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RISK-BASED DESIGN CHECK FOR COLLAPSE SAFETY USING FEW GROUND MOTIONS

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Abstract. *The 3R method (Response analysis, Record selection, Risk-based decision making), which is used to check the adequacy of structural collapse safety by few nonlinear dynamic analyses, is briefly presented. The 3R method uses characteristic ground motions, which are selected by two-step selection procedure. Hazard-consistent set of ground motions is selected in the first step, while in the second step a subset of a few ground motions is obtained on the basis of the seismic response analysis of equivalent single-degree-of-freedom model, which is not computationally demanding. All ground motions are scaled to single intensity level, which corresponds to target collapse risk. The objective of the method is not precise assessment of collapse risk, but decision making whether the collapse risk is lower or greater in comparison to the target collapse risk. For this reason simple decision model may be introduced. If collapse is observed for less than half of characteristic ground motions, it can be decided that the reliability of structure against collapse is appropriate and vice versa. For an example of reinforced concrete dual structural system it is shown that an intensity-based assessment can provide sufficiently accurate risk-based decision making.*

1 INTRODUCTION

Seismic safety of built environment should be guaranteed by an appropriate design of structures for earthquake resistance. Thus it would be appropriate to include an assessment of the seismic risk in design codes. In the simplest case the seismic risk can be communicated in terms of mean annual frequency of exceeding a designated limit state. In this paper collapse safety is taken under consideration, since this is the fundamental performance objective in designing structures for earthquake resistance.

Several procedures for risk-based seismic design of structures were already introduced (e.g. [1, 2, 3]). These procedures are aimed to satisfy the condition that the collapse risk is lower than the target collapse risk, which is assumed acceptable. However, the target collapse risk is to some extent subjective performance measure, which is dependent on potential fatalities, direct and indirect economic losses due to earthquakes in the lifetime of structures.

In general, the calculation of the collapse risk is a complex task, which is performed by integrating the risk equation that combines seismic hazard function with collapse fragility function. For example, definition of collapse fragility function requires large number of computationally demanding dynamic analysis of nonlinear structural model. For practical purposes the estimation of collapse risk was simplified by different procedures. Cornell [4] developed a closed form solution of risk equation, which assumes linear approximation of hazard function in logarithmic space and lognormal distribution of collapse intensities. On this basis Fajfar and Dolšek [5] proposed a practice-oriented estimation of the failure probability of building structures, where the collapse fragility function is determined by assumed standard deviation of collapse intensities and approximate evaluation of median collapse intensity by N2 method [6]. However, different failure modes may strongly impact the seismic behaviour of structures, which can be taken into account by nonlinear dynamic analysis. An important issue of the dynamic analysis is the appropriate selection of ground motions, which should be consistent with seismic hazard at the site and should produce unbiased estimate of seismic demand. Since this is not a trivial task, many ground motion selection procedures were developed (e.g. [7-9]). In addition, different procedures were proposed aiming to reduce the computational time needed to obtain seismic demand by nonlinear dynamic analysis, e.g. [10, 11]. Eads et al. [12] developed a practice-oriented procedure for seismic collapse risk estimation, where lognormally distributed collapse fragility function is determined by nonlinear dynamic analyses at two carefully selected intensities. Such an approach still requires large amount of dynamic analyses due to large sets of ground motions.

Recently, Dolšek and Brozovič [13] proposed the 3R method, which realized a concept of intensity-based assessment for risk-based decision making about adequate seismic collapse safety. Only few dynamic analyses at single intensity are needed to decide whether the seismic collapse risk is adequately low or not. The 3R method uses characteristic ground motions, which are selected by two-step selection procedure. In the first step hazard-consistent set of ground motions is selected, while in the second step a subset of a few ground motions is selected on basis of approximately estimated collapse intensities by using computationally non-demanding seismic response analysis for a proxy of the structural model. All ground motions are scaled to single intensity level, which corresponds to target collapse risk.

In the following the overview of the 3R method is firstly given. Then the application of the 3R method is demonstrated by means of the seismic collapse safety assessment for a dual structural system. At the end evaluation of the accuracy of the 3R method is given.

2 OVERVIEW OF THE 3R METHOD

The building codes, e.g. [14], commonly assume that structures designed according to simple design rules are safe against collapse due to earthquakes. It is clear that such a principal assumption should be checked in the design. 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 [13].

2.1 Decision model

The purpose of the 3R method is not precise assessment of seismic collapse risk, but introduction of the simple decision model to decide whether the collapse risk is lower or greater than then the target collapse risk λ_t,. Such an approach provides slightly less information in comparison to direct estimation of seismic collapse risk λ. However, the adequacy (acceptability) of seismic collapse risk can be estimated and the number of required dynamic analyses of nonlinear structural model is significantly reduced. 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. 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.

2.2 Assumptions

The 3R method uses several assumptions. A type of distribution and standard deviation of collapse intensities have to be assumed in order to definite the characteristic value of target collapse intensity $S_{a,ct}$, at which the seismic assessment is performed. Commonly lognormal distribution of collapse fragility function is used. Lazar and Dolšek [15] showed that standard deviation of natural logarithms of collapse intensities in terms of spectral acceleration at fundamental period in the case of reinforced concrete frames is within the interval from 0.3 to 0.5. To minimize the influence of error in assumed standard deviation of natural logarithms of collapse intensities β_t on the value of $S_{a,ct}$ Dolšek and Brozovič [13] showed that the target collapse intensity should be associated with a low percentile, so-called characteristic percentile, of collapse intensities. Due to simplicity a characteristic percentile was set to 16th percentile. There are several other reasons why the characteristic value of collapse intensity is selected at low percentile of collapse intensities. For example, (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 [16] and (iv) it is well known that the intensities which have the largest contribution to the collapse risk occur in the lower half of the collapse fragility function, e.g. [12].

In addition, it is assumed that a suitable subset consisting of CGMs can be selected from larger hazard-consistent set using proxy of collapse intensities, which can be obtained by the pushover-based methods. In this paper a number of the CGMs was set equal to seven. In this case the initial set 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 whole 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 can contain a large number of ground motions, since the approximate collapse intensities are obtained by selected simplified method of analysis, which is not computationally demanding.

2.3 Step by step procedure

In the following the algorithm of the 3R method is presented:

1) *Define the target collapse risk* λ_t. The target collapse risk can be defined by code-writing organizations, e.g. [14], or can be adopted on the basis of models of tolerable risk, e.g. [17]. It can also be simply prescribed by the stakeholders due to higher risk aversion.
2) *Obtain detailed information regarding the seismic hazard at the site of interest.* The results of probabilistic seismic hazard analysis are required in order to estimate the characteristic target collapse intensity $S_{a,ct}$ (i.e. the hazard function), and to select a hazard-consistent set of ground motions.
3) *Determine the characteristic value of the target collapse intensity* $S_{a,ct}$. The median value of target collapse intensity $\tilde{S}_{a,t}$ can be determined utilizing risk equation in closed-form or iteratively by numerical integration of the risk equation. In both cases, 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 [4]

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

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 16th percentile of the target collapse fragility function as follows

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

4) *Select a hazard-consistent set of ground motions.* The results consist of ground motions which are scaled to $S_{a,ct}$. Different procedures can be used to select appropriate ground motions. Disaggregation of the hazard is also required, if, for example, the conditional spectrum approach [8] is used for the selection of the hazard-consistent set of ground motions. Hazard-consistent set of ground motions selected in this step may be large, since the subset of ground motions is selected in the following.
5) *Perform conventional pushover analysis and define a simple model of the structure.* Conventional pushover analysis is performed with invariant distribution of the lateral forces. It is recommended that a load pattern is associated with the most important mode shape. The simple model is represented by an equivalent single-degree-of-freedom model, which can be defined, for example, by analogy to the N2 method [6]. However, the force-displacement relationship of the simple model can be represented by multi-linear idealization of the pushover curve taking into account strength degradation.
6) *Assess approximate collapse intensities.* Dynamic analysis should be performed at the level of the simple model. Each ground motion is scaled until collapse occurs, e.g. by performing incremental dynamic analysis [18].
7) *Determine the characteristic ground motions.* The subset of ground motions from the hazard-consistent set of ground motions (step 4) is obtained gradually, taking into ac-

count approximate collapse intensities from step 6. The selected subset of ground motions corresponds to approximate collapse intensities, which are close to the characteristic value of approximate collapse intensities. It is also required that the median value of approximate collapse intensities corresponding to CGMs closely match with the characteristic value of approximate collapse intensities.

8) *Perform nonlinear response history analysis using a nonlinear model of the entire structure.* The response history analysis is performed for all the CGMs at characteristic value of target collapse intensity $S_{a,ct}$.
9) *Make a risk-based decision.* It can be decided that the collapse risk of the investigated structure is less than the target collapse risk if collapse is observed for less than half of the CGMs. This means that the collapse ratio r_C, which is defined as the number of CGMs causing collapse divided by the total number of all the CGMs is lower than 0.5 (Figure 1). In the opposite case ($r_C > 0.5$), the structure is not safe against collapse due to earthquakes.

More details and description of alternative variants of the 3R method can be found elsewhere [13]. The 3R method requires a lot of steps, which are not computationally demanding, but for practical purposes it would be inconvenient to perform all of these steps manually. For this reason the web application for the selection of CGMs was developed [19], which automatically performs steps 3, 4, 6 and 7 from the above described step-by-step procedure.

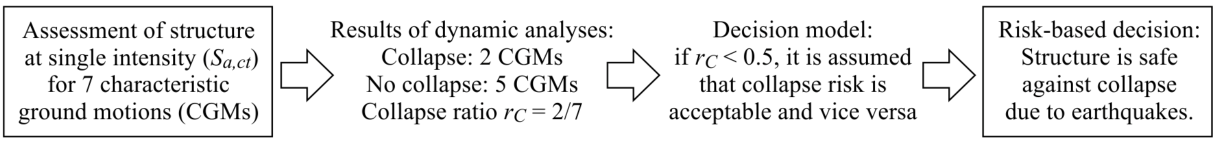

Figure 1: An example of risk-based decision making in the case of the 3R method.

3 CASE STUDY OF SEISMIC COLLAPSE SAFETY ASSESSMENT FOR THE 8-STOREY DUAL STRUCTURAL SYSTEM

3.1 Description of the structure

An 8-storey reinforced concrete dual structural system designed according to Eurocode 8 requirements for medium ductility class was investigated in X direction (Figure 2).

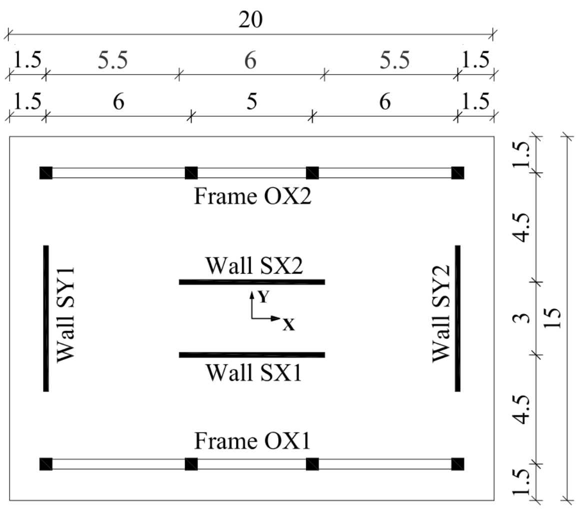

Figure 2: Typical plan view of dual structural system [22].

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 [20] in conjunction with PBEE toolbox [21], which was extended for analysis of dual structures [22]. The fundamental period of the structure was 0.87 s.

3.2 Hazard-consistent ground motion selection

The target collapse risk λ_t was selected to be $5\cdot10^{-4}$. The seismic hazard curve and disaggregation 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 0.96 g by taking into account lognormal fragility function with $\beta_t = 0.4$. The first four steps of proposed 3R method resulted in hazard-consistent set of 40 ground motions, which were selected by matching the conditional spectrum [8] determined for $S_{a,ct}$ (Figure 3a) by using computationally efficient ground motion selection algorithm for matching a target response spectrum mean and variance [23].

3.3 Selection of characteristic ground motions and decision-making

The pushover curve was idealized with a force-displacement relationship (Figure 3b) which was intentionally quite inaccurate at the tail of the pushover curve. This caused an additional bias in the approximate collapse intensities obtained by the SDOF model (Figure 4a). The subset of hazard-consistent ground motions (CGMs) was then selected and the dynamic analysis of the structure was performed taking into account CGMs. Since only two CGMs caused collapse ($r_C = 2/7 = 0.29 < 0.5$), as indicated in Figure 4a, it was decided that structure met the performance objective. Thus it can be concluded that the collapse risk of the investigated dual structure is less than the target collapse risk.

If the analyst would perform dynamic analysis for all ground motions from the hazard consistent set at $S_{a,ct}$, then the decision regarding the adequacy of the structure would be the same. Note that only 3 ground motions caused collapse of the structure (Figure 4a), which means that the $r_C = 3/40 = 0.075$. This is less than threshold value 0.16 associated with the characteristic percentile.

The decision made by 3R method was correct, since the collapse risk of the structure was estimated to $3.5\cdot10^{-4}$, which is less than the target (acceptable) collapse risk ($5\cdot10^{-4}$). In addition, the risk-based decision making of the 3R method was validated by calculating the collapse ratio r_C for multiple levels of the target collapse risk (Figure 4b). Dynamic analyses have been performed for the CGMs scaled to different intensities $S_{a,ct}$ corresponding to different levels of target collapse risk. On this basis an approximate collapse risk was obtained, which corresponded to the 50% collapse ratio (Figure 4b). Therefore, the decision based on 3R method for this particular example would be incorrect if the target collapse risk would be assumed somewhere in the interval between 'exact' collapse risk ($3.5\cdot10^{-4}$) and approximate collapse risk ($4.7\cdot10^{-4}$), i.e. the interval of target collapse risk indicated in Figure 4b with grey color. The largest possible error $\varepsilon_{\max}$ in terms of seismic collapse risk would be 32%. The method provide sufficiently accurate decision making in the case of a selected dual structure, although the intensities causing collapse of SDOF model are significantly different to the corresponding intensities obtained by the entire structural model (Figure 4a).

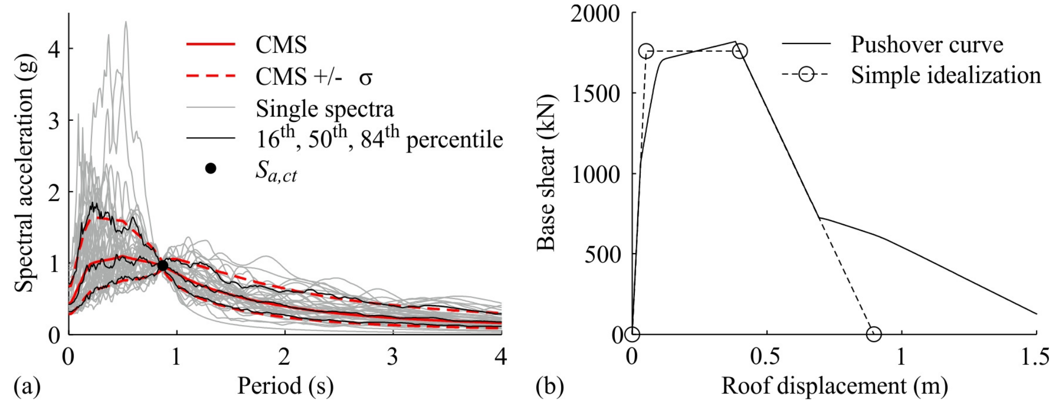

Figure 3: (a) Conditional spectrum consistent with the characteristic value of target collapse intensity $S_{a,ct}$, spectra of selected ground motions and the corresponding 16th, 50th and 84th percentile and (b) the pushover curve with simple idealization of base shear – roof displacement relationship.

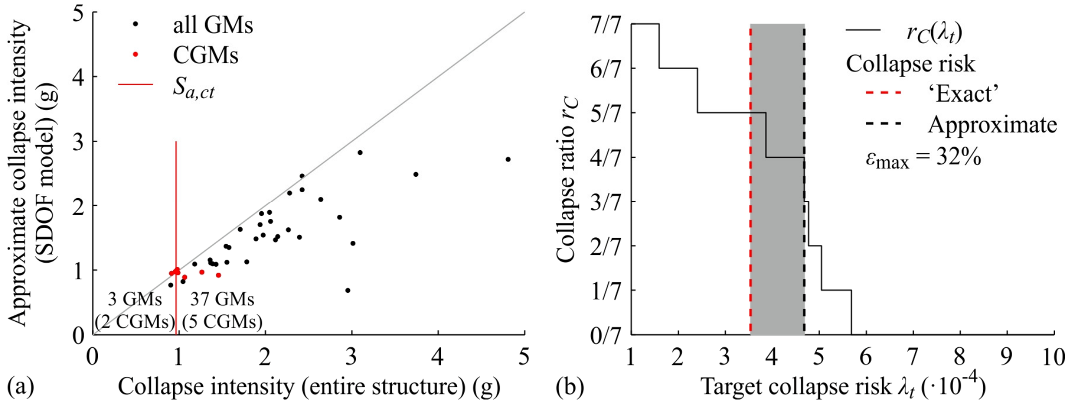

Figure 4: (a) Approximate versus 'exact' collapse intensities for 40 ground motions with indicated CGMs and the characteristic value of target collapse intensity $S_{a,ct}$ and (b) the collapse ratio r_C for multiple levels of the target collapse risk λ_t with the indicated interval of target collapse risk, for which the 3R method would result in an inaccurate risk-based decision making.

4 CONCLUSIONS

The theoretical background and application of the practice-oriented 3R method was briefly presented. The 3R method is intended to be used for checking the adequacy of collapse risk of structures on basis of few nonlinear dynamic analyses. Seismic demand is determined at single intensity, which is associated with target collapse risk, taking into account characteristic ground motions, which are selected by two-step ground motion selection procedure. If collapse is observed for less than half of characteristic ground motions, it can be decided that the design of the structure is appropriate and vice versa. The 3R method is not meant for estimation of precise collapse risk, but to decide whether the collapse risk of investigated structure is larger or lower in comparison to the target collapse risk, which is assumed acceptable.

The method was demonstrated by means of example of checking the seismic collapse safety of the reinforced concrete dual structural system. It was shown that the concept of intensity-based assessment for risk-based decision making can be applied to realistic structures. Decision made by the 3R method was confirmed by direct estimation of collapse risk on the basis of incremental dynamic analysis of the nonlinear structural model.

The proposed seismic analysis method requires only few (e.g. 7) nonlinear dynamic analyses of model of entire structure. This makes it attractive for practical purposes.. Additional work, which should be performed within the 3R method in order to obtain characteristic ground motions and an appropriate characteristic value of target collapse intensity is not computationally demanding and can be automated, which has actually already been realized by means of the web application. An advantage of the proposed method is that scale factors of ground motions are small, which reduces biased estimates of seismic demand.

The 3R method could be used for checking the collapse risk of newly designed and existing structures. Due to computational efficiency it could be also incorporated to iterative risk-based design procedures based on dynamic analysis of nonlinear structural model. However, additional studies are needed in order to assess the applicability of the method for other types of structures and performance objectives.

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