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The Global Earthquake Model Physical Vulnerability Database

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There are almost 50 years of research on fragility and vulnerability assessment, both key elements in seismic risk or loss estimation. This paper presents the online database of physical vulnerability models that has been created as part of the Global Earthquake Model (GEM) initiative. The database comprises fragility and vulnerability curves, damage-to-loss models, and capacity curves for various types of structures. The attributes that have been selected to characterize each function, the constraints of setting up a usable database, the challenges in collecting these models, and the current trends in the development of vulnerability models are discussed in this study. The current collection of models leverages upon the outputs of several initiatives, such as GEM's Global Vulnerability Consortium and the European Syner-G project. This database is publicly available through the web-based GEM OpenQuake-platform http://doi.org/10.13117/GEM.DATASET.VULN.WEB-V1.0

INTRODUCTION

Assessment of seismic damage and loss usually requires three main components: a seismic hazard input, an exposure model, and a set of fragility or vulnerability curves. The seismic hazard input provides information regarding the probabilistic distribution of a given intensity measure, whether just a single scenario is being considered, or all of the possible ruptures within a given region and time span. An exposure model indicates the geographical

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location of the elements exposed to the hazard and their physical characteristics, usually through the use of a building taxonomy (e.g. Brzev *et al*. 2013). In the third component, fragility curves establish the probabilities of reaching or exceeding a number of damage states conditional on a set of intensity measure levels, whereas vulnerability curves define the probability distribution of loss ratio at a number of intensity levels. The vulnerability component is of particular importance in risk mitigation, as the improvement of the seismic performance of the elements at risk may lead to a direct reduction of the likelihood of loss or damage, thus effectively reducing the potential for economic or human losses.

The development of fragility or vulnerability curves may involve the manipulation of large datasets, the use of expert elicitation, the development of computationally demanding numerical models, and the performance of complex statistical analysis, which may require advanced expertise in the various fields of earthquake engineering, together with a large investment in terms of time. For these reasons, it is important to leverage upon the wealth of existing functions that have been developed over the last decades by numerous scientists and practitioners (D'Ayala and Meslem 2012; Crowley *et al*. 2014; Rossetto *et al*. 2015).

The selection and use of existing models, such as fragility and vulnerability curves, in seismic risk analysis represents a challenging task. One of the main difficulties is that, until now, these curves are distributed across scientific journals, conference proceedings, technical reports and software manuals, rather than being accessible in a centralized repository that allows the visualization and acquisition of the main features of the curves in a straightforward and rational manner. Another important issue relates to the manner in which these curves are defined and presented. The statistical parameters employed to characterize each function can vary considerably, and in some cases only figures of the final curves are provided instead of the actual numerical values. In the latter case it is necessary to approximate the parameters defining each function, which inevitably introduces needless uncertainties and/or bias. Finally, it is often not clear which assumptions were made and which methodologies were employed during the derivation of the models, which hinders the evaluation of the reliability, accuracy and overall quality of the resulting models.

As a response to these issues, the GEM Foundation has supported the development of an online platform to store, visualize and explore a multitude of curves required to characterize the physical vulnerability of various elements exposed to seismic hazards. In addition to the already mentioned fragility and vulnerability curves, the platform also contains damage-to-loss models and capacity/pushover curves. This manuscript describes the main attributes characterizing each item in the database, the approach followed to define the structure of the database, an overview of the current graphical user interface (through GEM's OpenQuake-platform), and a description of the current trends in physical vulnerability assessment.

The development of this database has relied strongly on the outcomes of the Global Vulnerability Consortium (GVC) project (2010-2013) (Porter *et al*. 2012) launched by GEM, which includes the guidelines for developing analytical (D'Ayala *et al*. 2014; Porter *et al*. 2014) and empirical (Rossetto *et al*. 2014a) fragility/vulnerability curves, as well as recommendations for selecting existing empirical and analytical fragility/vulnerability curves (D'Ayala and Meslem, 2012, Rossetto *et al*. 2015). The fragility models collected within the European project Syner-G (Crowley *et al*. 2014) were also considered for the creation of the database, and the findings of Silva *et al*. (2014a) supported the identification of the requirements for the graphical user interface. All fragility and vulnerability curves that can be exported from the database can be used directly with the OpenQuake-engine, the open-source software of the GEM Foundation for seismic hazard and risk calculations (Pagani *et al*. 2014; Silva *et al*. 2014b).

THE GEM PHYSICAL VULNERABILITY DATABASE

MODELS INCLUDED

One of the challenges in the creation of a comprehensive and harmonized vulnerability database is the establishment of a well-accepted ontology for each model. For example, despite the fact that both Akkar *et al*. (2005) and Bonnet (2003) developed curves expressing the probability of reaching or exceeding three damage states, the former study addresses these results as fragility curves, whereas the latter adopts the term vulnerability curves. This section provides a brief description of what is meant by each of the items currently being supported by the database.

Fragility curves

Fragility curves establish the relation between the probabilities of reaching or exceeding a number of damage states and a set of intensity measure levels. These curves can be derived using analytical, empirical and expert elicitation methodologies or a hybrid combination of these. The first approach relies on numerical models or analytical formulations to represent the structural capacity of the building class, and the seismic demand is often represented by ground motion records or seismic response spectra. The combination of the capacity and the demand is usually performed through nonlinear dynamic analysis (e.g. Silva *et al*. 2014c) or nonlinear static procedures (e.g. Borzi *et al*. 2008). In the empirical approach, statistical regression analyses are applied to earthquake damage data to derive sets of fragility curves (e.g. Rossetto *et al*. 2003; Colombi *et al*. 2008). Fragility curves can also be derived based on the elicitation and pooling of the subjective opinion of a large group of experts (e.g. ATC-13 1985; Jaiswal *et al*. 2012). These are often termed judgement-based fragility curves. Finally, a combination of two or more of these approaches is also possible (i.e. the hybrid method), where for example, empirical damage data is used to calibrate analytically derived fragility curves (e.g. Singhal and Kiremidjian 1997), or numerical models are used to predict the expected distribution of damage for levels of intensity for which no empirical damage data is available (e.g. Kappos *et al*. 2006).

In the vast majority of existing fragility curves, a cumulative lognormal distribution function (parameterized by a mean and standard deviation) is employed to represent the probability of exceeding each damage state as a function of the intensity measure level. Alternatively, other probability distribution curves have been adopted (e.g. Rossetto and Elnashai 2003; Lang 2002) or even non-parametric curves have been proposed (e.g. Rossetto *et al*. 2014). For these cases, the probability of exceedance can be provided as a set of discrete values for a set of intensity measure levels. These two types of fragility curves are illustrated in Figure 1.

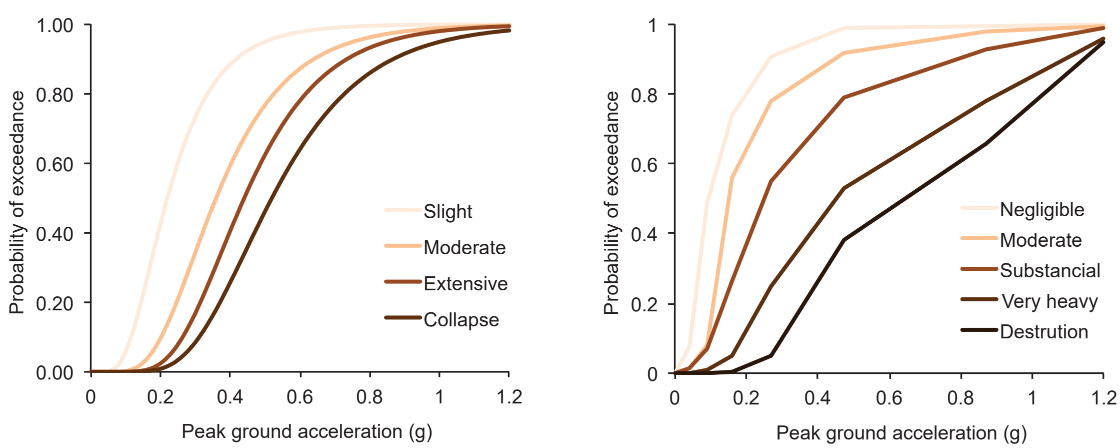

Figure 1 - Continuous fragility curves (left) for a low-code reinforced concrete moment frame in Taiwan (adapted from Liao *et al*. 2006) and discrete fragility curve (right) for old masonry structures in Lisbon (adapted from D'Ayala *et al*. 1997).

Vulnerability curves

A vulnerability curve establishes the probability distribution of the loss ratio, conditioned on an intensity measure level. Vulnerability curves can be empirically derived using loss data, usually collected through insurance claims or governmental reports. An analytical indirect approach can also be followed by coupling a set of analytical fragility curves with a damage-to-loss model (see the following sub-section) to calculate the distribution of the loss ratio at a number of intensity measure levels (e.g. Silva *et al*. 2014c). These analytical models can also be employed to directly calculate the fraction of loss at each intensity measure level, without the need to derive sets of fragility curves in this process (e.g. Martins *et al*. 2015). Within the GEM vulnerability guidelines (D'Ayala *et al*. 2014), the former approach is termed indirect, whilst the latter is called direct. This document also recommends appropriate statistical approaches for the derivation of vulnerability curves.

The variability in the loss ratio at each intensity measure level can be modeled with a continuous probability distribution function (e.g. lognormal or beta model – see e.g. Porter 2010; Maqsood *et al*. 2015), or using a discrete probability mass function (e.g. Sousa *et al*. 2015). However, since this level of uncertainty is often neglected, this feature has been defined as optional on the database, and instead it is possible to simply specify a single (mean) loss ratio for each level of intensity. In the vulnerability curve depicted in Figure 2 the variability in the loss ratio has been explicitly modeled.

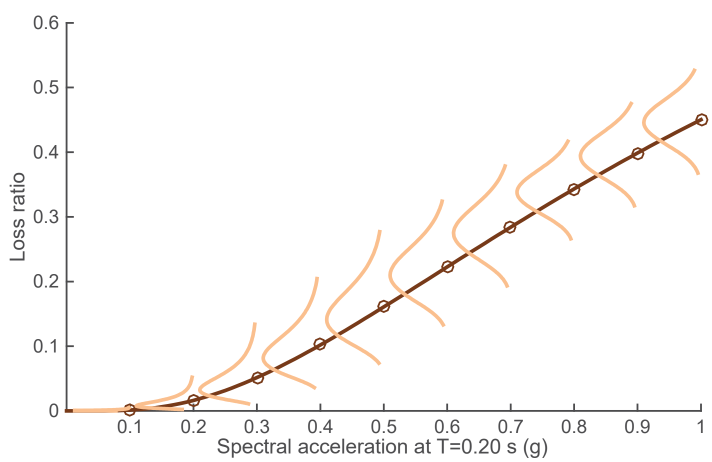

Figure 2 - Mean vulnerability curve and variability at a number of loss ratios for post-code reinforced concrete structures with 2 storeys in Portugal (adapted from Silva *et al*. 2014c).

Damage-to-loss models

Damage-to-loss models (also known as consequence models) relate physical damage with a fraction of loss (i.e. ratio between repair and replacements costs). Each model specifies a loss ratio for a number of different damage states, which can be provided as a single value (deterministic), or through the definition of a probabilistic distribution. In the latter case, a mean and coefficient of variation are usually assigned, along with the type of distribution (e.g. lognormal, beta). As previously mentioned, these models can be used to transform a fragility curve into a vulnerability curve. Thus, a damage-to-loss model has a direct impact on the vulnerability, as it defines the contribution of each damage state to the resulting loss ratio distribution per intensity measure level (Silva *et al.* 2014c).

Damage-to-loss relationships are usually derived from post-earthquake loss and damage data (e.g. Di Pasquale and Goretti 2002), and less frequently using analytical models (e.g. Martins *et al.* 2015). Figure 3 illustrates two damage-to-loss models with and without the consideration of the uncertainty around the loss ratio.

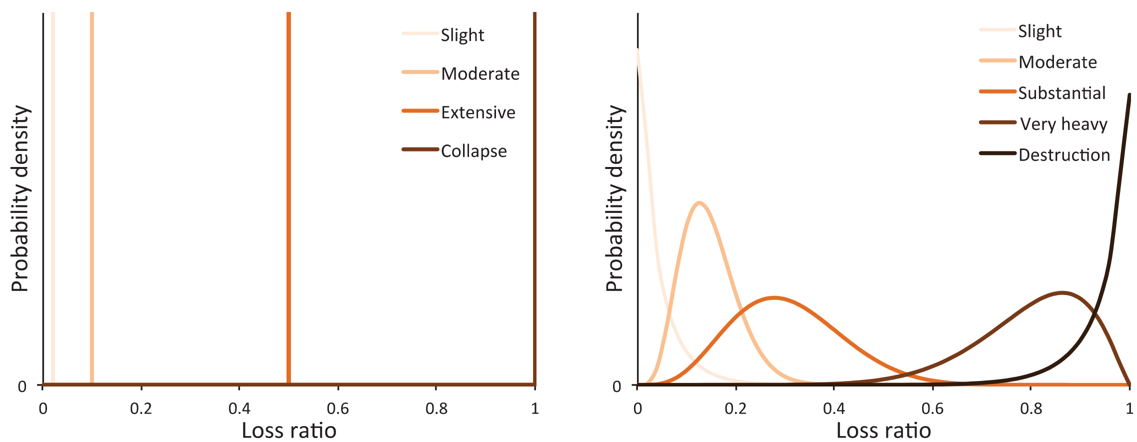

Figure 3 - Deterministic (left) and probabilistic (right) damage-to-loss models for buildings in California (FEMA-443, 2003) and Italy (Di Pasquale and Goretti, 2002), respectively.

Pushover and capacity curves

A pushover curve describes the relation between base shear and (typically) roof displacement of a structure (multi-degree-of-freedom system - MDOF) when an increasing lateral force is applied. The results of the MDOF system can be converted to what would be expected in an equivalent single-degree-of-freedom (SDOF) oscillator, leading to a representation of the capacity curve in terms of spectral acceleration versus spectral displacement. These curves are usually derived analytically (through so-called pushover analysis, e.g. Antoniou and Pinho 2004), but some examples of pushover curves derived through experimental work can also be found in the literature (e.g. Magenes *et al*. 1995). These curves can be tested against a set of ground motion records using nonlinear static procedures (e.g. N2 – Fajfar 1999; Capacity Spectrum method – Freeman 2004) to calculate fragility curves. For additional information regarding the limitations of non-linear static procedures, as well as alternative methodologies for the development of analytical fragility curves, please refer to the GEM vulnerability guidelines (D’Ayala *et al*. 2014). Figure 4 illustrates two examples of pushover and capacity curves.

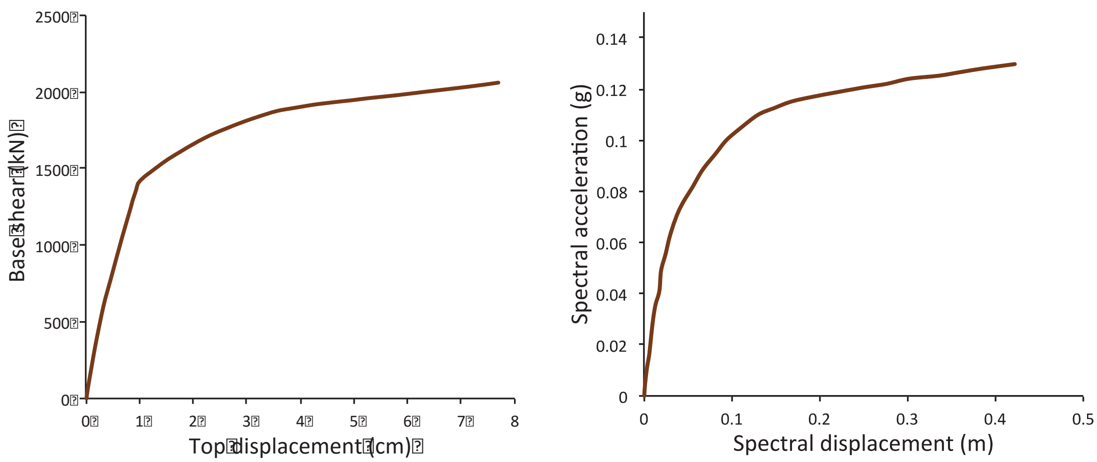

Figure 4 - Pushover curve (base shear versus top displacement - left) for a two-storey reinforced concrete structure (adapted from Martinez 2012), and capacity curve (spectral acceleration versus spectral displacement - right) for a five-storey reinforced concrete structure (adapted from Bonnet 2003).

DATABASE STRUCTURE

An extensive literature review on the assessment of seismic vulnerability, a collection of vulnerability/fragility curves (D’Ayala and Meslem, 2012; Crowley *et al*. 2014; Rossetto *et al*. 2015), a classification and evaluation of existing models (Rossetto *et al*. 2014b), and a development of tools for the management of these models (Silva *et al*. 2014a) has been performed in order to define the requirements and main fields of the database structure, as illustrated in Figure 5. This structure is organized into three main categories:

1. **General information**: which describes the geographical applicability, category of the model and guidance concerning the documentation.

2. **Type of item**: which defines the type of database item - fragility, vulnerability, damage-to-loss models, or capacity curves, along with the corresponding data (numerical values) and method of estimation (e.g. empirical, analytical).

3. **Modeling information**: which is comprised of a set of optional fields that allow the inclusion of additional information regarding the modeling process. For example, if an analytical approach was followed, the type of numerical model and uncertainty propagation method can be described.

The following sections describe the fields that can be currently specified in the database. Additional fields will be added in the future in order to accommodate the needs of more advanced users/data providers.

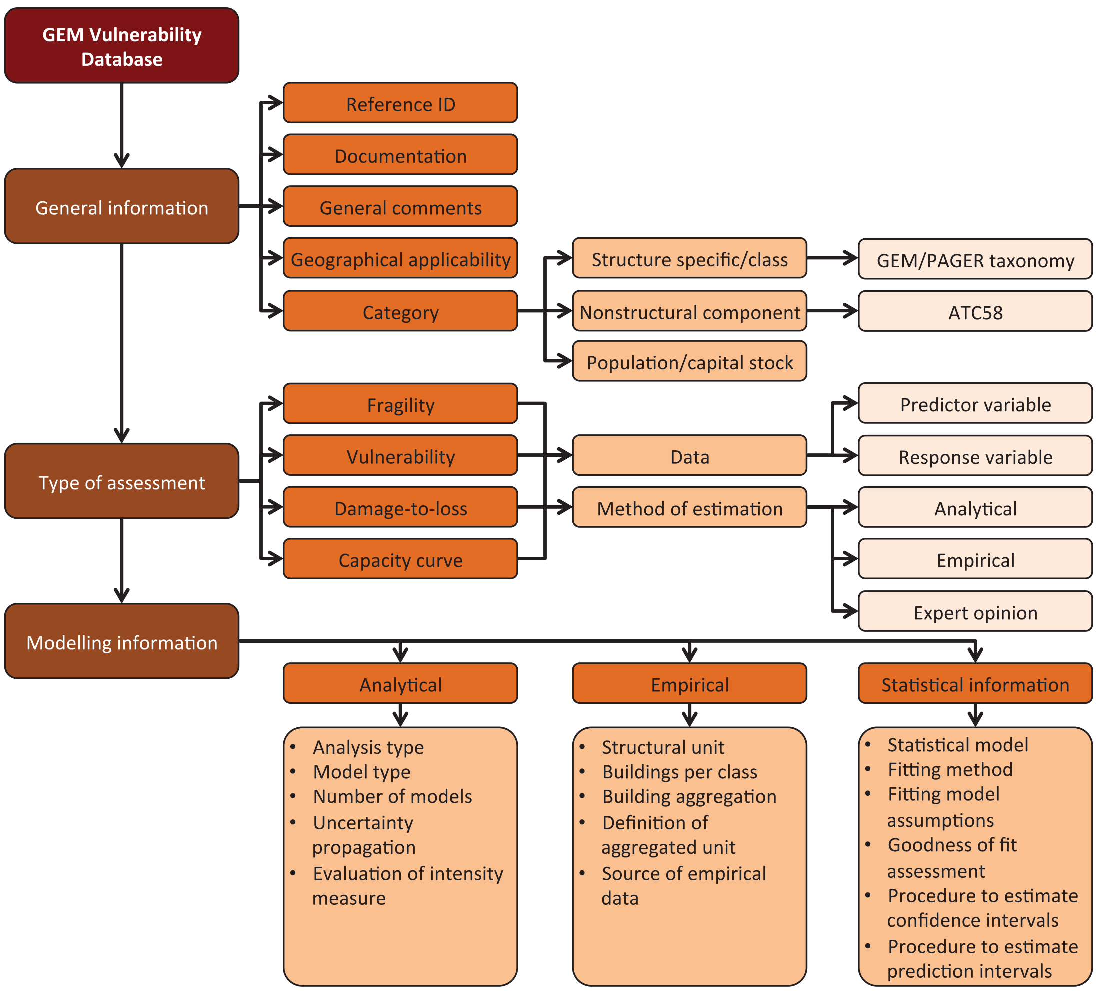

Figure 5 - General structure of the GEM Vulnerability Database.

General information (metadata)

The general information component comprises data regarding the characteristics of the element for which the model has been derived. Almost all of the attributes included in this section are mandatory, with the exception of the *general comments* and *use case information* (which provides description of case studies in which the functions have been utilized). A description for each of these attributes is provided below:

- *Reference ID*: corresponds to a unique name, defined by the user, that identifies the model in the database.

- *Documentation*: this field provides information about the authors, title of the study and type of publication (e.g. peer-reviewed journal, conference proceedings, technical report, other). When available, a web-link directing users to the online documentation can also be provided.

- *Geographical applicability*: this field provides information regarding the regional applicability of the model. There are four attributes for identifying the location of applicability of the model, and the user can select one or all of them depending on the level of information available. The first attribute is the region (e.g. Africa, South America, Europe), which represents the broadest classification. The second attribute is the country, and one or several countries can be selected, even if they are from different regions (e.g. Peru, Portugal and Iran). The third attribute is a description of the *area* where the element of interest can be found (e.g. Bogota, Quito and its metropolitan area). The last attribute is intended to specify a unique location through an address and/or the latitude and longitude coordinates.

- *Category*: this attribute identifies the type of asset (i.e. non-structural component, structural class, specific structure, population or capital stock) for which the model was developed. This attribute also allows users to provide additional information if a structural class or specific structure has been specified. In this context, a number of structural features can be described such as the construction material, lateral load resisting system, height or number of storeys and ductility level. This information can also be specified through a taxonomy string using the GEM Building Taxonomy (Brzev *et al*. 2013) or the PAGER-STR (Jaiswal *et al*. 2010) building classification. The graphical user interface of the database features a tool that can support users creating these taxonomy strings (according to the GEM

Building Taxonomy). For non-structural components the classification recommended in ATC-58 (2012) is adopted.

Type of model

This component identifies the type of model that is being introduced in the database (i.e. fragility curves, vulnerability curves, damage-to-loss models, or pushover/capacity curves). Data regarding the *predictor* (x axis) and *response* variables (y axis) that define each model are also specified within this component, along with the *approach* used to derive the model (analytical, empirical or expert opinion).

Modeling information

The options within this component depend on the *type of model* and should always be included if the documentation contains sufficient details. The main purpose of this component is to provide a better understanding of the procedures and limitations of the included models. This information has been organized into three groups: *analytical modeling*, *empirical modeling* and *statistical information*.

- *Analytical modeling*: as the name suggests, only contains information when the models have been derived using an analytical approach. It includes detailed information concerning the analysis type; structural model type; method of uncertainty propagation and the number of distinct structural models analyzed. For example, a set fragility curves could have been derived using nonlinear dynamic analysis of over a hundred different 2D element-by-element structural models, or, as described by D'Ayala *et al*. (2014), a set of index buildings could have been used to represent a class of buildings (i.e. a group of structural models that represent the overall population by capturing the joint probabilistic distribution of its most important characteristics). A larger list of attributes relevant for the assessment of the reliability of analytical fragility curves can be found in D'Ayala and Meslem (2012). For the sake of usability, only the most commonly found parameters have been included in this version of the Vulnerability Database.

- *Empirical modeling*: this group is only used if the model has been estimated using an empirical approach based on post-earthquake data. Information about the structural unit (dwelling or building), the number of buildings per class, the source of data, the level of data aggregation, the definition of aggregated unit, and range of seismic intensity measure levels can be provided.

- *Statistical information*: apart from the adopted statistical model, various sources of epistemic uncertainty and aleatory variability are involved, and it is essential to identify and quantify the different uncertainties. The following sources of uncertainty can be accounted for in the database: the statistical approach (e.g. fitting method, goodness of fit assessment) employed in the model; the uncertainties in the definition of the structural model and seismic demand; the curve fitting methodology; and the procedure for the construction of confidence and prediction intervals.

THE WEB-BASED INTERFACE OF THE DATABASE

The database was officially released at the end of 2014, through the GEM OpenQuake-platform (https://platform.openquake.org). This online web-based platform hosts a wide range of earthquake catalogues and damage databases; seismic hazard, exposure and vulnerability models; tools relevant to the development of the hazard and risk models (Weatherill *et al*. 2015; Silva *et al*. 2015); and GEM's open-source software for seismic hazard and risk calculations, the OpenQuake-engine.

The OpenQuake-platform allows each user to have their own profile, and through the web-based graphical user interface, it is possible to explore, visualize and upload any of the aforementioned curves. The main page of this interface contains four separators (one per type of model) and displays a list of all of the existing entries for the associated type of model. A filtering feature has also been developed, which provides the possibility to search models according to a number of attributes such as *Author*, *Category*, *Intensity Measure Type*, *Damage Scale, Country, Region, Method of Estimation, Material and Lateral load resisting system*. This interface is illustrated in Figure 6.

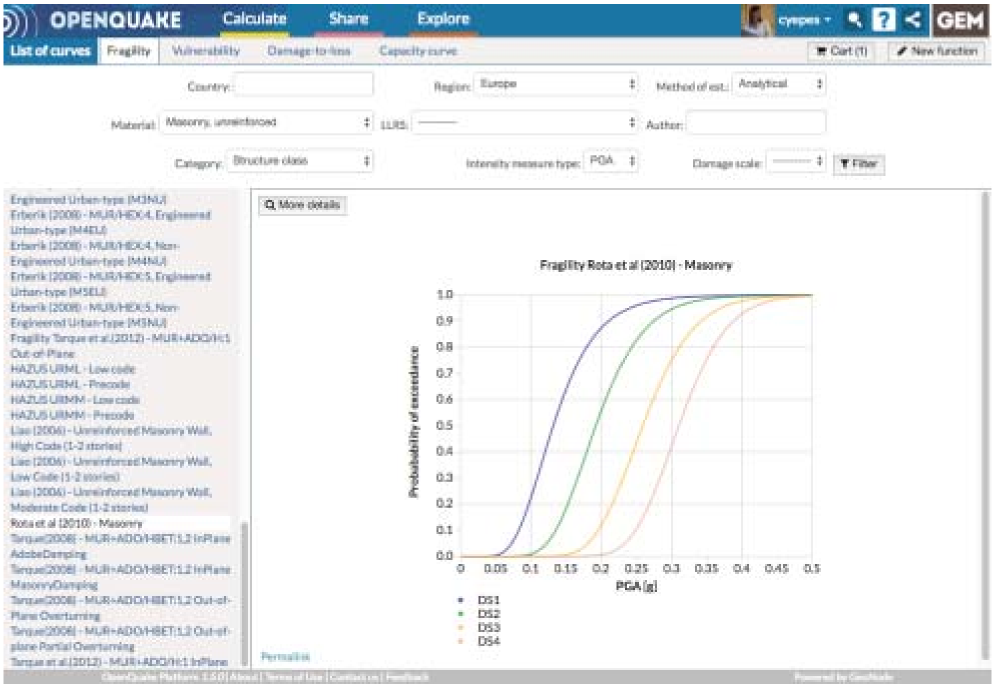

Figure 6 - Main page of the graphical user interface of the GEM Vulnerability Database.

From the main page of the user interface, it is possible to select one of the existing models, and request additional information as depicted in Figure 7. This page displays a graphical representation of the selected model, a table with the numerical parameters (e.g. mean and standard deviation for fragility curves), and detailed information concerning the database attributes described in the previous section. These attributes are organized in a number of sections: *General Information*, *Modeling Information* and *Statistical Information*. The Authors also recognize the need to evaluate the accuracy and reliability of existing models, but this first release of the Vulnerability Database does not yet support this feature. For additional information on guidelines for selection and evaluation of the available models, readers are referred to Rossetto *et al*. (2014b) and D'Ayala and Meslem (2012).

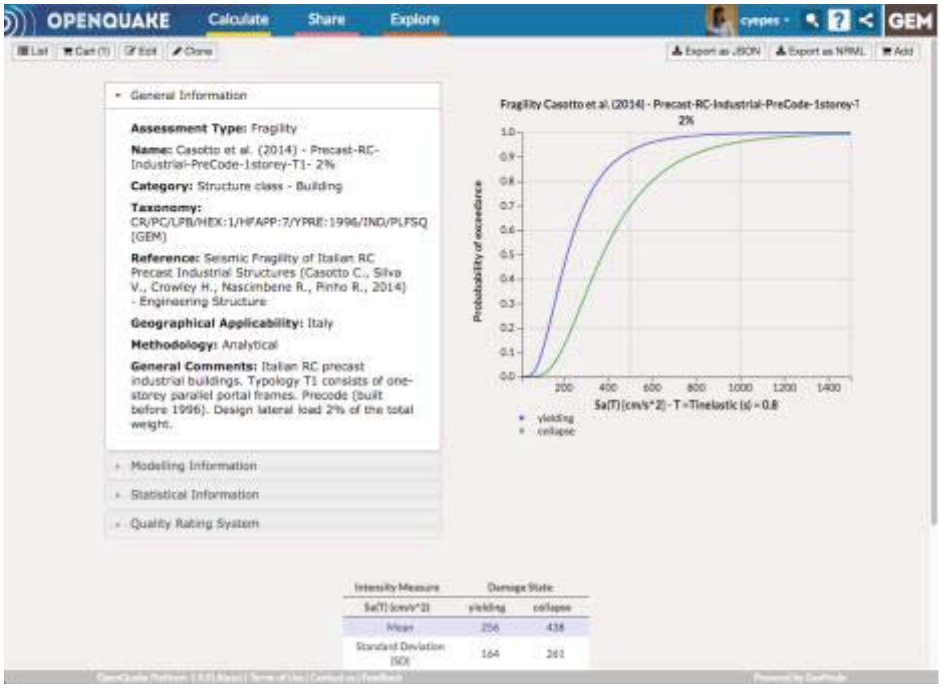

Figure 7 - Graphical user interface of the GEM Vulnerability Database for the visualization of a specific model.

Once the user has selected one or more models from the database, it is possible to export them in JSON format, or in the OpenQuake-engine format (natural hazards' risk markup language - *NRML*), and perform damage or loss calculations (granted that the necessary exposure and hazard models are available).

CURRENT TRENDS IN SEISMIC VULNERABILITY ANALYSIS

At the time of writing this paper, more than a thousand fragility/vulnerability curves, damage-to-loss models and capacity curves have been collected as a result of GEM's GVC project, the Syner-G project, and additional research performed by the GEM risk team.

Pushover and capacity curves are often generated as part of the process to develop analytical fragility/vulnerability curves, but usually not included in technical reports or scientific publications. Moreover, some of the pushover curves found in the literature have been developed with the purpose of testing a particular numerical model (e.g. Dolsek and Fajfar 2008) or analytical method for structural assessment (e.g. Chopra and Goel 2002), and not necessarily with the objective of generating a realistic set of capacity curves for fragility analyses. The Vulnerability Database currently comprises 62 pushover/capacity curves, mostly for structures in Europe and South America.

Damage-to-loss models have the lowest number of entries in the Vulnerability Database, with only 5 models for 4 countries (Turkey, Italy, Greece and United States). One of the reasons for this modest number of models is the fact that the vast majority of the existing literature is focused on damage (i.e. fragility), as opposed to losses (i.e. vulnerability).

The main focus of the Vulnerability Database is on fragility and vulnerability curves, as they can be used directly in seismic risk analyses. The GVC collected curves in two compendiums: 157 empirical fragility/vulnerability curves (Rossetto *et al.* 2015) and 145 analytical fragility curves (D'Ayala and Meslem, 2012). In the European project Syner-G (Crowley *et al.* 2014), 415 fragility curves were collected for buildings and 217 for bridges. The distribution of these models, including those collected by the GEM risk team, through time is illustrated in Figure 8. It is possible to observe that in the last decade there has been a significant increase in the generation of these curves. Some of the reasons for this increase include the release of advanced software for structural assessment and the support of large-scale projects with a strong component in vulnerability assessment like HAZUS (FEMA-443, 2003) in the United States, or RISK-EU (Mouroux and Le Brun, 2006) and LESSLOSS (Calvi and Pinho, 2004) in Europe.

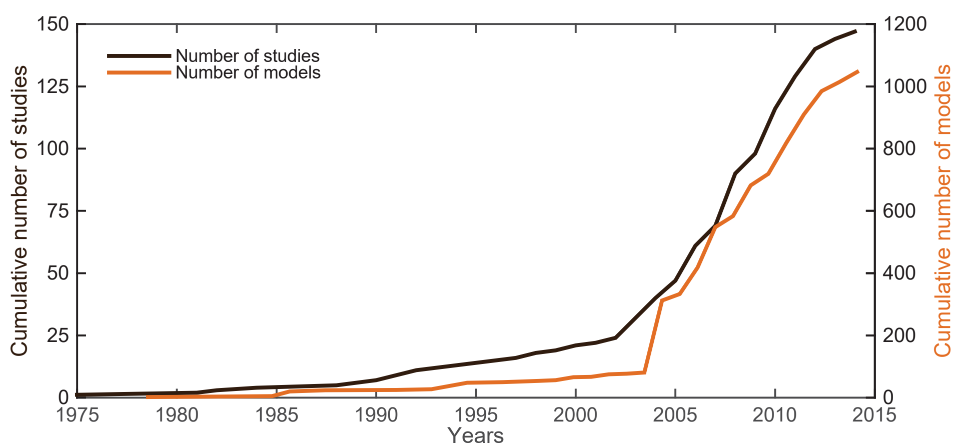

Figure 8 – Distribution with time of the models and studies that are currently included within the GEM Vulnerability Database.

Furthermore it is relevant to mention the contribution from the ATC-58 project (FEMA P-58, 2012), in which fragility and consequence functions were developed for several specific building classes. The resulting fragility and consequence database is open and available in the Performance Assessment Calculation Tool (PACT). The models developed within this project were oriented to assess the probable seismic performance of individual buildings, taking into consideration structural and non-structural components.

The geographical distribution of the Vulnerability Database is illustrated in Figure 9 in terms of number of curves, and in Figure 10 according to the number of studies. These curves are available for 36 countries, mostly located in seismic prone regions. In some cases these models have not been developed for a specific country, but rather for a region (e.g. Europe, North America or the Euro-Mediterranean countries).

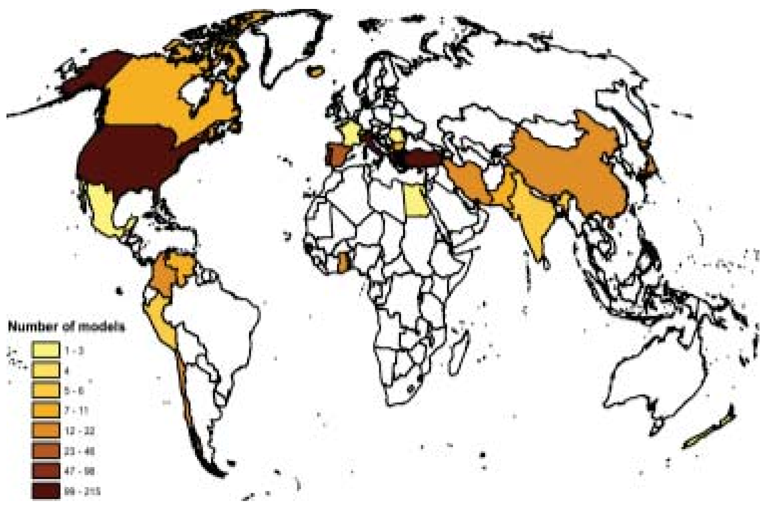

Figure 9 - Geographical distribution of the curves collected within the Vulnerability Database.

In terms of the derivation methodology, it is observed that the vast majority of the curves have been developed using an analytical approach, as depicted in Figure 10. As mentioned in several of the articles and technical reports collected in this study, one of the most frequent reasons to adopt an analytical approach is the lack of damage data to support an empirical methodology. Moreover, when these data exist, it is often statistically insufficient or characterized by a large uncertainty in the estimation of the seismic demand.

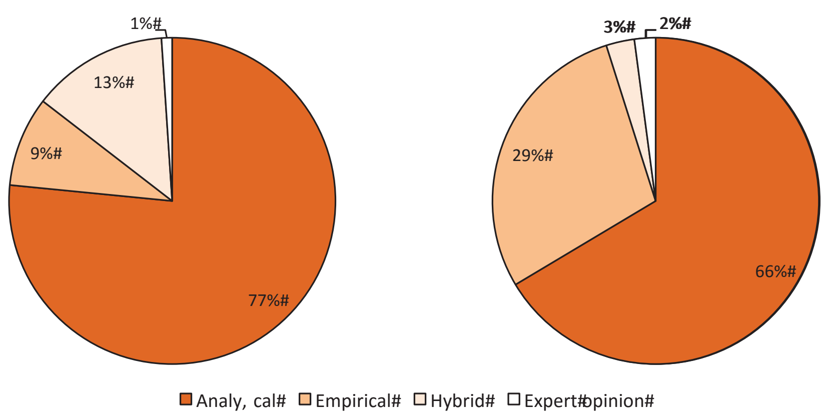

Figure 10 – Distribution of the models (left) and studies (right) in the GEM Vulnerability Database by type of derivation methodology.

Statistical analysis of the database reveals that reinforced concrete is the most studied type of construction, followed by masonry buildings, as depicted in Figure 11. It was also possible to observe that analytical methodologies are often preferred for the assessment of reinforced concrete structures, whereas empirical techniques are usually preferred for the assessment of masonry and adobe structures.

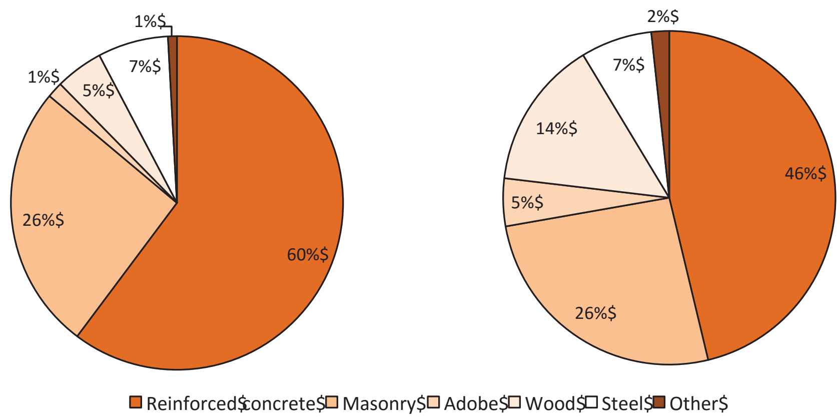

Figure 11 - Distribution of the models (left) and studies (right) in the GEM Vulnerability Database by type of construction.

In particular for fragility and vulnerability curves, the type of seismic intensity predictor has also been analyzed, considering five categories: peak ground acceleration (PGA); peak ground velocity (PGV); spectral acceleration (Sa); spectral displacement (Sd) and macroseismic intensity (MI). When spectral ordinates are adopted, the fundamental period of vibration, the period at the yielding point, or an inelastic period are frequently employed. The results in terms of number of curves and studies are presented Figure 12.

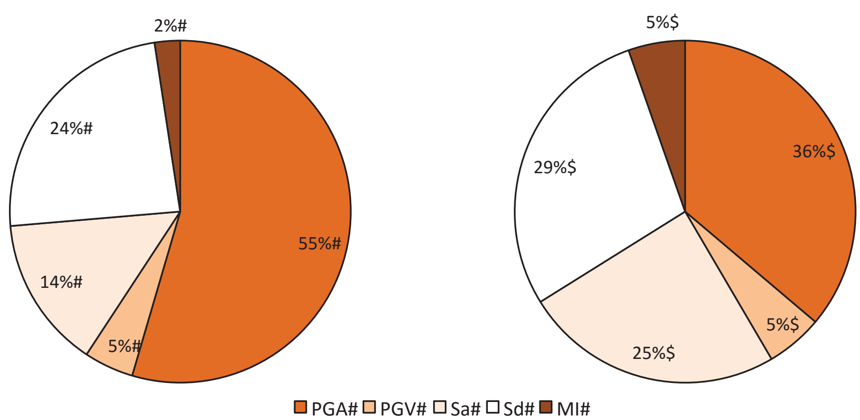

Figure 12 – Distribution of the fragility/vulnerability models (left) and fragility/vulnerability studies (right) in the GEM Vulnerability Database by type of seismic intensity predictor.

Clearly there is a preference to employ PGA in the development of fragility/vulnerability models, despite the fact that spectral ordinates tend to provide fragility/vulnerability curves with a better fit to damage data (e.g. Spence et *al*., 1992, Rossetto and Elnashai 2003). This tendency is potentially due to the wide availability of ground motion fields or hazard maps defined in terms of PGA. This analysis also reveals that macroseismic intensity is mostly used when an empirical approach is followed (thus when earthquake damage data is available), but there has been a strong decrease in the employment of this intensity measure type. In the last decade, only 5 studies have adopted macroseismic intensity. Some of the factors contributing to this decrease include the lack of attenuation models capable of predicting macroseismic intensity, or the fact that intensity and damage are correlated, which inevitably introduces a bias in the fragility curves (Rossetto *et al*. 2014a).

CONCLUSIONS

A comprehensive vulnerability database that is publicly available and includes fragility and vulnerability curves, damage-to-loss models and pushover/capacity curves for different type of structures has been created for the first time as part of the Global Earthquake Model (GEM) initiative.

The GEM Vulnerability Database has been developed with a flexible but complete architecture, through which users can indicate information regarding modelling assumptions, analysis techniques, statistical procedures and treatment of uncertainty approaches utilized to derive these models. The database is supported by a web-based graphical user interface that enables users to visualize and select a model based on a number of criteria, or to upload and edit their own curves, thus making them available to the wider community through the OpenQuake-platform.

Currently, the online database covers 62 pushover/capacity curves, 5 damage-to-loss models and 547 fragility/vulnerability curves for the most common types of construction in 36 countries, mostly located in developed countries in seismic prone areas. The database has been conceived for different categories: structure specific, structure class, non-structural components, population and capital stock. However, only curves for buildings (single structures or building classes) have been collected until now, and they come mainly from European and North American countries (more than 50% of the models have been developed for the United States, Greece, Italy and Turkey). However, it must be understood that these conclusions are conditional on the sample of models comprised in the database, which is not yet exhaustive.

The collection of models in the database has also revealed important gaps in the availability of vulnerability models in regions characterized by a high seismic risk. These include Central America (e.g. Guatemala, Nicaragua, El Salvador), South-east Asia (e.g. Myanmar, Indonesia, Philippines) or North Africa (e.g. Algeria, Morocco, Tunisia). Moreover, even in the regions where fragility or vulnerability curves are available (e.g. Colombia, Egypt, China), not all of the building classes are covered, and due to the consideration of distinct derivation methodologies, the reliability and accuracy of the curves vary considerably. Thus, there is a clear need to promote the development of vulnerability studies in these regions, following a uniform and scientifically sound approach (e.g. D'Ayala *et al*. 2014; Rossetto *et al*. 2014a). To mitigate this issue, the GEM Foundation and its partners are continuously collecting additional models from existing literature, and a large number of curves will soon be released as part of some of the regional partnerships of GEM and related bilateral collaborations (e.g. South America Risk Assessment (SARA) program (Villar *et al*. 2016); Sub-Saharan Africa; Canada; Nepal).

The main objective of this study goes beyond the creation of a database with a large number of existing curves. This tool is intended to be a community-based platform to search and share fundamental models for risk assessment, thus encouraging collaborative work and facilitating seismic risk assessment and earthquake loss estimation worldwide. The Authors would like to invite readers to upload their own models into the vulnerability database.

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REFERENCES

Akkar, S., Sucuoglu, H., and Yakut, A., 2005. Displacement-Based Fragility Functions for Low- and Mid-rise Ordinary Concrete Buildings, *Earthquake Spectra* 21(4), 901–927.

Antoniou, S., and Pinho, R., 2004. Development and verification of a displacement-based adaptive pushover procedure, *Journal of Earthquake Engineering* 8(5), 643–661.

Applied Technology Council (ATC), 1985. *Earthquake damage evaluation data for California*, ATC-13, Redwood City, California.

Applied Technology Council (ATC), 2012. *Guidelines for Seismic Performance Assessment of Buildings*, ATC-58, Redwood City, California.

Bonett Díaz, R.L., 2003. Vulnerabilidad y riesgo sísmico de edificios. Aplicación a entornos urbanos en zonas de amenaza alta y moderada. PhD Thesis, Universitat Politècnica de Catalunya, Barcelona, Spain.

Borzi, B., Crowley, H., and Pinho, R., 2008. Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings, *Engineering Structures* 30, 804–820.

Brzev, S., Scawthorn, C., Charleson, A.W., Allen, L., Greene, M., Jaiswal, K., and Silva, V., 2013. *GEM Building Taxonomy Version 2.0, Tech. Rep.* 2013-02, GEM Foundation, Pavia, Italy, DOI:10.13117/GEM.EXP-MOD.TR2013.02.

Calvi, M., and Pinho, R., 2004. *LESSLOSS - A European integrated project on risk mitigation for earthquakes and landslides*. IUSS Press, Pavia, Italy.

Calvi, M., Pinho R., Magenes, G., Bommer, J., Restrepo-Vélez, L., and Crowley, H., 2006. Development of Seismic Vulnerability Assessment Methodologies over the past 30 years, *ISET Journal of Earthquake Technology* 43(3), 75–104.

Chopra, A. K., and Goel, R. K., 2002. A modal pushover analysis procedure for estimating seismic demands for buildings, *Earthquake Engineering & Structural Dynamics* 31(3), 561–582.

Colombi, M., Borzi, B., Crowley, H., Onida, M., Meroni, F., and Pinho, R., 2008. Deriving vulnerability curves using Italian earthquake damage data, *Bulletin of Earthquake Engineering* 6(3), 485–504.

Crowley, H., Colombi, M., and Silva, V., 2014. *Epistemic uncertainty in fragility functions for European RC buildings. SYNER-G: Typology definition and fragility functions for physical elements at seismic risk: buildings, lifelines, transportation networks and critical facilities* Pitilakis, Crowley, Kaynia (eds.), Springer, Netherlands.

D'Ayala, D., Spence, R., Oliveira, C., and Pomonis, A., 1997. Earthquake loss estimation for Europe's historic town centres, *Earthquake Spectra* 13(4), 773–793.

D'Ayala, D., and Meslem, A., 2012. *Guide for Selection of existing analytical fragility curves and Compilation of the Database, Tech. Rep*, GEM Foundation, Pavia, Italy.

D'Ayala, D., Meslem, A., Vamvatsikos, D., Porter, K., and Rossetto, T., 2014. *Guidelines for analytical vulnerability assessment of low/mid-rise buildings. Tech. Rep.*, GEM Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2014.12.

Di Pasquale, G., and Goretti, A., 2001. Vulnerabilità funzionale ed economica degli edifici residenziali colpiti dai recenti eventi sismici italiani, in *Proceedings, 10th national conference L'ingegneria Sismica in Italia,* 9–13 September, 2001, Potenza-Matera, Italy.

Dolšek, M., Fajfar, P., 2008. The effect of masonry infills on the seismic response of a four story reinforced concrete frame - a deterministic assessment. *Engineering Structures* 30(7), 1991–2001.

Fajfar, P., 1999. Capacity spectrum method based on inelastic demand spectra. *Earthquake Engineering & Structural Dynamics* 28(9), 979–993.

Federal Emergency Management (FEMA), 2003. *HAZUS-MH Technical Manual, Tech. Rep. FEMA–443*, Washington, D.C.

Federal Emergency Management (FEMA), 2012. *Seismic Performance Assessment of Buildings. Methodology and Implementation, Tech. Rep. FEMA P-58-1*, Washington, D.C.

Freeman, S., 2004. Review of the development of the capacity spectrum method. *ISET Journal of Earthquake Technology* 41(1), 1–13.

Jaiswal, K.S., Wald, D., and Porter K.A., 2010. A Global building inventory for earthquake loss estimation and risk management. *Earthquake Spectra* 26(3), 731–748.

Jaiswal, K.S., Aspinall, W.P., Perkins, D., Wald, D., and Porter K.A., 2012. Use of Expert Judgment Elicitation to Estimate Seismic Vulnerability of Selected Building Types, in *Proceedings, 15th World Conference on Earthquake Engineering*, 24–28 September, 2012, Lisbon, Portugal.

Kappos, A., Panagopoulos, G., Panagiotopoulos, C., and Penelis, G., 2006. A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bulletin of Earthquake Engineering* 4(4), 391–413.

Lang, K., 2002. Seismic Vulnerability of Existing Buildings, PhD Thesis, Swiss Federal Institute for Technology.

Liao, W., Loh, C., and Tsai, K., 2006. Study on the Fragility of Building Structures in Taiwan, *Natural Hazards* 37, 55–69.

Magenes, G., Kingsley, G.R., and Calvi, G.M., 1995. Static testing of a full scale, two-story masonry building: test procedure and measured experimental response, in Experimental and numerical investigation on a brick masonry building prototype, Tech. Rep. 3.0 CNR-GNDT Numerical Prediction of the experiment: 1.1-1.41.

Martins, L., Silva, V., Marques, M., Crowley, H., and Delgado R., 2015. Development and assessment of damage-to-loss models for moment-frame reinforced concrete buildings. *Earthquake Engineering and Structural Dynamics* 45(5), 797–817.

Martinez Alfaro, J. G., 2012. Caracterización de la vulnerabilidad sísmica utilizando curvas de fragilidad y matrices de probabilidad de daño para algunas tipologías estructurales de hormigón armado. MSc Thesis, Austral University of Chile, Valdivia, Chile.

Mouroux, P., and Le Brun, B.T., 2006. Presentation of RISK-UE Project. *Bulletin of Earthquake Engineering* 4, 323–339.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., and Vigano D., 2014. OpenQuake-engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismological Research Letters* 85(3), 692–702.

Porter, K.A., 2010. Cracking an open safe: uncertainty in HAZUS-based seismic vulnerability functions. *Earthquake Spectra* 26(3), 893–900.

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., and Noh, H., 2012. Global Vulnerability Estimation Methods for the Global Earthquake Model, in *Proceedings, 15th World Conference on Earthquake Engineering*, 24–28 September, 2012, Lisbon, Portugal.

Porter, K.A,, Farokhnia, K., Vamvatsioks, V., and Cho, I.H., 2014. *Guidelines for analytical vulnerability assessment of high-rise buildings, Tech. Rep.* GEM Foundation, Pavia, Italy.

Rossetto, T., and Elnashai, A., 2003. Derivation of vulnerability functions for European-type RC structures based on observational data. *Engineering Structures* 25(10), 1241–1263.

Rossetto, T., Ioannou, I., and Grant, D. N., 2014a. *Guidelines for empirical vulnerability assessment, Tech. Rep.* GEM Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2014.11.

Rossetto, T., D'Ayala, D., Ioannou, I. and Meslem, A., 2014b. *Evaluation of Existing Fragility Curves. SYNER-G: Typology definition and fragility functions for physical elements at seismic risk: buildings, lifelines, transportation networks and critical facilities*, Pitilakis, Crowley, Kaynia (eds.), Springer, Netherlands.

Rossetto, T., Ioannou, I., and Grant, D.N., 2015. *Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection, Tech. Rep.* GEM Foundation, Pavia, Italy. DOI: 10.13117/GEM.VULN-MOD.TR2015.01.

Silva, V., Crowley, H., and Colombi, M., 2014a. *Fragility Function Manager Tool. SYNER-G: Typology definition and fragility functions for physical elements at seismic risk: buildings, lifelines, transportation networks and critical facilities*, Pitilakis, Crowley, Kaynia (eds.), Springer, Netherlands.

Silva, V., Crowley, H., Pagani, M., Modelli, D., and Pinho, R., 2014b. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment, *Natural Hazards* 72(3), 1409–1427.

Silva, V., Crowley, H., Pinho, R., Varum, H., and Sousa, L., 2014c. Investigation of the Characteristics of Portuguese Regular Moment-frame RC Buildings and Development of a Vulnerability Model, *Bulletin of Earthquake Engineering* 13(5), 1455–1490.

Silva, V., Casotto, C., Rao, A., Villar, M., Crowley, H., and Vamvatsikos, D., (2015). *OpenQuake Risk Modeller's Toolkit - User Guide, Tech. Rep.* GEM Foundation, Pavia, Italy. DOI: 10.13117/GEM.OPENQUAKE.MAN.RMTK.1.0/01.

Singhal A, and Kiremidjian, S., 1997. *A method for earthquake motion–damage relationships with application to reinforced concrete frames. Tech. Rep. NCEER-97-0008*, State University of New York at Buffalo, USA.

Sousa, L., Silva, V., Marques, M., and Crowley, H., 2015. Including Multiple Ground Motion Intensity Measures in the Derivation of Vulnerability Functions for Earthquake Loss Estimation, in *Proceedings, SECED Conference: Earthquake Risk and Engineering towards a Resilient World,* 9–10 July, 2015, Cambridge, United Kingdom.

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, in *Proceedings, 10th World Conference on Earthquake Engineering*, 19–24 July, 1992, Balkema, Rotterdam.

Villar, M., Silva, V., Yepes, C., and Crowley, H., 2016. Development of a Structural Fragility Model for South America. *Earthquake Spectra, submitted*.

Weatherill, G., Silva, V., Crowley, H., and Bazzurro, P., 2014. Exploring the impact of spatial correlations and uncertainties for portfolio analysis in probabilistic seismic loss estimation. *Bulletin of Earthquake Engineering* 13(4), 957–981.