# LEHIGH NHERI

Real-Time Multi-Directional Testing Facility

https://lehigh.designsafe-ci.org/facility/overview/

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## FACILITY OVERVIEW

To help meet the grand challenge of community resilience to natural hazards, the NHERI Lehigh Experimental Facility (EF) is a world-class, open-access facility which enables researchers to address key research questions associated with the challenge of community resilience. The Lehigh EF has a unique portfolio of equipment, instrumentation, infrastructure, testbeds, experimental simulation control protocols, large-scale simulation and testing experience in addition to know-how that does not exist elsewhere in the US. The unique strength of the Lehigh EF is accurate, large-scale, multi-degree-of-freedom and multi-directional simulations of the effects of natural hazard events on civil infrastructure systems (i.e., buildings, bridges, industrial facilities, etc.) with soil-foundation effects. The facility is managed and operated by a knowledgeable and highly skilled staff, enabling high quality experimental data to be obtained from tests performed at the Lehigh EF.

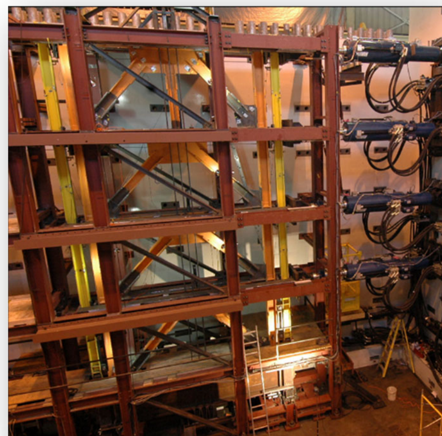


**Figure 1. Lehigh EF large-scale testing.**

The capabilities and resources of the NHERI Lehigh EF align themselves with the NHERI Science Plan by "enabling the assessment of the physical vulnerability of the civil infrastructure and social vulnerability of populations exposed to natural hazards, and the creation of technologies and tools to create a sustainable infrastructure for the nation" ("*Five-Year Science Plan*"). The NHERI Lehigh Experimental Facility (EF) provides added value to the natural hazards engineering research community and stakeholders by enabling the experimental investigation of the 3D effects of multi-natural hazards on the civil infrastructure to be readily performed. Performance-based engineering approaches can be developed and validated that enhance the resiliency of the civil infrastructure against the effects of natural hazards. The approach of using real-time multi-directional hybrid simulations (described below) enables synergistic investigations of the effects of various types of natural hazards on systems, where realistic demand associated with prescribed hazard levels are involved. This is in contrast to the traditional approach of investigating individual isolated components of a system under predefined quasi-static loading. The shortcoming of the traditional approach lies in the fact that it neglects the effects of the interaction of a component with the system and the environment under realistic loading and boundaries.

The types of laboratory simulations and tests enabled by the Lehigh EF include: (1) hybrid simulation (HS) which combines large-scale physical models with computer-based numerical simulation models; (2) geographically distributed hybrid simulation (DHS) which is a HS with physical models and/or numerical simulation models located at different sites; (3) real-time hybrid natural hazards simulation (RTHS), including earthquake, wind, and storm surge which is a HS conducted at the actual time scale of the physical models; (4) geographically distributed real-time hybrid simulation which combines DHS and RTHS; (5) shake table testing, which can be used either in a conventional manner (ST) or configured to be used in a real-time hybrid simulation manner (RTHS-ST); (6) dynamic testing (DT) which loads large-scale physical models at real-time scales through predefined load histories; and (7) quasi-static testing (QS) which loads large-scale physical models at slow rates through predefined load histories.

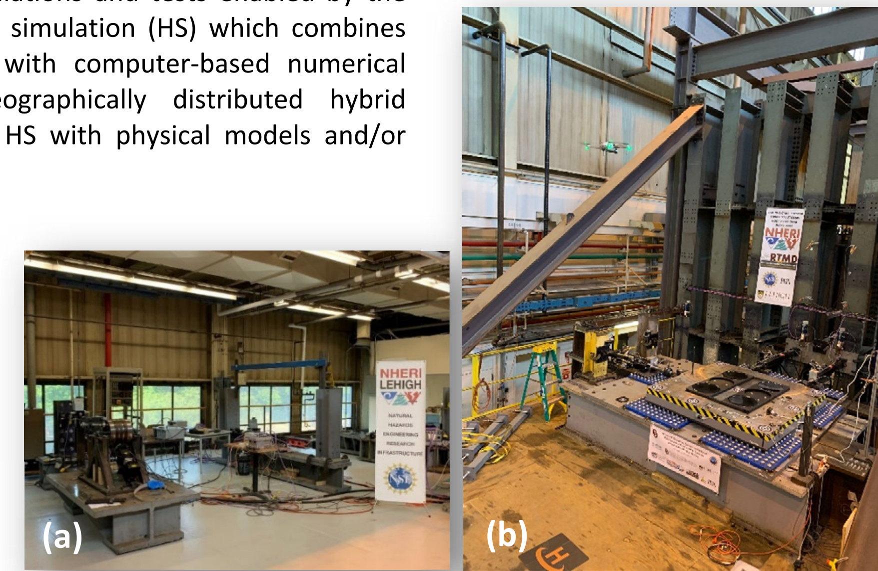



**Figure 2. Real-time Cyber-Physical Structural Systems Testing Laboratory: (a) Testbeds; and, (b) multi-directional shake table.**

The resources available at the Lehigh EF enable multiple large-scale simulations and tests to be conducted simultaneously, permitting numerous users to work concurrently without significant interruption.

The NHERI Lehigh Experimental Facility (EF) is located within the ATLSS Center, and consists of 2736 $m^2$ (29,450 $ft^2$) of floor space that features a 3-D multi-directional reaction wall and strong floor high-bay laboratory (see Figure 3). This and other resources available to researchers at the Lehigh EF are shown laid out in the floor plan in Figure 4, and described later. In addition to its world-renowned large-scale testing capabilities, the NHERI Lehigh EF now features the 372 $m^2$ (4000 $ft^2$) NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory (RCPSS). The laboratory features five test beds with 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 and the NHERI Lehigh Experimental Facility can readily perform 3-D real-time hybrid simulations consisting of multiple experimental substructures and nonlinear analytical substructures.

**Figure 3. ATLSS Center Multi-directional Reaction Wall and Strong Floor**

Staging areas for preparation and demolition of specimens exist at the front and rear of the Lehigh EF. These areas are serviced by the 180 kN and 90 kN overhead cranes, respectively, with access to outside loading docks via 7m tall overhead high-bay doors. In addition to these cranes, additional auxiliary equipment is available for handling specimen construction, handing, transport include forklifts, manlift, and the machine shop. There are indoor and outdoor storage areas for equipment and specimens.

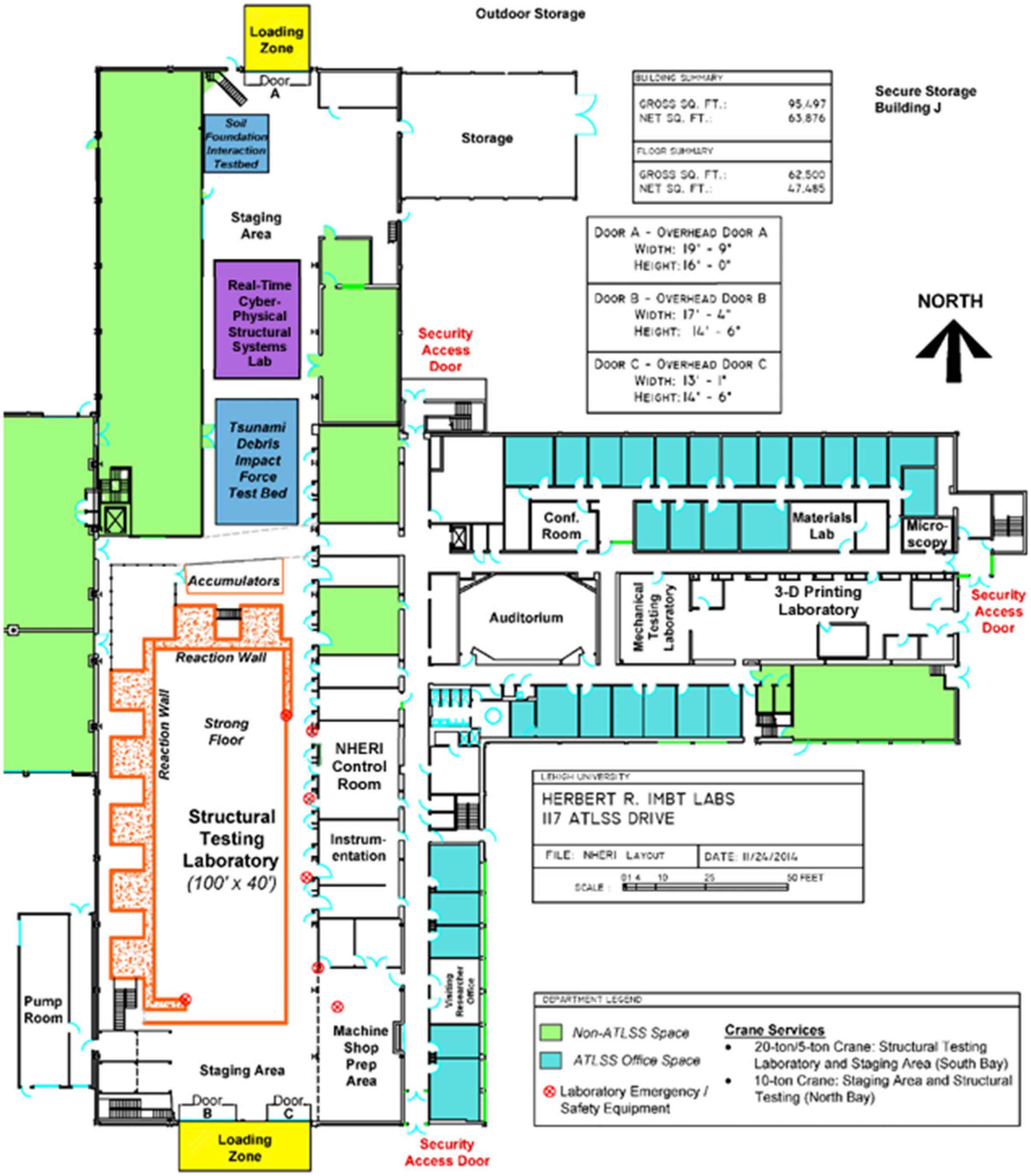


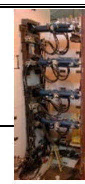
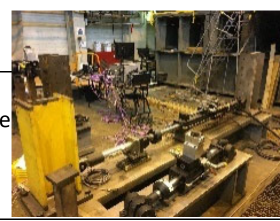
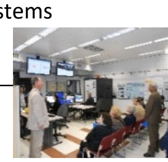

**Figure 4. Lehigh Experimental Facility Floor Plan.**

**EQUIPMENT**

A description of the NHERI Lehigh EF equipment and specifications are summarized in Table 1. The Lehigh EF equipment (see Table 1) includes: (1,2) five dynamic large capacity servo-hydraulic actuators; (3,4,5) five dynamic reduced-capacity servo-hydraulic actuators; (6) large capacity central hydraulic power supply system; (7,8,9,10) real-time integrated IT control system with three digital servo-hydraulic control systems, which integrates laboratory data acquisition, computational simulation, telepresence, local data repository, and servo-hydraulic actuator control in a single IT system; and (11,12) portfolio of sensors and local data repository. The five dynamic large-capacity actuators include two actuators with 2300 kN maximum force capacity, 838 mm/sec maximum velocity, with a 1000 mm stroke. The remaining three dynamic actuators possess 1700 kN maximum force capacity, 1140 mm/sec maximum velocity, and a 1000 mm stroke. The hydraulic power supply system features five 5-454 lpm pumps and a 3030 liter accumulation system that enables earthquake effects on structures to be sustained for more than 30 seconds during a large-scale multi-directional real-time hybrid simulation. It also enables the investigation of the multi-directional response of structural systems to natural wind hazards using real-time hybrid simulation.

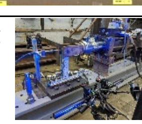
Additional resources through the ATLSS Center are available for research. The specifications for these resources are given in Table 2.

**Table 1 Lehigh EF Equipment**

| Resource | Features | Maintenance and Calibration |
|---|---|---|
| 1. Two large-capacity servo-hydraulic RTMD actuators ported with 3 high-flow 2080 lpm servo-valves | • maximum force = 2300 kN<br>• maximum velocity = 838 mm/sec<br>• 1000 mm stroke range<br> | External – MTS Corp maintenance contract |
| 2. Three large-capacity servo-hydraulic RTMD actuators ported with 3 high-flow 2080 lpm servo-valves | • maximum force = 1700 kN<br>• maximum velocity = 1140 mm/sec<br>• 1000 mm stroke range | External – MTS Corp maintenance contract |
| 3. Two 49 kN servo-hydraulic actuators with 2 high-flow 57 lpm servo-valves, housed in Real-time Cyber-Physical Structural Systems Laboratory | • maximum force = 49 kN<br>• maximum velocity = 736 mm/sec<br>• 508 mm stroke range<br> | External – MTS Corp maintenance contract |
| 4. One 80 kN servo-hydraulic actuators with 1 high-flow 342 lpm servo-valve, housed in Real-time Cyber-Physical Structural Systems Laboratory | • maximum force = 80 kN<br>• maximum velocity = 1295 mm/se<br>• 356 mm stroke range | External – MTS Corp maintenance contract |
| 5. Two 98 kN servo-hydraulic actuators with 2 high-flow 57 lpm servo-valves, housed in Real-time Cyber-Physical Structural Systems Laboratory | • maximum force = 98 kN<br>• maximum velocity = 381 mm/sec<br>• 152 mm stroke range | External – MTS Corp maintenance contract |
| 6. Two 247 kN servo-hydraulic actuators with 2 high-flow 342 lpm servo-valve, housed in Real-time Cyber-Physical Structural Systems Laboratory | • maximum force = 247 kN<br>• maximum velocity = 736 mm/sec<br>• 305 mm stroke range | External – MTS Corp maintenance contract |
| 7. RTMD hydraulic actuator power supply with central distribution system | • Five-454 l/min pumps<br>• 3030 liter accumulator system with 20800 l/min | External – MTS Corp maintenance contract |
| 8. RTMD Real-time integrated control system, housed in control room | • Two SpeedGoat Performance real-time systems<br>• Mathworks workstation; Data display workstation<br> | Internal – EF IT Systems Manager |

| | | |
|---|---|---|
| | • SCRAMNet GT with communication latency less than 180 nsec. | |
| 9. Three RTMD real-time servo-hydraulic digital controllers, one housed in control room, other housed in Real-time Cyber-Physical Structural Systems Laboratory, one housed on laboratory floor | • 2048 Hz speed<br>• independent multi-channel force or displacement control  | External – MTS Corp maintenance contract |
| 10. RTMD High speed data acquisition | • 4096 Hz speed<br>• 304 channels consisting of voltage, strain and temperature  | External – Pacific Instruments maintenance contract |
| 11. RTMD Real-time telepresence system | • 28 high definition cameras, real-time data streaming, video and imaging capabilities  | Internal – EF IT Systems Manager |
| 12. RTMD Sensors | • 12 temposonic displacement sensors of +/-750mm and +/- 1120mm stroke, 5 triaxial and 5 monoaxial +/- 10g accelerometers, and 8 bi-axis dynamic 360 degree grand inclinometers | Internal – ATLSS Center staff |
| 13. RTMD Local data Repository | • Synology 8 bay dual disk redundancy 32 TB, scalable  | Internal – EF IT Systems Manager |

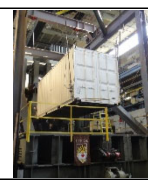
**Table 2 ATLSS Center Equipment**

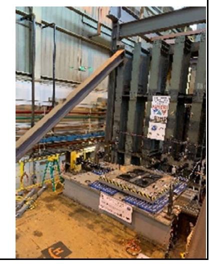
| Resource | Features |
|---|---|
| 1. 3-D multi-directional reaction wall and strong floor, high-bay | • Multi-directional wall with maximum height to 15.2 m<br>• strong floor12.2 m by 30.5 m in plan<br>• 1.5 m space anchor point with tie-down capacity of 2224 kN and 1334 kN in shear and tension.<br>• Overhead high-bay doors with access to loading docks, 7 m in height  |
| 2. 30 hydraulic actuators | • 130 kN to 2680 kN in size<br>• 125 to 750 mm stroke range<br>• 1800 kN follow core jacks  |
| 3. 4 digital servo-hydraulic controllers | • 1024 Hz speed, independent channel force or displacement control  |
| 4. 3 data acquisition systems | • 4096 Hz speed, combined over 704 channels; 200 total channels of signal conditioning |
| 5. Sensors | • Large array of displacement transducers (+/-6.4mm (LVDTs) to 1524mm stroke.<br>• Accelerometers +/-1g to +/-10g<br>• Inclinometers ranging up to +/-20 degrees<br>• Actuator load cells  |
| 6. 3 Digital Imaging Correlation Systems | • Non-contact 3-D full-field strain measurements under dynamic loading<br>• Measuring volume range of 10 x 7.5 mm to 2000 x 1500 mm<br>• Strain measure range from 0.01% to 100%<br>• Sampling rates of 250,000 frames/sec.  |
| 7. Auxiliary equipment | • 180kN and 90 kN cranes; forklifts; manlift; machine shop  |

**TESTBEDS**

Lehigh EF users will have readily access to several large-scale testbeds that exist at the ATLSS Center for conducting their research. A list of these testbeds are given in Table 3. The testbeds enable a wide range of large-scale experimental research, including real-time hybrid simulation, non-structural component research, damper and isolation bearing research, tsunami debris impact force research, and soil-structure interaction research. The testbeds also used for conducting demonstrations and training during researcher and training workshops, in addition to ECO activities.

**Table 3 Testbeds at ATLSS Center**

| Test bed | Features |
|---|---|
| 1. Lateral force resisting system testbed | • Test large-scale systems of up to 13.7 m in height, 11 m in width  |
| 2. Non-structural component multi-directional seismic simulator | • 12.2 m in length and 3.1 m in width<br>• Multi-directional loading  |
| 3. 5 full scale damper testbeds | • Maximum force of 2300 kN, 1143 mm/sec velocity, and 1000 mm stroke range<br>• Damper characterization; real-time hybrid sim  |
| 4. Tsunami debris impact force testbed | • High speed DAQ; high cameras  |
| 5. Two large-scale soil boxes for soil-structure interaction research | • Flexible designs (1.8 x 1.8 x 1.8 m and 1.8 x 1.8 x 0.9 m in size )<br>• Actuators with load cells; Data acquisition system<br>• Sensors for soil and foundation response measurements  |
| 6. Six reduced scale damper testbeds with dedicated nonlinear viscous dampers, rotary friction damper | • Maximum force of 247 kN, 1295 mm/sec velocity, and 736 mm stroke range  |
| 7. NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory: Testbeds | • Five Testbeds:<br>• Maximum force of 247 kN, 1295 mm/sec velocity, and 736 mm stroke range<br>• Five Dampers: Four Nonlinear Viscous Dampers; One Rotary Friction damper  |

| | |
|---|---|
| 8. NHERI Lehigh Real-time Cyber-Physical Structural Systems Testing Laboratory: Real-time Hybrid Simulation Shake table | • Real-time hybrid simulation with shake table capabilities<br>• 3 degrees of freedom: Bidirectional in-plane translations and rotation normal to platen<br>• 1.83 m. by 1.83 m. platen<br>• 45 kN payload at 1 g.<br>• ± 254 mm stroke NS, ± 177-mm stroke EW<br>• Maximum velocity of 737 mm/sec.<br> |

**REAL-TIME INTEGRATED CONTROL SYSTEM AND EXPERIMENTAL PROTOCOLS**

The Lehigh EF real-time testing architecture features a *Real-Time Integrated Control System* for both real-time and slow rates of multi-directional testing. A schematic of the real-time testing architecture at the NHERI Lehigh Experimental Facility is shown below in Figure 5.

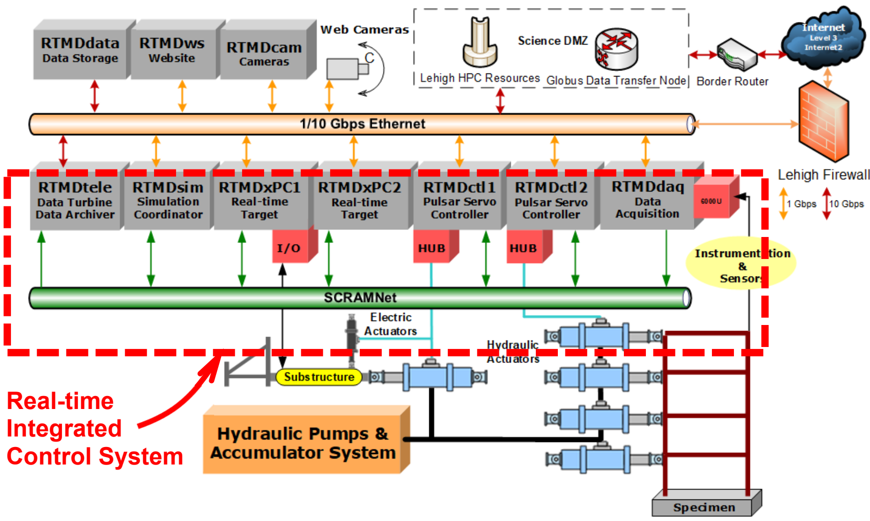



**Figure 5. Lehigh EF Real-time Integrated Control System**

A data structure for SCRAMNet exist that includes multiple states for commands and feedback signals, enabling advance servo-hydraulic control laws to be implemented and sophisticated testing methods to be performed. Actuator control for real-time testing is achieved using adaptive actuator delay compensation based on the ATS method (Chae et al. 2013a). For real-time hybrid simulation, numerous options exist for modeling the analytical substructure. The programs *HybridFEM-MH* and *HyCoM-3D* has been developed by Kolay et al. (2018) and Ricles et al. (2020) that enables 2D and 3D analytical substructures to be created using embedded MATLAB functions in a Simulink model. Source code can be compiled and run in real-time to conduct either 2D or 3D multi-hazard real-time hybrid simulations. *HybridFEM-MH* and *HyCoM-3D* both have an element library that includes nonlinear force-based and displacement-based fiber elements, nonlinear panel zone elements, nonlinear hysteretic connection elements, nonlinear geometric elements based on the co-rotational formulation (to model both P-Δ and P-δ effects), along with a material library that enables the hysteretic stress-strain behavior of structural steel, concrete, wood, and reinforcement bars to be modeled. Explicit integration algorithms including the Modified KR-α algorithm developed by the PI (Kolay et al. 2015, Kolay and Ricles 2014, 2019); the Rosenbrok-W algorithm (Lamarche et al. 2009), and the implicit HHT-α integration algorithm (Hilber et al. 1977) that are all unconditionally stable are available for conducting real-time hybrid simulations.

**EXAMPLE PROJECTS**

*HybridFEM-MH* and *HyCoM-3D* have been successfully used by researchers at the NHERI Lehigh EF to perform numerous projects involving real-time hybrid simulations of structural steel, composite steel and concrete, and reinforced concrete systems (Karavasilis et al. 2012, Chen et al. 2009, 2012, Chen and Ricles 2011a,b, Chae et al. 2013b, 2014). This includes 3-D multi-hazard real-time hybrid simulations of a 40 story building subjected to earthquake and wind natural hazards (Kolay et al. 2020, Al-Subaihawi et al. 2020), see Figures 6 and 7. The results from this research has demonstrated the importance of placing supplemental damper systems in tall buildings to mitigate the damaging effects of earthquakes and wind storms to such structures.

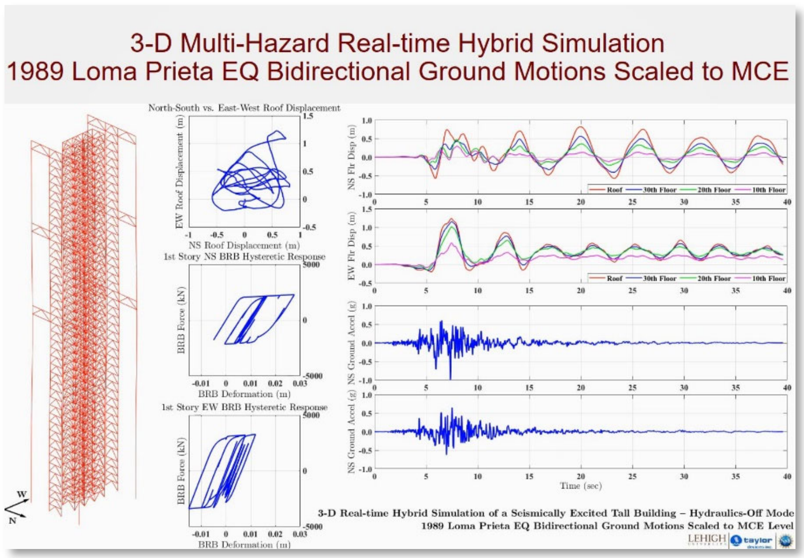



**Figure 6. 3D Real-Time Hybrid Simulation of a 40-Story Building Subjected to Earthquake Hazards (Ricles & Cao, Lehigh University).**

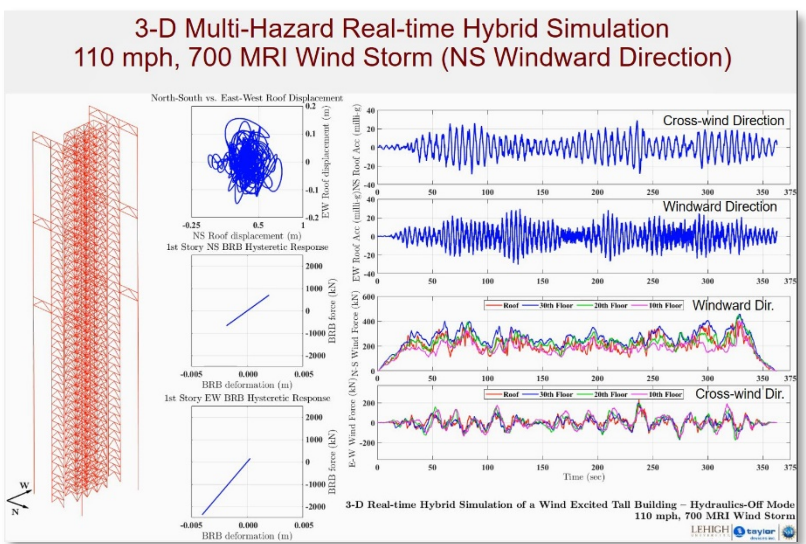



**Figure 7. 3D Real-Time Hybrid Simulation of a 40-Story Building Subjected to Wind Hazards (Ricles & Cao, Lehigh University).**

The portfolio of research projects includes real-time hybrid simulations that investigate the effects of multi-directional ground motions on moment resisting frames with non-structural components (see Figure 8). Researchers have also performed large-scale characterization tests at the NHERI Lehigh EF involving coupled reinforced concrete shear wall systems subjected to multi-directional loading, see Figure 9. Self-centering steel frame systems have also been tested using hybrid simulation (Figure 10(a)), in addition to performing real-time hybrid simulations with experimental substructure consisting of semi-active controlled dampers (see Figure 10(b)). In addition, full-scale experimental testing complemented by large computational finite element studies have been conducted by researchers at the NHERI Lehigh EF to advance knowledge on the performance of seismic collectors in steel building structures, see Figure 11. The outcomes of these test programs have led to the creation and validation of concepts for sustainable civil infrastructure systems.

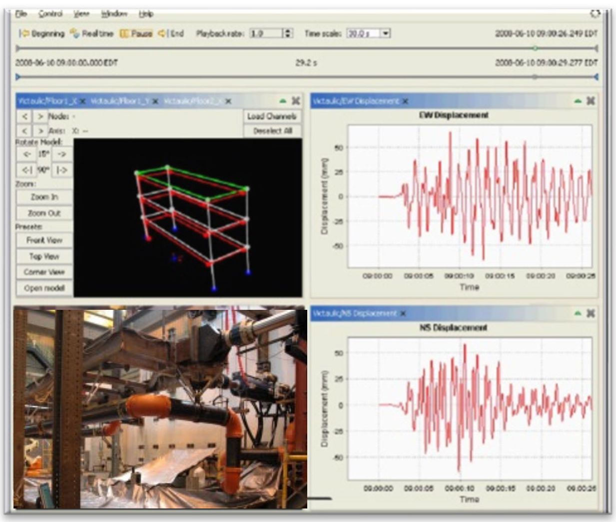



**Figure 8. 3D Large-scale RTHS of Building System Subject to Multi-directional EQ Ground Motions (Industry).**

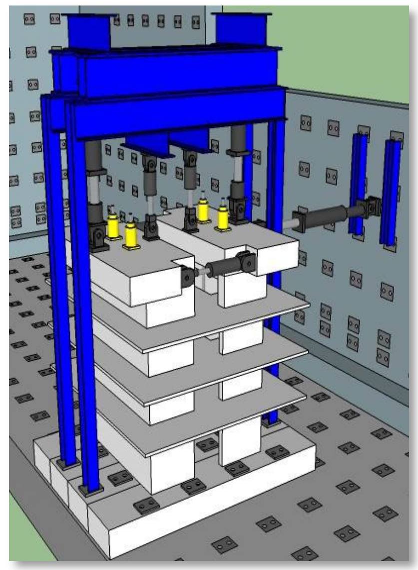


**Figure 9. Coupled Shear Wall Test Subject to Multi-directional Loading (Yahya Kurama, Notre Dame & Michael McGinnis UT Tyler).**

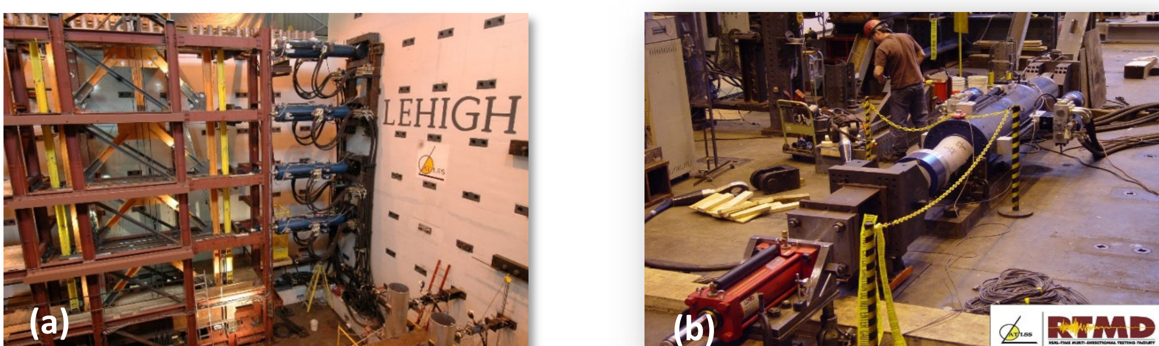



**Figure 10. Lehigh EF Large-scale (a) Self-Centering Lateral Force Resisting System (Richard Sause, Lehigh University), and (b) RTHS Semi-active Controlled Damper Testbed (Shirley Dyke, Purdue University).**

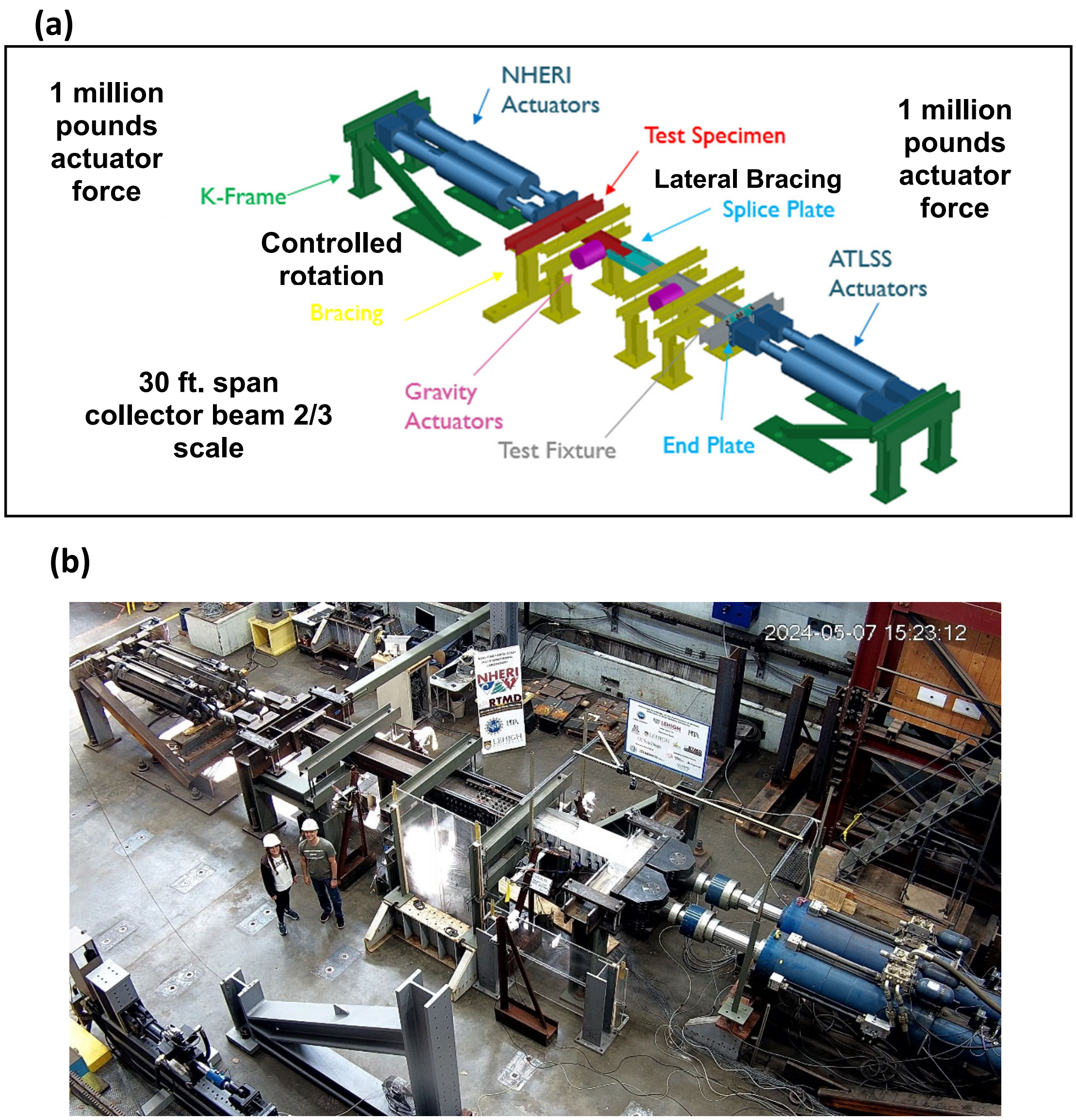



**Figure 11 Full-scale Investigation on the Performance of Seismic Collectors in Steel Building Structures: (a) Finite Element Modeling and Parametric Study; (b) 2-million Pound Test Setup for Full-scale Experiment Study (Robert B. Fleischman, University of Arizona).**

In addition to the sustainability of structural systems, resiliency also dictates that the contents of buildings be protected against the effects of natural hazards. Real-time hybrid simulations on floor isolation systems (FIS) have been conducted to evaluate the performance of these type of isolation systems under various hazard levels of multi-directional earthquake motions in protecting sensitive electronic equipment of mission-critical data centers (Figure 12). The multi-directional shake table was used to perform real-time hybrid shake table testing, where the floor isolation system was positioned on the upper floor of a multistory building with translational and torsional motions (Figures 12, 13). The outcomes of these tests led to the validation of FIS in protecting equipment in mission-critical data centers (Figure 14).

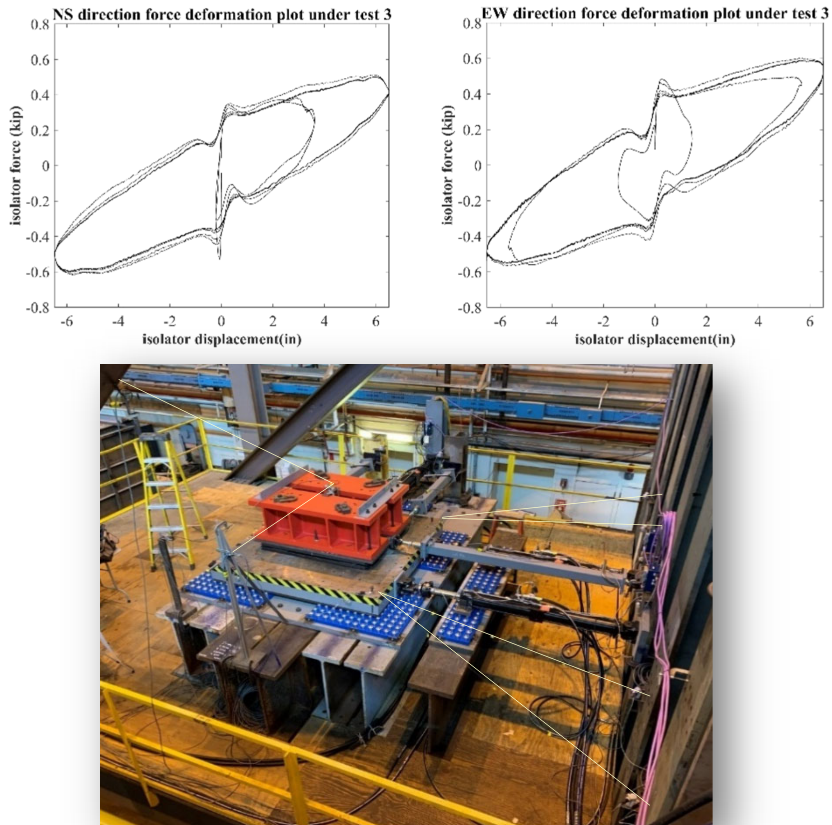



**Figure 12. RTHS of FIS in Buildings Subject to Dynamic Loading (Scott Harvey, University of Oklahoma).**

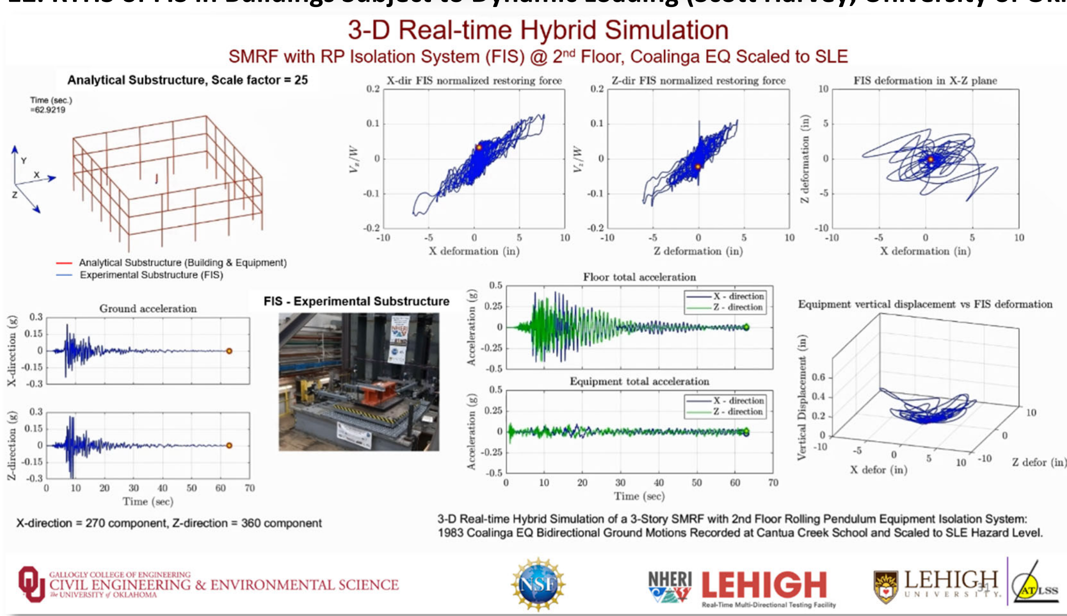



**Figure 13. RTHS of FIS in moment resisting frames subject to multi-directional earthquake ground motions (Scott Harvey, University of Oklahoma).**

| Reduction in Equipment Total Acceleration | |
|---|---|
| X-Direction | Z-Direction |
| 81.3% | 68.9% |

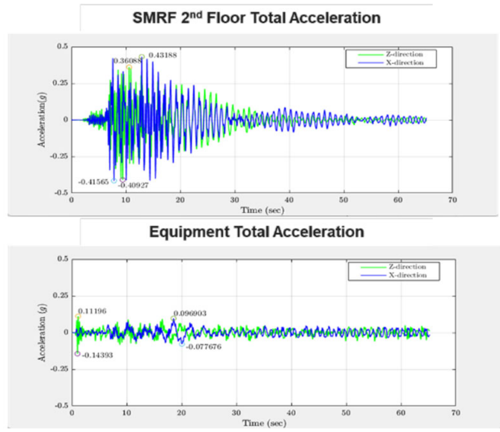



**Figure 14. RTHS Results: Illustration of the Reduction in Detrimental Equipment Accelerations By Using an FIS (Scott Harvey, University of Oklahoma).**

Finally, a capability building collaborative project has been performed with the Wall of Wind (WOW) NHERI EF located at Florida International University. The goal of this project is to extend real-time hybrid simulation to wind engineering, enabling the assessment of the aeroelastic response of structural systems to wind loading to be accomplished. The method is named *Real-time Aeroelastic Hybrid Simulation (RTAHS)*. It involves the use of the WOW wind tunnel, where an aeroelastic wind tunnel model of the system is located, combined with experimental and analytical substructures of the system located at the NHERI Lehigh EF (see Figure 15). This research has demonstrated that RTAHS method can led to more accurate test results compared to the conventional aero-dynamic test method currently in use in wind tunnels.

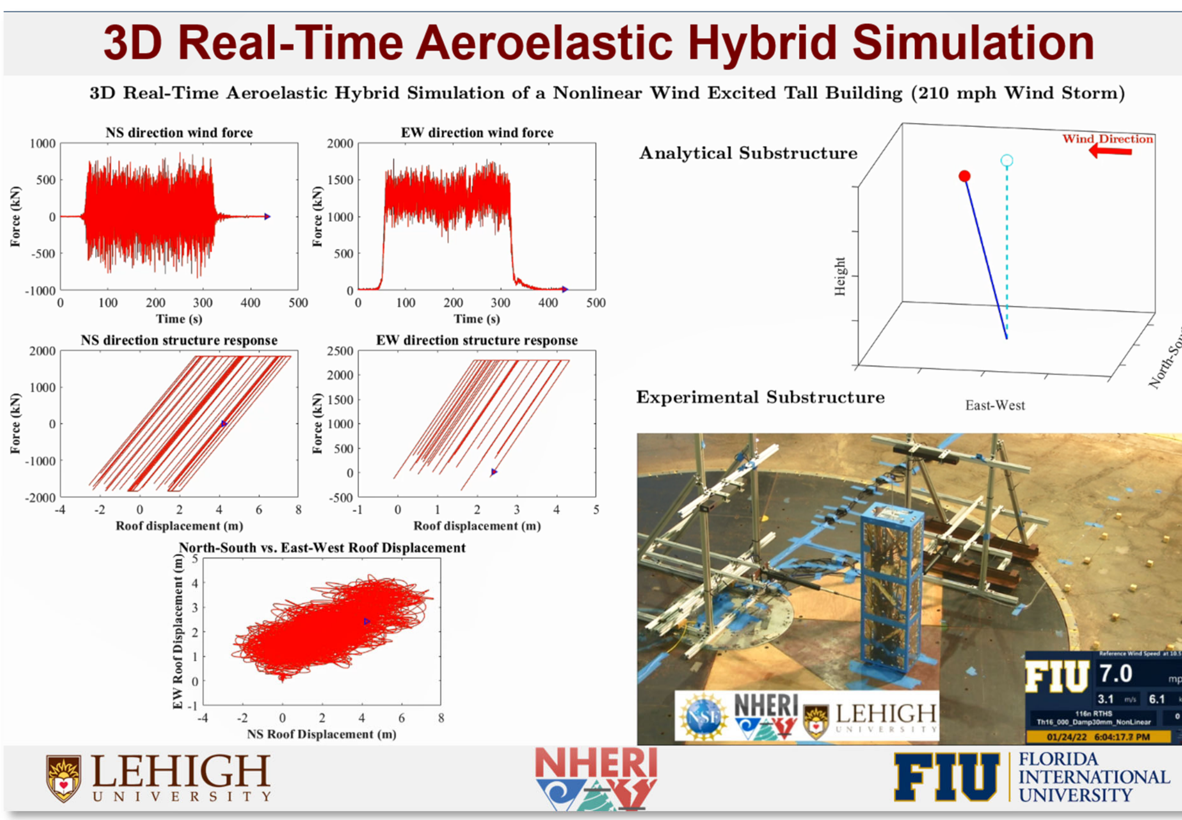



**Figure 15. 3D Nonlinear Real-Time Aeroelastic Hybrid Simulation of a Tall Building (Lehigh University and Florida International University).**

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