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RISK-TARGETED HAZARD MAPS FOR EUROPE

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Abstract

The design of new structures according to modern seismic regulations requires the definition of a uniform hazard spectrum conditioned on a given return period, and it is assumed that the resulting collapse probability will be equally uniform for all structures, regardless of their structural properties or location. However, the uncertainty in the probabilistic collapse distribution and variability in the slope of the seismic hazard curves lead to a level of risk that is site- and structure-specific, and thus not uniform for all structures across a region. The estimation of risk-targeted hazard maps allows for the definition of a design ground motion that leads to a uniform level of risk nationally, defined according to an acceptable risk threshold and collapse probability distribution. The parameters involved in the definition of the probabilistic distribution of collapse are evaluated herein through the analysis of hundreds of fragility models developed for European buildings. The seismic hazard results recently released under the FP7 European project SHARE are employed to estimate the variation of the annual probability of collapse across Europe, and risk-targeted hazard maps for a fixed annual probability of collapse are calculated. The preliminary results expose large areas where the design ground motion could be significantly altered without compromising the level of acceptable risk. Moreover, this study highlights the areas where additional research is still required in order to establish risk-targeted hazard maps as a reliable and efficient tool for the estimation of design ground motion.

Introduction

The vast majority of earthquake design regulations rely on seismic hazard maps to estimate the seismic demand at a given location, according to a pre-defined return period (e.g., 475 years for most of the countries in Europe or 2745 years in the United States). The decision to design a structure according to a "uniform" level of demand relies on the idea that such procedure would lead to the same probability of collapse wherever the building is located in the country. However, such an assumption does not hold true if uncertainty in the collapse capacity is introduced in the calculation of the probability of collapse. This uncertainty in the collapse is due to a large spectrum of sources of variability such as differences in the structural response from distinct building typologies, employment of different construction practices, human errors and decisions during the design and construction stages, amongst others. Thus, the level of demand for which the designed structure collapses is characterized by a large variability and, therefore, the associated probability of collapse is not only dependent on the probability of exceeding the design ground motion, but the whole spectrum of ground motion levels across the seismic hazard curve.

Recognition that designing structures considering only the ground motion for a given return period leads to different probabilities of collapse throughout a given region propelled the development of the so-called risk-targeted maps, first proposed by Luco *et al*. (2007) for the conterminous territory of the United States. These maps provide the ground motion that, if employed for design purposes, leads to the same nominal probability of collapse, or a uniform level of risk, nationally. This level of

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acceptable risk might vary depending on the importance of the structure, and as indicated by Douglas *et al*. (2013), it should be established through the involvement of not only structural engineers but also politicians, sociologists and other decision makers. The latter authors have also carried out a comprehensive study in which parametric analyses were performed to assess the influence of the various parameters involved in the estimation of the probability of collapse. This study was developed using mainland France as the region of interest.

In the study presented herein, the various components involved in the development of risk-targeted design maps are investigated, and then maps are derived for Europe using the recently released seismic hazard results from the FP7 European project SHARE (www.share-eu.org). The preliminary results from this study indicate that the employment of the risk-targeted hazard philosophy could change the ground motion for which a building should be designed by up to 30%, without compromising the risk a society might be willing to accept.

Definition of the collapse probabilistic distribution

One of the main sources of uncertainty in the estimation of the probability of collapse is related to the definition of the probabilistic distribution of the collapse capacity of seismically designed structures. The European building stock has been the target of numerous studies, which often resulted in the derivation of several fragility functions. The results from a great part of these studies have been used to compile a European database of fragility models (Crowley *et al*., 2014), as part of the FP7 European project Syner-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain). It is important to emphasise that the purpose of this evaluation is to assess the collapse probability of single structures, and the vast majority of the Syner-G fragility models has been derived for building classes. Nevertheless, in order to take advantage of existing models in the literature, these results will be utilized to investigate expected trends in the collapse probability.

The evaluation of the epistemic uncertainty in the structural fragility for certain structures or building typologies demonstrated a large variability. In Figure 1, several fragility curves are illustrated for reinforced concrete mid-rise buildings constructed following a seismic design code.

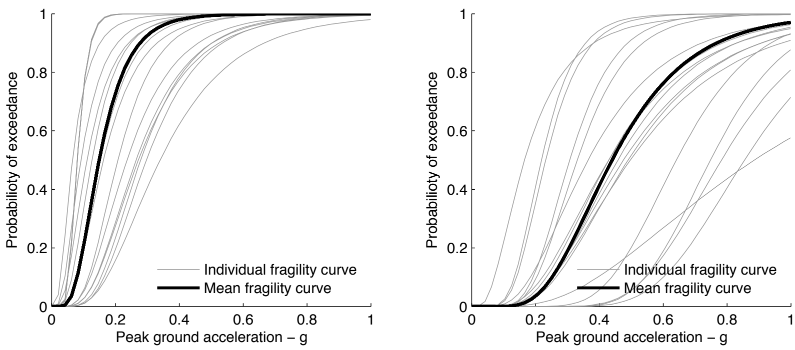

Figure 1. Individual and mean curves for yielding (left) and collapse limit states (right) for RC mid-rise buildings with lateral load design (adapted from Crowley *et al*. 2014).

Various causes for this large variability can be identified, such as the employment of different construction practices, consideration of different design codes (even if all of them contained seismic provisions) and most importantly, the fact that each structure might have been designed for a specific ground motion. Furthermore, it is also important to acknowledge the epistemic uncertainty due to the application of different analytical methodologies in the derivation of the fragility curves (Silva *et al*. 2013a, 2013b).

The influence of the mapped design ground motion in the resulting collapse probability has been demonstrated in several studies (e.g. Ulrich *et al*., 2014; Silva *et al*., 2014), and it is used herein to directly define the site-specific collapse fragility curve. The distribution of the collapse probability can be defined by a cumulative lognormal function with logarithmic mean μ and logarithmic standard deviation β of a ground motion parameter. Alternatively to the use of the logarithmic mean, this curve can also be defined by the ground motion corresponding to a certain percentile (or probability of collapse). Luco *et al*. (2007) analysed typical structures designed using the ASCE Standard 7-05

(FEMA, 2009) to derive a mean collapse fragility curve, and concluded that there is approximately a 10% probability of collapse at the mapped design ground motion (2745 years return period), with a logarithmic standard deviation of 0.8. Douglas *et al*. (2012) suggested values considerably different for these two variables: for what concerns the probability of collapse at the mapped design ground motion (475 years return period), a value of 10^{-5} is proposed, and a logarithmic standard deviation of 0.5 is assumed. The consideration of these distinct proposals will naturally lead to different collapse probability distributions, thus causing a direct impact in the risk-targeted hazard calculations. In Figure 2, collapse fragility functions were derived following the assumptions from both studies, and considering a seismic hazard curve for the city of Barcelona.

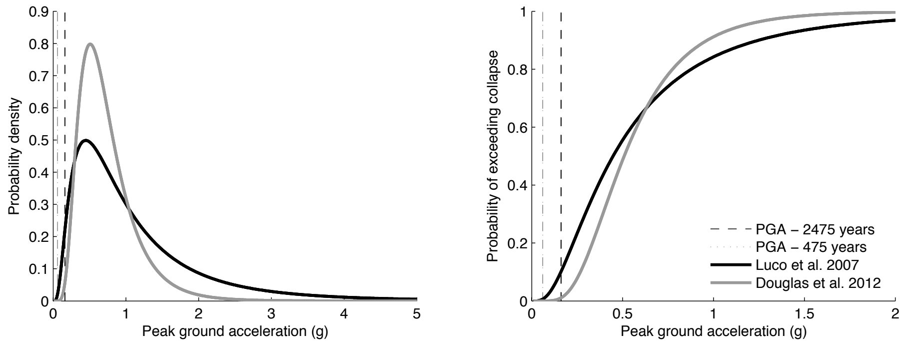

Figure 2. Probability density function (PDF) for the collapse capacity (left) and associated cumulative probability function (right) using both approaches (Luco *et al*. 2007 and Douglas *et al*. 2012).

Clearly the assumptions suggested by each study lead to different collapse fragility functions, which will directly influence the resulting probability of collapse. Whilst the estimation of the probability of collapse at the design ground motion may be a complex process, trends for the uncertainty in the collapse curve (β) can be derived through the evaluation of the hundreds of fragility models collected within the aforementioned European project. In Figure 2, several distributions of the parameter β are presented for different groups of buildings typologies.

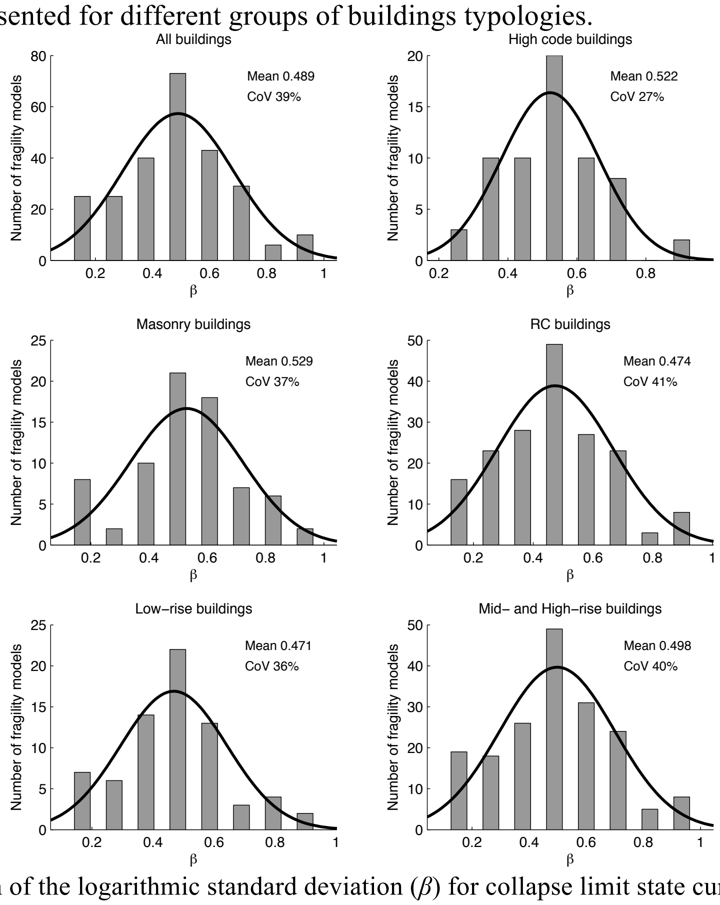

Figure 3. Distribution of the logarithmic standard deviation (β) for collapse limit state curves, using the results of Crowley *et al*. (2014) and considering different levels of aggregation.

For the purposes of this study, the logarithmic standard deviation indicated by Douglas *et al.* (2012) has been adopted (β=5). This value also seemed to be in agreement with the evaluation of existing fragility curves carried out in the previous section. However, it is important to understand that those curves were mostly for building typologies, and did not consider the wide spectrum of epistemic uncertainties associated with fragility derivation.

It was also observed that greater values of β often belonged to fragility functions representing large building classes (e.g. low-rise RC for Italy), as opposed to a better-constrained building typology (e.g. 3 storeys RC post-Code in northern Italy), which is probably more suitable to the study presented herein. Moreover, the employment of large values of β in regions with high levels of seismic hazard leads to collapse fragility curves which still indicate a low probability of collapse for extremely high ground motion values, which seems an unrealistic scenario. For these reasons, a decision was made to adopt a value of 0.5 for the parameter β.

The calculation of the probability of collapse at the design ground motion has been the targeted of limited investigation, as it requires the design and assessment of a large number of structures, considering a wide range of hazard levels. The evaluation of existing fragility models in the literature to assess trends for this parameter (as was done for β) is usually impractical, due to the fact that the design process and associated mapped ground motion are frequently not reported.

The design return period adopted in this study was 475 years, since it is the most commonly accepted design threshold in Europe (despite it being arbitrarily defined, as discussed further in Bommer and Pinho, 2006). Considering this return period and the design ground motion in terms of peak ground acceleration, Douglas *et al.* (2013) initially proposed a percentile of 10^{-5}, on the grounds that such value would lead to negligible changes in the current seismic hazard design maps for mainland France. More recently, a comprehensive study was carried out by Ulrich *et al.* (2014), in which a 3 storey RC structure was designed to increasing levels of peak ground acceleration (0.07g to 0.3g), and used to calculate a set of yielding and collapse fragility functions. The Authors concluded that the percentile of the collapse fragility function is dependent on the mapped ground motion, and proposed a value of 10^{-7} for low ground motion design, which increases up to 10^{-5} to the highest ground motion design level considered in their study. The considerably lower percentiles obtained for the structures designed according to low ground motion are mostly due to the fact that for such regions, the seismic action might not be the most aggravating effect, but instead other factors such as wind or snow loads, which can also offer an inherent lateral resistance. This sufficient seismic resistance for regions with low seismic hazard can also be observed even in structures that have not been designed according to the most modern seismic codes (Rossetto and Elnashai, 2003).

The mapped ground motion is commonly used to anchor a design spectrum, which is then used to estimate a spectral acceleration for the expected fundamental period of vibration of the structure being designed (e.g. Eurocode 8 - CEN, 2004). However, other seismic codes require directly estimates of spectral acceleration for specific periods of vibration (e.g. 0.2 and 1.0 secs for the BSSC, 2004), or provide pre-calculated response spectra for a number of seismic zones for the national territory (e.g. Portugal – RSA, 1983). Thus, it is important to understand the impact of employing other intensity measures in the definition of the collapse fragility curve, and ultimately, if the findings observed for peak ground acceleration also hold for spectral ordinates.

In the work of Silva *et al.* (2014), a large number of fragility functions were derived for RC regular moment-resisting frame structures according to different design regulations. The fragility assessment using the most recent national design code (RSA, 1983) was carried out considering four seismic zonations, with a range of peak ground acceleration from approximately 0.05 to 0.2 g. The design of these structures was done using pre-calculated response spectra for 5% damping on rock, which was altered afterwards to consider the effects of other types of soil conditions. These structures were tested against many ground motion records using nonlinear time history analysis, and each fragility model was derived using spectral acceleration for the yielding period, which tends to provide a better correlation with damage than peak ground motion (Bommer *et al.* 2002, Sousa *et al.* 2014). The percentile at the mapped ground motion was evaluated for every building typology, and similar trends to what was reported by Ulrich *et al.* (2014) were observed between low and high hazard regions, when utilizing spectral acceleration for very-short periods. For the building typologies with a higher number of storeys (for which spectral acceleration for longer periods was employed) higher values for the percentile at the mapped ground motion were obtained. Despite the good agreement between these two studies, it is important to clarify that such comparisons can only have a qualitative character, since distinct design regulations were employed in each study (e.g. distinctive procedures to calculate the seismic action; different over-strength and safety factors).

A simple investigation of the influence of using different intensity measure types will be presented herein, by calculating the collapse probability for three European cities with low (Vienna), moderate (Lisbon) and high (Istanbul) hazard and four intensity measures (PGA and Sa for 0.1, 0.3 and 1.0 secs). Nonetheless, the investigation of collapse fragility functions in terms of pseudo spectral acceleration to be used in risk-targeted hazard calculations are the scope of another on-going study, and in the work presented herein the Authors focused only on risk-targeted maps utilising collapse fragility curves defined in terms of peak ground acceleration, following the recommendations of Ulrich *et al*. (2014).

Acceptable probability of collapse

The concept of risk-targeted hazard maps relies on an acceptable level of seismic risk (either annually or for the life expectancy of the structure), for which a ground motion value is calculated. This level of acceptable risk might vary depending on the importance of the structure, and as indicated by Douglas *et al*. (2013), it should be established through the involvement of not only structural engineers but also politicians, sociologists and other decision makers.

Luco *et al*. (2007) estimated the average probability of collapse in the western regions of the United States, and determined that a national risk of 1% in 50 years (about $2x10^{-4}$ annually) is an acceptable threshold. On the other hand, Douglas *et al*. (2013) evaluated several studies from existing literature and concluded that a value of 10^{-5} is a suitable compromise amongst the various proposals.

Many countries in Europe have policies that require risk evaluations to be carried out for hazardous installations (such as nuclear power plants, oil refineries), railway systems, etc. Two risk metrics that are commonly applied in a risk evaluation include *individual risk* and *societal risk*. The former metric is defined as the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity, whilst the latter the provides a relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards (Jonkman *et al*., 2003). The thresholds of acceptable individual and societal risk vary from country to country. In the Netherlands, for example, the individual risk should be lower than 10^{-6} (per year). If we consider that past earthquake data suggests a fatality rate (number of fatalities divided by number of occupants) of between 10% and 30% in a collapsed building (So and Spence, 2013), we can infer that a threshold annual probability of collapse could be as low as 10^{-5}. On the other hand, existing buildings in earthquake prone areas of Europe, such as Italy, Greece and Earthquake, clearly have fatality rates that are higher than the values above. It would be unfeasible given the current resources and in many cases even technically impossible to retrofit existing buildings to ensure a level of safety compatible with the annual fatality rates above.

Probabilistic Seismic Hazard Assessment for Europe – SHARE

The calculation of risk-targeted hazard maps requires the availability of seismic hazard curves throughout the region of interest. In the present study, due to the need for a uniform probabilistic seismic hazard model covering the majority of the European countries, a decision was made to employ the recently released seismic hazard results from the European project SHARE (Seismic Hazard Harmonization in Europe – Danciu *et al*. 2013). Nonetheless, there is no reason not to combine the assumptions and methodologies from the present study with country-based seismic hazard models.

SHARE was an initiative founded by the European Commission within the Framework Program 7 (FP7) to create a probabilistic time-independent seismic hazard model, with the involvement of several institutions and experts throughout Europe (www.share-eu.org). The development of SHARE leveraged upon several national seismic hazard models, as well as previous large scale initiatives such as the Global Seismic Hazard Assessment Program (GSHAP – Giardini, 1999) or the Unified Seismic Hazard Model for the European-Mediterranean Region (SESAME – Jimenez et al. 2001). Using new historical and instrumental earthquake catalogues, a collection of fully parameterized seismic faults and a new tectonic regionalization with associated ground motion models, three independent seismic source models were developed based on area sources; fault and background sources; and Kernel-smoothed sources. New seismic hazard estimates were calculated for Europe, which can be used to revise current national seismic hazard maps, or to update design regulations such as Eurocode 8.

Amongst the various results coming out of SHARE, seismic hazard curves and maps in terms of peak ground acceleration and spectral ordinates up to 10 seconds, and exceedance probabilities ranging from 1% to 50% in 50 years were critical input to the work presented herein. These results are publically available through the European Facility of Earthquake Hazard and Risk (www.efehr.org). The seismic hazard map in terms of peak ground acceleration for a probability of exceedance of 10% in 50 years (475 years return period) is presented in Figure 2.

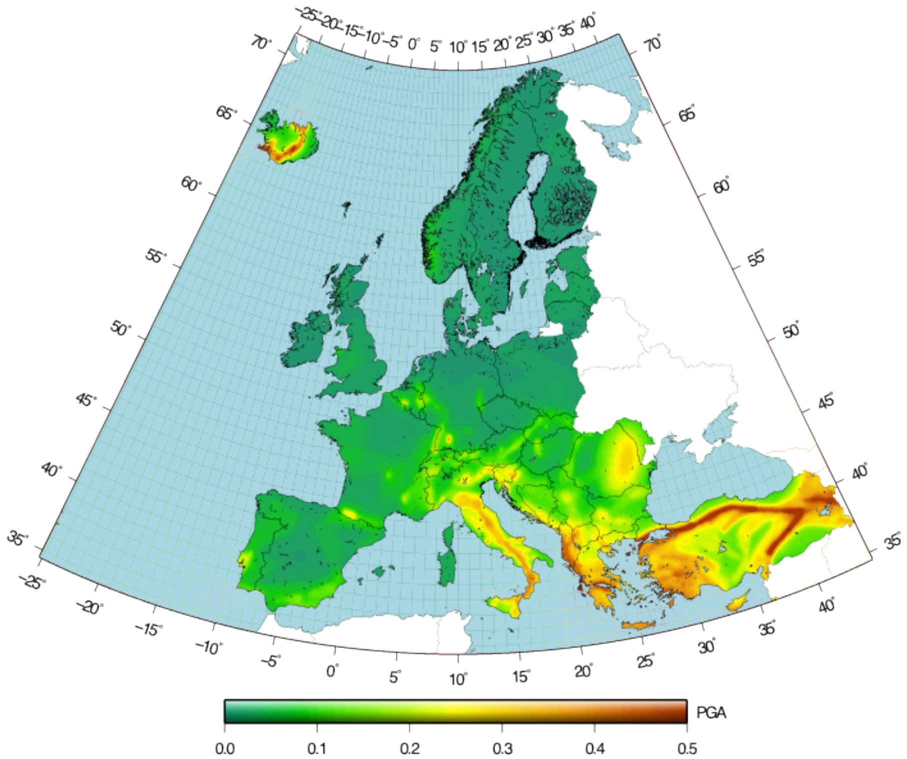

Figure 4. European mean seismic hazard map in terms of peak ground acceleration (in g) for the 475 years return period, produced within the European Project SHARE.

Iterative calculation of risk-targeted hazard

An iterative process is required for the estimation of the ground motion that will lead to the target acceptable risk. In the present work, the annual probability of collapse was calculated according to the procedure suggested by Eads *et al*. (2013), and described in the following steps:
The probability of collapse (required for the iterative calculation process that computes the ground motion that leads to the acceptable level of risk) has been estimated using an investigation interval of 1 year, as described by the following steps:

1. For each location, a seismic hazard curve is extracted from the results of the European project SHARE;
2. The seismic hazard curves are converted from probability of exceedance (PoE_{PGA}) in 50 years (T) versus PGA, into annual rate of exceedance (λ_{PGA}) versus PGA:

$$\lambda_{PGA} = -\frac{\ln\left(1 - PoE_{PGA}\right)}{T}$$

3. These curves are divided into a large number (m) of segments, and the slope (representing the rate of occurrence of the associated central PGA value) of each segment is derived.
4. A collapse fragility function is derived assuming a β of 0.5 and the peak ground acceleration for the 475 years return period as the mapped ground motion, and used to estimate the probability of collapse, conditioned on the central PGA value of each division ($P(C|pga_i)$);
5. The conditioned probability of collapse of each division is multiplied by the associated rate of occurrence, thus leading to a distribution of rate of collapse for a set of ground motion intensities. By numerically integrating this distribution, the annual collapse rate (λ_c) is obtained:

$$\lambda_c = \sum_{i=1}^{m} P(C|pga_i).\left|\frac{d\lambda_{PGA}(pga_i)}{d(pga_i)}\right|\Delta pga_i$$

6. The annual collapse rate is converted into annual probability of collapse (PC), and this value is compared with the acceptable annual risk (10^{-5}). Depending on whether the current PC is sufficiently close to the acceptable risk, the mapped ground motion might have to be adjusted accordingly, and step 4 and 5 repeated until the resulting PC is (according to a given tolerance), similar to the target risk.

The various steps from the iterative calculation process are illustrated in Figure 5.

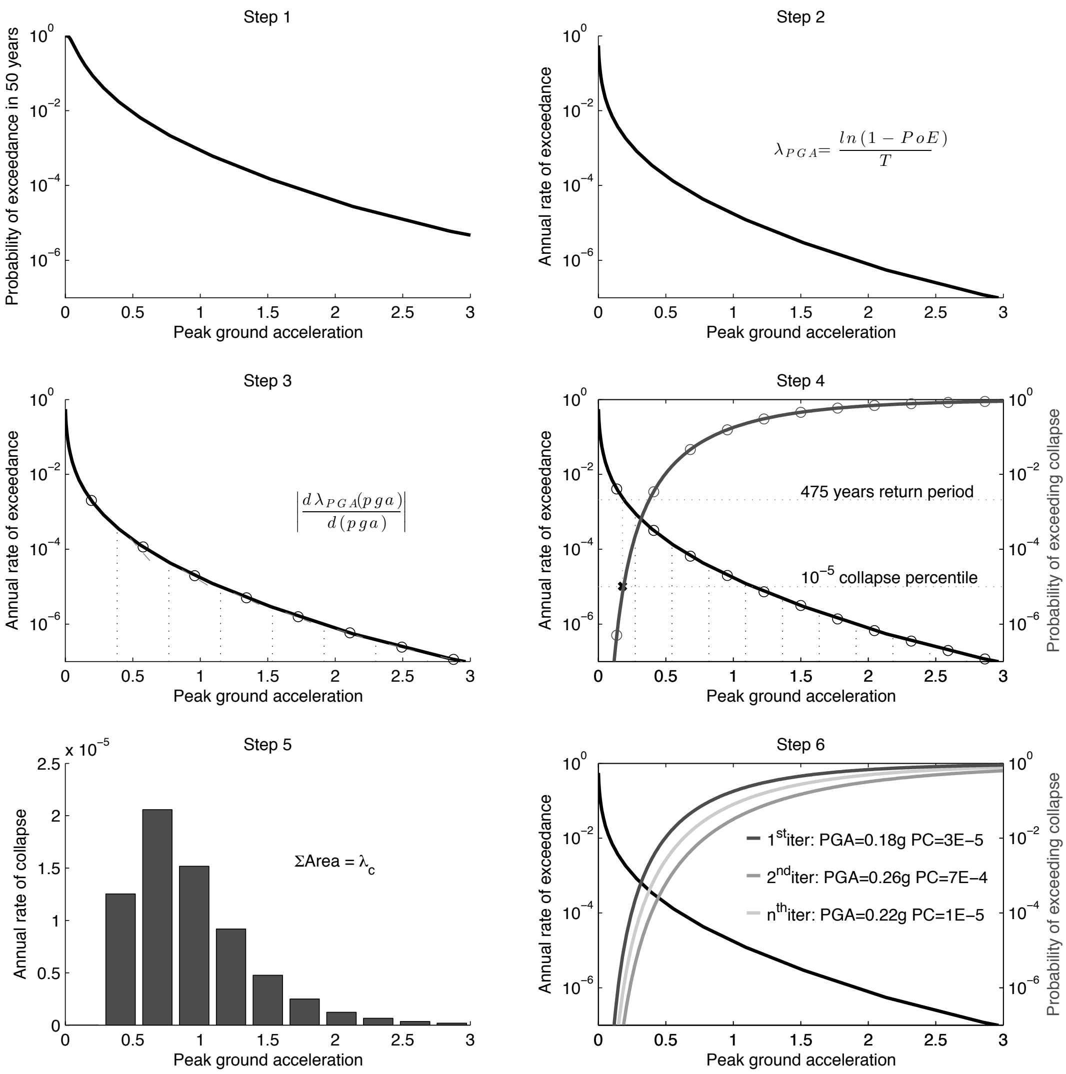

Figure 5. Iterative calculation process required for the computation of risk-targeted hazard maps.

Results

Influence of the chosen intensity measure type

The estimation of risk-targeted hazard maps is highly conditional on the assumptions followed in the definition of the collapse fragility function (logarithmic standard deviation and percentile for the mapped ground motion) and therefore, it is important to comprehend what factors might affect these parameters. The influence of the chosen intensity measure is evaluated herein, through the estimation of the probability of collapse for three cities: Vienna (low hazard - PGA≈0.1g), Lisbon (Moderate hazard - PGA≈0.2g), Istanbul (high hazard - PGA≈0.4g), and considering four intensity measure types (PGA and Sa for 0.1, 0.3 and 1.0 secs). The seismic hazard curves for these three locations and respective probabilities of collapse are presented in Figure 6.

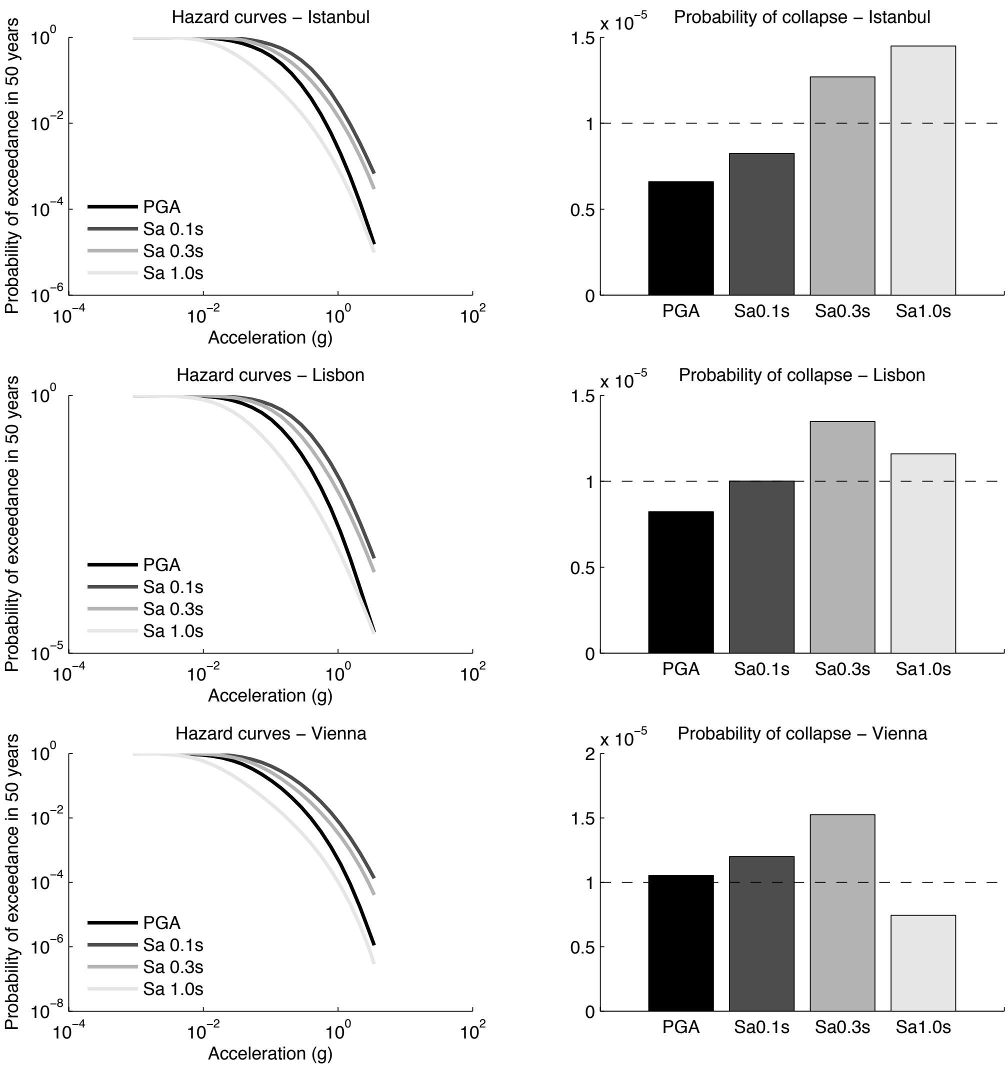

Figure 6. Seismic hazard curves and probability of collapse considering various intensity measure types for three European cities.

The evaluation of the probability of collapse distribution in the three cities led to significantly different results. Such discrepancies can be justified not just by the different intensities at the design return period, but also due the fact that seismic hazard curves from different intensity types are not parallel and therefore, the distribution of collapse rate for the various levels of intensity (see Figure 5, step 5), are not identical. In fact, a simple observation of the seismic hazard curves for each intensity measure type might be sufficient to conclude that if the same assumptions are followed in the definition of the collapse fragility function, significantly different probabilities of collapse will be obtained. In this particular example, it is interesting to observe that if peak ground acceleration is considered, then a probability of collapse below the acceptable risk is obtained for Istanbul and Lisbon, which signifies that the design ground motion could be reduced. On the other hand, if spectral acceleration for 1 second were preferred, then a level of risk above the acceptable threshold would be attained, which could lead to an increase in the design intensity. The inverse is observed for the city of Vienna.

These variations in the collapse probability levels indicate that additional research is required to understand how the parameters defining the collapse fragility curve vary depending on the chosen intensity measure type. Moreover, in the light of these results is it also evident that direct comparisons between the assumptions made by Luco *et al*. (2007) and Douglas *et al*. (2012) might not be valid, since one study used spectral acceleration whilst the other employed peak ground acceleration.

Probability of collapse across Europe

The annual probability of collapse has been calculated assuming collapse fragility functions with a β value of 0.5 and a 10^{-5} percentile at the mapped ground motion (using PGA). The results for the European countries covered by SHARE are illustrated in Figure 7.

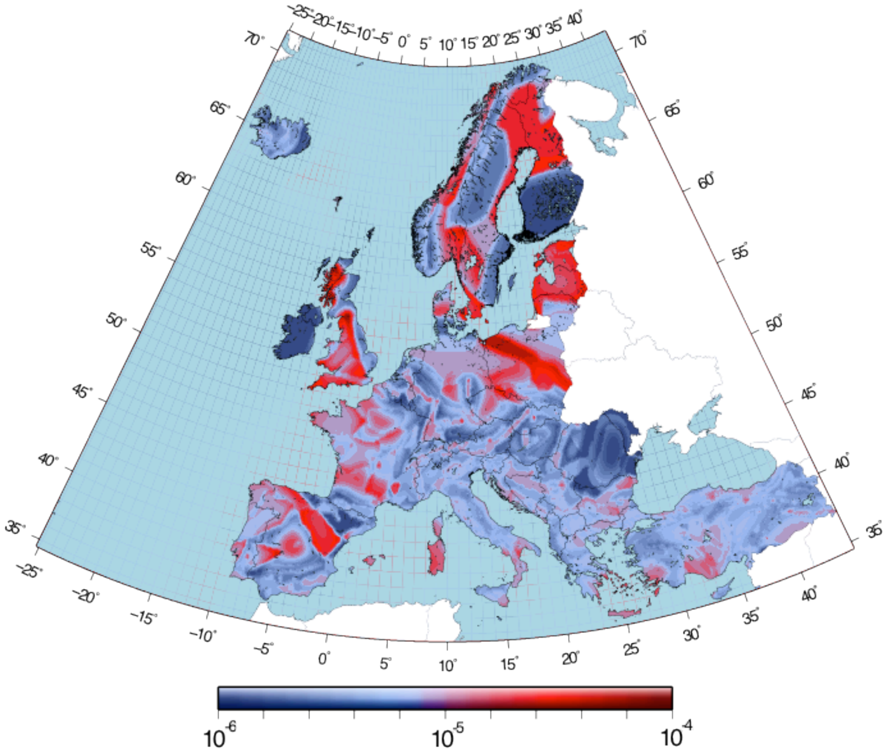

Figure 7. Distribution of the annual probability of collapse for new buildings using the seismic hazard results from the European project SHARE.

The evaluation of the probability of collapse across Europe reveals one of the main reasons as to why seismic design regulations should go beyond the definition of a design ground motion for a return period (regardless of whether it is in terms of peak ground motion or spectral ordinates), and start contemplating risk concepts in their formulation. Despite the large uncertainties around the definition of the collapse fragility function, it is clear that designing according to a ground motion for a given return period leads to collapse probabilities that can differ from one region to another by a factor of 5. Furthermore, it is also worth noticing that in certain areas in Europe, the annual probability of collapse is well above the risk threshold deemed as acceptable in this article.

Risk-targeted hazard maps for Europe

Using the iterative calculation process described in the preceding section, and assuming an acceptable annual collapse probability of 10^{-5}, risk-targeted hazard has been calculated for the European region covered by SHARE. The comparison between risk-targeted and regular hazard maps can be a difficult task, as small variations might not be apparent due to the colour scale employed. For this reason, a decision was made to present the differences between these two approaches through the so-called risk coefficients (i.e. ground motion leading to the uniform risk divided by the design ground motion for the 475 years return period), as illustrated in Figure 8. It is noted that a value less than one means a design seismic action that is lower than that given by the 475 years return period hazard.

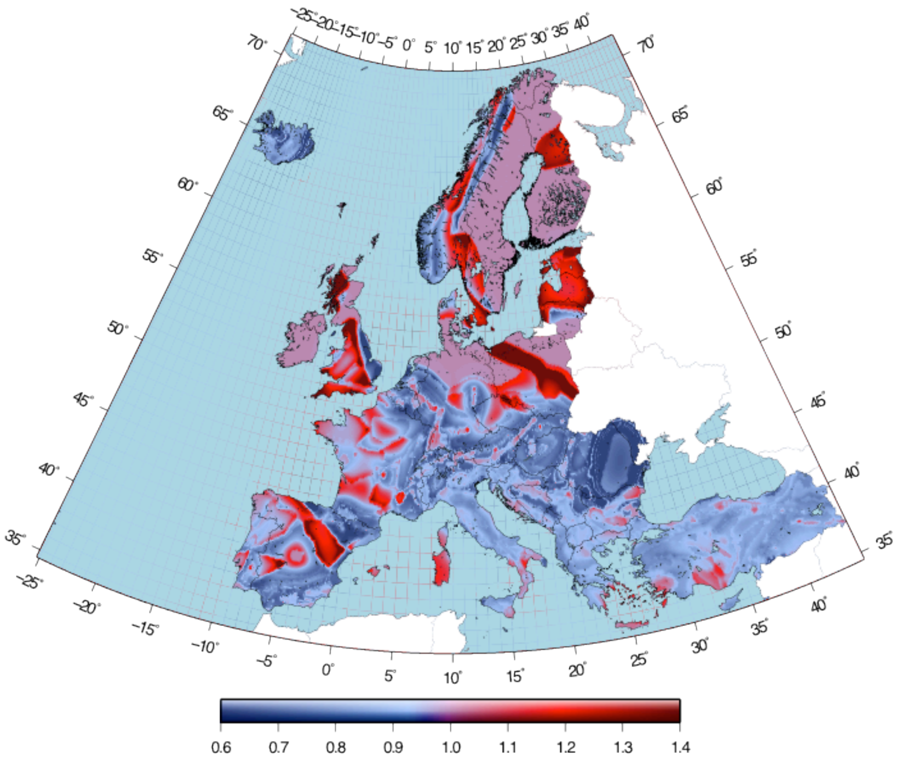

Figure 8. Risk coefficients for Europe using the seismic hazard results from the European Project SHARE.

Conclusions

The current knowledge on probabilistic seismic hazard analysis and structural modelling and assessment allows an unprecedented understanding of local seismic risk, which should not be neglected in the process of designing new structures, or even in the retrofitting of existing ones. The results from this study demonstrate that despite the consideration of the same hazard return period across Europe, the annual probability of collapse of new buildings differs considerably from region to region. This variation in the collapse probability arises from the fact that collapse is not only related to the mapped ground motion, but also to other possible ground motion intensities whose probability of being exceeded varies differently across regions (see Figure 6). Thus, even if the ground motion for a given return period is the same between two locations, the associated collapse probability might be significantly distinct, as demonstrated in the example of Figure 9.

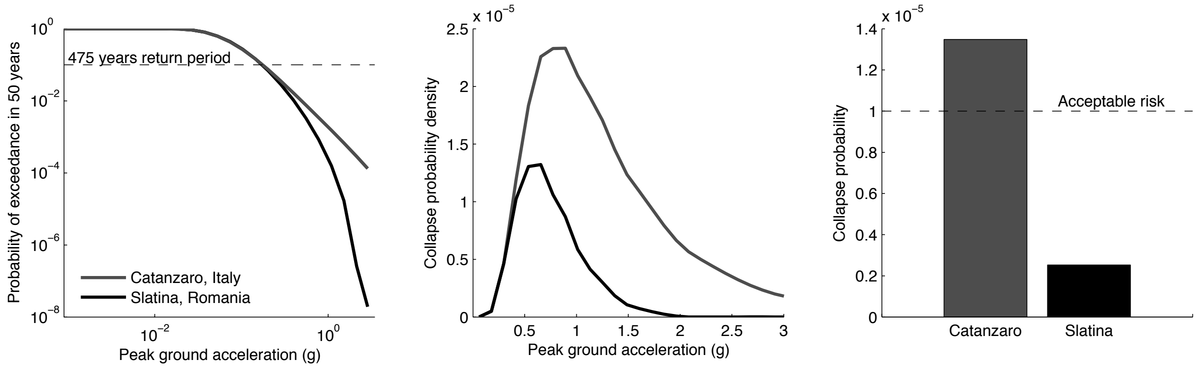

Figure 9. Comparison between the collapse probabilities of two cities with similar seismic hazard.

An evaluation of the parameters required to define the collapse fragility function was performed, using a large collection of fragility functions compiled within the European project SYNER-G, and findings from existing studies. For what concerns uncertainty in collapse and probability of collapse at the design ground motion, additional research is required in order to understand the impact of designing for low and high levels of hazard, as well as the influence in the chosen intensity measure type. In order to overcome this limitation, future developments should cover the design and assessment of a large number of structures, considering several hazard levels.

The initial results from this study indicate several regions in Europe where the current design ground motion could be decreased, and the acceptable national risk would still be respected. On the other hand, some regions where the probability of collapse is higher than the acceptable risk (about two times) were also identified. The employment of the risk-targeted hazard maps philosophy can alter the ground motion for which a building should be designed by up to 30%, which could either signify a decrease in the construction cost (by lowering the design ground motion), or a more robust and safe seismic design (by raising the design ground motion).

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