Structural Safety 55 (2015) 49–59

Contents lists available at ScienceDirect

Structural Safety

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

Robust optimum design of base isolation system in seismic vibration control of structures under random system parameters

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ARTICLE INFO

Article history:
Received 30 November 2013
Received in revised form 23 February 2015
Accepted 26 February 2015
Available online 25 March 2015

Keywords:
Seismic vibration
Base isolation
Parameter uncertainty
Unconditional response
Robust optimization

ABSTRACT

The optimum design of base isolation system to control seismic vibration considering uncertain system parameters are usually performed by minimizing the unconditional expected value of mean square response of a structure without any consideration to the variance of such responses due to system parameter uncertainty. However, the unconditional mean square response based designed may have larger variance of responses due to uncertainty in system parameters and the overall system performance may be sensitive. But, it is desirable that the optimum design should reduce both the mean and variance of dynamic performance measure under system parameter uncertainty. The present study deals with robust design optimization (RDO) of base isolation system considering random system parameters characterizing the structure, isolator and ground motion model. The RDO is performed by minimizing the weighted sum of the expected value of the maximum root mean square acceleration of the structure as well its standard deviation. A numerical study elucidates the importance of the RDO procedure for design of base isolation system by comparing the proposed RDO results with the results obtained by the conventional stochastic structural optimization procedure and the unconditional response based optimization.

1. Introduction

In last few decades, various passive control approaches have been suggested to prevent structural and non-structural failures of structures like buildings, nuclear reactors, bridges during earthquakes. Among various such approaches, the performance and effectiveness of base isolation (BI) systems such as rubber bearings, lead rubber bearings (LRB), high damping rubber bearings and friction pendulum in mitigating seismic vibration effects have extensively been demonstrated in the past [1–3]. The studies on response behaviour of BI systems considering stochastic nature of earthquake load provide useful insight about the behaviour of such systems [4–6]. These studies clearly indicate that the performance of isolation systems largely depend on the characteristics of external excitations as well as the isolator parameters. In fact, the studies on the optimum design of various types of isolation systems in seismic vibration mitigation are well known [7,8]. Usually the optimization of isolation system is performed by considering the earthquake load as the only source of randomness. The stochastic structural optimization (SSO) is performed by using the structural displacement or acceleration covariance as the performance measure assuming all other system parameters as deterministic. In such approach, the uncertainty in the performance-related decision variables cannot be included in the optimization process based on deterministic assumption of system parameters. However, the design of isolation system based on the single nominal model of a system may fail to create a control system ensuring satisfactory performance. The unavoidable presence of uncertainty is expected to cause a variation of the optimum value of the isolator parameters and may affect the overall performance of the system. Thus, for efficient design, the uncertainty associated with excitation and various parameters characterizing the mechanical model should be explicitly taken into account in the design. In fact, the developments in the field of passive vibration control considering system parameter uncertainty are well known [9–12]. The studies on BI systems considering uncertainty of mechanical model and ground motion filter parameters indicated that the uncertain parameters have significant roles on the performance of such system [13,14]. Nagai and Nishitani [15] estimated the safety and reliability of an isolation system considering

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http://dx.doi.org/10.1016/j.strusafe.2015.02.005
0167-4730/

fluctuations in the parameters involved in such hysteretic system. An equivalent linearization technique combined with perturbation approach is used for response statistics evaluation required for safety evaluation of the system. A stochastic-simulation-based nonlinear controller design for isolated benchmark building with elastomeric and friction pendulum type isolators is presented by Taflanidis et al. [16] considering probabilistic ground-motion model parameters. A computationally efficient reliability based design optimization of friction-based seismic isolation device in the framework of Monte Carlo simulation and response surface method is presented by Bucher [17]. A simulation-based framework for risk assessment and probabilistic sensitivity analysis of isolated structure by explicitly incorporating the uncertainties in the excitation and or structural model is presented by Taflanidis and Gaofeng [18].

The existing studies on the optimum performance of BI system under random system parameters as discussed above deals with minimization of unconditional mean square response of structure without any consideration to the variance of such responses due to system parameter uncertainty. However, the unconditional mean responses based designed may have larger variation of responses due to input system parameters and the overall performance of the isolator system so designed may be sensitive to the variations of the input system parameters. But, it is important that the optimum design should be least sensitive to the possible variation due to parameter uncertainty i.e. the BI system should exhibit performance robustness. The robustness is usually expressed in terms of the dispersion of a performance function from its nominal value, usually measured in terms of variance or percentile difference [19]. In this regard, the developments on robust design optimization (RDO) of structure under uncertainty in the recent past are noteworthy [20–22]. But, there have been a few applications of RDO procedure in vibration control. Hwang et al. [23] minimized the mean and variance of displacement at first resonance frequency of an automobile mirror system considering stiffness and mass variation. Son and Savage [24] proposed a probabilistic approach of designing vibration absorber parameters to reduce both the mean and variance of dynamic performance measure over the excitation frequency range. Pai [25] proposed a proportional-integral sliding mode control methodology for robust control of vibration of a linear uncertain system. The RDO in seismic vibration control were studied in the recent past for tuned mass damper [26,27]. The RDO of passive vibration control system considering uncertainty in the structural model parameters are primarily studied for tuned mass damper system. The study of robust optimization in the design of BI system for seismic vibration mitigation is not available. However, in order to achieve a more effective configuration of such system so that the final response reduction capability of the base isolated structure will be less sensitive to the variation of the system parameters due to uncertainty, a RDO approach is expected to be a desirable choice.

Keeping this view in mind, the present study focuses on the effectiveness of RDO of BI system in seismic vibration mitigation under system parameter uncertainty. This involves optimization of isolation system considering random system parameters characterizing the primary structure and stochastic earthquake load model. The RDO is obtained by solving a two criteria equivalent optimization problem, where the weighted sum of the mean value of the performance function and its standard deviation (SD) are optimized. The maximum root mean square acceleration (RMSA) of the primary structure is considered as the performance index. The conventional SSO assuming deterministic system parameters and usually adopted unconditional mean response based optimization procedure under system parameter uncertainty are also performed to demonstrate the relevance and importance of the proposed RDO approach. A five storied building frame with attached LRB type isolator is taken up to illustrate the effect of parameter uncertainty and importance of RDO approach by comparing the present RDO results with the results obtained by the usually adopted SSO and unconditional mean response based optimization procedures.

2. Response of base isolated building frame under random earthquake

A shear building model, isolated by LRB type isolator as shown in Fig. 1a is considered in the present study. The idealized mechanical model of the isolator and its idealized force–deformation behaviour is depicted in Fig. 1b and c. The structure under consideration can reasonably be assumed to be linear as BI system substantially reduces the structural response. However, the hysteretic energy dissipation in the LRB occurs through large shear deformation and yielding of the lead core. Consequently, the behaviour of LRB is highly non-linear and modelled accordingly.

The equation of motion of the N-storey superstructure subjected to horizontal component of earthquake ground motion can be written as:

$$[\mathbf{M}]\{\ddot{\mathbf{x}}\} + [\mathbf{C}]\{\dot{\mathbf{x}}\} + [\mathbf{K}]\{\mathbf{x}\} = -[\mathbf{M}]\{\mathbf{r}\}(\ddot{x}_g + \ddot{x}_b) \quad (1)$$

where $[\mathbf{M}]$, $[\mathbf{K}]$ and $[\mathbf{C}]$ are the matrices of size $N \times N$ representing the mass, stiffness and damping matrices of the superstructure, $\{\mathbf{x}\} = \{x_1 \quad x_2 \quad \dots \quad x_N\}^{\mathrm{T}}$ is the displacement vector containing the lateral displacement of each floor relative to the isolator, as shown in Fig. 1a. $\{\mathbf{r}\}$ is the influence coefficient vector given as $\{\mathbf{r}\} = [1 \quad 1 \quad \dots \quad 1]^{\mathrm{T}}$. $\ddot{x}_b$ is the relative acceleration of the isolator with respect to ground due to earthquake acceleration, $\ddot{x}_g$.

The equation of motion of the isolator mass (Fig. 1b) can be written as:

$$m_b\ddot{x}_b + c_b\dot{x}_b + F_b - c_1\dot{x}_1 - k_1x_1 = -m_b\ddot{x}_g \quad (2)$$

where m_b is the mass of the isolator, c_b is the viscous damping of the LRB, k_1 and c_1 are the stiffness and damping of the first storey. F_b is the restoring force of the isolator described by the differential Bouc–Wen model [28,29] and can be expressed as:

$$F_b(x_b, Z) = \alpha k_b x_b + (1-\alpha)F_Y Z \quad (3)$$

where k_b is the initial elastic stiffness, x_b is the displacement of the LRB and α is an index representing the ratio of the post to pre yield stiffness of the LRB, referred as rigidity ratio. F_y is the yield strength of the isolator. Z is a variable quantifying the hysteretic response of the isolator, expressed by Bouc–Wen model as:

$$q\dot{Z} = -\gamma|\dot{x}_b|Z|Z|^{\eta-1} - \beta\dot{x}_b|Z|^{\eta} + \delta\dot{x}_b \quad (4)$$

where q is the yield displacement of the isolator. The four parameters β, γ, η and δ appears in Eq. (4) and parameter α in Eq. (3) control the shape of the hysteretic loop. The parameter η controls the transition from the elastic to plastic phase. β depicts the nature of the model e.g. $\beta > 0$ implies hardening and $\beta < 0$ indicates softening behaviour. The parameters γ and δ control the shape and size of the hysteresis loop. The parameters adopted in the present study are $\alpha = 0.05$, $\beta = \gamma = 0.5$, $\delta = 1$ and $\eta = 1$, which corresponds to the force deformation characteristics as shown in Fig. 1c. The elastic to plastic transition become increasingly sharp with increasing value of η and the ideal sharp bilinear nature can only be attained at $\eta \to \infty$ (infinity). However, with the presently adopted value of $\eta = 1$, the smooth transition can adequately be taken to be close enough to the ideal bilinear behaviour. The post-yield stiffness (αk_b) of the isolator is selected in order to provide specific isolation time period, $T_b = 2\pi\sqrt{M/\alpha k_b}$. Here M is the total mass of the isolator–superstructure system, given by the sum of all the floor mass