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Reliability-based assessment/design of floor isolation systems

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ABSTRACT

Floor isolation systems have been becoming increasingly popular as a protective measure for critical structural contents such as computer servers or museum artifacts. Supplemental dampers, working in tandem with the isolation system, are also frequently considered in this context for reducing the isolated floor displacement or enhancing vibration suppression. This paper discusses a reliability-based optimization approach for this kind of applications that adequately addresses at the design stage the variability related to the earthquake hazard as well as the nonlinear dynamics of the coupled structure/isolation system. The floor isolation system is optimized based on reliability criteria, where the reliability of the system is quantified by the plausibility that the acceleration of the protected contents will not exceed an acceptable performance bound, and is calculated using stochastic simulation. The latter facilitates the adoption of complex numerical models for the coupled system. A stochastic ground motion model is utilized to characterize the seismic hazard, and an efficient stochastic optimization approach, called non-parametric stochastic subset optimization, is adopted for performing the associated design optimization. Near-fault directivity pulses are explicitly addressed within this modeling context and their effect on the optimal design is investigated in detail. Also, a global sensitivity analysis is integrated within the framework to investigate the importance of the different uncertain model parameters (risk factors) towards the system failure probability. For demonstrating the proposed framework, the protection of a computer server placed at different floors within a four-story structure is considered.

1. Introduction

Damages during earthquakes to critical building contents, such as computer servers or museum artifacts, may lead to significant economic losses due to repair and replacement costs or business interruption [1,2]. For protection of such sensitive components, application of base or floor isolation techniques has been gaining interest within the structural engineering community [3–12]. In the case of floor isolation, flexible isolators are used to "decouple" the floor portion containing the group of sensitive structural contents from the rest of the structure. Through proper design, this implementation may significantly reduce the isolated-component vibration. Application of supplemental dampers, working in tandem with the isolation system, has also been proposed [13–16] in this context, for reducing the isolated floor displacement (avoid collisions to other components or stoppers) or enhancing vibration suppression.

One key challenge in the performance assessment and more importantly in the design of floor isolation systems has been the characterization and inclusion of the variability of future ground motions in the analysis/optimization process. The behavior of these systems, extending to the level of suppression of the sensitive equipment acceleration and to the displacement of the isolators (creating demands for facilitating appropriate clearances), has a strong dependence on various characteristics of the excitation [13,16], such as the frequency content and intensity or the existence of a near-fault pulse component. Another challenge has been the explicit consideration of the nonlinear behavior of the isolators, the potential supplemental dampers and the structural system itself, while simultaneously addressing the model uncertainties that may impact this behavior. A reliability framework provides a critical tool for addressing such challenges through a probabilistic characterization of the various sources (excitation/structural) of uncertainty/variability that can impact the system performance [17–20]. This has motivated researchers to look into the reliability-based assessment of the performance of floor-isolation systems [13]. No attention has been given though on the explicit reliability-based design, to select the characteristics of the isolators and of the supplemental dampers to maximize the reliability of the system.

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This paper discusses a reliability-based design approach that adequately addresses the aforementioned two challenges. The floor isolation system is optimized based on reliability criteria, where the reliability of the system is quantified by the plausibility that the acceleration of the protected contents will not exceed an acceptable performance bound. In this context, uncertainty in the structural model parameters and more importantly in the seismic hazard is treated through the incorporation of a probabilistic description for them. For the latter, a stochastic ground motion model is adopted that can adequately characterize near-fault motions [21]; this model relates regional seismicity characteristics to the excitation properties (including properties for a potential near-fault component of excitation) through predictive relationships and further addresses the inherent variability of acceleration time histories through a stochastic white noise sequence. Description of the uncertainty in the regional seismicity characteristics and the predictive relationships leads then to a complete probabilistic model for future ground motions that ultimately facilitates a detailed quantification of the seismic hazard. The probability of existence of near-fault pulses is explicitly introduced within this ground motion model here. Stochastic simulation is used for evaluation of the reliability performance, which allows for adoption of nonlinear models for the coupled system model at the design stage. For the associated reliability optimization, to select the optimal parameters for the isolators and potential supplemental dampers, a recently developed efficient algorithm [22], called non-parametric stochastic subset optimization, is adopted. Additionally, a sensitivity analysis [23] is integrated in the approach to investigate what risk factors (uncertain model parameters) have greater contribution towards the overall seismic risk (system failure probability). This sensitivity analysis is extended here to distinguish between ground motions that have or do not have directivity pulses. This is then utilized to better evaluate the impact of near-fault pulses on the system reliability and establish a critical understanding of the correlation of the seismic hazard characteristics towards the overall seismic risk.

In Section 2 the numerical model for the coupled system is presented and in Section 3 the ground motion model is reviewed. Then Section 4 presents the reliability-based design problem and the computational framework for the associated design-optimization, including its extension for facilitating the proposed global sensitivity analysis. Finally Section 5 presents a case study that demonstrates the proposed design framework for protection of a computer server, located at different floors within a four-story structure.

2. Coupled structural system model

The reliability-based design approach discussed here supports a detailed evaluation of the floor isolation performance through time-history analysis. This allows for all important sources of nonlinearity to be directly incorporated into the adopted numerical model. This model is briefly reviewed here. For simplicity of the presentation, a planar model, as shown in Fig. 1, is assumed of a structure with n floors and a floor isolation system at the k^{th} floor, protecting some sensitive content with mass m_c. Note, though, that the adopted reliability-based framework can support complete three-dimensional models for the structure.

Let $\mathbf{x}_s$ be the n-dimensional vector of relative-to-the-base displacements for the structure, $\mathbf{M}_s$ and $\mathbf{C}_s$ the corresponding mass and damping matrices, $\mathbf{F}_s$ the vector of (possibly nonlinear) restoring forces per story, and $\mathbf{R}_s$ the vector of earthquake influence coefficients (i.e. an n-dimensional vector of ones in this case). Let also m_b be the mass of the floor isolation system (without the mass of the protected content), x_b its displacement relative to the displacement of the k^{th} floor, and $\mathbf{R}_{is}$ the location vector describing the position of the floor isolation within the structure. Ultimately this corresponds to an n-dimensional vector of zeros with only the $(k-1)^{th}$ component being equal to one. We will further include in the analysis the dynamics for the vibration of the protected content itself, modeled as a single-degree-of-freedom (SDOF) system with stiffness k_c, damping coefficient c_c and displacement x_c relative to the isolation system. The system of equations for the coupled system in Fig. 1 is then:

$$\begin{aligned}
&\mathbf{M}_s\ddot{\mathbf{x}}_s + \mathbf{C}_s\dot{\mathbf{x}}_s + \mathbf{F}_s - \mathbf{R}_{is}(f_{is} + f_d + f_{ct}) = -\mathbf{M}_s\mathbf{R}_s\ddot{x}_g \\
&m_b\ddot{x}_b + f_{is} + f_d + f_{ct} - (c_c\dot{x}_c + k_c x_c) = -m_b\mathbf{R}_{is}^T(\mathbf{R}_s\ddot{x}_g + \ddot{\mathbf{x}}_s) \\
&m_c\ddot{x}_c + c_c\dot{x}_c + k_c x_c = -m_c\left[\mathbf{R}_{is}^T(\mathbf{R}_s\ddot{x}_g + \ddot{\mathbf{x}}_s) + \ddot{x}_b\right]
\end{aligned} \tag{1}$$

where $\ddot{x}_g$ is the ground acceleration, f_{is} corresponds to the isolator forces, f_d to the damper forces and f_{ct} to contact forces due to impact on surrounding contents (or internal stoppers) when the floor isolation displacement exceeds the seismic gap threshold. For the case study discussed later, the restoring force vector $\mathbf{F}_s$ will be described through a parsimonious modeling approach [24], representing globally the restoring force for each story with a bilinear spring following a peak-oriented hysteretic behavior (details also shown in Fig. 1).

The hysteretic behavior of the isolators may be characterized by a Bouc–Wen model [25]:

$$u^y\dot{z} = \alpha_{is}\dot{x}_b - z^2(\gamma_{is}\text{sgn}(\dot{x}_b z) + \beta_{is})\dot{x}_b \tag{2}$$

where z is a dimensionless hysteretic variable that is constrained by values ±1, u^y is the yield displacement, and α_{is}, β_{is}, and γ_{is} are dimensionless quantities that characterize the properties of the hysteretic behavior. Typical values for these parameters are $\alpha_{is} = 1$, $\beta_{is} = 0.1$, and $\gamma_{is} = 0.9$ [25]. The isolator forces may be then described based on the variable z and the base displacement x_b. For example, for friction-pendulum isolators and lead-rubber bearings we have, respectively:

$$f_{is} = k_p x_b + \mu N z \tag{3}$$

$$f_{is} = k_p x_b + (k_l - k_p)u^y z \tag{4}$$

where k_p is the post-yield stiffness, $N = (m_b + m_c)g$ is the average normal force at the bearing, μ is the coefficient of friction, and k_l the pre-yield stiffness. For friction-pendulum isolators the post-yield stiffness is given by $k_p = (m_b + m_c)g/R_p$ where R_p is the radius of curvature of the concave sliding surface of the isolator. Also, it should be stressed that the model in (3) represents a simplification for the behavior of such bearings, as it neglects a detailed assessment of the impact of the overturning moment on the normal force. Though this impact in many instances is small, due to the low center of mass for many types of isolated components and small height-to-width (distance between bearings) ratios, it should be explicitly accounted for when it is expected to have a stronger influence on the system behavior. For this investigation the simplified model is assumed to capture well the lateral dynamics of the isolation system (which is the response quantity of interest here). Beyond friction-pendulum isolators and lead-rubber bearings discussed above, other isolation systems also exist such as rolling isolation [12,26,27] and can be implemented for the application considered here (floor isolation). Their integration within the proposed modeling framework simply requires a proper modification of the system of equations providing the isolator forces, something that can be easily accommodated within the advocated simulation-based approach.

Moving now to the supplemental dampers, when they correspond to (passive) fluid viscous dampers, their respective forces may be modeled by

$$f_d = c_d\text{sgn}(\dot{x}_b)|\dot{x}_b|^a \tag{5}$$