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Web Application for the Selection of Characteristic Ground Motions

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ABSTRACT

The characteristic ground motions (CGMs) represent a set of few response-specific ground motions which can be used for the intensity-based assessment in order to make risk-based decision regarding the adequacy of design of a new building or of the strengthening of an existing building. The aim of this paper is to demonstrate how CGMs can be quickly selected by a user-friendly web application, which includes the database of around 19000 one-component ground motions from PEER database and RESORCE database. The selection of CGMs is based on the conditional spectrum approach and refined selection procedure, which involves estimation of approximate collapse intensity for each ground motion from hazard-consistent set. By means of an example of an 8-storey reinforced concrete dual structure it is demonstrated that the risk-based decision making is sufficiently accurate if dynamic analysis is performed for only seven CGMs.

Introduction

The use of dynamic analysis for the design of new structures or for strengthening of existing structures is becoming more and more popular in research. However, there are many challenges before nonlinear dynamic analysis will be used for the design of ordinary buildings. In addition to the uncertainty in nonlinear models of structures there are several other issues, which still have to be solved. For practical applications it is also important that the number of dynamic analyses is reasonably low, since it is not likely that, for example, an automated performance-based design methodology, which involves computation of the expected annual losses in conjunction with a genetic algorithm (Rojas et al. 2011) could be applied to complex structures. Research has therefore been focused on methods which could be used to reduce the number of simulations during design of a structure. For example, the concept of a precedence list of ground motions was introduced which can be used in progressive incremental dynamic analysis (Azarbakht and Dolšek 2011). The method requires significantly fewer ground motions for the estimation of the 16^{th}, 50^{th} and 84^{th} percentiles of engineering demand parameters. Liel and Tuwair (2010) introduced an iterative procedure in which pushover analysis is performed in conjunction with dynamic analysis in order to significantly reduce the computational time when estimating the median collapse intensity. Eads et al. (2013) proposed computation of the collapse fragility function using intensity-based assessment, which is performed by dynamic analysis at two carefully selected levels of intensity. Bradley (2013) has shown that the seismic demand hazard can be estimated with sufficient accuracy using only three intensity measure levels that have exceedance probabilities of 50%, 10% and 2% in 50 years. Recently the so-called 3R method (Response analysis, Record selection and Risk-based decision making) was introduced by Brozovič and Dolšek (2014). The method represents a realization of the concept of intensity-

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based assessment for risk-based decision making. Since the objective of the method is not a precise assessment of the seismic risk, a simple decision model for risk acceptability can be introduced. The engineer can decide that the reliability of a no-collapse requirement is sufficient when collapse is observed in the case of less than half of, for example, seven characteristic ground motions (CGMs).

The aim of this paper is to demonstrate the use of the web application for the selection of CGMs (CGMapp). In the first part of the paper an overview of the 3R method is presented in order to provide some insight into the proposed methodology. The description of the CGMapp is then outlined, followed by a demonstration of the CGMapp by means of an 8-storey dual structure.

Overview of the 3R Method

One of the fundamental performance objectives in earthquake-resistant design of structures is collapse prevention. The building codes commonly assume that structures designed according to simple design rules are safe against collapse due to earthquakes. This could be validated by assessing the collapse risk, but such an approach is a computationally demanding task. To simply check the adequacy of collapse risk the concept of intensity-based assessment for risk-based decision making can be realized by means of the 3R method (Response analysis, Record selection, Risk-based decision making), which was recently proposed (Dolšek and Brozovič 2015).

The purpose of the 3R method is not precise assessment of seismic collapse risk, but introduction of the simple decision model aimed at deciding whether the collapse risk is acceptable, i.e. lower than target collapse risk λ_t, or not. Such an approach provides slightly less information in comparison to direct estimation of seismic collapse risk λ, but this information is sufficient for decision regarding the adequacy (acceptability) of seismic collapse risk. Consequently the number of simulations for risk-based decision making can be significantly reduced, which is the fundamental goal of the 3R method. In the 3R method, an assessment of structure is performed only at one intensity, so-called characteristic value of target collapse intensity $S_{a,ct}$, which corresponds to target collapse risk λ_t and seismic hazard at a site. In addition, assessment can be performed only for a few, e.g. seven, hazard consistent ground motions, so-called characteristic ground motions (CGMs), which are scaled to $S_{a,ct}$. Estimation of seismic collapse risk adequacy on basis of results of few dynamic analyses is then straightforward. The decision model is defined in such a way that if less than 50% of CGMs cause the collapse of a structure, it can be concluded that the structure is safe against collapse due to earthquakes. In the opposite case, the performance objective is not met.

The 3R method uses two basic assumptions. Firstly, the shape of the probability distribution (usually lognormal distribution) and the standard deviation (β_t) of collapse intensities have to be assumed for definition of the characteristic value of target collapse intensity $S_{a,ct}$, at which the seismic performance assessment is performed. From theory and observations (Dolšek and Brozovič 2015) it can be shown that this assumption is sufficient. For example, Lazar and Dolšek (2014) showed that standard deviation of natural logarithms of collapse intensities β in terms of spectral acceleration at fundamental period of reinforced concrete frames is within the interval from 0.3 to 0.5. If an intermediate value of β is assumed then the error due to assumed β_t

is almost negligible if the value of $S_{a,ct}$ is associated with a low percentile, the so-called characteristic percentile, from the collapse fragility function. For this reason characteristic percentile is set to 16^{th} percentile. However, this in not the only reason for selection of low value of $S_{a,ct}$. Additional reasons for this decision are: (i) uncertainties associated with the seismic hazard are controllable at lower intensity levels, (ii) scale factors of ground motions are more likely in the range which still allow unbiased estimates of seismic demand, (iii) the accuracy of simplified methods to provide approximate collapse intensities is greater for those ground motions which cause the collapse of buildings at low intensities (Brozovič and Dolšek 2014) and (iv) it is well known that the intensities which have the largest contribution to the collapse risk are smaller than the median collapse intensity (e.g. Eads et al. 2013).

The second assumption of the proposed method is associated with the selection of characteristic ground motions (CGMs). It is assumed that CGMs can be selected from larger hazard-consistent set using approximate collapse intensities, which can be obtained by seismic response of SDOF model. In the current version of CGMapp it was assumed that the sufficient number of the CGMs is equal to seven. In this case the hazard-consistent set of ground motions must contain at least 19 ground motions to assure that the median collapse intensity of CGMs is in the vicinity of characteristic value of collapse intensities for the entire hazard-consistent set of ground motions. If there are less than 19 ground motions, the accuracy of the method would be reduced. However, the hazard-consistent set of ground motions can be large, since the approximate collapse intensities are obtained by simplified method of analysis, which is not computationally demanding. Theoretically it is difficult to prove that such an approach would yield sufficiently accurate results, but parametric studies have shown (Dolšek and Brozovič 2015) that the decision regarding the target collapse risk using only a few characteristic ground motions is always correct if the difference between the target collapse risk and the actual collapse risk of the structure is not smaller than 30%. This error is practically negligible since, for example, the target collapse risk is of subjective nature.

Step by step description and more details of the 3R method can be found elsewhere (Dolšek and Brozovič 2015). Although the application of the 3R method is straightforward, it requires a lot of steps in order to obtain the characteristic ground motions. For practical purposes is thus convenient to perform these steps automatically by user-friendly web application (Klinc et al. 2015). When the CGMs are selected, the nonlinear dynamic analysis of structure has to be performed only for CGMs at single intensity in order to check whether the seismic collapse risk is appropriate or not.

Web Application for Selection of Characteristic Ground Motions

The CGM web application (CGMapp) involves a two-step procedure for the selection of ground motions. The result of the first step is the hazard-consistent set of ground motions, while in the second step the subset of seven characteristic ground motions is selected. The hazard-consistent set of ground motions is selected using the response spectrum matching technique (Jayaram et al. 2011). The target spectrum is defined by the conditional spectrum approach (CS) (Baker 2011, Lin et al. 2013), which is simply determined on basis of one ground motion prediction model (Campbell and Bozorgnia 2008) and mean earthquake scenario, i.e. mean values of magnitude, site-to-source distance and epsilon.

The mean earthquake scenario should correspond to the characteristic value of target collapse intensity $S_{a,ct}$, which represents the intensity level, which is used in dynamic analyses. Note that an intensity measure used in CGMapp is the spectral acceleration at the conditioning period $S_a(T^*)$. The computation of $S_{a,ct}$ starts by defining the target collapse risk λ_t. The CGMapp then uses seismic risk equation (numerical integration or closed-form) in order to estimate the median target collapse intensity $\tilde{S}_{a,t}$. In both cases, seismic hazard should be known and the standard deviation of collapse intensities in log domain β_t has to be assumed. If the closed-form solution of the risk equation is used, the median value of target collapse intensity $\tilde{S}_{a,t}$ can be determined from the following equation (Cornell 1996)

$$\lambda_t = k_0 \left(\tilde{S}_{a,t}\right)^{-k} \cdot e^{0.5 \cdot k^2 \cdot \beta_t^2} \tag{1}$$

where k and k_0 represent the slope and intercept of linear approximation to the hazard curve in log domain, respectively. However, the characteristic value of target collapse intensity $S_{a,ct}$ is then estimated at the characteristic percentile (i.e. at percentile which is close to the 16^{th} percentile) of the target collapse fragility function as follows

$$S_{a,ct} = \tilde{S}_{a,t} \cdot e^{K_x \cdot \beta_t} \tag{2}$$

where K_x is the inverse of the normal cumulative distribution function at the characteristic percentile (i.e. a value which is close to 1).

In the second step of ground motion selection procedure CGMs are selected. Dolšek and Brozovič (2015) showed that suitable CGMs can be selected from the hazard-consistent set of ground motions by using proxy for collapse intensities, which are obtained in the web application automatically by computationally non-demanding seismic demand analysis of single-degree-of-freedom (SDOF) model. The CGMapp uses an SDOF model which can be easily defined on the basis of pushover analysis in accordance with the N2 method (Fajfar 2000). The web application includes different materials for description of the hysteretic behaviour, where three or four-linear force-displacement envelopes can be defined. Damping should be defined by mass and/or stiffness proportional damping coefficients in accordance with the Rayleigh damping command (OpenSees 2011). The collapse intensities are approximately computed by incremental dynamic analysis (Vamvatsikos and Cornell 2002) of SDOF model for the the hazard-consistent set of ground motions. All analyses are done by the OpenSees (2011).

Finally, the web application performs selection of CGMs. The subset of ground motions from the hazard-consistent set of ground motions is obtained gradually, taking into account approximate collapse intensities. The selected subset of ground motions corresponds to approximate collapse intensities, which are close to the characteristic value of approximate collapse intensities.

Selection of Characteristic Ground Motions for Collapse Safety Assessment of an 8-Storey Dual Reinforced Concrete Building

An 8-storey reinforced concrete dual building, which was designed according to Eurocode 8 requirements for medium ductility class was examined in X direction (Figure 1, Brozovič and Dolšek 2015, Klinc et al. 2015). The height of each storey amounted to 2.8 m. The span of exterior and interior bays amounted to 6 m and 5 m, respectively. Cross sections of all columns and beams were, respectively, 50/50 cm and 40/45 cm. Slabs with 20 cm thickness were considered with beam effective width of 1.6 m. The width and thickness of the wall were 6 m and 20 cm, respectively. Concrete class C30/37 and reinforcement class S500 were prescribed. The structure was modelled with simplified nonlinear model utilizing OpenSees (2011) in conjunction with PBEE toolbox (Dolšek 2010), which was extended for analysis of dual structures (Kosič 2014). The fundamental period of the structure was 0.87 s.

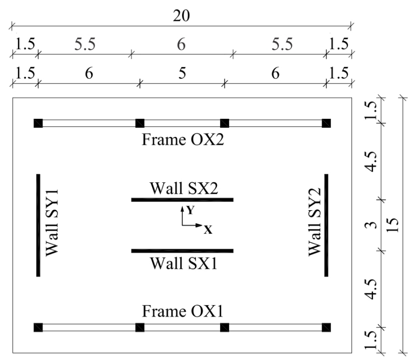

Figure 1. Typical plan view of dual structural system (Kosič 2014)

The target annual collapse risk λ_t was selected to amount $5\cdot10^{-4}$. This can be seen also in Figure 2, where a part of graphical user interface of the web application is shown. On basis of the seismic hazard function, target collapse risk λ_t and target standard deviation of collapse intensities β_t, the target collapse fragility function with the corresponding characteristic value of target collapse intensity $S_{a,ct}$ can be obtained. The seismic hazard function was obtained for site in Palo Alto, California from probabilistic seismic hazard analysis computation web tool prepared by United States Geological Survey (https://geohazards.usgs.gov/deaggint/2008/). It should be noted that spectral acceleration at fundamental period of structure $S_a(T_1)$ was used as intensity measure. On this basis the characteristic value of target collapse intensity $S_{a,ct}$ was estimated to be 0.96 g (Figure 2). The mean values of magnitude and site-to-source distance for mean earthquake scenario were then determined from disaggregation of seismic hazard at $S_{a,ct}$. The corresponding parameter ε, which represents the number of standard deviations between the target spectral acceleration, i.e. $S_{a,ct}$, and mean predicted logarithmic spectral acceleration value for a given magnitude and distance, was computed automatically within the web application. The conditional spectrum corresponding to the obtained mean earthquake scenario and ground motion prediction model was used to select the hazard-consistent set of 40 ground motions by computationally efficient ground motion selection algorithm for matching a target response spectrum mean and variance (Jayaram et al. 2011), which is incorporated in the web application.

Selection of CGMs is based on the approximate collapse intensities obtained by incremental dynamic analysis of simplified structural model. The mass of the SDOF model was obtained in accordance with the N2 method (Figure 3). Mass proportional damping was assumed ($\alpha_M = 0.72$, $\beta_K = \beta_{Kinit} = \beta_{Kcomm} = 0$). The envelope of the SDOF model was determined on basis of pushover analysis results. The pushover curve was idealized with a simple force-displacement relationship, which was used to define the hysteretic behaviour of the simplified model (Figure 3). The parameter for simulation of degraded unloading stiffness was set to 0.8.

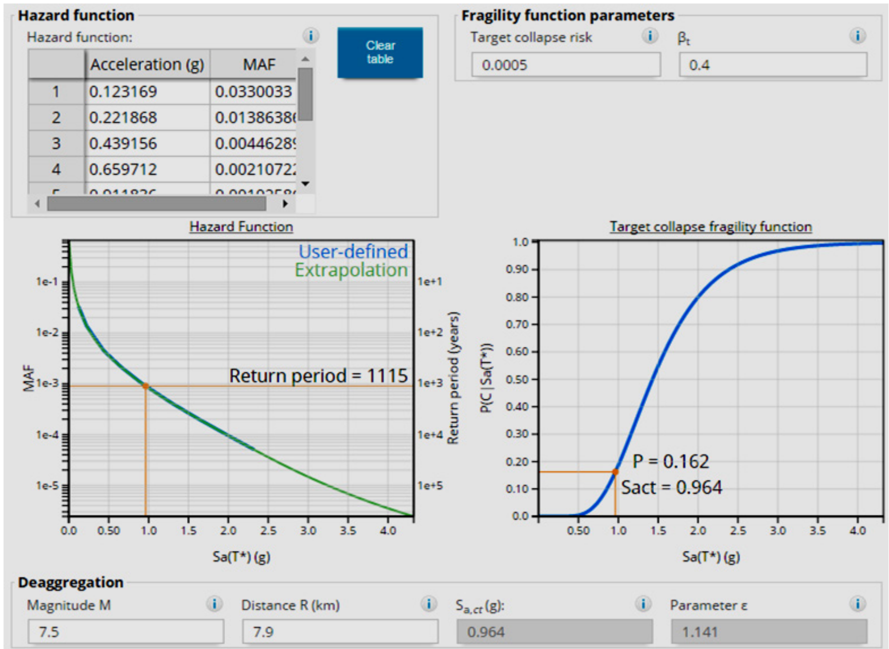

Figure 2. CGMapp user interface for calculation of characteristic value of target collapse intensity $S_{a,ct}$ and definition of the corresponding mean earthquake scenario on the basis of the seismic hazard function, the target collapse risk λ_t and the assumed standard deviation of collapse intensities β_t

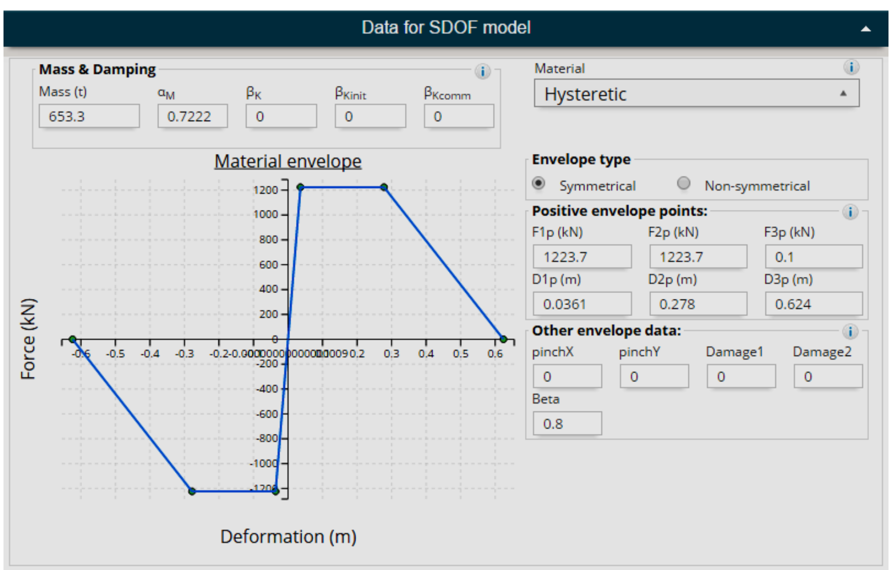

Figure 3. CGMapp user interface for input data for SDOF model of the 8-storey building

When all the required input data was inserted in the web application, the results were ready in few minutes. The web application shows the epicentre locations of the earthquakes associated with the selected ground motions, the corresponding magnitudes, site-to-source distances, soil types, comparison of acceleration spectra with target conditional spectrum and incremental dynamic analysis curves obtained for the SDOF model (Klinc et al. 2015). The final result is the list of all hazard-consistent ground motions with indicated CGMs (Figure 4).

Figure 4. CGMapp user interface showing the first characteristic ground motion from the list of selected hazard-consistent ground motions

The seven CGMs were used to check the seismic collapse safety of the investigated dual structure. Since only two out of seven CGMs caused collapse ($r_C = 2/7 = 0.29 < 0.5$), it can be concluded that structure met the performance objective, i.e. that the collapse risk is less than the target collapse risk. For comparison reasons, the collapse fragility function was estimated by the incremental dynamic analysis using model of entire structure. The collapse risk for the investigated structure was then estimated to $3.5 \cdot 10^{-4}$, which is less than the target (acceptable) collapse risk ($\lambda_t = 5 \cdot 10^{-4}$). This proves that the risk-based decision using 3R method was correct.

Conclusions

In this paper it was shown that the 3R method can be successfully applied to multi-storey dual buildings which are designed according to modern building code. Thus it can be concluded that fundamental performance objective of the building codes can be checked on the basis of only seven characteristic ground motions, which were in this case selected by a user-friendly web application (www.smartengineering.si). The use of information technology through a user-friendly web application significantly simplifies engineers' work since they can spend more time on those processes which cannot be done by computers.

Although the characteristic ground motions are selected on the basis of proxy of collapse intensity, the incorrect decision regarding the collapse safety of the structure is rarely observed. On the basis of many examples, which were performed by the authors, it can be concluded that the risk-based decision using only few characteristic ground motions is always correct if the difference between the target collapse risk and actual collapse risk is less than 30%, which is practically negligible knowing that the target collapse risk for different reliability classes varies by a factor of around 10.

Several possibilities exist for further development of the proposed method. For example, it would be very useful to implement the site response analysis for the selection of ground motions and for the estimation for proxy of collapse intensity. Such an approach would further improve definition of characteristic ground motions.

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