Science Plan
Lehigh University NHERI EF

Natural Hazards Engineering Research Infrastructure: Experimental Facility with Large-Scale Multi-Directional Hybrid Simulation Testing Capabilities

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5. Science Plan

5.1 Grand Challenge: Community Resilience to Natural Hazards

There is a strong national movement toward resilient communities (NRC 2004, Subcommittee 2005, NIST 2010, NRC 2011, The White House 2013, NAP 2014). Stakeholders are seeking resilient communities that recover quickly from natural hazard events, such as earthquakes (e.g., SPUR 2009) and wind events. The National Research Council Workshop Report on Grand Challenges in Earthquake Engineering Research (NRC 2011) identified five grand challenges associated with earthquake-resilient communities: (1) a community resilience framework; (2) improved decision making; (3) advanced simulation; (4) mitigation strategies and solutions; and (5) new, innovative materials and structural concepts, integrated into practice, to improve seismic performance. Similar challenges exist to increase community resilience for wind and wind induced (e.g. storm surge) hazards.

To help meet the challenge of community resilience to natural hazards, the Lehigh Experimental Facility (EF) will provide 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 EF will provide a unique portfolio of equipment, instrumentation, infrastructure, testbeds, and experimental simulation control protocols that does not exist elsewhere in the US**. The Lehigh EF will enable 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 EF.

The strength of the Lehigh 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 EF include: (1) **hybrid simulation** (HS) which combines large-scale physical models with computer-based numerical simulation models (e.g., Lin et al. 2013a,b, Sause et al. 2010a,b, 2014); (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., Ricles et al. 2007; Marullo et al. 2008); (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., Mercan et al. 2008, Chen et al. 2009, Karavasilis et al. 2011a, Chen et al. 2012, Cha et al. 2013, 2014, Friedman et al. 2014, Kolay et al. 2014, Dong et al. 2014a,b); (4) geographically **distributed real-time hybrid earthquake simulation** (DRTHS) which combines DHS and RTHS (Kim et al. 2012); (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., Ricles et al. 1999, 2002a, Sause et al. 2012, Riggs et al. 2014, Chae et al. 2013 a,b); 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., Cao and Naito 2009, Perez et al. 2013, Ricles et al. 2002b, Zhang and Ricles 2006, Zhang et al. 2011). 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., Barbachyn et al. 2014, Zhang et al. 2011). In the future, the Lehigh EF will seek to extend 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 EF, utilizing the resources available to the facility that includes the large laboratory space, number of skilled laboratory technicians, and multitude of equipment.

The vision for NHERI includes advancing computational modeling and simulation from component to system levels. These advancements require computational simulations which are strongly supported by system-level response data from laboratory simulations. **The large-scale, real-time, multi-directional hybrid simulation capabilities of the Lehigh 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 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.

5.2 Key Questions

The National Research Council Workshop Report on Grand Challenges in Earthquake Engineering Research (NRC 2011) states that community earthquake resilience requirements begin at the community level, where performance requirements for the built environment are established. As illustrated by the planes in Figure 5.1, the research challenges for community resilience to earthquakes are: (1) characterizing the earthquake hazard; (2) designing mitigation measures that minimize losses to the built environment; and, (3) evaluating how a community is affected and recovers from disruptions to the built environment from an earthquake. The Lehigh EF contributes to the middle plane by enabling research that seeks to minimize losses to the built environment; this research uses laboratory simulations along with computational simulations to link the lower Hazard plane with the upper Community plane.

Figure 5.1. Earthquake Community Resilience

The Lehigh EF will enable key research questions in natural hazard mitigation to be answered. For example, the Lehigh EF will enable researchers to: develop new hazard mitigation strategies and innovative structural system concepts; to more fully understand system performance by including soil-foundation interaction with the structural system; better account for system-level effects (boundary-condition effects) on components by using hybrid simulation to include the full structural and soil-foundation system; evaluate 3-D effects on components and systems; and use advanced instrumentation to obtain high quality experimental data. Such experimental research is essential to validate new, innovative structural concepts for design and retrofit that improve the performance of infrastructure systems to achieve the goal of community resiliency. High quality system-level data from laboratory simulations and tests are needed to validate computational simulation models that are needed to assess the performance of infrastructure systems subject to natural hazards.

5.3 Approach/Major Resources Provided

As noted earlier, the key features of the Lehigh EF are: (1) hybrid simulations (HS, DHS, RTHS, and DRTHS), (2) large-scale multi-directional, multi-degree-of-freedom simulations and tests, and (3) dynamic loading simulations and tests (RTHS, DRTHS, and DT). In a hybrid simulation (HS), selected portions of the system (which are not well understood) are implemented in the laboratory by one or more physical models (i.e., the experimental substructure), while the remaining portion of the system is modeled using one or more computational models (i.e., the analytical substructure), as shown in Figure 5.2. The hybrid simulation approach enables a complete system, which is much larger than is feasible to build in the lab, to be included in the simulation. As a result, the experimental substructure, which is in the lab because it is not well understood, is subjected to realistic loading and boundary conditions. In a real-time hybrid simulation (RTHS), these loading conditions are dynamic at real-time scale. In a HS, the two substructures have identical imposed displacements at their common degrees of freedom. The hybrid earthquake simulation approach requires integrating the dynamic equations of motion for earthquake loading, utilizing the restoring forces (which vary with the imposed displacements) from the two substructures. The approach, depicted in Figure 5.2, is conducted in real-time during a RTHS.

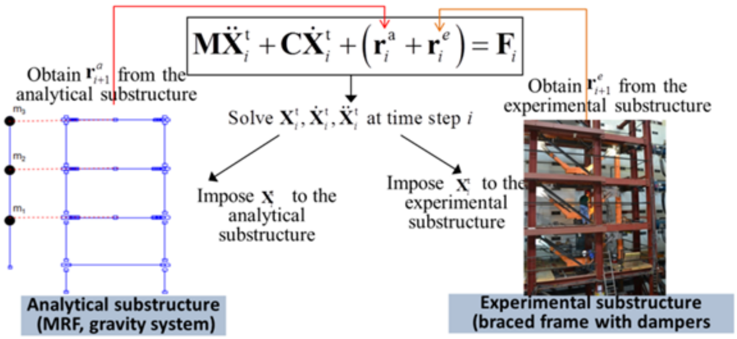

Figure 5.2. Overview of Hybrid Simulation Approach – NEES@Lehigh RTHS of Building with Viscous Dampers

During the past decade, the hybrid simulation approach for earthquake effects has developed into a reliable experimental method (e.g., Mercan et al. 2008, Chen et al. 2009, Karavasilis et al. 2011a, Chen et al. 2012, Cha et al. 2013, 2014, Friedman et al. 2014, Kolay et al. 2014, Dong et al. 2014a,b). A hybrid simulation approach for wind hazard effects is largely unexplored. The Lehigh EF is interested in conducting research with potential users to develop a **hybrid wind simulation** approach. Figure 5.3 shows the hybrid wind simulation concept, in which the Lehigh EF houses experimental and analytical substructure for determining the system response, while the wind loading forcing function F_i for the equations of motion is determined from a wind tunnel model or a computational fluid dynamics (CFD) model. The wind loading demands can be introduced through the internet from an off-site wind tunnel model or CFD model running on off-site high performance computing resources (i.e., the hybrid simulation may be a geographically **distributed hybrid simulation** (DHS) as shown in Figure 5.3.

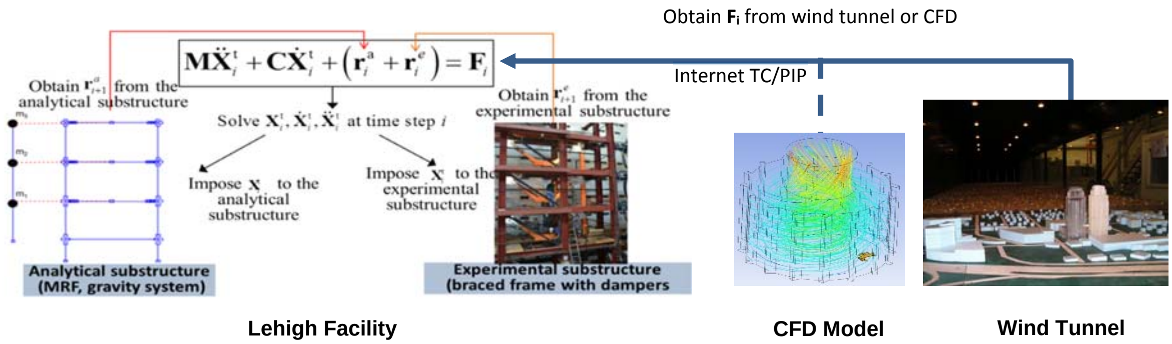

Figure 5.3 Distributed Hybrid Wind Simulation Concept

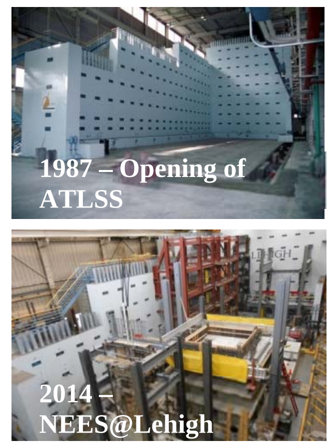

Figure 5.4. 3-D Multi-Directional Reaction Wall and Strong Floor

The Lehigh EF will operate in the Multi-Directional Testing Laboratory at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center at Lehigh University. Over 25 years of ATLSS Center operations, including the past 12 years as a the NEES@Lehigh equipment site, the Lehigh EF has acquired a unique portfolio of equipment and instrumentation, has assembled a well-trained and skilled staff, and has developed state-of-the-art algorithms, software, and tools for real-time integrated simulation control to enable large-scale real-time hybrid earthquake simulations to be performed on a routine basis. The unique equipment portfolio (capabilities exist only at Lehigh) includes: (1) three 1700 kN and two 2300 kN servo-hydraulic actuators with 1000 mm stroke and maximum velocities of up to 1140 mm/sec; (2) the hydraulic power supply system consisting of 5-454 lpm pumps and a 3030 liter accumulation system enables earthquake effects on structures to be sustained for more than 30 seconds during a large-scale real-time hybrid simulation; (3) the real-time integrated IT control system, which integrates laboratory data acquisition, computational simulation, and servo-hydraulic actuator control in a single IT system; and, (4) the ATLSS Center with its 3-D reaction wall-strong floor laboratory (see Figure 5.4), skilled laboratory staff (instrumentation, construction, hydraulics, and control) and additional resources (other servo-controlled actuators, instrumentation, digital image correlation system, mechanical testing laboratory, metallography and microscopy laboratory, non-destructive evaluation laboratory, machine shop, offices for visiting researchers, conference rooms, and an auditorium). Numerous large-scale testbeds exist that are available for users of the Lehigh EF. The testbeds include a large-scale damper characterization testbed, a non-structural component testbed, a soil-box with embedded piles and foundation, a tsunami debris impact testbed, and a lateral load resisting frame system testbed.

Services will be provided by the Lehigh EF that include: algorithms and software for users to perform experiments; routine scheduled calibration and maintenance of equipment to ensure its readiness; training users to use the tools and software to perform their experiments; safety training; staff to prepare test setups, configuring DAQ and experimental testing algorithms, operating the equipment to assist users in conducting experiments, assisting users with data backup and transfer to data repositories; and, organizing and hosting ECO activities.

With this portfolio and services in place, the Lehigh EF is the only laboratory in the US capable of routinely performing large-scale multi-directional RTHS. Real-time simulations are essential for systems with rate-dependent behavior, such as structures with supplemental dampers. The Lehigh EF also features the capability for dynamic tests (DT) or quasi-static tests (QS) on large-scale test specimens with custom-developed (as needed by a user) multi-directional, mixed-mode (combinations of force and displacement control) load control programs to implement a required experimental algorithm.

An example of routine use of RTHS is the recently completed project "NEESR-CR: Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems." In this project, large-scale (0.6-scale) 3-story steel frames with supplemental passive dampers were constructed in the laboratory to serve as the experimental substructure (Figure 5.5). The remainder of the 3-story building was represented as an analytical substructure, using computational models. Using the real-time integrated control system and software available at the Lehigh EF, numerous RTHS were conducted to provide a comprehensive and detailed data set documenting the response of a set of steel frame building structures with supplemental dampers under earthquake loading (Mahvashmohammadi et al. 2014, Dong et al. 2014). In particular: 122 RTHS were performed with the experimental substructure consisting of a 3-story steel frame with nonlinear viscous dampers; 10 RTHS were performed with the experimental substructure consisting of a 3-story steel frame with nonlinear viscous dampers plus an associated welded steel moment-resisting frame (MRF); and 43 RTHS were performed with the experimental substructure consisting of a 3-story steel frame with elastomeric dampers. Each of these RTHS was conducted with a ground motion selected to represent the frequently occurring earthquake (FOE), the design basis earthquake (DBE), or the maximum considered earthquake (MCE). Ground motions were varied, and the properties of the 3-story steel frame building were varied. The total of 175 RTHS conducted successfully for this project illustrates routine use of RTHS at the Lehigh EF to provide the high-quality system-level data needed to validate computational simulation models and to improve the performance of systems subject to natural hazards.

Figure 5.5. NEES@Lehigh Large-scale RTHS

The project "NEESR-CR: Post-Tensioned Coupled Shear Wall Systems" provides an excellent example of the use of quasi-static tests (QS) on large-scale test specimens with a custom-developed multi-directional, mixed-mode load control program. QS tests were performed on a set of two large-scale reinforced-concrete test specimens, where each specimen represented the lower 3 stories of an 8-story R/C building (Figure 5.6). The test specimens included shear walls, coupling beams, and floor slabs, with innovative concepts and details (e.g., unbonded post-tensioned coupling beams, unbonded mild reinforcement in the wall piers) (Barbachyn et al. 2014). 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 8-story building during seismic loading. The actuators loaded the test structure in two directions. A mixed-mode load control program was developed specifically for these QS tests to implement the required experimental algorithm. The program used force control for 10 actuators and displacement control for 1 actuator, to provide the intended distribution of forces on the test specimen. The control program included various force-error and displacement increment checks to eliminate loss of control during an unexpected or catastrophic failure of the test specimen. A comprehensive array of conventional sensors and numerous 2-D and 3-D digital image correlation (DIC) sensors measured the test specimen response.

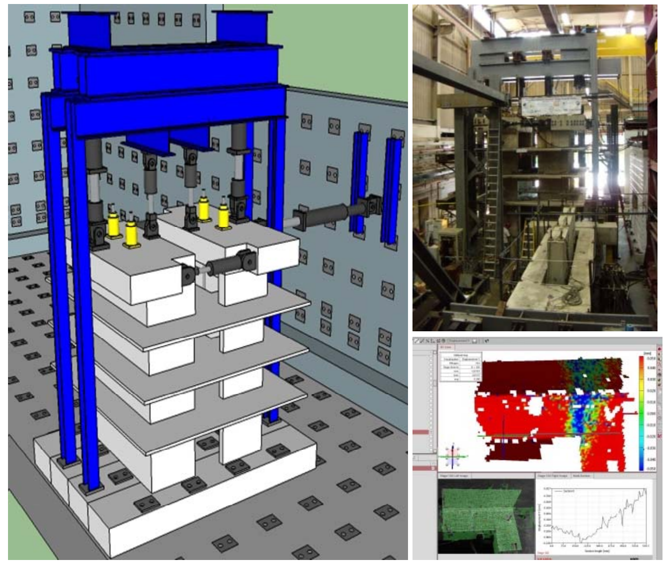

Figure 5.6 NEES@Lehigh Coupled Shear Wall Test Specimen with Multi-Directional Loading, Joint Strains Measured by DIC

5.4 Anticipated User Base

The anticipated future use of the Lehigh EF is estimated from past experience with the NEES@Lehigh equipment site. Seventeen research projects were conducted by researchers using NEES@Lehigh. These researchers performed 6891 tests that produced 3020 GB of data archived on NEEShub. The user base for the NEES@Lehigh equipment site grew steadily over 10 years of operation. During 2013, the NEES@Lehigh led all sites by providing service to seven active NEES research projects (NEEShub 2014). The largest number of NEES research projects serviced by other sites in 2013 was about one-half this number (i.e., four). The seven active projects at the NEES@Lehigh equipment site represented 25% of the 28 total projects conducted at all NEES equipment sites in 2013. Over the course of the 10 year NEES program, the NEES@Lehigh was the most active among the six NEES large-scale laboratory experimentation sites, providing research access and support for 23 research projects (pre-NEESR, NEESR, and shared-use projects) (NEEShub 2014). It is expected that this growth in research using the capabilities of the Lehigh EF will continue as users recognize the value of large-scale multi-directional hybrid simulations and tests in generating new discoveries and advances in performance of infrastructures systems for community resiliency.

The anticipated user base for the Lehigh EF include: (1) researchers interested in the developing and validating new, innovative structural system concepts leading to a new generation of low-damage earthquake resistant structures for earthquake-resilient communities; (2) researchers interested in retrofit strategies to improve seismic performance of existing structural systems; (3) researchers interested in developing computational simulation models and need full-scale dynamic characterization test data for load-rate dependent components or devices (e.g., dampers), using equipment with large force and velocity capacities; and (4) researchers interested in simulating earthquake effects on full soil-foundation-structural systems. In addition, the Lehigh EF anticipates user-led research projects to develop a **hybrid wind simulation** approach.

In addition to NSF-supported research projects, we anticipate that research projects using the Lehigh EF will be supported by other federal agencies (e.g., FHWA, NIST, etc.), non-profits (e.g., Applied Technology Council, American Institute of Steel Construction, American Concrete Institute, Precast/Prestressed Concrete Institute, Pankow Foundation, etc.), state governments and industry (e.g., Taylor Devices, Corry Rubber Company, Boeing, etc.). For non-NSF-supported projects, relevant user fees and recharge rates at the Lehigh EF will be applied. (Note: We are not claiming these organizations to be participating organizations in the proposed project).

5.5 Education, Community Outreach

The ECO programs of the Lehigh EF are aimed at integrating research into education. They will target a diverse audience at all levels and attract young individuals into science, technology, engineering, while also reaching out to educate and inform the engineering community about new discoveries and advancements in earthquake and wind hazard mitigation. Strategic partnerships in education and outreach will be targeted to be formed to provide the means to broaden the participation of underrepresented individuals in the educational opportunities of the Lehigh EF ECO program. The NCO-organized NHERI REU program will be leveraged with students from the ATLSS Center REU program, providing a strong community of REU students engaged in research.

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