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Natural Hazards Engineering Research Infrastructure at Lehigh: Large-Scale Real-time Multi-Directional Hybrid Simulation Experimental Facility

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Abstract

The Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility at Lehigh University, a National Science Foundation sponsored facility, will provide means to conduct research to mitigate the impact of natural hazards that includes earthquakes on structures. This facility provides experimental resources for accurate, large-scale, multi-directional simulations that enable the effects of natural hazard events on civil infrastructure systems with potential soil-foundation effects to be investigated. The facility's experimental resources, including a strong floor, multi-directional reaction wall, static and dynamic actuators, and testing algorithms supports large-scale, multi-direction, real-time hybrid simulations that combine physical experiments with computer-based simulations for evaluating performance of large-scale components and systems. The types of laboratory simulations and tests enabled by the facility 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 earthquake simulation (RTHS), which is a HS conducted at the actual time scale of the physical models; (4) geographically distributed real-time hybrid earthquake simulation, which combines DHS and RTHS; (5) dynamic testing (DT), which loads large-scale physical models at real-time scales through predefined load histories; and (6) quasi-static testing (QS), which loads large-scale physical models at slow rates through predefined load histories. The facility resources enable multiple, large-scale simulations and tests to be conducted simultaneously, enabling numerous users to work concurrently without significant interruption. The large-scale hybrid simulations are a unique resource for system-level response data, since they enable the definition of the "system" to be expanded well beyond the size of typical laboratory physical models. At the same time, due to its large size, the facility accommodates large-scale physical models, which reduces scaling effects associated with typical, small physical models. A broad array of instrumentation, large-scale data acquisition systems, and advanced sensors provides the system-level data needed for advancing computational modeling and simulation. The new discoveries and knowledge from these simulations will enable researchers to develop and validate new hazard mitigation solutions, and innovative hazard-resistant structural concepts.

Keywords: large-scale experiments, real-time hybrid simulation, multi-directional, computational simulation

1. Introduction

To help meet the challenge of community resilience to natural hazards, the Lehigh NHERI Experimental Facility (EF) provides a world-class, open-access facility which enables researchers to address key research questions associated with the grand challenge of community resilience to natural hazards. The Lehigh NHERI EF provides a unique portfolio of equipment, instrumentation, infrastructure, testbeds, and experimental simulation control protocols that does not exist elsewhere in the world. The Lehigh NHERI EF enables researchers to develop new hazard mitigation strategies and solutions, and to develop innovative materials and structural concepts in ways that are not possible without the Lehigh NHERI EF. Sharing of data is enabled through the NHERI Cyberinfrastructure, using the Data Depot, a multi-purpose data repository for experimental, simulation, and field data (https://www.designsafe-ci.org/data/browser/).

The strength of the Lehigh NHERI EF is accurate large-scale simulations of the effects of natural hazard events on infrastructure (i.e., building, bridge, industrial facility, etc.) systems. The types of laboratory simulations and tests made possible by the Lehigh NHERI EF include: (1) hybrid simulation (HS) which combines large-scale physical models with computer-based numerical simulation models (e.g., [1, 2]); (2) geographically distributed hybrid simulation (DHS) which is a HS with physical models and/or numerical simulation models located in different laboratories and connected through the internet (e.g., [3]); (3) real-time hybrid earthquake simulation (RTHS) which is a HS conducted at the actual time scale of the physical models and earthquake (e.g., [4 - 9]; (4) geographically distributed real-time hybrid earthquake simulation (DRTHS) which combines DHS and RTHS [10]); (5) dynamic testing (DT) which use high speed servo-controlled hydraulic actuators or other methods to load large-scale physical models at real-time scales through predefined force or displacement histories to characterize their dynamic response (e.g., [11 - 15]); and (6) quasi-static testing (QS) which use hydraulic actuators to load large-scale physical models through predefined force and/or displacement histories (e.g., [16 – 18]). Any of these simulations or tests can be multi-degree-of-freedom and multi-directional, in which physical models are loaded at multiple points in multiple directions using displacement control or mixed-mode (force and displacement) loading protocols (e.g., [19, 20]). Lehigh NHERI EF is currently extending the hybrid simulation approach to soil-structure systems, and to wind events on infrastructure systems and components.

Multiple large-scale simulations and tests can be conducted simultaneously at the Lehigh NHERI EF, utilizing the resources available to the facility that includes the large laboratory space, number of skilled laboratory technicians, and multitude of equipment. The large-scale, real-time, multi-directional hybrid simulation capabilities of the Lehigh NHERI EF are a unique resource for providing system-level response data, since they enable the definition of the “system” to be expanded well beyond the size of typical laboratory physical models. At the same time, owing to its physical size, the Lehigh NHERI EF accommodates large-scale physical models, which reduces scaling effects often associated with typical physical models. A broad array of instrumentation, large-scale data acquisition systems, and advanced sensors is available to provide the system-level data needed to support the goal of advancing computational modeling and simulation.

2. Lehigh NHERI EF Equipment Portfolio

The Lehigh NHERI EF is housed in the Multi-directional Experimental Laboratory at the ATLSS Engineering Research Center, Lehigh University (see Fig. 1). A plan view of the ATLSS Laboratory is shown in Fig. 2. The ATLSS Laboratory has a strong floor that measures 31.1m x 15.2 m in plan, and a multi-directional reaction wall that measures up to 15.2 m in height. Anchor points are spaced on a 1.5-m grid along the floor and walls. Each anchor point can resist 1.33 MN tension force and 2.22 MN shear force. Additional steel framing is used in combination with the strong floor and reaction walls to create a wide variety of test configurations. A 178-kN capacity overhead crane services the test area and an adjacent fabrication area. Additional smaller cranes with capacities of 45-kN and 27-kN also serve this area. The ATLSS Laboratory has a machine shop and material testing facilities.

The Lehigh NHERI EF equipment portfolio includes the following:

- Five dynamic, double rodded hydraulic actuators designed and manufactured by Servo Test Systems: (1) two 2300 kN dynamic actuators ported for three 2080 liters/min (550 gpm) servo-valves, +/- 500 mm stroke; and (2) three 1700 kN dynamic actuators ported for three 2080 liters/min servo-valves, +/- 500 mm stroke. The maximum velocity that can be achieved by these actuators is 840 mm/sec (2300 kN actuators) and 1140 mm/sec (1700 kN actuators).

- Ten three-stage 2080 liters/min high flow-rate servo-valves. Ten service manifolds, with a low-pressure and high-pressure setting, to operate at 24.2 MPa and a maximum flow of 2080 liters/min.

- Hydraulic oil reserve and two banks of accumulators that enables strong ground motion effects to be sustained for up to 30 seconds. The accumulators supply a total accumulated oil volume of 3030 liters. A hydraulic system that connects the accumulators to the pressure line of a five pump 2270 liter/min (600 gpm) hydraulic system, with dedicated connections for the high-flow hydraulic service manifolds, along with a return line from these dedicated connections to the pump house area, a hydraulic oil reservoir in the pump house area for the oil needed to fill the accumulators and to receive the return flow, and connections to the reservoirs, heat exchangers, and pumps.

- Two digital 8-channel 1024 Hz control systems with real-time hybrid control packages, with each channel of the controllers designed to follow an independent, random load, or displacement history. The digital control systems are manufactured by Servo Test Systems and Wineman, respectively.

- A high speed 304-channel data acquisition system manufactured by Pacific Instruments, capable of acquiring data up to 4096 Hz (4096 samples per second) per channel.

- A 12 TB, expandable local data repository.

- Conventional sensors, including 12 temposonic displacement sensors of +/-750mm and +/-1120mm stroke, 5 triaxial and 5 monoaxial +/- 10g accelerometers, and 8 bi-axis dynamic 360 degree inclinometers

- Digital video teleobservation system including a system of 12 digital high quality video cameras, network video cameras, digital video server, data server, restricted access web server, and a public access web server. Digital video and data are provided by means of the video and telepresence servers. The digital video is acquired from 4 pan-tilt-zoom web cameras and two fixed position cameras controlled through a user interface on the telepresence server. Data regarding experiments is streamed through the teleoperation workstation and provided in the same interface on the telepresence server.

- Teleoperation consisting of an application server that coordinates the data streams to/from the test process module, digital controller, and video server, synchronizes the time stamps between these with the time server, and allows a control client application to interact with these elements of the test scheme. Teleoperation of the control system is accomplished using supported network protocols on the teleoperation workstation which forwards valid control requests to the real-time simulation workstation over a secure VLAN (virtual local area network). The real-time simulation workstation communicates test streams with the control system and data acquisition system over an optical shared memory network providing a single synchronization source for experiments. An onsite repository of experimental data and metadata is maintained to provide the information in a timely manner.

- In addition to the above equipment, ATLSS has 27 existing actuators that can be used for static load applications (e.g., to apply gravity load to test specimens). These actuators range in capacity from 130 kN to 2680 kN.

- Advanced sensors are also available from ATLSS that include two digital image correlation (DIC) systems that can perform non-contact 3-D full-field strain measurements under dynamic loading. The measurement volume range is 10 x 7.5 mm to 2000 x 1500 mm, and the strain measurement range is from 0.01% to 100%. The maximum sampling rate is 250,000 frames/sec.

- Auxiliary equipment that includes 180 kN and 90 kN overhead cranes, forklifts, manlifts, and a machine shop.

3. Lehigh NHERI EF Testbeds

Various large-scale testbeds are available for Lehigh NHERI EF. The testbeds include: (1) a lateral force resisting system testbed; (2) a non-structural component multi-directional seismic simulator; (3) 5 full-scale damper testbeds; (4) a tsunami debris impact force testbed; and, (4) two soil boxes for soil-structure interaction research. Photographs of these testbeds are shown in Fig. 3. The specifications and features of each of the testbeds are given in Table 1. 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.

4. Lehigh NHERI EF Experimental Protocol and Specifications

A schematic of the real-time testing architecture for the Lehigh NHERI EF is shown in Fig. 4, and includes the Real-Time Integrated Control System. The Real-Time Integrated Control System is configured with the experimental protocol required by the user to perform their test. The algorithms to perform the different types of tests mentioned above reside on the RTMDxPC, which is a dedicated real-time xPC kernel. The algorithms were implemented by developing software which will be discussed below. All of the algorithms have been created in Simulink on the simulation coordinator (RTMDsim), and Simulink Real-Time from MathWorks, Inc. [21] is used to recreate real-time executable code that is subsequently loaded onto an RTMDxPC. If the experiment requires large computational models with many degrees-of-freedom to create the analytical substructure, then the executable code is parallelized and placed onto two RTMDxPCs such that multi-grid processing can be used to run a large experiment in real time [22]. The Real-Time Integrated Control System uses SCRAMNet to enable communication among the telepresence server (RTMDtele), the simulation coordinator (RTMDsim), real-time target PC (RTMDxPC), the servo-hydraulic controllers (RTMDctrl), and data acquisition system (RTMDdaq). The data exchange across SCRAMNet occurs within 90 nanoseconds, essentially enabling shared memory among the workstations, 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 to meet user needs and complex testing methods to be performed. Experiments can be run in real-time (e.g., real-time hybrid earthquake simulation, distributed real-time hybrid earthquake simulation, dynamic testing), or at an expanded time scale (e.g., hybrid simulation, distributed hybrid simulation, quasi-static testing). The Real-Time Integrated Control System is operated in distributed hybrid simulation mode using either UI-Simcor [23], OpenFresco, or custom software. The System is robust and of a flexible design, enabling software and middleware packages developed by the NEHRI CI or users to be plugged into the System and utilized for conducting tests.

The integrated control system has a hydraulics-off simulation mode for use in 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 [24]. 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.

For hybrid simulation, numerous options exist for creating the analytical substructure. The open-source program HybridFEM has been developed by Karavasilis et al. [25] that enables analytical substructures to be created using embedded MATLAB functions in a Simulink model. The source code can be compiled and run in real-time to conduct real-time hybrid simulations. HybridFEM has an element library that includes nonlinear fiber elements, nonlinear panel zone elements, nonlinear hysteretic connection elements, nonlinear geometric elements to model the P-Δ effect, along with a material library that enables the hysteretic stress-strain behavior of steel, concrete, and reinforcement to be modeled. User-defined elements can be readily added to HybidFEM. HybridFEM has been successfully used on numerous projects by users to conduct a variety of types of experiments, including real-time hybrid simulations of structural systems [8, 9, 26 – 33]. Translator software can be used to convert an OpenSees model to use in HybridFEM. The option also exists to use OpenSees on the RTMDsim for conducting hybrid simulations. OpenFresco is used to provide the interface between OpenSees (where the analytical substructure and integration algorithm resides) and the experimental substructure [34].

Hybrid simulations are conducted using explicit integration algorithms developed by the PI [8, 27, 35, 36]. These algorithms are unconditionally stable, have second-order accuracy, and do not require iteration to satisfy equilibrium of the equations of motion (making them ideal for conducting real-time hybrid simulation). One of these algorithms is based on the KR-α method [8]. In addition to being unconditionally stable and second-order accurate, the KR-α method features controllable numerical energy dissipation (i.e., numerical damping), enabling it to be used to model structures that develop significant nonlinear response involving fracture or strength degradation (e.g., non-ductile reinforced concrete structures that develop cyclic member cracking and strength degradation [37]).

The target displacements of a test structure (i.e., experimental substructure) are precisely achieved in real time using an actuator control law that is based on the Adaptive Time Series Compensator, an advanced adaptive delay compensation algorithm developed by the author [38]. The algorithm uses feedback signals from the measured state of the test structure to ensure that the test structure target displacements are accurately achieved. This is accomplished by avoiding displacement errors from developing in the simulation due to both actuator and test fixture dynamics [9, 39]. For multi-directional experiments it is necessary to correct for kinematic errors in real time that effect actuator control. The testing protocol uses kinematic compensation to avoid developing kinematic errors in multi-directional experiments that is based on an algorithm developed by the authors [40]. The algorithm accounts for the precise displaced configuration of the test structure and the actuators in determining the actuator command displacement signals issued to the servo-controller (RTMDctrl).

Real-time telepresence is available using teleobservation and tele-operation equipment (RTMDtele) that is tied to the testing systems using discrete and global sensors, including high-resolution digital video and imaging capabilities, making it possible for remote collaborators and observers to access the Lehigh EF. Real-time structural system animation software has been developed [41] to enable the real-time visualization of the response of the complete system, including analytical and experimental substructures that exist in hybrid simulations. The experimental protocol includes the use of the Lehigh Data Model [42] that enables post-testing use of archived data from a hybrid simulation.

The protocols and specifications are published in the Lehigh NHERI EF User's Manual [43]. The experimental protocols and specifications are presented to potential users at annual researcher workshops and users with research awards at training workshops to assist them to plan their experimental research.

5. Example Projects

Below are three selected example projects that were performed recently in the past using the equipment and algorithms that are currently available at the Lehigh NHERI EF.

5.1. Multi-directional RTHS of Building Piping System

A RTHS of a building piping system in a three-story moment resistant frame is subjected to bi-directional earthquake ground motions [44]. The pressurized piping on the third story is selected as the experimental substructure, while the rest of the structure is modeled analytically (see Fig. 5). To ensure accuracy and stability during the simulation, the unconditionally stable explicit CR integration algorithm [35] and inverse compensation method developed by Chen [45] for actuator delay are used. The two horizontal components of the 1994 Northridge earthquake ground motion recorded at Canoga Park are scaled to the maximum considered earthquake (MCE) seismic hazard level. Real-time hybrid simulations were performed (Fig. 6) to evaluate the seismic performance of the components of the piping system, including the bracing, joints, and piping members. During the hybrid simulation, there was no observable damage to the pipe system and pressure was maintained. It was observed that both the input motion generated by the actuators and the response of the piping system was characterized by low frequency content. A few of the bracing connections loosened slightly, but the integrity of the braces was maintained.

Upon dismantling of the piping system after the RTHS were completed, the pipe groove couplings were examined for damage. Some of the couplings were observed to have been slightly ovalized. However, these couplings were subsequently pressure tested and were found to have maintained their integrity. The results of these tests indicate that piping systems connected with these new groove couplings are very robust and are not sensitive to the performance of the seismic bracing. It should be noted however, that proper design and installation of the seismic bracing is important towards ensuring good seismic behavior of the piping system. The simulation results indicate that adequate piping joints and carefully designed bracing can enable the nonstructural piping system to perform well under strong earthquakes. The experimental study demonstrates the application of real-time hybrid simulation to the seismic testing of nonstructural components.

5.2. Post-Tensioned Coupled Shear Wall Systems

Quasi-static (QS) tests were conducted on two large-scale reinforced-concrete (R/C) test specimens. Each test specimen represented the lower 3 stories of an 8-story R/C building with coupled C-shaped shear walls. The test specimens included shear walls, coupling beams, and floor slabs (see Fig. 7). The specimens incorporated innovative concepts and details (e.g., unbonded post-tensioned coupling beams, unbonded mild reinforcement in the wall piers) to provide performance which is superior to conventional coupled shear walls while eliminating cumbersome details in the coupling beams to simplify construction [19].

A comprehensive array of conventional sensors was used to measure the test specimen response. The deformations of the test specimens were also monitored using numerous 2-D and 3-D DIC sensors, providing near-full-field deformation response data for critical regions of the wall piers, floor slabs, and coupling beams (see Fig. 7).

In the QS tests, a total of 11 servo-controlled hydraulic actuators loaded each test specimen at 11 different points to simulate the interaction of the 3-story test specimen with the upper 5 stories of the building during seismic loading. The actuators loaded the test structure simultaneously in two directions. A mixed-mode load control program was developed specifically for these QS tests to implement the required experimental algorithm. The program, running on digital controller, used force control for 10 actuators and displacement control for 1 actuator, to provide the distribution of forces on the test specimen required by the research team. To maintain test safety, the control program implemented various force-error and displacement increment checks to eliminate loss of control during an unexpected or catastrophic failure of the test specimen.

5.3. RTHS of a 3-story Building with Nonlinear Viscous Dampers

An experimental study of the seismic response of a 0.6-scale three-story building with nonlinear viscous dampers under the design basis earthquake (DBE) and the maximum considered earthquake (MCE) was performed. The building’s lateral force resisting system consisted of moment resisting frames (MRFs) with reduced beam sections (RBS) and damped braced frames (DBF) with nonlinear viscous dampers. Three MRF designs were studied, with the MRF designed for 100%, 75%, and 60%, respectively, of the required base shear design strength according to ASCE 7-10 [46]. The DBFs with nonlinear viscous dampers were designed to control the lateral drift demands. Earthquake simulations using ensembles of ground motions were conducted using the RTHS method. For the RTHS the experimental substructure consisted of a DBF with nonlinear viscous dampers and associated bracing, while the analytical substructure modeled the remaining parts of the building, namely, the MRF, gravity load system, and the tributary seismic floor masses (see Fig. 8). The study focused on quantifying and assessing the seismic response of the building under the DBE and MCE.

The experimental results show that a high level of seismic performance can be achieved under the DBE and MCE ground motions, even for a building structure designed for as little as 60% of the design base shear strength required by ASCE 7-10 for a building structure without dampers (see Figs. 9 and 10).

6. Summary and Conclusions

The main features and functionality of the Lehigh NEHRI EF established at the ATLSS Engineering Research Center at Lehigh University was presented. This facility has advanced experimental and analytical simulation capabilities to test large-scale structures in real time in order to validate more complex and comprehensive analytical and computer numerical models. Several testing algorithms are enabled at the facility, including: (1) hybrid simulation (HS); (2) geographically distributed hybrid simulation (DHS); (3) real-time hybrid earthquake simulation (RTHS); (4) geographically distributed real-time hybrid earthquake simulation; (5) dynamic testing (DT); and (6) quasi-static testing (QS). The facility resources enable multiple, large-scale simulations and tests to be conducted simultaneously, enabling numerous users to work concurrently without significant interruption. The large-scale hybrid simulations are a unique resource for acquiring system-level response data, since they enable the definition of the "system" to be expanded well beyond the size of typical laboratory physical models. At the same time, due to its large size, the facility accommodates large-scale physical models, which reduces scaling effects associated with typical, small physical models. A broad array of instrumentation, large-scale data acquisition systems, and advanced sensors provides the system-level data needed for advancing computational modeling and simulation. The new discoveries and knowledge from these simulations will enable researchers to develop and validate new hazard mitigation solutions, and innovative hazard-resistant structural concepts.

More information about the Lehigh NHERI EF can be found at the facility's website at https://lehigh.designsafe-ci.org/. This information includes facility overview, equipment portfolio, experimental protocol, resources, facility workshops, and contact information.

7. Acknowledgements

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8. References

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Table 1 – Lehigh NHERI EF Real-time integrated control system.

Testbed	**Specifications and Features**
Lateral force resisting system testbed	• Test large-scale systems of up to 13.7 m in height, 11 m in width
Non-structural component multi-directional seismic simulator	• 12.2 m in length and 3.1 m in width • Multi-directional loading
5 full scale damper testbeds	• Maximum force of 2300 kN, 1140 mm/sec velocity, and 1000 mm stroke range • Damper characterization; real-time hybrid simulation
Tsunami debris impact force testbed	• High speed DAQ; high speed 5000 fps cameras
Two 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

Fig. 1 – ATLSS Laboratory Multidirectional Reaction Wall

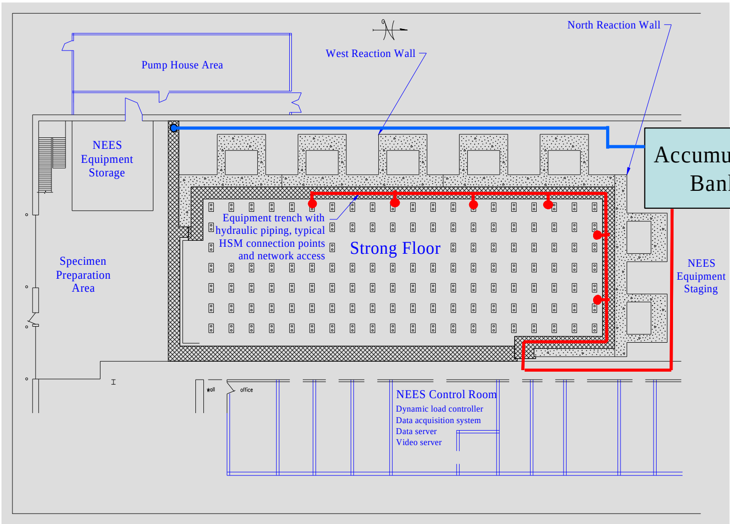
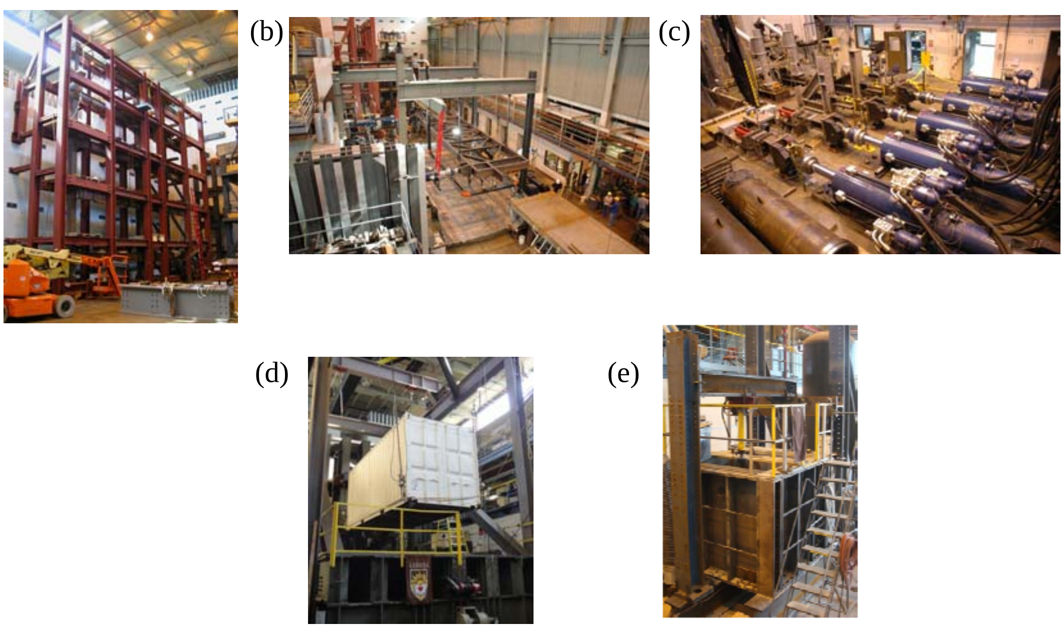


Fig. 2 – Floor Plan of ATLSS Laboratory with Lehigh NHERI EF.

(a) (b) (c)



(d) (e)

Fig. 3 – Lehigh NHERI EF testbeds: (a) lateral force resisting system testbed; (b) non-structural component multi-directional seismic simulator; (c) 5 full-scale damper testbeds; (d) tsunami debris impact force testbed; and, (e) soil boxes.

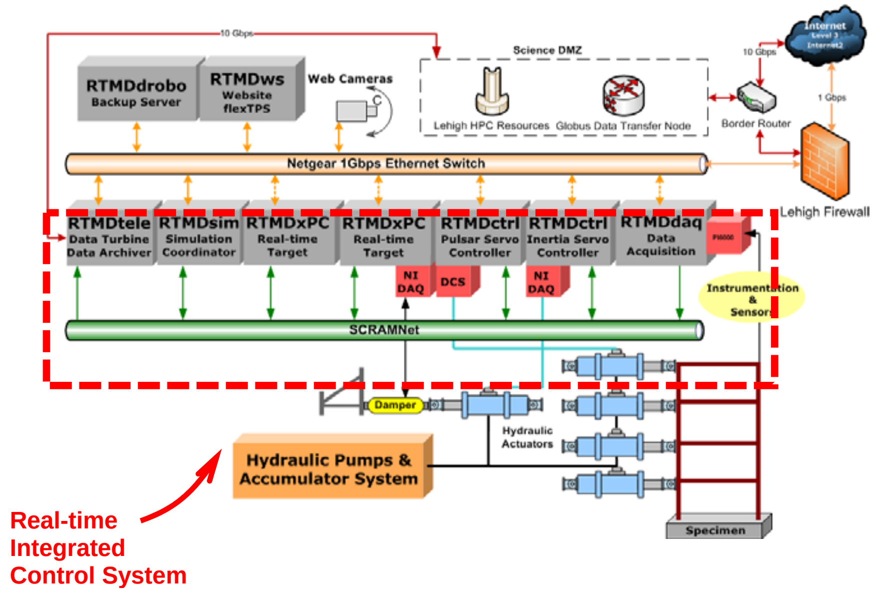


Fig. 4 – Lehigh NHERI EF Real-Time Integrated Control System.

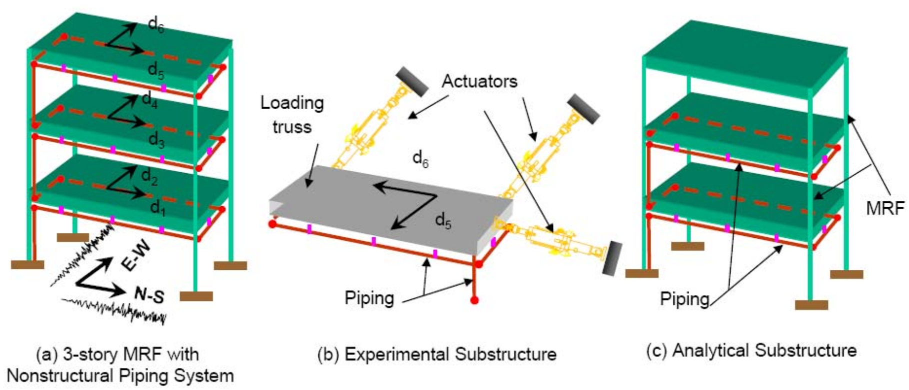


Fig. 5 – RTHS of 3-Story MRF with piping system subjected to bi-directional ground motions.

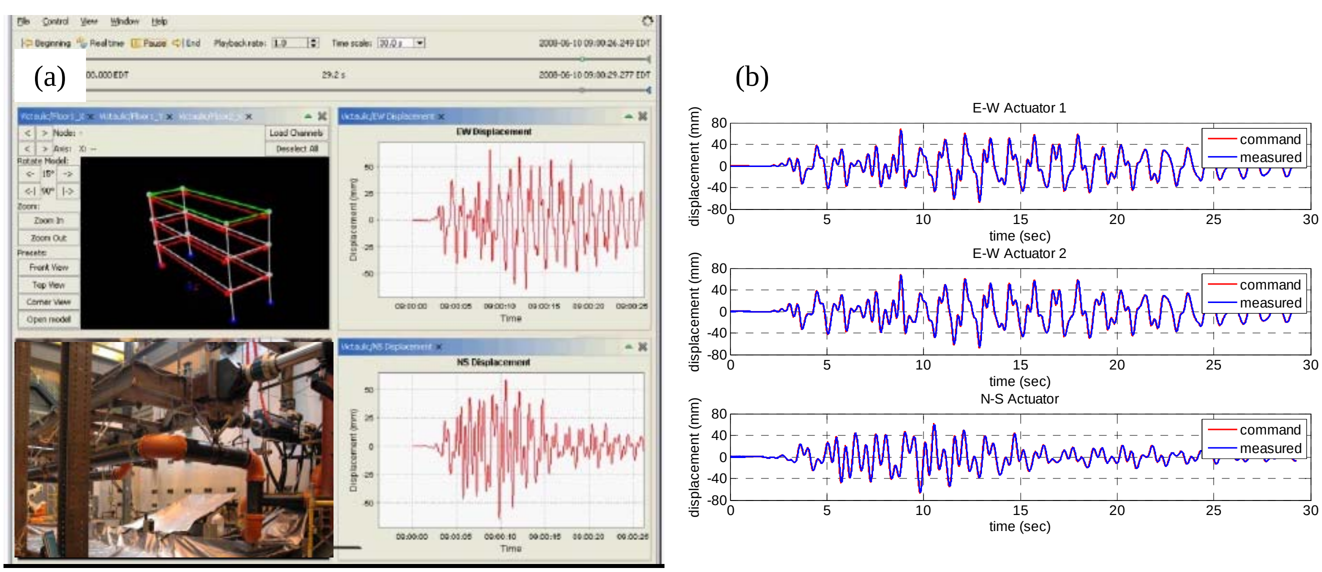


Fig. 6 – RTHS of 3-Story MRF with piping system: (a) teleobservation of animated system response, video of experimental substructure; and, (b) EW and NS 3rd floor displacements.

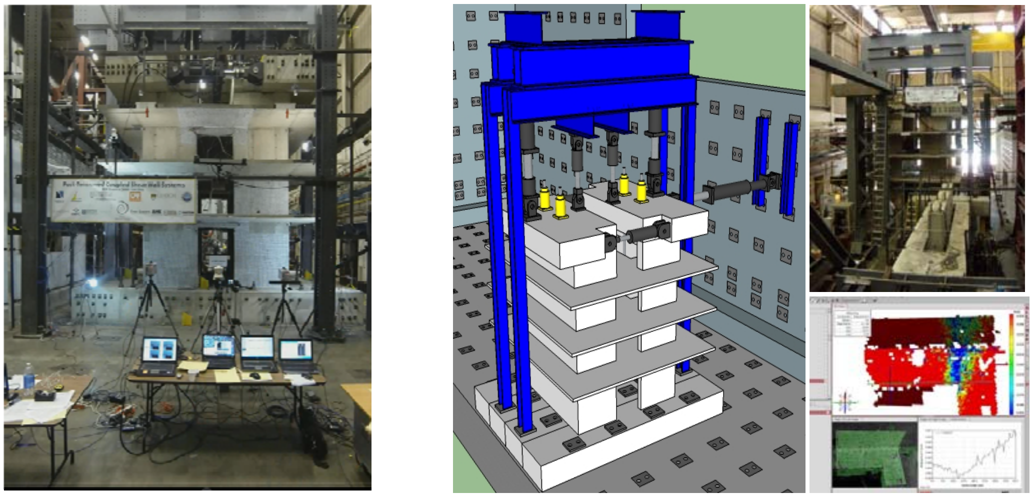


Fig. 7 Coupled shear wall test specimen with multi-directional loading, joint strains measured by DIC system

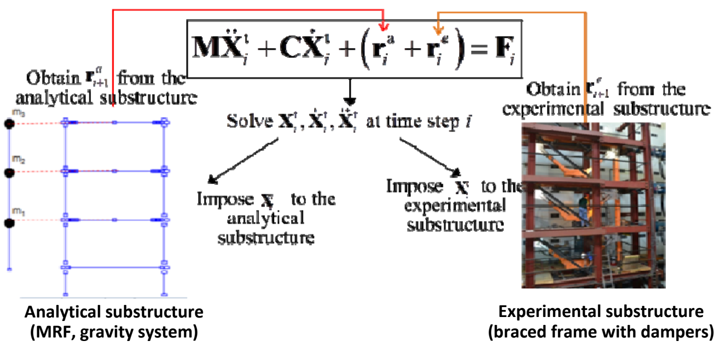


Fig. 8 Analytical and experimental substructures for RTHS of a 3-story building with nonlinear viscous dampers.

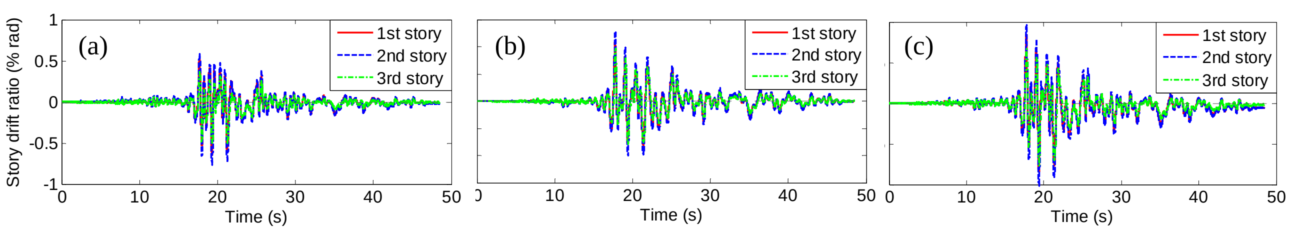


Fig. 9 Story drift ratio time histories from DBE level RTHS using HECTOR-11625090 record: (a) building designed for 100%, (b) 75%, and (c) 60% of the design base shear.

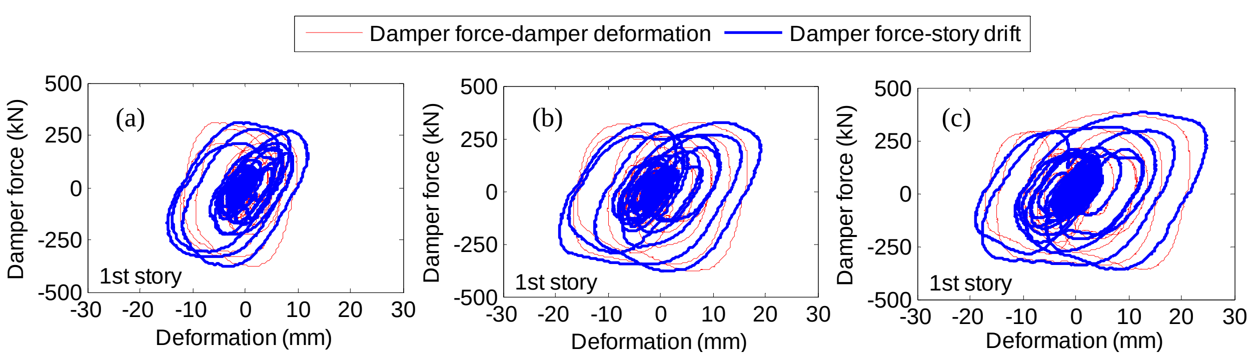


Fig. 10 Damper force-deformation responses from DBE level RTHS with HECTOR-11625090 record: (a) building designed for 100%, (b) 75%, and (c) 60% of the design base shear.