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FROM STRUCTURAL PERFORMANCE TO LOSS ESTIMATION FOR (RE)INSURANCE INDUSTRY NEEDS: AN OVERVIEW OF THE VULNERABILITY ESTIMATION APPROACHES WITHIN EARTHQUAKE CATASTROPHE MODELS.

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Abstract. *One of performance-based earthquake engineering (PBEE) targeted eventual applications in practice is within catastrophe models. Vendor catastrophe models are broadly used within the (re)insurance industry for pricing natural catastrophe risk. The aim of the vulnerability module of all catastrophe models is common, to connect hazard intensities to loss due to damage. Nevertheless there is huge variation in the methods adopted and assumptions made within each model's vulnerability module, depending on the vintage of the model and the understanding of the seismic hazard in the region. This overview was conceived after close evaluation of a large number of vendor catastrophe models for earthquake (for different regions and from different vendors). We summarize the general structure of catastrophe models and focus on the vulnerability module of seismic catastrophe models, including how PBEE approaches are used for vulnerability estimation and how uncertainty is quantified. The existing gap between the PBEE output and the loss calculation of catastrophe models is highlighted. A discussion is aimed to be initiated, regarding the future potential of PBEE to provide more useful outputs for loss estimation within cat models, for use in the (re)insurance industry.*

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1 INTRODUCTION

(Re)insurance companies use catastrophe models to assess the probabilistic risk from potential natural disasters. The probabilistic loss assessment is necessary to the (re)insurance companies in order to ensure that the potential losses from the insured risks can be sustained and also to be further used for pricing the premiums and contract terms in order to have a sustainable business.

The catastrophe (cat) models can estimate the probable loss at given return periods, provided the details of the insured assets are known (in terms of location and characteristics). Catastrophe models have made significant advances in the last 20 years with the inclusion of more countries and incorporation of up to date scientific methodologies. New features, for example liquefaction and tsunami risk, are continually introduced to enhance the risk estimation. Earlier models were said to operate within a black box as there was little understanding of the relationship between the exposure detail input and the probabilistic loss output. However, the evolution of these models has generated in most cases, more detailed, transparent and modifiable versions of the models. Nevertheless, there is still room for improvement. For example, the vulnerability component of these models, where the events' intensities are connected to physical damage in terms of loss, can benefit from various engineering advances.

This study is put together after the evaluation of many earthquake models with focus on their vulnerability modules and aims to provide in addition to an overview of the methodologies used to derive these modules, points where the advances in earthquake engineering can assist for enhancing the vulnerability calculation within the existing catastrophe models and reducing its uncertainty.

2 GENERAL STRUCTURE OF CATASTROPHE MODELS

In order to predict the possible losses arising from an event, the potential hazard intensities at each exposure location need to be connected to the monetary loss through a module that estimates the expected physical damage on the insured assets. For the (re)insurer, assessment of damage potential includes buildings, contents and business interruption. This assessment is covered within the vulnerability module of each catastrophe model. The probabilistic assessment of hazard, for example, for earthquake models, the characteristics of the potential earthquake events (e.g. Magnitude, recurrence rate) as well as their potential attenuation, is covered within the hazard module of the models. The key calculation modules within natural catastrophe models are shown in Figure 1. The building characteristics of the exposed assets have to be mapped within the exposure module. Lastly, the loss calculation is considering the policy conditions and financial aspects (arising from insurance and reinsurance contracts) and is carried out within the financial module of the models.

The most relevant module of catastrophe models to engineers is the vulnerability module since it deals with performance of structural and non-structural components of buildings. The vulnerability module estimates the damage potential for given disaster scenarios. The damage potential is expressed as a mean damage ratio (MDR), i.e. the ratio of average damage loss to total replacement value of the insured asset and is a function of the hazard intensities. The hazard intensities are expressed by relevant intensity measures (IMs). The vulnerability functions that connect MDRs and IMs are the key to the vulnerability assessment. Subsequently the MDR values together with the policy conditions are employed in the loss calculation to assess the probabilistic losses for different return periods.

The rest of this study focuses on the vulnerability module of earthquake cat models as derived by mainly three model vendors.

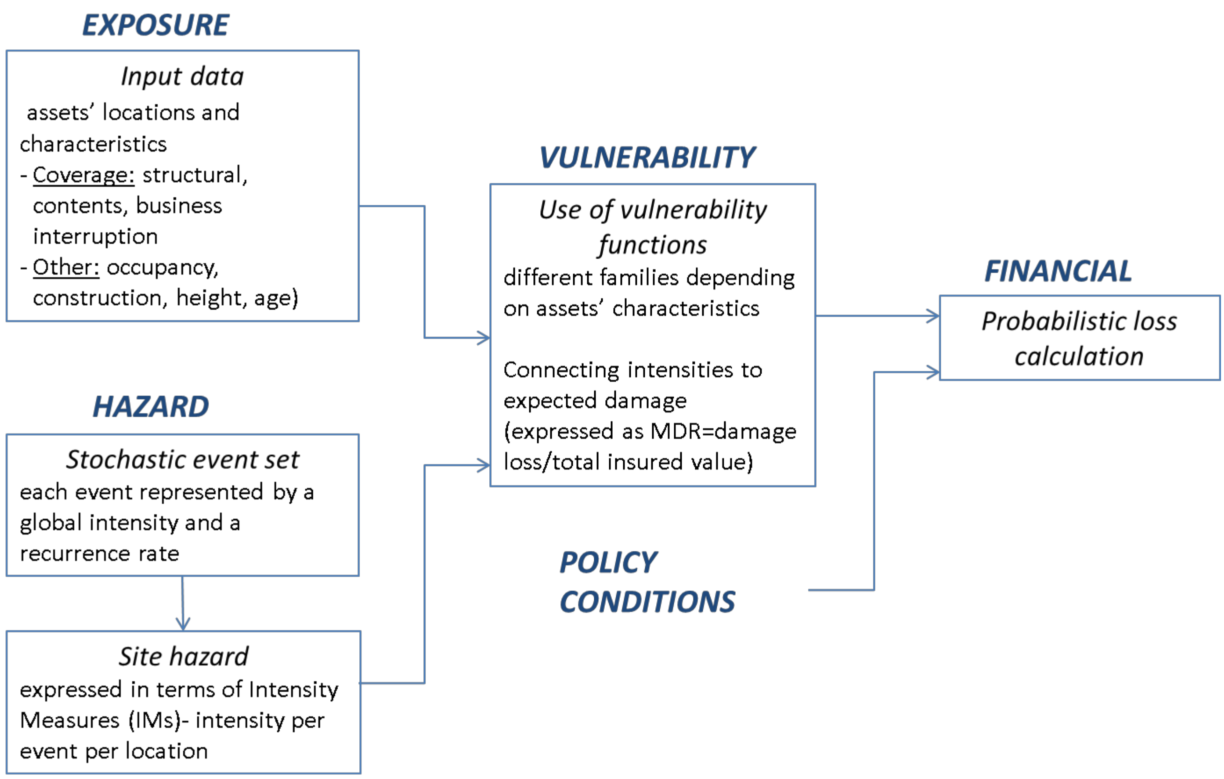

Figure 1: Key components of catastrophe loss assessment

3 DERIVATION OF VULNERABILITY MODULE OF VENDOR SEISMIC MODELS

The vulnerability module of each model is derived during the model development phase, through a two-stage process: the fragility estimation and the vulnerability assessment. At the first stage, the performance of the insured assets (structures, contents and business interruption) during events of various intensities is expressed in terms of engineering demand parameters (EDPs). These EDPs are calculated through a variety of methods in catastrophe models. The fragility assessment methodologies divide into two categories: the empirical and the analytical. Empirical methodologies derive the expected performance from past damage surveys of similar events, experts' judgement etc. In contrast, analytical methodologies can vary from considering very simple models, to very detailed ones. The empirical and very simplified analytical methods were employed in the development of early models but evolution has led to the incorporation of increasingly advanced and detailed analytical methods.

In the second stage of the vulnerabilty module development, the EDPs are translated to MDRs, that express the expected damage as a percentage of the replacement value of the assets.

Most of the models have some validation or even calibration of the derived vulnerability functions according to post-event damage data if they are available.

Modeling companies advertise that the fragility and vulnerability estimation within the seismic models is keeping pace with the earthquake engineering advances through consideration of the available updates in building and content earthquake performance. Nevertheless this is not the case for most of the existing models. Even if the models get regular general updates every few years, often the updates regard the hazard information update while the vulnerability module is left untouched. Some of the current models used in the industry have vulnerability functions developed before the year 2000 (e.g. simple MMI functions heavily based on expert judgment).

As already mentioned, both the fragility estimation and the translation from EDP to MDR are carried out during the development phase of the models. This in some cases means that there is some opaqueness in the procedure and the output of the vulnerability module. Often the documentation does not explicity describe the methodologies and assumptions used and the access to the vulnerability functions may be forbitten as some modeling companies consider the vulnerability functions as part of their intellectual property. Fortunately many of the modeling companies support more transparent models where the vulnerability functions (i.e. the relationships between event intensities, expressed in terms of Intensity Measures and MDR) are visible and even modifiable when using a model.

It is obvious that the end users of the models (in the (re)insurance industry) benefit from the openess in the methodology details and assumptions as well as from the access to the employed vulnerability functions since they can build a better understanding around the model components and consequently have an optimal use of the models suited to their needs.

3.1. Vulnerability module methodologies

Depending on the vintage of the model and the available data for the country, the earthquake models can have very different methodologies used to derive the necessary vulnerability functions. Some examples of the methodologies employed by current models are presented below.

A non-negligible number of models use empirically derived MMI vulnerability functions that are based heavily on engineering judgment (especially for regions with absence of claims data history). Unfortunately the model companies using these functions do not provide many details around their derivation. Their representatives support that the used functions are the best practice given the absence of validation data and more detailed models. On the other hand we may argue with that since in the absence of claims data history, the need of reliable analytical methodologies based on the structural performance of specific building typologies becomes even more obvious. The latter is also recognized by other model developers.

Since PBEE is becoming more popular, in particular in the USA (note that two leaders in the catastrophe modelling industry are USA based), more analytical methodologies are adopted for the vulnerability module derivation. From companies that are more open with sharing information regarding their models' architecture and underlying methodologies we can briefly note here some of the methods followed to derive vulnerability functions within earthquake catastrophe models.

Nonlinear static analyses within the Capacity Spectrum Method (CSM) are broadly used for deriving fragility functions for specific building typologies. Some models use this method exclusively for all building typologies even if they recognize that due to its assumptions the CSM is a reasonable analysis method for characterising the inelastic response only for buildings whose behaviour is dominated by their fundamental model of vibration. Indeed, the assumptions behind the CSM make it inadequate for structures where higher modes of vibration are participating highly to the response.

Since the weakness of the CSM method is recognised, the same company introduced also nonlinear dynamic analysis for the vulnerability function derivation. The model developers characterise this method as state-of-the art methodology for predicting structural response to earthquake events. The open-source software OpenSEES (Open System for Earthquake Engineering Simulation; *http://opensees.berkeley.edu*) is used as structural analysis software, where MDOF models are used to represent the building typologies of interest. Nonlinear dynamic analyses are carried out with large databases of accelerograms (order of 8000) and then regression analysis is carried out on the results to come up with the relationships between the intensity measures and the EDPs. The most commonly used EPDs from structural analyses are: maximum peak inter-storey drift and forces, roof displacements and peak storey accelerations. It should be noted that structural collapses are considered with a special statistical treatment during the derivation.

In some cases the vulnerability functions can be directly derived by the information collected from claims data during the past events. Indeed, for markets with abundance of claims data (a good example could be a region where a construction typology is predominant and there is a large insurance penetration, e.g. timber buildings in California), the mean damage ratio can be calculated from scatter plots of the damage ratio versus the intensity parameter (when data points are grouped in IM bins).

Some potential drawbacks of this method can be the large variability in the dataset that often obscures the overall trend, as well as the fact that these empirical functions are lacking the damage ratios for losses that occur below the insurance deductibles. The latter can introduce a positive bias in the damage ratio estimates and should not be neglected during the calculation. Last but not least the importance of the coherence between the building characteristics of the assessed population should be stressed. The empirical data usually do not come with the building characteristics behind the building performance, instead only an overall performance across the whole range of buildings is captured. Therefore the use of a homogeneous building population sample becomes necessary. Otherwise, for more mixed building population samples, engineering analyses is needed to quantify the impact of these differences to the MDR calculation. This kind of mixed methods of empirical data and engineering analyses are also common practise for countries with claims data available.

3.2. Uncertainty aspects within vulnerability modules of earthquake cat models

The most important uncertainty aspect assessed within the vulnerability module of earthquake cat model is the uncertainty of structural performance for a given intensity level. As is commonly seen during post-earthquake damage surveys, similar structures at the same location, that experienced similar shaking intensities, experience different levels of damage. The models' damage functions provide estimates of the mean, or expected, damage ratio corresponding to median ground motion at each affected site. Therefore this variation of structural performance (reflected as variation around the MDR) should be accounted for by the models. This variation is commonly represented by a beta distribution or a combination of two beta distributions. After analysis with a large number of claims data one of the modeling companies supports that the bi-beta distribution provides a much better fit to the observed damage patterns in past earthquakes.

Another company addresses the same issue by introducing the chance of loss concept. Chance of Loss is the probability of loss to incur for a certain risk and earthquake intensity. It is based on the idea that even if a particular risk is within the earthquake stricken area, a loss does not necessarily need to happen. The model developers regognise that there is a signifficant difference in the loss calculation if MDRs are used as aggregated data or as individual building information.

4 POTENTIAL IMPROVEMENTS OF VULNERABILITY ESTIMATION WITHIN CATASTROPHE MODELS BY PBEE CONTRIBUTIONS

Through detailed model evaluation, focusing on the vulnerability modules, some shortcomings are identified, where PBEE can contribute towards their improvement. Relevant research is carried out by research teams inside modeling and (re)insurance companies. Researches in these sectors are familiar with the advances of PBEE and therefore some recent models use the newest methodologies to derive their vulnerability modules. But of course the expansion to all the vulnerability modules of all the existing models will require more research resources. Earthquake engineers can have an active role in this expansion by leading research relevant to reinsurance business.

A few potential research key aspects are discussed below.

4.1. Ground motion intensity representation

4.1.1. Selection of intensity measures

The ground motion representation in the vulnerability functions can have a strong impact on the final loss estimation. A variety of IMs can be used to describe the hazard at each exposure location, given an event. Different models assessing the same peril for the same region may use vulnerability functions where the ground motion demand is represented by different intensity measures. As known, different intensity measures have different correlation to structural response. In other words, depending on the structural behavior, some intensity measures are better representatives of ground motions when estimating structural damage. Consequently loss estimation with more appropriate IMs can have decreased uncertainty compared to loss estimation with a less adequate IM. Undoubtedly the uncertainty in the loss calculation can be reduced through adoption of the most appropriate IMs.

The range of IMs used in seismic assessment within PBEE is very broad. On the other hand, the range of IMs used within the seismic cat models is not so big. In particular, older models mostly use the structural independent IMs, namely MMI and PGA to represent the ground motion intensity. More recent models (last decade) use also structural dependent IMs. These IMs are limited to the spectral ordinates (spectral acceleration and spectral displacement) at the natural frequency of vibration of buildings (period values can either be fixed to represent building height ranges or varying proportionally with the building height). Structural dependent IMs have a greater correlation to structural performance than structural independent IMs and thus can reduce calculation uncertainty. Nevertheless, the formers' advantage is valid only when the structural details (e.g. the building height - used as a proxy for estimating natural frequency of vibration of buildings) are known. The challenge of selecting the most appropriate IM remains for the buildings of unknown characteristics. If the building details are unavailable then use of such IMs can introduce randomness in the hazard representation and consequently errors to the loss calculation.

Figure 3 shows the different loss outcomes of four seismic events using structural dependent vulnerability functions derived from different building height assumptions (assuming the same insured value for the building units). Losses, assuming mid, high and tall rise buildings are compared to those based on a low-rise building assumption. In Event 1 the loss from a tall-rise building is 80% greater than that of low rise, while in Event 4 the loss from tall-rise building is 20% lower than that of low rise. This model is not appropriate to use where building heights are unknown; in this instance a model with structural-independent vulnerability functions could be more appropriate.

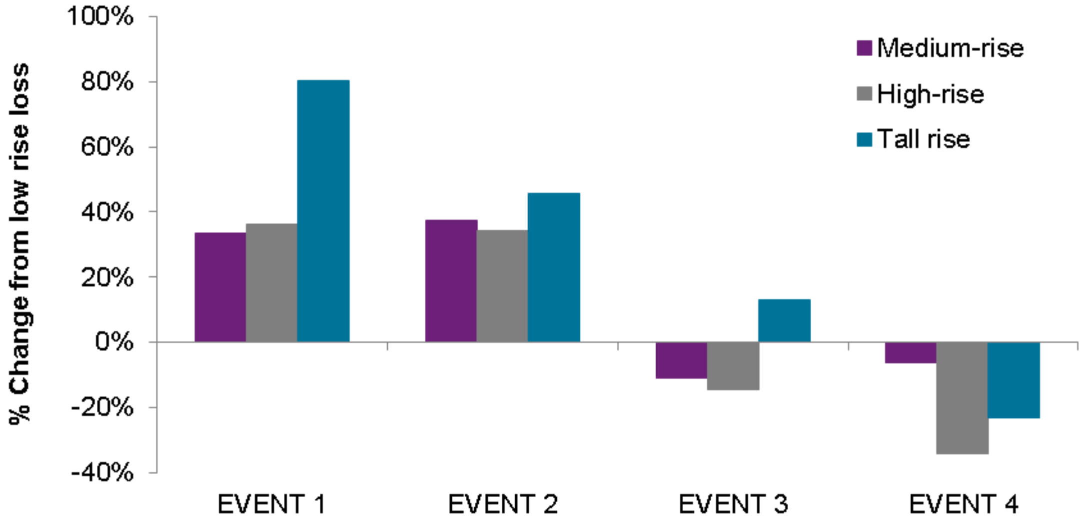

Figure 2: Percentage loss change of modelled earthquake event losses using different building assumptions.

Given this large impact, the need for selecting the most appropriate Intensity measures for the vulnerability modules becomes evident. In the last years with the broader use of PBEE, studies are carried out for establishing criteria and methodologies for selecting adequate intensity measures to represent ground motion in structural assessment. Studies for selecting optimal IMs have already been developed for various building typologies (e.g. URM buildings by Mouyiannou and Rota [1], for components within a number of different structures by Weatherill et al. [2]). The aforementioned methodologies and criteria can easily expand to cover the usability of the IMs within catastrophe models. The first consideration regards the hazard representation limitation (cat models have limited IMs to represent the hazard module outputs). Another consideration regards the selection of adequate IMs to represent the hazard intensities in vulnerability analysis of buildings with unknown characteristics. It is likely that different IMs have best correlation with structural response from buildings with a mix of characteristics rather than a specific typology (of known height, age etc.). Some further investigation will definitely be valuable.

4.1.2. Ground motion intensity translation

Models need to translate ground motion intensities as they are output by the hazard modules, expressed usually as PGA to intensity measures more relevant to damage metrics (e.g. MMI or Spectral ordinates) in order to be used in the vulnerability module to estimate potential damage to buildings and building contents (note that PGA may still be used in secondary calculations, such as liquefaction potential or landslide risk or business interruption).

An example of such intensity measure translation is shown in Figure 3 for two commercial catastrophe models. Specifically, the graph shows the MMI estimation for various values of PGA and includes translations of intensities corresponding to hazard maps of the same region for various return periods. One of the two models (Model 2) uses a single ground motion translation equation [3] for this translation and no uncertainty is taken into account in the calculation. The other model shown in the graph has more scatter in the translation. Model 1 also bases the translation on a ground motion translation equation (older than Model 2) [4] but modifies this calculation based on local observation data for key historical earthquakes. It is worth noting that there are available ground motion intensity translation methodologies more recent than those used by both models [5].

On a first glance at the plot we may notice that Model 2 has lower MMI values than Model 1 for the same PGA levels. Nevertheless what matters for the loss calculation is the intensity level at various return periods. Model 2 tends to have higher PGA values and consequently higher MMI values than Model 1 for the low return period range (e.g. 100 and 250 years) and it is lower for the range of high return periods (e.g. 5000 and 10000 years). Additionally we can observe that for any given return period, Model 1 has a broader distribution of intensities than Model 2 (for both the intensities shown here). For example for 100 years return period Model 1 has a range of intensities between 0.11g and 0.56g in terms of PGA that translates to a range between 6.15 and 9.21 in terms of MMI. For the same return period, Model 2 has a narrower range of PGA values from 0.25g to 0.44g that corresponds to MMI values between 7.24 and 8.16.

Consequently in the vulnerability calculation Model 1 will have more variation due to the ground motion intensity definition than Model 2.

This intensity translation step between the hazard module output and the vulnerability module input can impact the accuracy of the loss calculation and its actual outcome. There is a need for studies on the investigation of these translation methodologies.

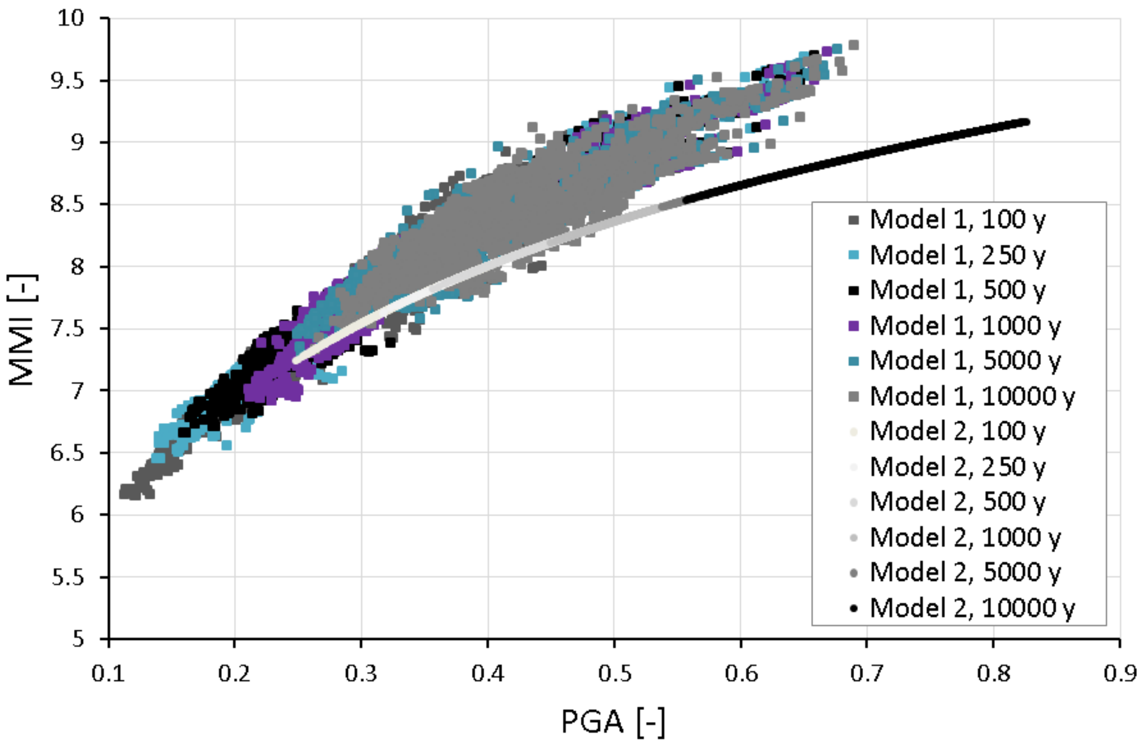

Figure 3 Ground motion intensity measure translation from Peak Ground Acceleration to Modified Mercalli Intensity, by different catastrophe models for the same region.

4.2. Simplified methodologies

A large number of analyses are carried out in order to assess models representing all building characteristic combinations for deriving all the necessary vulnerability functions for catastrophe models. Therefore the need for using methodologies that are not very computationally demanding is obvious. Nevertheless the right balance between method quality and easiness should be pursued. The methodologies should benefit from the recent advances of PBEE that should be expressed in the most appropriate simplified way possible. An important limitation should be kept in mind when developing vulnerability methodologies. The final functions need to be combined with the hazard module output within the risk calculation and as already discussed the ground motion intensity measures that represent the probabilistic seismic hazard are limited, especially within catastrophe models.

It should be noted that these methodologies can be useful for other industries since they can be applied in any large scale risk assessment, as for example in emergency planning, aftershock risk management etc. Lastly the methodologies can benefit back from the reinsurance side since their developers can use claims data from past earthquake events for validating and enhancing their assumptions.

4.3. Using already existing fragility and vulnerability functions

The catastrophe vulnerability modules can benefit both from their validation and their development from already existing vulnerability and fragility analysis results available in literature. There is a great volume of fragility functions derived by various building typologies around the world. But there is still a gap preventing this benefit. The gap is due to the existence of so many different functions that are derived according to different methodologies and assumptions which makes it impossible to reuse them for something more generic like their use within catastrophe models. The most common varying parameters are the definition of limit states and performance level indicators. Even for the same building typologies, different authors adopt different basic assumptions in their methodologies which make the functions appropriate to use only for the specific assessment they are aimed for.

There is a clear need of unified approaches or studies that combine already existing functions and harmonize them in order to be adequate for more generic uses. This concept is already explored by some recent studies. For example, Spillatura et al. [6] derived a set vulnerability functions based on existing functions for masonry buildings in Italy and Southern Europe. The authors derived a set damage ratio curves using PGA and MMI as intensity measures. It should be noted that the dispersion around the mean curve, which is computed in terms of 10th and 90th percentile curves, is quite large but the authors believe that the applicability of this study into seismic risk application is straightforward and can represent a useful aid to risk engineers for the generation of new vulnerability modules or the validation of existing ones.

An alternative option for using existing functions is by selecting the most representative functions for the desired region and building characteristics. This selection can be based on expert judgement or followed some established criteria in order to avoid subjectivity. Stone et al. [7] investigated the possibilities of using existing vulnerability functions, by selecting them from a large database of available seismic fragility and vulnerability functions. The authors acknowledge the many challenges of this practice, especially regarding the increased uncertainty in the results. The study investigates how the experts select functions from the available set of functions. For the group of experts studied, the selection process is statistically random. A framework for selecting existing functions is suggested, in order to give more objectivity to the selection process and guide the analyst toward more accurate results.

The potential benefit from more studies like the few mentioned here to catastrophe models and in general to risk assessment and its uncertainty quantification is apparent.

5 CONCLUSIONS

Catastrophe models currently incorporate methodologies according to the latest engineering advances. Improvements have been made to the vulnerability modules of earthquake models through the adoption of recent PBEE developments but still some points are identified where PBEE can improve the vulnerability modules of such models. These points are discussed in this study.

As a closing thought, we would like to stress the importance of natural disaster risk assessment, management and mitigation. There are more existing buildings already exposed to nat cat risk than all the buildings that the structural engineers will be called to design globally in the near future. Today, only 30% of the global built assets exposed to risk due to natural disasters are insured. A more precise risk calculation can assist with increasing the insurance penetration in the nat cat market. As earthquake engineers we can play a key role in the increase of this percentage. We must work on improving the calculation and limiting the uncertainties as well as simplifying and adjusting the methodologies in order to ensure that the advances are incorporated in the models used to calculate risk by insurance and other risk management bodies. In the end, a more precise risk estimation will benefit not only the insurance providers but most importantly the insurance holders.

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