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 following an event. The resulting social and economic losses can be minimized, or even eliminated, by reducing the seismic forces on building contents through vibration isolation. Floor isolation systems (FIS), in particular, are a promising retrofit strategy for protecting vital building contents. In this study, multi-directional real-time hybrid simulation (RTHS) is utilized to validate mathematical models of isolation systems, in this case utilizing full-scale rolling pendulum (RP) bearings which incorporate multi-scale (building–FIS–equipment) interactions, as well as evaluate a design methodology for multi-functional FISs. As part of the variables to be incorporated are the influence of different steel moment resisting frames (SMRFs) building configurations, each subjected to ground motions of different sources and hazard levels. This paper presents an overview of the NSF EPSCoR Track-4 project (OIA-1929151), which consists of RTHS tests on a multi-axial shake table conducted at the Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at Lehigh University. Details of the experimental test set-up, RTHS test protocol and main results on the multi-directional testing of a RP-based FIS are described. Challenges in conducting the multi-axial RTHS shake table tests, like kinematics transformation and compensation for inertial effects, are also discussed, along with the approaches used to overcome them.

Keywords: seismic isolation, multi-directional, equipment, RTHS

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, such as isolating an entire building [1]. Floor isolation systems (FIS) 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 functionality of the structure, and consequently, of business operation (Figure 1(a)). FISs are designed under the premise that an object (e.g., telecommunications apparatus, a raised floor of a building, etc.) can be decoupled (isolated) from the rest of a structure and its respective disturbances (Figure 1(b)). Thus, these systems decrease the transmitted vibrations and ultimately protect the sensitive and critical objects from damaging effects.

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 [2] was constructed and used, which was also used for characterization controlled-displacements tests in a preliminary stage. Real-time hybrid simulation (RTHS) combines numerical and experimental subsystems into a single simulation technique in real-time [3]. 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.

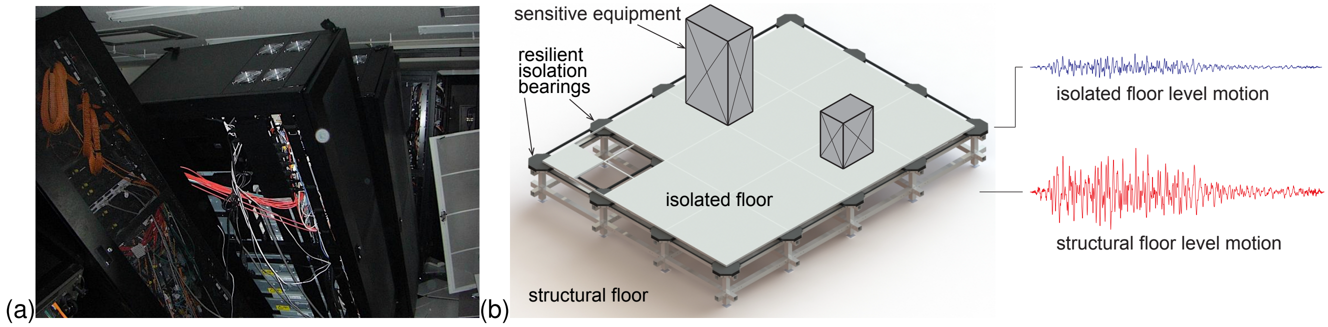

Figure 1: (a) Damage in a data center after an earthquake [4], and (b) schematic of resilient multi-functional FIS concept.

PROBLEM FORMULATION

To evaluate building–FIS interactions and real-scale RP isolation system's performance under earthquake excitation, 3-story (LA3) and 9-story (LA9) steel moment resisting frames (SMRFs) buildings designed for the SAC project for the Los Angeles, California region were used; see Ohtori et al. [5] for additional details on these buildings, including configuration layouts, material mechanical parameters and dynamic properties. Each building was modeled in 3D, including P-Δ effects, using OpenSees [6], to compare results and convergence, and HyCOM-3D [7], to run the RTHSs, obtaining in both cases equivalent natural frequencies from those reported in previous studies [5]. Inelastic (fiber-based) elements were used for all the columns and for the beams part of the MRF; for the gravity system's beams, elastic elements were implemented.

Characterization controlled-displacement tests were defined to study the response of the isolation system subjected to a variety of multi-directional conditions. Steady amplitude incremental sine motions with different frequencies, circles, squares, triangles, butterfly-like, among other shapes with and without rotations were developed to capture the envelope performance.

As the input to run the RTHS cases, a set of earthquake records was developed, following Section 16.2 approach of ASCE 7-16 [8]. First, a target, 5%-damped, MCE_R response spectrum was defined for the Los Angeles financial district (lat. 34.05, long. −118.26) [9], using this location because of its importance, building density and high seismic risk. The deaggregation analysis of the area [10] showed that even though far-field controls FOE hazard, DBE and MCE are controlled by the near-fault events; therefore, priority was given to near-fault (0 km to 15 km) records, which is a result expected for California. Using the NGA-West2 database and online tool for amplitude scaling [11], and defining various parameters—spectral ordinate RotD100, minimizing MSE, all fault types, magnitudes between 6 and 7.9, only one record per earthquake, 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. In summary, 3 far-field records were used for the FOE hazard dividing dividing the scale factors by 2; 13 near-fault without pulse and 7 pulse-like records were used for the DBE hazard dividing the scale factors by 1.5; finally, 13 near-fault without pulse-like records (the same used for the DBE) were used for the MCE_R hazard with scale factors of the analysis.

EXPERIMENTAL PROCEDURE

A single full-scale (4 RP bearings) OCTO-Base™ isolation system from WorkSafe™ 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 and a steel ball that rolls between these. Figure 2(a) shows a simplified schematics of the setup used. The bottom component of the isolation system is attached to the shake table, which is 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, 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,

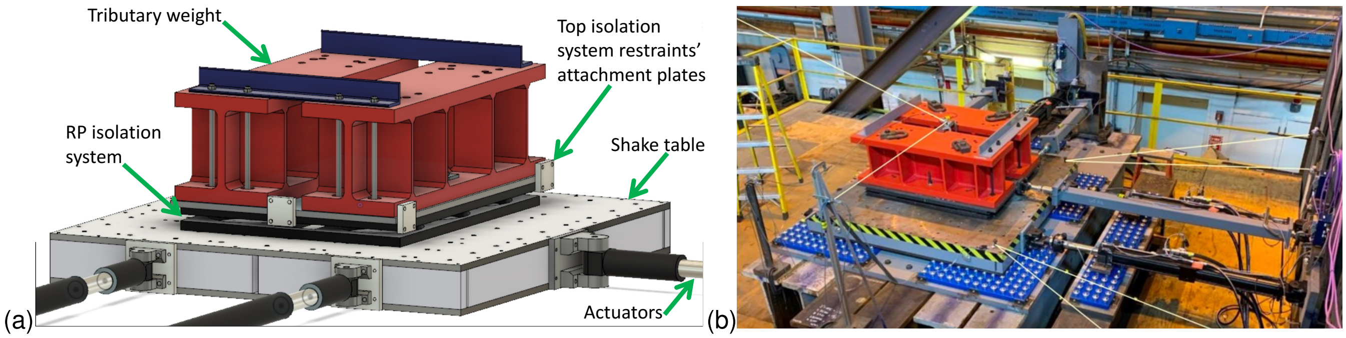

Figure 2: (a) Schematic of test setup on the shake table, and (b) final experimental setup as tested at NHERI Lehigh EF [2].

which is not restricted during the tests because the restraints had hinges in each end; the restraints' lengths were defined long enough to make vertical rotations negligible for the load measurements.

Figure 2(b) shows the final experimental setup. The in-plane restraints run parallel and over the actuators, attached to the top of the isolation system. Besides the instrumentation already discussed, 3 in-plane accelerometers on the shake table, and 1 accelerometer and 1 LVDT on the top isolation system, both vertical, were used. 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 [12]; string pots were used to monitor such transformations used in the actuators controls. In total, 19 characterization tests and 144 RTHS (matrix test conformed by a combination of buildings, earthquake records, and hazard levels) tests were performed.

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