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A simplified risk-targeted decision model for the verification of the seismic performance of critical infrastructure components to the operational limit state

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ABSTRACT

A simplified risk-targeted decision model for the verification of the seismic performance of infrastructure components to the operational limit state is presented. It assumes linearity between the intensity measure and the engineering demand parameter and requires the evaluation of the displacement demand for a hazard-targeted design earthquake and of the displacement capacity. The latter is defined as the ratio between the operational limit-state displacement and a risk-targeted safety factor, which depends on the seismicity of the relevant location, on the randomness of the intensity measures causing the operational limit-state, and on the acceptable (target) probability of exceeding this limit state. In the paper, the theoretical background of risk-targeted safety factor is first explained, followed by a discussion on the sensitivity of the risk-targeted safety factor to the input parameters. The design procedure involving the simplified risk-targeted decision model is then introduced and demonstrated by means of an example of a simple pipe rack located at a petrochemical plant. Within the scope of the presented example, the operational limit-state displacement of the pipe rack is estimated on the basis of the limit-state strains of a pipe attached to the frame. The risk-targeted safety factor is then evaluated, and the frame is designed. It is shown that the application of the proposed procedure is straightforward once the operational limit-state displacement has been determined. The advantage of the procedure is that the target risk is accounted for by the risk-targeted safety factor, which can be calculated with respect to the importance of the equipment of the critical infrastructure. Additionally, the proposed decision model can be easily adopted by engineers, because the seismic demand is calculated by analogy to the Eurocode. However, at this stage of the research, the application of the proposed decision model is limited to structures that do not exhibit any significant nonlinear seismic response at the operational limit state, and to structures where the equal displacement rule applies.

1. Introduction

Structures in seismic regions have to be designed in such a way that the requirements of no-collapse and damage limitation are met (e.g. [1]). However, in the case of critical infrastructures, several other limit states may be recognized. Guidelines for seismic design and qualification for Nuclear Power plants, as discussed in [2], and several standards for the seismic design of process plants (e.g. [3,4]), take into account the verification of the performance of plants for the Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE). It is required that the plant remains fully operational immediately after the OBE, which means that the equipment of the plant remains substantially elastic without any damage. In the case of SSE, the specific components important for nuclear safety must be designed to remain functional, but the other compontents may suffer some damage, provided that the safe shutdown of the plant is ensured. In addition, another performance objective in the case of petrochemical plants is that the loss of the hazardous material stored in the critical components of the plant has to be prevented, because the release of hazardous material can result in disastrous consequences not only for the plant itself but also for everyone living in its close vicinity [5–7]. If the components of the industrial facilities are not designed adequately, the consequences can be severe, such as quite frequently reported after some past earthquakes [8,9]. For these reasons, components of the critical infrastructures should, in general, be verified for several limit states.

In conventional earthquake-resistant design, the limit states are verified by considering the seismic demand corresponding to a design earthquake, which is characterized by a designated occurrence rate

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(e.g. [1,10,11]). Such an approach is intuitive and familiar to engineers, but the performance of the infrastructure is verified only for the seismic design intensity, whereas the effects of other earthquakes that may occur during the lifetime of the infrastructure are neglected. Being aware of this issue, regulators in several European countries tried to increase the level of safety in seismic design by increasing the occurrence rate that characterizes the design earthquakes [12]. However, the issue was overcome by introducing a risk-targeted decision model [13]. In the SAC/FEMA approach [13], the seismic demand and capacity are defined by engineering demand parameter (EDP). The seismic demand is risk-dependent, and the decision model considers safety factors in the demand and the capacity side of the decision model. In practice, the application of EDP-based approach is quite challenging, as discussed elsewhere [14]. Alternatively, the seismic demand and the capacity can be expressed by the intensity measure (IM). The IM-based probabilistic formats [15–18] were developed prior to the EDP-based probabilistic format [13,15], but their application is more practical, although the seismic demand in the case of the IM-based probabilistic format [15] is still risk-dependent.

Later on, many variants of seismic design procedures with the consideration of risk metrics were introduced [19–28]. These design procedures can be iterative, based on nonlinear response history analysis, or non-iterative using linear elastic analysis. However, the introduction of quantitative risk-based design is a very challenging task, because the procedure is computationally extremely demanding, especially in the case of a complex infrastructural system. For practical applications, simplifications are needed. One possibility, which was implemented in the building codes in the USA [27], involves replacing uniform hazard maps with risk-targeted hazard maps, which were introduced by Luco et al. [29]. Pilot studies addressing risk-targeted hazard maps for mainland France [30] and for Europe [31] were also performed. However, the seismic design action based on risk-targeted design maps is also risk-dependent. An alternative is to consider decision models where the seismic demand is independent of seismic risk, while the risk is controlled by the risk-targeted safety factor, which is the only safety factor applied at the capacity side of the decision model. The risk-targeted safety factor can be used in conjunction with nonlinear analysis [14] or with force-based design in order to quantify a risk-targeted reduction factor [28].

In this paper, an attempt has been made to introduce a simplified risk-targeted decision model for the verification of the seismic performance of a structure to the operational limit state. The decision model is applied to the verification of the structure, whereas the capacity of the structure is defined on the basis of the exceedance of the operational limit state in the critical equipment belonging to the structure. The simplified risk-targeted decision model is intentionally derived with consideration of Eurocode's decision model, which is familiar to engineering practitioners and which is not based on risk-dependent seismic design action. This means that the seismic demand is related to a certain design earthquake. The displacement capacity is obtained by dividing the operational-limit-state displacement by the risk-targeted safety factor, which is derived by taking into account the target (acceptable) probability for the loss of operation of the critical component of the infrastructure. The risk-targeted safety factor is the only safety factor and is applied on the capacity side, whereas the seismic response analysis of the structure is consistent with Eurocode's approach that is familiar to engineers. It should be emphasized that the proposed decision model is intentionally introduced in a form which is similar to the form of the decision model for the verification of damage limitation in [1], which accounts for the deformation of a structure in order to prevent the exceedance of the damage limitation limit state.

In the paper, the simplified risk-targeted decision model for the verification of the operational limit state is first presented. A risk-targeted safety factor is introduced for the verification of the performance of the structure in order to guarantee the operation of critical equipment with a predefined target (acceptable) probability of exceedance. The theoretical background for the evaluation of this risk-targeted safety factor, which involves the estimation of the spectral acceleration causing the operational limit state for a target probability of exceedance, is also explained. An expression for the definition of such a risk-targeted safety factor in closed form is derived as well. In the second part of the paper, the design procedure, which includes the proposed risk-targeted decision model for the verification of the operational limit state, is explained. An application is demonstrated by means of an example of the design of a frame belonging to a pipe rack of the type typically used in petrochemical plants. Some insights into the modelling of piping systems, which is used to estimate the operational limit-state displacement, are also presented.

2. The simplified risk-targeted decision model for the verification of operational limit state

2.1. Definition of the simplified risk-targeted decision model

The introduced risk-targeted decision model for the verification of the seismic performance of a structure to the operational limit state is derived from the decision model for the verification of damage limitation limit state exceedance of Eurocode 8 [1]:

$$d_r \nu \leqslant \alpha h \tag{1}$$

where d_r is the interstorey drift, h is the storey height, ν is a reduction factor which takes into account a shorter return period of the seismic action associated with the damage limitation requirement (it usually has a value equal to 0.4 or 0.5), and α is the proportion of the storey height associated with the displacement causing the damage limitation limit state.

The Eurocode's decision model for the verification of the damage limitation limit state is well understood by engineers. The left hand part of the decision model (Eq. (1)) represents the demand, whereas the right hand part represents the capacity. The interstorey drift d_r is the effect of a design earthquake characterized by the basic return period associated to the verification of ultimate limit states (e.g. a return period of 475 years in the case of buildings of ordinary importance). The factor ν is approximately calibrated in such a way that the seismic demand $d_r\nu$ on the left hand side of Eq. (1) corresponds to a design earthquake with a lower return period, which is prescribed for the verification of the DL limit state (e.g. 95 years in the case of buildings of ordinary importance). Thus the determined demand should be less than the displacement capacity (i.e. the right hand side of Eq. (1)).

The decision model according to Eq. (1) may be understood as a hazard-targeted decision model, since the demand corresponds approximately to an earthquake with a designated return period. The model can be used to check that the seismic demand is less than the capacity, but only for the seismic intensity level corresponding to the selected return period of the design earthquake. The reliability of exceedance of the limit state is thus not known, but it is controlled by the selection of the return period of the design earthquake. However, specific ground motions can cause exceedance of the limit state even at an intensity lower than the intensity of the design earthquake. Additionally, earthquakes with a higher level of intensity can occur, but their effect is disregarded in the conventional decision model, which is hazard-targeted. These limitations of hazard-targeted decision models may be problematic in the case of critical components of the infrastructure (e.g. petrochemical plants), for which the exceedance of the operational limit state can trigger a loss of functionality and business interruption, which can result in large economic losses or even societal disasters.

For this reason, it could be advantageous to verify the seismic performance of structures using a risk-targeted decision model, which means that the performance objective is defined by the target (i.e. acceptable) risk of exceedance of the operational limit state (e.g. probability of exceedance of limit state for a period of one year) rather than

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