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The numerical computation of seismic fragility of base-isolated Nuclear Power Plants buildings

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HIGHLIGHTS

- Seismic fragility of structural components in base isolated NPP is computed.
- Dynamic integration, Response Surface, FORM and Monte Carlo Simulation are adopted.
- Refined approach for modeling the non-linearities behavior of isolators is proposed.
- Beyond-design conditions are addressed.
- The preliminary design of the isolated IRIS is the application of the procedure.

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ABSTRACT

The research work here described is devoted to the development of a numerical procedure for the computation of seismic fragilities for equipment and structural components in Nuclear Power Plants; in particular, reference is made, in the present paper, to the case of isolated buildings. The proposed procedure for fragility computation makes use of the Response Surface Methodology to model the influence of the random variables on the dynamic response. To account for stochastic loading, the latter is computed by means of a simulation procedure. Given the Response Surface, the Monte Carlo method is used to compute the failure probability. The procedure is here applied to the preliminary design of the Nuclear Power Plant reactor building within the International Reactor Innovative and Secure international project; the building is equipped with a base isolation system based on the introduction of High Damping Rubber Bearing elements showing a markedly non linear mechanical behavior. The fragility analysis is performed assuming that the isolation devices become the critical elements in terms of seismic risk and that, once base-isolation is introduced, the dynamic behavior of the building can be captured by low-dimensional numerical models.

1. Introduction

The introduction of isolation systems in the design of strategic buildings is likely to become, in the next future, a widespread seismic protection measure. In fact, the anticipated better performance, when compared to the one of traditional buildings, in terms of acceleration response to design seismic actions, makes isolation techniques a very attractive choice for buildings whose functionality after the event is of utmost importance.

Two American Society of Civil Engineers standards (ASCE, 2000, 2005) report on the analysis and design of Nuclear Power Plants (NPP). The former in particular includes rudimentary provisions for the analysis and design of seismic isolation systems. In its revised version under development, it will comprise new prescriptions on the mathematical models for the non linear behavior of the isolation system and the nuclear buildings, which will satisfy the risk-informed goals of ASCE/SEI 43-05 (Huang et al., 2012). Furthermore, instructions and recommendations for qualifying control devices for Nuclear Power Plants application are also expected.

Such design prospect is the typical case of reactor buildings in future Nuclear Power Plants, where the adoption of isolation systems seems to be almost mandatory if the frequency of earthquake-induced accident scenarios must drop to values of the order of E-08/ry to make the seismic risk of the same order of magnitude if compared to risk related to internal events (Carelli et al., 2004). In this respect, isolation systems based on High Damping Rubber Bearings (HDRB) represent an attractive design solution, given their diffusion and proven reliability; in (Forni et al., 2010;

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Bianchi et al., 2011a,b) the application of this solution to the Nuclear Steam Supply System (NSSS) building designed within the International Reactor Innovative and Secure (IRIS) international project (Carelli et al., 2004) is described and some preliminary results are given. These results show how the isolation system is extremely effective in reducing the horizontal seismic acceleration transmitted to all structural and equipment components inside the building, this resulting in significant advantages for the design and standardization of the equipment. It must be observed, however, that in such conditions the isolation devices themselves are prone to become the critical components in terms of seismic fragility, since the response attenuation is obtained as the result of large relative displacements between the building and the foundation. Therefore, the need arises to assess the risk associated to the failure of the isolators, this being obviously related to "beyond design" loading conditions. In addition, the impact of the isolated superstructure on surrounding buildings or geotechnical structures is a critical aspect as well to be considered in the base isolated NPP configuration.

When the problem of risk evaluation is addressed, the fundamental role played by the hazard definition in the estimation of the seismic-induced CDF is immediately evident; both randomness and uncertainty, however, significantly affect also the evaluation of structural behavior under extreme loads and thus of seismic reliability. Though randomness cannot be avoided, since is inherent to most of the input data of the analysis, uncertainties, being related to the lack of complete and accurate knowledge about models and methods, must be reduced as much as possible by refining analysis procedures.

In light of the above considerations, the research activity described in the present paper is devoted to the probabilistic evaluation of the seismic performance of a NPP reactor building encompassing passive seismic isolation. An innovative procedure for fragility estimation (De Grandis et al., 2009) will be summarized in the next section focusing on the isolated case; in the following, the criteria adopted for a refined mechanical modeling of the nonlinear behavior of the isolators will be described. An example of application to a real life case will be finally shown.

2. The fragility analysis of NPP components

Starting from the 80s the seismic fragility of NPP components has been computed by means of the simplified but well consolidated procedure by Kennedy and co-workers (Kennedy et al., 1980; Kennedy and Ravindra, 1984), based on the structural performance at the SSE (Safe Shutdown Earthquake) and on the estimation of actual vulnerability by the introduction of a set of safety coefficients. Each coefficient accounts for both the randomness and/or uncertainty related to a particular aspect or parameter of the analysis and for its influence on the seismic performance; all coefficients are assumed to follow a lognormal distribution whose properties are defined by engineering judgment, experience and previous parametric studies.

Aim of the research here described is to develop a more sophisticated procedure, able to eliminate part of the uncertainties and thus of the conservatism which is inherent to the traditional methods, especially in the way the actual dynamic behavior of the building structure and the effect of random aspects/parameters are accounted for.

The proposed procedure (De Grandis et al., 2009) is based on classical methods of structural reliability analysis, as applied to systems with low-dimensionality, i.e. a limited number of random variables. In fact, as discussed in (De Grandis et al., 2009), the number of random aspects usually introduced in the fragility analysis of NPPs is of the order of 5–10 (ASCE, 2000 – Section A3.1, Table A1 "Parameters Considered in Fragility Analysis"). Even though each of these aspects (e.g. structural stiffness) should be described, in principle, by a large number of random variables (RVs), actually describing a stochastic field, we must consider that, if no local effect is of concern, the adoption, for each aspect, of a single RV representing a (spatial) average can be justified.

2.1. General formulation

Following the PEER (Pacific Earthquake Engineering Research) approach (Cornell and Krawinkler, 2000; Der Kiureghian, 2005), the annual failure rate for a mechanical component under seismic loading can be obtained from the integral:

$$P_f = \iint P\{DM > dm_f | EDP = edp\} p_{EDP} \times (edp|IM = im) p_{IM}(im) d(edp) d(im) \tag{1}$$

where DM is a Damage Measure, associated to the assumed limit state (dm_f denotes the damage level at failure), EDP is an Engineering Demand Parameter (support acceleration, relative displacement,...) expressing the level of the dynamic excitation imposed to the component due to the global seismic response of the structure (reactor building) and IM is an Intensity Measure (peak ground acceleration, spectral acceleration,...) characterizing the severity of the earthquake motion at the reactor site. As pointed out in (Der Kiureghian, 2005) all statistics in (1) must be intended in term of annual extreme values, so that the equation delivers a risk estimate in terms of annual probability of failure of the component.

In many practical cases the limit state can be directly defined in terms of the EDP value at failure edp_f, thus avoiding, or performing it at a different stage, the damage analysis step, i.e.:

$$P_f = \int P\{EDP > edp_f | IM = im\} p_{IM}(im) d(im) \tag{2}$$

where the integrand function can be written in terms of the following fragility function:

$$F(edp_f, im) = P\{EDP > edp_f | IM = im\} \tag{3}$$

When a traditional non-isolated building is considered a typical choice for edp within the above context is represented by the peak acceleration at the support point of critical equipment components; in this light, in (De Grandis et al., 2009) a numerical procedure for evaluating the seismic fragility was developed focusing on the cases in which linearity can be assumed for the building structural system. If a base-isolation system based on HDRB (High Damping Rubber Bearings) is introduced (see for example Forni et al., 2010) the acceleration values inside the building undergo a dramatic decrease. This is obtained at the price of significant relative displacements imposed to isolation devices, which are likely to become the "weakest link" in terms of seismic safety of the building; therefore the extreme value u of the relative displacement across the most strained isolator is a quite obvious first choice for the edp. The fragility function is thus expressed as:

$$F(edp_f, im) = P\{U > U_f | A_g = a_g\} = P_{exc}(U_f, a_g) \tag{4}$$

For a system under stochastic dynamic excitation, the associated limit state function can be expressed in the following "capacity minus demand" format:

$$g(\mathbf{X}, U, a_g) = C - D(\mathbf{X}, a_g) = U_f - U(\mathbf{X}, a_g) = 0 \tag{5}$$

In (5) U is the extreme value of relative displacement, i.e. a random variable whose distribution delivers, for fixed $\mathbf{X}$, the result of the random vibration analysis, while U_f is the relative displacement leading to failure of the most strained isolator. Note that U_f can be defined either as a deterministic or a random parameter.