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CONCEPT OF RISK-BASED SEISMIC DESIGN OF BUILDINGS USING METHODS OF NONLINEAR ANALYSIS

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Abstract. *Development of nonlinear methods of analysis and powerful software for simulation of seismic response of structures offered a possibility to overcome shortcomings of the standards for earthquake-resistant design of structures. Firstly, these shortcomings are briefly addressed, followed by an overview of the nonlinear methods for seismic performance assessment of buildings. An emphasis is given on the envelope-based pushover analysis procedure, which was recently developed, and assumes that the seismic demand for each response parameter is controlled by a predominant system failure mode that may vary according to the ground motion and intensity level. The second part of the paper deals with the concept of risk-based design procedure, which is an iterative process based on different methods for seismic performance assessment of buildings. The proposed design procedure involves definition of the initial structure, which is then assessed in order to check whether the seismic risk is below the acceptable/tolerable level. However, since several or many iterations will be needed in order to fulfill the criteria of acceptable/tolerable risk it is foreseen that this step of the risk-based design procedure will be based on approximate procedures for seismic performance assessment. The next step of the proposed design procedure will utilize the nonlinear response history analysis, which would be performed for few ground motions from a set of hazard-consistent ground motions. The risk-based design will be possible only by further development of comprehensive software for computational simulation. The paper is concluded with presenting pros and cons of the proposed design procedure. It is foreseen that, the risk-based seismic design of structures will represent a major step towards scientifically oriented design procedures employing high level of technology.*

1 INTRODUCTION

Earthquakes endanger built environment and consequently human lives more as it can be perceived in everyday life. For example, only the earthquake in Turkey (1999) caused more than eighteen thousand deaths [1] or in Haiti (2010), the earthquake caused estimated three hundred thousand deaths, displaced more than a million people, and damaged nearly half of all structures in the epicentral area [2]. 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 [3]. Although in Europe such great earthquake is not expected, the vulnerability of urban cities is not negligible. Recently, L'Aquila earthquake (2009) caused 308 losses of human lives [4], 1500 people were injured and 65000 homeless. Direct economic losses were around 4 billion Euros. Losses due to earthquakes in the last twenty years were observed also on the territory of Slovenia. The strongest earthquake in this period occurred on 12th of April 1998 in the upper Posočje region. This earthquake damaged over 4000 buildings. All these experiences from recent earthquakes around the world show that the risk of loss of life and property due to earthquakes is too high, if structures are not properly designed. This finding is not new although many societies associated earthquakes with mythological creatures and religion up to about 1755 Lisbon event [5], which produced profound change in the interpretation of the cause of earthquakes.

As mentioned above, the awareness of too high seismic risk in the case if structures are not properly designed has triggered development of regulatory documents for design of structures in seismic areas. Currently many different building codes and guidelines for earthquake-resistant design of structures exist, which were developed to reduce seismic risk, but due to the complexity of the problem they still involve many simplifications and assumptions. However, the first generation of Performance-based Earthquake Engineering (PBEE) procedures was implemented already in regulatory guidelines and standards such as ATC-40 [6], FEMA 273 [7], ACI 318-11 [8], Eurocode 8 [9], and others. Those regulatory documents were developed to reduce seismic risk, but building codes often prescribe the capacity design procedure for a given design earthquake. 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. However, comprehensive methodologies for probabilistic performance assessment of buildings exists (e.g. [10]), but its use in design phase of building is limited.

One component of the next-generation performance-based seismic design procedures should involve assessment of seismic risk, which is an essential ingredient of risk-informed management decisions [11], but it is still insufficiently communicated between structural engineers and facility stakeholders. The major contribution to the development of the new methodology has been made in the PEER Center [12]. The methodology is probabilistic and permits consistent characterization of the inherent uncertainties throughout the process. There are many variants of the PEER methodology. Probably the simplest closed-form solution for seismic risk assessment, expressed in terms of the mean annual frequency of exceeding a given limit state, was proposed by Cornell [13]. This approach was later further developed [14] by incorporating the epistemic uncertainties through a confidence level approach, which is one of the two approaches discussed elsewhere (e.g. [15,16]). However, recent studies have shown that a more general treatment of the epistemic uncertainty increases dispersion, but also affects the median seismic response parameters (e.g. [15, 17, 18]). Since seismic risk assessment is a complex problem, several simplified procedures have been proposed (e.g. [19, 20]), which could be used in the iterative process of design.

However, the final goal of earthquake engineering research community is that the structural performance will be assessed by using nonlinear response history analysis. Such an approach requires definition of an appropriate set of ground motions, as discussed by Evangelos et al. [21]. The most basic procedures for selection of records involve criteria associated with the earthquake magnitude and distance of the rupture zone from the location of the building of the interest. However, these procedures were not found to be very efficient in terms of nonlinear response of structure [22]. Thus selection of ground motion records based on magnitude and distance is often enhanced by spectral matching. A conservative version of this approach is adopted in the codes for seismic-resistant design of buildings, e.g. in Eurocode 8 [9], which prescribes that the uniform hazard spectrum should be used as a target spectrum. Baker [23] proposed an alternative target spectrum, termed a conditional mean spectrum (CMS). He showed that structural responses from ground motions matching the more probabilistically consistent conditional mean spectrum are significantly smaller than the response from ground motion matching the uniform hazard spectrum. However, Bradley [24] identified limitation of the CMS approach and proposed a generalized conditional intensity measure approach (GCIM) that allows determination of the conditional distribution of any arbitrary ground-motion intensity measure. All these methods do not address the issue of number of records required for sufficiently accurate prediction of seismic response of a structure. This issue was partly solved by introducing precedence list of ground motion records, which was firstly used for progressive incremental dynamic analysis (PIDA) [25].

Development of nonlinear methods of analysis and powerful software for simulation of seismic response of structures (e.g. [26]) offered a possibility to overcome shortcomings of the standards for earthquake resistant design of structures. Recently, Slovenian Research Agency approved three-year project entitled Design of structures for tolerable seismic risk using non-linear methods of analysis. 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 a brief overview of the project proposal with an emphasis on design procedure for collapse safety, which is one of the fundamental requirements of standards for earthquake-resistant design of structures.

Firstly, the shortcomings of current practice for earthquake-resistant design are addressed, followed by an overview of the nonlinear methods for seismic performance assessment of buildings. An emphasis is given on the envelope-based pushover analysis procedure [27], which was recently developed, and assumes that the seismic demand for each response parameter is controlled by a predominant system failure mode that may vary according to the ground motion and intensity level. The concept of the risk-based design procedure as foreseen in the project is then explained. The paper concludes with addressing pros and cons of the proposed procedure with an emphasis on underdeveloped components of the proposed risk-based design procedure.

2 CURRENT APPROACH FOR EARTHQUAKE-RESISTANT DESIGN OF BUILDINGS

Standard for earthquake resistant design of structures (Eurocode 8) [9] prescribes that structures are sufficiently designed if they are capable to withstand a design seismic action, which is defined for an 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 current standards for earthquake-resistant design of buildings do not control seismic risk to such an extent that would be acceptable for all types of structures and for all stakeholders.

A study which addresses the factors of safety in design of reinforced concrete frames using Eurocode 8 is presented in this conference [28]. The objective of the study was to show how different safety measures contribute to global parameters of structure, such as yield strength, 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, or the return period of the near-collapse limit state ($T_{R,NC}$). For this purpose the code-conforming buildings were analyzed on the basis of the pushover analysis. The requirements of Eurocode 2 and 8 were gradually taken into account, whereas the design assumptions 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 minimum requirements for dimensions and reinforcement of structural elements according to Eurocode 8, 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. More details regarding the variants of the building and the assessment procedure are given elsewhere [28]. However, interesting results were obtained. For the 11-storey building located in the region with moderate seismicity and designed for ductility class medium it was shown that the seismic action has the major impact on the yield strength of code-conforming building and on the peak ground acceleration causing near collapse limit state, whereas its contribution to the return period of the near collapse limit state is only minor. Furthermore, the capacity design principles practically did not contribute to any of structural parameter or to performance parameters, but their implementation in design process requires a lot of labour. Based on this study it can be concluded that partial safety factors of strength of material contributed around 50% to overall structural safety, whereas the factors corresponding to redundancy, minimum requirements of Eurocode 2 and 8, partial safety factors of material strength and the ratio between the actual and required reinforcement contributed 90% to overall safety of the building (see Figure 7 in [28]). Therefore it is argued that it would be better to make 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, the above-described argument is only one of a series of arguments which lean towards the risk-based or performance-based design procedures. According to FEMA P-58 [10] 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 stakeholders that is more meaningful and useful for decision-making purpose. This issue can be solved by adequate estimation of seismic risk in the design process of a building, which would probably be the best approach for mitigation of earthquake losses in the future. However, such approach requires use of nonlinear methods in the process of design.

3 OVERVIEW OF NONLINEAR METHODS FOR SEISMIC PERFORMANCE ASSESSMENT

Nonlinear analysis is basically classified in static and response history (dynamic) analysis. In the case of static analysis, the equilibrium equations are independent of time, which does not allow sufficient simulation of seismic response of a building. From a theoretical point of view this issue was solved by introducing the nonlinear response history analysis, which is capable of simulating the damage in the structure and the dynamic effects, which are important in the case of earthquake actions on a structure. Therefore the nonlinear response history analysis is the most advanced analysis for the simulation of structural response under seismic action. However, when the seismic performance assessment of a building is performed on the basis of nonlinear response history analysis, several issues have to be adequately considered. Firstly, the response history analysis is computationally extremely demanding. For this reason alone it is necessary to use simplified nonlinear models of structural elements, which are partly based on the empirical evidence. Furthermore, use of response history analysis requires hazard-consistent selection of ground motion, (e.g. [23, 24]), which is in itself quite complex procedure, selection of damping model as well as the numerical integration scheme of the equations of motion. All these ingredients of the response history analysis have impact on the analysis results and consequently affect the final design. Additionally, response history analysis of complex structural systems often becomes the subject of numerical non-convergence. For a practical application of response history analysis in the design process it is therefore necessary to develop appropriate software tools, guidelines for determination of structural models, procedures for selection of ground motions and methods which would enable predicting structural response with sufficient accuracy using only a small number of ground motions.

Due to the above-mentioned reasons it is foreseen that the nonlinear response history can be used only in final step of the risk-based design process, since seismic design based on nonlinear analysis requires iterations. The pushover-based methods could be used in the intermediate step of the design. Over the last two decades, the pushover-based methods become popular among both researchers and engineers, but these methods have several limitations. Many different procedures have been developed [29-35]. For brevity, the detailed description of these pushover-based methods is omitted in this paper. However, an overview of recently introduced envelope-based pushover analysis procedure [27] is given in the following subsection. This procedure involves nonlinear response history analysis for equivalent single-degree-of-freedom models, which correspond to pushover analyses based on invariant force vectors associated with the first three vibration modes. A new feature of the envelope-based pushover analysis procedure is the use of so-called failure-based SDOF models, which are capable of predicting approximate seismic response of buildings in the case if ground motions cause system failure modes which are significantly different to that observed for 'first-mode' pushover analysis.

3.1 Background and overview of envelope-based pushover analysis procedure

The variation of system failure modes, observed in the response history analysis, can be quite large due to the ground-motion randomness. Some ground motions would cause the system failure mode which is very similar to that corresponding to the 'first-mode' pushover analysis. In this case the basic-pushover based methods would provide sufficiently accurate estimate of collapse fragility. However, for some ground motions from a set, the system failure modes observed in the response history analysis cannot be simulated by the 'first-mode' pushover analysis. For this reason, the modal-based SDOF model becomes inaccurate in order to estimate the collapse fragility [27]. This awareness is not new. A similar conclusion was made by Bobadilla and Chopra [36] when evaluating the ability of the MPA procedure to estimate the seismic demands of reinforced concrete frame buildings. They concluded that the 'first-mode' SDOF models can estimate the median roof displacement to a useful degree of accuracy, whereas this may not be true in the case when the roof displacement is estimated for an individual ground motion. This inability of the modal-based SDOF model motivated Brozovič and Dolšek [27] to perform a detailed study in order to better understand when the 'first-mode' SDOF model provides inaccurate estimates of global response of structures. They came to an interesting conclusion, that for particular ground motions, the 'first-mode' SDOF model always provides sufficiently accurate estimate of global response of buildings regardless how tall the building is, whereas for some other ground motions, the response of buildings based on the ‘first-mode’ SDOF model cannot be simulated with useful degree of accuracy even for buildings having only four stories. Based on this finding, Brozovič and Dolšek proposed envelope-based pushover analysis procedure which involves so-called failure-based SDOF models [27]. The failure-based SDOF models utilize the displacement vectors corresponding to the system failure modes of the ‘second-mode’ and ‘third-mode’ pushover curves. This is the only difference in definition of the failure-based SDOF models and the modal-based SDOF models. Consequently the seismic demand given ground-motion intensity is greater in the case of failure-based SDOF model in comparison to corresponding modal-based SDOF model. This makes the failure based SDOF models capable of predicting the global response of structure with sufficient accuracy for the case when the ‘first-mode’ SDOF model provides inaccurate estimates.

The envelope-based pushover analysis procedure as introduced in [27] involves following steps:

1) **Pushover analyses:** perform pushover analyses for first, second and third mode distributions of lateral forces. This step is the same as in the case of the modal pushover analysis procedure [30].
2) **Equivalent SDOF models:** define modal-based SDOF model corresponding to idealized force-displacement relationship of the ‘first-mode’ pushover curve and the failure-based SDOF models corresponding to the idealized force-displacement relationships of the ‘second-mode’ and ‘third-mode’ pushover curves. Definition of the equivalent SDOF models is consistent with the N2 method [29]. However, the effective mass, period and the transformation factor of the failure-based SDOF model are calculated by using the displacement vectors corresponding to the system failure modes as defined elsewhere [27].
3) **Seismic demand for equivalent SDOF model:** perform nonlinear response history analysis for the modal-based and failure-based SDOF models.
4) **Seismic demand at structural level:** calculate the target displacement for each SDOF model and ground motion by multiplying the displacement demand of the SDOF model times the corresponding transformation factor. This step is the same as in the case of the N2 method [29], but it is performed for three SDOF models instead of one. Obtain the total seismic demand for each response parameter and for a particular ground motion by enveloping results associated with the target displacement and corresponding pushover analysis.

The envelope-based pushover analysis procedure therefore assumes that each response parameter is controlled by the predominant system failure mode caused by a ground motion. Brozovič and Dolšek [27] have shown that the envelope-based pushover analysis procedure enables sufficiently accurate prediction of collapse fragility parameters even for taller buildings, which may collapse in several different modes. Since the procedure is not computationally demanding, it can be used in the concept of risk-based design procedure, which is described in the following Section.

4 CONCEPT OF RISK-BASED SEISMIC DESIGN

The proposed design procedure is decomposed in several steps as presented in the flowchart (Figure 1). Firstly, the initial structure has to be defined. It is foreseen that the good approximation of final design could 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. However, 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 basic dimensions of their cross sections, or eventually by designing the building using software which supports current building codes.

The second step of the proposed design procedure is quite important since it involves determination of the nonlinear structural model. Since the results of performance assessment of structures are highly sensitive to the features of the nonlinear structural model, several guidelines will be needed in order to help the analyst to construct a simple yet sufficiently accurate nonlinear model of structure. Simplified nonlinear models could be used since it is sufficient that the models will be capable of simulating the most important system failure modes. The non-simulated failure modes, such as shear failure of structural elements and joints, could be designed on the basis of demand hazard analysis in order to prevent such failures in the case of great earthquakes and in order to guarantee that the simplified nonlinear model provides sufficiently accurate results.

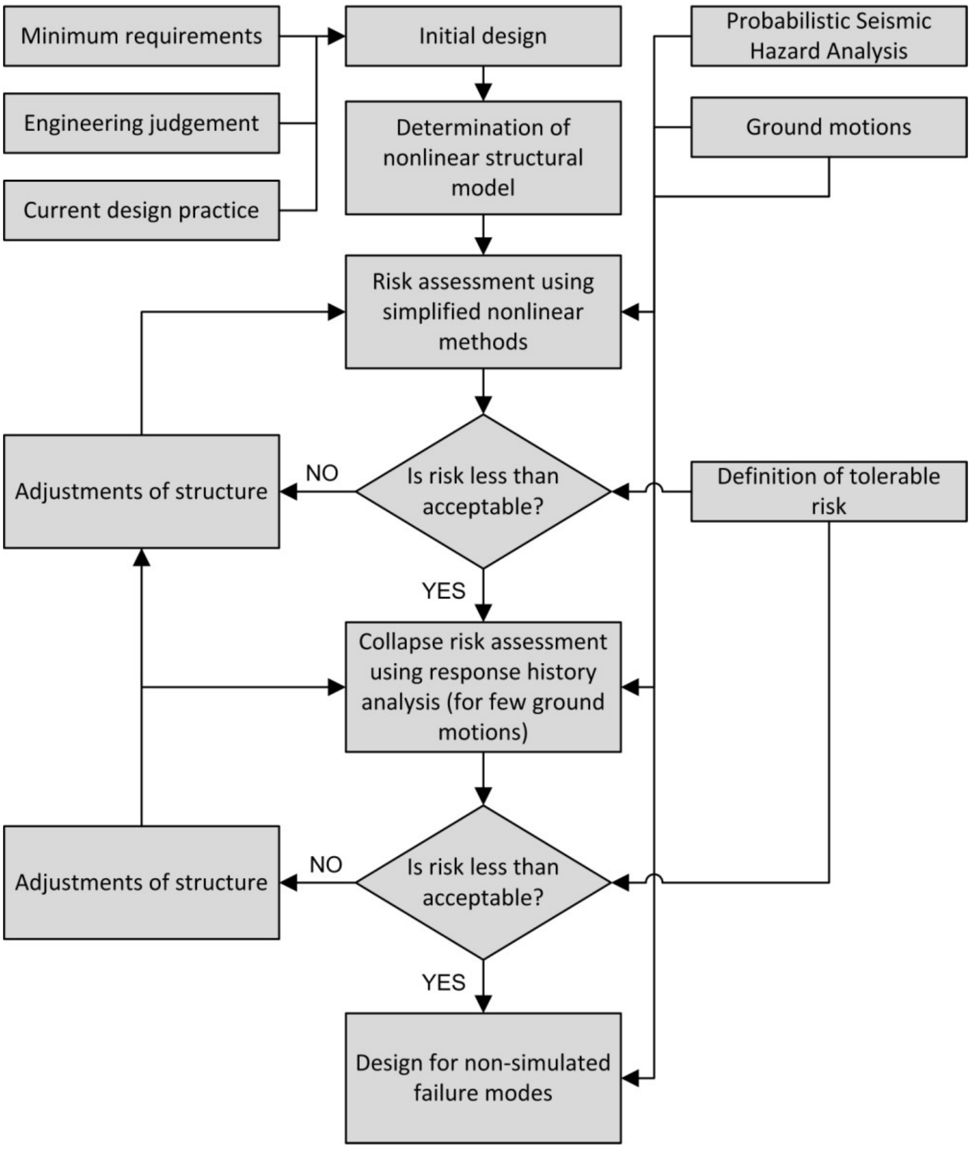

Figure 1: Flowchart of the proposed risk-based seismic design of buildings.

The simplified nonlinear model will be used for risk assessment of the initial structure. This is the third step of the proposed procedure, which requires additional information. 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 the simplified nonlinear method will be used, since this type of method is not computationally demanding. In the case if envelope-based pushover analysis procedure (Section 3.1) will be used, a set of hazard-consistent ground motions will be needed. Based on results of EPA, ground motions could be further selected in order to be used later on for checking the adequacy of final design on the basis of response history analysis. However, an important ingredient of the proposed design procedure, which is important for decision-making, is the model of acceptable/tolerable risk. 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 in [37].

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 methods, 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. Such guidelines could be developed using the results of a sensitivity analysis for different types of structures aiming to assess which parameters of structural configuration has the greatest impact on the global seismic response parameters and consequently on seismic risk. In this step of the proposed design procedure the creative work of the designer will be encouraged, since this iterative design process will offer excellent insight into the nonlinear response for different structural variants of the building. Such approach will enable most effective decisions regarding the design adjustments which would eventually optimally increase the strength and ductility of the building.

Once the final structure will be obtained on the basis of the iterative design process, it is foreseen that the final design will be checked by performing response history analysis for few ground motions (Step 5), which will be carefully selected using the results of the envelope-based pushover analysis. The Step 5 of the design procedure will be performed in combination with the Step 6 in order to increase the utilization rate in the case if some parts of the building will be 'over-designed' or to check the accuracy of the simplified nonlinear methods used in the previous step. However, Step 6 is intended to provide demand for those components, which will not be simulated with the simplified nonlinear model. Based on this demand, the non-simulated failure modes, such as shear failure of structural elements or joints, will be prevented with a reasonably low exceedance rate.

Although the proposed procedure is in the initial stage of development, it was preliminary used to design an eight-storey reinforced concrete frame building. For an interested reader, detailed description of this illustrative example is given in paper No. 1249, which is also presented in this conference [37].

5 PROS AND CONS OF THE PROPOSED PROCEDURE AND FUTURE DEVELOPMENT

The main advantage of the proposed risk-based seismic design procedure is that it involves use of variety of nonlinear analysis methods, which enable predicting actual building response and seismic risk. Therefore the analyst will get insight into the redistribution of internal forces in building, better information regarding the critical building's parts, which can suffer the most severe damage in the case of major earthquakes, and an excellent understanding how different structural adjustments affect seismic performance of the building. Additionally, the results of the design will be expressed in terms of probability. However, such approach will offer alternative ways of communicating performance to stakeholders that is more meaningful and useful for decision-making purpose, which is one of the shortcomings of current building codes [10].

However, design of structures for acceptable seismic risk requires information, which are highly uncertain (seismic hazard, nonlinear model, simplified nonlinear analyses, response history analysis, ground motions) and subjective (acceptable risk). Uncertainties should be appropriately taken into account. Therefore the treatment of uncertainties represents a disadvantage of the proposed concept of design in comparison to that incorporated in current building codes. Additionally, the risk-based design of realistic buildings is possible by using specific and powerful software and hardware. Therefore, algorithms and software tools aimed at facilitating the design process will have to be developed in the framework of the proposed research.

6 CONCLUSIONS

The concept of the iterative design procedure for acceptable/tolerable risk is presented in this paper. The proposed procedure is in the development stage within the basic research project Design of structures for tolerable seismic risk using non-linear methods of analysis, which is supported by the Slovenian Research Agency. The main objective of the proposed project 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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REFERENCES

[1] P.G. Bakir, H.M. Boduroglu. Earthquake Risk and Hazard Mitigation in Turkey. *Earthquake Spectra*, **18**(3), 427-447, 2002.

[2] R. DesRoches, M. Comerio, M. Eberhard, W. Mooney, G.J. Rix. Overview of the 2010 Haiti Earthquake. *Earthquake Spectra*, **27**(S1):1-21, 2011.

[3] K. Goda, A. Pomonis, S.C. Chian, M. Offord, K. Saito, P. Sammonds, S. Fraser, A. Raby, J. Macabuag. Ground motion characteristics and shaking damage of the 11th March 2011 Mw9.0 Great East Japan earthquake. *Bull Earthquake Eng*, **11**, 141–170, 2013.

[4] D. D'Ayala, M. Dolce. Guest editorial: L'Aquila earthquake: seismic sequence of the 6th April 2009, Abruzzo, Italy. *Bull Earthquake Eng*, **9**, 1-10, 2011.

[5] Severn R.T. (2012). Understanding earthquakes: from myth to science. *Bulletin of Earthquake Engineering*, **10**, 361-366.

[6] ATC. Seismic Evaluation and Retrofit of Concrete Buildings (ATC-40), Applied Technology Council, Redwood City, California, 1996.

[7] FEMA. NEHRP guidelines for the seismic rehabilitation of buildings (FEMA publication 273),Washington, DC, 1997.

[8] Amer. Conc. Inst. (ACI). Building code requirements for structural concrete and commentary. ACI 318-11, Farmington Hills, MI, 2011.

[9] CEN. Eurocode 8: design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings, 2004.

[10] FEMA. Seismic Performance Assessment of Buildings Volume 1- Methodology, FEMA P-58/Pre-Release, Federal Emergency Management Agency, August 2012.

[11] B.R. Ellingwood. Risk-informed condition assessment of civil infrastructure: state of practice and research, *Struct. and Infrastruct. E.*, **1**(1), 7-18, 2005.

[12] G. Deierlein. Overview of a comprehensive framework for earthquake performance assessment, Performance-Based Seismic Design – Concepts and Implementation, Fajfar P., Krawinkler H. eds., PEER Report 2004/05:15-26, Berkeley, 2004.

[13] C.A. Cornell. Calculating building seismic performance reliability, a basis for multi-level design norms. *Proc. of the 11th WCEE*, P.No. 2122, 1996.

[14] C.A. Cornell, F. Jalayar, R.O. Hamburger, D.A. Foutch. Probabilistic basis for 2000 SAC Federal Emergency Management Agency Steel Moment Frame Guidelines. *J. of Struct. Eng.* (ASCE), **128**(4), 526–533, 2002.

[15] A.B. Liel, C.B. Haselton, G.G. Deierlein, J.W. Baker. Incorporating modeling uncertainties in the assessment of seismic collapse risk of buildings. *Structural Safety*, **31**, 197-211, 2009.

[16] F. Zareian, H. Krawinkler, L. Ibarra, D. Lignos. Basic concepts and performance measures in prediction of collapse of buildings under earthquake ground motions. *The struc. design of tall and special build.*, **19**(1-2), 167-181, 2010.

[17] Dolšek M. Incremental dynamic analysis with consideration of modeling uncertainties. *Earthquake Engineering and Structural Dynamics*, **38**(6), 805–825, 2009.

[18] D. Vamvatsikos, M. Fragiadakis. Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty. *Earthquake Engineering and Structural Dynamics*, **39**, 141–163, 2010.

[19] M. Dolšek. Simplified method for seismic risk assessment of buildings with consideration of aleatory and epistemic uncertainty. *Struc. and I. Eng.*, **8**(1), 1-25, 2012.

[20] P. Fajfar, M. Dolšek. A practice-oriented estimation of the failure probability of building structures. *Earth. Eng. Struct. Dyn.*, **41**(3), 531-547, 2012.

[21] I. Evangelos, I. Katsanos, A.G. Sextos, G.D. Manolis. Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective. *Soil Dynamics and Earthquake Engineering*, **30**(4), 157-169, 2010.

[22] I. Iervolino, C.A. Cornell. Record selection for nonlinear seismic analysis of structures. *Earthquake Spectra*, **21(**3), 685-713, 2005.

[23] J.W. Baker. Conditional mean spectrum: Tool for ground-motion selection. *Journal of Structural Engineering*, **137**(3), 322-331, 2011.

[24] B.A. Bradley. A generalized conditional intensity measure approach and holistic ground-motion selection. *Earth. Eng. Struct. Dyn.*, **39**, 1321-1342, 2010.

[25] A. Azarbakht, M. Dolšek. Progressive incremental dynamic analysis for first-mode dominated structures. *Journal of Structural Engineering* **137**(3), 445-455, 2011.

[26] OpenSees. Open system for earthquake engineering simulation, PEER Center, Univ. of California, Berkeley, http://opensees.berkeley.edu/, 2012.

[27] M. Brozovič, M. Dolšek. Envelope-based pushover analysis procedure for the approximate seismic response analysis of buildings. *Submitted to Earthquake Engineering & Structural Dynamics* (in review), 2013.

[28] J. Žižmond, M. Dolšek. Deaggregation of seismic safety in the design of reinforced concrete buildings using Eurocode 8. 4th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2013, Paper No. 1226, 2013.

[29] P. Fajfar. A nonlinear analysis method for performance-based seismic design. *Earthquake Spectra*, **16**, 573-592, 2000.

[30] A.K. Chopra, R.K. Goel. A modal pushover analysis for estimating seismic demands for buildings. *Earthquake Engineering and Structural Dynamics*, **31**, 561-582, 2002.

[31] M.N. Aydinoğlu. An incremental response spectrum analysis based on inelastic spectral displacement for multi-mode seismic performance evaluation. *Bulletin of Earthquake Engineering*, **1**, 3-36, 2003.

[32] S. Antoniou, R. Pinho. Development and verification of a displacement-based adaptive pushover procedure. *Journal of Earthquake Engineering*, **8**, 643-661, 2004.

[33] H. Sucuoğlu, M.S. Günay. Generalized force vectors for multi-mode pushover analysis. *Earthquake Engineering and Structural Dynamics*, **40**(1), 55-74, 2011.

[34] C.J. Reyes, A.K. Chopra. Three-dimensional modal pushover analysis of buildings subjected to two components of ground motion, including its evaluation for tall buildings. *Earthquake Engineering and Structural Dynamics*, **40**(7), 789–806, 2011.

[35] M. Kreslin, P. Fajfar. The extended N2 method taking into account higher mode effects in elevation. *Earthquake Engineering and Structural Dynamics*, **40**(14), 1571–1589, 2011.

[36] H. Bobadilla, A.K. Chopra. Evaluation of the MPA procedure for estimating seismic demands: RC-SMRF buildings. *Earthquake Spectra*, **24**(4), 827-845, 2008.

[37] N. Lazar, M. Dolšek. Application of the risk-based seismic design of buildings using nonlinear methods of analysis. 4th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2013, Paper No. 1226, 2013.