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Impact of the type of the target response spectrum for ground motion selection and of the number of ground motions on the pushover-based seismic performance assessment of buildings

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ABSTRACT

The impact of the type of target response spectrum and the number of ground motions on the response of buildings is investigated. The parametric study involves the selection of ground motions based on the Eurocode 8 spectrum, a conditional spectrum using the official seismotectonic model of Slovenia, a uniform hazard spectrum based on the seismotectonic model of the SHARE project, and the corresponding conditional spectrum. In addition to the variation of the target response spectrum, the number of selected ground motions was varied from 7 to 60. Selected sets of ground motions were used to investigate the seismic response of eight reinforced concrete buildings with fundamental vibration periods from 0.15 s to 1.76 s. The aim of the study was to analyse the variation of target displacements obtained by a pushover-based method, i.e. the median displacement corresponding to a seismic intensity with a return period of 475 or 2475 years, and the median spectral acceleration causing collapse, which was estimated by incremental dynamic analysis. It was found that the target spectrum and the number of ground motions have a limited impact on the target displacement, especially if it corresponds to seismic intensities with a return period of 475 years. Additionally, the impact of the number of ground motions on the median spectral acceleration causing collapse is much lower than the impact of the target response spectrum. When the conditional spectrum was used as the target spectrum for ground motion selection instead of the design response spectrum prescribed by Eurocode 8, the resulting median spectral acceleration causing collapse increased by a factor of between 1.2 and 2.3.

1. Introduction

The earthquake resistant design of buildings is most often based on linear elastic analysis, which is also prescribed as the reference method of seismic analysis in the current standard for the seismic design of buildings in Europe, i.e. Eurocode 8 [1]. For buildings of ordinary importance the design seismic action corresponds to a peak ground acceleration with a return period of 475 years. However, such earthquakes as well as earthquakes of higher intensities, which can occur during the lifetime of a building, cause nonlinear behaviour of a structure and its contents, which cannot be predicted by linear methods of analysis. The new draft of Eurocode 8 [2] prescribes the use of a simplified pushover-based nonlinear method of analysis, i.e. the extended N2 method [3], and also provides the possibility for calculating the target displacement by means of nonlinear dynamic analysis (Annex E in [2]). The new draft of Eurocode 8 also includes the informative Annex F, which prescribes a simplified reliability format aimed at the design of structures for target risk. Although nonlinear analysis can provide more information to stakeholders, its application is subject to a number of uncertainties. This study focuses only on two parameters of the code which can be considered uncertain, and does not deal with the overall accuracy of simplified pushover-based methods. We investigate how sensitive is the median value of the target displacement (Annex E) with respect to the number of ground motions used for the determination of sample values of the target displacement. The study also addresses the impact of the type of target spectrum on the target displacement and the median spectral acceleration causing collapse of reinforced concrete buildings, which is used to estimate the fragility function and the seismic risk for collapse of the structure (Annex F).

In order to better understand how the target response spectrum, which is used for the selection of ground motions, and the number of selected ground motions affect the behaviour of structures, a parametric study was performed. It includes the nonlinear time-history analysis of single- and multi-degree-of-freedom models subjected to different sets

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of ground motions. The ground motion sets are based on different types of target spectrum and contain different numbers of ground motions. The response spectrum prescribed in Eurocode 8 was used as the basic target spectrum, since it is used for target displacement estimation according to the current standard and the new draft of Eurocode 8. In order to observe the impact of the selected target spectra, the conditional spectrum approach [4] was also used as a target spectrum. The conditional spectrum was estimated based on the official seismotectonic model of the region of Slovenia [5]. Additionally, a uniform hazard spectrum and a conditional spectrum were estimated based on a more recent seismotectonic model, which was defined during the SHARE project [6]. The ground motions sets were then selected by varying the number of ground motions from 7 to 60.

Firstly, the buildings used in the study are described, followed by the ground motion selection parameters and the response parameters observed in the parametric study. The impact of the number of considered ground motions and the target response spectrum used for ground motion selection on these response parameters is then presented.

2. Description of the observed buildings

The impact of the target response spectrum and the number of considered ground motions was observed for 7 reinforced concrete buildings designed according to the Eurocode 8 [1] provisions, i.e. 5 frame buildings [7,8] and 2 buildings with dual systems [7]. Additionally, a reinforced concrete roof supported by equally displaced columns was designed in order to incorporate a model with a very short period of vibration into the parametric study. The fundamental vibration periods of the buildings were estimated by taking into account cracking of reinforced concrete columns and beams (bending stiffness of elements was reduced to 50% of initial stiffness). The values range between 0.15 s and 1.76 s. Basic properties of the analysed buildings are presented in Table 1, whereas the elevations and plan views of frame buildings and dual systems are presented on Fig. 1.

The buildings are mostly symmetrical and regular in elevation, except for the 3-storey frame building 3F, which has an asymmetrical plan, and the 8-storey frame building 8F, which is irregular in elevation. The plan view of the two dual systems, 4D and 8D, is equal, except for the length of the walls in the X direction, which are 6 m long in the 4-storey building, and 4 m long in the 8-storey building. It can be seen from Table 1 that the buildings were modelled with 3-dimensional models or with 2-dimensional models. The structural models were consistent with the requirements of Eurocode 8 [1,9] and validated by experimental results (e.g. [10]). The flexural behaviour of the beam and column was modelled by means of one-component lumped plasticity elements which consisted of an elastic beam and two inelastic rotational hinges (defined by a moment-rotation relationship). The element formulation was based on the assumption of an inflexion point at its midpoint. Gravity loads were represented by uniformly distributed load acting on the beams, where plastic hinges were used for major axis bending only. In the case of the columns, two independent plastic hinges for bending about the two principal axes were used. The moment-rotation relationship before strength deterioration was modelled by a bi-linear relationship. A linear negative stiffness was assumed in the post-capping range of the moment-rotation relationship. The axial force due to gravity loads was taken into account when determining the moment–rotation relationship for the columns, whereas in the case of the beams zero axial force was assumed. The P-delta effect was taken into account. Best estimates of the material strengths were used for the calculation of the strength of the structural elements. The mean value of the compressive strength of the concrete was estimated as $f_{cm} = f_{ck} + 8\,\text{MPa}$, where f_{ck} is the characteristic compressive cylinder strength of the concrete. The approximate mean value of the yield strength of the reinforcement was estimated as $1.15{\cdot}f_{yk}$ [11], where f_{yk} is the characteristic strength defined by the design quality of the material. The ultimate rotations for the primary seismic elements were determined according to Eurocode 8-3 [9] by estimating the median values, i.e. by omitting any additional safety factors. For simplicity, only the X direction of loading is considered in the analyses, all of which were performed in PBEE Toolbox [10] in conjunction with OpenSees [12].

In order to investigate the impact of the number of ground motions on the response of buildings, single degree of freedom (SDOF) models were defined for all the observed reinforced concrete buildings. The SDOF models were defined based on the results of pushover analysis of the MDOF models. In the case of pushover analysis the invariant force vector corresponded to the product of the storey masses, and the first vibration mode was used to obtain the relationship between the total base shear F and the top displacement d (Fig. 2). The current version of Eurocode 8 [1] prescribes an elastic-ideally plastic idealization of the F – d relationship, but Annex E of the new generation of Eurocode 8 [2] foresees a multilinear idealization of the F – d relationship. For this reason a tri-linear relationship between force F and displacement d, with a softening branch, was taken into account (see Fig. 2). The initial stiffness of the SDOF models was considered equal to the initial stiffness of the MDOF models obtained by pushover analysis. The equivalent period of the SDOF models T^* was therefore equal to the fundamental vibration period T_{1X} presented in Table 1. The force-displacement relationship of SDOF models was obtained by dividing the forces and displacements of idealized force-displacement relationship of MDOF models with transformation factor Γ which was calculated according to annex B of Eurocode 8 [1]. The mass of equivalent SDOF model m^* was also calculated according to provisions of Eurocode 8 [1]. The near-collapse (NC) limit state was defined at the displacement corresponding to the occurrence of near-collapse limit state of the first column, as it was observed from the pushover analysis of the MDOF model. The nonlinear behaviour was modelled by means of the peak-oriented hysteretic model, i.e. the uniaxial "Hysteretic" material implemented in OpenSees [12], where all the parameters are set to 0, except the parameter beta, which controls the unloading stiffness and was assumed to be equal to 0.5. Damping proportional to the mass matrix was

Table 1
Basic properties of the analysed buildings: the type of model (2D or 3D), the fundamental period in the X direction (T_{1X}), the reference peak ground acceleration on type A ground ($a_{g,R}$), the soil type on the location of the building, the ductility class and the material class of the concrete and steel. The building labels consist of the number of storeys and the system type (F = frame, D = dual, C = column).

Building	Model	T_{1X} (s)	$a_{g,R}$ (g)	Soil type	Ductility class	Concrete class	Steel class
3F	3D	0.55	0.25	C	DCH	C25/30	S400
4F	3D	0.80	0.25	B	DCH	C25/30	S500
6F	3D	1.00	0.25	B	DCM	C35/45	S500
8F	3D	1.76	0.20	B	DCM	C30/37	S500
11F	3D	1.55	0.25	B	DCM	C35/45	S500
4D	2D	0.30	0.25	C	DCM	C30/37	S500
8D	2D	1.23	0.25	C	DCM	C30/37	S500
1C	2D	0.15	0.25	B	DCM	C25/30	S500