WEB APPLICATION FOR DETERMINATION OF RISK-TARGETED SEISMIC ACTION FOR FORCE-BASED SEISMIC DESIGN

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Abstract

Development of earthquake engineering in the last decades made it possible to introduce the risk-targeted design of structures into the codes. The design of structures for a target risk posed by natural hazards is a response to societal needs because it has been realized that the restoration process of an area hit by an earthquake could additionally harm societal well-being for many years after the adverse event. As a consequence, the seismic safety becoming a market category, which means that owners are becoming more and more involved in decision-making regarding the tolerable risk. Engineers responded to such interaction by developing a palette of methods for the design of the structure to the target risk. Among these methods, the simplest is the risk-targeted force-based design, which combines conventional force-based design and the risk-targeted design spectrum. In this paper, the theoretical background and the web application for the definition of the risk-targeted design spectrum are briefly presented. It is shown how the risk-targeted design seismic action is estimated through the user-friendly interface. The user has to define target collapse risk, the dispersion of limit state intensity, the seismic hazard curve at the site of interest and the shape of target spectrum for selection of ground motion for assessment of the structure. The properties of the structures are introduced by adopting the overstrength reduction factor and near-collapse ductility, which have to be ensured in the conventional force-based design. Then the capabilities of the web application are demonstrated by calculating the risk-target design intensities for a six-storey building. It is discussed that the target spectrum, which is used for the selection of ground motions for nonlinear dynamic analysis, has a significant impact on the values of the risk-targeted design spectral acceleration and reduction (behaviour) factor.

Keywords:risk-targeted design; risk-targeted seismic intensity; target risk; web application

1. Introduction

The risk-targeted seismic design of structures becomes applicable in practice because it is supported by a palette of methods either based on nonlinear analysis (i.e. dynamic or pushover analysis) and the corresponding decision models (e.g. [1–3]) or linear elastic analysis in conjunction with risk-targeted design spectrum [4–9]. The risk-targeted design is incorporated in the building codes [4,5] through the introduction of risk-targeted seismic design maps [6,7,9], which corresponds to the specific collapse risk. Such an approach is practical, but it also imposes several limitations. For example, it is well known that the dispersion of limit state intensity can vary significantly with respect to the building type. Therefore, risk-targeted design maps should be produced for a different type of buildings. The number of maps due to the differentiation of dispersion of limit state intensity can be reduced by plotting low (i.e. tenth) percentile seismic intensity instead of median seismic intensity as proposed by ASCE 7-10 [4], since at this percentile value the variation of the dispersion has a small impact on the design acceleration defined by the map. However, using such an approach, the insight into the required median capacity of the structure is lost. In addition, an engineer has no tool to enable him an insight on the design spectrum with respect to the target risk required by the owner.

In order to avoid the definition of numerous risk-targeted design maps, a web application (https://apps.smartengineering.si/qfactor/) for determination of risk-targeted design intensity was developed. The application supports the algorithm for the determination of risk-targeted intensity introduced by Žižmond and Dolšek [8]. The result can be quickly obtained through the user-friendly interface. An engineer simply inserts the target collapse risk, the dispersion of limit state seismic intensity causing collapse, the hazard curve at the location of the structure, the shape of the design spectrum and target spectrum which is used for selection of ground motion for performance assessment of the structure. In addition, it is necessary to adopt the overstrength factor and ductility, which have to be ensured in the conventional force-based design. The application then calculates the risk-targeted design intensity (spectral acceleration at the first vibration period) and the risk-target design spectrum. The application also offers the set of ground motions for the seismic performance assessment of the structure with respect to the target spectrum.

The aim of this paper is to demonstrate how the web application can be used for the calculation of the risk-targeted design spectrum. The basis for the determination of risk-targeted seismic intensity for force-based design, which is used to define the design spectrum, is briefly presented in the first part of the paper. This is followed by the presentation of the user interface of the web application and by demonstrating the use of the web application for the determination of the risk-targeted seismic design intensity for 6-storey reinforced concrete frame building.

2. Summary of theoretical background for risk-targeted design spectral acceleration for force-based design

Theoretical background for the determination of risk-targeted design spectral acceleration according to Žižmond and Dolšek [8] is summarized. Only the spectral acceleration at the first vibration period of a structure is considered as an intensity measure in the following derivation because the primary objective is to explain the estimation of the risk-targeted design spectral acceleration for force-based design which accounts for the available ductility and overstrength of the structure.

The derivation of the risk-targeted design spectral acceleration starts from the assumption that the performance objective is fulfilled when the probability of collapse of a structure P_C is less than the target (acceptable) annual probability of collapse $P_{C,a}$:

$$P_C \le P_{C,a} \tag{1}$$

Because the target (acceptable) annual probability of collapse $P_{C,a}$ (hereinafter called target collapse risk) is an input parameter for the design, it is considered as a known parameter. Thus the objective of the design is that the realized probability of collapse P_C, once the structure is designed, is as close as possible to $P_{C,a}$. Because in the design phase, a structure is not yet defined, the probability of collapse P_C cannot be explicitly estimated according to the conventional risk equation (e.g. [10,11]):

$$P_C \approx \lambda_C = \int_0^\infty P\left(C \middle| S_E = S_e; S_{e,C}, \beta_{Se,C}\right) \cdot \left| \frac{dH\left(S_e\right)}{\mathrm{d}\, S_e} \right| \cdot \mathrm{d}\, S_e \tag{2}$$

where, λ_C is the mean annual frequency of collapse exceedance, which is practically equal to the annual probability of collapse P_C (hereinafter called collapse risk) due to its low value, $H(S_e)$ is the seismic hazard function, i.e. the mean annual frequency of exceedance of intensity measure S_e, $P(C|S_E = S_e; S_{e,C}, \beta_{Se,C})$ is the collapse fragility function, which is usually defined by the lognormal cumulative distribution function having two parameters, i.e. by the median intensity causing collapse $S_{e,C}$ and the corresponding standard deviation $\beta_{Se,C}$.

The seismic hazard function $H(S_e)$ from Eq. (2) is considered to be known in the design phase and independent of the structural response. In order to calculate collapse risk P_C, the parameters of the collapse fragility function, i.e. $S_{e,C}$ and $\beta_{Se,C}$, have to be known, which is not the case in the design phase. Thus, Eq. (2) can be evaluated only in the assessment phase, once the structure has already been entirely defined. However, in the design phase, it is possible to estimate the target collapse fragility function based on a known value of target collapse risk $P_{C,a}$. In this case, Eq. (2) can be rewritten as follows:

$$P_{C,a} \approx \lambda_{C,a} = \int_{0}^{\infty} P\left(C \middle| S_E = S_e; S_{e,C,a}, \beta_{Se,C}\right) \cdot \left| \frac{dH(S_e)}{\mathrm{d}\,S_e} \right| \cdot \mathrm{d}\,S_e \tag{3}$$

where $P(C|S_E = S_e;\ S_{e,C,a},\ \beta_{Se,C,a})$ is the target (acceptable) collapse fragility function, which has to be calculated based on known $P_{C,a}$ and seismic hazard function $H(S_e)$. Because the target collapse fragility function has two parameters (i.e. the target (acceptable) median intensity causing collapse $S_{e,C,a}$ and the corresponding standard deviation $\beta_{Se,C,a}$), the value of $\beta_{Se,C,a}$ has to be assumed in order to calculate $S_{e,C,a}$ from Eq. (3). This assumption may not be critical, because it was shown (e.g. [12]) that the value of $\beta_{Se,C}$ does not vary significantly for specific types of structures. Additionally, it can be assumed that $\beta_{Se,C,a} \approx \beta_{Se,C}$ because the objective in the design is that $P_C \approx P_{C,a}$. Based on these assumptions, $S_{e,C,a}$ is the only unknown of Eq. (3) and can thus be obtained by solving Eq. (3). The result of such calculation is the target collapse fragility function (see Fig. 1). In order to fulfil the performance objective (Eq. (1)), the engineer has to design a structure in such a way that the actual (realized) collapse fragility function will be slightly on the right-hand side of the acceptable collapse fragility function (Fig. 1). In this case, the structure will be slightly over-designed in terms of acceptable collapse risk, whereas in the opposite case, when the actual (realized) collapse fragility function is on the left-hand side of the target (acceptable) collapse fragility function (Fig. 1), the structure will be considered under-designed and thus not safe against collapse. By inserting Eqs. (2) and (3) into Eq. (1), it can be realized that the risk-based objective for collapse prevention, as defined in Eq. (1), can be transformed into an intensity-based objective:

$$S_{e,C} \geq S_{e,C,a} \tag{4}$$

Eq. (4) can also be interpreted schematically by observing Fig. 1. If the collapse fragility function of the investigated structure is on the right-hand side with respect to the target collapse fragility function, then the engineer has satisfied Eq. (4) as well as Eq. (1).

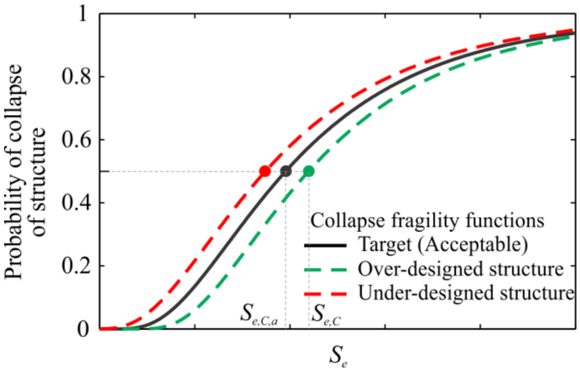


Fig. 1 – Target (acceptable) collapse fragility function, collapse fragility function of the under-designed structure, and collapse fragility function of the over-designed structure

In general, different approaches can be used to design a structure that fulfils the requirement defined by Eq. (4). However, it is challenging to assess $S_{e,C}$ exactly, because the estimation of the collapse of complex structures is quite uncertain and often associated with numerical non-convergence. It is therefore convenient to check the performance of the structure for a less severe limit state, i.e. a near-collapse (NC) limit state. The transition between the collapse and NC limit state was introduced in a previous study [2] by means of a limit-state reduction factor γ_{ls}, which relates the median spectral acceleration causing collapse $S_{e,C}$ to the median spectral acceleration causing the NC limit state $S_{e,NC}$ of a structure:

$$\gamma_{ls} = \frac{S_{e,C}}{S_{e,NC}} \tag{5}$$

By implementing the limit-state reduction factor γ_{ls} in Eq. (4), the design condition is defined as follows:

$$S_{e,NC} \geq \frac{S_{e,C,a}}{\gamma_{ls}} = S_{e,NC,a} \tag{6}$$

where $S_{e,NC,a}$ is an acceptable median spectral acceleration corresponding to the first vibration period and causing the NC limit state of a structure (also called risk-targeted spectral acceleration causing NC limit state of a structure). Note that, in general, the γ_{ls} can be related to any other limit state.

Eq. (4) or Eq. (6) can only be verified on the basis of nonlinear analysis. Because force-based design utilizes linear elastic analysis (e.g. response spectrum analysis) and it takes into account different design factors (e.g. [13]), additional assumptions are needed to estimate the risk-targeted spectral acceleration for force-based design $S_{e,D,a}$. It has to be realized that, due to the design factors in the force-based design and the inherent ductility of the structure (see [13]), the actual strength and deformation capacity of the structure are higher than the corresponding design values. As a consequence, the risk-targeted spectral acceleration causing the NC limit state of structure $S_{e,NC,a}$ has to be further reduced in order to estimate the risk-targeted spectral acceleration for the force-based design $S_{e,D,a}$. This reduction is performed by using the available reduction factor r_{NC}.

The r_{NC} has to be assumed in the design because it depends on the available ductility, the overstrength reduction factor, and the deformation and energy dissipation capacity. These parameters are not precisely known in the design phase, but they can be estimated once the structure has been fully defined. In this case, the r_{NC} can be calculated directly as the ratio between the spectral acceleration causing the NC limit state of structure $S_{e,NC}$ and the risk-targeted design spectral acceleration for the force-based design $S_{e,D,a}$ (also called risk-targeted design spectral acceleration):

$$r_{NC} = \frac{S_{e,NC}}{S_{e,D,a}} \tag{7}$$

One option to calculate the risk-targeted design spectral acceleration $S_{e,D,a}$ is to develop a model of the available reduction factor r_{NC} based on parametric studies for different types of structures. In such a case, the $S_{e,D,a}$ can be introduced by inserting Eq. (7) into Eq. (6). $S_{e,D,a}$ can then be formulated as follows:

$$S_{e,D,a} = \frac{S_{e,NC,a}}{r_{NC}} \tag{8}$$

Note that in Eq. (8) the symbol greater or equal was replaced by the symbol equal, because the objective in the design is that $S_{e,NC}$ is as close as possible to $S_{e,NC,a}$.

The risk-targeted spectral acceleration causing NC of structure $S_{e,NC,a}$ (i.e. the denominator in Eq. (8)), depends on the assumed value of the dispersion of the spectral acceleration causing collapse $\beta_{Se,C}$, the target collapse risk $P_{C,a}$, and the hazard function. $S_{e,NC,a}$ can be assessed as the ratio between $S_{e,C,a}$ and a limit-state reduction factor γ_{ls}, while $S_{e,C,a}$ can be calculated iteratively using Eq. (3), or, under some assumptions, also by using a closed-form expression, as explained in [8].

The values of the other parameter of Eq. (8) (i.e. the available reduction factor r_{NC}) have to be assumed. Since, the available reduction factor r_{NC} depends on the overstrength, deformation capacity, and cumulative energy dissipation capacity of the structure, it makes sense that the r_{NC} factor is decomposed. Different formulations are possible. In the case of pushover analysis, the available reduction factor r_{NC} can be decomposed into an overstrength reduction factor r_s and a ductility reduction factor $r_{\mu NC}$ (see also [14,15]). Starting from Eq. (8), r_{NC} can be decomposed as a product of two spectral acceleration ratios, as follows:

$$r_{NC} = \frac{S_{e,NC}}{S_{e,Y}} \cdot \frac{S_{e,Y}}{S_{e,D,a}} = r_{\mu NC} \cdot r_s \tag{9}$$

where $S_{e,Y}$ is the spectral acceleration at yielding, $r_{\mu NC} = S_{e,NC} / S_{e,Y}$ is a ductility reduction factor, and $r_s = S_{e,Y} / S_{e,D,a}$ is the overstrength reduction factor. The definition of the available reduction factor in Eq. (9) is based on seismic intensity measure, i.e. the spectral acceleration at the first vibration period of a structure. In general, $r_{\mu NC}$ and r_s can be estimated from the results of parametric studies, taking into account different building classes or even building sub-classes. However, r_{NC} can also be expressed directly by the risk-targeted design base shear $F_{D,a}$, yield strength F_Y, the available system ductility μ_{NC} (i.e. the ratio between the near-collapse displacement of structure D_{nNC} and the corresponding yield displacement D_Y) and the inelastic deformation ratio C_1 [16,17]:

$$r_{NC} = r_{\mu NC} \cdot r_s = \frac{\mu_{NC}}{C_1} \cdot \frac{F_Y}{F_{D,a}} \tag{10}$$

According to Eq. (10), the overstrength reduction factor r_s can be interpreted as the ratio between yield strength (F_Y) and the risk-targeted design base shear ($F_{D,a}$), whereas $r_{\mu NC}$ is defined as the available system ductility divided by the inelastic deformation ratio C_1, i.e. the parameter which couples the dynamic response of the elastic and inelastic system. Note that Eq. (10) can be precisely applied to an SDOF structure, as it is shown in the Appendix of [8], which also presents some approaches for the estimation of C_1.

The formulation of the risk-targeted design spectral acceleration $S_{e,D,a}$ is based on the assumption that seismic hazard is defined by a seismic hazard function. If the seismic hazard is defined by the traditional uniform seismic hazard maps related to a designated return period T_R (e.g. [18]), then the $S_{e,D,a}$ is not calculated directly from $S_{e,NC,a}$ but indirectly via spectral acceleration $S_{e,TR}$ corresponding to the return period of seismic intensity T_R. Thus, the risk-targeted approach can be incorporated into the design by introducing a risk-targeted reduction factor, which will be termed as q_a. By definition, the risk-targeted design spectral acceleration $S_{e,D,a}$ can be calculated as follows:

$$S_{e,D,a} = \frac{S_{e,TR}}{q_a} \tag{11}$$

The risk-targeted reduction factor can then be easily derived by considering that $S_{e,D,a}$ from the Eq. (11) shall be equal to that from the Eq. (8):

$$q_a = \frac{S_{e,TR}}{S_{e,NC,a}} r_{NC} \tag{12}$$

Note that the ratio between $S_{e,NC,a}$ and $S_{e,TR}$, was defined in a previous study [2] as the risk-targeted safety factor:

$$\gamma_{im} = \frac{S_{e,NC,a}}{S_{e,TR}} \tag{13}$$

γ_{im} can be interpreted as the multiplication factor for $S_{e,TR}$ (i.e. seismic demand) in order to obtain $S_{e,NC,a}$ (i.e. risk-targeted seismic capacity). However, if the risk-targeted safety factor for limit-state seismic intensity γ_{im} is introduced into Eq. (12), then the risk-targeted reduction factor for a specific target collapse risk ($P_{C,a}$) can be expressed in the following form:

$$q_a = \frac{r_{NC}}{\gamma_{im}} \tag{14}$$

The definition of $S_{e,D,a}$ according to Eq. (11) is very useful in the case when the seismic hazard is defined by uniform seismic hazard map related to a designated return period. Such an approach requires a model of risk-targeted safety factor γ_{im}, which is associated with $S_{e,TR}$. A possible procedure for the estimation of γ_{im} is presented in [2].

For a conventional force-based design using response spectrum analysis, the determination of the value of the risk-targeted design spectral acceleration $S_{e,D,a}$ is not sufficient, because it represents only one point of the design spectrum. Thus, for force-based design, the design spectral accelerations for a wide range of periods are needed to capture the higher mode effects. There are different possibilities for the definition of design spectra based on $S_{e,D,a}$. However, in the simplest case the design spectrum can be determined by normalizing the assumed shape of the spectrum (e.g. Eurocode 8 elastic spectrum [18]) to the risk-targeted design spectral acceleration $S_{e,D,a}$. In this way, the entire risk-targeted design spectrum is defined, which can be used for force-based design in precisely the same way as, for example, the design spectrum from Eurocode 8 [18].

3. Web application for the assessment of the risk-targeted spectral acceleration and risk-targeted reduction factor for the force-based design

The risk-targeted design spectral design acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a can be easily assessed via a web application, which was developed by IKPIR institute of the University of Ljubljana. The web application can be accessed and used from https://apps.smartengineering.si/qfactor/ once the user account is created by the user.

The user interface of the application is divided into two parts, i.e. the input data entry part and the part presenting the results. The input data entry part is divided into several blocks. Each block contains a specific type of input data and often some partial result (see Fig. 2). Information about input parameters and their valid range, as well as parameters, which are recalculated in case the value of the input parameter is changed, can be easily obtained by clicking on info point (ℹ) above the parameter.

From the definition of risk-targeted spectral design acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a it follows that the information about the structure to be design and the seismic hazard at the location of the structure have to be defined for the calculation of $S_{e,D,a}$ and q_a. The information about the structure is inserted in block *Structural parameters*. The user has to enter the predominant period of structure T_1, adopted overstrength reduction factor r_s and near-collapse ductility μ_{NC}, the standard deviation of collapse intensity in log domain $\beta_{Se,C}$ and limit-state reduction factor γ_{ls}. It should be noted that the assumed values of the overstrength and ductility factors should be based on the best estimates of their values without consideration of any safety factors. The target (acceptable) annual probability of collapse $P_{C,a}$ has also to be inserted in this block. The information about the seismic hazard on the site of the structure is inserted in the block *Hazard curve*. There are two possibilities for the definition of hazard curve, i.e. by entering the hazard curve in the table or by defining the hazard curve as a linear function in the log-log domain. In this case, the hazard curve's parameters k and k_0 have to be defined.

The definition of the parameters into the above-described blocks trigers the calculation of risk-targeted spectral acceleration causing collapse $S_{e,C,a}$ and NC limit state of a structure $S_{e,NC,a}$. The results are presented in the block *Risk-targeted intensities and safety factor*. The $S_{e,C,a}$ is calculated iteratively using Eq. (3). However, for the calculation of the risk-targeted safety factor γ_{im} and consequently the q_a, the reference spectral acceleration $S_{e,TR}$ corresponding to the return period of seismic intensity T_R has to be assessed (see Eqs. (13) and (14)). The spectral acceleration $S_{e,TR}$ is calculated from the hazard curve defined in the block *Hazard curve* by considering the return period T_R which is defined by the user. Please note that special attention is needed in case if the risk-targeted reduction factor q_a is used as a behavior factor in the determination of the design response spectra according to Eurocode 8 [18]. In this cases the reference spectral acceleration $S_{e,TR}$ must have the same value as the spectral acceleration corresponding to period T_1 from elastic spectrum according to Eurocode 8. This can be achieved by varying the value of return period T_R in the field in the block *Risk-targeted intensities and safety factor*.

The available reduction factor r_{NC} is the next parameter that has to be calculated in the assessment of the risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a. Based on the definition (see Eq. (10)) it is calculated as a product of overstrength r_s and ductility reduction factor $r_{\mu NC}$. The latter is defined as the ratio between assumed NC ductility of the structure μ_{NC} and inelastic displacement ratio C_1 (see Eq. (10)). The inelastic deformation ratio C_1, i.e. the parameter which couples the dynamic response of the elastic and inelastic system, can be estimated from models that were developed in past studies (e.g. from the model of Eurocode 8 [18], Vidic et al. [19], Miranda [16]). However, since the value of C_1 also depends on the intensity measure and the shape of the spectrum for the selection of ground motions for seismic performance assessment, it makes sense to calculate the C_1 using nonlinear dynamic analyses (e.g. incremental dynamic analysis [20], multiple-stripe analysis [21]) for a specific set of ground motions and intensity.

The web application uses incremental dynamic analysis (IDA) for a set of ground motions selected based on the target spectrum defined by the user, for the estimation of C_1. According to the Appendix from [8], the inelastic deformation ratio C_1, is defined as in the original papers [16,17]:

$$C_1 = \frac{D^*_{nNC}}{D^*_{eNC}} \tag{15}$$

where D^*_{nNC} is the near-collapse displacement of nonlinear SDOF system and D^*_{eNC} is the displacement of linear elastic SDOF system at the median value of spectral accelerations that cause D^*_{nNC} of nonlinear SDOF system. The displacement D^*_{nNC} can be simply calculated as a product of the yield displacement of the nonlinear SDOF system and the assumed value of near-collapse ductility μ_{NC}. However, in order to determine D^*_{eNC} , the median value of spectral accelerations which lead the nonlinear SDOF system to D^*_{nNC} have to be assessed. Therefore, in the web application, the IDA analyses are performed for nonlinear SDOF model using the set of appropriately selected ground motions. The target spectrum for ground motion selection is defined in the block *Spectrum for selection of GM for calculation of* C_1. It can be defined in two manners. In the first case, the target spectrum can be defined as a Eurocode 8 elastic spectrum for an arbitrary return period. The second option for the definition of the target spectrum is more general. The user can insert the periods and corresponding the mean values and logarithmic standard deviation of the target spectrum. However, it has to be emphasized that the ground motions are selected in such a way that they normalized to the value of the target mean spectrum at the first vibration period. Therefore, at this period, the standard deviation of the spectra of the selected ground motions is equal to zero, although the user might insert non-zero standard deviation. It has to be also noted, that in the case of selection of a set of ground-motions based on Eurocode 8 target spectrum, the target standard deviation is assumed to be zero for all periods.

In the process of the selection of the ground motions, a slightly modified procedure presented by Jayaram et al. [22] is used. The procedure requires the definition of some additional parameters that are taken into account in the process of ground-motion selection. These parameters are defined in the block *Ground motions selection*. The user has a possibility to define the number of ground motions to be selected and the maximum scale factor that is used in the selection. Ground motion selection can also be limited by specifying countries of earthquake origin, the database of the ground motions, the minimum and maximum magnitude of an earthquake, the minimum and maximum distance from the site to the raptured area and minimum and maximum average shear wave velocity in the upper 30 m of soil V_{s30} at the site of the recorded ground motions. Note that by default the V_{s30} restrictions are already set by the selection of soil type according to Eurocode. However, the user has the possibility to override these values. There are also some additional parameters that can be set. These parameters, which are described in details in the paper [22], are associated with a mathematical procedure of the selection of ground motions. They can be modified by clicking the option *Advanced settings*. Bet there is no need to change the default values of these parameters.

For the nonlinear dynamic analysis the SDOF model with three branch backbone is used (i.e. the uniaxial hysteretic material from Opensees [23]). The backbone of the model, which is defined automatically, is shown in the block *SDOF model parameters*. The period the SDOF model is considered equal to the assumed first period of the structure. The NC ductility of the SDOF model corresponds to the assumed ductility μ_{NC}, whereas the yield strength and the mass of the SDOF model are defined in such a way that the intensity causing the NC limit state (displacement) of the SDOF model is in the order of magnitude. The parameter, which controls the unloading stiffness (i.e. parameter β for uniaxial hysteretic material [23]), is assumed to be 0.80, whereas the 5% mass proportional Rayleigh damping model is predefined. However, the user can modify the mass and the strength of the model, the ratio between the rotation at zero moment at postcapping branch and the rotation at the maximum moment (called *sfth*) as well as the damping and hysteretic parameters of the backbone (see Fig. 2). Note that the strength of the model has quite a small impact on the value of the C_1 since it mainly depends on the period and ductility of the model.

Structural parameters

T_1 (s): 1
r_s: 2
μ_{NC}: 6
β_C: 0.4
$P_{C,a}$: 0.0001
γ_{ls}: 1.15

Hazard curve

Define hazard function as
○ Linear in log domain ● User-defined

User defined Hazard curve
Load sample Clear table

	Acceleration (g)	MAF
1	1E-12	1.206673085
2	0.0001	1.206672479
3	0.001	1.16781731
4	0.01	0.359262456
5	0.05	0.052136869
6	0.1	0.018221601

Risk-Targeted Intensities and Safety Factor

The QFactor application follows the procedure described in Zizmond & Dolsek, 2019.

$S_{e,C,a}$ (g): 1.687
$S_{e,NC,a}$ (g): 1.467
Return period for calculation of $S_{e,TR}$
T_R (year): 475
$S_{e,TR}$: 0.350
γ_{im}: 4.192

Spectrum for Selection of GM for Calculation of C_1

Select Spectrum for Ground Motion Selection
○ Eurocode Elastic Spectrum ● User Defined

User defined Spectrum
Load sample Clear table

	Period (s)	Median (g)	Sigma
1	0	0.304973026	0.338912265
2	0.020100503	0.324316428	0.352881917
3	0.040201005	0.339403246	0.374276269
4	0.060301508	0.384863615	0.387769959
5	0.08040201	0.426634484	0.404621697
6	0.100502513	0.472783096	0.419929124

Shape of Design Spectrum

Design spectrum: EC8: type-1
Soil Type: Soil type B

Design & Target Spectra

Ground motion selection

Ground Motions: 30
Scale Factor: ☑ 30
Advanced settings ▲

Weight Mean: 2
Weight SD: 1
Penalty: ☑ 0
Seed: 1
#Pertarget: 200
#Loop: 2

Select earthquake origin: All selected
Select database source: PEER, Resorce

Magnitude Min: ☑ 4
Magnitude Max: ☑ 7.5
Closest Distance Min (km): ☑ 4.5
Closest Distance Max (km): ☑ 50
Override Vs30 restrisctions already set by Eurocode Soil Type selection: ☑
Vs30 Min (m/s): ☑ 380
Vs30 Max (m/s): ☑ 800

Comment: Put your comments and notes here...

SDOF model parameters

The uniaxial bilinear hysteretic material is used to define the SDOF model. The damage ($damage1, $damage2) parameters are both set to 0.

Proposed Sfth: 2.2
Sfth for calculation: 2.2
β: 0.8
pinchx: 0
pinchy: 0
Damping
● Mass proportional ○ Custom
Percent of damping: 5.00 %
α_M: 0.628

Fig. 2 – The input data entry part of the user interface

The user also has to define the shape of the design spectrum, which can be done in the block *Shape of design spectrum*. The shape of this spectrum, scaled to the risk-targeted design spectral acceleration $S_{e,D,a}$, can be used for force-based design in precisely the same way as the design spectrum in Eurocode 8 [18].

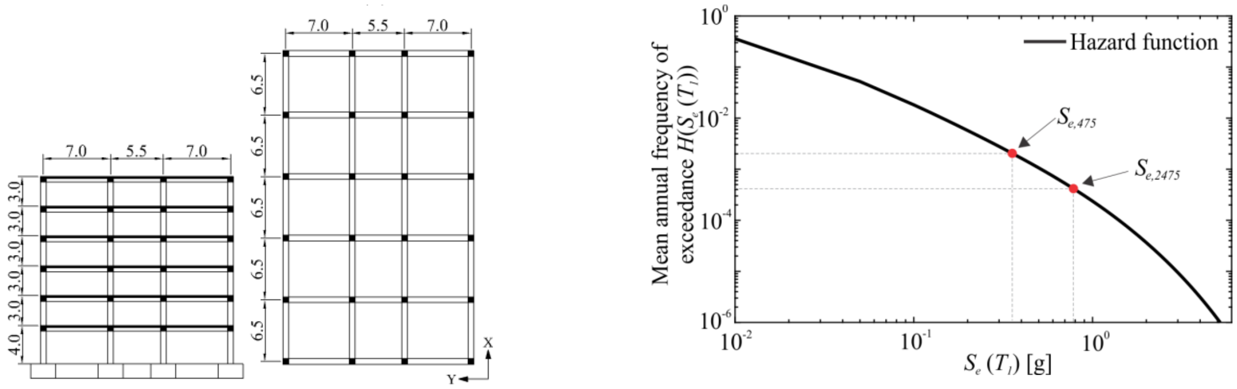
Once the input parameters are entered, the calculation can be run by clicking on the button *Calculate*. The input parameters are then sent to a dedicated computer cluster that is managed by the open-source high-throughput computing framework HTCondor [24]. The selection of the ground motions is performed using a slightly modified procedure proposed by Jayaram et. al [22], which was rewritten in ANSI C language in order to increase the speed of the selection. Incremental dynamic analysis of the SDOF model is performed with OpenSees [25]. The SDOF models for the incremental dynamic analyses are distributed and executed over multiple hosts within HTCondor framework. Computation time, therefore, depends primarily on the workload being passed to the dedicated HTCondor cluster. However, it is usually quite short. For example, in case the number of idle hosts within HTCondor cluster (i.e. processors that are used for the calculation) is equal to the number of requested analyses the computation time is usually less than 3 minutes.

The assessed values of the risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a are presented in the user interface dedicated to the results of the calculation. The interface shows the risk-targeted design spectrum (i.e. spectrum that can be directly used to calculate the design forces) as well as the spectra of the selected ground motions, the comparison between target spectra for ground motion selection and the mean spectrum of spectra of selected ground motions and the IDA curves. The ground motions records and the results of IDA analyses (i.e. IDA curves) are saved into the MATLAB [26] (*.mat) files which can also be downloaded.

4. Estimation of the risk-targeted spectral acceleration for six-storey reinforced concrete building by using the web application

The use of the web application is demonstrated by means of the estimation of the risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a for a six-storey reinforced concrete frame building (Fig. 3a, see also [8]). The investigated building consists of four bays in the X direction and six bays in the Y direction. The cross-section of the columns is 55/60 cm, whereas the slab thickness is 22 cm. Reinforcing steel B500B and concrete C35/45 are adopted in the design. The total mass of the structure amounts to 5193 t. The first vibration periods in X and Y directions are practically equal and amount to 1.00 s. The building is located in Ljubljana, Slovenia, on soil type B.

The risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a were calculated for the target collapse risk $P_{C,a}=10^{-4}$ (0.5% in 50 years) and for two target spectra (i.e. Eurocode 8 elastic spectrum and conditional spectrum [27]), which are used for ground-motion selection and affect estimation of inelastic deformation ratio C_1.



a) b)

Fig. 3 – a) the elevation and plan view of the investigated six-storey building and b) the seismic hazard function for Ljubljana

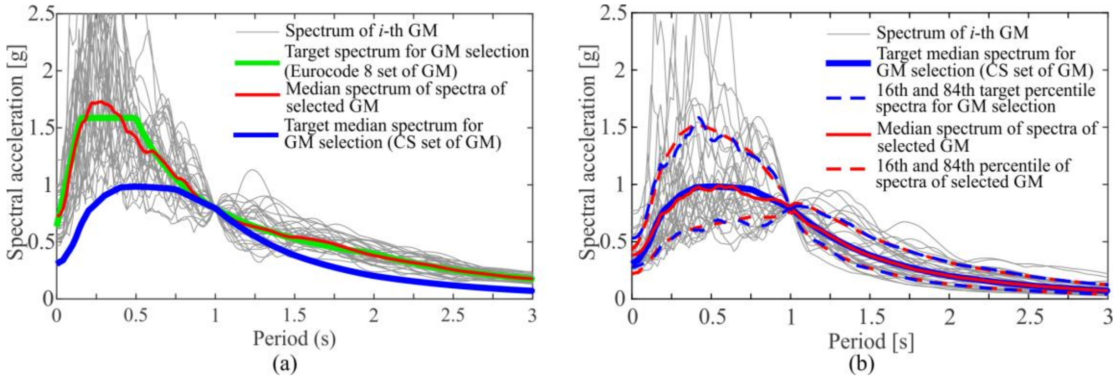
The overstrength reduction factor and ductility were adopted equal to $r_s=2$ and $\mu_{NC}=6$, respectively. These values are based on the results of the assessments of structures in previous studies (e.g. [13,28]), which show that typical values of the overstrength reduction factor r_s of multi-storey reinforced concrete frame buildings designed according to Eurocodes 2 and 8 vary from around 2 to 3, whereas the values of ductility of the structure associated with the near-collapse limit state μ_{NC} vary from around 5 to 8. The limit state reduction factor $\gamma_{ls} = 1.15$ and the standard deviation $\beta_{Se,C} = 0.40$ were adopted based on the models developed in the previous study by Dolšek et al [2].

The seismic hazard on the site of the structure was defined by inserting in the application the entire seismic hazard function, which was calculated for the spectral acceleration corresponding to the first vibration period of the structure $S_e(T_1)$, the location and the soil type of the structure (Fig. 3b) based on the official probabilistic seismic hazard analysis for Slovenia [29].

As mentioned previously, two target spectra were used for the selection of the sets of ground motions which are used in IDA in order to calculate the inelastic displacement ratio C_1. The first target spectrum is the Eurocode 8 elastic acceleration spectrum (EC8) for soil type B, which was scaled to spectral acceleration corresponding to return period 2475 years ($S_{e,2475}$=0.79 g). The second target spectrum is a conditional (CS) spectrum corresponding to the mean magnitude (M=6.2) and the mean distance (R= 7.3 km), which were obtained from the results of seismic hazard disaggregation with consideration of the spectral acceleration corresponding to the return period of 2475 years ($S_{e,2475}$=0.79 g) and the first vibration period of the structure. Note that CS spectrum is based only on the Sabetta & Pugliese ground motion prediction model [30], which was also used in the official probabilistic seismic hazard analysis for Slovenia [28]. The selection of the sets of 30 ground-motion was restricted by defining the minimum (4) and maximum (7.5) magnitudes of the events, the minimum (4.5 km) and maximum (50 km) source-to-site distances and the minimum (380 m/s) and maximum (800 m/s) shear-wave velocity in the upper 30 of the soil of the recording station.

The user interface of the web application for the assessment of the risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a based on the conditional target spectrum used for ground-motion selection is presented in Fig.1 So defined input fields in the user interface were then used for the calculation of $S_{e,D,a}$ and q_a. The set of ground motions, the $S_{e,D,a}$, q_a and the design spectrum were obtained by the web application in only few minutes, and are presented to the user in the part of the application dedicated to the results. Screenshots of this part of the web application user-interface are not presented due to the page limitation. However, the results are summarized hereinafter.

The resulting target spectrum and the spectra of selected ground motions are shown on Fig. 4. The risk-targeted design spectral acceleration $S_{e,D,a}$ and risk-targeted reduction factor q_a are presented in Table 1 for both variants of the target spectrum. From Fig. 4, it can be observed that the median spectrum of spectra of selected GM matches the target spectrum quite well. In Fig. 4a, it can also be observed that there is a quite significant difference between the target spectra based on Eurocode 8 spectrum (EC8) and conditional (CS) spectrum. A significant difference between target spectra can be observed, which results in quite different values of C_1 and the $S_{e,D,a}$ and q_a. The q_a calculated using EC8 target spectrum (q_a =2.30) is for 50 % smaller than the q_a corresponding to CS target spectrum (q_a =3.67). Consequently, the $S_{e,D,a}$ corresponding to CS target spectrum ($S_{e,D,a}$ =0.10 g) is for about 50 % smaller than that based on EC8 target spectrum ($S_{e,D,a}$ =0.15 g). The impact of the target spectra is quite significant. Therefore it is recommended that for the assessment of the $S_{e,D,a}$ and q_a the most appropriate hazard consistent target spectrum is used. However, it is also interesting to observe that the q_a assessed using CS target spectrum practically equal to the behaviour factor (q=3.9), which is prescribed in Eurocode 8 for RC frames and ductility class medium.



(a) (b)

Fig. 4 – a) the EC8 target spectrum and b) the CS target median and 16^{th} and 84^{th} percentile spectra for selection of sets ground-motion for calculation of C_1

Table 1 – Input parameters and results of the calculation of risk-targeted design spectral acceleration and risk-targeted reduction factor based on Eurocode target spectrum and conditional target spectrum.

Target spectrum	***Input data***					***Results***							
	$P_{C,a}$	r_s	μ_{NC}	γ_{ls}	$\beta_{Se,C}$	$S_{e,C,a}$	C_1	$r_{\mu NC}$	r_{NC}	$S_{e,D,a}$	γ_{im}	$S_{e,475}$	q_a
CS	$1\cdot10^{-4}$	2.0	6.0	1.15	0.40	1.69 g	0.78	7.66	15.32	0.10	4.19	0.35 g	3.67
EC8							1.24	4.82	9.64	0.15			2.30

4. Conclusions

The risk-target design spectral acceleration or risk-target reduction factor (i.e. behaviour factor) represents a basic design factor for the risk-targeted force-based design. The advantage of the proposed formulation [8] is in the coupling of conventional parameters of force-based design (i.e. overstrength factor, ductility, inelastic deformation ratio) with parameters of risk analysis (return period, target collapse risk, dispersion of spectral acceleration causing collapse). Thus the proposed formulation can be used for the rational estimation of the design spectral acceleration or the behaviour factor with respect to the target collapse risk, which may be controlled by the owner. In this paper, it was shown that the web application (https://apps.smartengineering.si/qfactor/) simplifies the calculation of risk-targeted design spectral acceleration and reduction factor. The application can be used simultaneously by several users because calculations are performed at a computer cluster of IKPIR institute.

In order to demonstrate the use of the application, the risk-targeted design spectral accelerations and the risk-targeted reduction factors were calculated for six-storey reinforced concrete frame building by setting target collapse risk to 0.5% in 50 years. The sensitivity of results was studied by considering different target spectra (i.e. Eurocode 8 elastic spectrum and conditional spectrum) which affect the estimation of inelastic deformation ratio. It was shown that the design spectral acceleration, as well as reduction factors, are affected significantly by the target spectra. The risk-targeted design spectral acceleration corresponding to the conditional target spectrum was 50 % smaller than the risk-targeted design spectral acceleration corresponding to EC8 target spectrum. It is thus recommended that the risk-targeted design spectral acceleration and the risk-targeted reduction factor are based on the unbiased estimation of the inelastic deformation ratio, which means that the conditional spectrum is used as target spectrum for ground motion selection. In this case, the estimated risk-targeted reduction factor was almost equal to the behaviour factor prescribed in Eurocode 8.

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