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Multi-Directional Real-Time Hybrid Simulation Study of Rolling Pendulum Isolation Systems for Seismic Risk Mitigation of Critical Building Contents

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ABSTRACT

Damage caused by earthquakes to buildings and their contents (e.g., sensitive and critical equipment) can impact life safety and disrupt business operations. The resulting social and economic losses can be minimized if the seismic demands on building contents are reduced through vibration isolation. In this regard, floor isolation systems (FIS) are a promising retrofit strategy for protecting vital building contents. Therefore, this paper presents an overview of an ongoing research effort, which consists of real time hybrid simulation (RTHS) tests of FISs on a multi-axial shake table conducted at the Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at Lehigh University. Multi-directional RTHS is utilized to validate the performance of full-scale rolling pendulum (RP) bearings, incorporating multi-scale (building–FIS–equipment) interactions. Parametric variation includes the influence of different steel moment resisting frame (SMRF) configurations, each subjected to ground motions of different sources and hazard levels. Details of the experimental test set-up, RTHS test protocol and main results on the multi-directional testing of an RP-based FIS are described. Challenges in conducting the multi-axial RTHS, like kinematics transformation and compensation for inertial effects, are also discussed, along with the approaches used to overcome them.

Introduction

Earthquakes can heavily damage civil structures causing great economic and, in the worst cases, human losses. Several design strategies have been developed to minimize and mitigate the impact of the forces these natural hazards imposed on structures [1], such as isolating an entire building [2]. Floor isolation systems (FISs) are gaining popularity over other isolation techniques as they have shown to be a valuable retrofitting approach for protecting essential building contents, besides to facilitate and accelerate the post-event

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functionality of the structure, and consequently, of business operation (Fig. 1(a)). FISs are designed under the premise that an object (e.g., telecommunications apparatus, medical equipment, sculptures, a raised floor of a building, etc.) can be decoupled (isolated) from the rest of a structure and its respective disturbances (Fig. 1(b)). Thus, these systems decrease the transmitted vibrations and ultimately protect the sensitive and critical objects from damaging effects.

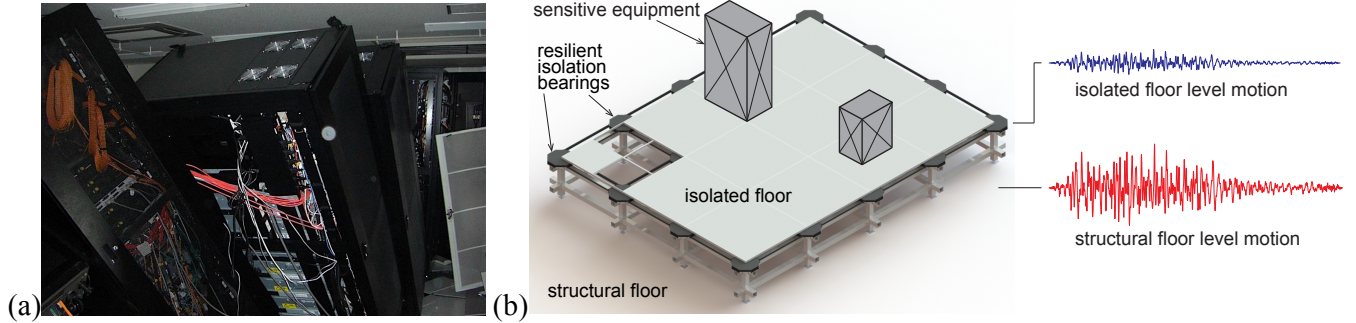


Figure 1. (a) Damage in a data center after an earthquake [3], and (b) schematic of resilient multi-functional FIS concept.

FISs composed of full-scale rolling pendulum (RP) bearings under multi-directional in-plane (X – Y) loading are studied in this paper; as well, multi-scale (building–FIS–equipment) interactions are studied. To do so, a new real-time cyber-physical structural systems multi-directional shake table at NHERI Lehigh Experimental Facility [4] was constructed and used, which was also used for controlled-displacement characterization tests in a preliminary stage. Real-time hybrid simulation (RTHS) combines numerical and experimental subsystems into a single simulation technique in real-time [5]. Thus, by implementing RTHS tests, it is possible to numerically model buildings and equipment while only physically testing an isolation unit, as well as to accurately measure the effect of interactions between the former and the latter. By adding any possible movement in the plane through the use of the shake table, more realistic and complex studies of the RP isolation system, for instance, bi-directional earthquake excitation and torsional effects, can be performed.

Analytical Formulation

To evaluate building–FIS interactions and real-scale RP isolation system’s performance under bi-directional earthquake excitation, 3-story (LA3) and 9-story (LA9) steel moment resisting frame (SMRF) buildings designed for the SAC project for the Los Angeles, California region were used; see Ohtori et al. [6] and FEMA-355C [7] for additional details on these buildings, including configuration layouts, material mechanical parameters and dynamic properties. Each building was modeled in 3D, with the masses lumped at the beam-to-column joints, using a master node to define diaphragm action at each level, and including P – Δ effects by means of a lean-on column slaved to each master node, using OpenSees [8], to compare results and convergence, and HyCoM-3D [9], to run the RTHS, obtaining in both cases equivalent natural frequencies from those reported in previous studies [6, 10]. Inelastic explicit force-based fiber beam-column elements (*forceBeamColumn*) were used for all the columns and for the beams in the MRFs; these explicit formulated elements are set to be integrated under a Gauss-Lobatto scheme with 10 integrations points along each element, with a maximum number of iterations of 10 and a tolerance of 10^{-12} (see Kolay and Ricles [11] for complete details). For the gravity system’s beams, elastic elements were implemented. For both structures, 2%-Rayleigh damping at the fundamental period of each building model and at a fixed value of 0.2 s, as established during the SAC project [10], were used. In the specific case of the RTHS tests using the HyCoM-3D [9] models, the integration of the MKR- α algorithm [12–15] in real time was performed at a sample rate of 1024 Hz; as well, to control the numerical dissipation, the parameter ρ^* that controls numerical damping was set to 0.5 for all the tests [15]. For the OpenSees models, the HHT (Hilber-Hughes-

Taylor) time-stepping method with a 0.75 value of α was used as the integration scheme [8].

As the input to run the multi-directional RTHS cases, a set of earthquake records was developed, following section 16.2 approach of ASCE 7-16 [16] for nonlinear response history analysis. First, a target, 5%-damped, MCE_R response spectrum was defined for the Los Angeles financial district (lat. 34.05, long. 118.26) [17], using this location because of its importance, building density and high seismic risk. The deaggregation analysis of the location showed that even though far-field controls FOE hazard [18], DBE and MCE are controlled by the near-fault events [19]; therefore, priority was given to near-fault (0 km to 15 km) records, which is a result expected for California [20]. Using the NGA-West2 database and online tool for amplitude scaling [21], and defining various parameters—spectral ordinate RotD100, minimizing MSE, using predominantly faults mechanisms identified for Los Angeles area (strike-slip and thrust) [22], magnitudes between 6 and 7.9, only one record per earthquake, a period range between 20% of the smallest LA3's first-mode and 2 times the largest LA9's first-mode, and scale factors less than 4.0—13 near-fault and 3 far-field bi-directional scale records were obtained; additionally, 7 near-fault pulse-like records were chosen [20]. In summary, 3 far-field records were used for the FOE hazard dividing the scale factors by 2; 13 near-fault without pulse and 7 near-fault pulse-like records were used for the DBE hazard dividing the scale factors by 1.5; finally, 13 near-fault records without pulse (the same used for the DBE) were used for the MCE_R hazard with the scale factors obtained from the analysis above explained.

Reviewing article 16.2.3.2 of ASCE 7-16 [16] for amplitude scaling in the case of near-fault without pulse, the average of the scaled maximum-direction spectra (RotD100) from all the ground motions is under 90% the target spectrum over 3.5 s by a maximum difference of 11.5 % in the period range, likely because the intention was matching a relatively long period (i.e., the 4.5 s upper limit of the period range), using short distances (near-fault) to the source. In the case of article 16.2.4 of ASCE 7-16 [16] for orthogonality, again, only in the case of near-fault without pulse, the average of the component response spectrum for the records applied in each direction, fell inside ± 10 % the average spectra of all records applied for the period range. Therefore, the same scale factor is applied in each case to both orthogonal records, and no vertical accelerations, if available, are applied.

Experimental Procedure

A single full-scale (4 RP bearings) OCTO-BaseTM isolation system from WorkSafeTM Technologies was used as the prototype; each RP isolation unit is made up of two conical steel plates (upper and lower) covered by an elastomeric coating (QuakeCoatTM) and a steel ball that rolls between these. Fig. 2(a) shows a simplified schematic of the set-up used. The bottom component of the isolation system is attached to the shake table, which is mounted on top of a roller bearing bed and free to move and rotate in the plane by means of 3 actuators (2 in one direction and 1 in the perpendicular). Attached atop is an assembly composed of I-beams and transfer plates connected by angles and threaded-rod bolts, which represents the tributary weight on the system, in this case, 17.9 kN.

Even though standard shake table tests, where actions are imposed at the bottom and the isolation system is completely free to move, are possible, for this study it was more meaningful to restrict the top component from horizontal movement for two reasons: first, it allowed imposing controlled-displacement motions according to specific desired characterization tests (see below), and second, for the RTHS and by using uniaxial load cells in these points, allowed obtaining directly the restoring experimental force necessary for solving the equations of motion to determine a new target displacement in each time step; accordingly and similar to the case of the actuators but in opposite order, 3 restraints were used, 2 in one direction and 1 in the perpendicular. Finally, because the concave properties of the isolation units, every horizontal movement produces a vertical displacement, which is not restricted during the tests because the restraints had hinges in

each end; therefore, the restraints' lengths were defined long enough to make vertical rotations negligible for the load measurements.

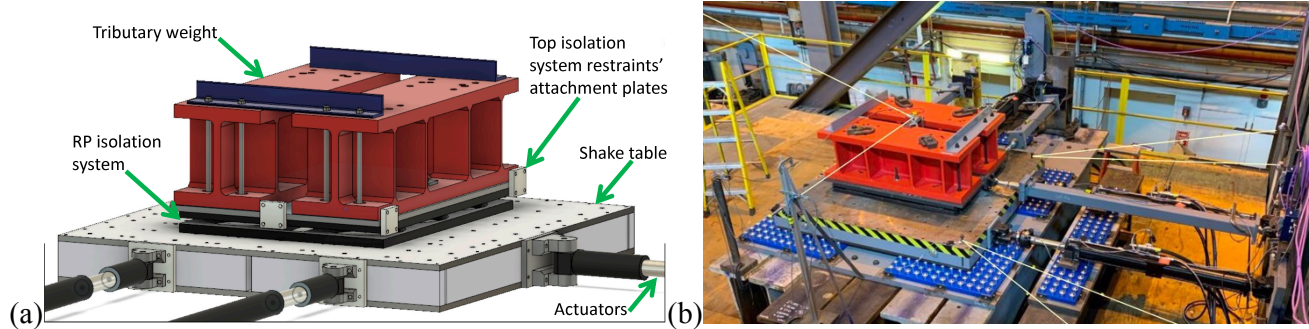


Figure 2. (a) Schematic of test setup on the shake table, and (b) final experimental setup as tested at NHERI Lehigh EF [4].

Fig. 2(b) shows the final experimental set-up. The in-plane restraints run parallel and over the actuators, attached to the top of the isolation system. In addition to the instrumentation already discussed, 3 accelerometers on the shake table measured its in-plane acceleration, and 1 accelerometer and 2 LVDTs were used to measure the vertical motion on the top of the isolation system. Due to the inherent multi-directional characteristics of the tests, a kinematic relationship was necessary in order to adequately define the trajectory of the shake table [23]; string pots were used to monitor such transformations used in the actuators' controls.

Controlled-displacement characterization tests were defined to study the response of the isolation system subjected to a variety of multi-directional conditions [24]. Specifying different frequencies and speeds for the actuators, steady amplitude incremental sine motions, circles, T-like, squares, triangles, butterfly-like, among other shapes with and without rotations were developed to test and capture the envelope performance of the shake table and the isolation system. These responses are additionally an opportunity to finish calibrating and fine-tuning the experimental set-up previously to the more sensitive RTHS tests. In total, 19 characterization tests were defined and performed prior to the RTHS study.

A campaign of RTHS tests was performed defined by an extensive experimental test matrix, which incorporated a combination of building models (LA3 and LA9 buildings), space location in each structure (first 3 floors), earthquake records (far-field, near-fault without pulse and near-fault pulse-like), and hazard levels (FOE, DBE and MCE_R).

Conclusions

Protecting essential building contents, besides facilitating and accelerating the post-event functionality of business operations, has become a major issue in recent years, where the use of RP-based FISs can play an important role. Therefore, determine and validate their multi-directional performance under dynamic excitation and conditions similar as possible to reality (using RTHS), is key for their implementation in design applications. The use of the multi-directional shake table at NHERI Lehigh Experimental Facility for this and future projects, will facilitate improving the level of safety of devices that act in 3D but that in the past were possible to study only in 2D.

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