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Presentation of the Risk Modeller's Toolkit, the open–source software for vulnerability assessment of the Global Earthquake Model

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Abstract

In the last decade several software packages for seismic hazard and risk assessment have been released, thus making it easier for hazard and risk modellers to run complex analyses without the need to code their own implementations of the scientific algorithms. However, the development of the input models for such analyses is often an equally challenging task, and the availability of tools to support experts in this stage is still very limited. Three main input models are required for earthquake risk analysis: a seismic hazard model, an exposure dataset, and a set of physical fragility or vulnerability functions. The latter component describes the probability of damage or loss conditional on different levels of ground shaking, and assumes a special role since an improvement in the seismic performance of the building stock can directly reduce the associated seismic risk.

This study presents the Risk Modeller's Toolkit (RMTK), a suite of tools to support risk experts in the derivation and verification of fragility or vulnerability models. The development of the RMTK followed an open-source and transparent approach. Thus, its code can found in a public repository (https://github.com/GEMScienceTools/rmtk), and all of the implemented methodologies have been fully documented in the RMTK manual. The current version of the RMTK comprises four modules: 1) generation of structural models, represented by pushover curves or single-degree-of-freedom (SDOF) oscillators, to represent the variability in the capacity of the building stock; 2) conversion of results from multi-degree-of-freedom models into the equivalent SDOF systems; 3) derivation of fragility functions by combining capacity models with sets of ground motion records or response spectra; 4) conversion of fragility models into vulnerability functions through the employment of damage-to-loss models. These modules contain some of the most well-known methodologies in seismic vulnerability assessment, which allow the propagation of a wide spectrum of aleatory uncertainties, such as the variability in the structural capacity of the building stock; uncertainty in the definition of the damage criterion; or the record-to-record variability. The employment of distinct fragility methodologies will inevitably lead to different results (epistemic variability), which may have a significant impact on the associated seismic risk estimates.

The RMTK is currently being employed in the development of fragility functions for the most common building classes in South America, eastern Sub-Saharan Africa, Canada, Costa Rica and Nepal. The outcomes of the RMTK are fully compatible with the OpenQuake-engine, the open-source software for seismic hazard and risk analysis of the Global Earthquake Model initiative.

Keywords: Global Earthquake Model; Risk Modeller's Toolkit; fragility functions; vulnerability functions; open source software

1. Introduction

In recent years several free and open-source software packages for seismic hazard and risk assessment have been developed. The OpenQuake-engine developed by the Global Earthquake Model (GEM) [1–3] is one such software which provides state-of-the-art scenario-based and probabilistic seismic hazard and risk calculations. The availability of such software has made it easier for hazard and risk modelers to run complex analyses without needing to code their own implementations of the scientific algorithms. However, the development of the input models for seismic risk analyses is often an equally challenging task, and the availability of tools to help modelers in this stage are very limited.

Seismic fragility and vulnerability functions form an integral part of a seismic risk assessment project, along with the seismic hazard and exposure models. The lack of reliable tools for developing fragility and vulnerability models may require risk modelers to use tools that were not specifically designed for the creation of seismic risk models. Alternatively, modelers justifiably create their own implementations of standard methodologies, leading to a possible lack of consistency between different implementations, even if the methods selected in the model preparation process were the same. Quality assurance and maintenance of code is another issue that modelers are required to deal with. There is clearly a strong motivation for extending the philosophy of open-source software development, review, and maintenance also to the process of fragility and vulnerability model preparation.

With a view toward bridging this gap, GEM has developed in addition to the OpenQuake-engine, a suite of open-source tools for the preparation of physical fragility and vulnerability models for application in seismic risk assessment [4]. This suite of tools has been released in the form of the OpenQuake “Risk Modeller’s Toolkit”, or RMTK, under the free GNU Affero General Public License. The RMTK makes it possible for a risk modeler to select from several commonly used methods to derive seismic fragility or vulnerability functions for individual buildings or a class of buildings. As with the OpenQuake-engine, the RMTK is developed primarily using the Python programming language, and the software and documentation are updated regularly by scientists and engineers working within GEM, in collaboration with a worldwide community of experts on earthquake engineering. The latest version of the software is always available at a public web-based repository at the following address: https://github.com/GEMScienceTools/rmtk.

2. Derivation of fragility and vulnerability functions

Empirical methods are often preferred for the derivation of fragility and vulnerability functions when relevant data regarding the levels of physical damage and loss at various levels of ground shaking are available from past earthquakes [5]. However, the major drawback of empirical methods is the highly limited quantity and quality of damage and repair cost data and availability of the corresponding ground shaking intensities from previous events.

Instead, the analytical approach to derive fragility and vulnerability functions for an individual structure relies on creating a numerical model of the structure and assessing the deformation behavior of the modelled structure by subjecting it to selected ground motion acceleration records or predetermined lateral load patterns. The deformation then needs to be related to physical damage by employing suitable damage threshold criteria to obtain the fragility functions. The fragility functions can be combined with an appropriate consequence model to derive a vulnerability function for the structure. Fragility and vulnerability functions for a class of buildings (a “building typology”) can be obtained by simulating a number of structures considered to be representative of that class.

Several methodologies for the derivation of fragility functions are implemented in the RMTK, but most of them follow an overall procedure comprising the following steps: (1) define the distribution of the capacity parameters; (2) generate non-linear single-degree-of-freedom (SDOF) structural models represented by capacity curves sampled from the specified distribution; (3) define damage state thresholds; (4) obtain a relationship between ground motion intensity and damage state exceedance probabilities through non-linear static or dynamic analyses; (5) fit fragility functions to the damage exceedance results; (6) convert fragility models into vulnerability functions through the employment of damage-to-loss models. The following subsections describe these steps.

2.1 Define capacity parameters

Buildings are modelled as non-linear Single Degree of Freedom (SDOF) systems in the RMTK. The structure is represented as a single 1-D element and its fundamental features can be adequately described using a pushover curve. A pushover curve for a building describes the relationship between the lateral load resistance of the building and the lateral displacement of the building. Typically, the pushover curve is presented in the form of base shear versus peak story drift or roof displacement.

In the process of deriving fragility functions, a key intermediate step involves estimating the relationship between the lateral displacement of the building (measured in terms of an engineering demand parameter, “EDP”), and the level of ground shaking (described in terms of an intensity measure, “IM”). To facilitate this analysis step, the building pushover curve is converted into a capacity curve, by transforming the base shear into spectral acceleration and the lateral displacement into spectral displacement.

2.1.1 Convert from MDOF to SDOF

Several structural analysis packages allow the user to perform a reliable pushover analysis on a nonlinear model of the MDOF structure. Often, these MDOF pushover curves need to be converted to simplified SDOF models for use in nonlinear static analysis methods. The RMTK includes two methods for converting MDOF pushover curves to equivalent SDOF capacity curves: (1) Conversion based on first mode of vibration as described in ATC-40 [6] and FEMA-440 [7]; and (2) Conversion using an adaptive approach as recommended in Casarotti and Pinho [8].

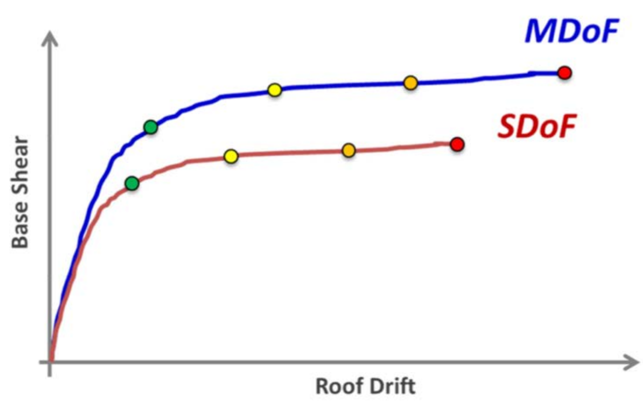


Fig. 1 - An MDOF pushover curve transformed into an equivalent SDOF curve [9].

2.1.2 Idealize capacity curves

Some methodologies require capacity curves to be idealized in the form of multi-linear elasto-plastic models. The RMTK includes the ability to transform any input capacity curves into either a bilinear or a quadrilinear idealized capacity curve. Fig. 2 below illustrates this idealization process.

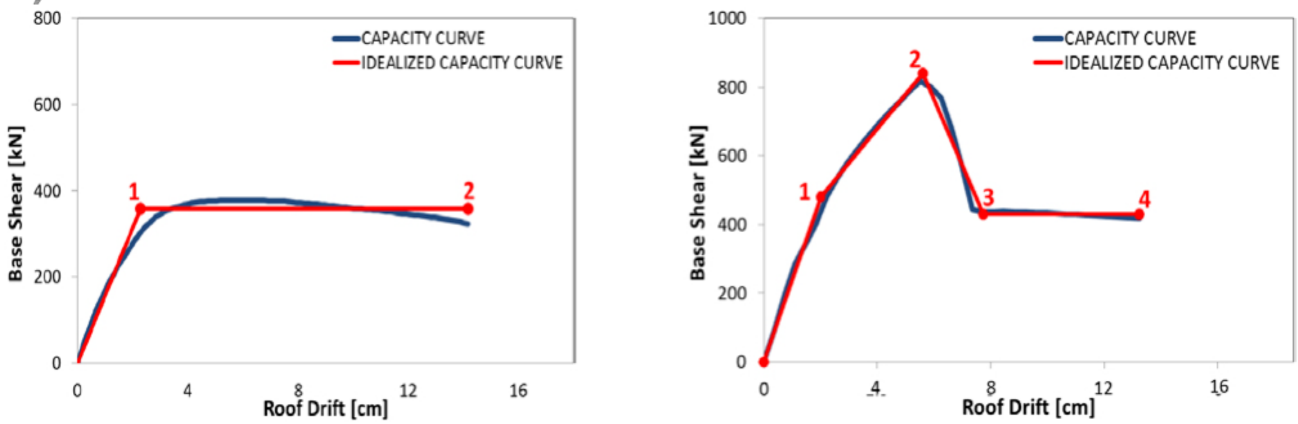


Fig. 2 - Idealized capacity curves: bilinear (L), quadrilinear (R)

2.2 Simulate index buildings

The RMTK allows the user to simulate multiple index buildings based on the capacity parameters provided by the user. By simulating a large sample of buildings, the analyst can account for the building-to-building variability within the same class. Capacity curves are generated for each simulation based on the specified median and dispersion in the capacity parameters.

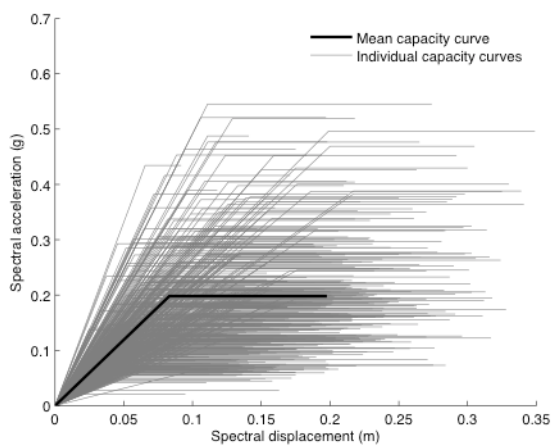


Fig. 3 - Multiple simulated bilinear elasto-plastic capacity curves

2.3 Define damage state thresholds

The derivation of fragility models requires the definition of a criterion to allocate one (or multiple) structures into a set of damage states, according to their nonlinear structural response. These rules to relate structural response with physical damage can vary significantly across the literature. Displacement-based methodologies frequently adopt the strain of the concrete and steel [10]. The vast majority of the methodologies that require equivalent linearization methods or nonlinear time history analysis adopt inter-storey drifts (e.g. [11]), or spectral displacement calculated based on a pushover curve (e.g. [12, 13]). All four of these options for defining the damage state threshold are available to the analyst in the RMTK. Fig. 4 illustrates a capacity-curve based damage model.

Damage State	Damage Threshold
Slight	$0.7S_{dy}$
Moderate	$0.75S_{dy}+0.25\ S_{du}$
Extensive	$0.5(S_{dy} + S_{du})$
Collapse	S_{du}

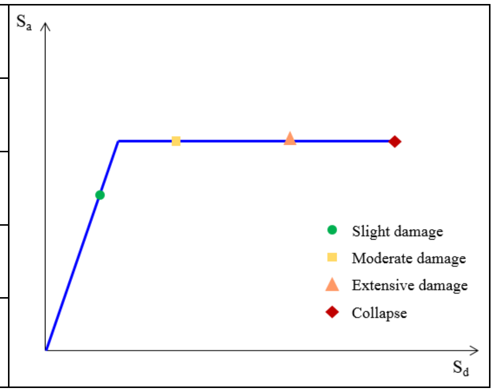


Fig. 4 - Example of a capacity-curve based damage model [14].

2.4 Evaluate structural response through nonlinear analysis

Nonlinear structural analysis is then employed to obtain a relationship between the structural deformation (measured using a suitable EDP) and the ground motion intensity (measured using a suitable IM). Different researchers have proposed different methodologies to derive fragility functions using pushover or capacity curves in nonlinear static or dynamic analyses [9].

The level of sophistication employed during the structural analysis stage is constrained both by the amount of time and the type of information regarding the structure that are available to the modeler. Although performing nonlinear dynamic analysis of a highly detailed model of the structure using several ground motion records is likely to yield a more representative picture of the dynamic deformation behavior of the real structure during earthquakes, nonlinear static analysis is often preferred due to the lower modelling complexity and computational effort required by static methods.

Table 1 below lists the different methods currently implemented in the RMTK.

Table 1 - Methodologies for fragility function derivation currently implemented in the RMTK

Non-linear Dynamic Analysis	1. Cloud Analysis 2. Incremental Dynamic Analysis 3. Multiple Stripe Analysis
Direct Non-linear Static Analysis	1. SPO2IDA [15] 2. Dolsek and Fajfar [16] 3. Ruiz Garcia and Miranda [17]
Record Based Non-linear Static Analysis	1. Vidic, Fajfar and Fischinger [18] 2. Miranda [19] for firm soils 3. N2 (EC8 [20]) 4. Capacity Spectrum Method [7] 5. Lin and Miranda [21] 6. DBELA [10]

The non-linear dynamic analysis module of the RMTK deserves special attention due to its ability to incorporate a large number of uncertainties while still maintaining an acceptable computational performance. This methodology performs a series of non-linear time history analyses (NLTHA) over one or multiple single degree of freedom (SDoF) systems. It is typically assumed that the fundamental mode of vibration corresponds to the predominant response of the structure. This is usually valid for buildings with fundamental periods of vibration up to approximately 1.0 s. Otherwise, higher modes should be taken into account. The demand is represented by a set of ground motion records. The response of each SDOF system is given by the solution of the equation of motion for an inelastic SDoF under earthquake excitation. The nonlinear time history analyses are performed using the open-source software for structural analysis OpenSees [22]. This method has been recently employed for the development of a fragility and vulnerability models for South America and the United States, as described in Section 3.

2.5 Fit fragility functions

The results in the damage probability matrix are used to fit a lognormal cumulative distribution function for each damage state. The parameters of the fitted functions (mean and standard deviation) can be estimated using either least squares regression or the maximum likelihood method.

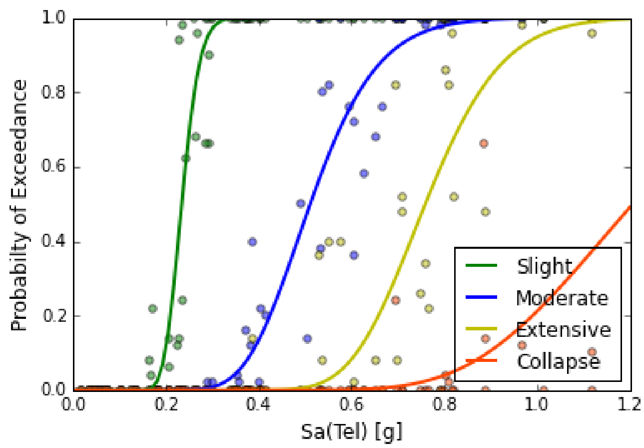


Fig. 5 – Fitting of lognormal functions considering the damage distribution from the non-linear analysis.

2.6 Derive vulnerability functions

A vulnerability function for a building or a class of buildings defines the probability of exceedance of loss values as a function of the intensity of ground motion. A vulnerability model can be derived directly from loss data from previous seismic events, or by combining a set of fragility functions with a consequence model. A consequence model, sometimes also referred to as a damage-to-loss model - describes the loss distribution for different damage. In this process, the fractions of buildings in each damage state are multiplied by the associated damage ratio (from the consequence model), in order to obtain a distribution of loss ratio for each intensity measure type. Currently only the latter approach is implemented in the Risk Modeller's Toolkit, though the former method will be included in a future release.

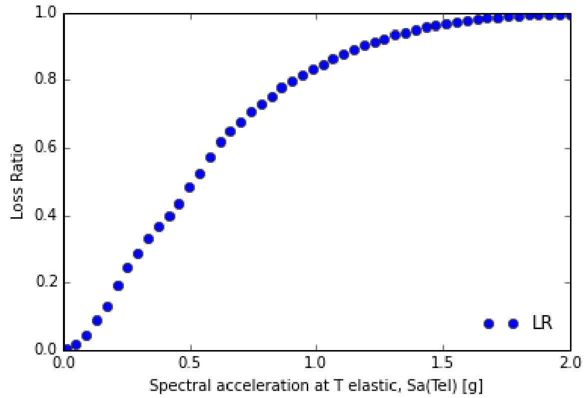


Fig. 6 – Derivation of a vulnerability function through the combination of fragility and damage-to-loss models.

2.7 Uncertainty modelling and propagation

Using the RMTK, a risk analyst can model and propagate the aleatory uncertainties through the various steps involved in building the fragility and vulnerability models, such as the variability in the structural capacity of the building stock; uncertainty in the definition of the damage criterion; the record-to-record variability in ground motions; and the uncertainty in the damage-to-loss models. By offering the analyst the option to use different methodologies for the derivation of the fragility functions, the RMTK also makes it possible to explore the epistemic uncertainty in the derived models. These aspects are investigated in the study described in the following section.

3. Case study – Fragility model for South America

South America, and in particular the Andean countries are exposed to high levels of seismic hazard. The elevated concentration of population and properties in these regions has led to an alarming potential for human and economic losses. Although several fragility models have been developed in recent decades for South America, and occasionally used in probabilistic risk analysis, these models have been developed using distinct methodologies and assumptions, which renders any direct comparison of the results across countries questionable, and thus application at a regional level unreliable. For this reason, Villar *et al.* [14] developed a uniform fragility model for the most representative building classes in the Andean region, for large-scale risk analysis. Sets of SDOF oscillators were created and subjected to a series of ground motion records using non-linear time history analyses, and the resulting damage distributions were used to derive sets of fragility functions.

The identification of the most common types of construction were performed based on the exposure model developed by Yepes et al. [23] for the residential building stock in the Andean countries. This study indicated that the vast majority of the building stock is composed of masonry and earthen structures, followed by reinforced concrete and wooden buildings (see Fig. 7). Each building class was represented by a number of SDOF systems, whose dynamic (period of vibration) and structural properties (yielding and ultimate displacement) were defined based on existing literature and expert judgement.

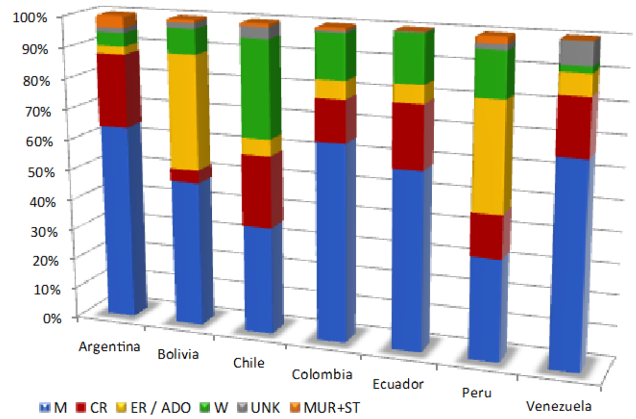
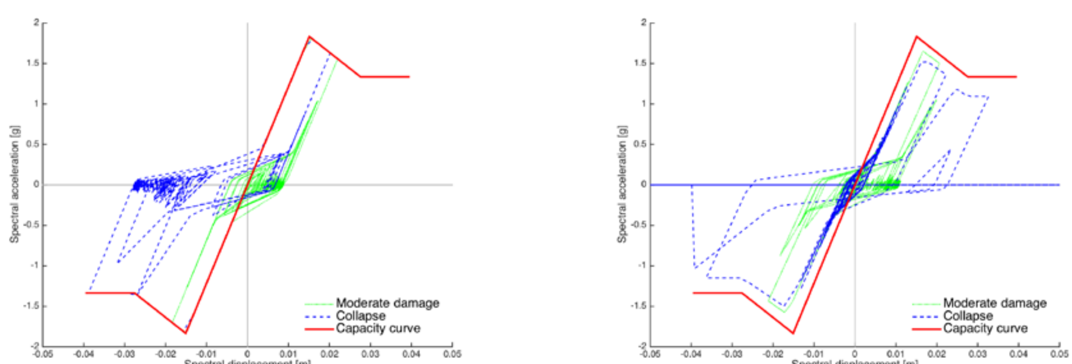


Fig. 7 – Distribution of the residential building stock according to the most common construction materials in the Andean countries [23].

The damage thresholds in this study were defined based on the capacity curves of each SDOF system, as illustrated in Fig. 3. Thus, fragility functions considering four damage states were derived: slight, moderate, extensive and collapse.

The selection of the ground motion records was performed taking into consideration the tectonic environment and seismicity in South America. Most of the seismic activity in this region involves the subduction of the Nazca and Antarctica plates beneath the South American plate. Slip along the dipping interface of these plates generates frequent and often large interplate earthquakes at depths of approximately 10 km to 60 km [24]. In addition, there are also significant events due to shallow crustal faults. For long distances ($R > 50$ km), ground motion records with moment magnitudes between M7 and M9 were selected, while for shorter distances ($R \leq 50$ km), records with moment magnitudes between M5 and M7 were considered. These records were selected from the PEER (Pacific Earthquake Engineering Research) database. A rock soil type was assumed during the selection process, and data from recording stations at a distance below 10 km were excluded, in order to avoid near fault effects.

An elastic damping of 5% was considered for the reinforced concrete structures, 10% for the masonry classes [25] and 2% for the wooden systems. Structural degradation was included in the non-linear time history analysis, as depicted in Fig. 8. In these plots the hysteretic curves for a two-storey confined masonry structure are presented with and without the consideration of damage degradation.



a) b)

Fig. 8 – Hysteretic curves for a 2-storey confined masonry with (a) and without (b) structural degradation.

Each fragility function was modelled following a cumulative lognormal distribution, whose statistical parameters (i.e. logarithmic mean (λ) and logarithmic standard deviation (ζ)) were estimated using the least squares method.

This regression analysis was performed considering spectral acceleration for a wide range of periods of vibration, in order to understand which intensity measure type provided a better correlation with the damage distribution. This feature is also available within the RMTK. In total 57 fragility models were derived, covering more than 80% of the residential building stock in the Andean countries. Fig. 9 presents the fragility functions derived for confined ductile masonry structures with two storeys and adobe buildings with one storey.

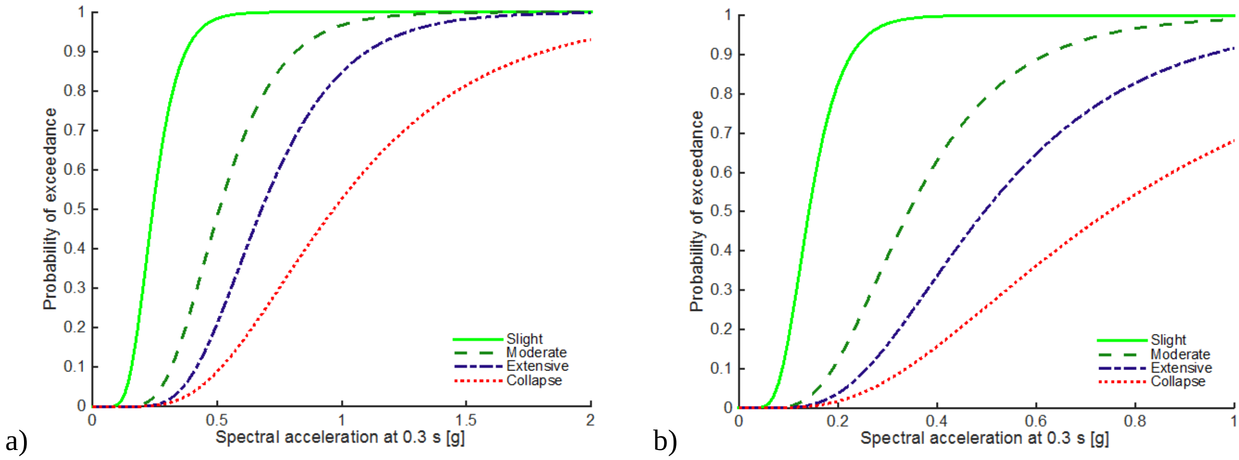


Fig. 9 – Fragility function for ductile confined masonry with two storeys (a) and adobe buildings with one storey (b).

These functions are currently being used in probabilistic earthquake loss assessment in South America, as well as in the development of earthquake scenarios for large metropolitan areas.

4. Conclusions

The development of fragility and vulnerability models can be a complex process that requires sophisticated computational tools. The vast majority of the existing models have been developed using code developed by the Authors of the models, as there is no common agreement within the scientific community regarding which approach should be followed. The OpenQuake Risk Modeller's Toolkit developed by the GEM Foundation aims at supporting experts around the world with a suite of open-source tools for the evaluation and derivation of fragility and vulnerability models. The current capabilities of the RMTK include several methodologies, capable of propagating a wide spectrum of aleatory and epistemic uncertainties. All of the code is available on a public repository and the methodologies, formulae and assumptions are described in the RMTK manual.

The RMTK is currently being used in the development of fragility and vulnerability models for several parts of the world including South America, eastern Sub-Saharan Africa, United States, Canada, Costa Rica and Nepal. The employment of the same tools and methodologies increases the uniformity of the models, and allows a direct comparison of the vulnerability of building classes from different regions.

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