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Simplified probabilistic seismic assessment of RC frames with added viscous dampers

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ABSTRACT

The object of this paper is the study of simplified probabilistic procedures for the seismic assessment of nonlinear structures equipped with nonlinear fluid viscous dampers. The considered reference probabilistic approach is the SAC-FEMA method, which allows to obtain the probability of exceeding a given performance level. The specific purpose is to study the correlation between the results obtained through the probabilistic seismic assessment method for structures with and without dampers, with emphasis on these results in terms of dispersion. A wide set of recorded ground motions was therefore selected and applied to the considered RC frames. The study was performed without applying scaling factors to the earthquake records, but by selecting different sets of records for increasing values of seismic intensity. All the obtained results were examined considering different criteria, in order to determine the set of time-history analyses to be used for the probabilistic evaluation. Different methods were then applied to obtain the dispersion of the seismic demand. With reference to the application of the SAC-FEMA method, a sensitivity analysis was also performed, considering different procedures to interpolate the hazard curve. From the analyses, it was possible to derive the expressions that allow the results for structures with and without dampers to be correlated, as well as to offer suggestions for applying the SAC-FEMA method. A second purpose of the paper is to propose and apply, in the probabilistic assessment, a direct procedure. This procedure was recently presented by some of the authors as a method to be used for obtaining the response of nonlinear structures with nonlinear viscous dampers as an alternative to expensive nonlinear dynamic analyses.

1. Introduction

Over the past fifty years, a large part of research has been dedicated to earthquake-resistant systems developed to raise seismic performance levels while keeping construction costs within reasonable levels. This aspect is particularly evident in the case of existing buildings that are unable to satisfy the seismic requirements provided by current codes. The retrofit objective of satisfying the seismic requirements of new structures is often economically prohibitive and very difficult to achieve. In these cases an innovative technique as the dissipation of energy by added damping devices may be very promising in improving the seismic performance [1–12]. In rehabilitation interventions, fluid-viscous dampers offer some advantages [3,4], as their behaviour is independent of frequency and their dissipative capacity is very high.

Performance-Based Earthquake Engineering (PBEE) is a framework used to identify and define desired structural performances for specified seismic intensity levels. Currently, the most advanced PBEE methodologies, such as the PEER PBEE procedure [13,14], have been developed to evaluate seismic performance in terms of expected economic losses, a parameter of particular interest to decision makers. The PEER PBEE procedure consists of four steps of analysis: hazard analysis for the specific site of the building, structural analysis, damage analysis and loss analysis. In all the steps, the related uncertainties are explicitly considered in a probabilistic manner. The second step, in particular, involves a series of nonlinear time-history analyses executed to obtain a probabilistic description of the seismic demand for the building at increasing seismic intensity levels.

In this framework, the widespread probabilistic SAC-FEMA approach [15] can be useful for developing simplified procedures [16,17]. This method provides a closed form expression for evaluating the annual probability of exceeding a given limit state, while accounting for record-to-record variability and modelling uncertainties. The method is based on the first two steps in the PBEE process, hazard analysis and structural analysis, and, in general, it requires a series of nonlinear time-history analyses to be performed. This probabilistic approach has been followed in the present study. The purpose of this paper is to

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study the correlation between the results of the probabilistic assessment method for structures with and without dampers, with particular emphasis on the results in terms of dispersion caused by ground motion variability. This paper has studied, in particular, the variability and influence of the parameters in the closed form expression, such as the dispersion of seismic demand. This research takes into account the near collapse limit state, a wide set of ground motions and different methods to approximate the hazard curves. The analyses were performed without applying scaling factors to the earthquake records, and different records for increasing values of seismic intensity were instead used.

Considering the current trend of developing simplified procedures to assess performance while avoiding expensive nonlinear time-history analyses, a second purpose of the paper is to apply a direct procedure for assessing the response of nonlinear structures with nonlinear viscous dampers. This procedure was recently proposed by some of the authors and was applied within the considered probabilistic approach. Entitled DAM (direct assessment method) [18], this procedure requires knowing only the pushover curve of the structure, and it can also be applied to derive the response for increasing values of seismic intensity (IDAM). The idea was to apply this procedure in place of costly nonlinear dynamic analyses to estimate the engineering demand parameters that are needed in the SAC-FEMA approach. When simplified assessment methods are used in the place of nonlinear time-history analyses, it becomes necessary to solve the issue of uncertainties, such as record-to-record variability. A possible solution can be to use the default dispersion values available in literature [14,16]. The results of the correlation study performed as the first objective of this research can give useful indications for the specific case of existing structures retrofitted with viscous dampers. Here, when applying the probabilistic assessment together with DAM, the values obtained from the nonlinear dynamic analyses were adopted as the values of the dispersion.

The case study considered is a typical RC frame, with three bays and six floors, designed to resist gravity loads only. Nonlinear fluid viscous dampers were inserted for the seismic retrofit. The seismic demand parameters here considered are the maximum displacement at the top of the structure and the maximum inter-storey drift. Nine return periods were chosen to identify nine values for seismic intensity and twenty ground motions were selected for each. The analyses reported consider two different models for the behaviour of the plastic hinges, where the first model includes post-peak strength deterioration and the second does not. In the first case, the results were elaborated only for the records where the analyses converged for both structures. In the second case, the results were elaborated for all the considered records, that is, all 180 records for each structure.

2. Probabilistic approach

The SAC-FEMA method [15] provided the basis for the FEMA350 [19] guidelines in the structural design of steel moment-resisting frames under seismic action and can be used to determine the probability of failure for a structure in a closed form. This method specifies a closed form expression for evaluating the seismic risk of a structure in terms of P_{PL}, the annual probability of exceeding a specified performance level (e.g. the annual probability of collapse or the annual probability of exceeding the life safety level). Three approximations were proposed to obtain a closed form expression for P_{PL}, one for the probabilistic representation of ground motion intensity, one for displacement demand and one for displacement capacity. For the first approximation, the assumption is that the site hazard curve can be approximated in the region of hazard levels close to the limit state probability P_{PL} through the following relationship:

$$H(S_a) = k_0 S_a^{-k_1} \tag{1}$$

where $H(S_a)$ is the annual probability of exceeding S_a, S_a is the spectral acceleration at the fundamental period (assumed as the intensity measure), and k_1 and k_0 are constants that depend upon the interpolation of the hazard function in a log-log plot in the region of interest. For the second approximation, the assumption is that the median drift demand $\hat{D}$ can be represented by the following relationship:

$$\hat{D} = a(S_a)^b \tag{2}$$

where a and b are constants that depend upon the interpolation of the results in terms of seismic demand. Lastly, for the third approximation, the assumption is that the drift demand D is lognormally distributed about the median, using the standard deviation of the natural logarithm, $\beta_{D|Sa}$. This will be considered as the definition of dispersion. In addition, the drift capacity C is assumed to be lognormally distributed with dispersion β_C. Using the previous approximations, it is possible to derive the following expression:

$$P_{PL} = H(S_{a,1}^{\hat{C}}) \exp\left[\frac{1}{2}\frac{k_1^2}{b^2}\left(\beta_{D|S_a}^2 + \beta_C^2\right)\right] \tag{3}$$

where $S_{a,1}^{\hat{C}}$ is the spectral acceleration associated to attaining the drift capacity. From Eq. (3), it can be seen that the record-to-record variability and modelling uncertainties are able to affect P_{PL} through the exponential correction factor.

3. Direct Assessment Method (DAM) for nonlinear structures equipped with nonlinear viscous dampers

The DAM procedure, recently proposed and verified by some of the authors [18], was applied in this research as an alternative to nonlinear dynamic analyses. For completeness, it is explained here very briefly and, for more details, see Ref. [18]. The procedure consists of two steps.

The first step is used to obtain the direct estimate of the supplemental damping provided by the nonlinear viscous dampers applied to a linear elastic structure. In the case of nonlinear viscous dampers, the supplemental damping is dependent on the structural response. Therefore, a new dimensionless parameter is introduced for both the single (SDOF) and the multi-degree-of-freedom (MDOF) systems. This parameter is called the damper index [20] and it does not depend on the structural response. If a MDOF system is considered, the damper index for the first mode can be defined as:

$$\varepsilon_1 = \frac{T_1^\alpha \lambda \sum_{j=1}^{N_D} c_{NLj} f_j^{1+\alpha} \phi_{rj1}^{1+\alpha}}{(2\pi)^{1+\alpha} (\Gamma_1 \ddot{u}_{g0})^{1-\alpha} \sum_{i=1}^{N} m_i \phi_{i1}^2} \tag{4}$$

where c_{NLj} is the damping coefficient, λ is a constant depending on the exponent of velocity α, N_D and N are, respectively, the number of devices and degrees of freedom (DOF), f_j is an amplification factor related to the geometrical arrangement of the damper and T_1 is the elastic period of the first mode of vibration. In addition, ϕ_{rj1} is the difference between the first modal ordinates associated with the DOFs j and j-1, Γ_1 is the first modal participation factor, $\ddot{u}_{gO}$ is the peak ground acceleration (PGA) and m_i is the mass of the DOF i. In general, the damper index ε and the supplemental damping under elastic condition ξ_{ve} can be related through the following equation:

$$\xi_{ve} = \varepsilon \cdot [\overline{S}_a(T, \xi_{ve})]^{\alpha - 1} \tag{5}$$

where $\overline{S}_a$ is the spectral acceleration normalized to the PGA. Once the damper index is known, it is possible to calculate the supplemental damping ξ_{ve} using particular spectra of the supplemental damping as a function of the elastic period, for constant values of the damper index. These spectra can be obtained by applying Eq. (5) once the spectrum of the seismic action is known. They can, specifically, be derived on the basis of the code spectrum.