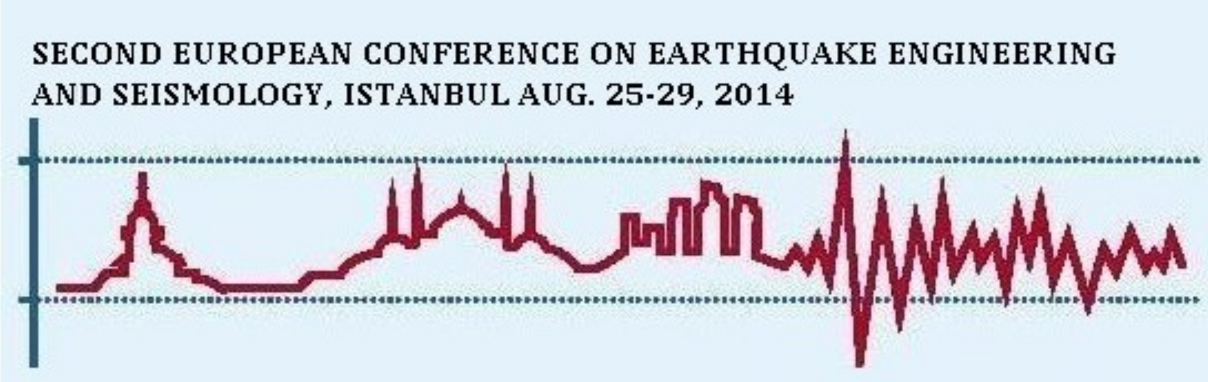

GEM VULNERABILITY DATABASE FOR THE OPENQUAKE-PLATFORM

Catalina Yepes-Estrada[1], Vitor Silva[2], Helen Crowley[3]

ABSTRACT

This paper presents the work towards the development of an online global vulnerability database that includes fragility, vulnerability, damage-to-loss functions and capacity curves for different types of structures. The database leverages upon the output of several projects, such as the Global Earthquake Model (GEM) Vulnerability Consortium and the European project SYNER-G, and it will be publically available through the GEM OpenQuake-platform, which will be officially released towards the end of 2014. The database contains information about approaches utilized to derive these functions/curves, like modelling assumptions, analysis techniques, statistical procedures and treatment of uncertainties, with an associated quality rating system. Therefore, the information available in the database will allow users to better understand the limitations and applicability of the models, to derive new physical vulnerability functions, and to review and improve existing models. Its web-based graphical user interface will allow users to select functions based on a number of criteria, visualize each curve, and even to upload their own functions, thus making them available to the wider community.

INTRODUCTION

Seismic risk assessment and loss estimation are essential prerequisites for reducing the effects generated by earthquakes. In order to perform these analyses, it is fundamental to have a reliable seismic hazard model, a comprehensive exposure model and a set of vulnerability/fragility functions. The latter component must be capable of providing either the distribution of loss ratios or the probability of exceeding a number of damage states, for a set of intensity measure levels.

Various methodologies have been proposed for the derivation of these models in the last few decades and four main categories can be defined: empirical, analytical, hybrid or expert opinion-based methods (Calvi et al. 2006). Empirical vulnerability models require large samples of post-earthquake damage data (e.g. Colombi et al. 2008; Rossetto et al. 2013) and thus their employment is restricted to the regions in the world where such data has been properly collected. Alternatively, numerical models can be created to simulate the seismic performance of a number of key structures from a building stock to derive an analytical vulnerability model. However, such approach requires a good knowledge of the material and geometric properties of the structures of interest and it can be very computational demanding (e.g. Silva et al. 2013a). Furthermore, by combining empirical and analytical methodologies, hybrid vulnerability models can be derived. Finally, expert opinions from structural and earthquake engineers can be used to derive vulnerability/fragility functions, despite the large variability and strong subjectivity associated (e.g. Jaiswal et al. 2012).

[1] Seismic Risk Modeler, GEM Foundation, Italy - Pavia, catalina.yepes@globalquakemodel.org
[2] Risk Coordinator, GEM Foundation, Italy - Pavia, vitor.silva@globalquakemodel.org
[3] Seismic Risk Consultant, EUCENTRE, Italy - Pavia, helen.crowley@eucentre.it

Regardless of the chosen methodology, it is clear that the development of a new physical vulnerability model can be a very challenging task, in terms of data availability, modelling complexity and time. For this reason, when performing seismic risk analysis it might be important to take advantage of existing vulnerability models compatible with the building portfolio being analysed. Therefore, an online vulnerability database that includes fragility, vulnerability, damage-to-loss functions and capacity curves for different types of structures has been created for the first time as part of the Global Earthquake Model (GEM) initiative.

A great portion of this database has been developed thanks to the work carried out within the context of the Global Vulnerability Consortium (GVC)[4] project (2010-2013) (Porter et al. 2012), launched by GEM as one of its many international projects. Several institutions worldwide were included in this consortium, and their activities included the creation of guidelines for developing analytical (D'Ayala et al. 2014; Porter et al. 2014) and empirical (Rossetto et al. 2014) fragility or vulnerability functions, as well as recommendations for selecting existing empirical and analytical fragility or vulnerability functions (D'Ayala and Meslem, 2012, Rossetto et al. 2013). The latter guidelines have been strongly utilised herein to establish the set of parameters required to define each artefact within the database. In addition to the set of functions collected by the GVC and the results from the European project SYNER-G (Crowley et al. 2014), individual publications that provide information about fragility, vulnerability, damage-to-loss functions and/or capacity curves with the level of details and flexibility expected for this database have also been collected by the authors.

This paper provides an overview of the current status of development of the GEM Vulnerability Database, including a description of the parameters and attributes needed to classify a function and/or a curve, the global coverage and main characteristics of the current collection of artefacts, and the preliminary graphical user interface within the OpenQuake-platform.

THE GEM VULNERABILITY DATABASE

An extensive literature review concerning the development of fragility, vulnerability, damage-to-loss functions and capacity curves has been considered in the creation of this database, initiated by GEM's GVC project. The common characteristic among these functions/curves is that they attempt to define the performance of a particular asset (e.g. a building), or an asset class (e.g. a building typology), under seismic excitation. Assets may refer to buildings, critical facilities, transportation systems, networks, lifeline utility systems, population, amongst other elements at risk.

Once the database is available on the online OpenQuake-platform, users will be able to select a number of functions based on a set of criteria or upload their own models, providing as much information as requested/desired. Figure 1 illustrates the general organization of the database structure, which is divided into five main categories: General information, Data, Geographical location, Modelling information and Quality rating. The first three categories contain mandatory attributes that need to be provided as the minimum information to define functions or curves, while the last two categories are intended for those models on which detailed information may be available. Additional attributes can be added in the future in order to accommodate the needs of more advanced users/data providers.

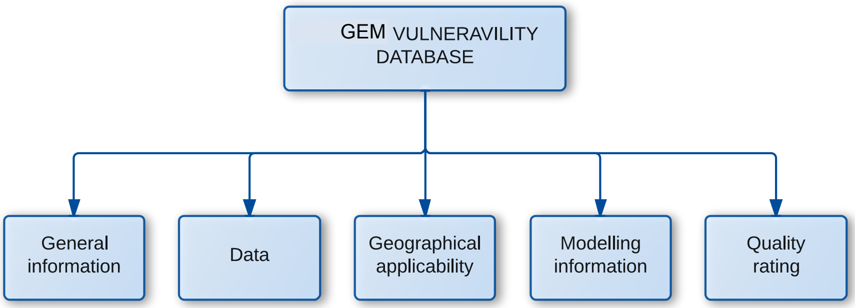

Figure 1. General organizational structure of the GEM Vulnerability Database

[4] http://www.globalquakemodel.org/what/physical-integrated-risk/physical-vulnerability/

The "General information" category comprises data about the characteristics of the element for which a function or a curve is defined. In addition, use case information and general comments can be specified. The following attributes are included:

- *Category:* this attribute identifies the type of structure for which the curves were developed (e.g. structural class, specific structure, or non-structural component), and it also contains the minimum characteristics to describe it. Depending on the type of asset, different information is required. For example, a building or a building class can be described through a taxonomy string using the GEM Building Taxonomy[5] or PAGER-STR (Jaiswal et al., 2010) classifications. The graphical user interface features a tool that supports the classification of assets according to the GEM Building Taxonomy. In any case, the minimum information that must be provided is material, lateral load resisting system (LLRS), height or number of storeys and ductility level.
- *Type of assessment:* there are four options available, which include fragility functions, vulnerability functions, damage-to-loss models and capacity curves. Fragility functions represent the probability of exceeding a number of damage states for a set of intensity measure levels. On the other hand, vulnerability functions define the distribution of loss ratio given an intensity measure level. Damage-to-loss models (also known as consequence models) correlate physical damage with fraction of loss. Finally, capacity curves provide the relation between the spectral acceleration and spectral displacement of an equivalent SDOF system.
- *Documentation:* this field provides information about the author, title of the study and type of publication (e.g. peer-reviewed journal, conference, report). When available, a web link directing users to the online documentation can also be provided.

In the "Data" category, information regarding the attributes that define a function or curve are specified in accordance with the type of assessment (as described above). The first attribute in the "Data" category defines the method of estimation. In general, various methodologies can be utilised to derive the models covered herein, and they can be classified into analytical, hybrid, empirical or expert opinion. The robustness and reliability of each methodology is influenced by several considerations, and it depends on the information available for the studied category.

The following attributes in this category define the predictor and response variables, which depend on the type of assessment. For fragility functions, the predictor variable is represented by the ground motion intensity measure (IM), while the response variable corresponds to the probability of exceedance a given limit state, which is usually correlated with an Engineering Demand Parameter (EDP). For vulnerability functions, the predictor variable is also the IM, but in this case the response variable is represented by a loss ratio (e.g. ratio between a repair cost and total replacement cost). For damage-to-loss models, the predictor variable is represented by the different damage states, and the response variable is the corresponding fraction of loss. Finally, for capacity curves the predictor variable is represented by the spectral acceleration, and the response variable can be the spectral displacement.

The last attribute specifies the manner in which the function has been defined, and it is only applicable for fragility and vulnerability functions. The database supports discrete and continuous functions. The discrete approach requires the definition of a set of intensity measure levels and corresponding probabilities of exceedance or loss ratios, while continuous functions are defined assuming a probabilistic distribution (e.g. lognormal) with associated moments (e.g mean and standard deviation).

The "Geographical location" category provides information regarding the regional applicability of the model. There are five options for specifying the location: *region* (the broadest classification, e.g. Europe); *sub-region* (e.g. eastern Europe), *country* (e.g. Italy), *administrative region* (e.g. province of Lombardia) and *unique location* (detailed information regarding the address of the specific structure).

[5] http://www.nexus.globalquakemodel.org/gem-building-taxonomy/posts

The "Modelling information" category depends on the type of assessment and it is only included if the documentation contains those details. The main purpose of this category is to provide a better understanding of the procedures and limitations of the developed functions/curves. This category is organized into three classes: Analytical modelling, Empirical modelling and Statistical information.

The attribute *Analytical modelling* can only be used when the functions or curves have been calculated using such methods. It includes detailed information concerning the analysis type, model type, method of uncertainty propagation and the number of distinct structural models analysed. For example, a set fragility functions could have been derived using non-linear dynamic analysis in more than 100 different 2D element-by-element structural models. Or, as proposed by D'Ayala et al. (2014), a set of index buildings could be used to represent a class of buildings, i.e. a group of buildings that represent the overall population by capturing the joint probabilistic distribution of its most important characteristics.

On the other hand, if the models have been derived using empirical methods, then the attribute *Empirical modelling* should be utilized, and information about the structural unit (dwelling or building), the number of buildings per class, the source of empirical data, the building aggregation and the definition of aggregated unit should be provided.

The last attribute in this category refers to the *Statistical information.* Regardless of the procedure or methodology used to develop the models, various sources of epistemic and aleatory uncertainty are involved. Some of these functions may be the product of two or more independent procedures. For instance, vulnerability functions can be obtained by combining fragility curves and damage-to-loss models. Therefore, it is fundamental to identify and quantify the different sources of uncertainties (i.e. uncertainties in structural model, seismic demand and damage analysis). Depending on the chosen assessment and modelling approach, different sources of uncertainty can be accounted for in the database: the statistical approach employed in the model, the fitting method, the procedure for the construction of confidence and prediction intervals.

Finally, the "Quality rating" category provides useful information regarding the reliability of the data, methodology and results. Due to the large uncertainty and complexity in the derivation of these functions, the quality rating system is formulated in order to assess the robustness, quality and applicability of the resulting models. The system presented herein is adopted from Porter (2011) for analytical fragility and vulnerability curves, and it has been extended to empirical curves using the suggestions by Rossetto et al. (2012).

The rating system is based on four categories: data quality, rationality, documentation quality and representativeness. Four possible values can be assigned to each category: Superior (S), Average (A), Marginal (M) and Not applicable (NA). Depending on the type of assessment for which the curves were developed, each category contains different attributes to rate.

The first sub-category (*Data quality)* represents an overall rating for the data used to derive the curves in terms of input data for modelling/analysing and seismic demand considerations. The sub-category *Rationality* is responsible for rating the quality of the methodologies used in the analysis phase when deriving the function/curves. For example, it rates the cross validation (how the function agrees or disagrees with some prior accepted model) and the treatment of uncertainties (how well the authors identified and treated the major sources of uncertainty). Furthermore, the third category (*Documentation quality),* describes the degree to which all the necessary inputs, outputs, and analytical steps are clearly documented, as well as whether the documentation is readily available to future users and has been independently peer reviewed. The last sub-category (*Representativeness)* measures how well the observed specimens are representative of the asset category. In brief, the quality rating provides a qualitative description on different sub-categories that facilitates the understanding of the limitations that a function/curve can include. However, the process of rating a function is likely to be subjective, and interpretations of the general criteria may change according to the intended use and the understanding of the reviewer (Rossetto et al. 2012).

Figure 2 summarizes all of the attributes mentioned above and included in the design of the database.

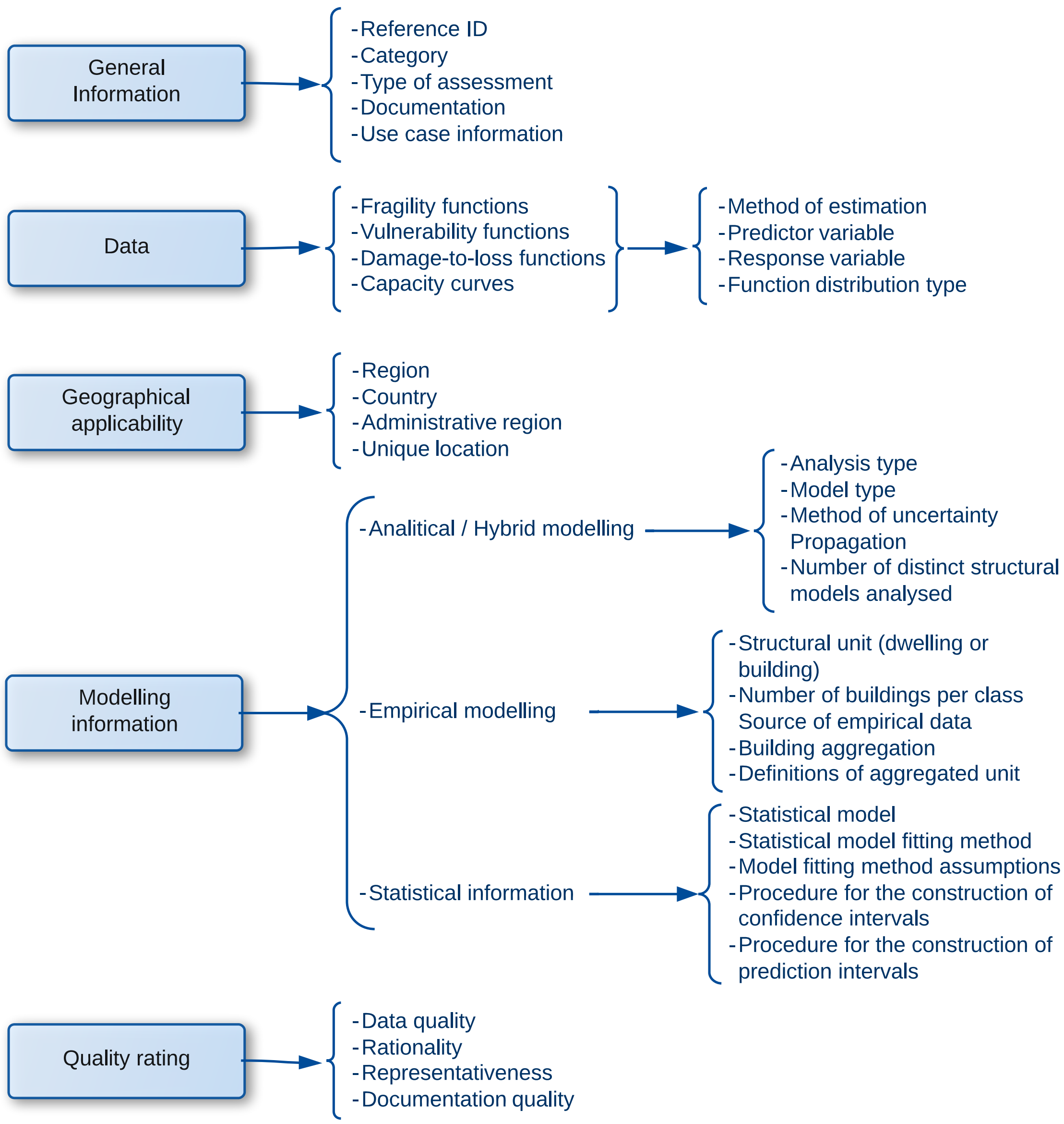

Figure 2. Detailed organizational structure of the GEM Vulnerability Database

DATA INVENTORY

An initial population of the database has been made using the functions and curves collected by the GVC, which are currently organized in two compendiums: 157 empirical fragility/vulnerability functions (Rossetto et al. 2013) and 145 analytical fragility functions (D'Ayala and Meslen, 2013). In addition, the curves from the European project SYNER-G (Crowley *et al.* 2014) were included, as well as additional material gathered by the GEM risk team. In total, more than 750 fragility/vulnerability functions, damage-to-loss models and capacity curves have been collected. Moreover, a large number of models are also expected to be delivered soon as part of some of the regional partnerships of GEM (e.g. South America Risk Assessment program; Earthquake Model for the Middle East project).

Figure 3 illustrates the countries where existing functions and curves are available in the database. It can be observed that the database covers information for the majority of the countries located in seismic prone countries.

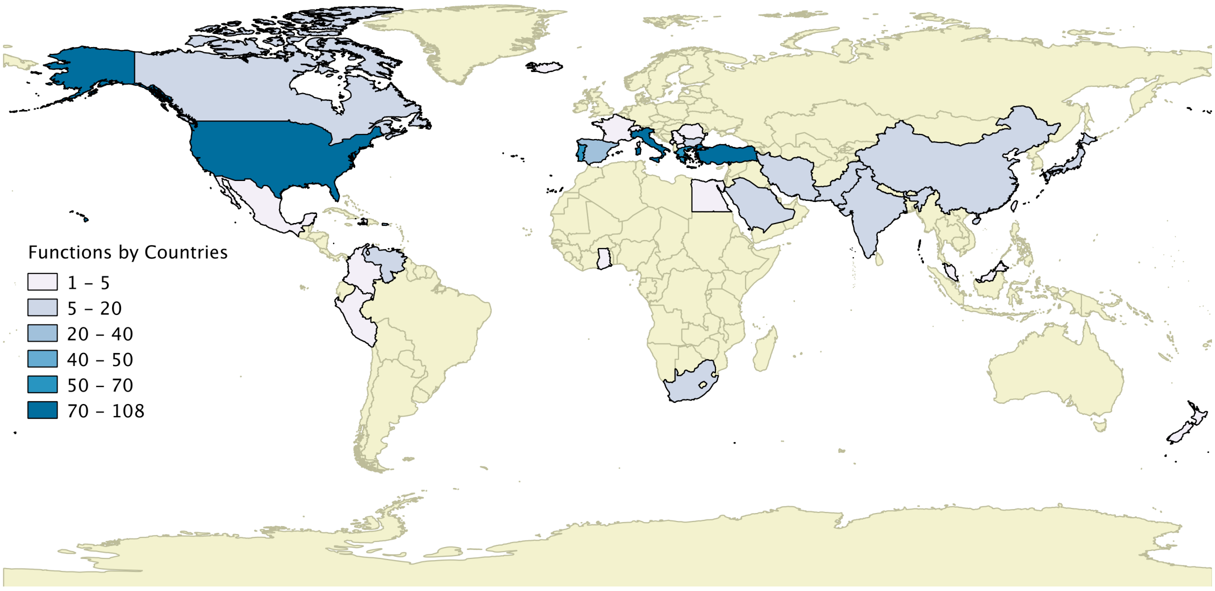

Figure 3. Regions with available functions and/or curves.

The distribution of the various models per country or region is illustrated in Figure 4. It is worth mentioning that some of the items have not been developed for a specific country, but rather to a wider region such as Europe or North America.

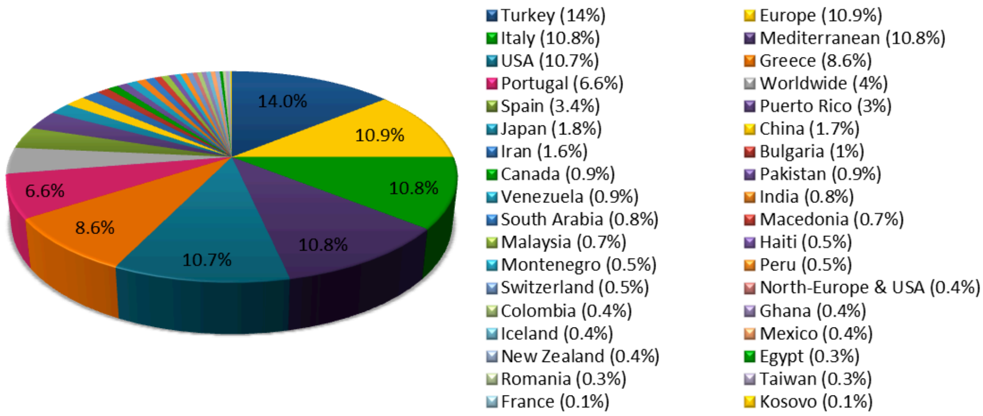

Figure 4. Geographical distribution of the vulnerability models within the GEM Vulnerability Database.

One of the main strengths of the database described herein is the possibility of filtering and selecting models according to a wide spectrum of criteria. The available information can be filtered according to the following attributes: category, material type, lateral load resisting system, height, geographical location, type of assessment, method of estimation, intensity measure type, damage scale and author. For example, Figure 5 illustrates the percentage of fragility functions available in the database according to the type of assessment, the lateral force resisting system, the material and the intensity measure.

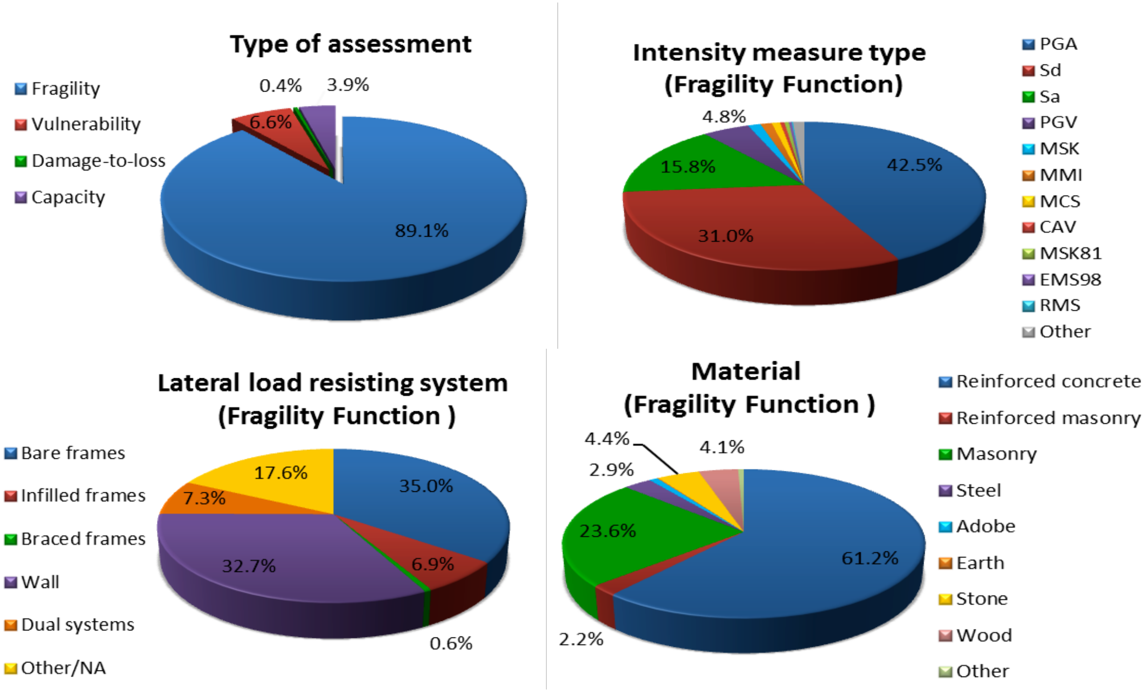

Figure 5. Number of functions available in the database according to different attributes.

The database will be publically available through the GEM OpenQuake-platform[6]. This online web-based platform is being developed to host a wide range of seismic hazard, exposure and vulnerability models; databases and tools relevant for the development of the aforementioned models; as well as GEM's seismic hazard and risk calculation engine. Each user of the platform will have their own profile, and the web-based graphical user interface of the vulnerability database will allow users to select models, visualize each curve and even to upload their own functions, thus making them available to the wider community. Figure 6 shows the preliminary graphical user interface of the platform, for the visualization of a specific fragility model in the database. Once a user has viewed, compared and selected models from the vulnerability database, it will be possible to extract them in a format that will allow them to be used for seismic risk calculations with the OpenQuake-engine (Silva et al. 2013; Pagani et al. 2014).

[6] http://www.globalquakemodel.org/openquake/about/

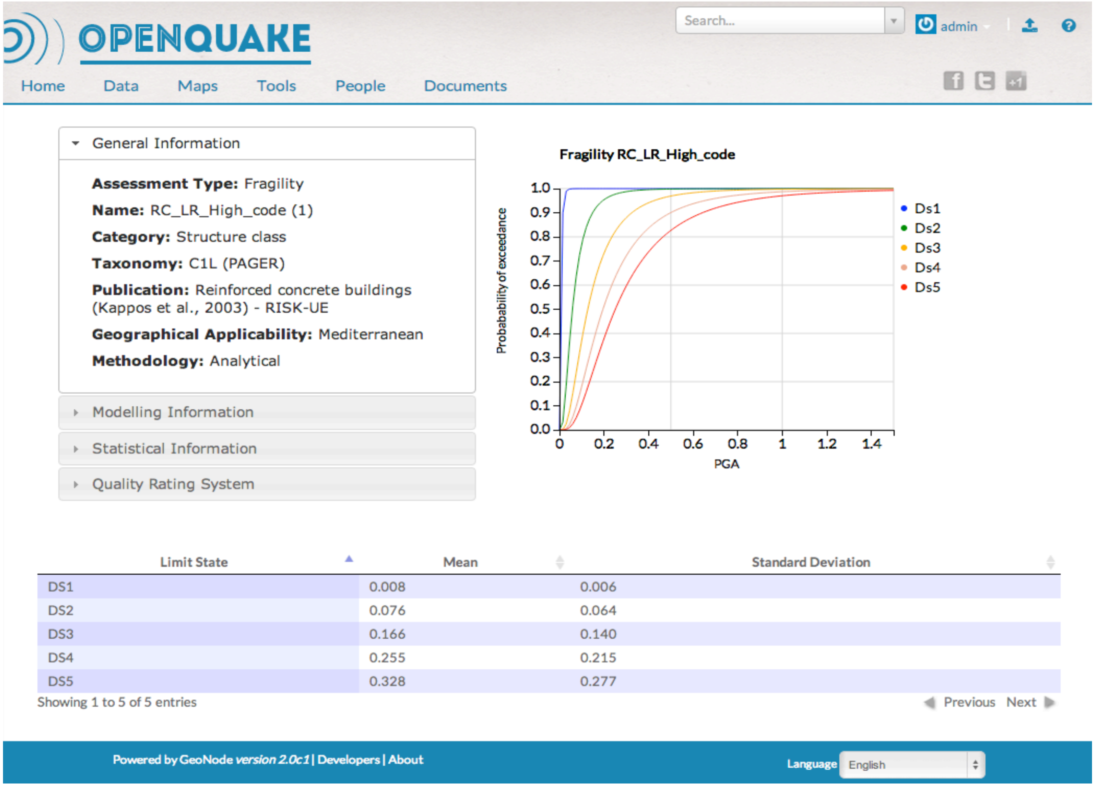

Figure 6. Preliminary OpenQuake graphical user interface for visualising fragility functions

CONCLUSIONS

The development of a comprehensive physical fragility/vulnerability model for seismic risk assessment and loss estimation might be a daunting task, which requires the availability of reliable data, and an adequate understanding of structural and statistical methodologies. Therefore, it is important to take advantage of existing models that might be compatible with the building portfolio being analysed. To this end, the Global Earthquake Model has developed the GEM Vulnerability database where fragility, vulnerability, damage-to-loss functions and capacity curves can be stored and globally shared.

The information available in the database can also be employed in the development of new physical vulnerability models. For example, capacity curves can be used to derive fragility functions through nonlinear static procedures (e.g. Capacity Spectrum Method - ATC-40; Displacement Coefficient Method - FEMA-440; N2 Method - Fajfar 1999). These fragility functions can then be converted into vulnerability functions by combining the fragility results with an existing damage-to-loss model.

The database comprises information about modelling assumptions, analysis techniques, statistical procedures and treatment of uncertainties approaches utilized to derive these curves. Using this information and the quality rating system, users will be able to have a greater understanding of the limitations and applicability of the available models.

Currently, the database covers over 750 functions and curves for the most common building typologies located in seismic prone regions. The GEM risk team is continuously collecting additional models from existing literature, and as part of the various GEM regional initiatives. The database has been conceived for different categories: structure specific, structure class, non-structural components, population and capital stock. However, only functions and curves for buildings have been collected until now, and they come mainly from European and North-American countries.

The objective of this study goes beyond the creation of a database with a large number of existing functions. This database will be publically available online through the web-based OpenQuake-platform, scheduled to be publicly released at the end of 2014. This tool is intended to be a community-based platform to search and share fundamental models for risk assessment. Moreover, the database can be utilised to extract vulnerability and/or fragility functions in the format required by the OpenQuake-engine in order to perform seismic risk assessment.

ACKNOWLEDGMENT

The authors would like to acknowledge the scientists that participated in the Global Vulnerability Consortium project (2010-2013): K.A. Porter, K. Farokhnia, I.H. Cho, T. Rossetto, I. Ioannou, K. Jaiswal, D. Wald, D. D'Ayala, A. Meslem, E. So, A.S. Kiremidjian, H. Noh and D. Grant. The documentation produced during the course of the project was the base for the development of the database.

REFERENCES

ATC [1996]. "Seismic Evaluation and Retrofit of Concrete Buildings," Report ATC-40, Applied Technology Council, Redwood City, California, U.S.A.

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

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, 6(3):485-504.

Crowley, H., Colombi, M., Silva, V. (2014) "Chapter 4: Epistemic uncertainty in fragility functions for European RC buildings," In: SYNER-G: Typology definition and fragility functions for physical elements at seismic risk: buildings, lifelines, transportation networks and critical facilities, Ed: Pitilakis, Crowley, Kaynia, *in press*

D'Ayala D., Meslem A. (2012) "DRAFT Guide for Selection of existing analytical fragility curves and Compilation of the Database" version 1.0, GEM Global Component Report (Available at: http://www.nexus.globalquakemodel.org/gem-vulnerability/posts/guidelines-for-analytical-vulnerability-assessment)

D'Ayala D., Meslem A., Vamvatsikos D., Porter K., Rossetto T. (2014) "Guidelines for analytical vulnerability assessment of low/mid-rise buildings", GEM Technical Report Series 2014, GEM Foundation, in press.

Fajfar, P. [1999] "Capacity Spectrum Method Based on Inelastic Demand Spectra," Earthquake Engineering And Structural Dynamics, Vol. 28, pp. 979-993.

FEMA [2005] "Improvement of Nonlinear Static Seismic Analysis Procedures," Report FEMA 440, Federal Emergency Management Agency, Washington, DC, U.S.A.

Jaiswal K.S, Aspinall W.P, Perkins D, Wald D, Porter K.A (2012) "Use of Expert Judgment Elicitation to Estimate Seismic Vulnerability of Selected Building Types", *Proceedings of the fifteenth World Conference on Earthquake Engineering*, Lisbon, Portugal, 23-24 September.

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

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

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 (2012) "Global Vulnerability Estimation Methods for the Global Earthquake Model", *Proceedings of the fifteenth World Conference on Earthquake Engineering*, Lisbon, Portugal, 23-24 September.

Porter K.A, Farokhnia K, Vamvatsioks V, Cho I.H, (2014) "Guidelines for analytical vulnerability assessment of high-rise buildings" GEM Technical Report Series 2014, GEM Foundation, in press.

Porter K.A (2011) "GEM Vulnerability Rating System", GEM Global Component Report (Available at: http://www.nexus.globalquakemodel.org/gem-vulnerability/posts/gem-vulnerability-rating-system)

Rossetto T., Ioannou I., Grant D.N. (2013) "Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection" version 1.0, GEM Global Component Report (Available at http://www.nexus.globalquakemodel.org/gem-vulnerability/posts/existing-empirical-vulnerability-and-fragility-relationships-compendium-and-guide-for-selection).

Rossetto T., Ioannou I., Grant D.N. (2014) "Guidelines for empirical vulnerability assessment," GEM Technical Report Series 2014, GEM Foundation, in press.

Silva V, Crowley H, Pagani M, Modelli D, Pinho R (2013) "Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment" *Natural Hazards*.

Silva V, Crowley H, Varum H, Pinho R, Sousa R (2013) "Evaluation of analytical methodologies used to derive vulnerability functions" *Earthquake Engineering & Structural Dynamics*, DOI: 10.1002/eqe.