Engineering Structures 78 (2014) 90–99

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Performance-based seismic risk assessment for buildings equipped with linear and nonlinear viscous dampers

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ARTICLE INFO

Article history:
Available online 12 June 2014

Keywords:
Performance-based earthquake engineering
Seismic risk assessment
Viscous dampers
Non-stationary random process

ABSTRACT

This paper introduces an efficient methodology for assessing the seismic risk of structural systems equipped with linear and nonlinear viscous damping devices while accounting for the uncertainties affecting both seismic input and model parameters. The proposed methodology employs a combination of efficient and accurate analytical and simulation techniques to estimate the probabilistic properties of the structural response under a seismic input modeled as a non-stationary stochastic process.

The effectiveness of the proposed methodology is illustrated through a parametric study, with respect to the dampers' properties, of the performance of two adjacent steel buildings connected by linear and nonlinear viscous dampers. The results of the study provide useful information regarding the accuracy of the approximations introduced by the proposed reliability assessment approach, and the effectiveness of the added dampers in reducing the system seismic risk.

1. Introduction

In the last two decades, the use of viscous and visco-elastic dampers has become increasingly widespread in the design and retrofit of civil structures excited by wind and earthquake loads, due to the capability of these devices to mitigate undesirable aspects of the structural response [1,2]. Experimental and analytical studies have demonstrated that viscous dampers placed inside the buildings or between adjacent buildings permit to control and significantly mitigate the motion amplitude, interstory drifts, and absolute accelerations induced by earthquake actions [2–9].

The assessment of the seismic reliability of structures equipped with viscous/visco-elastic damping devices is a complex task that requires a probabilistic approach in order to rigorously account for the uncertainties that characterize the seismic input (record-to-record and intensity variability), as well as the properties of the structural systems and of their models (model parameter uncertainty (MPU)) [10–15]. Although stochastic simulation procedures (e.g., direct Monte Carlo simulation (MCS) [12,13] or subset simulation [16,17]) can be employed to solve this type of problem, they usually require a very large number of analyses to obtain accurate results when small failure probabilities need to be estimated. Thus, when possible, analytical techniques based on random vibration theory are preferred to direct stochastic simulation techniques [18–23]. In fact, several methodologies available in the literature employed analytical techniques for the probabilistic assessment and reliability-based design of viscously damped systems [3–6,9]. However, the complexity of the analytical treatment of this problem led to the adoption of numerous simplifications concerning the reliability evaluation, the seismic input description, and the uncertainty of the structural models. With regard to the reliability evaluation, many existing procedures focused only on the mean-square response of the buildings, without explicit reliability considerations regarding the structural performance as measured by the risk of damage and losses (see [9] for a comparison of different stochastic performance measures for stationary response). Furthermore, only few studies considered the effects on the system reliability of the statistical dependence among different failure modes, albeit these effects can be very significant [9]. With regard to the seismic input description, numerous studies employed oversimplified stochastic models that neglect the non-stationarity of earthquake ground motion. Finally, regarding the uncertainty of the structural models, a significant portion of the research performed in this field disregarded the effects of MPU, which can have a non-negligible influence on the structural performance [10–15].

This study presents a hybrid approach that combines efficient analytical and simulation techniques for reliability analysis to

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http://dx.doi.org/10.1016/j.engstruct.2014.04.052
0141-0296/

estimate the seismic risk of structural systems equipped with linear or nonlinear viscous dampers. This approach accounts for the correlation between different failure modes, the non-stationarity of the earthquake ground motion excitation, and the effects on system reliability of MPU. In the first part of the paper, the direct reliability problem consisting in the evaluation of the seismic risk is formulated consistently with modern performance-based earthquake engineering (PBEE) frameworks, such as the Pacific Earthquake Engineering Research Center (PEER) PBEE framework [24,25]. Successively, the problem solution is presented for the case of structural systems and performance levels for which the hypothesis of linear structural behavior is satisfied with good accuracy. The effects of the seismic input uncertainty are taken into account through random vibration techniques. In particular, in the case of linear dampers, recently derived closed-form analytical solutions [21] for the statistics of the stochastic structural response are employed. In the case of nonlinear dampers, an existing stochastic linearization technique is used to efficiently estimate the response statistics [26,27]. In both the cases, a simulation approach based on Latin hypercube sampling [28] is proposed to account for the uncertainty in the model parameters.

The proposed methodology is applied in this paper to evaluate the seismic risk of two adjacent steel buildings coupled by viscous dampers. A parametric study is performed to investigate the influence of the damper properties and nonlinearity level on the risk estimates. Comparisons with pertinent MCS results are made to assess the accuracy of the proposed approach.

2. Formulation of the reliability-based assessment problem

2.1. Mean annual frequency of limit state exceedance based on the PEER PBEE framework

The PEER PBEE framework [24,25] is a general probabilistic methodology for the performance assessment of structures subjected to seismic hazard. The aim of the framework is to evaluate the mean annual frequency (MAF) of exceedance of a decision variable (i.e., of a measurable attribute of a specific structural performance that can be defined in terms of cost/benefit for the users and/or the society). The computation of the decision variable is disaggregated into the following four probabilistic analysis components: (1) probabilistic seismic hazard analysis, which describes the uncertainty of the ground-motion intensity measures (IMs); (2) probabilistic seismic demand analysis, which describes the uncertainty of the engineering demand parameters (EDPs) used to monitor the structural response conditional on the IMs; (3) probabilistic seismic damage analysis, which describes the uncertainty of the damage measures (DMs) or limit states that can be correlated with the chosen decision variable; and (4) probabilistic seismic loss analysis, which describes the uncertainty of the decision variable. The reliability-based procedure developed in this paper involves only the first three steps of the framework since it provides the MAF of exceedance of a set of specified limit states related to the building components (e.g., structural elements and dampers). This MAF can be expressed as:

$$\nu_{\mathbf{DM}}(\mathbf{dm}) = \int_{\mathbf{im}} \int_{\mathbf{edp}} G_{\mathbf{DM}|\mathbf{EDP}}(\mathbf{dm}|\mathbf{edp}) \cdot |\mathrm{d}G_{\mathbf{EDP}|\mathbf{IM}}(\mathbf{edp}|\mathbf{im})| \cdot |\mathrm{d}\,\nu_{\mathbf{IM}}(\mathbf{im})| \tag{1}$$

in which $\nu_{\mathbf{IM}}(\mathbf{im})$ denotes the MAF of exceeding a given value **im** of the vector of IMs; $G_{\mathbf{EDP}|\mathbf{IM}}(\mathbf{edp}|\mathbf{im})$ denotes the complementary (joint) cumulative distribution function of the vector of EDPs, **EDP**, conditional on **IM = im**; and $G_{\mathbf{DM}|\mathbf{EDP}}(\mathbf{dm}|\mathbf{edp})$ denotes the complementary (joint) cumulative distribution function of the vector of DMs, **DM**, conditional on **EDP = edp**. In this paper, for the IMs, EDPs, and DMs, upper case letters denote random quantities, lower case letters denote specific realizations, italic characters denote scalar quantities, and bold characters denote vector quantities.

An important intermediate result of the PBEE procedure is given by the following convolution integral:

$$P_{\mathbf{DM}|\mathbf{IM}}(\mathbf{im}) = \int_{\mathbf{edp}} G_{\mathbf{DM}|\mathbf{EDP}}(\mathbf{dm}|\mathbf{edp}) \cdot |\mathrm{d}G_{\mathbf{EDP}|\mathbf{IM}}(\mathbf{edp}|\mathbf{im})| \tag{2}$$

which provides the probability of exceedance of the considered damage limit states conditional on the seismic intensity. For each damage limit state, Eq. (2) can be specialized as:

$$P_{DM_i|\mathbf{IM}}(\mathbf{im}) = \int_{\mathbf{edp}} G_{DM_i|\mathbf{EDP}}(dm_i|\mathbf{edp}) \cdot |\mathrm{d}G_{\mathbf{EDP}|\mathbf{IM}}(\mathbf{edp}|\mathbf{im})|\,; \quad i = 1, 2, \ldots, N_{ls} \tag{3}$$

in which DM_i and dm_i denote the i-th components of vector **DM** and **dm**, respectively, N_{ls} denotes the number of limit states, and $P_{DM_i|\mathbf{IM}}(\mathbf{im})$ denotes the probability of exceedance of the i-th damage measure (limit state) conditional on **IM = im**. Combining Eqs. (1) and (2) gives the MAFs of exceedance of damage level **DM = dm**:

$$\nu_{\mathbf{DM}}(\mathbf{dm}) = \int_{\mathbf{im}} P_{\mathbf{DM}|\mathbf{IM}}(\mathbf{im}) \cdot |\mathrm{d}\,\nu_{\mathbf{IM}}(\mathbf{im})| \tag{4}$$

2.2. Seismic risk assessment as a direct reliability problem

Seismic risk assessment consists in computing the probability that a structure exceeds any specified damage level or limit state (at a component and/or system level) during its assumed design life, t_L. In this type of direct reliability problems, the structural properties of the building and the mechanical properties of the dampers, as well as the seismic input characteristics at the building site, are uncertain quantities for which a probabilistic description is available. This paper considers discrete limit states only, using a similar approach as that followed in numerous PBEE studies available in the literature [25].

The evaluation of the reliability of a multi-component structural system requires selecting suitable limit states that are correlated with the components' performance. This study focuses on limit states related to structural damage, and the interstory drifts (defined as the difference in the lateral deflection measured at the top and bottom of a story, and divided by the story height) are employed as global EDPs [29,30]. Several guidelines and seismic codes provisions [31,32] provide the values of the interstory drifts corresponding to different limit states and/or structural performance levels. It is noteworthy that other EDPs (e.g. absolute floor accelerations) and limit states can be of interest in monitoring the performance of buildings [9,33,34]. The performance of the dampers is another important aspect in evaluating the system reliability, since the proper and continuous operation of the damping devices is critical in ensuring that the buildings achieve the desired target performance level. In the literature, limits are considered for the shear deformation that can be attained in visco-elastic dampers [4,35], or for both the stroke (displacement) and force demand in fluid viscous dampers [36]. The computation of the conditional probability of failure of the components $P_{DM_i|\mathbf{IM}}(\mathbf{im})$ and of the system $P_{f|\mathbf{IM}}(\mathbf{im})$ requires solving a time-variant reliability problem by accounting for the pertinent sources of uncertainty, e.g., randomness in the seismic input and MPU. The probability $P_{f|\mathbf{IM}}(\mathbf{im})$ is a special case of the probability $P_{\mathbf{DM}|\mathbf{IM}}(\mathbf{im})$ given in Eq. (2), which is obtained when discrete limit states are considered. The plot of $P_{f|\mathbf{IM}}(\mathbf{im})$ versus **IM** is commonly called fragility curve in the literature [25].

The system failure probability conditional on **IM = im**, $P_{f|\mathbf{IM}}(\mathbf{im})$, depends on the system configuration and on the statistical