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NEES REAL-TIME MULTI-DIRECTIONAL SEISMIC TESTING FACILITY FOR LARGE SCALE STRUCTURES

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SUMMARY

As part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program, Lehigh University has established the Real-Time Multi-Directional (RTMD) earthquake simulation facility at the ATLSS Engineering Research Center. The RTMD earthquake simulation facility is a next-generation earthquake research facility for seismic performance evaluation of large-scale structural systems. This facility has advanced experimental and analytical simulation capabilities to test and validate more complex and comprehensive analytical and computer numerical models, leading to advances in earthquake engineering and experimental methods. Real-time multi-directional seismic testing of large-scale structural components and systems at the RTMD earthquake simulation facility can be performed using either the effective force method, pseudo-dynamic testing method, or the pseudo-dynamic hybrid testing method. The facility features a multidirectional reaction wall, five dynamic actuators, advanced instrumentation, and a teleparticipation system consisting of digital high quality video and network video cameras and multiple servers connected to the Internet. Hydraulic power for the servo-actuator system is supplied by a system consisting of five pumps and three banks of accumulators that enables strong ground motion effects to be sustained in real-time for up to 30 seconds.

INTRODUCTION

Under Phase II of the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) solicitation, Lehigh University was awarded a grant to develop the Real-Time Multi-Directional (RTMD) earthquake simulation facility. The RTMD earthquake simulation facility is a shared-use research facility. The facility enables multi-directional real-time seismic testing of large-scale structural components, structural subassemblages, and superassemblages (systems), and supports methods for real-time testing, including the real-time pseudo-dynamic testing method (Mercan and Ricles [1], Zhang et al. [2], Shing et al. [3], Nakashima and Masaoka [4], Horiuchi et al. [5]), real-time hybrid testing method (Mercan and

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Ricles [1], Shing et al. [2], Mosqueda, [6]), as well as the effective force test method (Zhang et al. [7], Thewalt and Mahin [8]; Dimig et al. [9]).

In the past, few structural experiments have been performed at large-scale with load rates approaching those that occur in actual structures under earthquake loading. Although there is a long tradition of using structural tests to advance the state-of-the-art in seismic design and performance of structural systems in the US, experiments on large-scale (near real-scale) structural subassemblages, components and connections have become common only during the past two decades. The integration of the capabilities of the RTMD earthquake simulation facility with analytical research will enable the seismic design and performance of the civil and mechanical infrastructure systems in the U.S. to be significantly advanced. The integration of experimental and analytical research will occur in two ways: (1) real-time hybrid testing will be conducted, where parts of the structural systems will be analytically modeled and coupled to the test subassembly, or multiple test subassemblies, to simulate real earthquake forces on the complete structural system; and (2) information from the experiments will be acquired, archived, and disseminated in a form that enables evaluation of existing or the development of new analytical models and material constitutive relationships.

The integrated experimental-analytical research based on large-scale real-time tests using the RTMD earthquake simulation facility will enable new analytical methods and models, and new design methods to be advanced rapidly into use by researchers and practitioners. Support from high quality experimental data is essential to gain acceptance of new analysis and design methods.

RTMD FACILITY EQUIPMENT PORTFOLIO

The RTMD earthquake simulation facility is housed in the Multi-directional Experimental Laboratory at the ATLSS Engineering Research Center, Lehigh University (see Figure 1). A plan view of the ATLSS Laboratory is shown in Figure 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.

Figure 1 ATLSS Laboratory Multidirectional Reaction Wall.

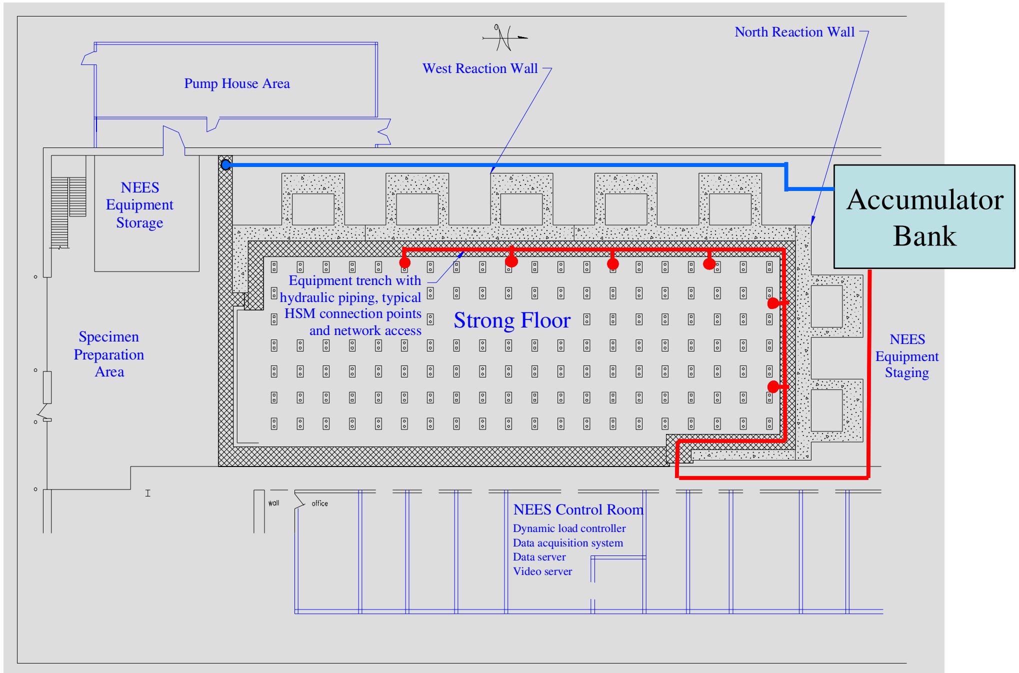


Figure 2 Floor Plan of ATLSS Laboratory with NEES RTMD Facility.

To create the RTMD earthquake simulation facility, various pieces of equipment have been installed in the ATLSS Laboratory. This equipment includes:

- Five dynamic, double rodded hydraulic actuators designed and manufactured by Servo Test Systems: (1) two 2050 kN dynamic actuators ported for three 1500 liters/min (400 gpm) servo-valves, +/- 500 mm stroke; and (2) three 1500 kN dynamic actuators ported for three 400 gpm servo-valves, +/- 500 mm stroke. The maximum velocity that can be achieved by these actuators is 750 mm/sec (2050 kN actuators) and 1000 mm/sec (1500 kN actuators).
- Ten three-stage 1500 liters/min (400 gpm) high flow-rate servo-valves. Ten service manifolds, with a low-pressure and high-pressure setting, to operate at 24.2 MPa (3500 psi) and a maximum flow of 1500 liters/min (400 gpm).
- 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 (800 gallons). Hydraulic system modifications to connect the accumulators to the pressure line of the existing five pump 2250 liter/min (gpm) hydraulic system, with dedicated connections for the new, high-flow hydraulic service manifolds, along with a new return line from these dedicated connections to the pump house area, and a new hydraulic oil reservoir in the pump house area for the oil needed to fill the accumulators and to receive the return flow, as well as make connections of this reservoir to the existing reservoirs, heat exchangers, and pumps.
- A digital *8*-channel 1024 Hz control system with real-time hybrid control packages, with each channel of the controller designed to follow an independent, random load, or displacement history. Five of the eight channels are operational for controlling the dynamic actuators (i.e., five control system modules were purchased to enable the five actuators for the RTMD earthquake simulation facility to be independently controlled). The digital control system is also designed and manufactured by Servo Test Systems.

- A high speed 256-channel data acquisition system manufactured by Pacific Instruments, capable of acquiring data at 1000 Hz (1000 samples per second) per channel.

- Advanced sensors that include wireless MEMS-based accelerometers, piezoelectric transducers (strain measurement), and fiber optic strain gages of Stimulated Brillouin Scattering principles. Under the cooperative agreement with NSF, prototype piezoelectric transducers and fiber optic strain gages sensors have been developed and integrated into the data acquisition system for the RTMD earthquake simulation facility.

- Digital video teleobservation system including a system of 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. Authentication for access to the equipment is through the NEESgrid onsite NEES Pop to provide secure control and public access to the information. An onsite repository of experimental data and metadata is maintained to provide the information in a timely manner.

In addition to the NEES 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 capacity.

OVERVIEW OF SERVO-HYDRAULIC CONTROL SYSTEM CONFIGURATION

The configuration for the servo-hydraulic control system for the RTMD earthquake simulation facility is shown in Figure 3. The digital controller (identified as the Real-time Control Workstation in Figure 3) with the 1024 Hz clock speed controls the motion of the actuators. During testing, the real-time Control Workstation is integrated with a real-time Simulation Workstation and Data Acquisition Workstation, as well as a real-time Teleoperation Workstation using SCRAMNet. SCRAMNet is a fiber optic communication device that enables shared memory and time synchronization to the Control Workstation. The control system configuration permits complex testing algorithms, servo-hydraulic control laws, and analytical substructures to be placed on the Simulation Workstation. The latter is used for hybrid testing. Command signals for imposing motion on a test structure (either force or displacement, depending on the method of testing) are generated on the Simulation Workstation, where complex analytical models (e.g., MATLAB or OpenSees) may reside for integrating the equations of motion in conjunction with a physical test structure, or hybrid physical test structure(s) and a analytical model. Feedback signals for determination of the command signal for the next time step during a test are acquired from the Control Workstation and the Data Acquisition Workstation (e.g., measured actuator forces and current position of the test structure to enable kinematic compensation for multi-directional real-time pseudo-dynamic tests to be accounted for).

Prior to performing a test, information that needs to be passed to each workstation from the Simulation Workstation in order to initialize them is done so using a secure VLAN connection. As an alternative to using the Simulation Workstation as explained above, the DSP in the controller can also be programmed for new servo-hydraulic control laws as well as real-time testing algorithms. This approach for testing is however limited, due to the computational capacity of the DSP.

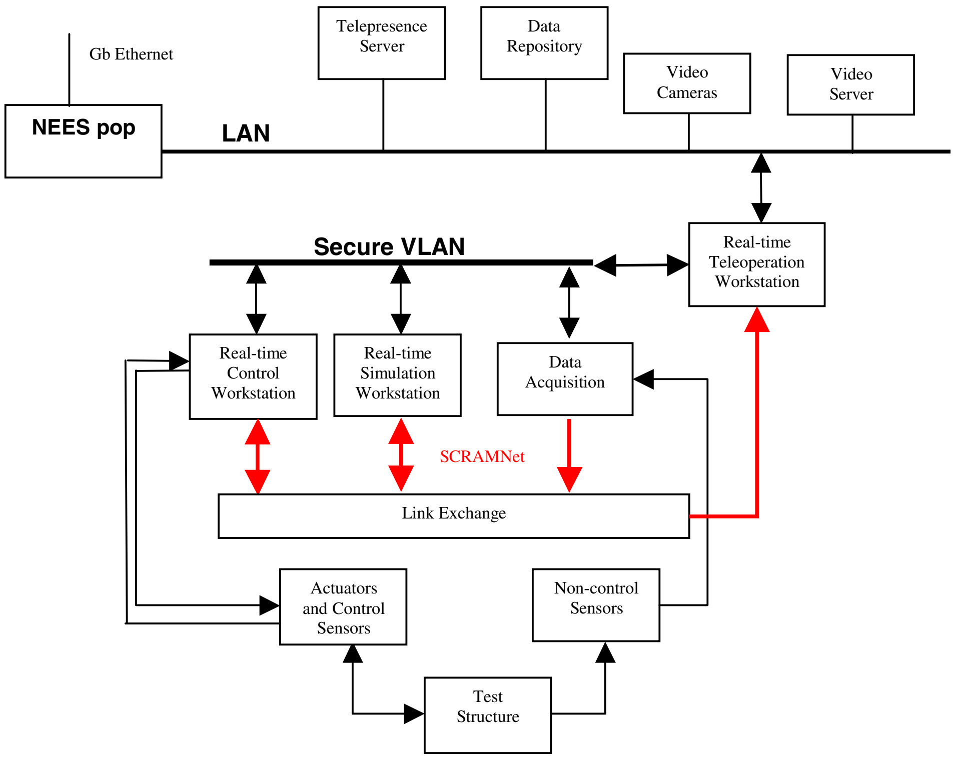


Figure 3 RTMD Earthquake Simulation Facility Control System Configuration.

The configuration of the servo-hydraulic control system also enables distributed hybrid testing to be performed, where a remote experimental and/or computational facility is engaged in the testing. Distributed hybrid testing is accomplished over the Internet, using the NTCP and NEESGrid software developed by the NEES System Integrator, with information transferred through the NEES Pop and real-time Teleoperation Workstation. Remote laboratories will be able to participate in hybrid testing by having the NTCP and NEESGrid locally installed at their facility.

STRUCTURAL TESTING

The functional flexibility of the RTMD earthquake simulation facility will create numerous possibilities for structural testing. These include not only complex seismic testing but also testing to evaluate response to other types of loading conditions, including wind and bridge structures with moving traffic loads. The seismic response of a complex structural system can be evaluated in three ways using the RTMD earthquake simulation facility to (1) test the structural superassembly (by either the real-time pseudo-dynamic testing method or effective force testing method), (2) to test one or more components of the system using the hybrid testing method combined with substructuring, or (3) to test one or more components of the system using the distributed hybrid testing method in conjunction with other laboratories. As depicted below in Figure 4, the test structure would be secured to the strong floor and the actuators placed on the reaction wall and attached to the test structure at the dynamic degrees of freedom. Figure 4(a) shows a two-story frame with four active/passive control devices being tested using all five of the RTMD dynamic actuators to control four degrees of freedom. In Figure 4(b) the frame (beams, column, and slab) are analytically modeled and coupled to the test structure consisting of four components (the four active/passive control devices).

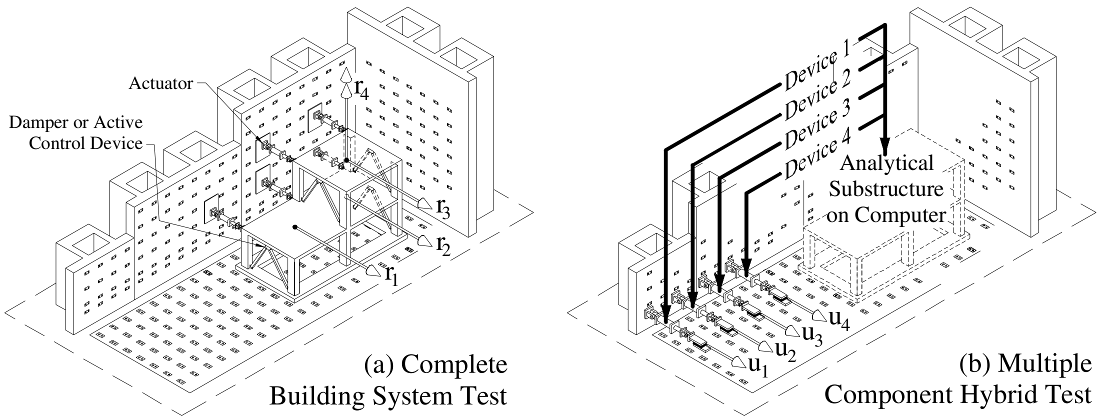


Figure 4 RTMD Earthquake Simulation Facility.

Given below are three examples of types of studies that can be conducted using the RTMD earthquake simulation facility which illustrate the capabilities of the facility. Providing teleparticipation links via the Internet not only will enable collaborators to remotely observe and operate these simulations, but also provide links to multimedia classrooms for educational purposes. Practicing professionals, educators, and students in multimedia classrooms will be able to observe a test as it is performed, providing them with visual and measured response information that will provide deep insight into the response of a structural system or component to earthquake loading. Visual data and measure response data from prior tests will be stored on a archive server, and be available for teleobservation. Hence, the response of several structures tested using the RTMD facility can be observed, providing a powerful means of education though examining and comparing the response of different structural systems and components to earthquake loading.

Structural System Test with Dampers

Recent research indicates that important interactions occur between damping devices and other components of the structural system (Fan [10], Fan et al. [11], Sause et al. [12], Higgins and Kasai [13], Escobedo and Ricles [14]). Since most damping devices are load-rate dependent, real-time experiments are needed to investigate these systems.

This example is a two-story building outfitted with natural rubber dampers, as shown in Figure 4(a). The dampers are placed in the building structure to form a passive damping system to mitigate earthquake damage. The dampers are a new rubber material having ultra high damping characteristics, are temperature insensitive, but are sensitive to excitation frequency. The effects of load-rate on the material are illustrated in Figure 5, where the hysteretic response of natural rubber dampers tested at different loading frequency by researchers at Lehigh University (Sause et al. [15]) is shown. Instead of a passive damper system, the performance of a semi-active damper system consisting of magnetorheological (MR) dampers (Spencer, B. F. et al. [16]) to mitigate seismic hazards could also be investigated.

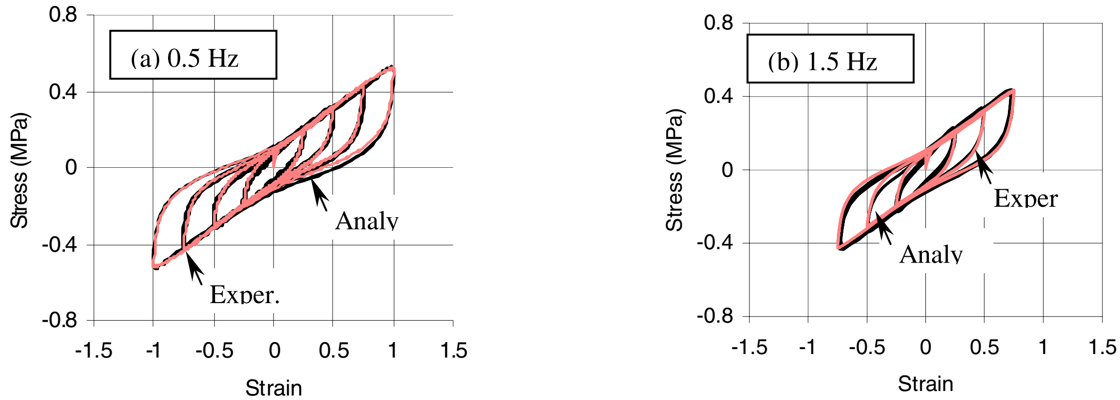
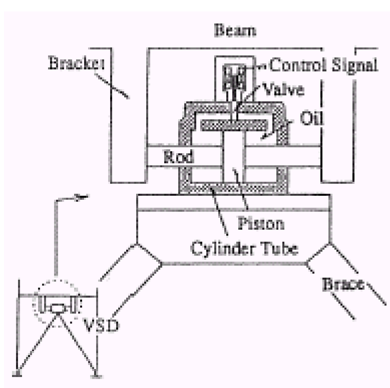


Figure 5 Hysteretic Behavior of Ultra-high Damping Rubber at Two Loading Frequencies.

Multiple Component Hybrid Test of Structural System with Semi-Active Control Devices

This example is a research project that would be conducted to evaluate the performance of a new class of semi-active control devices for mitigating seismic damage. Recently, a class of semi-active control algorithms referred to as Active Interaction Control (AIC) have been developed as a means of suppressing the vibration of building structures during moderate to large earthquakes (Zhang [17], Zhang and Iwan [18, 19]). Figure 6 shows a schematic of an AIC control device that is used to facilitate the interaction between the brace and primary structure. The AIC control device shown here is a variable stiffness device (VSD) made by Kajima Corporation, Japan. It is used to develop an active variable stiffness (AVS) system (Takahashi et al. [20]). The device is rate-dependant and the measured floor and brace-top accelerations are used in the control algorithm to suppress ground motion effects. It is noteworthy that the recently developed magnetorheological damper (Spencer, B. F. et al. [16]) can also be used for the active interaction elements in AIC control system, which can be operated using a low power supply. Previous computer simulation studies by Zhang [17] and Zhang and Iwan [19] have shown that AIC algorithms are capable of significantly suppressing the inter-story drift of building structures subjected to medium to large earthquake excitations. But before this control approach can be used for real structures, large-scale real-time structural experiments must be performed to further verify the control performance of the AIC algorithm in real structures subjected to real earthquakes. Due to the limitations on the load capacity of existing shaking tables only reduced-scale structures with active control devices can be tested on a shaking table. The building to be tested is shown in Figure 4(a), and has four AIC control devices. The experiment is conducted using the effective force test method, which requires that the true mass of the structure be included in the test structure. Considering seismic ground motions in one direction, there are two



(a) Outline of VSD mechanism

Design Load	35tonf
Size	730mm × ∅290mm
Weight	250kg
Stroke	±50mm
Diam. of Piston	∅180mm
Diam. of Rod	∅100mm

(b) Specification of VSD

Figure 6 Schematic of a Variable Stiffness Device (VSD) (Takahashi et al. [20]).

generalized force degrees-of-freedom at each floor level in the test structure, as shown in Figure 4(a), requiring the use of a total of five dynamic actuators. The control of the structure requires a feed back loop that is driven by the measured floor brace-top accelerations. Piezoelectric sensors developed by researchers at Lehigh University are used to measure structural response. Piezoelectric sensors are ideal for recording structural response signals such as accelerations and strains under dynamic testing because they have high resolution, high sensitivity and fast response.

Bridge System with Pile Foundation

Another example research project that could be conducted at the RTMD earthquake simulation facility is the large-scale multi-directional testing of a reinforced concrete bridge cap beam - pier - foundation subassembly. As a result of the damage caused by the Loma Prieta and Northridge earthquakes a number of experimental investigations have been conducted on reinforced concrete bridge systems (Priestley [21], Naito et. al. [22]). Little work however has been conducted in real-time or with realistic boundary conditions. The objective of this study is to investigate the effects of soil-structure interaction on bridge structures subjected to realistic (4-DOF) seismic demands, and to acquire data for verifying analytical predictions. Using the multidirectional reaction wall, the structural test component will be tied down to the strong floor and the dynamic actuators arranged to load the specimen, as illustrated in Figure 7. The bridge cap beam and pier are set on top of its pile foundation (which is placed in the soil box). The size of the box will be adjusted so that the distance from the edge of the pile group to the box wall will be at least equal to the width of the group. The interface between the soil and the soil box will be instrumented to monitor the boundary responses in the soil mass. The soil will be obtained from a local site and compacted in layers at it natural water content. Pre-loading may be applied to bring the soil density to near field conditions if necessary. Since the portion of the superstructure between bridge bents is known to remain elastic, it and other remaining parts of the bridge not appearing in the test structure are analytically modeled and coupled to the test structure. The test structure has four displacement degrees of freedom (longitudinal displacement, transverse displacement, torsion of the cap beam, and rotation of the cap beam parallel to the bridge span) and two load degrees of freedom (to represent the gravity load effects from the adjacent superstructures). The top of the bridge pier is subjected to bi-directional earthquake loading (resulting in transverse, longitudinal, torsional, and rotational motions to the top of the bent with simultaneous gravity loading from existing static actuators), where the displacements are based on the real-time pseudo-dynamic hybrid testing method. The torsional motion in the example project is induced through the two horizontal actuators normal to the bridge span shown in Figure 7. This test setup takes advantage of all five RTMD actuators, as well as, two existing ATLSS actuators.

In addition to conventional instrumentation, the structural behavior as well as the soil behavior will be measured, using a grid of MEMS accelerometers and fiber-optic sensors that are embedded in the soil and reinforced concrete. A fiber sensor assembly will be embedded in the concrete piers during the casting of the concrete. The sensing capability of each assembly will be based on Stimulated Brillouin Scattering (SBS) phenomenon (Brown, et al, [23]), therefore a single fiber coiled in the longitudinal direction inside each pile will serve as the strain sensor for the entire length of these members. In addition to concrete, the rebar cage may also be wrapped with a continuous fiber to serve as the stain sensor for the steel. Similarly, continuous bare fibers will be coiled horizontally inside each soil layer as the soil box is constructed from bottom to top around the pier assembly. The data from an SBS distributed sensor will be mapped digitally to obtain real-time evolution of strains over 2D or 3D configurations. The vision for the above experimental setup is to capture the evolution of distributed strains in the soil, and the structure independently. Digital mapping of these strains can help to better visualize and ultimately model the soil-structure interaction.

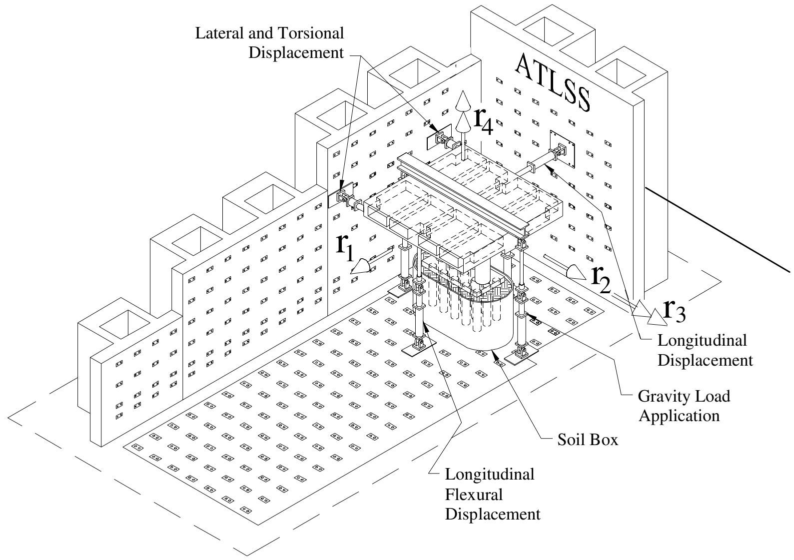


Figure 7 Bridge System with Pile Foundation Setup.

Prior to each test being performed in the laboratory, numerical simulations of the test are to be conducted using simulations tools developed by researchers at Lehigh University. These tools enable a test to be simulated using the workstations (i.e., real-time Control Workstation, real-time Simulation Workstation, Data Acquisition Workstation, real-time Teleoperation Workstation) and SCRAMNet, with the hydraulic power supply turned off. The simulation tools utilize Simulink to model the servo-valves, actuators, and test structure. Shown below in Figure 8 is a model used to simulate an effective force test of a 2-DOF moment resisting frame subjected to the north-south component of the 1940 El Centro earthquake record.

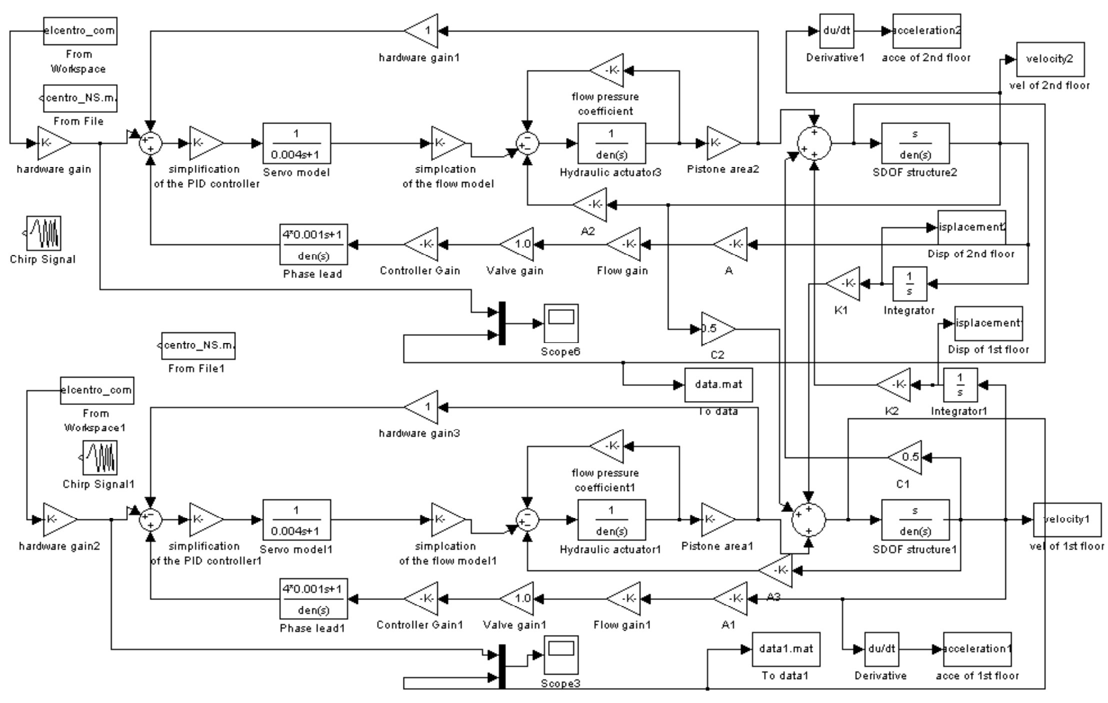


Figure 8 Numerical Simulation of MDOF Effective Force Test.

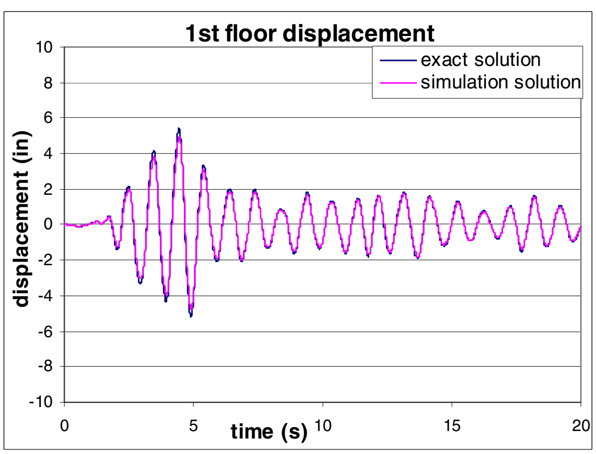
The characteristics of the test structure, which is an idealized elastic two-story shear building, are given below in Table 1. The numerical simulation was used to confirm the calibration of the PID hydraulic control parameters as well as to establish whether the demand imposed on the RTMD equipment by the test did not exceed the capacity.

Table 1 Two-Story Shear Building Test Structure Characteristics

Quantity	Value
M_1- First floor mass	1.5 kips-sec^2/in
M_2 - Second floor mass	0.75 kips-sec^2/in
K_1 - First floor interstory stiffness	102 kips/in
K_2 - Second floor interstory stiffness	102 kips/in
T_1 - First mode elastic period	1.0 sec.
T_2 - Second mode elastic period	0.41 sec.
ξ_1 - First mode viscous damping	0.034
ξ_2 - Second mode viscous damping	0.023

Note: 1 kip = 4.448 kN, 1 inch = 25.4 mm

The results for the time history response of the first and second floor displacements are shown plotted in Figure 9, where they are compared to the *exact solution* for the structure subjected to the earthquake record. The *exact solution* is based on numerically integrating the equations of motion using the Newmark-Beta method with average-constant acceleration. The *simulation solution* is the one obtained using the simulation tools described above, where the servo-valves, actuators, and structure were modeled. Excellent agreement is seen between the two, implying that the RTMD earthquake simulation facility would be able to execute this test and obtain accurate results.



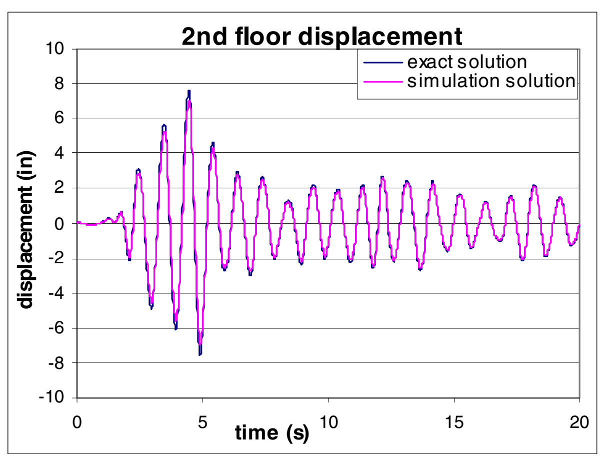


Figure 9 Results of simulations for first and second floor lateral displacements.

In addition to providing a means of calibrating the parameters for the control system and test methodology, as well as checking the demand on the equipment, the simulation tools are also to be used for training researchers on the use of the control system for the RTMD earthquake simulation facility.

SUMMARY AND CONCLUSIONS

The main features and functionality of the Real-Time Multi-Directional (RTMD) earthquake simulation facility established at the ATLSS Engineering Research Center at Lehigh University as part of the George E. Brown, Jr. Network for Earthquake Engineering Simulation are 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 real-time testing algorithms are employed at the facility, including the real-time pseudo-dynamic testing method, real-time hybrid testing method, and the effective force testing method. By having several different real-time testing algorithms available, a wide range of complex structures can be tested.

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