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A conceptual framework for seismic design of buildings using nonlinear analysis methods

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Abstract. Over the last twenty years different methodologies and software tools for seismic performance assessment have been developed under the framework of Performance-based Earthquake Engineering (PBEE) in order to achieve better protection of built environment against earthquakes. Some of these methodologies are already included in current regulatory documents, which still favouring the use of force-based design procedures, which involve so-called design earthquake in conjunction with the capacity design principles. Based on such design practice it cannot be claimed that the seismic risk is controlled to such an extent that would be acceptable for all types of structures and for all investors. However, the development at this stage offers the possibility to overcome shortcomings of the standards for earthquake-resistant design of structures in order to achieve well-informed decision-making. In the paper an overview of the research project entitled Design of structures for a tolerable seismic risk using non-linear methods of analysis is given. The project is sponsored by the Slovenian Research Agency. The main objective of the project is development of innovative procedure for design of structures, which will represent a major step towards scientifically oriented design procedures employing high level of technology.

Keywords: Performance-based earthquake engineering, seismic risk, tolerable risk, seismic design, envelope-based pushover analysis, nonlinear response history analysis

1 INTRODUCTION

Earthquakes endanger societies throughout the world even in 21st century. For example, Tohoku Earthquake (2011) caused the second largest nuclear disaster in the world and revealed weakness and vulnerability of urban cities and modern society in Japan, which were thought to be one of the most earthquake-prepared nations in the world (Goda et al. 2013). Such a great earthquake is not expected in Europe, but the vulnerability of urban cities is not negligible. Recently, several events occurred in Italy, which caused huge losses. L'Aquila earthquake (2009) caused 308 losses of human lives (D'Ayala and Dolce 2011), 1500 people were injured and 65000 homeless. Direct economic losses were around 4 billion Euros. If we look a bit more into the past, it can be realized that the risk for losses due to earthquakes is much larger as it is perceived in everyday life. According to current knowledge, quite strong earthquakes may occur also in regions with moderate seismicity. In 1895 a strong earthquake (M_L=6.1) hit Ljubljana, which was at that time a part of Austro-Hungarian Monarchy. The earthquake, which was also felt by citizens of Vienna, caused damage at approximately 10% of building stock, which were mostly demolished later on (Vidrih, 2008). However, the consequences of the earthquake were not just negative. For example, Ljubljana was renovated, implemented were guidelines for construction in earthquake-prone region, and two years after the earthquake Ljubljana got the first monitoring station in the Austro-Hungarian Monarchy.

The awareness of too high risk triggered development of regulatory documents for earthquake-resistant design of structures. Current documents still based on several simplifications and assumptions. Consequently, new buildings are not yet designed by explicit assessment of seismic risk, which requires use of nonlinear methods of analysis although the first generation of Performance-based Earthquake Engineering (PBEE) procedures are implemented in the standards. Therefore it cannot be claimed that the current building codes for earthquake-resistant design of structures control seismic risk to such an extent that would be acceptable for all types of structures and for all investors.

In order to contribute to the solution of the above-mentioned issue, the Slovenian Research Agency approved three-year project entitled Design of structures for tolerable seismic risk using non-linear analysis methods. The objective of the proposed project is development of procedures and tools for design of structures for a tolerable level of seismic risk. It is foreseen that the innovative procedure for design of structures will represent a major step towards scientifically oriented design procedures employing high level of technology.

This paper basically represents an overview of the project proposal. Firstly, a brief description of current approach for earthquake-resistant design of buildings is given with an emphasis on discussion which factors contribute to seismic safety in such design procedure. In the second part, the concept of the risk-based seismic design is presented. The paper concludes with discussion regarding the simplified nonlinear models, which are foreseen to be used in the proposed design procedure, but are capable of simulating just few failure modes.

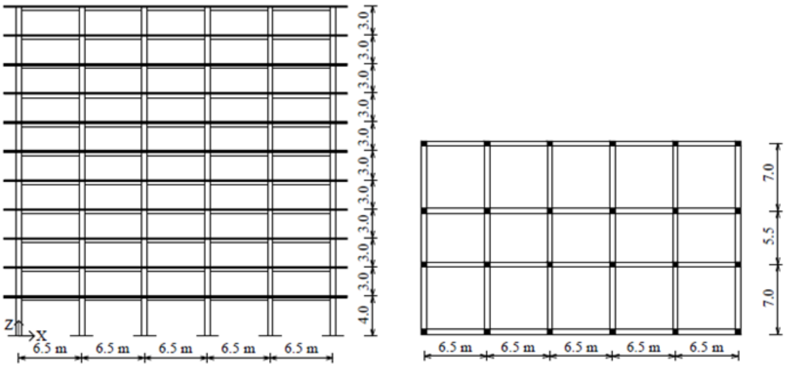
2 MOTIVATION: DEAGGREGATION OF SEISMIC SAFETY BASED ON CURRENT DESIGN PRACTICE

Eurocode 8 (CEN 2004a) prescribes that structures are sufficiently designed if they are capable to withstand a design seismic action, which is defined for a given earthquake recurrence interval associated with a limit state of interest. Usually design procedures involve elastic analysis method and design acceleration spectrum, which implicitly takes into account the ability of inelastic energy absorption of the structural system. Thus, seismic risk of newly designed structures is only implicitly controlled through the q-factor (R-factor) concept and capacity design procedure. Therefore the question arises, which factors and to which extent these factors contribute to the seismic safety as achieved by current standards for earthquake-resistant design of buildings.

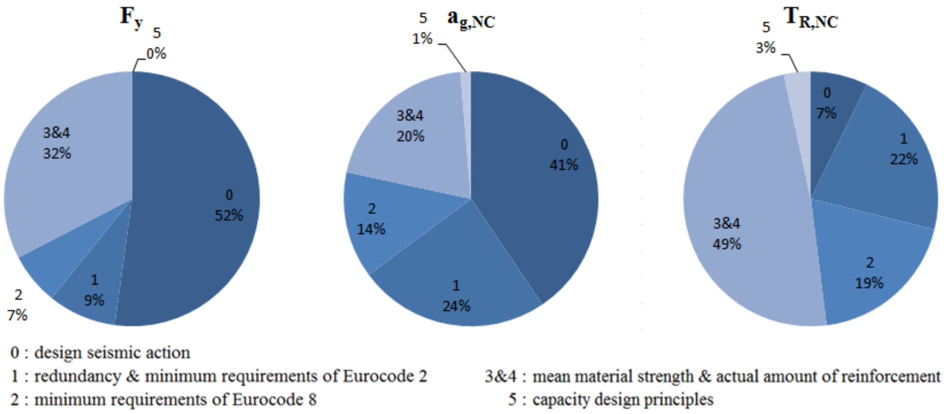
Recently, Žižmond and Dolšek (2013) addressed the above-mentioned issue. For this purpose several reinforced concrete frames were designed according to Eurocode 8 for a ductility class medium. The objective of the study was to show how different safety measures contribute to global parameters of structure, such as yield strength (F_y), ductility corresponding to the near-collapse limit state, and the so-called structural performance parameters, such as the peak ground acceleration causing near-collapse limit state ($a_{g,NC}$), or the return period of the near-collapse limit state ($T_{R,NC}$). In the study it was assumed that the following factors have a direct or indirect impact on the seismic safety achieved by the standards:

- seismic design action
- minimum requirements of Eurocode 2 (CEN 2004b) for detailing and dimensioning of structural elements
- minimum requirements of Eurocode 8 for detailing and dimensioning of structural elements
- ratio between the actual (mean) and design strength of material
- ratio between the actual and required amount of reinforcement in structural elements
- capacity design principles prescribed in Eurocode 8.

The escalation of safety was achieved by gradual consideration of design requirements according to Eurocode 2 and 8, whereas the design assumptions (factors of safety) were gradually excluded in the performance assessment of buildings. Such approach resulted in six variants of the structure, which gradually take into account the effect of design seismic action, the effect of redundancy and the minimum requirements for dimensions and reinforcement of structural elements according to Eurocode 2, the effect of partial factors of the strength of material, the effect of the difference between actual (selected) and required (calculated) reinforcement, and the effect of the capacity design principles. All variants of the buildings were analysed using a practice-oriented method for estimation of the failure probability of buildings (Fajfar and Dolšek 2012). More details are given elsewhere (Žižmond and Dolšek 2013). For illustration purpose, the results of the study for the case of 11-storey building, which was located in the region with moderate seismicity and designed for ductility class medium, are presented in Figure 1.



a) the elevation, plan view of code-conformed 11-storey building



b) deaggregation of F_y, $a_{g,NC}$ and $T_{R,NC}$ for code-conformed 11-storey building

Figure 1. a) the elevation, plan view of code-conforming 11-storey building and b) the results for deaggregation of yield strength, ground acceleration causing near-collapse limit state and the return period of the near-collapse limit state (according to Žižmond and Dolšek (2013)).

From Figure 1 it can be observed that the major contribution to the strength of the building is the consequence of the design seismic action, follows the impact of the material safety factor in conjunction with the effect of the ratio between the actual and required amount of reinforcement. The effect of the redundancy together with the effect of the minimum requirements for the reinforcement according to Eurocode 2 or the effect of more rigorous requirement for minimum reinforcement according to Eurocode 8, was less than 10%, whereas the capacity design principles practically have no impact on the strength of the building. Similar observation can be made for deaggregation of peak ground acceleration causing the near-collapse limit state, which was obtained in the post-capping range of pushover curve when all the rotation in all the columns or beams in one storey exceeded the corresponding ultimate rotation. However, the impact of the redundancy and the minimum requirements for reinforcement is doubled. Consequently, some other factors become slightly less important, but the impact of the capacity design principles on the $a_{g,NC}$ is again almost negligible. Interesting results were obtained for deaggregation of return period of the near-collapse limit state. In this case, the material safety factors contributed around 50% to overall seismic safety, whereas the design seismic action and the capacity design principles contributed only 10% to overall safety if expressed in terms of return period of the near-collapse limit state, whereas their implementation in the design process requires a lot of labour. Therefore it would probably be more efficient if structural engineer would prepare the nonlinear model of the building and explicitly design the building for tolerable risk based on several iterations rather to use capacity design approach in conjunction with elastic intensity-based assessment.

However, there are several other arguments for redefinition of the process for design of buildings for achieving seismic safety. Some additional arguments are well addressed in FEMA P-58 (2012), where it is argued that the limitations in present-generation of earthquake-resistant design of structures are associated with questions regarding the accuracy and reliability of available analytical procedures in predicting actual building response, the level of conservatism present in acceptance criteria, the inability to reliably and economically apply performance-based procedures to the design of new buildings, and the need for alternative ways of communicating performance to stake-holders that is more meaningful and useful for decision-making purpose.

3 OVERVIEW OF THE FRAMEWORK FOR SEISMIC DESIGN OF BUILDINGS BASED ON NONLINEAR ANALYSIS

The use of nonlinear analysis in the process of design of structure can solve most limitations of the current standards for earthquake-resistant design of buildings, but the complexity of the design process considerably increases. Seismic design based on nonlinear analysis is very complex process, since it requires large amount of data, a lot of knowledge of analyst and high level of technology. One approach for a solution of such a complex problem is its decomposition on more manageable components, which are in the case of proposed seismic design procedure as follows:

- Definition of tolerable risk (performance objectives)
- Seismic hazard analysis and ground motions
- Initial design procedure
- Nonlinear model
- Type of nonlinear analysis and assessment procedure
- Guidelines or algorithm for structural adjustment within iterative design process
- Design for non-simulated failure modes
- Treatment of uncertainty
- Sophisticated software

Each component is an important ingredient of the design process. Some components may be developed independently whereas some others are strongly related to each other. There are several variants for each of the component and even more variants for joining these components together. A possible workflow for design based on nonlinear analysis is presented in Figure 2 (Dolšek 2013). First step involves the initial (preliminary) design of structure. Good approximation of final design can be achieved by taking into account the minimum requirements for dimensions and reinforcement of structural elements as defined by current building codes and by using engineering judgment, which could be used for approximate determination of the expected amount of reinforcement with consideration of seismicity of the region, the structural system, regularity of the building and other factors. Initial design could also be based on simple design checks, such as the criteria for the level of normalized axial force in vertical structural elements in order to obtain initial dimensions of their cross sections, or eventually by designing the building using software which supports current building codes.

In the next step, the nonlinear structural model should be created on the basis of initial design. Definition of nonlinear structural model is very important since it is likely that results of nonlinear analysis are highly sensitive to the features of the nonlinear structural model. Therefore several guidelines (constraints) will be needed in order to help the analyst to construct a simple yet sufficiently accurate nonlinear model of structure. Since all structural models are rough reflection of reality, the (simplified) nonlinear models are capable of approximately simulating just some of the failure modes of a structure. Consequently, results of the seismic performance assessment are adequate if the non-simulated failure modes, such as shear failure of structural elements and joints, are designed on the basis of demand hazard in order to prevent such failures with a certain degree of likelihood.

The design process in the next steps involves iterations since the decision regarding the adequacy of the structural is based on seismic risk assessment (e.g. collapse risk), which requires use of nonlinear analysis. In general detailed results of probabilistic seismic hazard analysis are needed in order to assess seismic risk of a structure with sufficient accuracy. It is foreseen that in this step of the design process a simplified (pushover-based) nonlinear method will be used, since this type of method is not computationally demanding. On the other hand, these methods provide results with limited accuracy. However, an envelope-based pushover analysis procedure was proposed recently (Brozovič and Dolšek 2013). The procedure enables approximate consideration of different failure modes caused by ground motions. Additional result of this method is therefore more refined selection of ground motions in order to be used later on for checking the adequacy of final design on the basis of a few response history analyses. However, an acceptable/tolerable risk should be defined in order to make decision regarding the adequacy of the structural. The most basic criterion for determination of acceptable or tolerable risk is related, respectively, to the probability of collapse of the facility or to the probability of loss of life. Several models for determination of acceptable risk are available. Some of them are briefly discussed elsewhere (Lazar and Dolšek 2013).

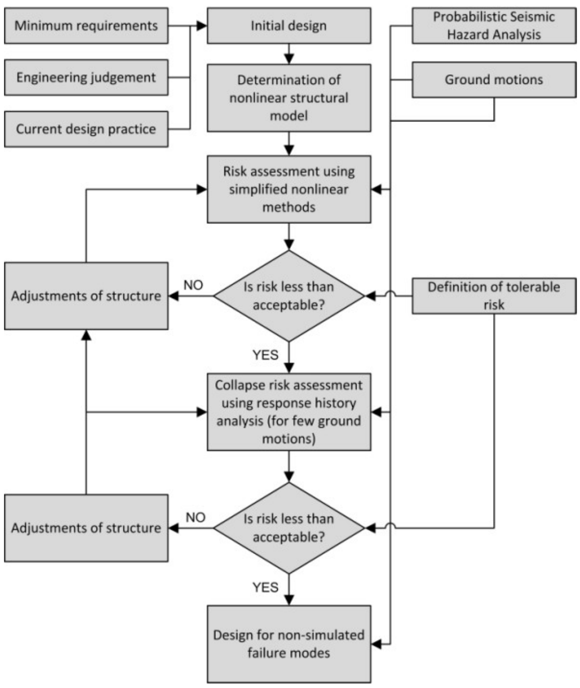


Figure 2. Flowchart of the proposed risk-based seismic design procedure of buildings (according to Dolšek 2013).

Most probably several iterations will be needed in order to satisfy the criteria for acceptable risk. Since risk assessment in this step will involve simplified nonlinear models and performance assessment procedures, iterative design procedure could be applied to realistic structures. However, the efficiency of the design procedure in terms of the number of iterations will depend on the ability of the analyst to adopt the best decisions regarding structural adjustments of the current structural variant (Step 4: Structural adjustments). Rather to use genetic algorithms or optimization methods, it is proposed to develop simple guidelines for structural adjustment in order to meet the criteria of acceptable risk with the smallest number of iterations and to achieve high utilization rate for all structural parts of the building. In this step of the proposed design procedure the creative work of the designer will be encouraged, since this iterative design process will offer an excellent insight into the nonlinear response for different structural variants of the building. The analyst will have to understand how the earthquake forces redistribute on different parts of buildings, which type of plastic mechanism occur on the basis of pushover analysis. It will be important to determine the envelope of utilization rate of structural elements corresponding to the formation of plastic mechanism, which controls the strength of the building. Based on this information the analyst will be able to decide how to increase or decrease the strength of the structural elements in order to adjust the strength of the building and the global ductility. However, several guidelines for structural adjustment will have to be developed on the basis of parametric studies performed for typical structures.

Simplified nonlinear methods for seismic performance assessment of buildings are not capable of simulating all types of engineering demand parameters to an acceptable degree of accuracy. Therefore the adequacy of the structure obtained from the iterative design process, will have to be checked by performing the response history analysis. Optimally the response history analysis will be performed for a few ‘critical’ ground motions, which will be carefully selected using the results of the response history analysis for a set of single-degree-of-freedom models from envelope-based pushover analysis. The results of the response history analysis for a few ‘critical’ ground motions will be used to check if the structure is ‘over-designed’ or ‘under-designed’. In the first case the analysis response history analysis could be performed for some other variant of structure, which will be already available from the iterative process. Alternatively, a new variant of structure can be defined and analysed. It should be noted that in this step the structure will be sufficiently designed for those failure modes, which will be simulated by the simplified nonlinear model, whereas the non-simulated failure modes, such as shear failure of structural elements or joints, will be designed on the basis of so-called demand hazard. It is foreseen that this will be the last step of the design process. It will be based on response history analyses, which will be performed at relatively small intensity levels using hazard-consistent set (or sets) of ground motion records. Once the seismic demand will be obtained on the basis of demand hazard analysis, the amount of reinforcement can be calculated according to procedures prescribed in current standards for earthquake-resistant design.

Most of components of the proposed design procedure are still at the initial stage of development. However, the iterative design procedure based on simplified risk assessment has been demonstrated by means of an example of reinforced concrete frames. The results of these studies are described elsewhere (e.g. Lazar and Dolšek 2013a, 2013b).

4 SIMPLIFIED NONLINEAR MODELS AND SOFTWARE TOOLS

The proposed design process will be possible by using comprehensive software, which will be developed on the basis of OpenSees (2012).

This software has advantages in comparison with the commercially available software since it provides a comprehensive library of nonlinear elements, material models, analysis types and solvers. From this point of view OpenSees is probably the most comprehensive software framework in earthquake engineering. However, the use of sophisticated nonlinear models quickly becomes computationally extremely demanding. Therefore the use of such models within the proposed procedure for seismic design of buildings is currently limited.

Recently a PBEE toolbox (Dolsek, 2010) was developed in conjunction with OpenSees. PBEE toolbox is a set of Matlab functions, which enable rapid definition of simple nonlinear structural models of RC buildings, the post-processing of the results of analyses and structural performance assessment with different methods. The use of simplified nonlinear models is permitted in different structural codes, where it is prescribed that the nonlinear behaviour can be modelled with concentrated plasticity. In this case the most time-consuming part of the work involves the determination of the properties of the plastic hinges. Since the PBEE toolbox automatically generates the properties of plastic hinges, based on data regarding material strength, reinforcement and section properties, the amount of work which is needed to prepare a structural model is reduced significantly. However, the PBEE toolbox supports determination of nonlinear model for OpenSees on the basis of following assumptions:

- the floor diaphragms are assumed to be rigid in their own planes, and the masses and moments of inertia of each floor are lumped at the corresponding centre of gravity,
- the beam and column flexural behaviour is modelled by one-component lumped plasticity elements, composed of an elastic beam and two inelastic rotational hinges (defined by a moment-rotation relationship). The element formulation is based on the assumption of an inflexion point at the midpoint of the element. For beams, the plastic hinge is used for major axis bending only. For columns, two independent plastic hinges for bending about the two principal axes are used,
- the moment-rotation relationship before strength deterioration is modelled by a bi-linear or tri-linear relationship. Zero axial force and the axial load due to gravity loads are taken into account when determining the moment-rotation relationship for beams and columns, respectively. A linear negative post-capping stiffness is assumed after the maximum moment is achieved.
- gravity load is represented by the uniformly distributed on the beams and/or by concentrated loads at the top of the columns.

The PBEE toolbox has to be upgraded in order to be used for design of structures according to described procedure. Recently a new function was developed, which supports seismic performance assessment of buildings by envelope-based pushover analysis procedure (Brozovič and Dolšek 2013), which combines several pushover analyses by the response history analysis using equivalent SDOF models and a set of ground motions matched to a certain acceleration spectrum. In progress is development of function for the selection of few ground motions for assessing the adequacy of the structure for collapse safety. However, a set of functions for post-processing of analysis results, for computationally-efficient demand hazard analysis and functions for prevention of those failure modes which cannot be simulated using the simplified nonlinear models still have to be developed.

5 CONCLUSIONS

The conceptual framework for seismic design of structures using nonlinear analysis methods is briefly presented in the paper. The proposed approach for design of structures will be developed under a 3-year project entitled Design of structures for tolerable seismic risk using non-linear methods of analysis. The main objective of the project, which is supported by the Slovenian Research Agency and will start at the end of this year, is development of procedures and tools for design of structures for an acceptable/tolerable level of seismic risk. It is foreseen that the innovative procedure for the design of structures will overcome shortcomings of the current building codes and thus make a contribution towards scientifically-oriented design procedures employing high level of technology and expert knowledge.

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