Appendix C6: Lehigh University - Large-Scale Multi-Directional Hybrid Simulation Testing

EXPERIMENTAL FACILITY OVERVIEW

The Lehigh NHERI Experimental Facility (EF), known as the Multi-Directional Real-Time (RTMD) Hybrid Simulation Facility, operates in the Multi-Directional Testing Laboratory at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center at Lehigh University. Over 25 years of ATLSS Center operations, including 12 years as a NEES@Lehigh equipment site and the past three years as a NHERI EF, the Lehigh NHERI Experimental Facility has acquired a unique portfolio of equipment and instrumentation, has assembled a well-trained and skilled staff, and developed state-of-the-art algorithms, software, and tools for real-time integrated simulation control to enable large-scale real-time hybrid simulations to be performed on a routine basis. The strength of the Lehigh NHERI Experimental Facility is accurate large-scale simulations of the effects of natural hazard events on civil infrastructure.

Large-Scale Hybrid Simulation of a Self-Centering Steel Moment Resisting Frame Building under Simulated Eathquake Loading

The unique equipment portfolio (capabilities exist only at Lehigh) includes:

- Three 1700 kN and two 2300 kN servohydraulic actuators with 1000 mm stroke and maximum velocities of up to 1140 mm/sec.
- Hydraulic power supply system consisting of 5-454 lpm pumps and a 3030 liter accumulation system enables earthquake effects on structures to be sustained for more than 30 seconds during a large-scale real-time hybrid simulation.
- Real-time integrated IT control system, which integrates laboratory data acquisition, computational simulation, and servo-hydraulic actuator control in a single IT system.
- ATLSS Center with its 3-D reaction wall-strong floor laboratory, skilled laboratory staff (instrumentation, construction, hydraulics, and control) and additional resources (additional servo-controlled actuators, instrumentation, digital image correlation system, mechanical testing laboratory, metallography and microscopy laboratory, non-destructive evaluation laboratory, machine shop, offices for visiting researchers).

Real-time Cyber-Physical Structural Systems Facility

The NSF-sponsored NHERI Lehigh Experimental Facility also features the NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory (RCPSS). This is a resource that has the purpose of enhancing the experience of participants through hands-on experiences in research, education and community outreach (ECO) activities, and training in cyber-physical systems (i.e., hybrid simulation).

The laboratory features five test beds that have dedicated dynamic actuators along with a multi-directional shake table. A real-time integrated control system connects the test beds and shake table, enabling users of the RCPSS to conduct concurrent testing that is synchronized in real-time by simultaneously engaging the various test beds and the shake table. The real-time integrated control system includes tools for creating nonlinear models (both with material and geometric nonlinearities) that can be used for numerical simulation or real-time hybrid simulation. Users of the RCPSS can readily perform 3-D real-time hybrid simulations consisting of multiple experimental substructures and nonlinear analytical substructures. An example real-time hybrid simulation could consist of multiple experimental substructures comprised of structural response modification devices that are each placed in various test beds along with a structural assembly placed on the shake table. These multiple experimental substructures are linked to the analytical substructure to define the complete system subjected a natural hazard, such as an earthquake or wind storm. Tools are available to include the effects of soil-foundation-structural system interaction in experiments by modeling the soil and foundation numerically as part of an analytical substructure, or creating another experimental substructure using the facility's soil box.

Cyber-Physical Structural Systems Testing Laboratory Testbed: characterization testing of a next-generation Banded Rotary Friction Damper for mitigating dynamic vibrations in structural systems.

Real-time Cyber-Physical Structural Systems Facility Test Beds Specifications

A dynamic actuator and test specimen can be placed in each test bed of the RCPSS. The specifications and of the features of these test beds include:

- Five test beds, each with a dynamic servo-hydraulic actuator. The actuators can achieve peak velocities up to 51 inch/sec with a stroke of 20 inches. Actuator specifications are included below in Table 1.
- The actuator of each test bed is controlled using a multi-channel digital controller with a 1024 Hz clock speed. Each actuator can be controlled independently or in unison to enable synchronized experiments using multiple test beds.
- Specimens up to about 24 to 36 inches in length can be accommodated in each test bed.
- A real-time integrated control architecture with software exists that is identical but independent of the Lehigh NHERI Experimental Facility integrated control system for performing multi-directional real-time hybrid simulations. It enables real-time hybrid simulations to be performed using multiple test beds and the multi-directional shake table (described below), where it can be linked to nonlinear analytical substructures that model the remaining part of a structural system and its foundation system.
- Multi-channel digital controller with clock speeds of 1024 Hz and 2048 Hz.
- Four small scale 8 kip nonlinear viscous dampers and a 10 kip banded rotary friction damper are available for use in the test beds.

- Elevated temperatures (up to 140 F) and cold temperatures (down to about 32 F) can be imposed on specimens in the test beds using heating coils and the environmental temperature chamber.
- 64-channel 4096 Hz 50 channel data acquisition system and an array of sensors to measure displacement, rotation, temperature, and acceleration are available to acquire measured test data.
- A digital imaging correlation system is available for performing non-contact measurements of displacements and strains in specimens

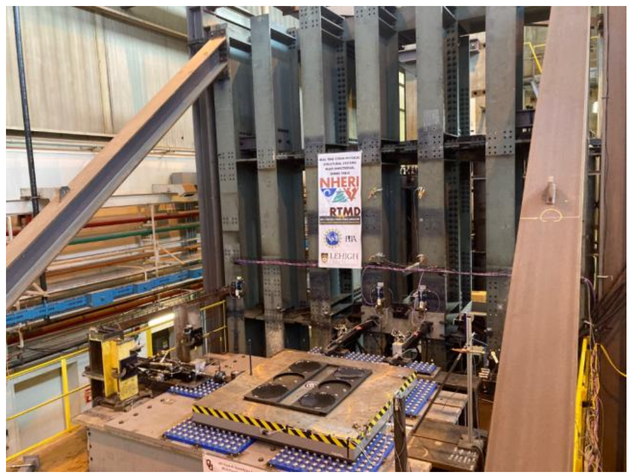
Table 1. Actuator Specifications

Quantity	Actuator		
	MTS 244.21G2	MTS 244.20G2s	MTS 244.20
Max Force	50 kN (11 kips)	82 kN (18.5 kips)	100 kN (22 kips)
Max disp.	±254 mm (±10 in)	±177 mm (±7 in)	±76 mm (±3 in)
Max velocity	0.74 m/s (29 in/s)	1.29 m/s (51 in/s)	0.38 m/s (15 in/s)
Servo Valve	30 gpm	90 gpm	30 gpm

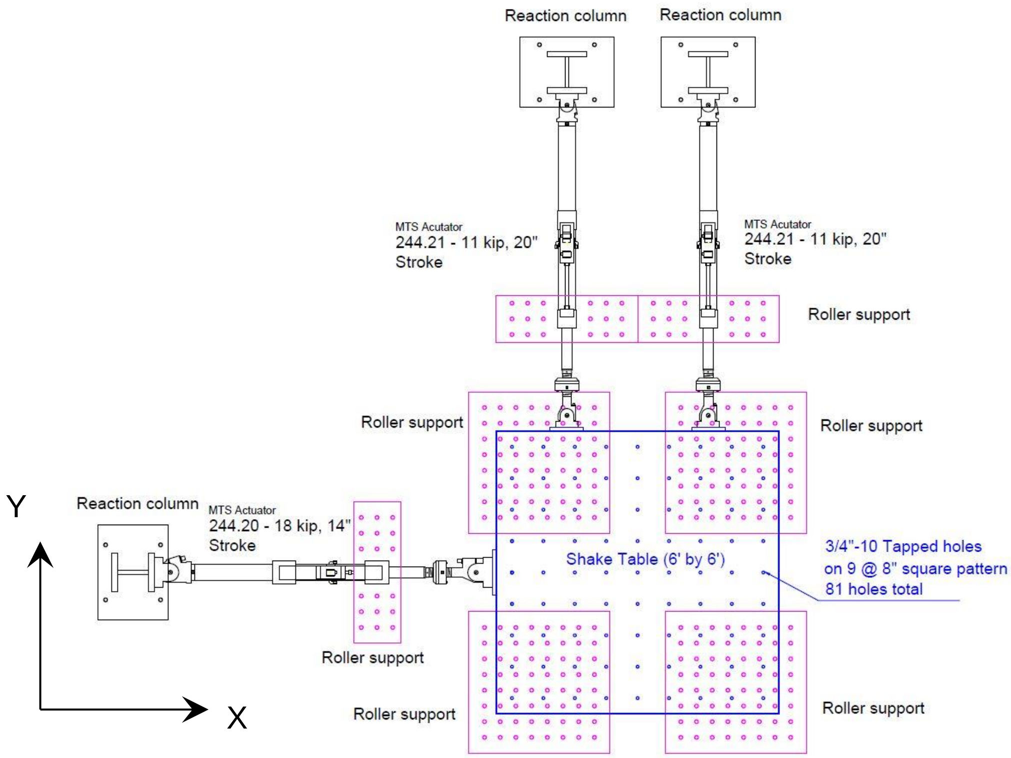
Real-time Cyber-Physical Structural Systems Facility Shake Table Specifications

The table can be used in different configurations in order to perform a range of experiment, including: real-time hybrid shake table simulations; traditional shake table testing; and quasi-static or dynamic testing. The shake table features include:

- Multi-directional motions, including two orthogonal translations (X and Y-axis) and in-plane rotation.
- Multi-channel digital controller with 1024 Hz clock speed.
- 64 channel 4096 Hz 50 channel data acquisition system.
- Real-time integrated control architecture with software that is identical to that of the Lehigh NHERI Experimental Facility multi-directional real-time hybrid simulation system, enabling real-time multi-directional shake table hybrid simulation.
- Three MTS actuators, including one MTS Model 244.20 Hydraulic Actuator (X-axis) and two MTS Model 244.21 Hydraulic Actuators (Y-axis).
- A payload of 13 kips (5.9 tons) with 1g acceleration.
- Table platen size of 6 ft × 6 ft.
- Maximum table motions of ±7 in. (X-axis) and ±10 in. (Y-axis).
- Peak velocities of 51 inch/sec (X-axis) and 29 inch/sec (Y-axis).



Cyber-Physical Structural Systems Testing Laboratory Shake Table – setup for performance testing of equipment floor isolation systems in buildings subject to wind and seismic loading.



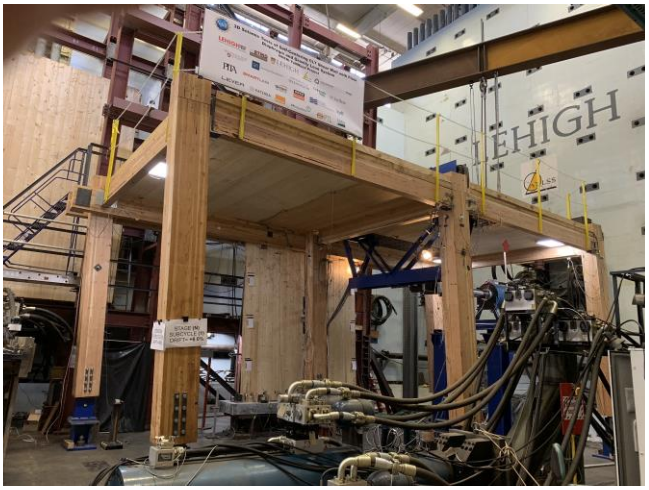
Plan view of Cyber-Physical Structural Systems Testing Laboratory Shake Table: table dimensions, actuator force and stroke capacities.

Additional information regarding the facility and leadership group is available at the DesignSafe website https://lehigh.designsafe-ci.org/facility/overview/

RESEARCH OPPORTUNITIES

Characterization of Large-Scale Response Modification Devices

Stakeholders are interested in promoting resiliency of their structural to the effects of natural hazards. Consequently, there has been an interest in developing new and innovative response modification devices and structural systems that reduces damage and downtime of a building following an extreme natural hazard, such as wind or an earthquake event. The equipment at the NHERI Lehigh EF can be used to characterize large-scale devices that are placed in structural systems for the purpose of modifying the building response in order that the system become more resilient to these events. Examples of these devices include passive controlled dampers (e.g., nonlinear viscous dampers, elastomeric dampers, negative stiffness dampers), semi-active controlled dampers (e.g., magnetorheological damper), and yielding devices (e.g., buckling restrained braces). Several testbeds and an environmental chamber exist at the Lehigh EF that can be used to perform the characterization tests on response modification devices considering as parameters: displacement amplitude, frequency of loading, and ambient temperature. Such data is useful to develop and calibrate computational models for the purpose of performing numerical simulations to investigate the effectiveness of these devices in improving the resiliency of the building.



Large-Scale Multi-Directional Testing of a Cross-Laminated Self-Centering Shear Wall - Floor Diaphragm System under Simulated Eathquake Loading

Use of Supplemental damping Systems in Mitigating the Multi-directional Effects of Natural Hazards

A number of building codes have published criteria for using supplemental damping systems to mitigate the effects of earthquake and wind. However, experimental validation of the criteria is lacking, enabling improved design criteria and efficiency to be developed and utilized by the profession. An example is the allowable reduction of the design base shear to 75% of the code seismic design base shear. Is this an acceptable value that results in an adequate margin against collapse under extreme earthquake or wind loading? A testbed exists at the NHERI Lehigh EF that will enable multi-directional real-time hybrid simulations to be performed on lateral load resisting systems outfitted with dampers, or other types of response modification devices. The large-scale dynamic actuators in combination with the

Enhancing the Resiliency of the Built Environment – Lehigh NHERI RTMD Large-scale Hybrid Simulation Facility

The Real-Time Multi-Directional (RTMD) Large Scale Hybrid Simulation NHERI Facility at Lehigh University provides researchers access to unique equipment and simulation tools. Keri Ryan, associate professor of civil and environmental engineering at the University of Nevada, Reno used the facility to investigate the performance of non-structural components in buildings subject to multi-directional earthquake ground motions. This study would not have been possible at her home institution. With the NHERI Lehigh facility, however, Professor Ryan was able to develop innovative non-structural component details that remain damage-free under strong earthquake ground motions and advance community resilience.

multi-directional reaction wall enables large-scale specimens to be tested. Through multi-directional real-time hybrid simulation, the interaction of the lateral load resisting system, the supplemental damper system, the gravity load system, and soil and foundation system can be investigated.

Large-Scale Damper Testbeds for Characterization and Real-time Hybrid Simulation of Structural Systems Subjected to Wind or Earthquake Loading

Multi-direction Real-time Hybrid Simulation of Semi-active controlled Base Isolation Systems

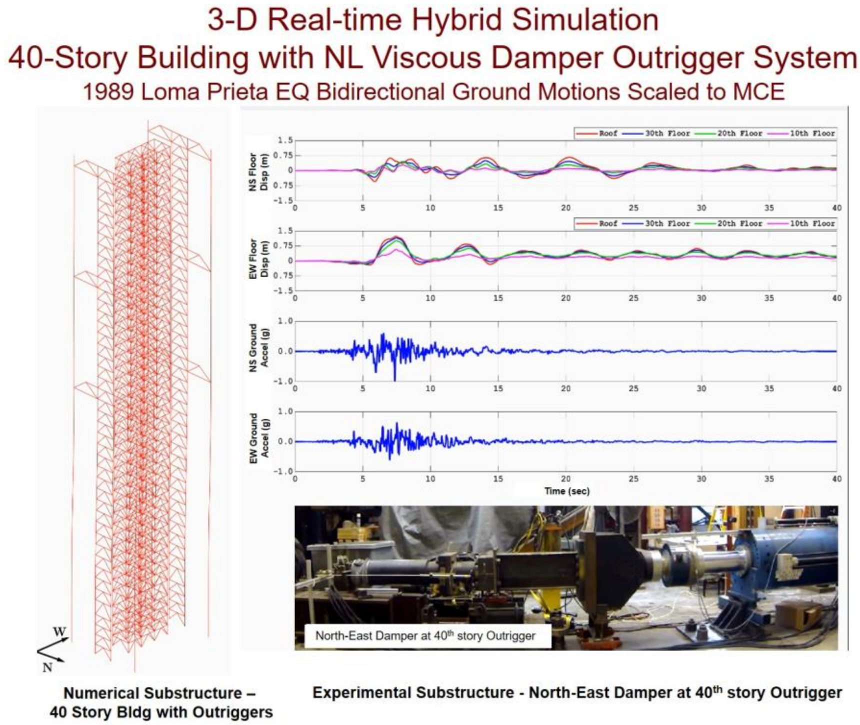
Base isolation has become a popular technique to mitigate the effects of strong ground motions caused by earthquake that leads to damage and downtime. However, there are still a number of research questions that need to be addressed, particularly the effects of near-fault earthquake ground motions on base-isolated structures. It has been shown analytically that conventional base-isolated systems do not perform as well under these type of ground motions compared to far-field ground motions. A possible solution is to incorporate semi-active devices to create a semi-active controlled base isolation system. Multi-directional real-time hybrid simulations can be performed at the NHERI Lehigh EF, where the isolation system is located in the laboratory (i.e., is the experimental substructure) and kinematically linked to the superstructure through their common degrees of freedom. The superstructure is modeled numerically through the analytical substructure. This is an economical approach to test the complete system, since only the isolators need to be physically constructed, enabling many tests to be performed using the same testbed and isolators. The NHERI Lehigh EF has hardware in its real-time integrated control system that enables researchers to implement and study different semi-active control laws for the isolation system.
Geographically Distributed Hybrid Simulation

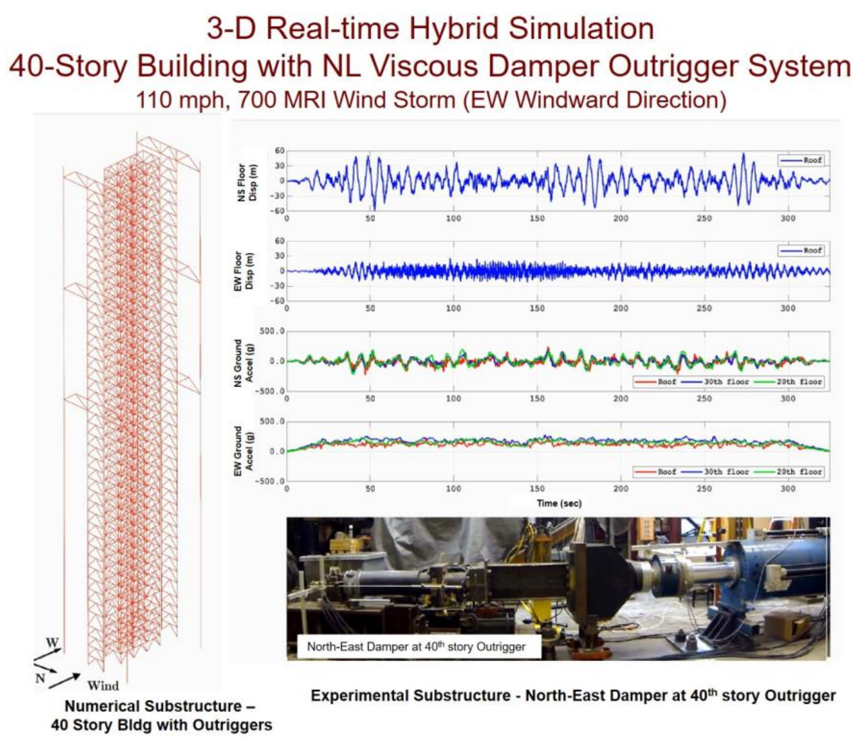
Often the size of the test specimen exceeds the capabilities of the experimental testing facility (e.g., number of testbeds, actuators, laboratory-testing space). The NHERI Lehigh EF has capabilities to team up with other testing laboratories to perform geographically distributed hybrid simulation of structural systems. An example of a geographically distributed hybrid simulation is where several experimental substructures are located at Lehigh and at the collaborator’s laboratory. A conductor, using the Internet with communication protocols to issue command displacements and obtain feedback forces, directs the simulation. This method can be used to investigate the response of a structure to wind or earthquake hazards with a large response modification devices. Testbeds for the devices are located amongst the laboratories. The devices are linked to the remaining part of the structure that is modeled numerically (i.e., analytical substructure) for the hybrid simulation.

The effects of soil-structure interaction on the multi-directional response of a structural system to wind or earthquake hazards can also be investigated using this simulation approach. Components of the foundation can be located in a soil box either at Lehigh or remotely at another laboratory, where this experimental substructure is linked to other experimental substructures of components of the superstructure located at Lehigh.

Building Community Resilience to Natural Hazards Using Large-scale Hybrid Simulation

The Lehigh University Real-Time Multi-Directional (RTMD) Large Scale Hybrid Simulation NHERI Facility is the largest facility of its kind in the nation. This unique, shared-use facility is dedicated to enabling transformative research that reduces the impact of natural hazards and advances the resiliency of the nation's civil infrastructure. Researchers have access to state-of-the-art equipment and simulation tools to study the response of civil infrastructure to 3D wind or earthquake loading, where the complete structural and foundation systems are included in the investigation. This is accomplished through real-time hybrid simulations that combine physical experiments with state-of-the-art computer-based simulations for evaluating the performance of large-scale components and systems.

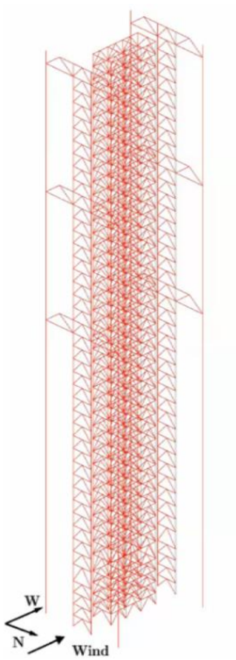




3-D Large-scale Real-time Hybrid Simulations of Structural Systems Subjected to Wind and Earthquake Loading

3D Real-time Hybrid Simulation Study: Mitigation of Wind Hazards in Tall Building Using a Next-Generation Rotary Friction Tuned Mass Damper System

Tall buildings are subjected to wind forces that can generate unpleasant vibrations that disturb the occupants. Strategies need to be developed that mitigate these effects caused by wind storms by reducing the response of buildings to these natural hazard events. To develop and validate these strategies, 3D real-time hybrid simulations are performed. The structure for the study is a 40-story building subjected to a 100 mph wind storm with a 700 year MRI. A nonlinear analytical substructure model is created using the Lehigh NHERI EF real-time hybrid simulation modeling software. A response modification device consisting of a next-generation rotary friction tuned mass damper system is positioned on the roof to negate wind vibrations developed in the building. This next-generation device is placed in one of the test beds of the Cyber-Physical Structural Systems Testing Laboratory, where it becomes the experimental substructure for the simulation. 3-D wind pressures from a wind tunnel model are obtained from wind tunnel testing at the NHERI FIU WOW Expeimental Facility and applied to the analytical model to simulate the wind demand on the building. The soil-structure interaction effects on the tuned mass damper's effectiveness are investigated by including the soil-foundation system in the analytical substructure for the simulation. A series of 3D real-time hybrid simulations are performed to assess the effects of wind directionality, characteristics of the tuned mass damper system, soil-structure interaction, and nonlinearities in the analytical substructure on the response of the building.

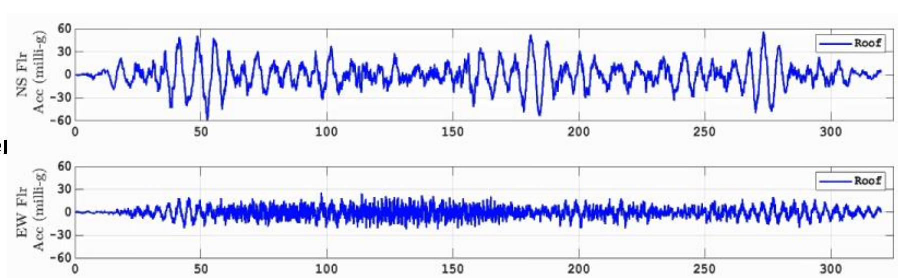


Experimental Substructure

Rotary Friction Tuned mass Damper at Roof

Analytical Substructure

40 story Building with Outrigger



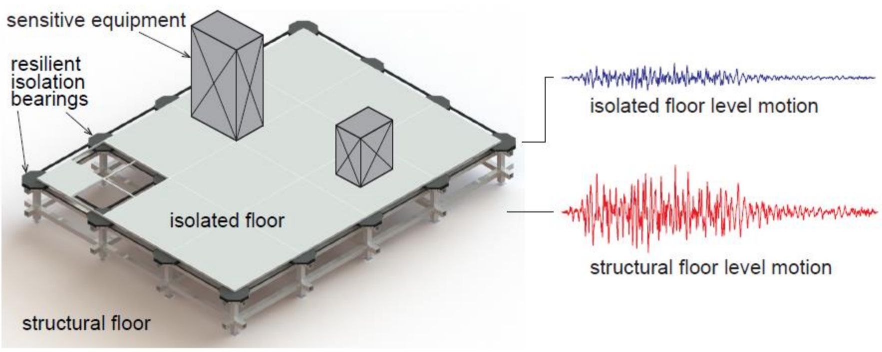
Results

Roof Acceleration Time Histories

3-D Real-time hybrid simulation of a tall building with tuned mass rotary friction damper subjected to a 700 MRI year 110 mph wind storm.

3D Real-time Hybrid Simulation Study: Effectiveness of Floor Isolation Systems in Buildings to Mitigate Equipment Damage During a Seismic Event.

A community's resilience to natural hazards is defined by its ability to absorb an extreme event and maintain an acceptable level of functionality following the event. The community's capacity to meet these objectives depends on the individual components comprising the community, especially critical buildings such as lifeline centers (hospitals) and telecommunication networks. Property, economic, and human losses may be reduced if the uninterrupted operation of such facilities is ensured — one of the thirteen Grand Challenge Problems in earthquake engineering research identified by the National Research Council. In buildings where it is not practical or economical to retrofit the building's structural system, floor isolation systems (FISs) provide an attractive alternative for protecting vital, yet sensitive, building contents and equipment from earthquakes. These systems utilize a compliant interface, composed of isolation bearings, that decouples the sensitive contents from harsh floor motions (see figure below). An innovative new class of FISs is proposed that function as dual-mode vibration isolator/absorber systems protecting both the equipment and the supporting structure. The absence of experimentally validated, practical design methodologies hinder this approach from gaining traction with building owners and investors.

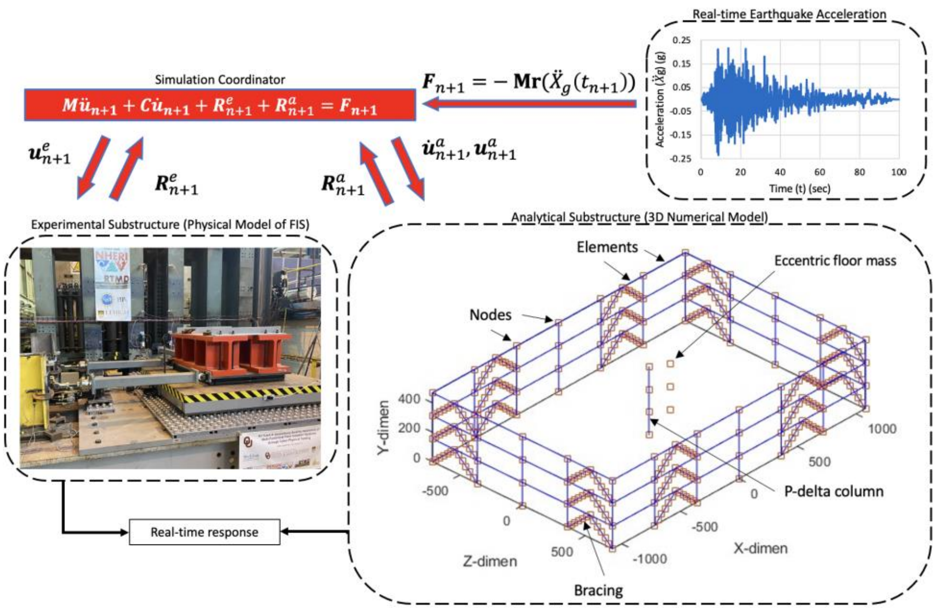


Resilient multi-functional floor isolation system (source: Scott Harvey, University of Oklahoma)

An experimental campaign consisting of characterization tests and real-time hybrid simulations is ideal for acquiring characterization data for computational and design model development, in addition to experimentally validating the performance of the floor isolation system and the design methodology in reducing acceleration demands on equipment housed in a building. Shown below is the test setup for conducting the characterization tests.

Test setup for multi-directional characterization tests and real-time hybrid simulations of floor isolation systems (RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing (OIA 1929151), PI - Scott Harvey, University of Oklahoma).

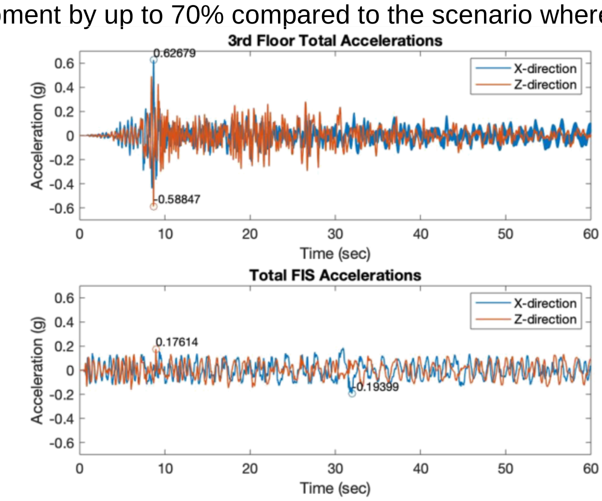
The setup also serves as the experimental substructure for the multi-directional real-time hybrid simulations. For the real-time hybrid simulations the floors isolation system is located on the third floor of a three-story concentrically braced frame. The building has eccentric mass, resulting in a coupled translational-torsional response. Diagonal brace buckling is considered in the simulation by modeling the braces using a co-rotational brace element with nonlinear material and geometric nonlinearities that is available via the Lehigh NHERI EF real-time hybrid simulation modeling software. In addition, the equipment that is being isolated is considered in the simulations by incorporating it into the analytical substructure. The Cyber-Physical Structural Systems Testing Laboratory multi-directional shake table is used to create the experimental substructure to enable multi-directional translations and torsion motion to be applied to the isolation system. The layout of the multi-directional hybrid simulations is shown below. A series of real-time hybrid simulations are conducted to investigate the effects of earthquake record-to-record variability, building properties, location of the isolation system, and seismic hazard level (frequent, design, and maximum credible earthquakes).



Configuration of real-time hybrid simulations of floor isolation systems in concentrically braced frame systems subject to bi-directional earthquake ground motions

The results from one of the real-time hybrid simulations are shown below, where the time history of the 3rd floor total accelerations in the bidirectional directions along with the total accelerations of the isolated equipment are shown. The results from the real-time hybrid simulations reveal that the floor isolation system was able to reduce the total accelerations in the equipment by up to 70% compared to the scenario where the equipment was not isolated.

Reductions in Acceleration	
X-Direction	Z-Direction
69%	70%



Results of real-time hybrid simulations of floor isolation systems in concentrically braced frames subject to bi-directional earthquake ground motions: reduction in accelerations of isolated equipment (RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing (OIA 1929151), PI - Scott Harvey, University of Oklahoma).

NSF Funding

Experimental Facility with Large-Scale Multi-Directional Hybrid Simulation Testing Capabilities

(NSF award No. CMMI-1520765 and XXXX)