Earthquake Vulnerability Assessment of Buildings for Catastrophic Risk Analysis in Urban Areas

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SUMMARY
A catastrophic risk model has been developed to evaluate, building by building, the probabilistic losses and pure premiums of different portfolios. The model includes a hazard module, an exposure module, a vulnerability module and a risk module. A brief summary of the methodological approach adopted for catastrophic risk assessment and an improvement methodological approach for the vulnerability assessment of building structures is presented. Dynamic nonlinear or simplified nonlinear analysis, the consideration of multiple damage functions for different types of components of the construction and a repair cost methodological approach are proposed in order to integrate the total economic losses for the building, for different performance levels of analysis. The methodology is illustrated with a one-story, one-bay reinforced concrete moment resisting frame with unreinforced masonry infill walls. Preliminary conclusions and recommendations are presented for the implementation of the proposed methodology.

Keywords: Seismic vulnerability functions, risk analysis, economic losses.

1. INTRODUCTION

Estimating probable damages and losses due to earthquakes in urban areas, has created powerful incentives for countries to develop integrated disaster risk management programs including mitigation programs for vulnerability reduction, planning options and tools, financial retention and transfer strategies, emergency response plans, cost-benefit analysis for retrofitting programs and others risk measures.

On the other hand, the frequency of seismic disaster events is particularly low with very limited historical data. Considering the possibility of future high destructive events, risk estimation has to focus on probabilistic models which can use the limited available information to best predict future scenarios and consider the high uncertainty involved in the analysis. Therefore, risk assessments need to be prospective, anticipating scientifically credible events that might happen in the future. Seismological and engineering bases are used to develop earthquake prediction models which permit to assess the risk of loss as a result of a catastrophic event. Since large uncertainties are inherent in model estimates with regard to event severity and frequency characteristics in addition to consequent losses caused by such events, the earthquake risk model is based on probabilistic formulations that incorporate this uncertainty into the risk assessment. [Cardona, O.; Ordaz, M.; Arámbula, S.; Yamín, L.; Mahul O., and Ghesquiere, F., 2006].

The probabilistic risk model (PRM) is built upon a sequence of modules and quantifies potential losses arising from earthquake events as shown in the Fig. 1. [Cardona et al., 2006]. Details of the model can be found in www.ecapra.org.

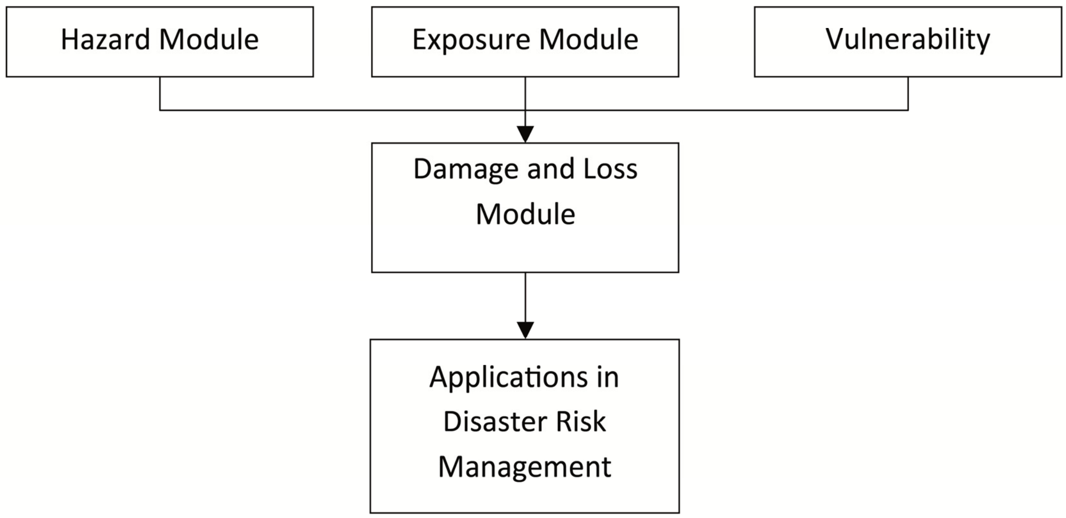

Figure 1. Probabilistic earthquake risk model (PRM).

The main sources of uncertainty in the risk analysis are the seismic hazard estimation and the vulnerability assessment of each one of the building structures included in the analysis. In particular the vulnerability assessment involves a great degree of uncertainty due primarily to the high variability in structural details even for the same type of building construction considered, and to the fact that each building can be composed of different types of partitions, facades, floor and roof finishes, internal utilities and contents, elements that will certainly have an important participation in the total expected economic losses.

In this paper, the analytical approach adopted for each one of the above-mentioned modules is summarized as well as a new improved methodological approach for the assessment of the vulnerability of any building construction.

2. SEISMIC HAZARD MODULE

The hazard module defines the frequency and severity of a peril at a specific location. This is done by analyzing the historical event frequencies and reviewing scientific studies performed on the severity and frequencies in the region of interest. Once the hazard parameters are established, stochastic event sets are generated which define the frequency and intensity distribution of thousands of stochastic events. The model includes the attenuation of the event from its location to the site under consideration and the proneness of local site conditions to either amplify or reduce the intensity.

The detailed procedure for the evaluation of the seismic hazard is presented elsewhere [Cardona et al., 2006]. The seismic hazard is expressed in terms of the exceedance rates of any seismic intensity parameter (SIP). SIP usually includes the peak ground acceleration (PGA), the spectral acceleration or any other. The SIP selected in the hazard analysis should be in agreement with the input parameter required for the vulnerability assessment.

Local soil response is included in the analysis through the definition of amplification functions in different locations of the city. The selected seismic intensities can then be obtained as input hazard parameters for different return periods at ground level through the area of analysis. Fig. 2 presents some examples of spectral accelerations at ground level in Bogotá for a specific return period of analysis [Zuloaga et ál., 2012].

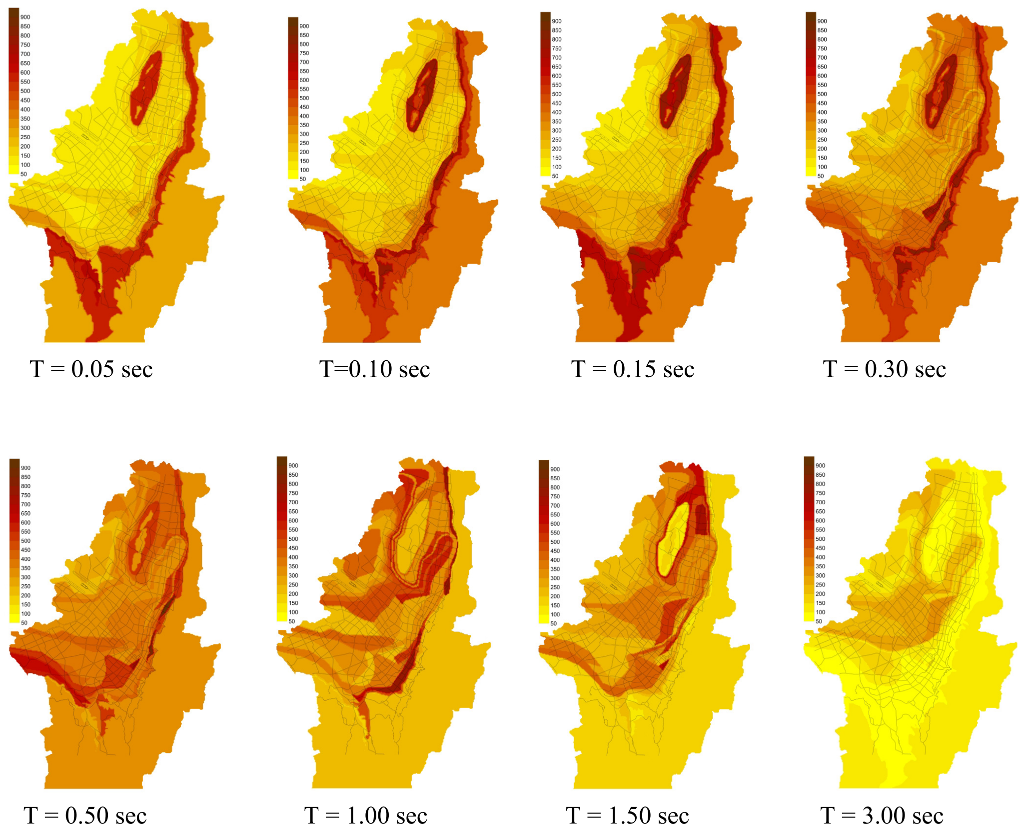

Figure 2. Seismic hazard maps for a 475 year return period for Bogotá- Colombia

3. EXPOSURE MODULE

The exposure values of “assets at risk” are estimated either from available secondary data sources such as existing databases or they are derived from simplified procedures based on general macro-economic and social information such as population density, construction statistics or more specific information. This “proxy” approach is used when the preferred specific site by site data is not available. Based on the information available, a GIS data base is constructed with the specific required information. Table 1 summarizes the minimum information for analysis required by the system.

Table 1. Minimum Information Required For Analysis

Location for hazard evaluation	Exposure	Vulnerability
Department	Value at risk	Building type
Municipality	Exposure limit	Number of stories
Address	Structural description	Construction year
GPS coordinates	Non-structural elements and contents description	Additional structural and non-structural characteristics

Special routines allow for the visualization of the database information and general interpretation indices are calculated. Fig. 3 presents example maps of Bogotá’s database used for analyzing all building constructions in the city, with up to 1 million individual buildings.

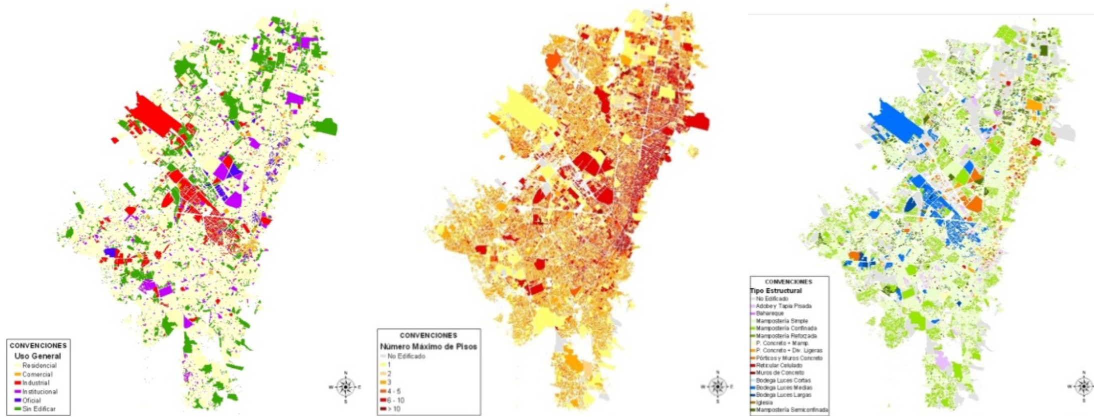

Figure 3. Index maps of building use, number of stories and structural class distribution for Bogotá.

4. VULNERABILITY MODULE

The vulnerability module quantifies the damage caused to each asset class by the intensity of a given event at a site [Miranda, 1999]. The development of asset classification is based on a combination of construction material, construction type (say, wall & roof combination), building usage, number of stories and age. Estimation of damage is measured in terms of the mean damage ratio (MDR). The MDR is defined as the ratio of the repair cost to the total replacement cost of the structure. A vulnerability function is defined relating the MDR to the SIP. The MDR given a value of a SIP for a certain building type can be calculated using equation 4 [Miranda, 1999; Ordaz, 2000].

$$E(\beta \mid \gamma_{\mathrm{i}}) = 1 - \exp\left[\ln 0.5 \left(\frac{\gamma_{\mathrm{i}}}{\gamma_0}\right)^{\varepsilon}\right] \tag{4}$$

Specific vulnerability functions can be defined for building contents and for business interruption (BI) costs. Several construction classes are included in the system as detailed in Fig. 4. Some of them are defined in terms of the spectral acceleration and other in terms of the maximum drift. The system also allows the use of customized vulnerability models. For each specific vulnerability function, a dispersion curve is also specified in order to allow for the uncertainty in the vulnerability description.

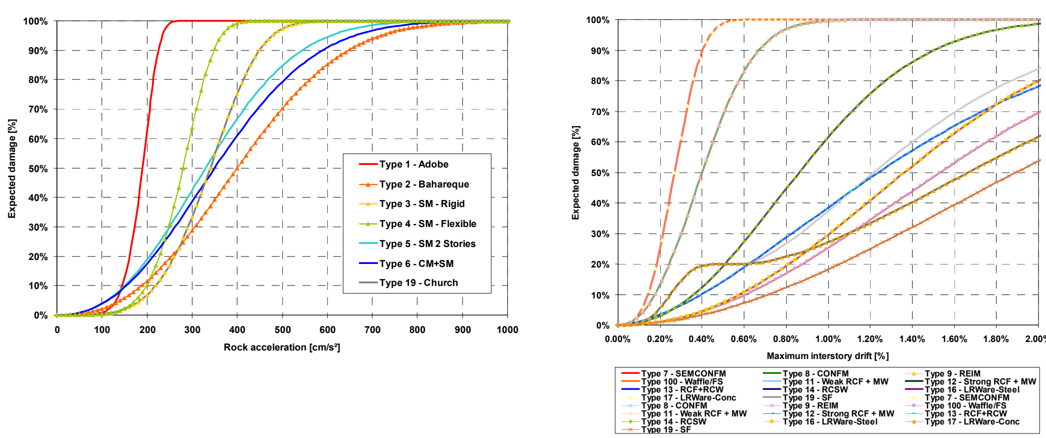

Figure 4. Vulnerability models used for different construction classes in Colombia.

5. DAMAGE AND LOSS MODULE

To calculate losses, the damage ratio derived in the vulnerability module is translated into economic loss by multiplying the damage ratio by the exposed value for each individual building at risk. This is done for each asset class at each location. Losses are then aggregated as required [Ordaz et al., 1998; Ordaz, 2000; Arámbula et al., 2001]. The loss module estimates the losses from the damage distribution, based on the insurance information (e.g., deductible, sum insured). Building upon a sequence of the described modules, the model quantifies potential losses that might arise as a result of an earthquake. Risk metrics produced by the model include the average annual loss, the loss exceedance curve and the corresponding values of pure risk premium and probable maximum loss (PML) [Cardona et al., 2006]. Fig. 5 presents the distribution of the average annual loss distribution for buildings in Bogotá [Zuloaga et al., 2012].

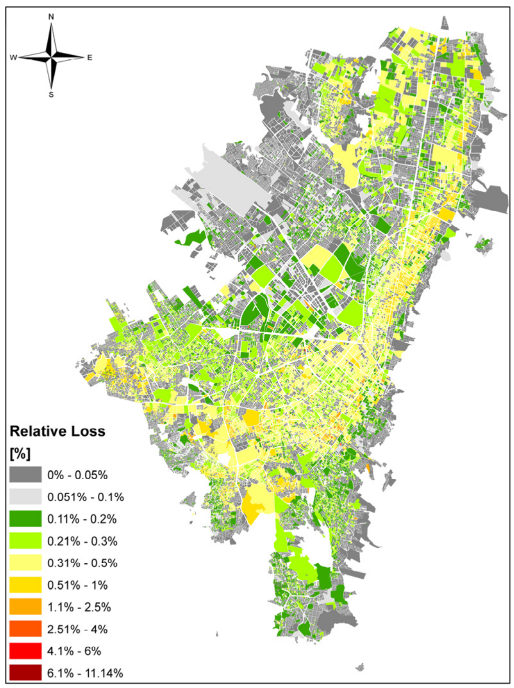

Figure 5. Distribution of the average annual loss for buildings in Bogotá.

6. PROPOSED IMPROVED METHODOLOGY FOR ANALYTICAL DETERMINATION OF VULNERABILITY FUNCTIONS

In the previous described catastrophic risk model, vulnerability functions are defined for each construction type relating the MDR to the seismic intensity parameter which can be expressed in terms of maximum acceleration, spectral acceleration or any other seismic demand parameter (SDP). As mentioned before, the hazard analysis has to be evaluated in terms of the same SDP used in the vulnerability description.

Analytical determination of vulnerability functions requires detailed nonlinear dynamic analysis of representative construction systems. Alternatively simplified non-linear analysis (pushover analysis) may be used in order to estimate relevant building response parameters at specific performance levels according to standard analytic procedures (ATC-40). In both cases, incremental analysis shall be implemented in order to obtain parameters to estimate mean damage ratios at different performance levels.

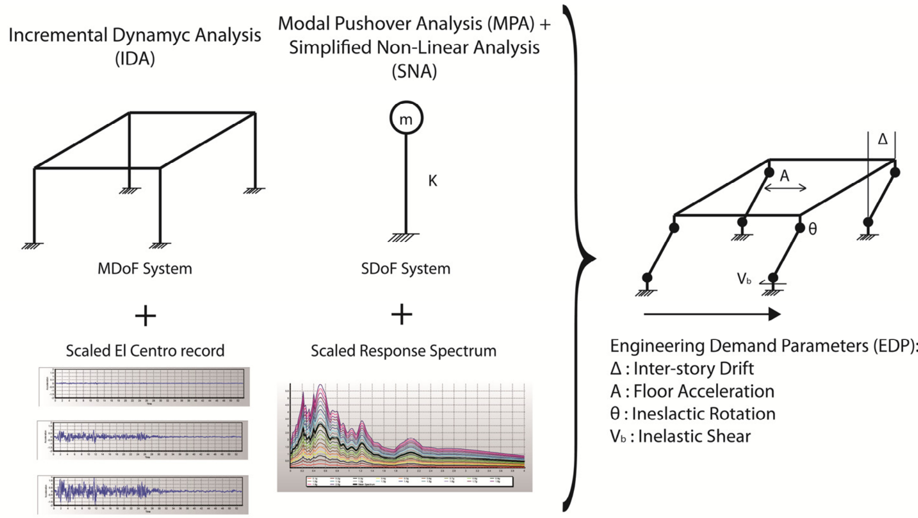

Figure 6. Model analysis considerations.

Non-linear dynamic analysis requires in general the definition of a complete integrated 3D analytical model of the building construction, including the definition of potential plastic hinges at critical elements. Widely used commercial computer program already include those analytical features (Perform 3D, SAP2000, OpenSees). For the analysis, specific site earthquake signals should be defined for increasing earthquake intensities. Methodologies for selecting the best possible signal are already proposed in the literature [Reyes, Chopra, 2010; Reyes, 2009]. On the other hand, the simplified non-linear analysis would require the definition of incremental site specific response spectra in order to obtain building EDP at specific performance levels. EDP usually include maximum values of inter-story drift, floor accelerations, inelastic rotation and shear demands at critical elements.

Using the different EDP for each one of the performance levels of analysis, damage for structural and non-structural components of the structure can be estimated using specific damage functions, which relates the local damage for each type of element or component with the corresponding EDP. Several specific damage functions are already published based on experimental and/or analytical procedures [Krawinkler et al., 2005; Porter 2005].

In order to integrate damage levels at different individual components of the building, a repair-cost based methodology is implemented. Using the estimated replacement value and the mean damage ratio for each individual component, the total repair cost for the entire building can be established for each performance level of analysis. Finally, the total repair cost is divided by the total replacement value of the building in order to obtain a relation between, any specific SIP and the corresponding MDR for the entire building.

In order to account for the uncertainty in the damage estimation, a dispersion curve is also specified in terms of standard deviation of the MDR values for all possible values of the SDP. The preliminary proposed values have to be calibrated in the future using Monte Carlo simulation techniques [Hurtado et al., 2012].

7. ILLUSTRATIVE SIMPLIFIED EXAMPLE

In order to illustrate the determination of a specific vulnerability function, a hypothetical one-story, one-bay structure is used to simulate the proposed methodological approach.

Fig. 7 illustrates the geometry and structural characteristics of the proposed model for analysis.

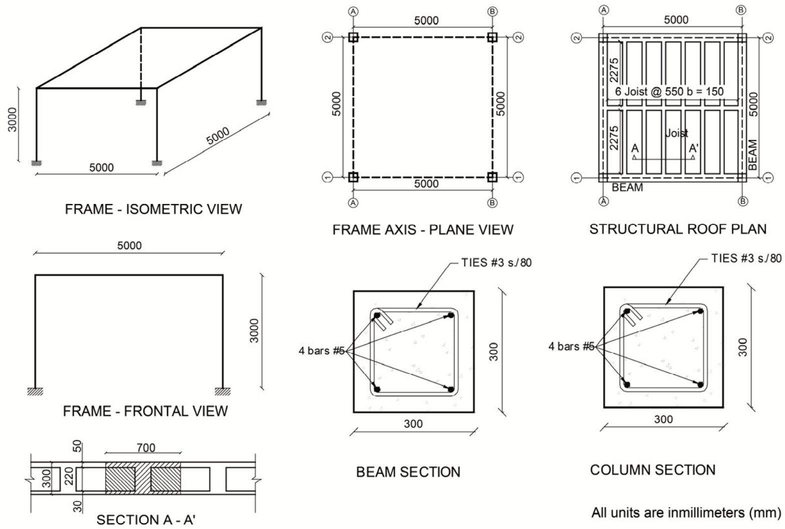

Figure 7. Geometry of hypotetical model.

Fig. 8 presents the EW El Centro record scaled to different peak ground accelerations (from 0.1g up to 2.0 g, at intervals of 0.1g) as well as the corresponding response spectra for 5% damping coefficient.

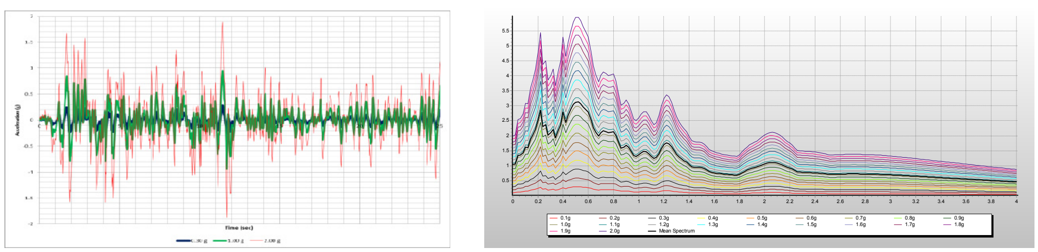

Figure 8. Record scaled and Response Spectra for 5% damping coefficient for several PGA of El Centro E-W record.

Fig. 9 presents the total base shear vs. maximum roof drift from the non-linear dynamic incremental analysis and from the simplified non-linear response spectrum analysis together with the pushover curve.

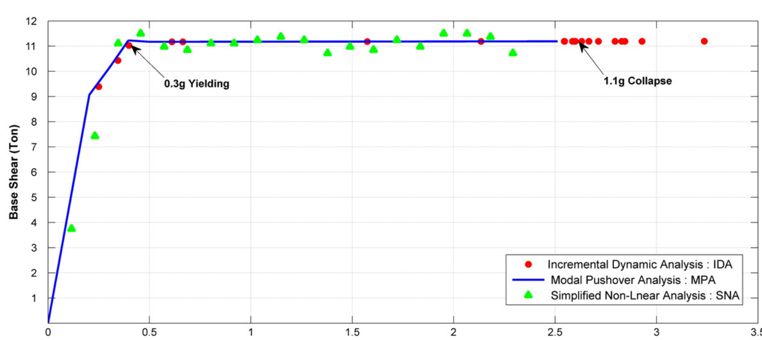

Figure 9. Total Base shear vs. Maximum roof drift.

Fig. 10 presents the results from IDA methodology which permits to conclude that the collapse of the building will occur approximately for a PGA of about 1.1g and story-drift of about 2.7%.

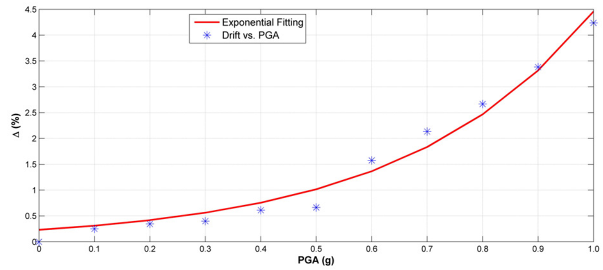

Figure 10. Story-drift vs. Seismic Intensity Parameter.

Once the nonlinear analysis is completed and interpreted, a repair-cost based methodology is implemented in order to estimate the repair value for each individual component of the structure and the total repair cost for the entire building for each performance level.

Fig. 11 presents illustrative cost-damage functions for structural and non-structural components.

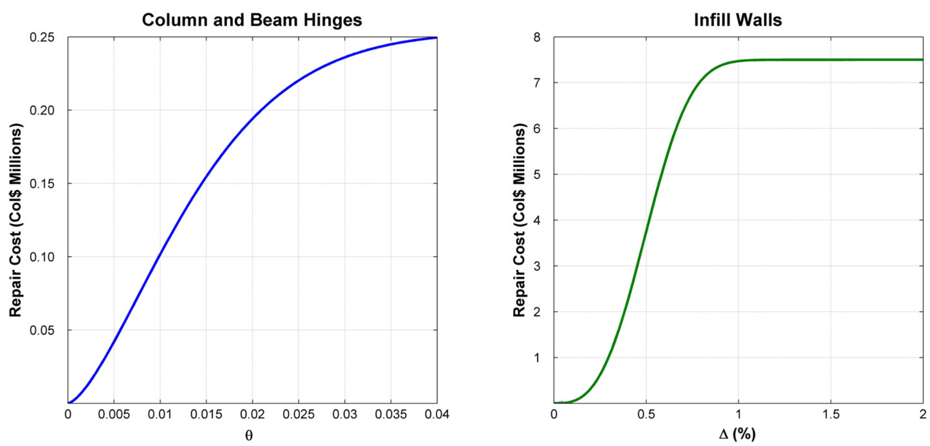

Figure 11. Cost-Damage Functions.

Finally, Fig. 12 illustrates the MDR for the entire structure against the SIP selected. This final curve represents the vulnerability function of this particular building.

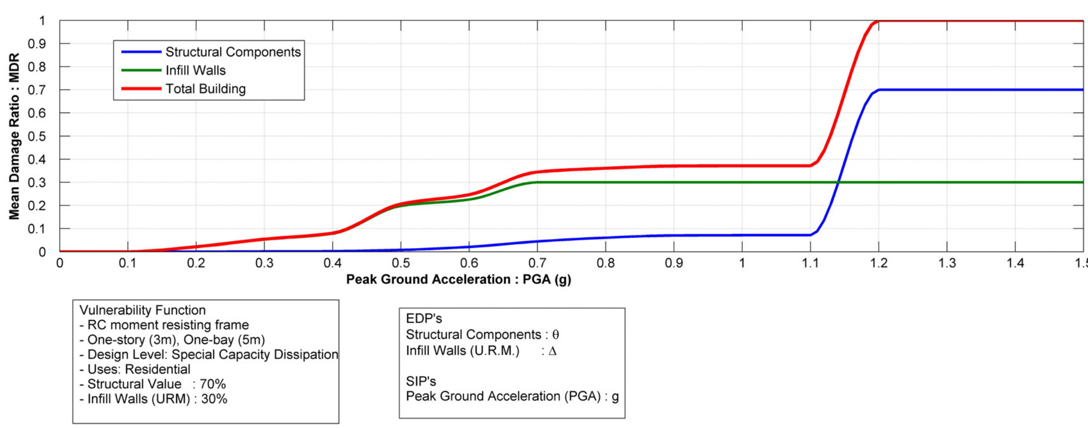

Figure 12. Vulnerability function of the hypothetical building.

8. CONCLUSIONS

A new methodological approach to evaluate vulnerability functions for integration into probabilistic risk models is proposed. The methodology is based on the repair cost of both structural and non-structural components of buildings at different performance levels. Performance levels are defined for incremental values of a certain SIP (PGA, spectral acceleration or any other) and by the corresponding EDP (inter-story drift, inelastic rotations, floor acceleration, base shear). In addition, published damage functions for individual component of the building are used in order to estimate their damage ratios for the corresponding value of the EDP which better correlated with its damage description. Finally the repair cost for each individual component or element is estimated based on its replacement value and the total repair cost of the building is calculated for each performance level. The relation between the total MDR and the corresponding value of the SIP represents the vulnerability functions for this specific building.

The advantages of this new methodology are the following:

- Both, nonlinear dynamic analysis and non-linear simplified analysis can be used in the determination of the vulnerability function.
- Any type of building configurations, for both structural and non-structural components can be subjected to analysis.
- The general model is completely flexible and all variables related to the analysis and repair cost evaluation, can be modified and adjusted to any specific case of analysis.
- Already published damage functions for individual components or elements can be used in the analysis.
- Variability of results can be evaluated through Monte Carlo simulation once the probability distribution functions of all relevant stochastic variables are defined.
- Vulnerability of building contents can be included, once a damage function is assigned to them, using any one of the SDP considered in the analysis.
- Structural variables such as design code level, type of confinement for RC elements, type and ductility of joints for steel structures, the structural participation of masonry in the building behavior and all other possible situations of analysis can be included.

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