Real-Time Hybrid Simulation Study of Multi-Functional Floor Isolation Systems with Building-Isolator-Equipment Interactions

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ABSTRACT

Damage caused by earthquakes to buildings and their contents (e.g., sensitive 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 (FISs), in particular, are a promising retrofit strategy for protecting vital building contents. In this study, real-time hybrid simulation (RTHS) is utilized to validate mathematical models of isolation systems that incorporate multi-scale (building-FIS-equipment) interactions, as well as evaluate a design methodology for multi-functional FISs. At low-to-moderate disturbance levels, the multi-functional FISs are to function primarily as isolators, and they will passively adapt under strong disturbances to function as essentially nonlinear (vibro-impact) dynamic vibration absorbers to protect the primary building system from collapse. A series of RTHS tests will be conducted at the Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at Lehigh University. This paper presents an overview of the NSF EPSCoR Track-4 project (OIA-1929151), which includes two rounds of RTHS tests. Details of the experimental testbed and RTHS test protocol for the first tests (Summer 2020) are presented, along with results from these tests focused on FIS-equipment interactions and rigorous evaluation of different rolling pendulum (RP) isolation bearing designs through RTHS. Additionally, preliminary planning for the second tests (Summer 2021) is described. Foreseeable challenges in conducting the multi-axial RTHS tests are also discussed, along with approaches to overcoming these challenges.

Keywords: isolation, seismic, equipment, hybrid simulation

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 put on structures [1]. FISs are gaining popularity over other isolation techniques as they have shown to be a valuable retrofitting approach for protecting vital building contents and the post-event functionality of the structure. 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(a)). Thus, these systems decrease the transmitted vibrations and ultimately protect the sensitive objects from damaging effects.

FISs composed of RP bearings under uniaxial loading are studied in this paper. In specific, a model of an RP isolator unit is to be calibrated and validated. As well, multi-scale (building-FIS and FIS-equipment) interactions are studied. To do so RTHS is implemented. RTHS combines numerical and experimental tools into a single simulation technique in real-time [2]. Thus, by implementing RTHS tests it is possible to numerically model buildings and equipment while only physically testing an isolator unit, as well as to accurately measure the effect of interactions between the former and the latter. A new testbed was designed, fabricated and tested to represent a single RP isolator unit.

EXPERIMENTAL SETUP AND MATHEMATICAL MODEL

Figure 1(b) shows the final setup used to perform characterization and RTHS tests. A single RP isolator unit is made up of two

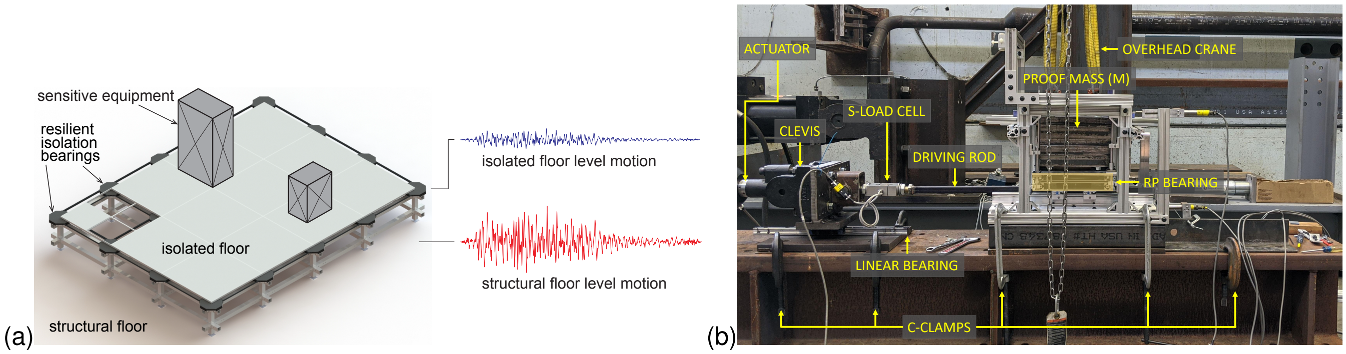

Figure 1: (a) Schematic of a FIS and (b) Final experimental setup as tested at the NHERI at Lehigh

conical steel plates (upper and lower) and a steel ball that rolls between these. Attached atop is proof mass M which represents the tributary load on one isolator unit. The lower rolling surface is constrained to move only horizontally while the upper is to do so vertically by horizontal and vertical guides, respectively. Theses guides are set in place through aluminum framing rails, which at the same time hold the setup together and provide lateral stiffness. To input lateral displacements to the lower rolling surface, the lower part of the setup is attached to a horizontal driving rod, which is attached to a load cell, a clevis and an actuator. The mass of the driving rod and the lower assembly of the setup is m. The clevis is mounted on top of horizontal linear bearings to prevent additional loads going into the setup, and is aligned to so that the driving rod is completely horizontal. C-clamps were used to hold in place the different parts of the experimental setup on top of a base-beam.

Due to said constraints and the rolling surfaces' geometry, a horizontal displacement u in the lower of these causes a vertical displacement v in the upper one. It is the potential energy associated with the vertical motion of this mass that generates the restoring force in the RP isolator. The mass m associated with the lower assembly is not physically present in an actual isolation system, and needs to be compensated for in the RTHS tests.

The vertical displacement v of the proof mass M is kinematically constrained by the rolling of the ball across two concave surfaces having identical profiles $y(x)$. Assuming rolling without slipping, the ball will displace half of the horizontal displacement u of the lower platform. Hence, the kinematic constraint is given by $v = 2y(u/2)$. Given this constraint, and that the kinetic energy of the system is associated with both u and v and the potential energy is only dependant on v, after using Lagrange's equation, the equation of motion of the experimental setup can be expressed in terms of only u as follows:

$$m\ddot{u} + M\ddot{u}[y'(u/2)]^2 + M\dot{u}^2 y'(u/2)y''(u/2)/2 + Mgy'(u/2) + f_d = r^e(t) \tag{1}$$

where r^e is the force applied experimentally to the lower platform in the direction of u, and f_d is the dissipative force due to rolling resistance.

The setup seeks to emulate the behavior of a RP bearing, for which the lower assembly is attached to the floor/ground and m is not present (i.e., $m = 0$). Thus, contrary to the model of the experimental setup, for an actual RP bearing the kinetic energy is dependant only on M. For such system, after applying Lagrange's equation the equation of motion in terms of u is

$$M\ddot{u} + M\ddot{u}[y'(u/2)]^2 + M\dot{u}^2 y'(u/2)y''(u/2)/2 + Mgy'(u/2) + f_d = -M\ddot{x}_\mathrm{f}(t) \tag{2}$$

where $\ddot{x}_\mathrm{f}(t)$ is the building floor acceleration. Eq. (2) is almost identical to that of the RTHS setup [Eq. (1)], with exception of the first (inertial) term—$M\ddot{u}$ for the isolation system, and $m\ddot{u}$ for the RTHS setup—and the right hand sides of the equations. At last, to equate the behavior of the experimental setup to that of an actual RP bearing in a RTHS, the compensated equation to be integrated through the RTHS tests is given as:

$$(M - m)\ddot{u}(t) + r^e(t) = -M\ddot{x}_\mathrm{f}(t) \tag{3}$$

Eq. (3) is integrated by a numerical algorithm [3] in real time to determine the target displacement which is imposed on the test setup. Then, the restoring force $r^e(t)$ is measured by the S-shaped load cell which is fed back into the numerical model to determine a new target displacement and so on. This procedure can be extended for flexible equipment as discussed in the following section.

REAL-TIME HYBRID TESTING

The experimental setup was subjected to a series of characterization and RTHS tests. A test protocol was developed to perform characterization test through a series of harmonic waves with varying frequencies and amplitudes according to IEEE-693 [4]. From these tests, a computer-based model was calibrated. The model was validated through testing the experimental setup under the VERTEQ-II synthetic floor described in GR-63 [5]. Both conical and flat surfaces were used to investigate the rolling resistance induced by elastomeric coating, which is added layer by layer to bare steel rolling surfaces. Different levels of coatings were used to understand the effect of such in the damping of the isolator unit. A total of 15 unique configurations of the test setup were used in order to measure and evaluate the effects of the rolling surface's rolling resistance and shape, and the tributary mass on the bearing.

For the RTHS tests, the experimental setup was subjected to synthetic and recorded ground motions in accordance to GR-63 [5] and FEMA 461 [6]. To evaluate the FIS-equipment interaction, sensitive equipment was numerically modeled as a cantilever beam with both rigid and flexible characteristics. FIS-equipment interactions were only evaluated under synthetic floor motions. To evaluate the building-FIS interactions, a Hybrid-FEM numerical model of a 3-story steel moment resisting frame [7] was developed and used. For this, earthquake records at different intensities were applied as input motions.

DISCUSSION

In total, 240 tests among characterization and RTHS were performed. RHTS allows for numerically compensating for the extra mass in the experimental setup (m) through the equation of motion's integration in Matlab scripts and Simulink models. In this study, the effect of varying parameters (rolling surfaces' rolling resistance and shape, and isolated equipment weight) are evaluated. Furthermore, the inertial effects of the non-linear RP-bearing under uniaxial loading are analyzed. In this study, the conical rolling surfaces load-deflection relationships show hysteretic behavior in the system, which can be effectively modeled with a Bouc-Wen model. A preliminary model for unaxial loading will set ground to develop more advanced models for upcoming studies involving biaxial and triaxial loadings in the second round of tests. Foreseeable challenges for the second round of tests regarding the experimental setup are related to physically applying motion constrains and incorporating vertical motion into the RP bearing.

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