LEHIGH UNIVERSITY FACILITIES, EQUIPMENT AND OTHER RESOURCES

OVERVIEW OF FACILITY

The research project will involve the use of the NHERI Lehigh RTMD Experimental Facility (Lehigh EF), which is housed within the ATLSS Center on the Lehigh University campus. The proposed project will utilize resources available at the NHERI Lehigh Experimental Facility and the ATLSS Center. These resources are described below and are available for the complete duration of the proposed project.

The ATLSS Center has 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 1). This and other resources available for the Lehigh EF are shown laid out in the floor plan in Figure 2. The other resources include: servo-hydraulic power supply, servo-controlled actuators, real-time integrated control system, instrumentation, NHERI control room, testbeds, staging areas and loading zones, machine preparation area, laboratories, offices space, and an auditorium. The description of these resources follows below.

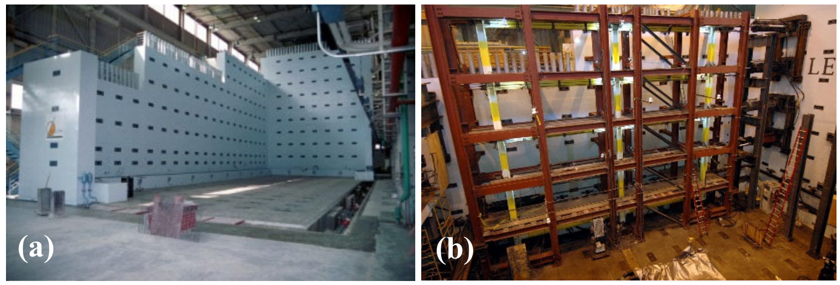


Figure 1. Lehigh EF (a) 3-D Multi-Directional Reaction Wall and Strong Floor High-bay Lab, and (b) Large-scale Lateral Force Resisting System Testbed

EQUIPMENT

A description of the 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.

The Lehigh EF will leverage ATLSS Center resources. These include the above mentioned 3-D multi-directional reaction wall-strong floor high bay laboratory which is serviced by an overhead crane. The strong floor provides 372 m^2 of testing area, with the encompassing reaction wall having a maximum height of 15.2 m. The specifications for these and other ATLSS Center resources available to users of the Lehigh EF are given in Table 2, and include: (1) 3-D multi-directional reaction wall-strong floor high-bay laboratory; (2,3,4,5,6) additional servo-hydraulic actuators, controllers, data acquisition systems, instrumentation, digital image correlation systems; and (7) auxiliary equipment that includes of two overhead cranes, forklifts, manlift, and a machine shop. ATLSS has unique capabilities, extensive equipment, and a well-trained staff. The resources available from ATLSS enable several multiple large-scale projects to be simultaneously supported at the Lehigh EF.

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.

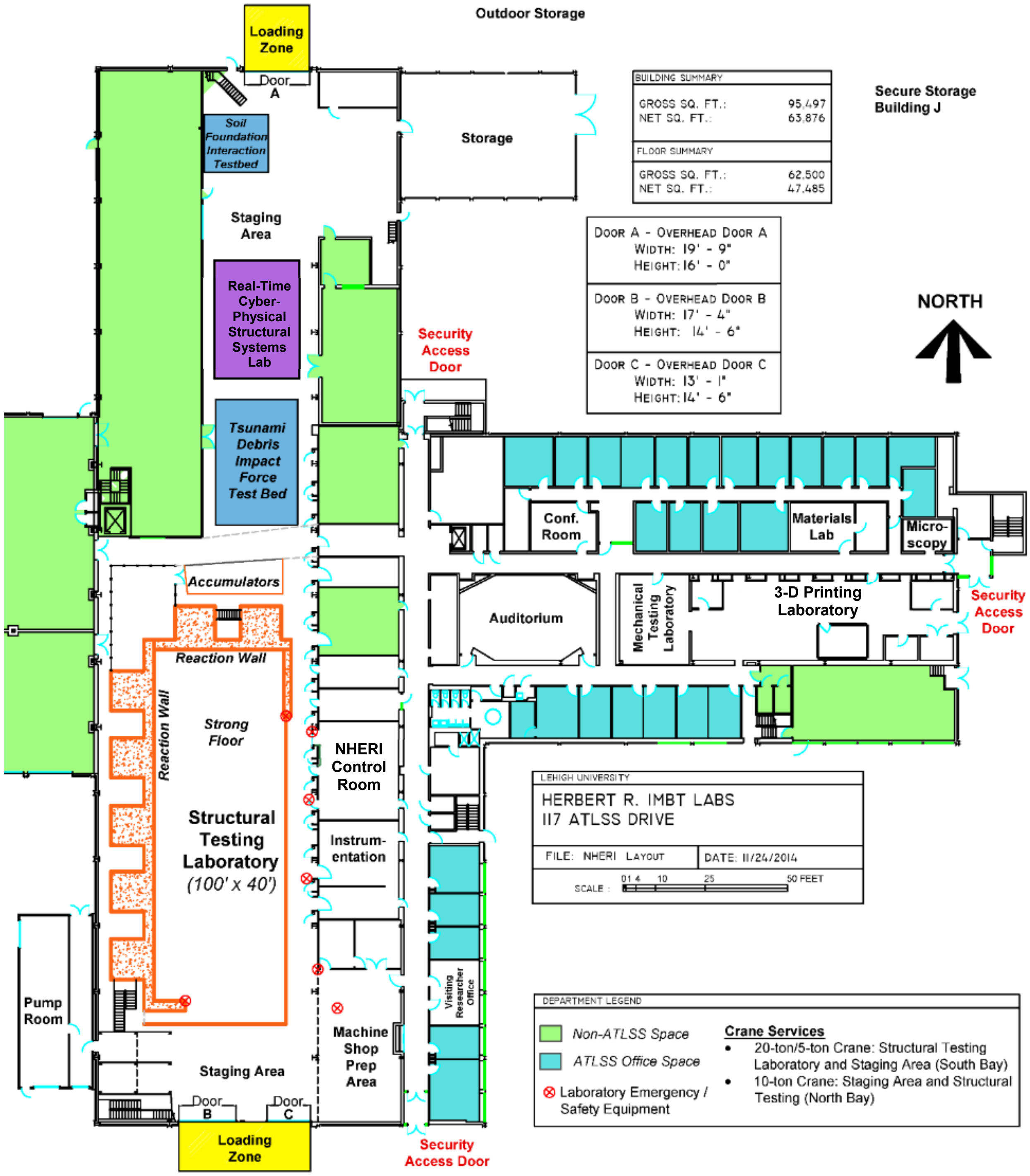


Figure 2. Lehigh Experimental Facility Floor Plan.

Table 1 Lehigh EF Equipment

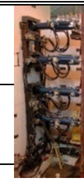
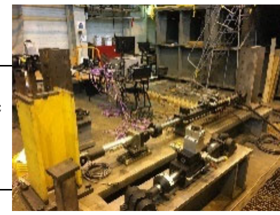
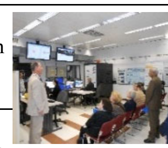
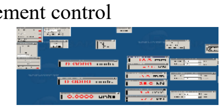
Resource	Features	Maintenance and Calibration
1. Two large-capacity servo-hydraulic RTMD actuators ported with 3 high-flow 2080 lpm servo-valves	• maximum force = 2300 kN • maximum velocity = 838 mm/sec • 1000 mm stroke range 	External – MTS Corp maintenance contract
2. Three large-capacity servo-hydraulic RTMD actuators ported with 3 high-flow 2080 lpm servo-valves	• maximum force = 1700 kN • maximum velocity = 1140 mm/sec • 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 • maximum velocity = 508 mm/sec • 736 mm stroke range 	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 • maximum velocity = 1295 mm/sec • 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 • maximum velocity = 381 mm/sec • 152 mm stroke range	External – MTS Corp maintenance contract
6. Multi-directional shake table, housed in Real-time Cyber-Physical Structural Systems Laboratory	• Multi-directional motions, including two orthogonal in-plane translations and in-plane rotation • Payload of 13 kips (5.9 tons) at 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). 	External – MTS Corp maintenance contract
7. RTMD hydraulic actuator power supply with central distribution system	• Five-454 l/min pumps • 3030 liter accumulator system with 20800 l/min	External – MTS Corp maintenance contract
8. RTMD Real-time integrated control system, housed in RTMD control room	• Two SpeedGoat Performance real-time systems • Mathworks workstation; Data display workstation • SCRAMNet GT with communication latency less than 180 nsec. 	Internal – EF IT Systems Manager
9. Real-time Cyber-Physical Structural Systems Laboratory Real-time integrated control system, housed in RCPSS Lab control room	• One SpeedGoat Performance real-time systems • Mathworks workstation; Data display workstation • SCRAMNet GT with communication latency less than 180 nsec	Internal – EF IT Systems Manager
10. Three RTMD real-time servo-digital controllers, one housed in RTMD control room, one housed in Real-time Cyber-Physical Structural Systems Laboratory, the other housed on laboratory floor	• 2048 Hz speed • independent multi-channel force or displacement control 	External – MTS Corp maintenance contract
11. Two RTMD High speed data acquisition systems, one housed in the RTMD control room, the other in the Real-time Cyber-Physical Structural Systems Laboratory control room.	• 4096 Hz speed • 304 channels consisting of voltage, strain and temperature • 32 channels consisting of voltage, strain and temperature 	External – Pacific Instruments maintenance contract
12. RTMD Real-time telepresence system	• 28 high definition cameras, real-time data streaming, video and imaging capabilities 	Internal – EF IT Systems Manager
13. 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
14. 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 • strong floor12.2 m by 30.5 m in plan • 1.5 m space anchor point with tie-down capacity of 2224 kN and 1334 kN in shear and tension. • Overhead high-bay doors with access to loading docks, 7 m in height 
2. 30 hydraulic actuators	• 130 kN to 2680 kN in size • 125 to 750 mm stroke range • 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. • Accelerometers +/-1g to +/-10g • Inclinometers ranging up to +/-20 degrees • Actuator load cells 
6. 3 Digital Imaging Correlation Systems	• Non-contact 3-D full-field strain measurements under dynamic loading • Measuring volume range of 10 x 7.5 mm to 2000 x 1500 mm • Strain measure range from 0.01% to 100% • Sampling rates of 250,000 frames/sec. 
7. Auxiliary equipment	• 180kN and 90 kN cranes; forklifts; manlift; machine shop 

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 3. As seen in this figure, it includes the following servers: data repository (RTMDdata); website and point of presence (RTMDws); video and webcam (RTMDcam); telepresence (RTMDtele); integrated control (RTMDsim); two real-time target PCs (RTMDxPC1 and RTMDxPC2); two servo-hydraulic controllers (RTMDctrl1 and RTMDctrl2); and a workstation for data acquisition (RTMDdaq).

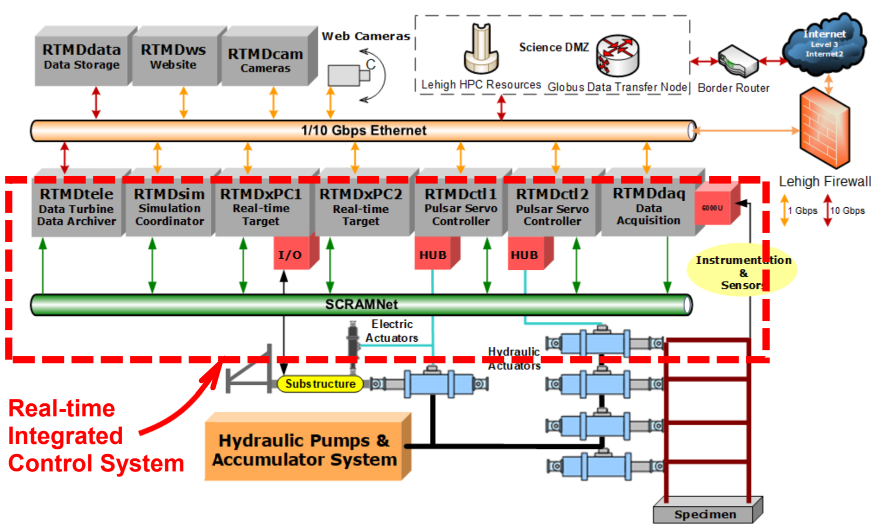


Figure 3. Lehigh EF Real-time Integrated Control System

Algorithms that enable real-time testing reside on the RTMDxPC, which is a dedicated real-time xPC kernel. These algorithms enable real-time hybrid simulation and real-time effective force testing. Multi-directional kinematics is accounted for by algorithms that also reside on the RTMDxPC. All of the algorithms are created in Simulink, and Real-Time Workshop from MathWorks, Inc. is used to recreate real-time executable code. The *Real-Time Integrated Control System* is created by using SCRAMNet to enable communication among the telepresence server (RTMDtele), real-time target PC (RTMDxPC), the servo-hydraulic controller (RTMDctrl), and data acquisition system (RTMDdaq). The data exchange across SCRAMNet occurs within 90 nanoseconds, essentially enabling shared memory among the workstations, including the servo-hydraulic controller and the RTMDxPC, thus enabling real-time testing capabilities. Synchronization is maintained through the use of a pulse trigger placed on SCRAMNet at the rate of 1024Hz. A data structure for SCRAMNet is in place 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. (2018a) and Ricles et al. (2020c) 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 the P-Δ effect), 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, 2019a); the Rosenbrok-W algorithm Lamarche et al. 2009), and

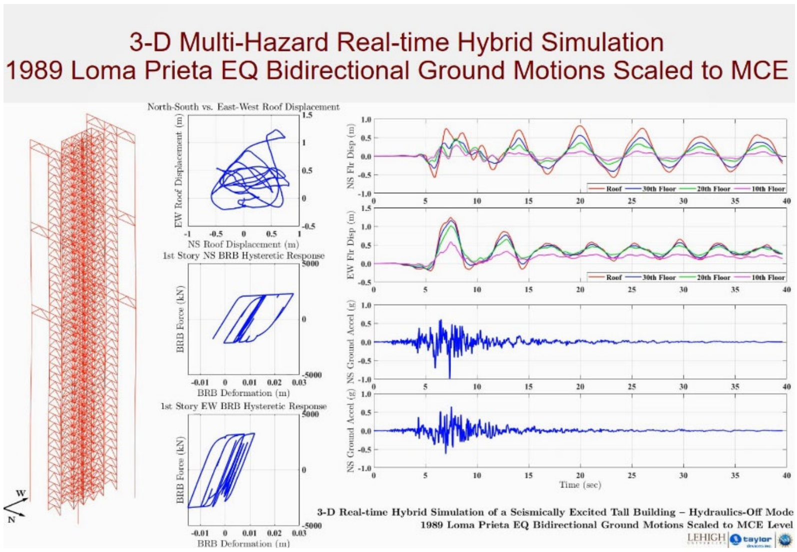


Figure 4. 3D Real-Time Hybrid Simulation of a 40-Story Building Subjected to Earthquake Hazards.

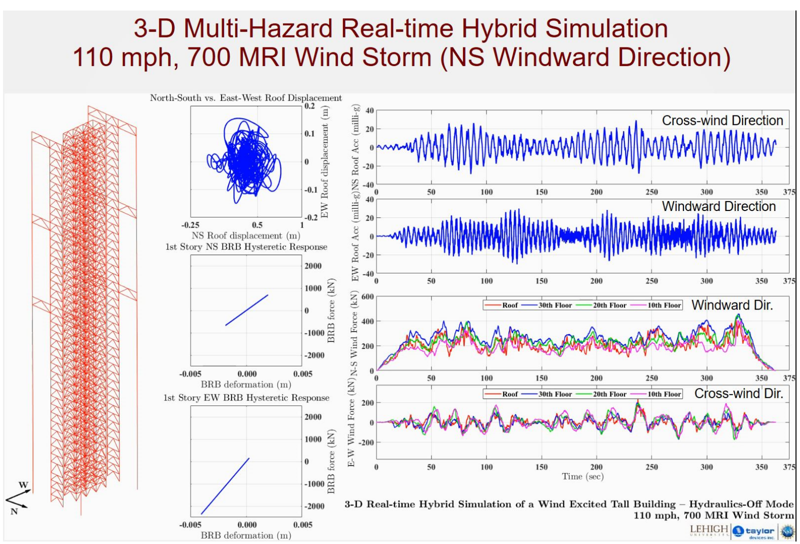


Figure 5. 3D Real-Time Hybrid Simulation of a 40-Story Building Subjected to Wind Hazards.

the implicit HHT-α integration algorithm (Hilber et al. 1977) that are all unconditionally stable are available for conducting real-time hybrid simulations. *HybridFEM-MH* and *HyCoM-3D* have been successfully used by researchers at Lehigh University on numerous projects to perform 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 4 and 5.

Another option to create analytical substructures is to use OpenSees (Mazzoni et al. 2014) or other finite element software on the RTMDsim, where OpenFresco (Schellenberg et al. 2008) is used to communicate with this software. The integrated control system has a hydraulics-off simulation mode for use in the validation of testing methods, training, and education. In the hydraulics-off simulation mode, the servo-hydraulic equipment (e.g., actuators, servo-valves) and test structure are analytically modeled. Models of the servo-hydraulic equipment have been developed in Simulink for this purpose, and have been calibrated based on system identification tests of the equipment (Zhang et al 2005). To ensure the safety of personnel and equipment during a test, software limits are enabled on the RTMDxPC and RTMDctrl, hardware piston stroke limit switches are placed on the actuators, and an emergency stop system is activated throughout the laboratory. The *Real-Time Integrated Control System* can also be operated to participate in distributed hybrid simulations using UI-Simcor (Kwon et al. 2005), OpenFresco (Schellenberg et al. 2008), or user-written Java routines.

The existing algorithms to be used for performing tests for the proposed study reside on the RTMD Real-time Integrated Control System. The System is readily able to incorporate new algorithms if needed. Some other examples of projects involving hybrid simulations performed in the recent past are shown in Figures 4 through 7.

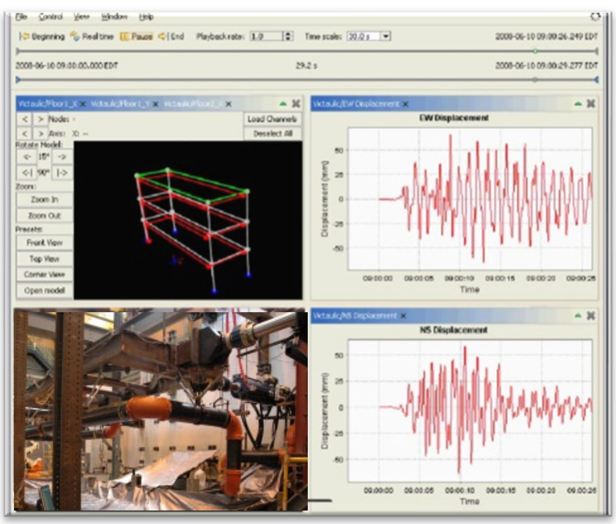


Figure 6. 3D Large-scale RTHS of Building System Subject to Multi-directional EQ Ground Motions.

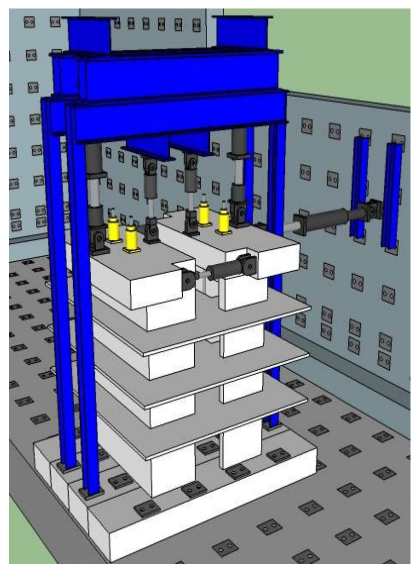


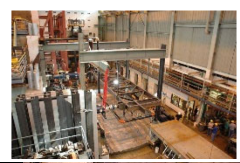
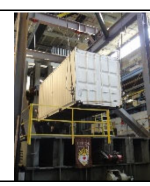
Figure 7. Coupled Shear Wall Test Subject to Multi-directional Loading.

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.

Figure 8. Lehigh EF Large-scale (a) Lateral Force Resisting System, and (b) Damper Testbeds.

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 • Multi-directional loading 
3. 5 full scale damper testbeds	• Maximum force of 2300 kN, 1143 mm/sec velocity and 1000 mm stroke range • Damper characterization; real-time hybrid sim 
4. Tsunami debris impact force testbed	• High speed DAQ; high speed 
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) • Actuators with load cells; Data acquisition system • Sensors for soil and foundation response measurements 
6. Six reduced scale damper testbeds with dedicated nonlinear viscous dampers, rotary friction damper	• Maximum force of 98 kN, 1295 mm/sec velocity, and 736 mm stroke range 

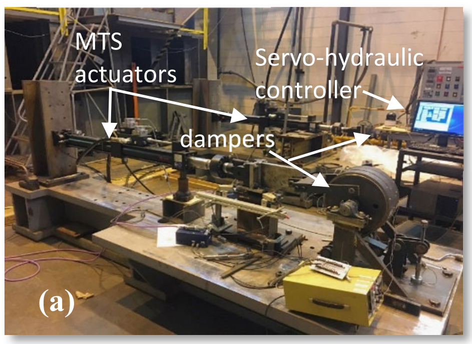
RESEARCH LABORATORIES AND ACCOMMODATIONS

Resources available to Lehigh EF users include the **Lehigh Real-time Cyber-Physical Structural Systems (RCPSS) Laboratory** (Figure 9), a mechanical testing laboratory (Figure 10), a metallography and microscopy laboratory, a non-destructive evaluation laboratory, and a machine shop. The RCPSS Laboratory is a multidisciplinary research entity that is focused on reduced-scale cyber-physical testing for mitigating the effects of natural hazards on the civil infrastructure. The RCPSS Laboratory will be available to users for the purpose of education and outreach activities, training, and research.

Mechanical Testing Laboratory - Capable of standard mechanical property tests of metallic, timber, cementitious and composite construction materials. Features 267 kN and 2668 kN universal testing machines, and Charpy V-Notch fracture toughness testing machine. The Mechanical Testing Laboratory also operates a 220kN MTS dynamic universal test machine that has +/-150 mm stoke and is ideal for cyclic load and characterization testing of dampers and other rate-dependent devices and materials.

Metallography and Microscopy Laboratory - The Metallography and Microscopy Laboratory is equipped for metallographic sample preparation and material characterization by light optical and electron microscopy techniques with hardness and micro hardness capabilities. The facility features SEM and Light Microscopy equipment.

Non-destructive Evaluation Laboratory - The Nondestructive Evaluation Laboratory is equipped to perform basic laboratory and field evaluation work on steel and concrete materials and structures. The laboratory also includes a variety of electronic hardware for bench top testing including oscilloscopes, function generators and filters. The laboratory is equipped for both undergraduate and graduate research, and undergraduate instruction.



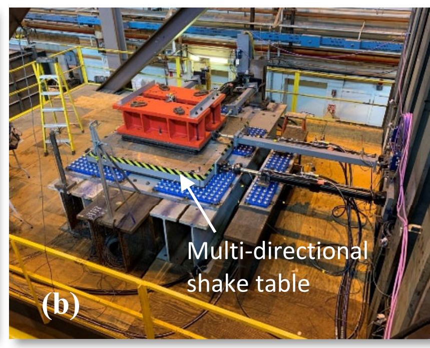


Figure 9. RCPSS Laboratory for Training, Education, and Research: (a) Dynamic Test Beds; (b) Multi-directional Shake Table

Machine Shop - The machine shop is well outfitted to handle fabrication (include cutting, drilling, machining, and welding) and machining tasks requiring a high precision with close tolerances.

Figure 10. Mechanical Testing Laboratory.

STRUCTURAL ENGINEERING COMPUTATION TOOLS

In addition to the software mention above that is part of the Real-time Integrated Control System, A number of structural analysis tools are available within the Lehigh EF, including: ABAQUS, OpenSees, ANSYS, SAP 2000, MATLAB, Maple, Simulink, Mathematica, Python, Fortran, C, C++, and Java compilers.

LABORATORY STAFF

The ATLSS Lab is staffed by laboratory technicians that have many years of experience and are well trained to provide support for large-scale experiments on a wide variety of structures. The staff is available to assist researchers in all aspects of their experimental programs including specimen fabrication and erection, instrumentation, testing, and post-test specimen demolition and disposal.

SPACE AND RESOURCES TO BE MADE AVAILABLE FOR PROJECT HEADQUARTERS AND STAFFING.
As the Lehigh EF is located within the ATLSS Center, faculty and staff offices are assigned to all Lehigh EF senior and other personnel funded through NHERI NSF funds, excluding engineering technicians who do not require office space to perform their duties. Additionally, a dedicated visiting researcher office is available for utilization by external users during their residence at the Lehigh EF. Offices will have desktop computers with a 10 GPs internet connection. Each office is connected to a central network printing system, and equipped with a LAN telephone system. Xeroxing and scanning machines connected to the internet are located throughout the ATLSS Center, and will be accessible to all personnel, staff, faculty, and users of the facility.

All offices have secured entry that requires the use of an assigned key to unlock the office door. The ATLSS Center has secure access doors that require authorized entry after normal work hours. Lehigh University police perform security checks and walk-throughs during non-working hours and on weekends.

The ATLSS Center has a 100 seat auditorium (Figure 11) and several large conference rooms, all having teleconferencing capabilities via the Internet. They are available for NHERI activities for meetings, workshops, and ECO activities at no cost to the project.

Figure 11. Auditorium for ECO Activities.