M (19)	European events mainly	-	-	B	RC				99 S	S_d	S_a,$S_{dinelastic,}$ PGA,	RGM, GM
Amiri et al (2007)	IR	686,548	3	2003 Bam 1997 Ghaen 1990 Manjil	-	-	B	Adobe M W RC				13S	S_a	PGA	RGM, GM

	Country s of data	Sample surveyed building	No of ev	Source	Complet	Other bi	Structur	Materia	Structur	Height	Age/Des	Isoseism	Main	Other	Source c	No of D
Colombi et al (2008)	IT	113,262/ 96,282	M	1980 Irpinia 1990 Sicily 1997 Umbria-Marche 1998 Umbria 1998 Pollino 2002 Molise, 1991C	N*	B6 B5	B			Low-rise M Mid-rise M Low-rise RC Mid-rise RC		M	S_d		GMPE	4
Rota et al (2008bb)	IT	163,000/ 91,394	M	1980 Irpinia 1984 Abbruzzo 1997 Umbria-Marche 1998 Pollino 2002 Molise	N**	B6	B			Mixed 1–2 Mixed X3 Reinforced concrete—seismic design 1–3 Reinforced concrete—no seismic design 1–3 Reinforced concrete—seismic design ≥4 Reinforced concrete—no seismic design ≥4 Masonry—irregular layout—flexible floors—with tie rods or tie beams 1–2 Masonry—irregular layout—flexible floors—w/o tie rods and tie beams 1–2 Masonry—irregular layout—rigid floors—with tie rods or tie beams 1–2 Masonry—irregular layout—rigid floors-w/o tie rods and tie beams 1–2 Masonry—irregular layout—flexible floors—with tie rods or tie beams ≥3 Masonry—irregular layout—flexible floors –w/o tie rods and tie beams ≥3 Masonry—irregular layout—rigid floors—with tie rods or tie beams ≥3 Masonry—irregular layout—rigid floors—w/o tie rods and tie beams ≥3 Masonry—regular layout—flexible floors—with tie rods or tie beams 1–2 Masonry—regular layout—flexible floors—w/o tie rods and tie beams 1–2 Masonry—regular layout—rigid floors—with tie rods or tie beams 1–2 Masonry—regular layout—rigid floors—w/o tie rods and tie beams 1–2 Masonry—regular layout—flexible floors—with tie rods or tie beams ≥3 Masonry—regular layout—flexible floors—w/o tie rods and tie beams ≥3 Masonry—regular layout—rigid floors—with tie rods or tie beams ≥3 Masonry—regular layout—rigid floors—w/o tie rods and tie beams ≥3 Steel All		M grouped in 10 PGA ranges	PGA	HI	GMPE	5
Liel and Lynch (2009)	IT	483	S	2009 L’ Aquila	N	-	B			RC buildings (mainly frames of various heights)		4 areas of 1 M, each building had different IM	PGA			5
Spence et al (2011)	Wordwide	40,000	M	Martin Centre	-	-	B			Brick and block masonry without an RC slab		4 isoseismal areas	MMI			6
Hancilar et al. (2011)	HT	240,672	2	Remote Sensing, Field data		B10	B			No classification, 1-2 storey simple RC frames,		15 municipalities	PGA	MMI PGV	ShakeMap	6

Reference	Country/Cou s of data orig	Sample size	No of events	Source	Completenes	Other biases	Structural ur	Material	Structural sy:	Height	Age/Design c	Isoseismic Ur	Main	Other	
Scholl (1974)	USA	205	S	FS	-	-	B	>80% low rise wood frames >40 years old				2 S	Average S_a between T=0.05 and 0.2s		
Swathorn (1981)	JNP		S	FS	-	-	B	Low-rise residential wood frames					S_a		
Steinbrugge (1982)	USA	-	M	Insurance claims mostly	-	-	B	Wood frame-small, family dwellings Wood-frame large All Metal –small All Metal-large Steel frame-earthquake resistive Steel-frame ordinary Steel frame-other RC-earthquake resistive RC-ordinary RC-precast RC-other Mixed construction-earthquake resistive Mixed construction-ordinary resistive Mixed construction-ordinary non-resistive Mixed construction-hollow masonry, adobe				4C	MMI		Repair co
Petrovski et al (1984)	ME	105	S	-	-	-	B	Strengthened masonry RC frames				7 Co,700 Se	equivalent PGA		repair and cost of r
Dowrick and Rhoades (1990)	NZ	3131	S	1987 Edgecumbe	Y		B	Houses				3 isoseismal units	MMI		Indemı prope
Thráinsson (1992)	IS	-	2	1934 and 1976 earthquakes	-	-	B	Low-rise wooden frames Unreinforced concrete shear walls				V	MMI		
Thráinsson and Sigbjörnsson (1994)	IS	-	2	1934 and 1976 earthquakes	-	-	B	Unreinforced concrete shear walls				V	M, R		
Cochrane and Schaad (1992)	W	-	M	Swiss-Re data	-	-	B	Wood frame with lights exterior wall finish Wood frame with brick veneer finish Steel frame with steel bracing or RC shear walls or with light cladding Steel frame w/o steel bracing or shear walls and with non-load bearing walls of RC, brick, glass etc RC frame with RC or M shear walls RC frame w/o shear walls but with load or non-load bearing walls of precast concrete, brick, glass etc Precast RC frame with lift slab buildings with or w/o shear walls Precast RC tilt up, reinforced masonry or reinforced hollow clock bearing (or non bearing with plaster) Unreinforced hollow block bearing				-	MMI		

Reference	Country/Countries of data origin	Sample size	No of events	Source	Completeness	Other biases	Structural unit	Material	Structural system	Height	Age/Design code	Isoseismic Unit	Main	Other	
Comerio (2006)	USA	~ 440,000 400	S	1994 Northridge 1989 Loma Pieta	-	-	B	Single family buildings, mobile homes, multi-family buildings							Downt from the com

Table A.9. Main characteristics of existing direct methodologies developed for the construction of vulnerability functions (fatalities

	Source of statistics				Quality of Surveys		Building Classification					Intensity Measure			Loss
Reference	Country/Countries of data origin	Sample size	No of events	Source	Completeness	Other biases	Structural unit	Material	Structural system	Height	Age/Design code	Isoseismic Unit	Main	Other	Definition
Samardjieva and Badal (2002)	Worldwide	-	M	1900-1950 1950-1999	B9	-						IC	M, MSK		Casualty count
Nichols and Beavers (2003)	Worldwide		M			-							M		Casualty count
So and Spence (2008)	Worldwide	-	M									IC	MMI		% of injured, died in b
Jaiswal et al (2009)	Worldwide	-	M	Past surveys from 1973		-						IC	MMI		FR

APPENDIX B Rating of Existing Empirical Vulnerability and Fragility Functions

Table B.1. Rating of existing direct and indirect vulnerability functions.

Reference	Data quality				Rationality				Documentation
	Data quantity	Constrained categories	Excitation observations	Damage/Loss Observations	Hindcasting	Cross validation	First Principles	Treat uncertainty	Documentation quality
Direct Vulnerability Functions for Economic Loss									
Scholl (1974)	H	M	H	H	L	L	H	L	M
Scawthorn et al (1981)	H	M	L	M	L	L	H	L	M
Steinbrugge (1982)	M	M	L	M	L	L	H	L	L
Petrovski et al (1984)	H	L	L	M	L	L	H	L	L
Dowrick and Rhoades (1990)	H	L	L	H	L	L	H	M	M
Thráinsson (1992)	M	H	L	L	L	H	H	L	L
Thráinsson and Sigbjörnsson (1994)	M	H	L	M	L	L	H	L	M
Cochrane and Schaad (1992)	M	M	M	L	L	L	H	L	L
Wesson et al (2004)	H	M	M	H	L	L	H	H	H
Vulnerability Functions for Casualty									
Murakami et al. (1992)	H	M	L	L	L	L	H	L	M
Samardjieva and Badal (2002)	H	L	L	L	L	L	H	M	M
Nichols and Beavers (2003)	H	H	L	H	L	L	H	M	M
So and Spence (2008)	H	H	L	M	L	L	H	L	M
Jaiswal and Wald (2010)	H	H	L	M	L	L	H	M	M
Frolova et al. (2011)	H	L	L	M	L	L	H	L	M
Vulnerability Functions for Downtime									
Comerio (2006)*	M	L	L	L	L	L	L	L	L
Indirect Vulnerability Functions for Economic Loss									
Yang et al (1989)	H	L	L	L	L	L	H	M	M
Jara et al. (1992)	M	L	L	H	L	L	H	L	L
Eleftheriadou and Karabinis (2011)	H	L-M	L	L	L	H	H	L	H

*It is extremely difficult to rate this function due to the lack of information provided

Table B.2. Rating of existing fragility functions.

Reference	Data quality				Rationality				Documentation
	Data quantity	Constrained categories	Excitation observations	Loss Observations	Hindcasting	Cross validation	First Principles	Treat uncertainty	Documentation quality
				DPMs					
Whitman et al (1973)	M	L	L	H	L	L	H	L	H
Scholl et al (1982)	L-H	L	M	M	L	L	H	L	H
Gűlkan et al (1992)	M	L-M	L	M	L	L	H	L	M
Spence et al (2003)	M	H	L	M	M	L	H	L	H
Goretti and Di Pasquale (2004)	H-M	M	L	H	L	L	H	H	H
Eleftheriadou and Karabinis (2011)	H	L-M	L	H	L	M	H	L	H
Braga et al (1982)	H	M	L	H	L	L	H	H	H
Sabetta et al (1998)	H	M	M	H	L	L	H	L	H
Di Pasquale et al (2005)	H	L-M	L	L	L	L	H	L	H
Roca et al (2006)	H	M	L	H	L	L	H	L	M
Şengezer and Ansal (2007)	H	M	L	M	L	L	M	M	M
Spence and So (2008)	M	L	L	H	L	L	H	L	H
Murakami (1992)	M	L	L	L	L	L	L	L	M
				Fragility curves					
Jara et al (1992)	M	H	L	H	L	L	H	L	M
Spence et al (1991)	H	L	L	H	L	L	H	L	H
Tavakoli and Tavakoli (1993)	H	L	L	L	L	L	H	L	L
Orsini (1999)	H	M	L	M	M	L	H	L	H
Karababa and Pomonis (2010)	L-H	H	M	H	L	L	H	L	H
Miyakoshi et al (1998)	H	M-H	H	M	L	H	H	L	M
Yamaguchi and Yamazaki (2000)	H	L-H	L	M	L	L-H	H	L	M
Yamazaki and Murao (2000)	H	M	L	H	L	L	H	L	M
Yamaguchi and Yamazaki (2001)	H	H	M	H	L	H	H	L	M
King et al (2005)	L-M	M	M	H	L	H	H	L	H
Rossetto and Elnashai (2003)	H	L	M	H	L	L	H	L	H
Amiri et al (2007)	H	L	L	H	L	L	L	L	L
Colombi et al (2008)	H	M	L	L	L	H	L	L	H
Rota et al (2008b)	M-H	H	M-H	H	L	H	H	L	H
Liel and Lynch (2009)	M	L	L	H	L	L	H	L	H
Frolova et al. (2011)	M	M	L	M	L	L	H	L	M
Pomonis et al. (2011)	M	M	L	L	L	L	H	L	H
Spence et al. (2011)	M	M	L	L	L	L	H	L	M
Ioannou et al (2012)	H	L	L	M	L	L	H	M	H
				Alternative fragility functions					
Scholl (1974)	M	M	H	H	L	L	H	L	H
Tavakoli and Tavakoli (1993)	H	L	L	L	L	L	H	L	M
Scawthorn et al (1981)	L-M	L-M	L	L	L	L	L-H	L	H
Petrovksi et al (1984)	H	L	L	M	L	L	H	L	L
Petrovski and MIlutovic (1990)	H	L	L	M	L	L	H	L	L
Benedetti et al (1988)	H	L	H	H	L	H	H	M	H

THE GLOBAL EARTHQUAKE MODEL

The mission of the Global Earthquake Model (GEM) collaborative effort is to increase earthquake resilience worldwide.

To deliver on its mission and increase public understanding and awareness of seismic risk, the GEM Foundation, a non-profit public-private partnership, drives the GEM effort by involving and engaging with a very diverse community to:

- Share data, models, and knowledge through the OpenQuake platform
- Apply GEM tools and software to inform decision-making for risk mitigation and management
- Expand the science and understanding of earthquakes.

GEM Foundation

Via Ferrata 1
27100 Pavia, Italy
Phone: +39 0382 5169865
Fax: +39 0382 529131
info@globalquakemodel.org
www.globalquakemodel.org

APRIL 2015

GLOBAL EARTHQUAKE MODEL
working together to assess risk