NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory

The NSF-sponsored NHERI Lehigh Experimental Facility now features the NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory (RCPSS). This new acquisition is a resource that was created to enhance the experience of participates 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 facilities soil box.

Users of all experience levels are welcome to check out the RCPSS. Training workshops are planned to provide participants with hands-on experience. These workshops will enable participants to discover how real-time hybrid simulation is performed and to become familiar with the technique through the hands-on exercises that use the test beds, shake table, and 3-D nonlinear modeling resources. In addition to training and ECO activities, the facility is available for users to perform pilot studies for generating data to include in their NSF-sponsored research proposals.

Curious how the RCPSS can enhance your understanding of hybrid simulation and advance your research? The NHERI Lehigh Experimental Facility team encourages inquiries from perspective users. Inquiries can be directed to Dr. Liang Cao, NHERI Lehigh EF Research Engineer (lic418@lehigh.edu) or Professor James Ricles, NHERI Lehigh EF Director (jmr5@lehigh.edu). Information about the additional resources and capabilities of the NHERI Lehigh Experimental Facility for performing large-scale experiments can be found on our web site at https://lehigh.designsafe-ci.org/facility/overview/.

Real-time Cyber-Physical Structural Systems Test Beds

The RCPSS features five test beds. In each test bed a dynamic actuator and test specimen can be placed. The features of the test beds include:

1) 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.
2) The actuator of each test bed is controlled using a multi-channel digital controller with a 2048 Hz clock speed. Each actuator can be controlled independently or in unison to enable synchronized experiments using multiple test beds.
3) Specimens up to about 24 to 36 inches in length can be accommodated in each test bed.
4) A real-time integrated control architecture with software that is identical to that of the NHERI Lehigh Experimental Facility integrated control system for performing multi-directional real-time hybrid simulation. It enables real-time hybrid simulations to be performed with multiple test beds and the multi-directional shake table (described below), where they can be linked to nonlinear analytical substructures that model the remaining part of a structural system and its foundation system.
5) Four small scale 6.6 kip capacity nonlinear viscous dampers and a 10 kip capacity friction damper are available for use in the test beds.
6) Elevated temperatures (up to about 140 F) and colder temperatures (down to about 32 F) can be imposed on specimens in the test beds using heating coils and the controlled temperature chamber.
7) 32-channel high-speed data acquisition system and an array of sensors to measure displacement, rotation, temperature, acceleration, strain and force are available to acquire measured test data.
8) A digital imaging correlation system is available for performing non-contact measurement of displacements and strains in specimens.

Table 1. MTS Actuator Specifications

Quantity	Actuator		
	244.21G2	244.20G2s	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 Test Beds Usage Examples

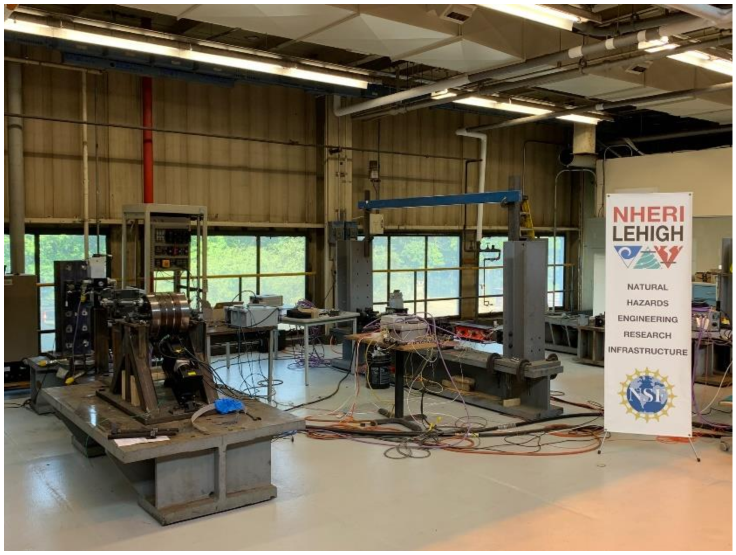


Figure 1. Test beds of NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory.

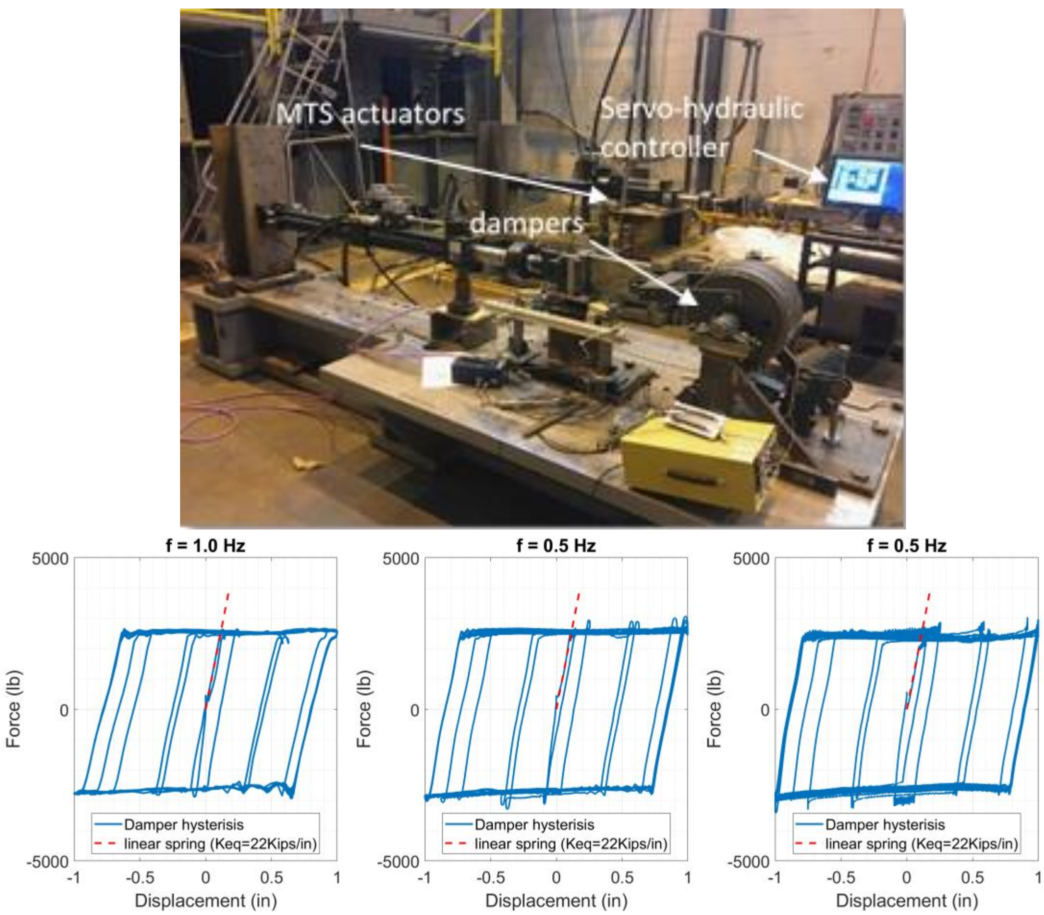


Figure 2. Characterization testing of a next-generation rotary friction damper.

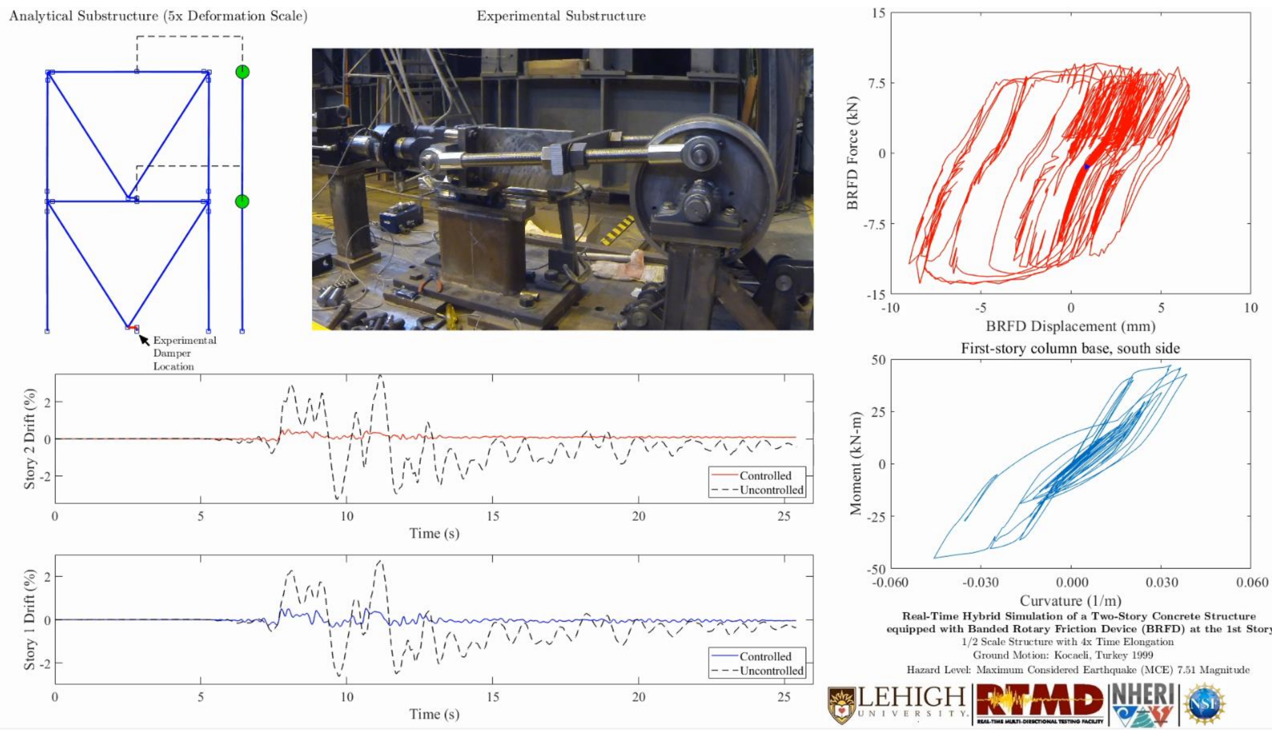


Figure 3. Real-time hybrid simulation of a 2-story reinforced concrete structure with a next-generation rotary friction damper subject to earthquake ground motions scaled to the MCE hazard level.

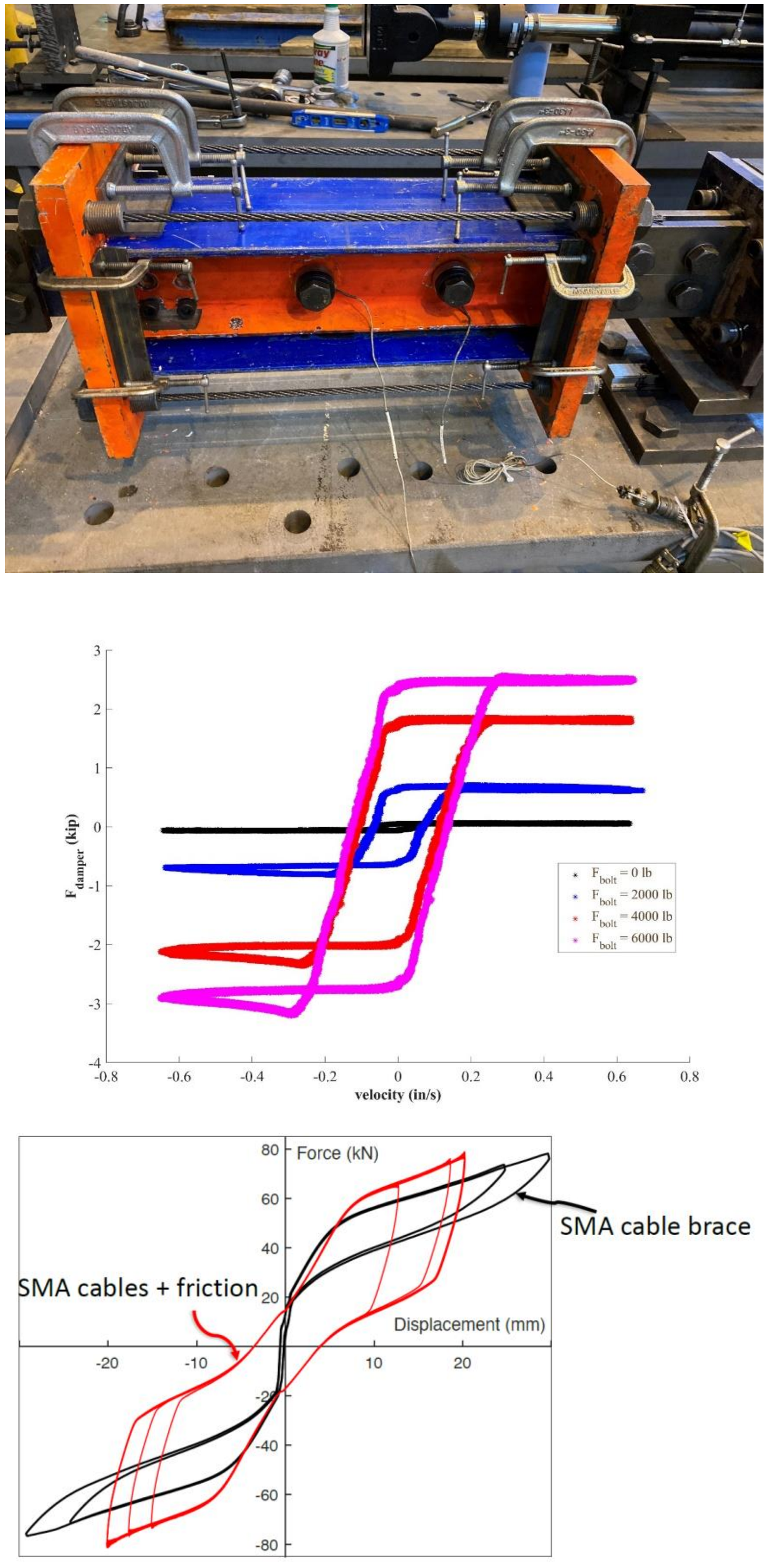
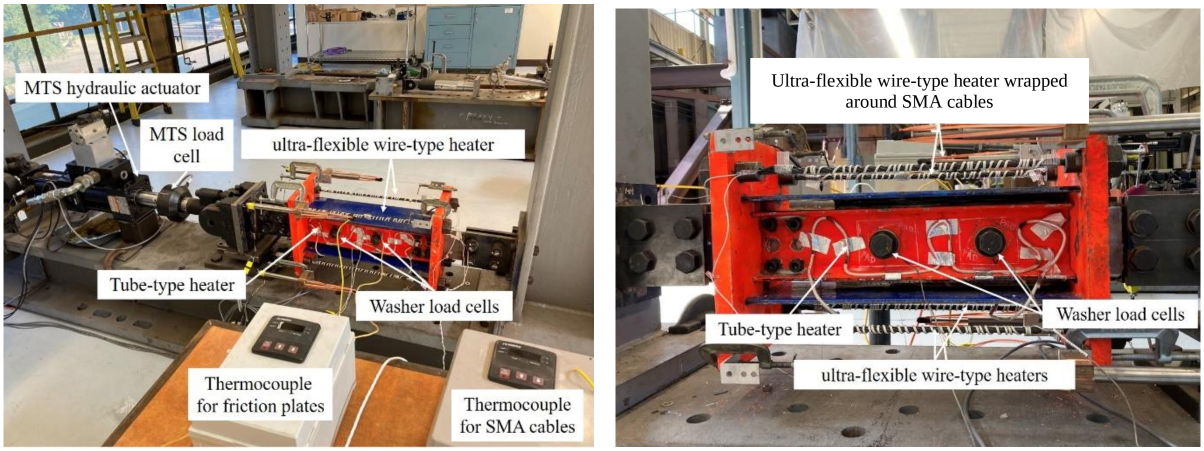
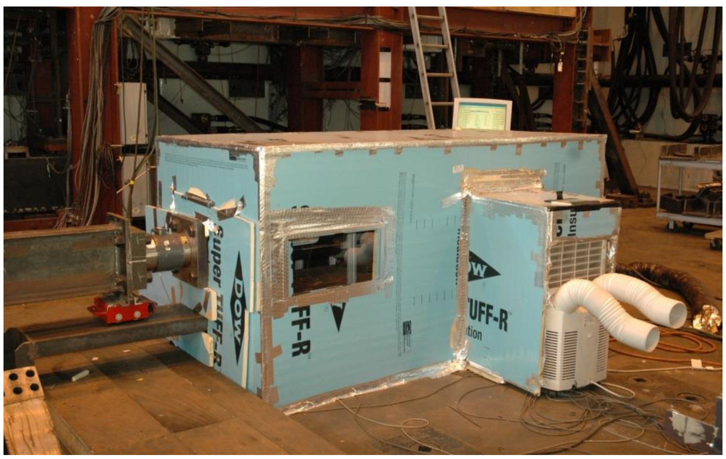


Figure 4. Characterization testing of a shape memory alloy-friction damper.

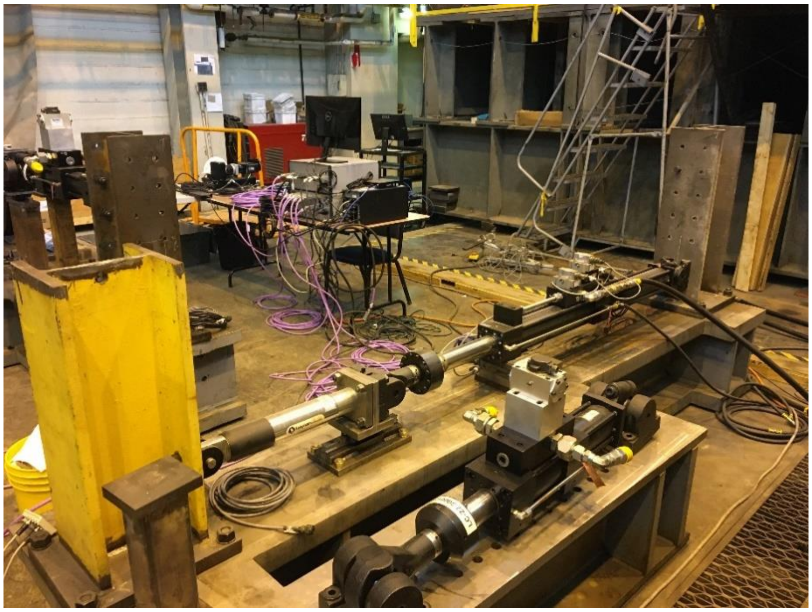


Elevated temperature heating elements

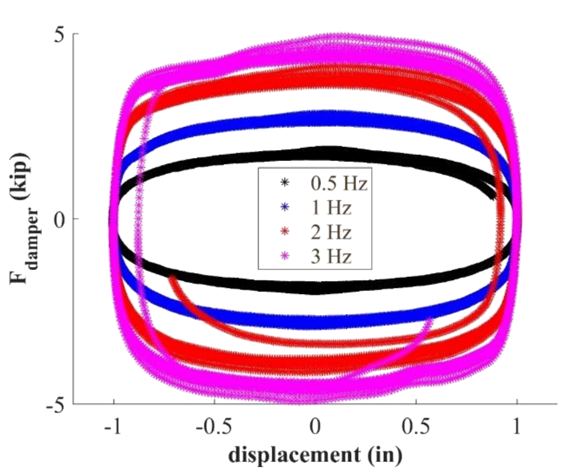


Controlled cold temperature chamber

Figure 5. Characterization testing of a shape memory alloy-friction damper at elevated temperatures using heating elements and cold temperature chamber.



Test setup for characterization testing **Viscous dampers**



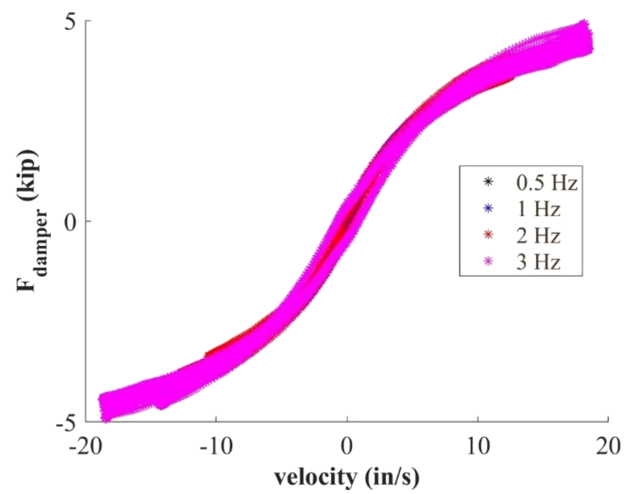
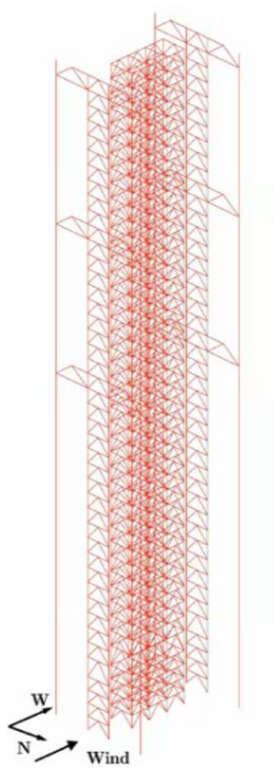
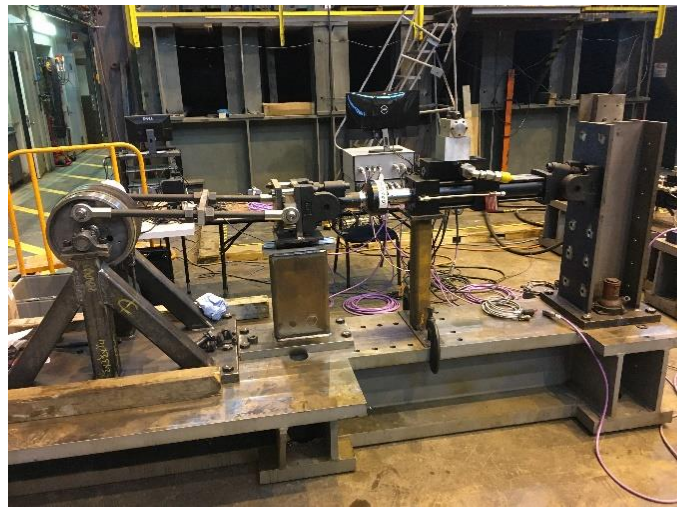


Figure 6. Characterization testing of a nonlinear viscous damper.





<u>Analytical Substructure</u>
40 story bldg with outriggers

<u>Experimental Substructure</u>
Tuned mass rotary friction damper at roof

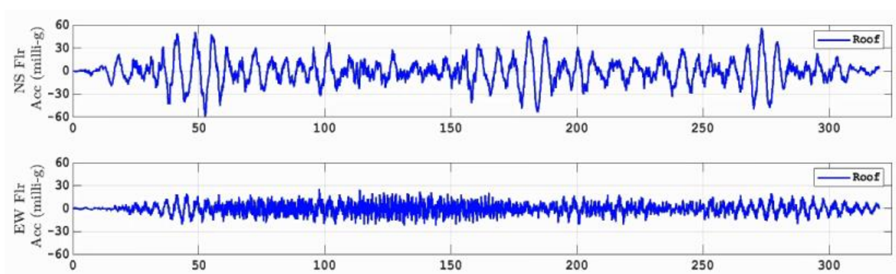


Figure 7. 3-D Real-time hybrid simulation of a tall building with tuned mass rotary friction damper subjected to a 700 year MRI 110 mph wind storm.

Real-time Cyber-Physical Structural Systems Multi-directional Shake Table

The multi-directional shake table can be arranged in different configurations in order to perform a variety of experiments, including: real-time hybrid shake table simulation; traditional shake table testing; and quasi-static or dynamic testing. For a real-time hybrid simulation involving the shake table, additional dynamic actuators are used to create the experimental substructure and control the interface degrees of freedom between the experimental and analytical substructures.

The first series of experiments will be performed beginning in August, 2021 for the NSF project *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 experiments will involve real-time hybrid simulations of floor isolation systems in multi-story buildings subject to multi-hazards, including wind and earthquake events.

The features of the shake table include:

1) Multi-directional motions, including two orthogonal translations (X and Y-axis) and in-plane rotation.
2) Multi-channel digital controller with 2048 Hz clock speed.
3) 32-channel high-speed data acquisition system and an array of sensors to measure displacement, rotation, temperature, acceleration, strain and force to acquire measured test data.
4) A real-time integrated control architecture with software that is identical to that of the Lehigh NHERI Experimental Facility multi-directional real-time hybrid simulation integrated control system, enabling real-time multi-directional shake table hybrid simulations to be performed. The multi-directional shake table can can be linked to multiple experimental test beds and nonlinear analytical substructures that model the remaining part of a structural system and its foundation system to perform real-time hybrid simulations that concurrently use the shake table and the test beds.
5) A payload of 13 kips (5.9 tons) at 1g acceleration.
6) Table platen size of 6 ft × 6 ft.
7) 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).

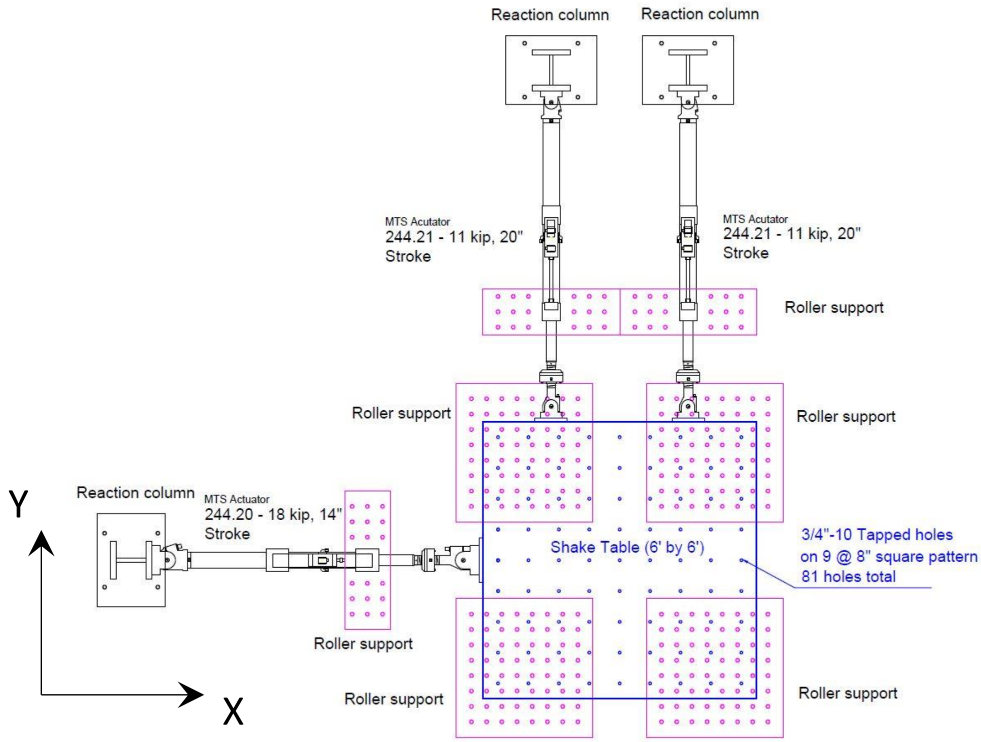


Figure 8. Plane view schematic of multi-directional shake table.

Figure 9. Photograph of multi-directional shake table during construction showing roller bearing system.

Figure 10. Photograph of completed multi-directional shake table with multi-directional translation and torsional in-plane motion applied.

Cyber-Physical Structural Systems Shake Table Example Project Usage

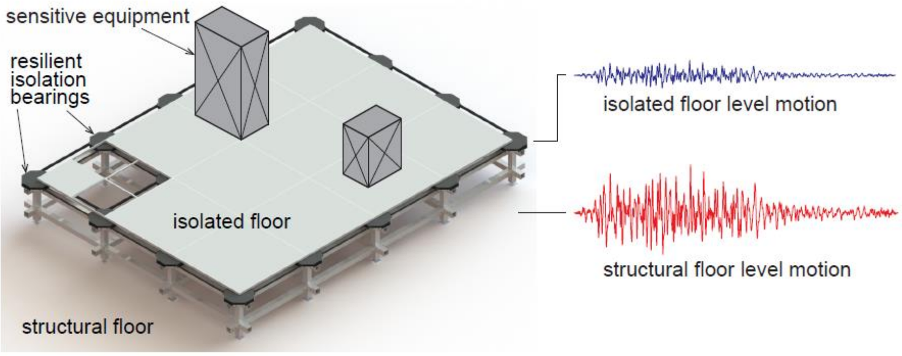


Figure 11. Resilient multi-functional floor isolation system (source: Scott Harvey, University of Oklahoma).

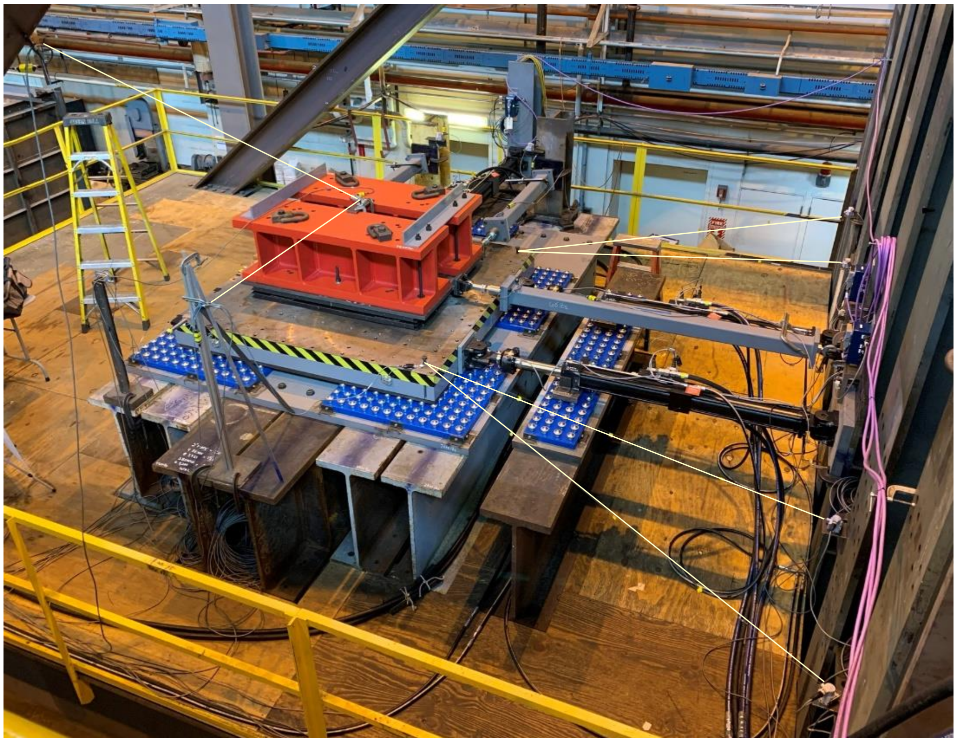


Figure 12. Real-time hybrid simulations of floor isolation systems (RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing (OIA 1929151), PI - Scott Harvey, University of Oklahoma).