Seismic Design Code Calibration Based on Individual and Societal Risk

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ABSTRACT

Fragility functions that are available for a number of reinforced concrete building types designed to Eurocode 8 (EC8) under different levels of PGA have been used herein to identify the design PGA values that would need to be mapped across a given case study region to ensure uniform acceptable levels of individual risk, for the purposes of seismic design code calibration. However, this calibration considers each building individually, and yet when a natural disaster like an earthquake strikes, the impact is experienced on a regional scale. This study thus takes the calibration of design codes one step further, and investigates whether the performance requirements in EC8 are adequate from a societal risk perspective. Societal risk, or group risk, is defined through an F-N curve (i.e. the frequency of occurrence F, of a predicted number of deaths, N) and, in a similar manner to individual risk, many countries have established F-N curve thresholds. The F-N curve for the case study area, based on the fragility functions of buildings designed to EC8, has been calculated and compared with accepted thresholds in different European countries. The outcome of such assessment gives insight into the adequacy of performance objectives in the code from a group risk point of view.

Keywords: Seismic design code; seismic actions, individual risk; societal risk; group risk.

1. INTRODUCTION

Recent developments in seismic design code calibration have been based on ensuring that the seismic actions used in the design lead to a uniform probability of collapse across the region of application, leading to so-called risk targeted hazard maps (e.g. Luco et al. 2007; Silva et al. 2015). Hence, rather than including ground motions with a fixed return period in the code, the ground motions are defined such that they lead to a uniform risk across the given region of interest. The acceptable probability of collapse might be related to a specific value of individual risk, such as the annual probability of loss of life for a hypothetical person that is constantly inside or nearby a given building, which is an established parameter in the risk policy of some countries in Europe (e.g. Switzerland, the Netherlands). In order to calculate the seismic actions that lead to an acceptable probability of collapse (or other risk metric), it is necessary to estimate the fragility of buildings designed to different levels of ground motion. Fragility functions that are available for a number of reinforced concrete building types designed to EC8 (CEN, 2004) under different levels of PGA have been used herein to identify the design PGA values that would need to be mapped across a given case study region to ensure uniform acceptable levels of individual risk.

However, the aforementioned calibration considers each building individually, and yet when a natural disaster like an earthquake strikes, the impact is experienced on a regional scale. This study thus takes the calibration of design codes one step further, and investigates whether the performance requirements in EC8 are adequate from a societal risk perspective. The latter is defined through an F-N curve (i.e. the frequency of exceedance F, of a predicted number of deaths, N) and, in a similar manner to individual risk, many countries have established F-N curve thresholds. The F-N curve for

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the case study area, based on the fragility functions of buildings designed to EC8, has been calculated and compared with accepted thresholds in different European countries. The outcome of such assessment gives insight into the adequacy of current performance objectives in the code from a group risk point of view.

2. CALIBRATION OF DESIGN CODES BASED ON INDIVIDUAL RISK

2.1 Fragility functions for EC8-designed buildings

The current version of EC8 (CEN, 2004) requires the seismic actions used in design to be anchored to mapped values of peak ground acceleration (PGA) for a specified return period, typically taken as 475 years for the life safety performance objective of ordinary residential buildings. However, due to changes in the slope of hazard curves across a given country or region, and the uncertainty in the collapse capacity of structures, the resulting probability of collapse of structures designed to these seismic actions will actually vary (Silva et al. 2015). In order to identify the ground motions that would instead lead to a uniform level of collapse or risk, and following the approach first outlined in Luco et al. (2007), it is necessary to assign the probability of collapse, conditional on the seismic actions prescribed in the code. In other words, what is the probability that a building designed to Eurocode 8 (EC8) would collapse, should it be impacted by levels of seismic action equal to those used in the design?

To answer this question, Martins et al. (2017) developed analytical ‘near collapse’ or ‘complete’ fragility functions for a large number of mid-rise reinforced concrete (RC) moment resisting frame (MRF) structures designed to EC8 under increasing levels of ground shaking ranging from 0.05g (i.e. low seismic hazard) to 0.40g (i.e. moderate to high seismic hazard). The limit state of ‘near collapse’ was identified as the point where the base shear reduced by 20%. The findings of this study were later used to establish relationships between the design acceleration and the median (θ) and logarithmic standard deviation (β) of the collapse fragility functions (see Figure 1). The results of Figure 1 can thus be used to identify the fragility functions for buildings designed to EC8 under varying levels of PGA. It is noted that PGA has been used in this study as it is the parameter that is currently used to anchor the design spectrum in EC8, but the Authors recognize that other intensity measures provide a better correlation with building damage. Moreover, this methodology presented in this study can easily be employed with ordinates of spectral acceleration.

![Figure 1. Relationship between (Left) design PGA (dsgPGA) and median of ‘near collapse’ fragility functions (theta) and (Right) design PGA and dispersion of fragility functions (beta) for mid-rise (3-5 storeys) RC MRF structures designed to EC8 (adapted from Martins et al. 2017)](image-url)
2.2 Acceptable Risk Thresholds

In order to calibrate the seismic actions in a design code based on a uniform level of risk, it is necessary to identify acceptable thresholds of risk. Some countries in Europe (e.g. the Netherlands, Switzerland) have established acceptable thresholds of individual risk, such as the annual probability of loss of life for a hypothetical person that is constantly inside or nearby a given building. To use these risk metrics in the calibration of a design code, they need to be associated with the annual probability of collapse of structures, and this can be done through fatality models that estimate the probability of death, given collapse. Alternatively, a decision made by code drafters to specify directly an acceptable annual probability of collapse. Further discussion on the values of annual probability of collapse that have been used in risk-targeted ground motions for design is provided in Luco et al. (2007), Douglas et al. (2013) and Silva et al. (2015).

2.3 Calculation of Risk-Targeted Ground Motion Maps

Greece has been chosen as a case study to illustrate the concept of risk-targeted ground motions herein. The latest European seismic hazard model (Woessner et al. 2013) has been used to define the seismic actions, as this is an openly available model that can be used with the OpenQuake-engine, an open-source seismic hazard and risk engine (Pagani et al. 2014; Silva et al. 2013). However, the same calculations can be undertaken with any seismic hazard model for which hazard curves of PGA are available on a grid of points across the region of interest. Figure 2 shows the hazard from the SHARE model based on the values obtained at the centroid of each administrative boundary. This is a simplified representation of the hazard that has been used to reduce the number of calculations used in this illustration of the methodology. A denser grid of hazard curves (in terms of multiple intensity measures) across the country can be exported from the European Facility for Earthquake Hazard and Risk (EFHER – http://www.efehr.org).

![Figure 2. Map of 475 year return period PGA values in Greece](image)

The value of 475 year return period PGA within each administrative boundary shown in Figure 2 has been used together with the relationships presented previously in Figure 1, to assign a fragility function to the mid-rise RC MRF buildings that would be designed in each municipality based on this
hazard map. The annual probability of collapse at each location can then be calculated by combining these fragility functions with the PGA hazard curves at the same location. If this annual probability of collapse is greater than the threshold, the design PGA needs to be increased and a new fragility function is obtained from Figure 1 and the annual probability of collapse is calculated. This procedure continues in an iterative fashion until the acceptable annual probability of collapse is reached, and the design PGA is identified. In these calculations an acceptable annual probability of collapse of $5 \times 10^{-5}$ has been used (following the recommendation in Silva et al. 2015), and this has led to the design PGA values shown in Figure 3. These design PGA values no longer correspond to a return period of 475 years, but to a variation of return periods which can be as low as 200 years or as high as 900 years, as shown in Figure 4.

Figure 3. Map of design PGA values leading to uniform annual probability of collapse

Figure 4. Map of design return periods for uniform annual probability of collapse.
3. CALIBRATION OF DESIGN CODES BASED ON SOCIETAL RISK

As mentioned in the Introduction, the calibration of a design code based on individual risk metrics does not consider whether the impact of earthquakes on the designed buildings would be acceptable from a group or societal perspective. In this section, the performance of EC8-designed (i.e. high code) RC mid-rise (3 to 5 storeys) moment-frame buildings across the whole of Greece, and within selected cities, is explored. This study therefore does not consider the whole building stock in Greece, but looks at the fatality risk from a residential building typology that is commonly used in Greece, and explores what would happen if all of these existing buildings were instead designed to the latest code requirements. An initial study in this direction was undertaken by Crowley et al. (2012), but in that case the focus was placed on the economic impact of collapse rather than on loss of life.

3.1 Societal Risk and Acceptable Risk Thresholds

Societal risk, also referred to as group risk, is typically presented using F-N curves which show the annual frequency of exceedance (F) of numbers of deaths (N) for a specified group of people. When defining acceptable levels of group risk, the co-called societal risk equation is often used and is defined by $C/x^n$, where $x$ is the number of fatalities, $C$ is a constant that fixed at different values in different countries, and $n$ is often between 1 and 2 (with a higher value leading to a more “risk averse” approach) (see e.g. Jonkman et al. 2003). The minimum value of $x$ to be considered in the societal risk equation is equal to 10 (Ball and Floyd, 1998). If the F-N curve for the region is above the threshold curve, the risk is deemed unacceptable, whereas when it is below it may fall within the ALARP (as low as reasonably practicable/achievable) region (where it is allowable to weight the risk against the trouble, time and money needed to control it) or it may be identified as acceptable risk. Acceptable thresholds of group risk from some international standards are shown in Figure 5. The large difference in these standards illustrates how different the level of risk averseness can be between countries.

![Figure 5. Some international standards in F-N format (adapted from Jonkman et al. 2003). The region above these curves is defined as unacceptable risk, whereas below the curve it is either acceptable, or falls within an ALARP region](image)

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### 3.2 F-N Curves for the Case Study

In order to produce F-N curves for the whole of Greece, a realistic representation of the distribution of buildings considered herein (i.e. mid-rise RC MRF) and their occupants is needed. This has been obtained from an exposure model that is being developed for Greece as part of the European seismic risk framework work package of the SERA project (Crowley et al. 2017). Although this model includes buildings that have been designed with different design codes, the objective of this study is to see what the group risk would be if all of these buildings were designed (or retrofitted) according to the performance requirements of EC8.

This exposure model provides the number of occupants within the relevant building typology within each municipality in Greece (shown in the previous maps). However, for the purposes of group risk calculations, where the number of collapsed buildings under a given earthquake need to be aggregated, it is necessary to properly account for the spatial distribution and correlation of ground motions (see e.g. Crowley et al. 2008), and this in turn requires a higher spatial resolution. The municipality-based exposure model has thus been disaggregated onto a grid using the population distribution available on a 30 arcsec resolution from CIESIN (2017) (see Figure 6), i.e. the density of population of the grid cells within a given municipality was used to distribute the total number of people within the selected building typology onto the grid.

The OpenQuake-engine has been used together with the SHARE model to create a stochastic catalogue of events (of 100, 000 years), and then for each event in the catalogue, the ground motions at each grid cell was simulated, considering the spatial correlation between pairs of locations (based on the model by Jayaram and Baker, 2010). The fragility functions for the buildings at each location have been assigned by combining the design PGA values shown in Figure 3 with the relationships presented in Figure 1. In order to calculate the number of fatalities, the fragility functions (which provide the probability of collapse, conditional on a level of ground motion) need to be transformed to vulnerability functions (i.e. the mean probability of loss of life, conditional on a level of ground motion). This has been undertaken herein by using the proposed collapse rates and fatality rates for RC MRFs in HAZUS (FEMA, 2004). Hence, the probability of collapse under the ground motions for each simulated event in the catalogue is calculated at each location, and this is transformed to the mean probability of loss of life, and multiplied by the number of occupants in the buildings at that location to obtain the number of fatalities. For a given event in the catalogue, the total number of fatalities across all locations that are subjected to ground motions is then calculated. By repeating this process for the large number of events in the stochastic catalogue, it is possible to calculate the annual frequency of exceedance of increasing numbers of fatalities, leading to an F-N curve.

Figure 7 presents the group risk curve for the whole of Greece, and compares the F-N curve with the international standards presented previously in Figure 5. As can be seen from this plot, it appears that EC8 (calibrated with risk targeted ground motions) would almost meet the UK standards, but it would be deemed unacceptable in all other countries. However, when an earthquake strikes, it does not typically impact the whole country, hence it makes sense to consider smaller groups of the population in the calculation of F-N curves, and these results can be used to identify which areas of the country are not meeting the F-N standards. Hence, F-N curves for three selected cities have been computed, as shown in Figure 8. In the selected cities the UK F-N standards are all met, which indicates that other parts of the country have higher group risk and require further investigation.

Should a country wish to adapt the code based on societal risk standards, further measures would be needed to adapt the seismic actions across the country. A single individual risk metric, as presented in the previous section, may thus not be sufficient, and different levels of acceptable risk may need to be defined as a function of the density of population and seismic hazard.
Figure 6. Population count at 30 arcsec resolution (CIESIN 2017).

Figure 7. F-N curve for Greece, compared with the international standards shown in Figure 5.
4. CONCLUSIONS

This paper has illustrated how concepts of individual and societal risk can be used to calibrate seismic design codes, with a focus placed herein on EC8, given that fragility functions for buildings designed to EC8 have recently been developed. The practice of using acceptable levels of collapse of individual buildings, or acceptable thresholds of individual risk (i.e. the annual probability of loss of life for a hypothetical person that is constantly inside or nearby a given building), has been discussed in a number of academic publications over recent years, but the use of societal risk measures has not received much attention. A preliminary study was thus presented herein to investigate the performance of a code (calibrated using individual risk metrics) from a societal risk perspective, and F-N curves for buildings designed to EC8 were developed and compared with international standards. The results show that the societal risk standards/regulations of some countries would not be met, and that further calibration of the seismic actions within the code could be needed across the country, should there be a desire to meet these risk norms. On the other hand, there may also be a need to place more focus on defining appropriate societal risk standards.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


