# Advances on Risk-targeted Hazard Estimation within the European context

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ABSTRACT: The design of new structures according to modern seismic regulations requires the definition of a ground motion for a given return period, for which the structure is designed. The implicit assumption is that the resulting annual collapse probability is equally uniform for all structures, regardless of their structural properties or location. However, the uncertainty in the collapse capacity and discrepancies in the slope of the seismic hazard curves at different sites 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 would lead to a nominal uniform level of risk nationally, compliant with a transparent and pre-specified risk threshold. In this paper, the seismic hazard results recently released under the FP7 European project SHARE are employed to compute risk-targeted hazard maps for Europe, according to a fixed annual probability of collapse that is in agreement with current levels of safety. The preliminary results shown here expose large areas of Europe where the design ground motion could be significantly lowered without compromising the current level of accepted risk.

## 1. INTRODUCTION

The majority of seismic regulations rely on seismic hazard maps associated with a return period, $R_p$, of exceedance (e.g., 475 years for most of the countries in Europe) of a specific ground motion intensity measure (IM) to estimate the design seismic demand at a given location. 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 regardless of the location of the building. However, such an assumption does not hold true if one considers the uncertainty in the collapse capacity of a building. This uncertainty in the assessment of the IM value that causes collapse of the building stems from a large spectrum of sources such as characteristics of the material properties, employment of different construction practices, human errors and decisions during the design and construction stages, record-to-record variability, amongst others. Therefore, the probability of collapse is not only dependent on the probability of exceeding the design IM, but on the probability of observing at the building site the whole spectrum of levels spanned by the seismic hazard curve for that IM.

Recognition that designing structures considering only the IM value for a given $R_p$ leads to distinct seismic risk for different structures 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, as described in ASCE (2005). These maps provide the IM value that, if employed for design purposes, would lead to the same, pre-specified, nominal probability of collapse. This level of acceptable risk may vary depending on the importance of the structure, and should be established through the involvement of not only structural engineers but also sociologists and other decision makers. In this context, Douglas *et al*. (2012) have performed a comprehensive study in which parametric analyses were carried out to assess the influence of various parameters on the probability of collapse, and a risk-targeted hazard map was calculated for the territory of France.

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).

## 2. PROBABILITY DISTRIBUTION OF COLLAPSE CAPACITY

One of the main sources of uncertainty in the estimation of the probability of collapse of newly designed structures is the definition of the collapse capacity in terms of an IM (e.g. peak ground acceleration). The European building stock has been the focus of numerous studies, which have often resulted in the derivation of fragility functions that provide the probability of exceeding different levels of damage, conditional on a level of IM. The results from a great part of these studies have been used to compile a European database of fragility models (Crowley et al., 2014, Silva et al., 2014a), as part of the FP7 European project Syner-G (Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain). The results from these studies (which were often derived for building classes rather than individual structures) were utilized to investigate the range in the probability distribution of the collapse capacity. Figure 1 displays several collapse fragility functions for reinforced concrete mid-rise buildings designed according to a seismic design code.

Some causes for this large variability are the employment of different construction practices, the distinct seismic provisions of different design codes and, most importantly, the fact that each structure might have been designed for a specific IM.

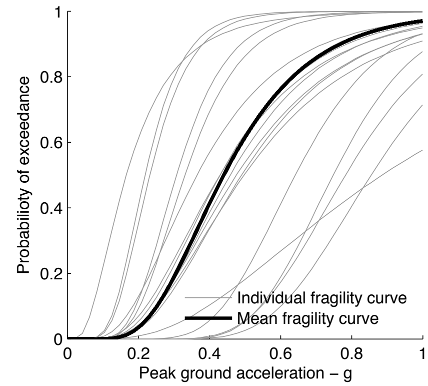


*Figure 1. Collapse fragility functions for RC mid-rise buildings with lateral load design (adapted from Crowley et al. 2014).*

The influence of the design IM on the resulting collapse probability of a building has been demonstrated in several studies (e.g., Ulrich *et al*., 2013; Silva *et al*., 2014c), and it is used herein to directly define the site-specific collapse fragility curve. The distribution of the collapse capacity in terms of a specific IM can be defined by a cumulative lognormal function with logarithmic mean, $\mu$, and logarithmic standard deviation, $\beta$. Luco et al. (2007) considered analyses from FEMA P-695 of typical structures designed using the ASCE Standard 7-05 (ASCE, 2005) to conclude that there is approximately a 10% probability of collapse at the MCE (2475-year $R_p$ where not deterministically capped) ground motion level used for design in the US. The uncertainty in the capacity was modeled using a cumulative lognormal distribution with a logarithmic standard deviation of 0.8. On the other hand, Douglas *et al*. (2012) found a probability of collapse of only $10^{-5}$ at the 475-year $R_p$ design ground motion level for buildings in France, and a significantly lower logarithmic standard deviation of 0.5. Figure 2 illustrates the collapse fragility curves derived using the parameters defined by the aforementioned studies.

Clearly the assumptions suggested by each study lead to different collapse fragility curves, which when coupled with the hazard curves for the building site will directly influence the resulting annual probability of collapse. Thus, the definition of the collapse probability at the design ground motion and the uncertainty in the collapse capacity assume major importance in the application of the risk-targeted hazard methodology.

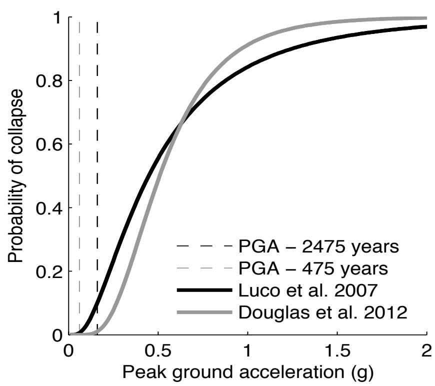


*Figure 2. Collapse fragility functions for structures designed according to seismic regulations, using the parameters from both approaches (Luco et al., 2007 and Douglas et al., 2012).*

### *2.1. Definition of the logarithmic standard deviation (β) of the collapse capacity*

If there were no uncertainty in the collapse capacity ($\beta$=0), then the collapse fragility function would be a vertical line, and the probability of collapse would be equal to one if the ground motion were to exceed the ground motion capacity, and zero otherwise. The parameter $\beta$ takes into consideration several sources of uncertainty in the collapse capacity, such as the record-to-record variability, the uncertainty in the collapse definition (damage criterion), and ideally also other sources of uncertainty such as human error, that even the most advanced numerical models cannot accommodate.

Whilst estimation of the probability of collapse at the design ground motion may be complex, trends for the uncertainty in the median collapse capacity ($\beta$) can be derived from the evaluation of the hundreds of fragility models collected within the aforementioned European project. This approach is reasonable for the estimation of $\beta$ as long as the original studies included a realistic modeling of the sources of uncertainty mentioned above. The evaluation of the distribution of the logarithmic standard deviation across the various fragility models suggested that a $\beta$=0.5 is a reasonable value, as also suggested by Douglas *et al*. (2012). Moreover, the employment of large $\beta$ values (above 0.8) in highly seismic regions leads to collapse fragility curves that indicates a low probability of collapse even for extremely low ground motion values and, conversely, a rather low collapse probability for extremely large levels of shaking, a scenario that seems an unrealistic.

In order to understand the extent to which the epistemic and aleatory uncertainties were indeed considered in the various models collected within the Syner-G project, some of those studies were randomly chosen and further analyzed. This verification demonstrated that the vast majority of the selected studies seem to be underestimating some sources of uncertainty, as summarized bellow:

- Some studies employed non-linear static procedures to assess the seismic demand, which might underestimate the record-to-record variability (e.g., Silva *et al*., 2013);
- In the studies where nonlinear dynamic analysis were employed, often a limited number of ground motion records were used, which is probably insufficient to represent the full record-to-record variability in the estimate of the collapse capacity (e.g., Haselton *et al*., 2012);
- The epistemic uncertainty in the definition of a damage allocation criteria (which leads to different damage distributions), and the aleatory uncertainty in the definition of the value of the engineering demand parameter (e.g., maximum interstory drift) corresponding to the onset of each damage state, were frequently neglected.

Moreover, as stated in the FEMA P-58 (2013), despite the recent advances in ground motion and structural modeling, it is important to recognize that there are still limitations in our ability to predict structural demand, response and capacity, which potentially causes an underestimation of the dispersion. For these reasons, we believe that a value of 0.5 is, at most, a lower bound for the uncertainty in the probability distribution of collapse, and that perhaps a better estimate might be between the $\beta$=0.5 proposed by Douglas *et al.* (2012), and the $\beta$=0.8 suggested by Luco *et al.* (2007).

Thus, based on the evaluation of existing fragility models, the proposals by the various authors, and our expert judgment, for the purposes of this study a logarithmic standard deviation $\beta$=0.6 has been adopted. This estimate is also in agreement with what has been defined in the ASCE (2010) regulation for the design of new structures.

### *2.2. Definition of the probability of collapse at the design ground motion (PC|gm)*

The calculation of the probability of collapse at the design ground motion has been the target of limited investigation, as it requires the design and assessment of a large number of structures and the consideration of a wide range of hazard levels. Extracting the range of PC|gm in a systematic manner from fragility models existing in the literature is impractical due to the fact that the design process and associated design ground motion are frequently not reported.

The design $R_p$ adopted in this study is 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). As mentioned earlier, Douglas *et al*. (2012) initially proposed that this ground motion would correspond to $10^{-5}$ collapse probability, on the grounds that such value would lead to negligible changes in the current seismic hazard design maps for mainland France. More recently, a more comprehensive study carried out by Ulrich *et al.* (2013) considered a 3-story RC structure designed to increasing levels of peak ground acceleration (0.07g to 0.3g) for the 475-year, $R_p$ and calculated a set of yielding and collapse fragility curves. Ulrich *et al.* (2013) proposed a value of $10^{-7}$ for low, frequent ground motion design levels, a value that increases up to $10^{-5}$ for the higher and rarer design ground motion considered in their study. It should be noted, however, that the low collapse probability proposed in that study for low ground motion levels may be due to the fact that for such regions, the seismic action is likely not the controlling load in the design.

In a recent study by Ramirez *et al.* (2012), the seismic fragility of a large number of reinforced concrete moment frame buildings designed according to modern seismic codes was evaluated, considering a design ground motion equal to 2/3 of the ground motion for the Maximum Considered Earthquake (MCE), leading to a level of shaking similar to what would be expected for the 475-year $R_p$. A range of probabilities of collapse at this design ground motion between 0.4% and 4.2% was obtained. These values are consistent with the collapse probability ranges established by FEMA (2009), and in agreement with the findings of Goulet *et al*. (2007) and Haselton *et al.* (2011). The structures evaluated in these studies were located in western United States, and thus designed considering moderate to high seismic hazard, which might justify the higher collapse probabilities at the design ground motion.

As previously mentioned, Luco *et al.* (2007) used a collapse probability of 10% at the ground motion corresponding to the 2,475-year $R_p$, to define the probability distribution of collapse. Considering this probability of collapse (10%) and $\beta$=0.8, the probability of collapse for the 475-year $R_p$ was calculated using the seismic hazard curves from the European project SHARE (see section 4). A range between $10^{-2}$ and $10^{-3}$ was obtained, which is in agreement with the aforementioned studies for buildings in the United States.

Given these premises, for the purposes of our study a decision was made to adopt a value of $10^{-3}$ for the probability of collapse at the design ground motion level.

## 3. ACCEPTABLE PROBABILITY OF COLLAPSE

As stated by Masden *et al.* (1986), various design codes such as the International Building Code (IBC, 2000) or the NEHRP Provisions (BSSC, 1997) agree that it is not possible to ensure complete safety, and that instead an acceptable level of risk should be established.

Luco *et al.* (2007) adopted an acceptable national risk of 1% in 50 years (about $2.0 \times 10^{-4}$ annually). This threshold was estimated through the evaluation of the average annual probability of collapse for a fine grid of locations in the United States, using the assumptions described in the previous section for the definition of the collapse fragility curve. On the other hand, Douglas *et al.* (2012) considered several studies from the literature, in which the annual probability of collapse of a number of structures designed according to modern regulations was determined. These researchers concluded that a value of $1.0 \times 10^{-5}$ (annually) is instead a reasonable compromise value.

Many countries in Europe have policies that require risk evaluations to be carried out for potentially hazardous installations. Two risk metrics that are commonly applied in a risk evaluation include individual risk and societal risk, and these thresholds may vary from region to region. For example, in the Netherlands, the individual risk of death should have a probability of occurrence lower than $1.0 \times 10^{-6}$ per year (Jonkman *et al*., 2003). However, in earthquake prone areas of Europe (such as Italy or Greece) earthquake fatality rates in standard buildings are certainly greater than the values provided above. Diamantidis *et al*. (2006) discusses acceptable risk thresholds for structures subjected to geohazards, and indicated an acceptable annual probability of loss of a single life not greater than $1.0 \times 10^{-5}$. The same value is tolerated for regions with low to moderate risk in New Zealand (GNS, 2012). Given these premises, for the purposes of this study a value of $5.0 \times 10^{-6}$ between the previous two thresholds is employed.

Despite the importance of understanding the individual risk that a society might be willing to accept, for the employment of the risk-targeted hazard methodology, it is necessary to establish an acceptable annual probability of collapse, and not an acceptable annual probability of loss of life. This level of acceptable loss of life can be related to an annual probability of collapse through the employment of statistics from past earthquakes regarding fatality rates in collapsed buildings. Spence (2007) suggests fatality rates ranging from 6% (for one-story masonry buildings) to 28% (for reinforced concrete buildings with at least four storeys).

Considering an average fatality rate of 10% and the acceptable risk of human loss described above, an approximate annual probability of collapse of $5.0 \times 10^{-5}$ was obtained, and used in the following sections. This level of risk is also within the range discussed in JCSS (1999), whose values reflect the background values used in the calibration of the Eurocode

## 4. 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 countries in the region of interest, the hazard results from the European project SHARE (Seismic Hazard Harmonization in Europe – Danciu *et al*., 2013) were considered.

Amongst the various results from SHARE, seismic hazard curves and maps in terms of PGA and spectral accelerations, $S_a(T)$, for $T$ up to 4s, and exceedance probabilities ranging from 1% to 50% in 50 years were critical to the work presented herein. The seismic hazard map in terms of PGA for 475-year $R_p$ is presented in Figure 3.

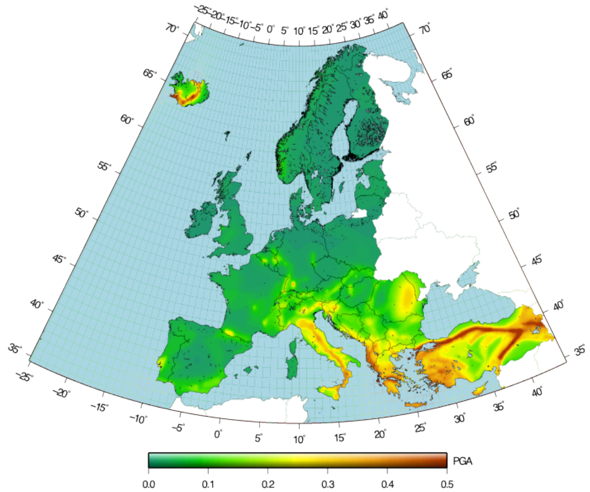

*Figure 3. Mean seismic hazard map in terms of PGA (in g) for the 475-year return period.*

## 5. ITERATIVE CALCULATION OF RISK-TARGETED HAZARD

An iterative process is required for the estimation of the ground motion consistent with 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:

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 of PGA in 50 years, into annual rate of exceedance of PGA;
3. These curves are divided into a large number of segments, and the rate of occurrence of the associated central PGA value of each segment is calculated;
4. A collapse fragility curve is derived assuming $\beta$=0.6 and a probability of collapse of $10^{-3}$ at the 475-year $R_p$ PGA value for the first iteration, and at the adjusted PGA value from Step 6 for subsequent iterations. This curve is used to extract the probability of collapse conditioned on the central PGA value of each segment;
5. The conditioned probability of collapse of each segment is multiplied by the associated rate of occurrence for PGA values belonging to that segment, 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 is obtained;
6. The annual collapse rate is converted into annual probability of collapse (PC) assuming a Poissonian process, and this value is compared with the selected acceptable annual collapse probability value of $2.0 \times 10^{-5}$. Depending on whether the current PC is higher or lower than the selected value, the design ground motion is adjusted accordingly, and Steps 4 and 5 are repeated until the resulting PC is, within a tolerance of ±1%, equal to the target collapse probability value.

## 6. RISK-TARGETED HAZARD RESULTS FOR EUROPE

Using a $\beta$=0.6 and $PC|gm=10^{-3}$ and the acceptable annual risk of $5.0 \times 10^{-5}$ discussed in the previous section, the spatial distribution of risk coefficients (i.e., ground motion values leading to the uniform risk divided by the 475-year design ground motion value at each site) is presented in Figure 4. The risk-targeted maps are only provided for regions with an expected seismic hazard above 0.05g for the 475-year $R_p$. At all other lower-hazard locations the risk coefficient has been set equal to one.

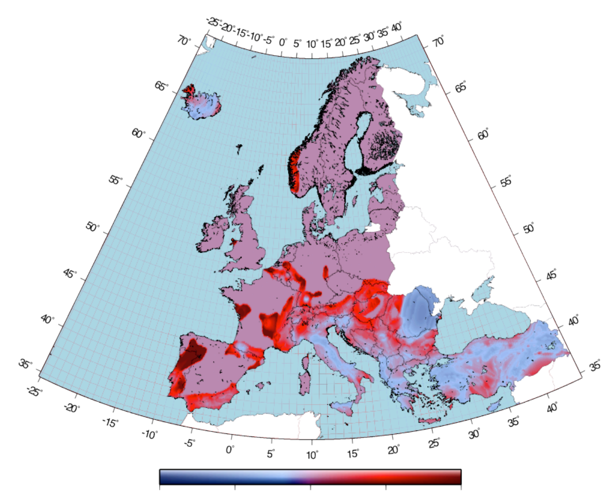

*Figure 4. Risk coefficients for Europe assuming a collapse distribution with a $\beta$ = 0.6 and a $PC|gm = 10^{-3}$, and an acceptable annual risk of $5.0 \times 10^{-5}$.*

## 7. CONCLUSIONS

The current knowledge on probabilistic seismic hazard analysis and structural modeling and assessment allows an unprecedented understanding of seismic risk, that should be considered in the process of designing new structures and, although not discussed here, in retrofitting existing ones. The results from this study demonstrate that despite the consideration of design ground motions corresponding to the same $R_p$ (here 475 years) across Europe, the annual probability of collapse of new buildings differs considerably from region to region.

An evaluation of the parameters required to define the collapse fragility curve of new buildings was performed, using a large collection of fragility curves compiled within the European project Syner-G, findings from other existing studies, and statistical analysis performed within this study. For what concerns uncertainty in collapse capacity and probability of collapse of new buildings at the design ground motion, additional research is required in order to better understand the impact of designing for ground motion at lower and higher levels of hazard.

A logarithmic standard deviation $\beta$ of 0.6 in the collapse capacity and a probability of collapse at the 475-year design ground motion of $10^{-3}$ were used in this study. With this set up, the initial results from this study indicate several regions in Europe where the current design ground motion could be decreased, given an acceptable notional annual risk. On the other hand, some regions, such as South Turkey and West Romania, 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). It is emphasized, however, that the fragility curves used here were derived from studies that do not necessarily consider newly designed buildings but also existing ones. The use in our calculations of fragility curves specifically derived for newly designed buildings may have changed the considerations made previously. Finally, other values for the definition of the probability distribution of collapse could have been adopted (such as those from Luco *et al*., 2007, or Douglas *et al*., 2012), but certainly an unequal spatial distribution of annual probabilities of collapse across Europe would have still been obtained.

## 8. REFERENCES

ASCE (2005). Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities (ASCE 43-05). ASCE, Reston, VA.

ASCE (2006). Seismic Rehabilitation of Existing Buildings (41-06) (ASCE 43-06). ASCE, Reston, VA.

ASCE (2010). Minimum Design Loads for Buildings and Other Structures (ASCE 7-10), ASCE, Reston, VA.

Bommer J, Pinho R (2006). "Adapting earthquake actions in Eurocode 8 for performance-based seismic design," EESD, 35, 39-55.

Building Seismic Safety Council (BSSC) (2004). NEHRP Recommended provisions for seismic regulations for new buildings and other structures, 2003 ed. (FEMA 450), BSSC, National Institute of Building Sciences, Washington D.C., USA.

CEN (2004). Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General rules, seismic actions and rules for buildings. European Committee for Standardization, Brussels, Belgium.

Crowley H, Colombi M, Silva V (2014) "Epistemic Uncertainty in Fragility Functions for European RC Buildings". Chapter 4 - SYNER-G: Type Definition and Fragility Functions for Physical Elements at Seismic Risk. Springer, Netherlands.

Danciu L, Woessner J, Giardini D and SHARE Consortium (2013) A community-based Probabilistic Seismic Hazard Maps for the Euro- Mediterranean Region. *Congress on Recent Advances in Earthquake Engineering and Structural Dynamics*, Vienna, Austria.

Diamantidis D, Duzgun S, Nadim F, Wöhrle M (2006) "On the Acceptable Risk for Structures

Subjected to Geohazards". *Proc. of Geohazards, ECI Symposium Series*, volume P07, Lillehammer, Norway.

Douglas J, Ulrich T and Negulescu C (2013) "Risk-targeted seismic design maps for mainland France", *Natural Hazards*, 65, 1999–2013, DOI: 10.1007/s11069-012-0460-6.

Eads L, Miranda E, Krawinkler H, Lignos D G (2012). "An efficient method for estimating the collapse risk of structures in seismic regions". EESD, 42:25–41.

FEMA (2009) Quantification of building seismic performance factors. Technical report FEMA P695, ATC, Redwood City, California.

FEMA P-58 (2013). Seismic Performance Assessment of Buildings. ATC, Redwood City, California.

GNS (2012). Understanding life safety risk concepts for rockfall and cliff collapse in the Port Hills. Technical Report, Christchurch, New Zealand.

Goulet C, Haselton C, Mitrani-Reiser J, Beck J, Deierlein G, Porter K, Stewart J (2007) "Evaluation of the seismic performance of a code-conforming reinforced-concrete frame building - from seismic hazard to collapse safety and economic losses". EESD, 36:1973–1997.

Ghobarah A (2001) "Performance-based design in earthquake engineering: state of development", *Engineering Structures,* 23, 878-884.

Haselton C, Whittaker A, Hortacsu A, Baker J, Bray J, Grant D (2012) "Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses". Proc. of the 12th WCEE, Lisbon, Portugal.

Haselton C, Liel A, Deierlein G, Dean B, Chou J (2011) "Seismic Collapse Safety of Reinforced Concrete Buildings. I: Assessment of Ductile Moment Frames." *J. of Structural Engineering,* 137(4), 481-491.

International Building Code (IBC) (2000). Building Officials and Code Administrators International, Inc., International Conference of Building Officials, and Southern Building Code Congress International, Inc., Birmingham, AL.

Joint Committee on Structural Safety (JCSS), (1999). Probabilistic Assessment of Existing Structures. RILEM Publications S.A.R.L., France, edited by D. Diamantidis.

Jonkman S N, Gelder P, Vrijling J K (2003) "An overview of quantitative risk measures for loss of life and economic damage," *J. of Hazardous Materials*, A99, 1-30.

Luco N, Ellingwood BR, Hamburger RO, Hooper JD, Kimball JK, Kircher CA (2007) "Risk-targeted versus current seismic design maps for the conterminous United States". In: SEAOC 2007 convention proceedings.

Madsen, H. O., Krenk, S., and Lind, N. C. (1986). Methods of Structural Safety. Prentice Hall, Inc., Englewood Cliffs, N.J.

Ramirez C, Liel A, Mitrani-Reiser J, Haselton C, Spear A, Steiner J, Deierlein G, Miranda E (2012) "Expected earthquake damage and repair costs in reinforced concrete frame buildings" EESD, 41(11) 1455–1475.

Silva V, Crowley H, Pinho R, Varum H (2013) "Extending Displacement-Based Earthquake Loss Assessment (DBELA) for the computation of fragility curves", *Engineering Structures* 56:343 – 356.

Silva V, Crowley H, Varum H, Pinho R, Sousa R (2014a) "Evaluation of analytical methodologies used to derive vulnerability functions" EESD, 43(2), 181–204.

Silva V, Crowley H, Pinho R, Varum H, Sousa L (2014b) "Investigation of the Characteristics of Portuguese Regular Moment-frame RC Buildings and Development of a Vulnerability Model", *Bulletin of Earthquake Engineering*, submitted.

Silva, V, Crowley H, Colombi M, (2014c) "Fragility Function Manager Tool". Chapter 13 - SYNER-G: Type Definition and Fragility Functions for Physical Elements at Seismic Risk. Springer Netherlands.

Spence, R. (ed) (2007). "Earthquake disaster scenario prediction and loss modelling for urban areas". IUSS Press, Pavia, Italy, ISBN 978-88-6198-011-2.

Ulrich T, Negulescu C, Douglas J (2013) "Fragility curves for risk-targeted seismic design maps". *Bulletin of Earthquake Engineering*. http://dx.doi.org/10.1007/s10518-013-9572-y.