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Assessment of a rolling isolation system using reduced order structural models

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ABSTRACT

This paper examines the performances of lightly- and heavily-damped rolling isolation systems (RISs) located within earthquake-excited structures. Six steel structures of varying height and stiffness are selected so as to represent a range of potential RIS installations. Computation models of representative frames from each of the six structures are reduced through dynamic condensation and assembled with models for biaxial isotropic hysteretic behavior within each floor. A novel reduced order modeling approach is presented in this paper. The method combines a dynamic condensation of a linear-elastic frame with the inelastic-push over curve for a detailed elastic–plastic frame model and a novel bi-axial hysteretic model for the net inter-story inelastic behavior. The reduced inelastic model combines stiffness and mass matrices from the reduced linear model with the bi-axial inelastic floor model, and is subsequently fit to push-over curves from the detailed hysteretic model. The resulting reduced order model has three coordinates per floor and provides a much simpler model for simulating the floor responses of inelastic structures. The resulting inelastic structural models are isotropic in plan and uniform along the height. Suites of recorded ground motions representative of near-fault and far-field hazards are scaled and inputted into these hysteretic reduced models. The bidirectional floor responses at varying heights are then applied to experimentally-validated models of lightly- and heavily-damped RISs. Empirical cumulative distribution functions of peak isolator responses (relative displacement and total acceleration) for the two systems are compared, from which installation guidelines are presented.

1. Introduction

Performance-based aseismic design of new buildings aims to ensure structural integrity, immediate occupancy, and operational performance levels following an earthquake. Critical facilities, such as emergency response centers and hospitals [1], must remain functional during and after major earthquakes for the public welfare and safety. However, the functionality of these critical facilities is not solely dictated by the structure's integrity, but instead must also consider damages to the building contents – which typically occur at lower levels of shaking intensity than structural damage. Even in the absence of damage to structural components, the services these buildings provide should also remain uninterrupted. Disruption of services in data centers, telecommunication networks, industrial facilities, or technology centers may result in major direct and indirect economic losses [2,3].

The societal and economic impacts of damage to valuable or mission-critical building contents – such as medical equipment, computer servers, or priceless artifacts – can far outweigh the cost of the building itself [4]. For the protection of such vibration-sensitive components, seismic isolation has steadily gained interest in the engineering community [5]. Seismic isolation reduces the seismic demand on structures and their contents by decoupling the motion of the structure (equipment) from the harsh base (floor) motion [6]. Seismic isolation has been successfully implemented at various scales – from the entire structure [7–12], to floors within the structure [13–16], and down to the component level [17,18].

This work focuses on assessing the performance of rolling isolation systems (RISs) used to protect individual pieces of equipment. Previous studies have been carried out to assess the in-building performance of isolated objects, but were limited to planar structural responses and unidirectional excitations [13–18]. RISs are known to exhibit strong coupling between transverse (and

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rotational) responses [19]. Furthermore, ground motions, structural responses, and equipment responses are inherently multidirectional. This paper addresses the bidirectional (horizontal x and y) response of RISs *in situ*, subjected to simulated floor responses of a variety of building heights, stiffnesses, and ductility excited by recorded ground motions. An extensive parameter study, involving time history analyses (as opposed to floor response spectra [11]), is facilitated by a new hysteretic model reduction technique, alleviating the computation demands of dynamic finite element simulations of the building response.

Previous methods of model reduction for hysteretic structures have either (a) been limited to reducing only the linear aspects of the system (retaining all the nonlinear elements present in the system at some computational expense) [20,21] or (b) approximated the nonlinear system using modal superposition with time-varying modes [22,23]. In the reduced-order modeling method presented here, the elastic restoring forces of a condensed linear model are simply replaced by hysteretic forces. The reduced linear model is computed via dynamic condensation [24]. The coordinates of the condensed model correspond to selected coordinates of the full model, and the condensed model matches the full model at any selected frequency. The hysteretic forces are evolutionary [25,26] and are calibrated to match the push-over behavior of the detailed inelastic frame model. Note that the number of hysteretic variables need not be larger than the number of condensed coordinates and time-varying (or 'nonlinear') modes are not involved.

This paper builds upon the comparison presented in Ref. [27] by examining the performances of a lightly-damped RIS and a heavily-damped RIS located within earthquake-excited structures (Fig. 1). Six structures of varying height and stiffness [28] are chosen to represent a range of potential RIS installations, and finite element (FE) models of the six structures are first derived for representative planar frames (see Section 2). Then (Section 3) the proposed hysteretic model reduction method is described, which involves first reducing the full FE models via dynamic condensation, and then incorporating the three-dimensional (3D) models with hysteretic coupling in orthogonal directions. Section 4 describes three suites of ground-motion records that are scaled and inputted into the reduced hysteretic models. Finally (Section 5) the performance of RISs, located at varying heights within the buildings, is assessed. The bidirectional floor responses of the seismically excited building are applied to the experimentally-validated models for lightly- and heavily-damped RISs [19,27], and empirical cumulative distribution functions (CDFs) of peak equipment responses (accelerations and displacements) are compared and design guidelines are presented.

2. Structural systems considered

The buildings considered in this study are six steel moment-resisting frame building with 4, 8, and 12 stories designed and analyzed by Santa-Anna and Miranda [28]. As indicated in Fig. 2, these building have three bays at 7.32 m with uniform mass distribution over their height. For each of the aforementioned heights, two different buildings are considered: one is designed to be relatively *flexible* and the other to be relatively *rigid*. All are designed using the lateral load distribution specified in the 1994 Uniform Building Code for Zone IV. The rigidities of their beams and columns were tuned to obtain fundamental periods of vibration that are representative of existing steel buildings in California.

The *complete* models of the six buildings are briefly reviewed here. The ith node of a planar-frame model of a three-bay, n-story buildings ($n = 4,\ 8$, and 12, see Fig. 2) possesses three degrees of freedom (DOF) – lateral displacement x_i, vertical displacement z_i, and rotation φ_i – resulting in $3 \times 4 \times n$ DOF in total. The lateral displacements x_i are measured relative to the ground. Let $\mathbf{d} = [x_1, z_1, \varphi_1, \ldots, x_{4n}, z_{4n}, \varphi_{4n}]^\mathsf{T}$ be the $12n$-dimensional vector of displacements and rotations, and $\mathbf{M} \in \mathbb{R}^{12n \times 12n}$ and $\mathbf{K} \in \mathbb{R}^{12n \times 12n}$ the corresponding mass and stiffness matrices. The differential equations governing the response of the building to horizontal ground motion $\ddot{u}_g(t)$ are as follows:

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{K}\mathbf{d} = -\mathbf{M}\,\imath\,\ddot{u}_g \tag{1}$$

where the $12n$-dimensional influence vector,

$$\imath = [1\ \ 0\ \ 0 \mid 1\ \ 0\ \ 0 \mid\ \cdots\ \mid 1\ \ 0\ \ 0]^\mathsf{T}$$

applies $\ddot{u}_g$ to the lateral nodal displacement x_i.

The mass and stiffness matrices of the planar frames (Fig. 2) were generated using FRAME3DD [30]. Additional mass was required in order for the natural periods to match those those reported by Santa-Anna and Miranda [29]. To wit, the necessary additional floor mass was determined by varying the added mass applied to the (horizontal) girder elements until the first natural period matched those of Ref. [29]. Table 1 gives the added mass and the first four natural frequencies of the frames considered.

The complete model $(\mathbf{M}, \mathbf{K})$ discussed here is for a *planar* frame. In order to evaluate the equipment isolation performance for

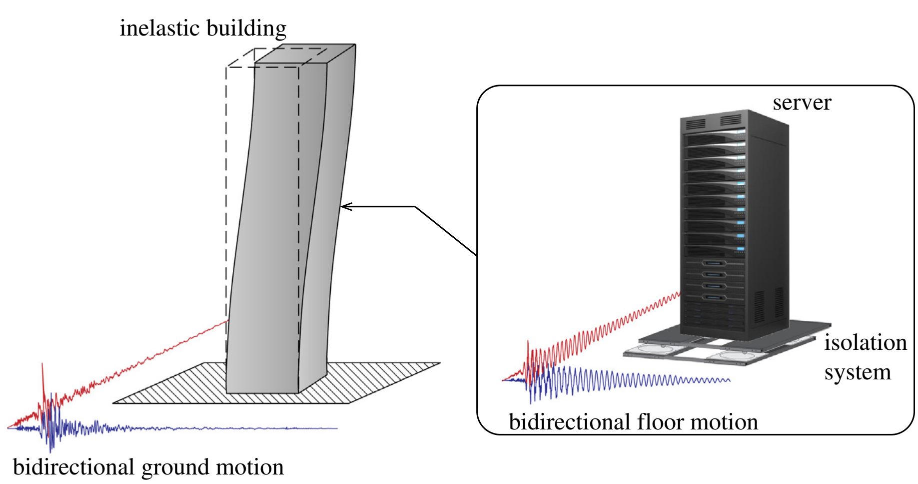

Fig. 1. Model of an inelastic building, subjected to bidirectional ground motion, equipped with an isolation system.