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Computationally efficient fragility assessment using equivalent elastic limit state and Bayesian updating

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ABSTRACT

Conventionally, the seismic response of primary structures such as buildings and secondary systems such as piping is evaluated through uncoupled analyses. Many studies have illustrated that the two systems interact in many different ways (mass interaction, non-classical damping, phasing, etc.). An analysis of the coupled system is not only rational but also eliminates the excessive conservatism that exists in an uncoupled analysis. Consequently, fragility assessments based on uncoupled analysis are also incorrect and a coupled analysis must be conducted in such evaluations. However, nonlinear analyses of such complex systems particularly in the context of fragility assessment, which requires a large number of nonlinear analyses, becomes computationally prohibitive. Tadinada and Gupta (2017) presented an equivalent elastic limit state concept with an intent to reduce the computational effort needed in these assessments and yet evaluate the seismic fragility with sufficient accuracy. This paper outlines some of the limitations that have been experienced in the use of originally proposed equivalent limit-state formulation and presents valuable enhancements. The novel contribution of this study is focused on accounting for the effect of uncertainty in nonlinear characteristics and the effect of non-classical damping. Unlike the originally proposed formulation, the proposed formulation also considers the asymmetric variation of the equivalent limit state with respect to tuning ratio. Furthermore, a Bayesian approach is incorporated into the proposed methodology for increasing the accuracy of seismic fragilities in the case of tuned or nearly tuned primary-secondary systems. Numerical examples are used to illustrate that the modified form improves the accuracy for both the tuned and the detuned systems. In summary, the proposed approach provides an efficient framework of seismic fragility assessment and risk evaluation for coupled systems.

1. Introduction

In a seismic probabilistic risk assessment, the reliability of structures, systems and components requires estimation of fragility curves which gives conditional probability of failure for a given seismic intensity parameter such as peak ground acceleration (PGA), spectral acceleration (SA), Arias intensity, moment magnitude (Mw), etc. A detailed description on fundamentals of fragility analyses of complex structural systems can be found in Casciati and Faravelli [2]. Development of appropriate seismic fragility curves often requires large quantities of data from either laboratory/field measurements or computationally intensive simulations. For large structural systems, sufficient quantity of measured data is typically not available. Therefore, engineers rely on large scale simulations that involve conducting multiple time history analyses of the nonlinear systems. Depending upon the complexity of a simulation model and consideration of uncertainties in it, such an approach can become computationally impractical.

Estimation of fragilities for equipment or piping systems in critical industrial facilities such as hospitals, data centers, toxic chemical facilities, and nuclear power plants exhibits such complexity. Seismic response of such secondary systems depends on their interaction with the primary system (buildings) on which they are supported. Historically, seismic analyses of equipment and piping systems are conducted by uncoupling them from the primary structure. The primary structure is analyzed to obtain the floor motions. These floor motions are then used as input into an uncoupled model of the secondary system. Such conventional uncoupled analysis gives inaccurate responses which are, in general, excessively conservative [3,4]. An analysis of the coupled building-equipment or building-piping system must correctly account for: (i) the tuning between the modes of the primary and secondary systems, (ii) the mass interaction between the two systems, and (iii) the effect of non-classical damping. The concept of coupled analysis as well as its significance has been studied by many

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researchers [5,6,7,8]. USNRC conducted a benchmark program and developed many different benchmark problems for validation and verification of such coupled analyses [9].

Ju and Gupta [10] and Ju et al. [11] present the results of detailed studies on calculating piping fragilities. They illustrate that the nonlinearities in a piping system are typically localized to joints between straight pipes and components such as Tee-joints. They evaluated piping fragilities by incorporating the experimental data on nonlinear behavior of piping joints into a system level building-piping model and conducting multiple time history analyses. Ju et al. [11] also consider nonlinearities in the building and study their influence on the piping fragility. However, such analyses require significant computational resources thereby making it almost impossible to implement such an approach into practice. Thus, availability of an approach to calculate fragilities of secondary systems accurately through an equivalent linearization of the localized nonlinearity can be quite effective in overcoming such a limitation.

Many equivalent linearization methods have been studied and proposed in literature. These have been reviewed in detail by Proppe et al. [12] and Crandall [13]. The existing methods can be broadly categorized into following types:

(1) Equivalent viscous damping method [14]
(2) Elastic strain energy method [15]
(3) Empirical method [16,17,18]
(4) Stochastic linearization method [19,20]
(5) Secant stiffness method [21]
(6) Equivalent elastic limit state (ELS) concept [1]

Almost all these studies have focused on an equivalent linearization of the primary system alone by minimizing the average error between the responses of nonlinear and the linearized systems. In the seismic fragility analysis of the secondary systems, it is desirable that the equivalent linearization method minimizes the error between the maximum responses of interest instead of the average error. Tadinada and Gupta [1] propose a novel concept of equivalent limit-state (ELS) to reduce the computational effort needed in such fragility studies. In this paper, we present several enhancements to the concept of equivalent limit-state. These can be summarized as:

- Consideration of a more realistic model for the nonlinearities in the secondary system: The original study considers only an idealized bi-linear behavior with pinching effect to model the nonlinearities in the piping joints. An idealized bi-linear behavior is not appropriate for modeling the nonlinearities in some types of pipe joints as well as in the mounting arrangements of equipment [22,23].
- The study accounts for the effects of uncertainties in the nonlinear model as well as the effects of non-classical damping in the development of the equivalent limit state: Specifically, it is important to determine the change in responses due to a variation in input parameters of a complex model [24]. Details on methodologies for sensitivity analyses and uncertainty quantification are available in Xu and Gertner [25], Saltelli et al. [26], and Kwag and Ok [27].
- Modification to account for the asymmetric nature of the variation in equivalent limit-state with the tuning ratio (a ratio that represents the degree of tuning between the frequencies of the primary and the secondary systems): The equivalent limit-state for negative values of tuning ratio is not symmetric to that for positive values of tuning ratio.
- The applicability of the proposed modifications in the ELS concept is evaluated by considering various coupled systems.

It must be noted that the evaluation of seismic fragility using ELS concept is based on minimization of error between the response quantities of interest as evaluated from a nonlinear and a linearized system. The matching of the seismic fragility curve obtained from multiple nonlinear time history analyses with that obtained using the ELS concept is quite sensitive to the degree of localized nonlinearity and uncertainties in it particularly for systems with tuning ratio equal to zero (perfectly tuned systems) or close to zero (nearly tuned systems). Therefore, a probabilistic approach is adopted by incorporating Bayesian updating wherein the initial fragility curve obtained by the ELS concept is considered as the prior curve and updated to obtain a fairly accurate posterior fragility curve [28,29,30,31] by conducting a relatively small number of computationally intensive nonlinear analyses.

2. Equivalent elastic limit state (ELS) concept

The equivalent elastic limit state (ELS) is the optimal value V^* of the response quantity (displacement or rotation, etc.) that is considered as the failure limit state for the linearized system such that the seismic fragility evaluated from the linearized system is close to the seismic fragility for the nonlinear system. The linearization of the nonlinear system is performed by using same initial stiffness and damping coefficient of nonlinear system, but adopting the different ELS V^* which is not the same as the nonlinear limit state D_{nl}. The concept of ELS for a SDOF system is illustrated in Fig. 1. The ELS V^* can be obtained by formulating the problem as an optimization problem given by Eq. (1). Optimization is intended to find the solution for which the failure probabilities from the linear system responses P_f^l as defined by Eq. (2) are close to failure probabilities of nonlinear system P_f^{nl} as defined by Eq. (3). The error between P_f^l and P_f^{nl} is represented as the root mean squared (RMS) error.

$$\underset{\{\text{Find} \quad V^*\}}{\text{Minimize}} : \sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(P_f^{nl}(a_i; D_{nl}) - P_f^l(a_i; V^*)\right)^2} \tag{1}$$

$$P_f^l(a; V^*) = P[v_{\max}(a) > V^* | PGA = a] \approx \sum_{i=1}^{N} 1(a \cdot v_{\max}^i(1g) > V^*)/N \tag{2}$$

$$P_f^{nl}(a; D_{nl}) = P[u_{\max}(a) > D_{nl} | PGA = a] \approx \sum_{i=1}^{N} 1\left(u_{\max}^i(a) > D_{nl}\right)/N \tag{3}$$

where k is the number of PGA levels, N is the number of time history analyses at one level of PGA (or the number of different input ground motions), and $v_{max}(a)$ and $u_{max}(a)$ denote the random variables representing the peak displacement response under an earthquake of PGA = a in equivalent linear system and nonlinear system, respectively. Note that for a full description of a seismic fragility curve using linear time history analyses, we need N responses at only a single PGA value as the responses at other PGAs can be acquired simply by scaling the values for the single PGA case. On the contrary, N times n ($N \times n$) responses are needed to determine a fragility curve by using nonlinear time history analyses.

3. Mathematical modeling of coupled system

3.1. Nonlinear hysteretic nonlinear model

The original concept of ELS as proposed by Tadinada and Gupta [1] consider a bi-linear model with pinching to characterize the nonlinearities in the secondary system. In this paper, we enhance