RTMD

REAL-TIME MULTI-DIRECTIONAL TESTING FACILITY

User’s Guide

August 26, 2014

Preface

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 complex and comprehensive analytical and computer numerical models, leading to advances in earthquake engineering and experimental methods. The facility features a multi-directional reaction wall, five dynamic actuators, advanced instrumentation, and a teleparticipation system consisting of real-time streaming data and video. 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. 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. Distributed hybrid pseudo-dynamic testing can also be performed using the RTMD facility in conjunction with other laboratory sites.

This User's Manual is intended to provide to the reader basic information about the RTMD facility to enable visitors to get acquainted with the facility, and assist researchers in preparing proposals to use the facility. The information provided in the Manual includes: information about the RTMD facility and equipment, test methods, telepresence, education and outreach, policies and procedures for using the facility and the organization of the RTMD facility. In addition to the RTMD facility, information about the ATLSS Engineering Research Facility and associated non-NEES equipment and facilities available to researchers is provided. The RTMD has an assortment of training materials, which along with the training workshop schedule, are summarized on the Lehigh NEES web page (see http://www.nees.lehigh.edu). The reader is referred to this link for information on training.

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1 Facility Information

1.1 RTMD Overview

Lehigh University's NEES Real-time Multi-directional (RTMD) earthquake simulation facility is located within the Center for Advanced Technology for Large Structural Systems (ATLSS) on Lehigh University's Mountaintop Campus. Lehigh University is located in Bethlehem, Pennsylvania. The RTMD facility allows for multi-directional real-time seismic testing, combined with real-time analytical simulations, to investigate the seismic behavior of large-scale structural components, structural sub assemblages, and super assemblages (systems). This is achieved through the combined use of dynamic actuators, reaction wall, and strong floor. This facility is also designed to support the development of new hybrid testing methods for real-time multi-directional testing of large-scale structures, including multi-substructures, where the substructures involved are at different geographic locations connected by the NEES network.

Figure 1-1 ATLSS Multi-directional reaction wall

The Lehigh NEES Equipment Site has the capabilities to perform real-time testing using the effective force method, pseudo-dynamic testing method, or the pseudo-dynamic hybrid testing method for the testing of large-scale structural components, structural subassemblages, and superassemblages under earthquake excitations. The laboratory includes a strong floor that measures 31.1m x 15.2 m in plan, and reaction walls 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 equipment portfolio and resources of the Lehigh NEES equipment site include:

- **Actuators** - five dynamic actuators, each ported for three servo-valves with stroke ranges of +/- 500 mm, and having the following maximum force capacity:

- 3 actuators @ 1700 kN capacity at 20.7 MPa (3000 psi)
- 2 actuators @ 2300 kN capacity at 20.7 MPa (3000 psi)
- The maximum velocity that can be achieved by the actuators is 840 mm/sec (2300 kN actuators) and 1140 mm/sec (1700 kN actuators) when three servo-valves are placed on the actuators and the supply hydraulic pressure is 20.7 MPa (3000 psi). With a force on the actuator, the velocity capacity will be reduced. Shown below in Figure 1-2 is the force-velocity capacity relationship for each actuator, with the number of servo-valves on the actuator ranging from 1 to 3.

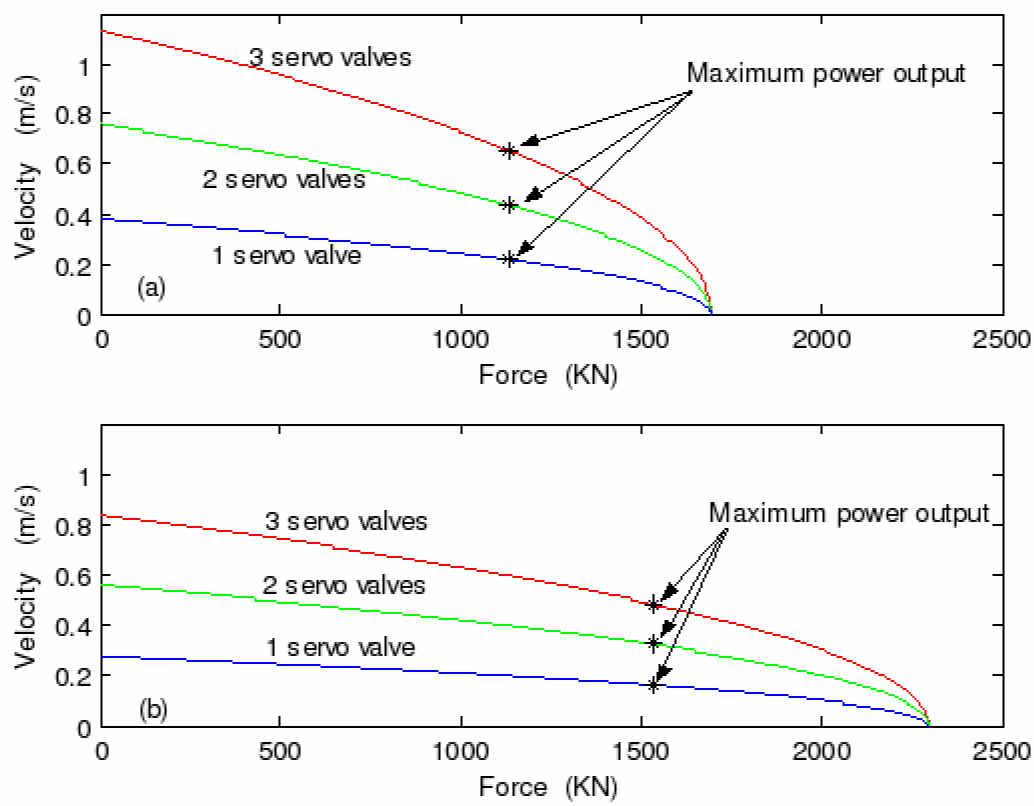


Figure 1-2 Hydraulic actuator power envelop for (a) 1700 kN actuators, and (b) 2300 kN actuators (20.7 MPa supply pressure)

- **Servo-valves** - ten three-stage, high flow-rate servo-valves rated at 1500 liters/min at 11 MPa (400 gpm at 1600 psi).

- **Hydraulic distribution lines and service manifolds** - low-pressure and high-pressure settings to operate at 20.7 MPa (3000 psi) with a maximum flow of 1500 liters/min (400 gpm). Surge tank and three banks of accumulators that will enable strong ground motion effects to be sustained for up to 30 seconds. Each bank will consist of twelve 114-liter (30 gallon) accumulators, to supply a total accumulated oil supply of 4090 liters (1080 gallons).

- **Accumulators** - 3028 liters (800 gallons) total capacity with a maximum operating pressure of 24 MPa (3500 psi). A hydraulic system connects the accumulators to the pressure line of a five pump 2250 liter/min (594 gpm) hydraulic system. The total hydraulic power supply therefore consists of the five pump system and the accumulators. Peak flow rates of 15,150 liter/min (4000 gpm) have been obtained using this hydraulic power supply, and enables typical strong ground motion effects to be sustained for up to 30 seconds.
- **Control Systems**
    - Servotest Pulsar DCS digital 8-channel 1024 Hz control system 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 NEES actuators.
    - Wineman INERTIA-based real-time, integrated, multi-loop control and data acquisition system for servo-hydraulic applications. The PXI/SCXI-based system supports control of ten servo values for multiple configuration of actuator load and displacement control along with 128 channels of data acquisition. INERTIA is a configurable test executive, which allows significant end user configuration.
- **Video System** - 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.
- **Simulation System** - combination of a host workstation and two target real-time xPCs. This applies the algorithms that generate commands for actuators and act as supplemental data acquisition. Synchronizes data channels from the control system and data acquisition system with simulation data and triggers camera snapshots aligned with simulation data. Support for MATLAB and LabVIEW configurations along with NEES hybrid protocols.
- **Data Acquisition System** - high speed 264-channel (384 max) data acquisition system, capable of acquiring data up to 1 million samples per second. Current configuration limits to 10kHz samples per second and in conjunction with SCRAMNet synchronization acquisition is limited to 2kHz samples per second.
- **Risk Mitigation** – 8GB Dual Redundancy network file system for system and test data backups along with nightly offsite mirroring at NEES.org.
- **Conventional sensors** - DC-LVDTs, load cells, accelerometers and inclinometers.

1.2 ATLSS Overview

The ATLSS Center includes a multi-directional testing laboratory with a 12.1 m (39.7 ft) by 30.5 m (100.1 ft) strong floor and reaction walls up to 15.3 m (50.2 ft) in height along two full sides and parts of two others. The reaction wall and test floor have a 1.524 m (5.0 ft) square grid of high capacity anchor points which allow large-scale two-and three-dimensional test structures and test frames to be fastened to the wall and floor to facilitate multi-directional (multi-axis) loading.

The lab is equipped to generate multi-directional static and time-varying loads. The hydraulic power system consists of five pumps that deliver 2272 liters/min (600 gpm) at 24 MPa (3500 psi).

The ATLSS Center has three main data acquisition systems (1 with 256 channels and 2 with 192 channels) for conditioning and acquiring data from experimental research. More than 200 channels of signal conditioners are available for use with these systems. Data acquisition systems for remote data logging are available for field tests; these systems are also used in the lab. The laboratory floor has been equipped with a switched gigabit network, providing network connections every 4.57 m (15.0 ft) along the reaction walls. Network connections in the laboratory currently connect to the main campus backbone by way of a switched fiber optic network.

Adjacent to the strong floor is a sizeable service area for specimen fabrication, preparation, instrumentation, and storage. The service area contains welding equipment, a large-bed drill press, a band saw, a grinder, and an array of hand tools.

The ATLSS Multidirectional Experimental Lab is served by a radio-controlled overhead traveling crane with a 178 kN main hoist and a 45 kN auxiliary hoist. Large overhead doors (6.1 m tall by 7.6 m wide) (20.0 ft tall by 24.9 ft wide) and large paved areas outside the lab provide easy access for tractor-trailer trucks delivering test specimens, equipment, materials, and supplies to the lab.

Within the Imbt Laboratories Building, the ATLSS Center operates a Mechanical Testing Laboratory, a Welding and Heat Treating Laboratory, and Metallography and Microscopy Laboratories. See Section 6 for details.

1.3 RTMD Equipment Specifications

1.3.1 Hydraulic Supply System

The hydraulic supply system consists of 5 pumps, 450 liters/min (118.9 gallons/min) each and 16 piston accumulators, 190 liters (50.2 gallons) each connected to 9 Nitrogen gas bottles, 1325 liters (850.2 gallons) each. This configuration enables a typical earthquake to be simulated on a 4-floor one-half scale frame structure in real time for 30 seconds with the supply pressure maintained within 20.7~24.1 MPa. The accumulators and gas bottles are expandable. If there is a higher flow rate demand, more gas bottles and accumulators may be purchased and configured.

1.3.1.1 Pumps

There are 5 variable axial piston pumps. Each of them provides a flow rate of 450 liters/min (120 gpm). The pump pressure limits are set at 24 MPa (3500 psi). When the supply pressure reaches this limit, the pump outputs zero flow. Table 1-1 lists the pump system specification.

Table 1-1 Pump system specifications

Pump Flow Capacity	2,250 liters/min (total)
Pump Pressure	24.1 MPa
Continuous Power Rating	1,800 kW (input power capacity)
Continuous Power Output	912.2 KW (output power)
Fluid Viscosity @ 40C	46 cSt (mm2/s)
Fluid Density @ 15C	0.87 Kg/m3

1.3.1.2 Accumulators

There are 16 piston accumulators connected to 9 gas bottles. Each piston provides 190 liters (50 gallons) of flow and each gas bottle combines 1325 liters (350 gallons) of Nitrogen. The hydraulic pressure can be charged to 24 MPa (3500 psi) by the pumps. When fully discharged, the accumulators still maintains hydraulic pressure above 20.7 MPa (3000 psi) if the subsequent flow rate demand can be sustained by the 5 pumps. The specification for the accumulator system is listed in Table 1-2.

Table 1-2 Accumulator system specifications

Accumulator Gas Volume	11,923 liters
Accumulator Oil Volume	3,028 liters
Peak Flow Capacity	> 13,605 liters/min
Normal Operation Pressure	20.7~24.1 MPa
Peak Power Capacity	> 4,693.7 KW

1.3.2 Actuators

There are 5 hydraulic actuators. Two of them have a maximum load capacity of ±2300KN at 20.7 MPa (517 kip at 3000 psi). The remaining three actuators have a maximum load capacity ±1700KN at 20.7 MPa (382 kip at 3000 psi). However, the external physical dimension and appearance for these five actuators are all same. The nominal supply pressure for the actuators is 20.7 MPa (3000 psi) but a pressure of 24.1 MPa (3500 psi) can also be supplied. Table 1-3 lists the hydraulic actuator specification. Detailed drawings of the Actuator can be found in Table 1-4.

Table 1-3 Hydraulic actuator specifications

Actuator Type	200-100-1700	200-1000-1250
Quantity	2	3
Load Regulation Accuracy	0.2% FS (but no higher than ±0.23KN)	0.2% FS (but no higher than ±0.17KN)
Load Tracking Dynamic Bandwidth	> 10Hz	> 10Hz
Displacement Regulation Accuracy (Static)	0.2% FS (but no higher than ±0.1mm)	0.2% FS (but no higher than ±0.1mm)
Displacement Tracking Dynamic Bandwidth	> 10Hz	> 10Hz
Load Capacity	±2300KN @ 20.7MPa	±1700KN @ 20.7MPa
Speed Capacity	0.84m/s (33in/s)	1.14m/s(45in/s)
Piston Diameter	424mm	378mm
Piston Rod Diameter	200mm	200mm
Stroke	±500 mm	±500 mm
Total Chamber Volume	114 liters	84 liters
Chamber Internal Leakage	0.15 liters/min/bar	0.15 liters/min/bar
Chamber External Leakage	0.01 liters/min/bar	0.01 liters/min/bar
Moving Part Mass (Piston & Rod Assembly)	950Kg (approximately)	900Kg (approximately)
Actuator Weight	6100Kg	6120Kg
Actuator Dimension (Clevis End to Clevis End at mid stroke)	5.355m x 1.25m x 1.35m (length x width x height)	5.355m x 1.25m x 1.35m (length x width x height)
Actuator Dimension (Clevis Pin to Clevis Pin at mid stroke)	4.955m x 1.25m x 1.35m (length x width x height)	4.955m x 1.25m x 1.35m (length x width x height)
Actuator Dimension (Foot End to Foot End at mid stroke)	5.495m x 1.25m x 1.35m (length x width x height)	5.495m x 1.25m x 1.35m (length x width x height)

Note: The actuators are all double rod actuators (i.e., the left and right chamber effective actuating areas are the same). Hydrostatic bearing at both headers make them frictionless.

Table 1-4 Equipment Drawings

Equipment	Link to Drawing (PDF)
Actuator Assembly (200-9004)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Actuator Assembly 1700kN (200-9004).pdf
Load Cell Assembly (200-9401)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Load Cell Assembly 2000kN (200-9401).pdf
Load Cell Mounting Assembly (200-9412)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Load Cell Mounting Assembly (200-9412).pdf
Pressure Transducer Assembly (000-0388)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Pressure Transducer Assembly (000-0388).pdf
Self Aligning	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Self

Bearing Assembly (200-9507)	Aligning Bearing Assembly (200-9507).pdf
Self Aligning Bearing Assembly (200-9508)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Self Aligning Bearing Assembly (200-9508).pdf

1.3.3 Servo-valves

10 servo valves (labeled as A,B,C,D,E,F,G,H,J,K) are configured to the 5 actuators. The default configuration has Valves A and B assigned to Actuator 1 (±1700KN) (±382 kip), Valves C and D to Actuator 2 (±1700KN) (±382 kip), Valves E and F to Actuator 3 (±1700KN) (±382 kip), Valves G and H to Actuator 4 (±2300KN) (±517 kip), and Valves J and K to Actuator 5 (±2300KN) (±517 kip). If an actuator needs to have three servo-valves mounted, the third valve can be selected from one of these 10 servo-valves. The servo-valve specification is listed below in Table 1-5.

Table 1-5 Servo-valve specification

Servo-Valve Model	SV1200 (Servotest)
Servo-Valve Stages	3
Pilot Valve Model	G772-204(Moog)
Servo-Valve Quantity	10
Flow Rate Capacity (Single Valve)	550gpm @ 20.7MPa (3000psi)
Dynamic Bandwidth	30Hz @ -6db
Working Temperature	< 55C
Servo-Valve Assembly Weight (Single)	Approx 50Kg (including bladder accumulators)
Single Bladder Accumulator Volume and Initial Gas Pressure	10 liter capacity, supply port pressure = 170bar, return port pressure = 10bar
Supply Pressure Ports	38.1mm-6000SAE x 2
Return Ports	50mm-3000SAE x 2

Note: The servo-valve is a 4th order system with certain nonlinear properties. A 30 Hz bandwidth is measured when the spool opening amplitude is equal to 100%. For small opening sinusoid tracking, the bandwidth may go higher to 140 Hz.

Table 1-6 Equipment Drawings

Equipment	Link to Drawing (PDF)
3 Stage Servovalve Assembly (000-1693)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/3 Stage Servovalve Assembly (000-1693).pdf
Servovalve Assembly (000-1396)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Servovalve Assembly (000-1396).pdf

1.3.4 Hydraulic Service Manifold (HSM)

There are 10 HSMs, each connecting one of the 10 servo-valves with the pump-accumulator hydraulic supply system. Each HSM is configured for one servo-valve, providing high pressure, low pressure, and shutoff operations.

The high pressure state is the normal operation state which passes through a maximum flow rate of 2082 liters/min (550 gpm) and a normal supply pressure of 20.7 Mpa ~ 24.1 Mpa. If the supply pressure is lower than 15 MPa (2176 psi), this state will be disabled.

The low pressure state provides a low pressure of 7 MPa (1015 psi) with an adjustable flow rate of 0~70 liters/min (which is adjusted by a throttle valve). The low pressure state is often used for configuration of the actuators for test preparation.

The shutoff state is used to disconnect the hydraulic supply from the servo-valves or actuators. It is often used after the test is done or when an emergency stop (E-Stop) needs to be activated.

Each of the HSMs have the dimensions of 465 mm x 420 mm x 451 mm (1.5 ft x 1.4 ft x 1.5 ft) (length x width x height). Each HSM connects to a servo-valve using two 38.1 mm (1.5 in) diameter hydraulic hoses for the hydraulic supply pressure line and two 50 mm (2.0 in) diameter hydraulic hoses for the hydraulic return line. The hydraulic pump-accumulator supply system connects to each HSM using two 50 mm (2.0 in) diameter hydraulic hoses for the hydraulic supply pressure line and two 50 mm (2.0 in) diameter hydraulic hoses for the return line. The HSM specification is given below in Table 1-7.

Table 1-7 Hydraulic Service Manifold specifications

Model	B550-3412
Serial No.	6162~6171
Quantity	10
Low Pressure Output	0~7MPa
Low Pressure Flow Rate	0~70liters/min
High Pressure Pass Through	16~28MPa
High Pressure Flow Rate Capacity	2082 liters/min
Low/High Switching Pressure	15MPa
Inlet Pressure Ports	50 mm-6000SAE x 2
Inlet Return Ports	50 mm-3000SAE x 2
Outlet Pressure Ports	38.1 mm-6000SAE x 2
Outlet Return Ports	50 mm-3000SAE x 2

Table 1-8 Equipment Drawings

Equipment	Link to Drawing (PDF)
Solenoid Control Manifold (550-9104)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Solenoid Control Manifold (550-9104).pdf
Hydraulic Control Box 2 (6463)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Hydraulic Control Box 1 (6463).pdf

Hydraulic Control Box 2 (6464)	http://www.nees.lehigh.edu/wordpress/uploads/usermanual/drawings/Hydraulic Control Box 2 (6464).pdf

1.3.5 Control Systems

1.3.5.1 Servotest Servo-Controller

The servo controller (DCS 2000, and referred to herein as Controller), communicates with all of the servo-valves, actuators, transducers, HSM control box and simulation computer (RTMDsim) as part of the servo-control system. The Controller consists of the following components:

The Host Computer, running Windows 2000 (referred to in this Guide as RTMDctrl), is an IBM-based PC. The software for system control is called Pulsar which consists of a series of modules such as: Control, Monitor, Limits, Database, Oscilloscope, Data Logger, Reply, Filter and Wavegen. A PID control module is built in. For developing a user's control law, implementation is achieved through Socket building. MATLAB and SIMULINK is used to program the user's control law and Real-Time Workshop is used to generate C-code, which is loaded into the database by the Socket Wizard. Thus, a user's control law can be implemented, including a simulation using hydraulic-off mode.

The Controller consist of a Digital Signal Processor (DSP) Real-time Control Card (Module 2201), which is plugged into the RTMDctrl. The card contains a TMS320C30 DSP to deliver sustained (33MFLOP) performance in real-time, local memory, and a high speed Bus Master Interface to RTMDctrl. The DSP can control up to 16 actuators. Sampling rate is set at 1024Hz.

Two External Conditioning 'XBus' Subsystems enclosures are connected to the DSP Controller at RTMDctrl via shielded high speed bus cables. The XBus systems each contain individual power supplies and a backplane bus into which are plugged various input/output cards. All analogue channels have individual 16 bit resolution ADC or DAC systems which convert simultaneously to improve throughput and eliminate signal skew. The cards installed for the five actuators are:

- Five 2202-0 conditioner cards, which process transducer signals, converting them into digital form for the DSP and performs the carrier signal generation for the transducer. Each card serves the load cell conditioning and displacement transducer conditioning for one actuator.
- Ten 2203-0 3-stage servo-valve system drive cards, which take digital data from the XBus and converts to analogue valve drive current. Each card serves one servo-valve such that there are 10 cards configured for these 10 servo-valves.

- One 2206-0 Digital I/O card, which provides a group of digital channels, writable and readable from the XBus.

Two 2207-2 Hydraulic Control Boxes, which operate the Hydraulic Service Manifold (HSM) via solenoid valves switch on/off hydraulic supply to/from servo-valves (one HSM for one servo valve). Each Box can hub 5 HSM control units. Two boxes exist for the 10 HSMs. These boxes are connected to two External Conditioning 'XBus' Subsystems. An emergency stop (E-stop) is configured within.

One SCRAMNet card is hosted in the Controller and connected to the RTMDsim via fiber optical network running a developed Platinum protocol. The SCRAMNet card communicates with the RTMDsim through 64 input and 64 output values, memory assignable, and is intended for controllers up to 8 actuator channels.

The design of the servo-controller system enables control of up to eight actuators. Currently, the system is configured for five actuators. Detailed information of the servo-controller system is given Table 1-9 (some of modules in the Table 1-9 are currently not available at the RTMD facility).

Table 1-9 DCS2000 specification

Control	
Channel x Frequency Product	800Hz (200Hz for up to 4 ch from Q4 1997)
Maximum Channels	32 (to approximately 25Hz)
Maximum Frequency	500Hz (1 channel)
Maximum Control Iteration Rate	4.096 KHz, typically 1.024 KHz or 2.048 KHz
Control Iteration Rate Range	100Hz to 5KHz (102.4 Hz to 4.096 KHz)
Servo Control Resolution	16 bits
Available Control Types	PID, Vibration, Adaptive. Further Types can be added any time. Different control methods can be applied simultaneously to different channels. Load (Force), Displacement, Velocity, Acceleration or any other external input signals. 64, 32 Strain Gauge or LVDT type inputs, plus 32 Current (Charge) or Voltage inputs.
Internally Generated Signals	
Number of Simultaneous Generators	0 to 8 (typical), or more if lower iteration rate
Linking Modes Between Multiple Generators	Linked Delay (0 to 800,000 seconds) Linked Cycles (0 to 200,000 Cycles) Linked Simultaneous Start and Stop
Common Properties	
Frequency Range	30Hz to 400Hz
Instantaneous Frequency Resolution	Better than 1 part in 10^5N
User Frequency Adjustment	To 0.0001Hz
Frequency Accuracy	10ppm/Hz
Frequency Drift	15ppm/C
Individually Adjustable Properties	
Wave Shapes	Sine, Square, and Triangular
Number of Cycles	0.25 to 200,000 cycles in 0.25 cycle steps
Modes	Continuous, Continuous with Soft Start and Soft Stop (soft

	period adjustable between 0.02 and 800,000 seconds)
Initial Phase Angle	1 degree to 30,000 degrees in 1 degree steps
Sweep Modes	Bi-directional, unidirectional, Number of Sweeps, Sweeping duration, Linear and Logarithmic
Sweep Rates(can be increased on request)	Linear: 0.0001 Hz/s to 10,000 Hz/s Logarithmic: 0.0001 Oct/min to 100 Oct/min
Signal Inputs and Outputs	
2202 2-channel Conditioner Card (2x16bit, 20KHz acquisition, opto-isolated ADC channels on each card. Channels convert simultaneously) (max 32 cards)	1 off 10KHz carrier channel for strain gauge or LVDT type transducers, plus 1 DC channel for current (charge) transducer (i.e. accelerometer) or voltage transducer (i.e. velocity)
2203 1-channel Servo Drive Card (max 32 cards)	1 servo drive amplifier. Can drive multiple two stage of 1 off three stage servo-valves. Has third stage spool control on card and 16 bit self-calibrating opto isolated ADC for monitoring spool position.
2204 4-channel Analog Input Card (max 8 cards)	16bit auto re-calibrating, opto-isolated ADC inputs. Max. input scale ± 10 Volts. Apparent scale software changeable. 4th order (24 dB/oct) 500 Hz low pass anti-aliasing filter on each input.
2205 6-channel Analog Output Card (max 4 cards)	16bit opto-isolated DAAC voltage outputs. Max. output scale ± 10 Volts. Apparent scale can be changed in software.
2206 16-channel Digital I/O Card (max 8 cards)	All channels fully bi-directional, opto-isolated open collector, active high or low in software.
Signal Handling and Monitoring	
Real Time Polynomial Linearization	Individual 5th order (6 terms) equation applied to carrier based transducer inputs.
Scale and Offset Error Reduction	Determination can be carried out at any time, in real-time.
Real Time Valve Linearization	Individual 3rd order (4 terms) equation may be applied to any servo valve output.
Real Time Multiple Version Generation	RMS, Peak, Instantaneous and Mean versions of any signal can be generated.
On Screen Monitors (Number of available monitors limited by Windows resources only)	Any version of an external or internal signal can be displayed in engineering units. Visual update rates: Instantaneous - 1 sec. RMS, Peak and Mean adjustable between 0.5 and 800,000sec.
Trip Settings (trips 'pop-up' on screen)	Can be applied to any conditioned signal. Individually adjustable Max. and Min. levels and Trip actions. Maintains Trip Log.
On Screen Oscilloscopes (max 2 off) Adjustable Time base, Sweep positions and scales.	4 channel, 4K (Max) samples per channel display. Inputs can be any version of any external, internal, or conditioned signal.
Data Logging (adjustable acquisition rate)	Max. 16 channels at 1KHz continuous sampling, saved to Hard Disk Storage in Real Time. Inputs can be any version of external, internal or conditioned signal.
Signal Overload	All inputs and outputs accurate to full scale deflection ± 9% and saturate safely to known values.
Hardware Configuration	All input and output cards have corresponding individual Configuration 'Templates' Windows.
Calibration	
Calibration	Transducers carry calibration, which can be entered into "Templates" at any time. Servotest or User transducers can be re-characterized using the optional software Calibration

	Module.
Real Time Data Analysis and Display	Dynamic Data Exchange (DDE) links with other applications, to update graphs and statistics in Real time. Optional Network DDE support can be provided.
Post Testing Analysis and Display	A wide range of file formats can be produces to support many Data Analysis systems.
Compressor Module	
Number of simultaneous Compressors	0 to 8 (typically), or more if lower iteration rate
Compression Range	± 700dB (internal Floating Point representation)
External Dynamic Range	70dB min.
Rate	Adjustable, 0 to 6dB per cycle.
Counter Timer Module	
Number of simultaneous Modules	0 to 8 (typically), or more if lower iteration rate
Modes of Operation: **Time Duration** **Event/Cycles Count**	 0 to 9 Years, resolution of one control iteration 0 to 4000 million (approx) resolution of 1 cycle.
Actions on Completion	Indicate, Trip or Shut down.
Sweep Test Control Module	
Adjustable Parameters	Signal Amplitude Profile, Control Breakpoints
Breakpoints	1 to 32
Control Modes	Any signal can be selected as the control parameter between any two breakpoints
Resonance Dwell Module	
Modes of Operation	Phase or Peak Amplitude
Accuracy: **Phase** **Peak Amplitude**	 1 degree of Phase Lock 1dB of Maximum Peak Amplitude
Seek Rate	Adjustable. Same range as frequency sweep rate.
Tracking Filter(s)	Optional Extra: 2nd order (12dB/Oct) or 4th order (24dB/Oct) Low pass or Band pass
Cross Coupling Module	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Real Time Polynomial Coupling	Individual 5th order (6 terms) equation applied to a selected signal and coupled to another selected signal.
Patching Module	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Real Time Signal Patching	Up to 3 signals can be individually proportioned and summed to provide a further signal
Pump and Solenoid Control	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Modes of Operation	Individual or linked
Configuration	Can be connected to any available channel on the Digital I/O cards (type 2206)
Emergency Stop	Hard-wired mushroom head button placed adjacent to keyboard. More buttons can be provided on request
Functionality	Start, Stop, No, Low (if specified) and High Pressure, Pump and Solenoid signals monitored by Trips Module(s)
Operator Panels	
Operator Panels	Optional Panels can be configured and interfaced to the I/O cards on request
Safety Monitoring	
Transducers	Wrong or damaged Transducers, Broken Connections.

Control	Loss of control and/or unexpected actuator behavior
User Inputs	Stop and/or Shut testing on screen. Emergency Stop Button. Multiple User Limits and Limit Actions
Physical	
Host Computer	800MHz, 128MB ram, 13.2GB hard disk, 24” LCD Monitor, 3.5" fdd, 102 key Keyboard, mouse, Servotest DSP card.
Xbus Enclosure (Max 4 off) (can be 19" rack mounted on request)	Max. 16 I/O cards. Fan cooled. Max. Dimensions 480 x 440 x 150mm.
Uninterruptable Power Supply (can be 19" rack mounted on request)	Rated to system requirements, 8 mins full backup (10 more mins on request). Data link to test systems. On screen and audible warnings: Power Fail, Batteries low, Shut down imminent

1.3.5.2 Wineman INERTIA Servo-Controller

The INERTIA control system, developed by Wineman Technology Inc., is a fully customizable real-time servo-hydraulic control and data acquisition system. The system was implemented to supplement and eventually replace the Servotest controller described in section 1.3.5.1.

All ServoTest actuators, feedback sensors and hydraulics have been upgraded to be compatible with both systems allowing all external components to be interchanged between systems. The system communicates with the existing IT architecture of the RTMD lab via SCRAMNet.

The INERTIA system is also compatible with the ATLSS Center’s existing inventory of hydraulic actuators and both system can be operational the same and time expanding NEES testing capabilities.

The INERTIA software is a LabVIEW based real-time control program that allows the user to fully customize system I/O and hardware layout, system configuration, screen layout and user interface. It also has built in calibration, test profile control, data acquisition and PID tuning utilities.

The main features of this software include (See table 1-7 below for full system details):

- Hardware setup utility for system I/O, conditioning, and control procedures.
- Unlimited control groups with multiple closed loop PIDs for each group (actuator).
- Multiple simultaneous control methods with support for bumpless mode switching.
- Integrated utilities for PID control loop tuning, calibrations, system alarms and profile control.
- Multiple screen capability with customizable graphical displays and layout.
- Independent control and data acquisition rates.
- Integrated test profile editor with control procedure commands and model execution.
- Scalable output for traceable calibration
- Standalone operation for remote test setup without real-time system.

The complete system includes the following components:

- Full size Chassis with distributed power for hydraulics and conditioning, latching relay safety circuit. and built in work station
- Host computer running Windows XP and INERTIA, connected to the real-time PXI controller via Ethernet connection.
- NI PXI-144 14 Slot PXI chassis for PXI hardware
- NI PXI-6251 16 Channel Analog Input – SCXI Interface
- NI PXI-8106 Core 2 Duo 2.16 GHz Embedded Real-Time Controller
- Two NI PXI-6733 High-Speed 16-Bit, 8 channel Analog Output
- Two NI PXI-6514 Industrial Digital I/O with ~~32~~ 64 channels of programmable DIO.
- NI SCXI-1001 12 Slot SCXI chassis for SCXI hardware
- Two SCXI-1102 32-channel Voltage/Thermocouple Input
- Two SCXI-1520 8-channel Universal Strain Gage Input
- Two SCXI-1540 8-Channel LVDT Input
- Five VC2124 Voltage to Current Converters, 2 channels per converter
- SCRAMNet+ SC150 Fiber Optic Shared Memory
- Wineman production rack mount terminal blocks

Table 1-10 INERTIA specification

PID Control	
Control/Output Channels	10 Configured; 16 Available
Loop Rates	1kHz, Variable up to 10kHz
Output Drive	±10 V, ±100 mA
Gain Parameters	Proportional, Integral, Derivative, Feedforward and Model Based Control
Compensation	Amplitude Control, Phase Compensation
Data Acquisition	
Resolution	16-bit
Sample Rates	1kHz, Variable up to 10kHz
Range	Voltage, current, strain gauge, AC LVDT, IEPE, Frequency, digital, thermocouple
Number of Channels	144, Scalable through additional hardware up to 8,000
Calculated Channels	Unlimited custom variables for up to 500 user defined numeric functions
Operator PC Interface	
Host-Target Connection	Ethernet RJ45
Operating System	Windows XP Professional
Drivers	National Instruments LabVIEW Run Time, NI DAQ MX
Utilities	PID Tuning, Data Reporting, Test Editor, User Administration, Screen Editor, Error Monitor, Alarm Monitor
Operator Screens	Unlimited customizable screens
System Configuration	System configuration utility for defining input channels, output channels, shutdown procedures, PID control loops, and alarms

Alarms	Unlimited on any variable
Calibration	
Types	3rd order polynomial curve fit, lookup tables, thermocouple linearization
History	Unlimited calibration history per channel with roll back capability
Coefficients	Automatic calculation or manual entry
Units	Complete customization of engineering units with conversion capability
Test Generation	
Waveform	Sine wave, Triangle, Square, Haversine, Ramps, Holds, Point Playback, Dwell
Number of Channels	Unlimited
Frequency Range	0.0001Hz to 200Hz
Custom Steps	Conditional profile branching, Discrete parameter adjustment
Data Logging	
Number of Log Files	8 independently rate controlled
File Formats	ASCII, TDMS, ATF
Data Rates	Up to Maximum Acquisition Rate
Triggering Modes	Periodic Time, Periodic Cycles, Crash, In-Limit, Out-of-Limit
Trigger Channels	Any System Variable

1.3.6 Data Acquisition

The DAQ Mainframe (also referred to as the Model 6000) is a high-speed data acquisition and conditioning system that acquires data from strain gauges, accelerometers, LVDTs, and thermocouples. The DAQ Mainframe consists of three enclosures housing three different types of I/O modules: (1) Model 6013 for LVDTs and thermocouples; (2) Model 6014 for accelerometers; and (3) and Model 6033 for strain gages. There are a total of 9 modules of Model 6013, 3 modules of Model 6014, and 21 modules of Model 6033. Each module conditions 8 channels. The DAQ Mainframe hosts a SCRAMNet card that broadcasts real time data over a fiber optical network to the RTMDsim and/or RTMDxPC for integrated simulation and control and to the RTMDtele for telepresence. Below is a summary of the description, features, and configuration for the Model 6000 and specifications for the modules for Model 6013, 6014, and 6033.

Model 6000 description:

The 6000 Mainframe has an IEEE-488 interface for control and data output with mounting for 16 input and output modules. It supports up to 31 additional slave enclosures or up to 32,000 channels. A rear mounted fan circulates air to the power supplies and input/output modules. An integral cable tray routes the input and output cables to exit from the rear. All access for channel module installation and service is from the front. The 6000 and 6001 slave have removable doors to facilitate installation and wiring.

Mainframe and slave enclosures that are cabinet mounted should be supported on sturdy mounting rails. A rail set, RAL2, is available from Pacific in sizes that fit most cabinets.

Model 6000 features:

- Up to 1 million samples per second
- 304 channel total expandable to 384
- 24 accelerometers channels (model 6014)
- 72 thermocouple / double ended voltage transducers (model 6013)
- 208 strain gage and single-ended voltage sources (model 6033) 16 bit resolution
- SCRAMNet interfaced equipment
- 2000Hz recording rate over SCRAMNet with all 304 channels
- Selectable channel recording rates for other configurations

Model 6000 configuration:

- Model 6000 Mainframe (128 Channels) expandable up to 15 slaves
- Two Model 6001 Slaves (128 channels capability each)
- Data Storage on computer and/or dump to SCRAMNet (no on-board storage)
- Nine 6013 8-channel voltage boards (Capable of 10kHz/channel)
- Three 6014 8-channel voltage boards (Capable of 10kHz/channel)
- Twenty 6033 8-channel strain gage boards (Capable of 10kHz/channel)
- PI660 Windows based software (Compatible with MTS, MATLAB, Excel, and LabVIEW)

I/O Module 6013 description:

Each channel on the 6013 has a programmable gain, differential input instrumentation amplifier, low-pass filter and sample and hold. Sample and hold outputs are multiplexed to a 16-bit analog-to-digital converter. A regulated, bipolar 12 or 15 Volt supply provides power for transducers like DC LVDTs. Each channel's power is fused by a resettable polyswitch. The companion 6084 thermocouple junction box has a precision temperature sensor that when used together with the 6013 performs cold junction referencing.

I/O Module 6013 features:

- Thermocouple, DC LVDT or voltage
- ±12 or ±15 VDC for transducers
- Voltage substitution calibration
- Gains from 1 to 5,000
- Four-pole, low-pass filter

I/O Module 6014 description:

The 6014 has eight channels of AC or DC coupled programmable gain instrumentation amplifier, filter and sample and hold. A high-level multiplexer selects each channel for digitizing and output to the 6000 data bus. It includes constant current excitation for use with current driven transducers. The 6014 is primarily for use with transducers that have a built-in, low-impedance output amplifier or charge to voltage converter. It may also be used with voltage inputs where AC coupling is desired . AC or DC coupling and current excitation are selected by jumpers for each channel. A continuous analog output is available for monitoring and output to tape recorder or display.

I/O Module 6014 features:

- Excitation for current driven transducers
- Gains 1 to 5,000 with 0.05% accuracy
- AC or DC input coupling
- Automatic zero

I/O Module 6033 description:

Each channel is a complete transducer signal conditioning amplifier with excitation voltage regulator, automatic bridge balancing, differential instrumentation amplifier and sample and hold. The sample and hold outputs are multiplexed to a 16-bit analog-to-digital converter. The 6033 features four levels of programmable output alarms and excitation short and open alarms.

I/O Module 6033 features:

- ¼, ½ and full bridge transducers
- Programmable excitation, 0 to 12 Volts
- Automatic balance and zero
- Shunt and voltage substitution calibration
- Four-pole, low-pass filter

1.3.7 Instrumentation

1.3.7.1 Advanced Instrumentation

- Fiber Optic Strain Sensor: the specifications for the Fiber Optic Strain Sensors are given in Section 1.8.1 of this guide (see Table 1-11 Distributed Fiber-Optic Strain Sensor Specifications Developed at Lehigh NEES laboratory using Corning SMF28 test fiber).
- Wireless MEMS Accelerometers: the specifications for the wireless MEMs accelerometers are given in Section 1.8.2 of this manual (see Table 1-13 ADXL202 accelerometer specifications).

- Piezoelectric Strain Sensors: the specifications for the piezoelectric strain sensors are given in Section 1.8.3 of this manual (see Table 1-16 Summary of Current Piezoelectric Paint Strain Sensor Specifications).

1.3.7.2 Conventional Instrumentation

The RTMD earthquake simulation facility, as part of an upgrade to the facility, has purchased the following instrumentation:

Displacement Sensors:

- Six (6) Temposonic position sensors with a ±30 in stroke, input range +9 to +28.8 VDC, and output range -10 to -10 VDC.
- Six (6) Temposonic position sensors with a ±44 in stroke, input range +9 to +28.8 VDC, and output range -10 to -10 VDC.

Figure 1-3 Temposonics

Accelerometers:

- Triaxial capacitive accelerometers with ±10 g range, 180 Hz frequency bandwidth, and 200 mV/g sensitivity.

Figure 1-4 Triaxial Accelerometer

- Five (5) monoaxial accelerometers with ±10 g range and 300 Hz frequency bandwidth.

Inclinometers:

- Bi-axis dynamic inclinometers with a 150 Hz sampling rate, 360 degree inclination angle range, and a resolution to within 0.1 degrees.

Figure 1-5 Inclinometer

1.4 RTMD IT Systems

The RTMD IT Infrastructure systems are comprised of seven major systems and a shared memory protocol:

- **RTMDpop:** This is the web server and the FlexTPS web camera server for video telepresence.
- **RTMDrepos:** This is the local repository server for the RTMD facility. This system has a 5.5 TB DroboPro FS dual-redundancy RAID drive attached and mirrored to the onboard 3.5 TB RAID-5 storage array. This is used as the local backup library for experiment data and metadata.
- **RTMDdaq:** This is a computer that interfaces directly with the Pacific Instruments PI6000 data acquisition system through PI660 Windows software for the purposes of configuration and monitoring data acquisition. This system has an active role in configuration and a passive role in monitoring data acquisition, since data acquisition data is shared with other RTMD systems by means of the SCRAMNet interface.
- **RTMDxPC:** This is a computer that runs Mathworks' real-time Target PC software package, xPC Target. This dedicated kernel guarantees reliability and timing for compiled models. This system is compiled with SIMULINK models, provides commands to and receives feedback from RTMDctrl in real time over SCRAMNet and synchronizes data from RTMDdaq and RTMDctrl over SCRAMNet. It provides the ability to integrate data acquisition signals or controller feedback signals for various

testing methods. It also provides an external timing signal to the data acquisition to ensure time synchronization. The testing methods are discussed in Chapter 2.

- **RTMDsim:** This is a computer that configures and coordinates various testing methods and communicates with the RTMDxPC. This host system provides a configuration interface to the RTMDxPC through MATLAB and SIMULINK. It also provides a platform for running non real-time and distributed-based testing methods.
- **RTMDctrl:** This is a computer that interfaces directly with the servo controller (Controller) to provide customized programming functions. It also contains the control model for actuator, HSM, valve, and PID configuration and tuning. Model-based control is accomplished by sending commands and receiving feedback over the SCRAMNet with RTMDxPC or RTMDsim. The controller attached to this system provides the basic timing signal at 1024Hz.
- **RTMDtele:** This is a server that interfaces with the SCRAMNet shared memory bus, and provides a synchronized source of data from the PI6000 mainframe, the controller, RTMDsim and RTMDxPC for telepresence using Data Turbine.
- **SCRAMNet:** The underlying communications mechanism between the DAQ mainframe, RTMDsim, RTMDxPC, RTMDtele, and controller based on a proprietary shared memory bus and fiber optic network technology. A LinkXchange switch provides a configurable mechanism for mapping each of the systems attached to the network.

The above systems enable integrated control, where the user has the ability to configure the systems for an experiment. The procedure for configuring the systems is discussed in Section 1.6, Configuring an Experiment.

In the following section, a description of how the systems are integrated together during an experiment is laid out in order for users to gain an understanding of the system functionality.

1.5 Integration of RTMD IT Systems

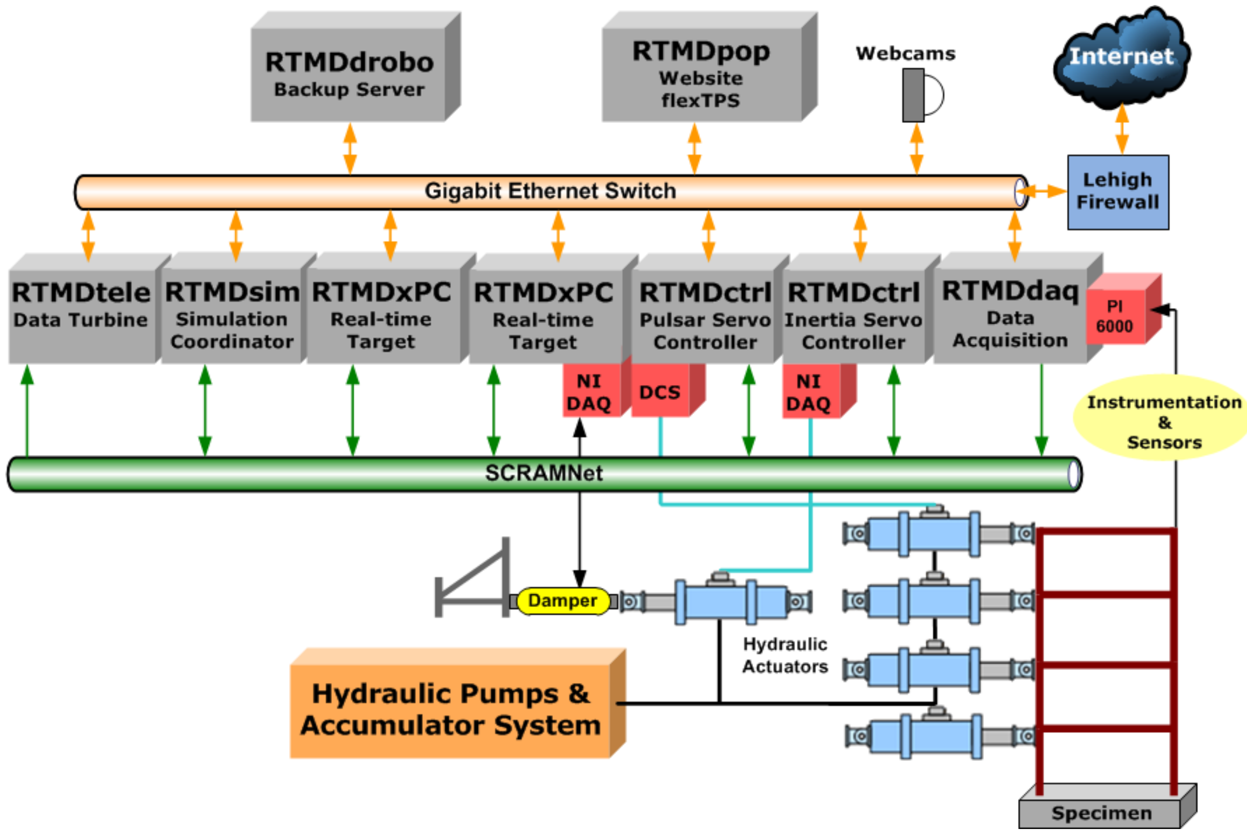


Figure 1-6 RTMD IT Infrastructure

The RTMD IT infrastructure, shown above in Figure 1-6, provides the framework for data and metadata to be transferred among systems. RTMDsim and RTMDxPC have a host-target relationship via Ethernet cable which enables the user to develop models on the host and download to the target. RTMDdaq, RTMDctrl along with RTMDsim, RTMDxPC and RTMDtele are all connected via SCRAMNet enabling real-time, synchronized data transfers. The data exchange for one data block (4 bytes) across SCRAMNet shared memory bus occurs within 200 nanoseconds, facilitating synchronized real-time testing capabilities at the 1024Hz control rate. A data structure for SCRAMNet is defined 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 along with creating streams of data for telepresence.

While an experiment is being conducted, RTMDtele provides a single point of access for streaming and archived data and video to remote participants. RTMDpop provides the web site and project web pages along with live cameras in the RTMD lab. As gateways, these systems provide a layer of functional protection for controlling an experiment, while also providing access to experimental data and offsite control in a moderated manner. The RTMDrepos functions as the repository for data after an experiment. During the experiment, data in the repository is secured, and not updated. After the experiment, all data and configuration information is archived to this location and mirrored at NEEScomm.

1.6 Configuring an Experiment

Experimental researchers planning on conducting an experiment must first provide the details for performing the experiment. A researcher will then need to access configuration programs to configure the RTMDdaq, RTMDsim, RTMDxPC, RTMDctrl, RTMDtele along with setting up project web pages at NEES.org and NEES@Lehigh. These configuration programs generate configuration information for data acquisition, simulation, control and telepresence applications as part of integrated simulation control that are specific to the experiment to be performed. Each of these required steps is briefly described below.

NEES.org: Project Warehouse and Project Group are created for collaboration and data and metadata organization. All data, metadata, sensor plans, specimen details and configuration files will eventually be archived at NEES.org, per the requirements of using the NEES@Lehigh equipment site.

RTMDdaq: A sensor list is defined for data acquisition of sensors. This includes choosing the channel types, entering descriptive information, location information, calibration factors and activating the channel for inclusion in the experiment. Screens for shows real-time acquired data are also configured here.

RTMDsim/RTMDxPC: User will configure their simulation or experiment through the RTMDsim using Mathworks' software or a user-defined program. If performing a real-time experiment, the SIMULINK model is downloaded to the RTMDxPC. The reader is referred to Chapter 2 for more information on types of integrated simulation control.

RTMDctrl: The user will configure the hydraulic control software to enable servo-valves, actuators and set PID parameters and actuator limits along with configuring the channel mapping for the SCRAMNet and integrated control.

RTMDtele: The user will configure the telepresence streaming and data archiving on the RTMDtele system. This application provides an interface for the user to define which channels from the RTMDdaq, RTMDsim/RTMDxPC and RTMDctrl are streamed.

RTMDpop: Users are required to define a project web page describing in details their experiment and specimen at NEES@Lehigh.

The NEES servo-hydraulic equipment that is maintained and operated at the RTMD is of dynamic nature. It is the responsibility of the RTMD equipment site to ensure that the equipment is operated in a safe manner that does not present a risk to the safety of laboratory staff and researchers present in the lab as well as any potential of damaging the equipment. All testing proposed by the researchers will need to be reviewed by the RTMD staff prior to testing to ensure the testing protocol does not present a risk to the safety of laboratory staff and researchers of any potential for damaging the equipment. The review process will involve providing a test matrix to the RTMD NEES Research Operations Manager with all of the details associated with the testing protocol, including the demand to be imposed on the equipment such as maximum actuator stroke, velocity, force, frequency of loading (when repetitive loading histories such as sinusoidal loading as well as band limited white noise tests are involved). It is expected that state-of-the-art procedures be used to develop the prediction for the demand on the equipment. The method and procedure used to arrive at the prediction of the test specimen response that imposes the demand on the equipment must be provided. The researchers must also include a statement as to what is the expected damage that will occur to the test specimen during each test. No testing will commence until either the Lehigh Equipment Site PI, Co-PI, or Research Scientist of the RTMD has approved in writing the test matrix. No deviation from the test matrix is permitted without the approval of either the Lehigh Equipment Site PI, Co-PI, or Research Scientist of the RTMD.

Once the above steps are completed, it is necessary for all the systems to be validated. Balancing and calibrating sensors requires RTMD technical support. Control programs are developed and validated through hydraulics off simulations with the RTMD IT Manager. Limits and hydraulic control parameters are defined with assistance from the RTMD Operations Manager. Telepresence applications are also developed with assistance from the RTMD IT Manager. All aspects are tested in a safe manner before any experiment is conducted.

1.7 Conducting an Experiment

When all steps in the previous section are completed, the experiment is ready to be performed. Listed below are the typical steps a user will take to perform an experiment from start to finish.

1. User will verify with the RTMD IT Manager that data acquisition system is valid and operational on RTMDdaq.
2. User will verify with the RTMD Operations Manager that hydraulic control is stable using RTMDctrl.
3. User will verify with the RTMD IT Manager hat RTMDtele is streaming configured data streams.
4. User will verify with the RTMD IT Manager that RTMDpop is streaming required web cameras.
5. User will verify with the RTMD IT Manager that a previously approved[1] simulation model is loaded on the RTMDsim/RTMDxPC.
6. User will verify with ATLSS Laboratory Operations Manager and RTMD Operations Manager that all safety limits are in place and operational.

[1] The Equipment Site Director, NEES Research Engineer, or Equipment Site Director must approve all simulation models before a specimen is tested.

7. User will confirm with the ATLSS Laboratory Operations Manager, RTMD IT Manager and RTMD Operations Manager that all steps have been executed and testing is ready to be performed.
8. User will run the experiment and collect all data required from the RTMD systems.
9. User will confirm with the ATLSS Laboratory Operations Manager and RTMD Operations Manager that all testing is completed and have the hydraulics system shut down.
10. User will stop the data acquisition and telepresence streams with help from the RTMD IT Manager.

1.8 Advanced Instrumentation

1.8.1 Fiber Optic Strain Sensors

Stimulated Brillouin Scattering Fiber Optic Strain Sensor

Summary

A single laser source photonics assembly was developed and calibrated to facilitate use of distributed application of SBS strain sensor to civil infrastructures. The single laser source assembly greatly simplified the overall process by limiting the power losses, and also requiring access to only one end of the fiber, which makes the system suitable for large scale sensing applications. The specifications and the functionality of the current Stimulated Brillouin Scattering fiber optic sensor developed at Lehigh University are presented in this document for potential users to consider adapting this tool in their testing schemes.

Introduction

Use of fiber optic sensors is a viable real-time data gathering approach by surface adhering or embedding the optical fiber to a specimen under evaluation. There are several types of measurement techniques involving optical one-dimensional waveguides based on different physical phenomena. Among these are Fiber Bragg Gratings, (FBG), Optical Time Domain Reflectometry (OTDR), evanescent pulse technique and the nonlinear techniques such as Raman and Brillouin scattering. The Brillouin Scattering in standard optical fibers makes it possible to obtain strain measurements at intermitted positions along a single fiber due to thermal or mechanical loading. The premise of Brillouin optical time domain sensing technique goes back to 1920 when Léon Brillouin (1889-1969), first studied the diffusion of light by acoustic waves. One of the distinctive features he observed was a frequency change of the scattered light. This effect, named after its discoverer, has remained for a long time within the frame of purely academic research.

After the invention of the laser in 1958 and the optical fibers shortly after, the Brillouin effect was thoroughly studied and quantified.

Some features of the Brillouin scattering sensor such as the distributive capability, self-referencing and drift free measurement, high strain resolution and calibration free application led to considerable interest from the civil engineering community (Jackson 1995, Kurashima, et al. 1997, Czarske, et al. 1996, Culshaw and Michie 1997). These sensors are not based on "interactions/losses" type of detection, therefore present major advantages for health monitoring of civil infrastructure because of long gauge capability. Although data acquisition and conditioning systems for these sensors can be elaborate, they have been demonstrated to be highly accurate. Thevenaz et al. in 1999 reported the first full-scale application of a Brillouin scattering sensor (Bao, et al. 2001a). In this study, they implemented the sensor into a concrete dam structure. They measured the concrete curing temperature distribution over 72 hours. Since then, the sensor has been used successfully in the laboratory for measuring compressive, tensile, and flexural strains in structural components (Bao, et al. 2001b, Kim, et al. 2002, Zeng, et al. 2002, Kwon, et al. 2002). It has been also used to measure temperatures during the construction of a building (Ohno, et al. 2002), and to measure strains in concrete pile (Buckland and Boyd 1997).

Physics of Brillouin scattering

When light travels through a transparent media, part of it is scattered. This phenomenon is related to the inhomogeneities in the material structure. In a dielectric material like the silica of an optical fiber, material tends to densify in the region of high intensity electrical field. Hence, periodic compression zones create a density wave moving in the material. If the speed of this wave corresponds to the speed of sound in the material: an acoustic wave is created. An acoustic wave travelling through a transparent material scatters light in a defined direction. Brillouin Scattering results from the scattering of the incident (pump) light by acoustic waves. These acoustic waves can backscatter the light at a longer wavelength or lower frequency, and the separation between the frequencies of the incident and scattered light is called the Brillouin frequency shift. The scattered light is shifted downward in frequency to the Stokes frequency. The Stimulated Brillouin Scattering (SBS) occurs when the Stokes wave interferes with the incident light and reinforces the amplitude of the acoustic wave (Horigushi, et al. 1989).

The frequency shift of the Stokes waves, referred to as the Brillouin frequency shift, υ_B , is given by the following equation:

$$\upsilon_B = \frac{\Omega_B}{2\pi} = \frac{2nV_A}{\lambda_p}$$

(Equation 1-1)

where, λ_p, n, V_A are the wavelength of the incident pump light wave, the refractive index of the fiber core and the acoustic velocity of the core, respectively.

The Brillouin gain spectrum $g_B(u)$, which follows a Lorentzian type expression, peaks at $v = v_B$ characterizing the growth of a Stokes wave. Figure 1-7 shows a typical Brillouin gain spectrum for AllewaveTR monomode test fiber. The full width of D_{v_B} at half of maximum Brillouin gain is related to the phonon lifetime as: $D_{v_B} = \frac{G_B}{2_p}$. The phonon lifetime, which is the inverse of damping G_B, is approximately 10ns. When Brillouin gain occurs at a particular position, i.e., a single point in the fiber, measured with a pump pulse of duration "w" seconds, will return a signal for "w" seconds. The signal measured at the single point in the time domain will contain information from the section of fiber preceding it. The length of fiber length detected will be equal to the pump pulse duration times the return-trip speed of light in the fiber, which is approximately 10cm/ns. Therefore, for pulse duration of 10ns, the minimum spatial resolution, or gauge length of detection is effectively 100cm (10ns x 10cm/ns). This spatial resolution of detection can be improved by reducing the duration of the pump pulse.

Measurement of strain

According to (Equation **1-1)**, the Brillouin frequency shift is directly proportional to the acoustic velocity of the optical fiber; hence any change of this velocity results in a shift of the v_B. The elastic properties of silica make any induced strain a volume change, resulting in locally modified material density. When the refractive index, n, of the fiber is known, by measuring the Brillouin shift v_B, one can determine the local change in the acoustic velocity and the induced strain. Indeed, empirical relations show that there is a pseudo linear relation between v_B and strain (Horigushi, et al. 1989). Hence, by determining the proportionality constant between the two quantities, one can obtain the strains corresponding to v_B measured at discrete points along the fiber.

Figure 1-7 Brillouin gain spectrum in a 2.5 km unstrained AllewaveTR monomode test fiber

The acoustic velocity, V_A , depends on the Young's Modulus, E , the Poisson's ratio n , and the mass density, ρ of the fiber core. Hence:

$$V_A = \left(\frac{E\,(1-\nu)}{\rho\,(1+\nu)\,(1-2\nu)} \right)^{\frac{1}{2}}$$

(Equation 1-2)

The following relation holds for the normalized Brillouin frequency shift:

$$d_\varepsilon = \frac{d_{\upsilon_B}}{\upsilon_B \cdot C}$$

(Equation 1-3)

where, C is a dimensionless coefficient that describes the collective change in refractive index, elastic modulus, mass density and Poisson's ratio of the silica fiber subjected to strain.

Considering a sensing region of optical fiber stretched between two secured points, the axial stress and strain developed in the fiber can be expressed as follows:

$$\sigma_a = \left(\frac{E\,(1-\nu)}{(1+\nu)\,(1-2\nu)} \right) \varepsilon$$

(Equation 1-4)

$$\varepsilon - \varepsilon_0 = \frac{\upsilon_B - \upsilon_{B_{(\tau_0)}}}{C\upsilon_{B_{(\tau_0)}}}$$

(Equation 1-5)

where, ε_0 is the reference strain in the fiber, which is normally taken as zero under the absence of mechanical loading. The Brillouin shift frequency, $\upsilon_{B_{(\tau_0)}}$ is the Brillouin measurement of the fiber at reference strain.

Temperature corrections for Brillouin frequency and strain

Fiber optic strain measurements should be compensated for temperature variation of the environment or the specimen under test. A reference measurement of Brillouin frequency shift solely due to change in temperature, T, is needed for this purpose. The following equation describes a comprehensive formulation of strain corrected for temperature:

$$\upsilon_B = \upsilon_{B_{(\tau_0, T_0)}} \left[1 + C_1 \Delta\varepsilon + C_2 \Delta T\right]$$

(Equation 1-6)

where, $C_1 = \frac{\partial \upsilon_{B_{(T_0)}}}{\partial \varepsilon} \frac{1}{\upsilon_{B_{(\tau_0, T_0)}}}$ and $C_2 = \frac{\partial \upsilon_{B_{(\tau_0)}}}{\partial T} \frac{1}{\upsilon_{B_{(\tau_0, T_0)}}}$

$\upsilon_{B_{(\tau_0, T_0)}}$ = Brillouin frequency measured at reference strain and temperature

$\upsilon_{B_{(T_0)}}$ = Brillouin frequency measured at test strain and reference temperature

$\upsilon_{B_{(\tau_0)}}$ = Brillouin frequency measured at test temperature and reference strain

The C_1 and C_2 are coefficients determined using calibration charts and reference readings for the sensing fiber. Accordingly, the strain can be computed as:

$$\varepsilon - \varepsilon_0 = \frac{1}{C_1 \upsilon_{B_{(\tau_0, T_0)}}} \left[\upsilon_B - \upsilon_{B_{(\tau_0, T_0)}} \left(1 + C_2 \Delta T\right)\right]$$

(Equation 1-7)

When temperature is constant ($\Delta T = 0$), (Equation 1-7) reduces to (Equation 1-5), with $C_1 = C$.

Strain resolution

The strain resolution, d_ε is determined using Equation (1.3), where $d_\varepsilon = d_\upsilon / \left(\upsilon_{B_{(\varepsilon_0)}} C\right)$, and d_υ is the bandwidth of the probe wave. To illustrate, using the theoretical expressions provided by Mallinder and Proctor (1964), the C coefficient for *Truewave*^{TM} fiber is determined to be equal to 4.14. Taking d_υ as 10 MHz, (line width of Stokes wave), and the Brillouin frequency of the unstrained *Truewave*^{TM} fiber, $\upsilon_{B_{(\varepsilon_0)}}$, as 10694.625 MHz, the strain resolution is computed 2 x 10^{-4}.

Using an Electrical Spectrum Analyzer (ESA), which delivers 50 kHz bandwidth measurements, d_ε can be as low as 1 x 10^{-6}.

Lehigh NEES Single Laser Source SBS Fiber Optic Strain Sensor

Photonics Assembly

In a single-laser source assembly, as shown in Figure 1-8, the *Pump Laser* beam is pulsed by an Electro Optical Modulator (EOM), driven by a Microwave Generator and a Pulse Generator. The electro-optical modulator is the key element of this assembly since it is used on the one hand for pulsing light from a single frequency laser to form the pump signal, and on the other hand for the generation and frequency tuning of the probe signal. Both the pump and the probe are generated from the same continuous wave light source at 1550nm, passed through a gated electro-optic modulator that is driven by the microwave generator set at the Brillouin frequency. The frequency shift on the laser light is achieved by simply applying a microwave signal on the electro-optic modulator electrodes. This creates side-bands in the laser spectrum. When the modulation frequency f_m is close to the Brillouin frequency shift υ_B, the first lower side-band (the high frequency side band) lies in the Brillouin gain spectrum and is amplified through the Brillouin interaction. The Brillouin gain spectrum can then be determined by simply sweeping the modulation frequency, f_m and recording the probe intensity. The SBS signal emerging from the circulator is filtered through a Bragg grating (25 GHz bandwidth) and recorded on a sampling oscilloscope.

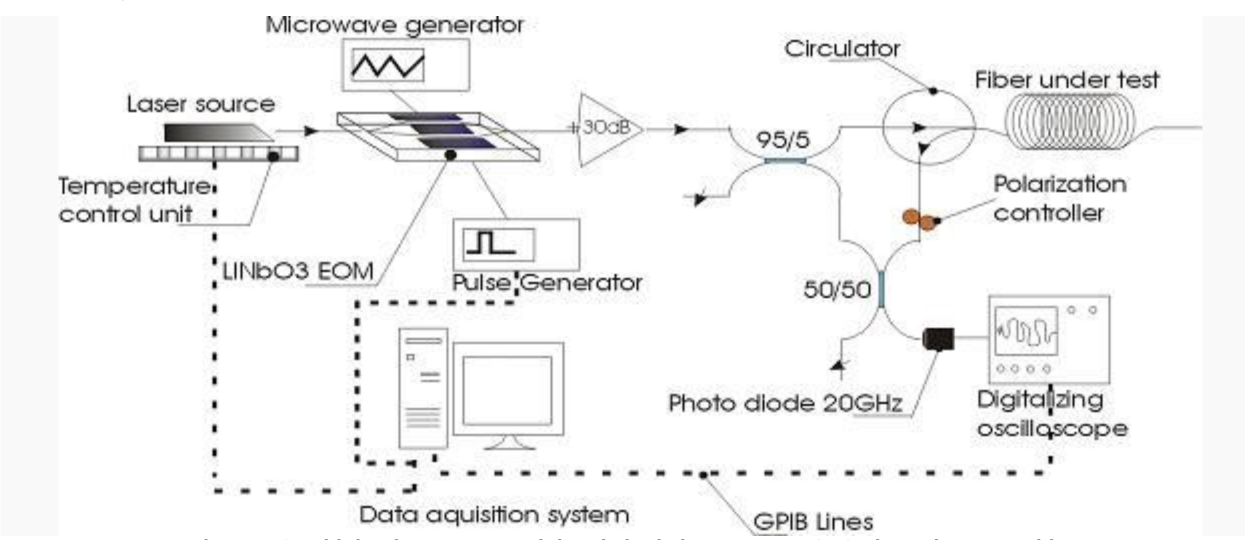


Figure 1-8 Lehigh's frequency modulated single laser source SBS photonics assembly

Strain Sensor Calibration and Verification

- **Placement requirements:** The sensing fiber is mounted either by bonding it on the surface or embedding it inside the test specimen. The measurements are made by linear positioning of the fiber.

As such, depending on the physical shape or configuration of the specimen, the fiber may be wrapped (i.e., column section), coiled or laced in layers (i.e., in soil mass) in order to outline the specimen or cover the points of interest for measurement. Most optical fibers should not be wound or coiled below a limiting diameter of curvature to avoid loss of light energy to refraction. As an example, minimum diameter of curvature for *Truewave*^{TM} fiber was measured as 3.29 cm, below which, the output power through the fiber dropped significantly.

- **Strain Calibration:** For calibration of *Corning SMF28* fiber, first a 86.4cm section of 120m fiber was secured at two end points. The fiber was stretched and the strains measured using a translation stage with an accuracy of 10µm. The results of Brillouin frequency shift detection on *Corning SMF28* fiber, using one-laser source photonics assembly is shown in Figure 1-9. It is observed that the probe signal bandwidth is uniform at 100MHz for the three different strain measurements. The gain signal fits a Gaussian distribution with an acceptable accuracy of less than 0.01% over the full range of bandwith (0.002 GHz/25GHz). This is a tenfold improvement over the average accuracy for the two-laser source system, computed on the order of 0.1% . The average strain resolution achieved in these measurements was on the order of 2.4×10^{-4}.
- **Strain Verification:** Next, the same fiber was loaded with several calibrated weights from 1kg to 7kg in 1kg increments. The stress in the fiber was computed using $s_a = \omega / 2a$, where a is the cross sectional are of the fiber (core and cladding). The corresponding Brillouin shift was recorded for each applied stress. The variation of independently measured Brillouin frequency shift with the applied stress and the strain are shown in Figure 1-10. Since each frequency shift corresponds to a unique stress and strain in the fiber, a one-to-one relation is found between these independently measured values. Hence, the Brillouin determined stress-strain behavior of the test fiber (*Corning SMF28*) is plotted in Figure 1-11. The elastic constant between the stress and strain is computed as 79.7 GPa. Taking Poisson's ratio of 0.14, the Young's modulus, *E* of the test fiber is estimated as 76 GPa, which is close to the elastic modulus of silica (72 GPa). In this case, slight deviations from pure silica properties are expected, since most of the optical fibers are doped with property enhancing elements (i.e., germanium).

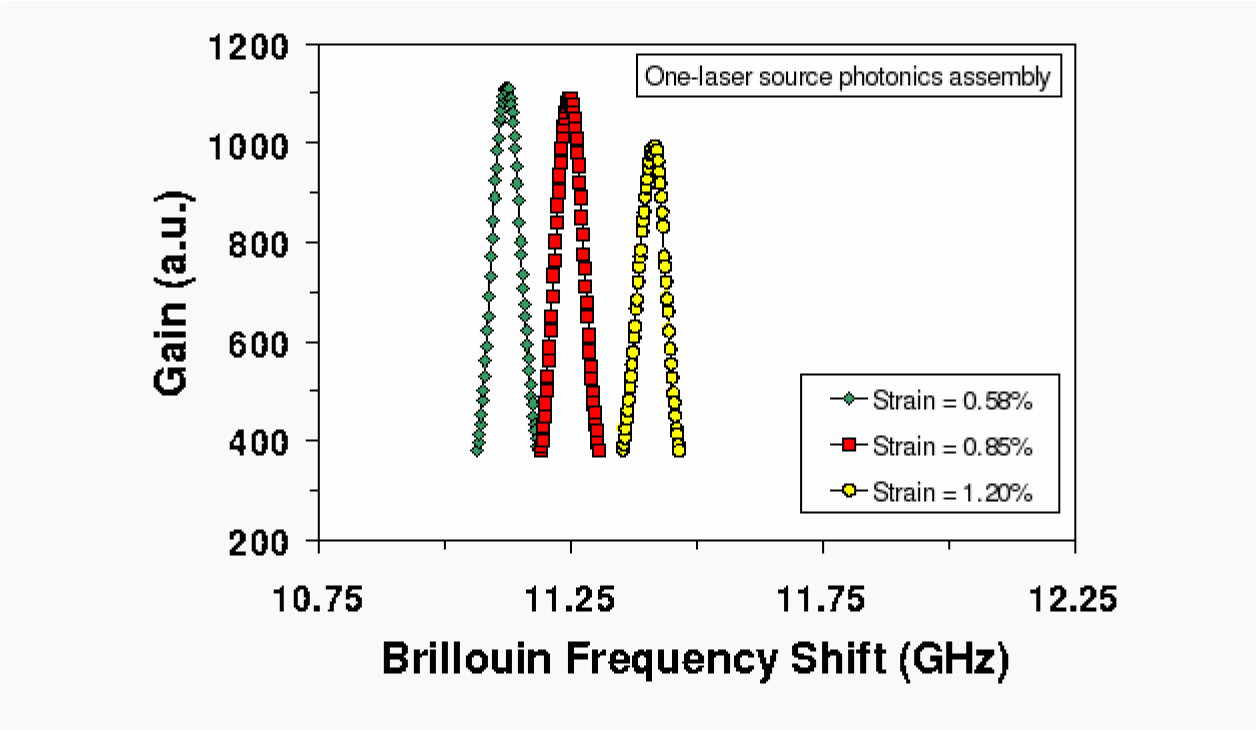


Figure 1-9 Variation of Brillouin frequency with strain measured using a one-laser source phothonics assembly (strain induced by translation stage on Corning SMF28 test fiber)

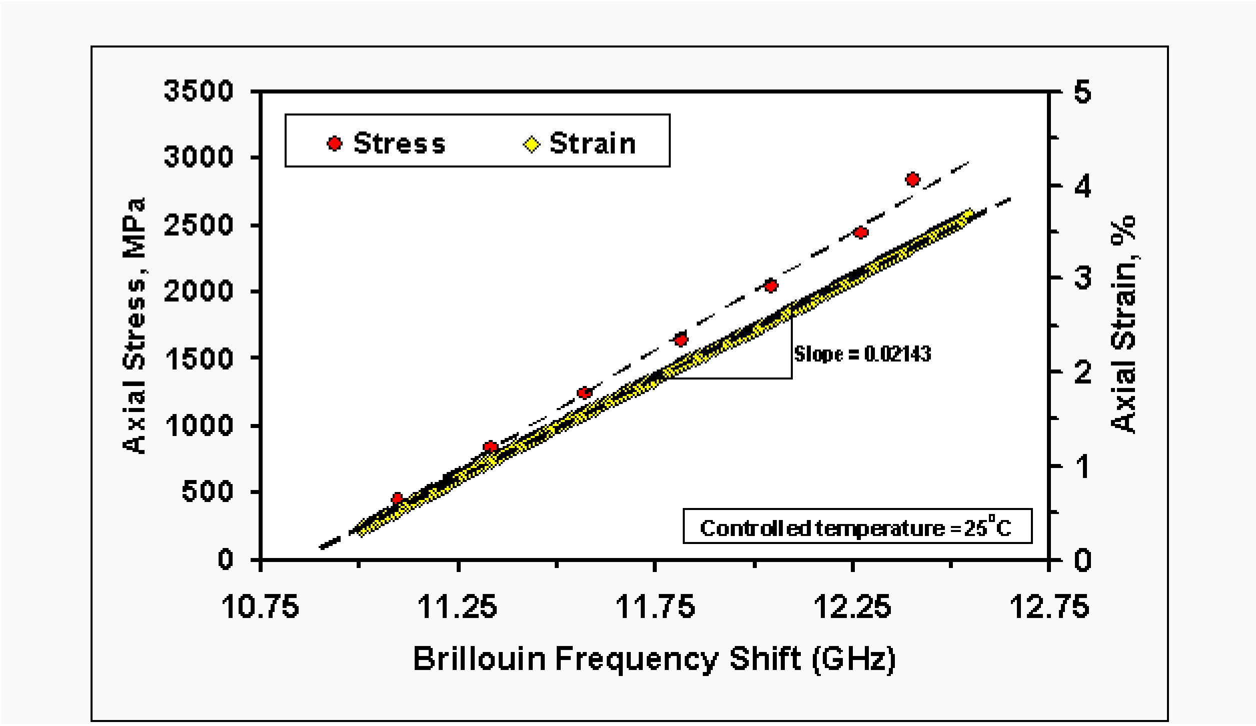


Figure 1-10 Brillouin Frequency Shift measurement with independently applied stress and strain to Corning SMF28 test fiber

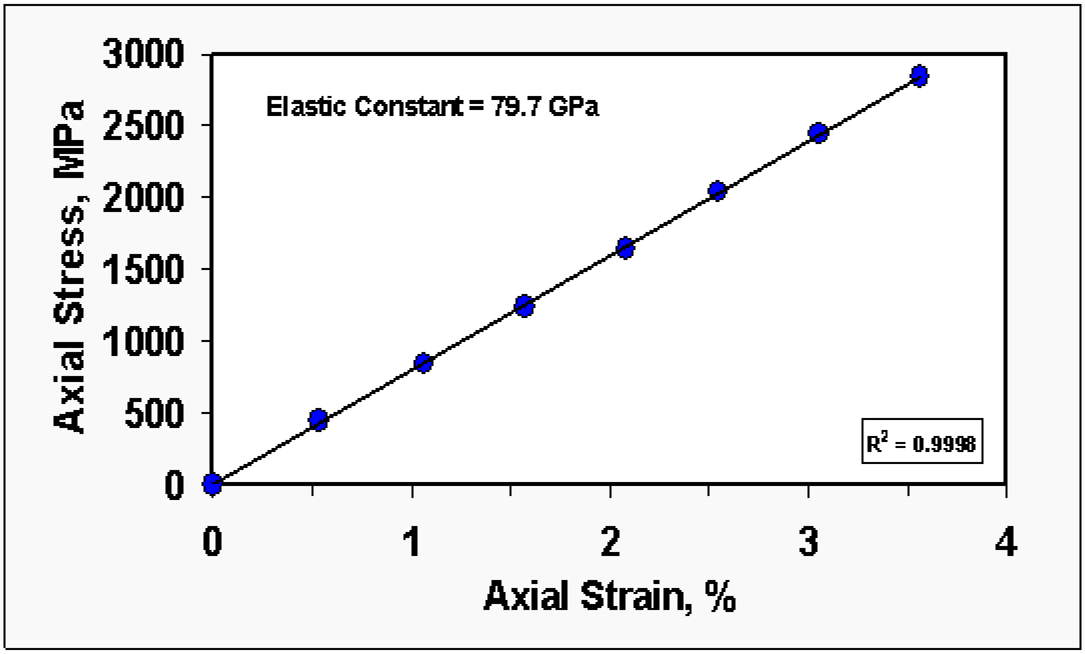


Figure 1-11 The stress-strain curve generated from independently applied stress and strain and their correlation to Brillouin frequency shift measurements on a Corning SMF28 test fiber

Verification of SBS fiberoptic strain measurements under damped harmonic oscillations

SBS fiber optic measurement of strain for the damped harmonic oscillation of a long, thin steel bar was compared to that of a strain gauge mounted on the same bar. In this experiment the strain measurements were recorded every 10ms with 0.01% accuracy.

The test set up is shown in Figure 1-12, and consisted of a bar that was simply supported as a beam at it ends at 914 mm. A lumped mass of 0.00777 lbs-sec^2/in was located at 254 mm from each end of the bar. The cross section of the bar was 38 mm wide and 3.2 mm thick. The Young's modulus of elasticity of the steel bar was about 203 GPa. The theoretical fundamental damped natural frequency was approximately 4Hz.

A Corning SMF28 test fiber was epoxy glued inside a thin groove running over the middle third of the 914 mm long span of the steel bar. The total length of the test fiber was 35 meters, of which only an 800 mm-section was actually bonded to the test bar. The fiber was mounted on one side of the bar only, such that when the bar was flexed towards the fiber side, the fiber stretched measuring positive strains. When the bar was flexed in the opposite direction, fiber compressed measuring negative strains. A typical test consisted of manually applying a maximum of 50 mm deflection at the center of the steel bar and releasing it into free vibration. The sensor readings, averaged over the 800 mm bonded fiber were recorded and plotted instantaneously. A conventional strain gauge mounted on the bar was used to verify independently the fiber optic sensor measurements.

Figure 1-13 shows a comparison of the strains induced by the free vibration of the steel bar as measured by the fiber optic sensor and the conventional strain gauge. The two plots follow each other very closely with an average frequency of oscillation of 4.2 Hz (close to the theoretical natural frequency of 4 Hz), and a maximum measured strain of approximately 500 me.

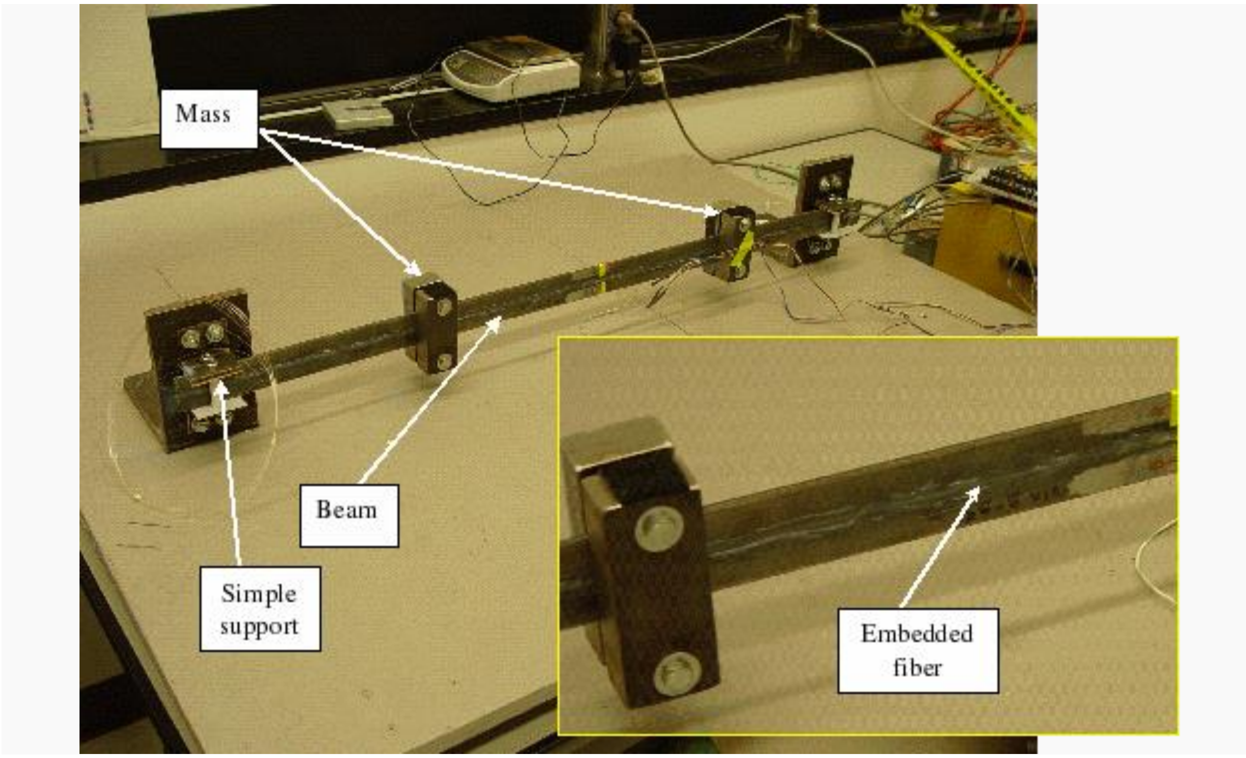


Figure 1-12 Test setup

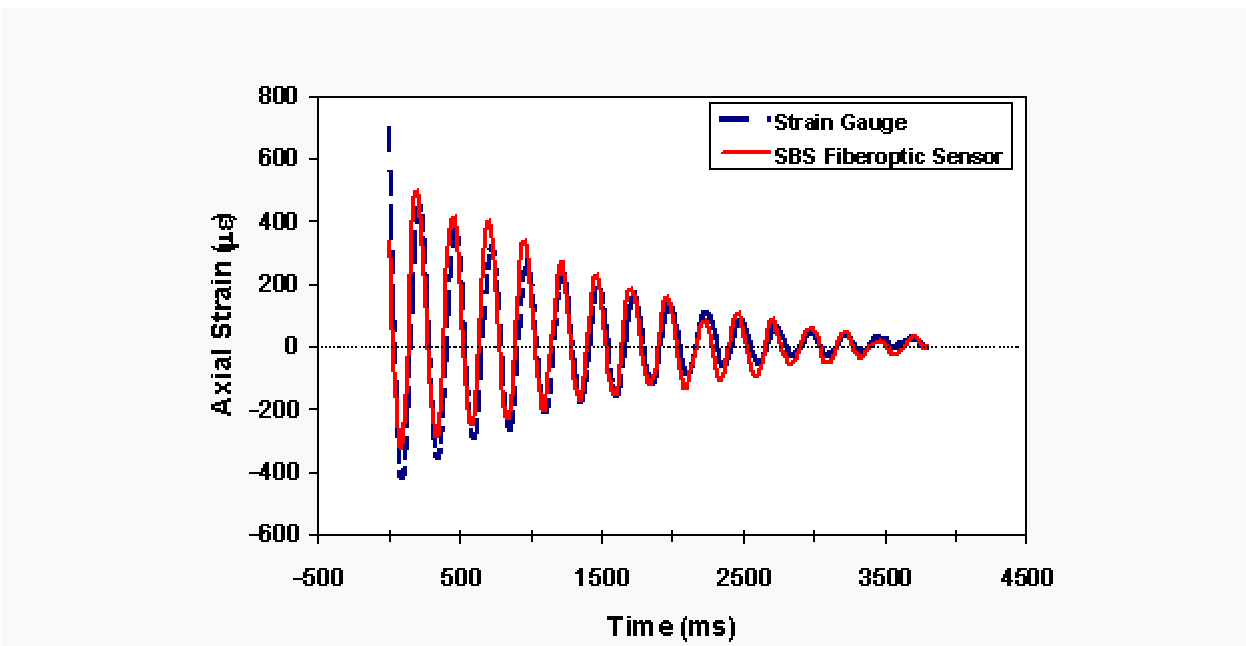


Figure 1-13 Independent verification of SBS fiberoptic measurements using a conventional strain gauge

Specifications of current SBS fiber optic strain measurement assembly at Lehigh

A set of specific parameters and their ranges were determined for potential use of the Corning SMF28 test fiber as a SBS fiber optic strain sensor at Lehigh NEES laboratory. These specifications were developed based on the laboratory testing and calibration of the Corning SMF28 test fiber under controlled temperature (25 C). Hence these specifications may not apply to other types of fibers. The calibration procedure described here should be repeated for all test fibers as described in Sections above prior to mounting them on the test specimens. Additionally, these fibers should be calibrated for temperature variation if the test specimen resides at a location other than a temperature-controlled room.

Table 1-11 presents the specifications developed for the Corning SMF28 test fiber in controlled laboratory tests. The calibration constant, C, used in (Equation 1-5) was determined from the plot of the measured axial strains (induced by translation stage) versus the Brillouin frequency shift (as shown in Figure 1-10 and the Brillouin frequency shift of the unstrained fiber measured as 10.8564 GHz. The slope of the strain versus Brillouin frequency shift line $D_{\varepsilon}/D_{\upsilon_B}$, as shown in Figure 1-11 is *0.02143*. Accordingly,

$$\frac{\Delta \upsilon_B}{\Delta \varepsilon} \bullet \frac{1}{\upsilon_{B_{(\tau_0, T_0)}}} = \left(\frac{1}{0.02143}\right) \bullet \left(\frac{1}{10.8564}\right) \approx 4.3$$

(Equation 1-8)

The Brillouin based strains used in the calibration verification for the two test fiber, Truewave and Corning SMF28, were determined using (Equation 1-5) and the following parameter values:

Table 1-11 Distributed Fiber-Optic Strain Sensor Specifications Developed at Lehigh NEES laboratory using Corning SMF28 test fiber

Fiber Type	Calibration Constant, C	Unstrained fiber Brillouin frequency shift vb(e0,r0), Ghz
Truewave	4.14	10.6946
Corning SMF28	4.30	10.85

Sensing Type	Distributed Strain (discontinuous)
Gauge length	0.25 -10m
Strain Resolution	1 - 200 um (10-4% - 10-2%)
Accuracy	0.01%
Strain Range	30,000 με (3%) in tension
Sampling frequency	1 sample packet/second
One sample packet	up to 25 selected strain amplitudes within the range (sensed over the entire length of test fiber)
Lag between each strain sweep	0.5msec

Sampling duration	up to 12.5 msec/sample packet

1.8.2 Wireless MEMS Accelerometers

As part of the National Science Foundation George E. Brown Jr. NEES@Lehigh equipment grant, a series of advanced sensors were examined for application in earthquake simulation. This report examines a proprietary wireless MEMS accelerometer system produced by Xbow Corporation. The system has the potential for rapid low cost installation making it an ideal tool for placement of large data arrays in earthquake engineering research projects. An overview of the device, a summary of the capabilities and limitations and the methodology for NEES integration is discussed.

Equipment Overview

The wireless sensor system consists of a four parts show in Figure 1-14: 1) the mote - MICA2 processor/radio board, 2) the sensor board (MTS310CA), 3) the proto/data acquisition board (MDA500CA), 4) the serial PC interface board (MIB500CA). The wireless portion of system device consists of the MTS310CA sensor board mounted on the MICA2 processor/radio board with attached battery. This device transmits to the MDA500CA proto/data acquisition board mounted on the PC interface board

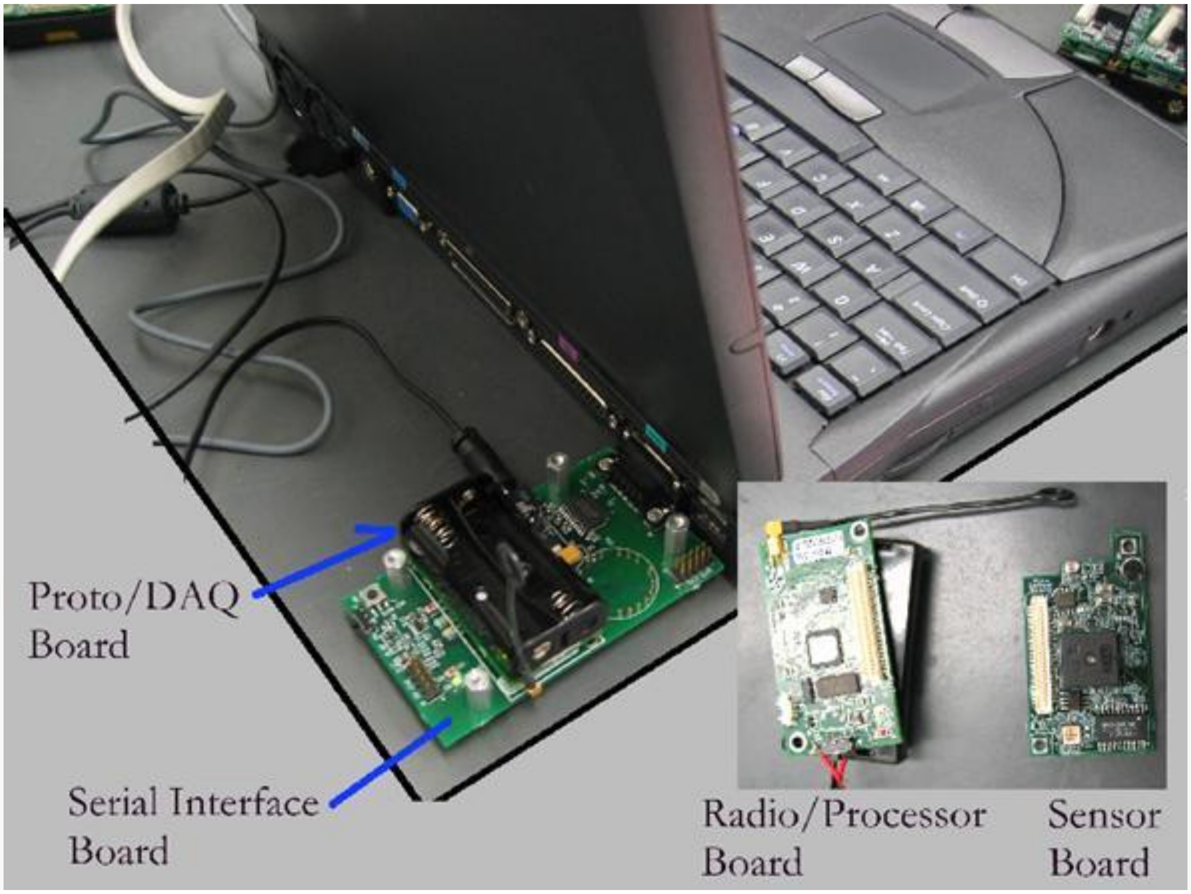


Figure 1-14 Device layout

The Motes used in this research are the third generation of modules MICA2 and MICA2DOT which are shown in Figure 1-15(a) and (b) respectively. The MICA2 mote was chosen for integration in the NEES system. The design goal of these motes is to enable low-power wireless sensor networks. As shown in Figure 1-16, the major components of the motes include: (i) micro-processors modules with both digital IO and analog IO interfaces, (ii) a tunable frequency radio module for transmission and receipt of messages using the attached antenna. (iii) a logger flash module for the non-loss program, and (iv) an IO expansion slot for sensor inputs.

Figure 1-15 Mote processor/transmission board

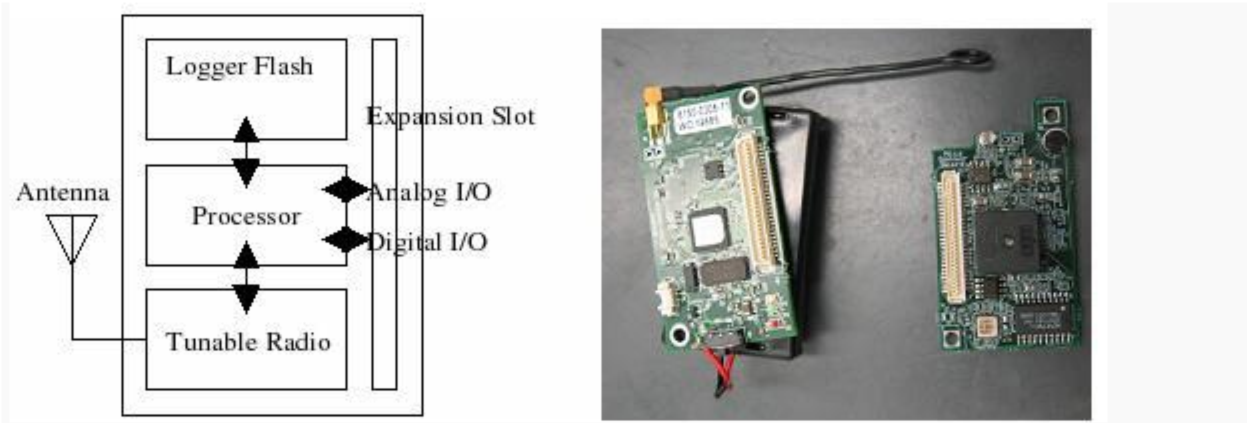


Figure 1-16 Mote components

The following features make the MICA2 and MICA2DOT suited to laboratory and field structure measurements:

- 868/916MHz, 433 or 315MHz multi-channel transceiver with extended range.
- TinyOS (TOS) Distributed Software Operating System v1.0 with improved networking stack and remote re-programming capabilities.
- Wide range of sensor boards and data acquisition add-on boards.
- MICA2DOT quarter-sized Mote is compatible with the much larger yet powerful MICA2 mote.

The mote has a transmission capability of 38.4kbaud bandwidth. This allows for a maximum of 3840 10-bit samples to be transmitted in a single-hop network (i.e., one transmission leg from the sensor to the receiver). For larger networks with links that are more than one hop away from the sink node, the maximum value of data transmission rate will decrease. In our test system, every ten samples are packed as a 20-bit data packet with a 6-bit packet header. With this configuration, the maximum packet the network can allow is approximately 184 packets per second. If a rate of 100 samples per second is used, the maximum sensors the system can support are 18. Additional details on the motes are presented below in Table 1-12.

Table 1-12 MICA2 and MICA2DOT mote specifications

Mote	MICA2	MICA2DOT
Processor Type	ATmega128L	ATmega128L
Program flash memory	128Kbytes	128Kbytes
Measurement flash	512Kbytes	512Kbytes
Configuration EEPROM	4Kbytes	4Kbytes
Serial communication	57600bits/s UART	19200bits/s UART
Analog to digital converter	8 10bits ADC	6 10bits ADC
Other interfaces	DIO, I2C, SPI	DIO

Current draw (Normal/Sleep)	8mA/<15uA	8mA/<15uA
Center frequency	868/916	868/916
Number of channels	4/50	4/50
Data range	38.4 Kbaud	38.4 Kbaud
Outdoor range	500ft	500ft
Current draw(Trans/Recv)	27mA/10mA	27mA/10mA
Battery	2xAA	3V Coin Cell
Size	58x32x7mm	D=25mm, depth=6mm
Weight	18g	3g
Expansion interface	51pin	18pin

Sensor Board

The MTS310CA sensor board obtains all measurements. The board is equipped with a Photo Diode, Thermistor, Microphone, Sounder, Magnetic Sensor, and a Micro Electrical Mechanical System (MEMS) based Accelerometer sensor. The arrangement of sensors on the board is illustrated in Figure 1-17.

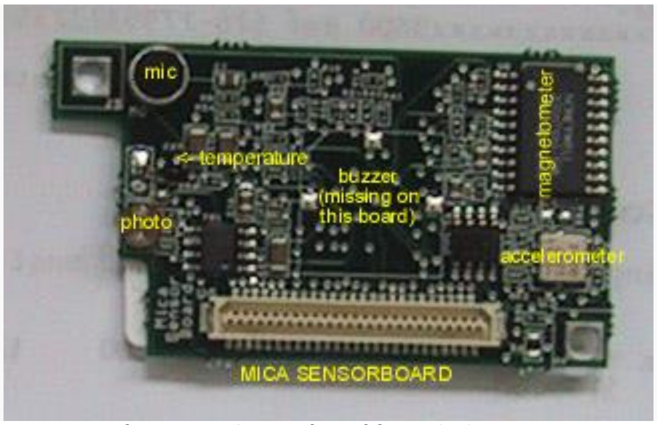


Figure 1-17 Sensor board for MICA2 motes

The sensing board includes multiple analog sensors that can be sampled by the ATML128's internal 10-bit AD converters. The sensors evaluated for this series of experiments are the bi-axial accelerometer ADXL202JE produced by Advanced Devices. Specification about that accelerometer indicate that the ADXL202JE is a low-cost, low-power, complete 2-axis accelerometer with a digital output, all on a single monolithic IC. It will measure accelerations with a full-scale range of -2 g to +2g. The ADXL202JE can measure both dynamic acceleration such as vibrations and static acceleration like gravity. The accelerometer properties are summarized below in Table 1-13.

Table 1-13 ADXL202 accelerometer specifications

# Axis	2
Range	+/- 2.0g
Sensitivity	12.5% / g

Supply Current	0.6mA
Supply Voltage	2.7 to 5.0 V
Bandwidth	6 kHz
Resolution at 60Hz	2mg
Shock Survival	1000 g
Temp Range	-40 to 85C

Receiver Board

Another MICA2 mote is used as the receiver board in our test system, the functionality of the receiver board includes: (i) to receive the data packet from the sensors, (ii) to relay the data into the COM port of a PC through the PC Interface Board, and (iii) to recalculate the timestamp such that the sensing data from the asynchronized sensors can be displayed in the same screenshot. The receiver board will take the sensor node it discovered first as the reference sensor node. On receiving data packet from another sensor node, it changes the LastSampleCount variable in the packet according to the following formula:

PC Interface Board

The PC interface board enables the motes to talk with the computer. It enables (1) the computer to download compiled program to motes, and (2) the bi-direction communication between the mote and the computer in run-time through the UART port at speed 57600 bit/s for MICA2 (For MICA2DOT, the speed is 19200 bits/s). (3) An external power source is available such that the receiving mote will always have reliable power supply.

In the experiment, the COM port is configured as following:

- Speed: 115200 (any value larger than 57600 works fine)
- Data bits: 8
- Parity: Even
- Stop bits: 1
- Flow Control: None

Sensor nodes

Ten sensing data are put together with necessary information in the format of:

```
typedef struct OscopeMessage
```

The packets are unicasted to the sink nodes by the sensor nodes once they are ready.

Sink nodes

On receive these sensing packet, the sink node will adjust the LastSampleCount varible, such that the results from different sensors with different starting time can be shown in the same view-shot by the java program.

Java Program

The goal of the java program running on the PC that is connected with the sink node through an interface board is to receive all UART inputs and display them on the screen.

NEES Integration

The Wireless system transmits data to a host computer via a serial port connection. To integrate this data into the main RTMD facility data stream a Data Turbine tool is used.

Data Turbine is a dynamic data server and viewer based on ring buffer technology. It is easily integrated with any Java-based application such as the application used for communicating with the MEMs wireless acceleration sensors using a simple API.

When the MEMs application is loaded, an exclusive Data Turbine connection is established for every wireless sensor on the network. When a packet of data is received from any wireless sensor at the host PC, the packet is parsed into usable data such as ID, timestamp and raw acceleration data. The MEMs application sends the acceleration data to the Data Turbine protocol using a name ID for each sensor. The data is stored in the ring buffer and can be viewed by any user with an Internet browser.

Data Turbine is part of the NEES system and is formally accessed through the RTMDtele. The data is synchronized to a timestamp value and/or a count status. The data collected by Data Turbine is saved in the NEES repository and will have the capabilities of post-test viewing in the future. The viewer and the ring buffer are two different programs working together and the Data Viewer remains on RTMDtele at all times.

To display data from the Data Turbine, Real-time Data Viewer (RDV) should be used. This package is available at the RTMD facility website.

Laboratory Feasibility Study

To assess their capability for laboratory measurement the MOTES were examined at the ATLSS Research Center NEES facility. The accuracy, the propensity for data loss, and the delay for the wireless testing system is examined. This evaluation is conducted through a side-by-side comparison of a hard wired accelerometer and two wireless MOTES. The wired accelerometer is connected directly to the NEES@Lehigh Pacific Instruments 6000 data acquisition system. To ensure accurate readings the wired accelerometer is sampled at 500 samples per second.

A simple test fixture is used to evaluate the accelerometers (Figure 1-18). A cantilevered steel bar with a lumped mass is used. The mass consists of the self weight of the motes and the wired accelerometer. Three cantilever distances are used to evaluate different frequency ranges. One channel of data is sampled from each wireless accelerometer and compared to the wired value.

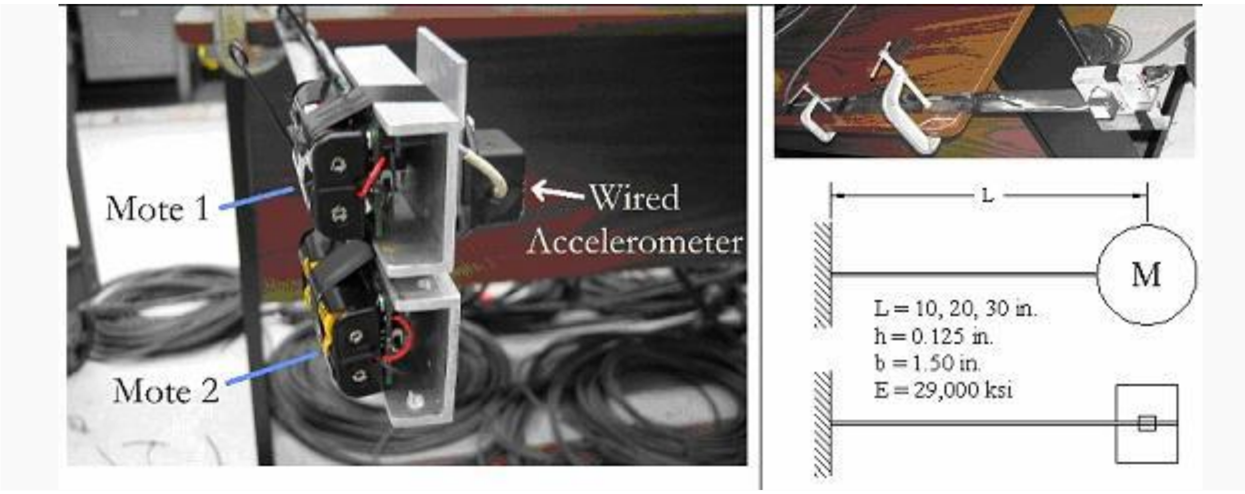


Figure 1-18 Cantilever test setup

To examine transmission issues, the wireless system is examined within the ATLSS test facility. The receiver computer is located within the NEES control room adjacent to the test floor. Four transmission locations are chosen to represent the different interference that may occur within the lab environment. The first location is within the control room. This setup minimizes any physical or electronic interference that could occur. The second location is directly outside of the control room on the lab floor. In this location the device is subjected to electronic as well as moderate physical interference. The third location is along the walkway. This location represents the most severe conditions. Significant physical interference (note all ATLSS walls are steel) and electronic interference exist. The final location is across the lab floor in the main region where NEES studies will be conducted. See Figure 1-19 for locations.

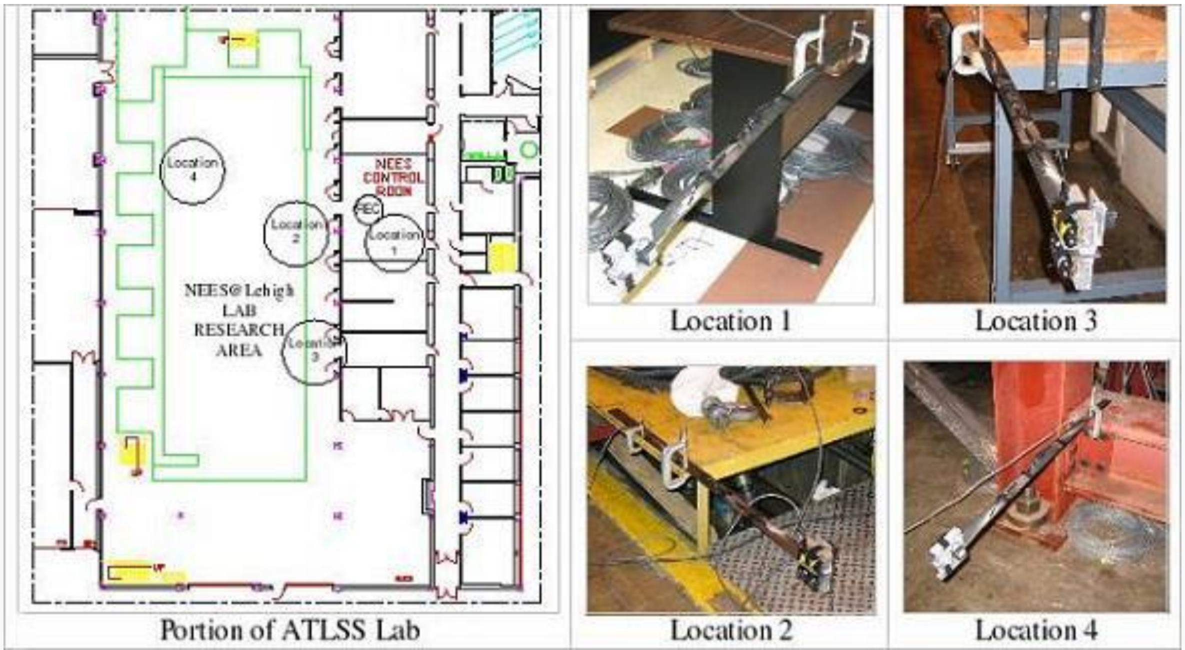


Figure 1-19 Sample locations

The relationship between packet lost rate and the transmission distances and the relative vibration frequency are shown in Table 1-14 and Table 1-15.

From the table, we conclude that (i) the distance in which the wireless node can effectively communicate without losing significant amount of sample data is limited. (ii) The sample data loss rate of the out-of-shelf system will be affected by the frequency and strength of the system vibration dramatically. (iii) For different sensor nodes, the pattern of the affection can be completely different. Since the pattern is not completely understood yet, we suggest that in order to establish a reliable test system, research on the affection patterns should be conducted such that the consistency of the system can be improved. To minimize data loss a multi-hop transmission and multiple sink configurations should be considered. To decrease data error at high frequencies the device characteristics need to be improved.

Table 1-14 Relationship between packet lost rate and the transmission distances

Test	Cantilever Length [in.]	Distance from Mote to Receiver / Location	Mote 1 Packet Loss [%]	Mote 2 Packet Loss [%]
1	30	8.5ft (Location 1)	3.7	4.55
2	20	8.5ft (Location 1)	0	2.63
3	10	8.5ft (Location 1)	3	1.21
4	30	25ft (Location 2)	1.4	0
5	20	25ft (Location 2)	0.95	0.95
6	10	25ft (Location 2)	44.4	1.48
7	10	45ft (Location 3)	34.3	98.1
8	10	45ft (Location 3)	29.8	-

9	20	50ft (Location 4)	2.1	52.17
10	30	50ft (Location 4)	7.8	3.64
11	10	50ft (Location 4)	33.7	87.36
12	10	50ft (Location 4)	35.8	-

To examine the accuracy of the system the measured frequencies are compared. The results obtained through wireless sensor #1 and wireless sensor #2 are compared with the reference result measured from the wired sensor output. The resulting values correlate well.

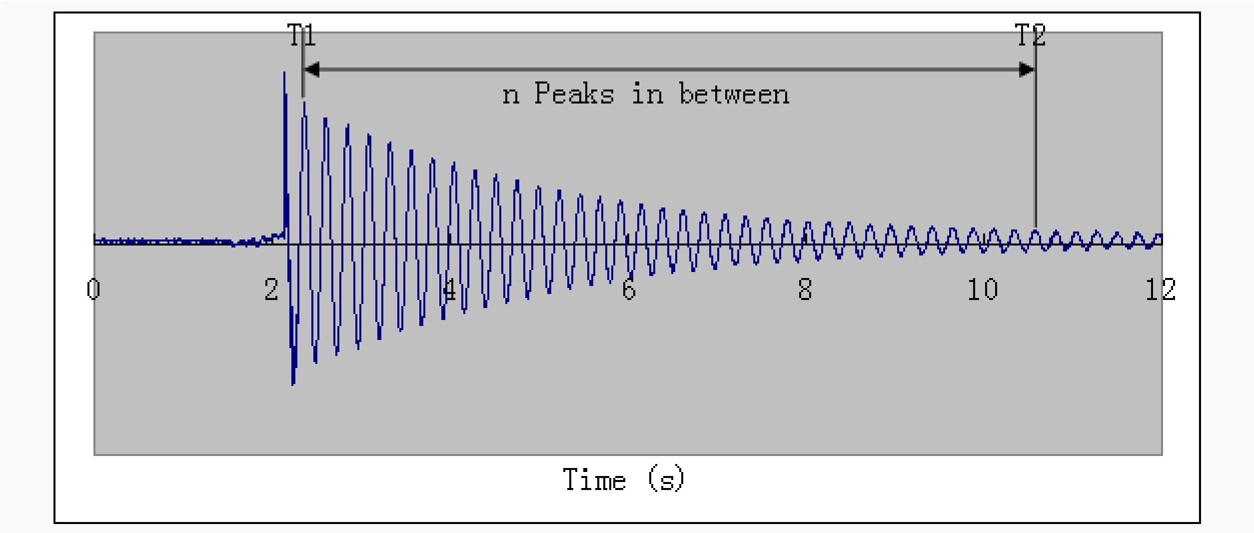


Figure 1-20 Vibration frequency calculation method

The vibration frequencies are calculated as following: (i) According to each set of samples, a vibration curve is generated (see Figure 1-20). (ii) The time value of the first peak point is recorded as T_1. (iii) The time value of another peak point that belongs to the same vibration sequence as T_1 is recorded as T_2. (iv) The number of peaks between T_1 and T_2 are counted as n (v) The frequency value under this condition can be calculated as $f = \frac{n+1}{T_2 - T_1}$. In most cases 34 consecutive peaks are measured. In cases where data loss occurs a smaller number of cycles are used to compute the measured frequency.

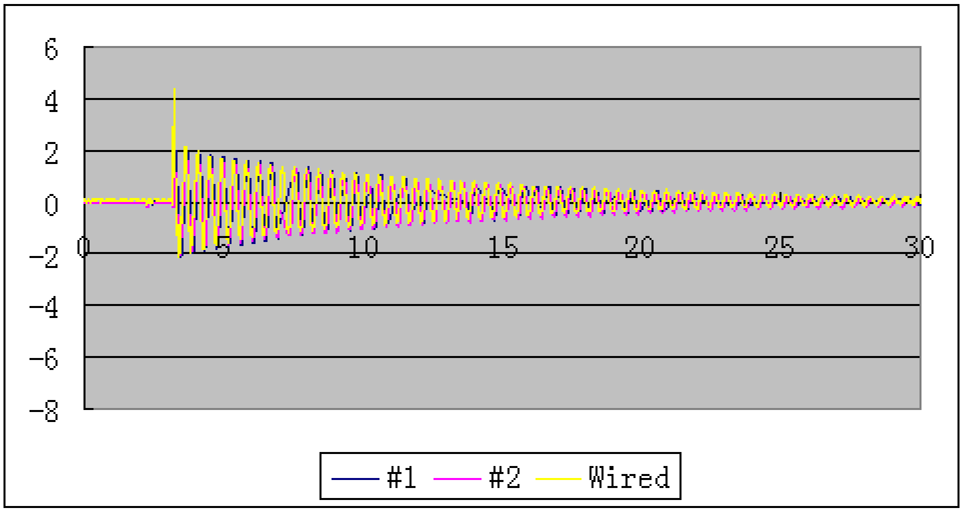
Table 1-15 Measured frequency response

Test	Wired Device	Mote 1		Mote 2	
	Frequency(reference)	Frequency	Error	Frequency	Error
1	N/A	9.406	N/A	9.390	N/A
2	4.11	4.252	-3.29%	4.252	-3.3%
3	N/A	2.271	N/A	2.267	N/A
4	12.38	12.063	2.60%	11.913	3.9%
5	4.31	4.344	-0.78%	4.344	-0.8%
6	2.33	2.312	0.60%	2.302	1.0%
7	2.31	2.344	-1.27%	N/A	100%

8	2.32	2.327	-0.26%	2.327	-0.3%
9	4.39	4.394	-0.13%	4.425	-0.8%
10	11.64	11.711	-0.57%	11.377	2.4%
11	2.32	2.275	1.90%	N/A	100%
12	2.29	2.275	0.73%	2.275	0.7%

The 12 tests results of the wired measurement system and the #1 and #2 of wireless sensor nodes are shown in Table 1-15**.** The results indicate that if the wireless transmission is not affected the error will be less than 4%.

Several data records are shown in the following figures to depict the process of the experiments. Since the MEMs measurement system and the wired sensing system do not share the same timing reference, there is a constant time lag need to be removed from the two systems. Moreover, during the experiments, we start the two systems by clicking the buttons at roughly the same time, which provides another random time delay difference between the two systems. The following figures present the measured wired and wireless data. The data is shifted to in time to align the data. The wireless data lags the wired data by 0.1 to 30 seconds.



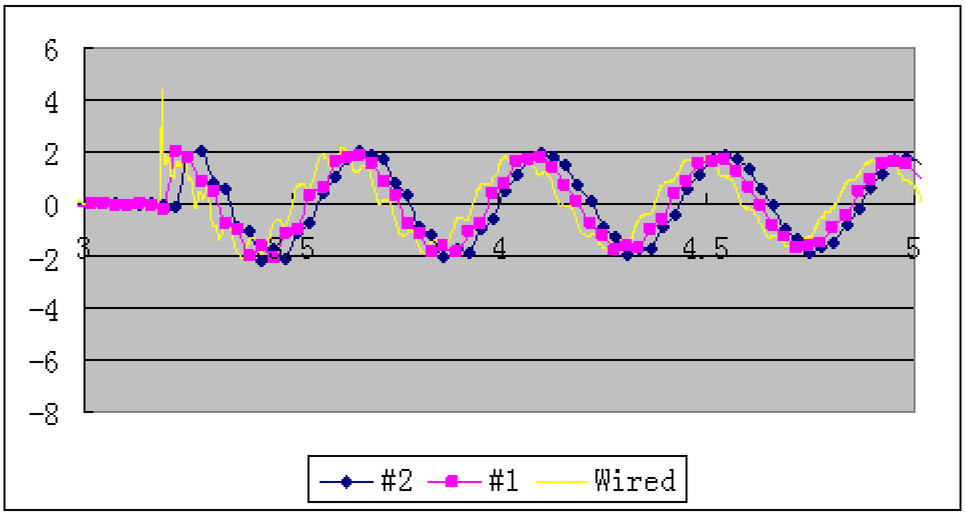


Figure 1-21 Acceleration (g's) vs. time for cantilever length of 10 in. at location 2 (a) Entire vibration curve wired result shift left for 0.77s (b) magnified view

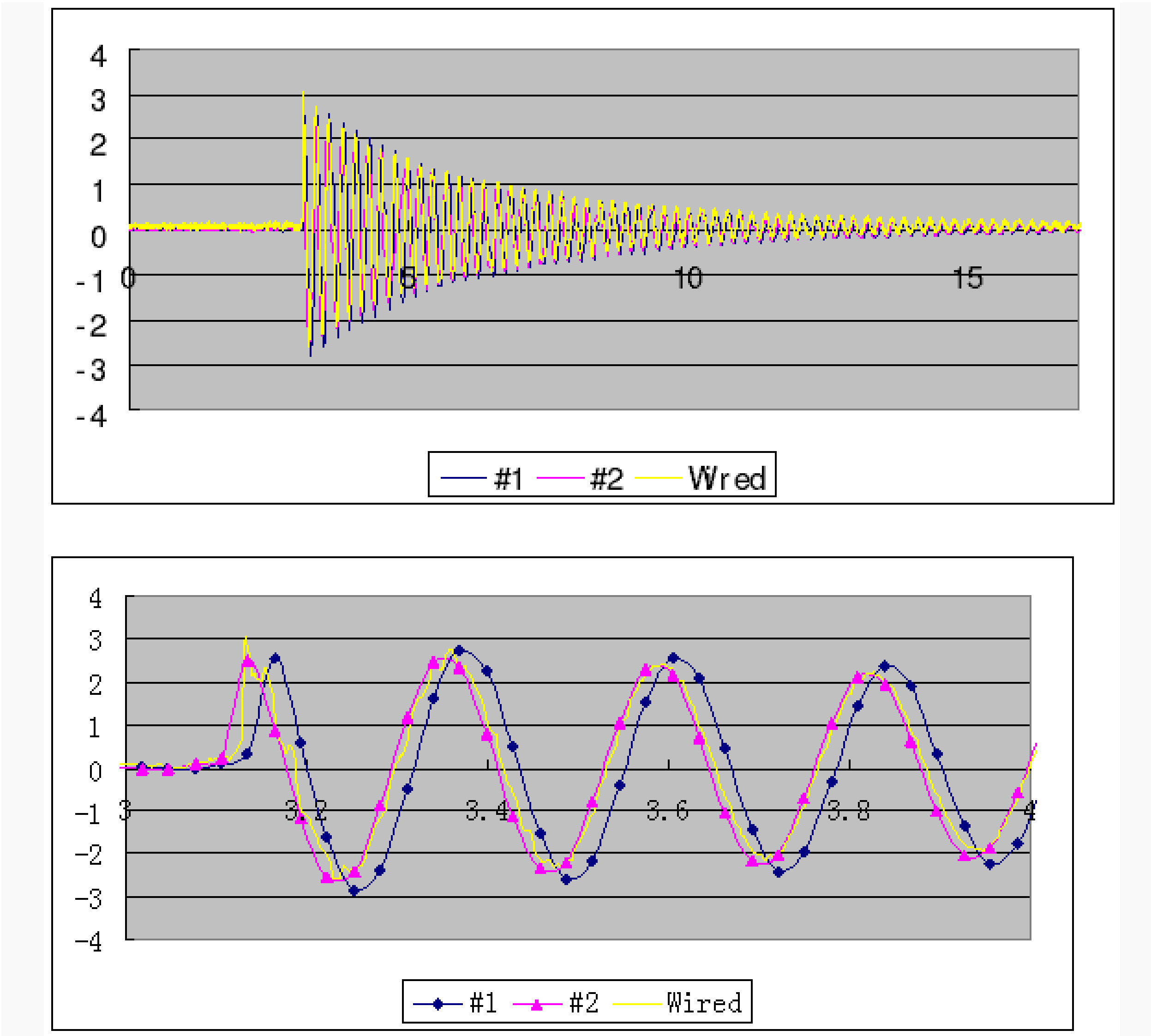


Figure 1-22 Acceleration (g's) vs. time for cantilever length of 20 in. at location 2 (a) Entire vibration curve wired result shift left for 0.59s (b) magnified view

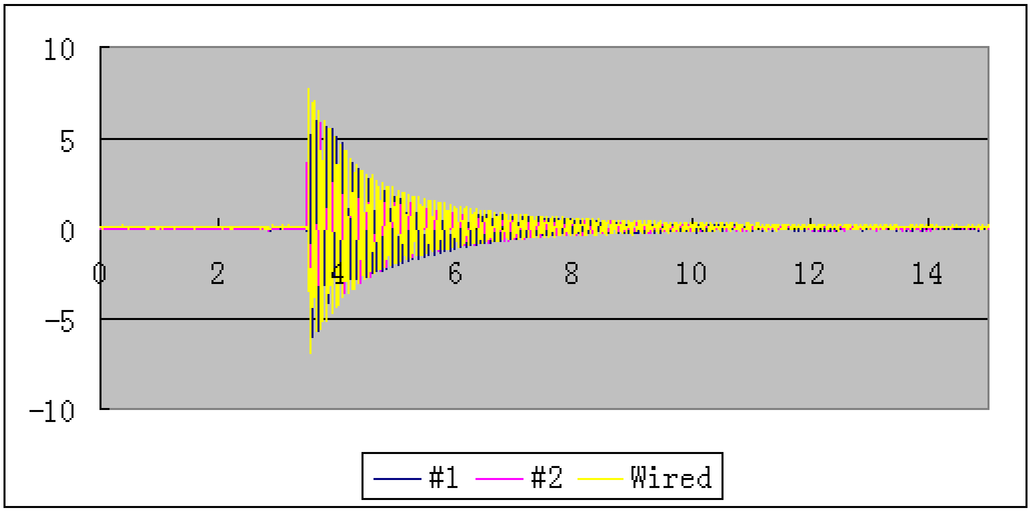


Figure 1-23 Acceleration (g's) vs. time for cantilever length of 30 in. at location 2. Entire vibration curve wired result shift left for 1.1s.

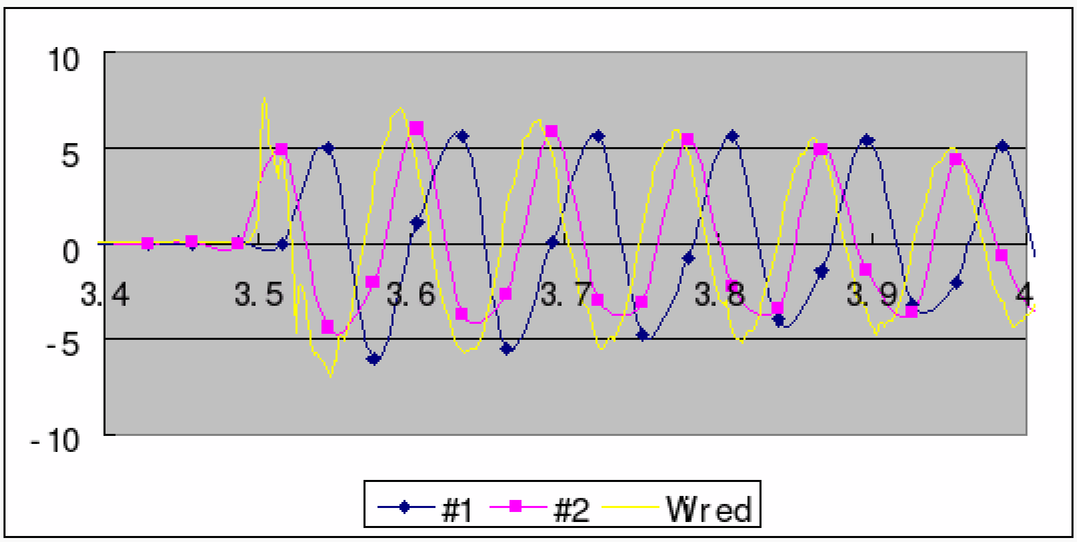


Figure 1-24 illustrates the condition in which significant packet losses occur. In (a), the curve reconstructed from #1 sensor's data is a 30% packet loss occurs while sensor #2 has a loss greater than 90%. Notice that in the zoomed-in view, the packet losses happens without any peak points lost.

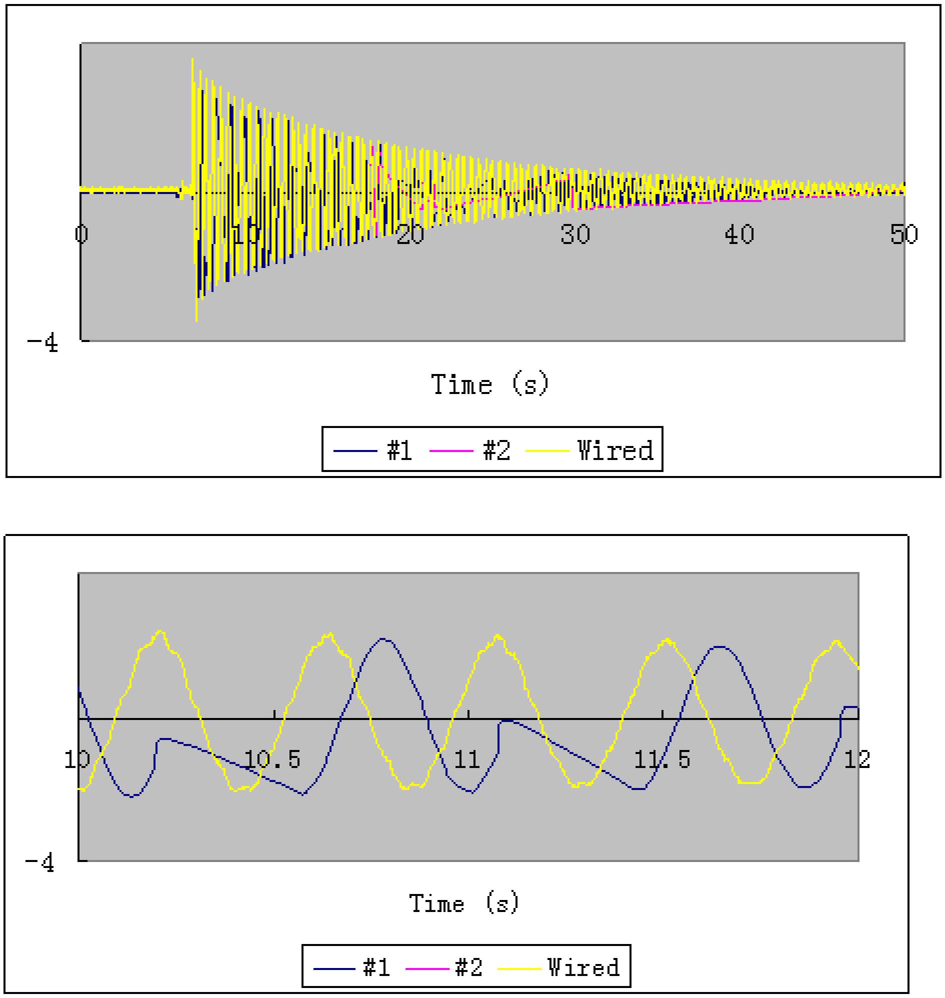


Figure 1-25 Acceleration (g's) vs. time for cantilever length of 30 in. at location 3 (a) An entire vibration with wired result shift left for 11s (b) A zoomed-in view

Expansion Costs

Future expansion of the wireless system can be accomplished with the purchase of additional motes. The cost for the system as of September 2004 is provided below:

- MOTE-KIT 5040 Quantity 1 $1,995

Professional developer's kit (4xMPR500CA, 4xMPR400CB, 3xMTS310CA, 2xMDA500CA, and 1xMIB500CA). Includes four MICA2DOT processor/radio boards (MPR500CA), four MICA2 processor/radio boards (MPR400CB), three MTS310CA sensor boards, two MDA500CA proto/data acquisition boards, and one PC interface board (MIB500CA).

The cost of an individual mote and sensor board is presented below.

- MICA2 Mote Quantity 1 $150

- MICA2DOT Mote Quantity 1 $115
- MICAz Mote Quantity 1 $150
- MTS310 Multi-sensor board Quantity 1 $120

The MEMs wireless sensors have been integrated into the NEES site. The devices are usable at close distances under limited ranges. Limitations on transmission distance, data loss and accuracy however need to be resolved for wide spread use can be achieved. This work is continuing under Professor Liang Cheng.

Prof. Liang Cheng at Lehigh University is developing various protocols that can improve the performance of wireless sensors in the actual measurement systems. The major areas include:

- Multi-hop ad-hoc data transmission in wireless networks.
- Reliable data transmission mechanisms to recover the packet loss in transmission.
- Power control mechanisms to enlarge the lifetime of wireless sensors.
- High accuracy and low cost multi-hop time synchronization protocols.
- Low cost node positioning system that enables the self-positioning of sensors in the network.

In 2004 XBow released a new mote called MICAz that take advantages of the IEEE 802.15.4 protocol. It uses the 2.4GHz frequency to conduct up to 250 Kbps communication. This dramatically increase of communication bandwidth allows a larger measurement network to be constructed and maintained. With this capability, a single hop test system with one sink and 10-20 wireless sensors is achievable. We are also confident that more complicated applications can be enabled by this progress.

1.8.3 Piezoelectric Strain Sensors

Piezoelectric paint belongs to piezoelectric composite materials. Piezoelectric composites are designed to combine the superiority of polymers and ceramics. Toughness, flexibility, lightness, and ease of processing are typical features of polymers; however, their piezoelectric activity is usually low. On the other hand, ceramics have a strong piezoelectric response, but they are heavy, brittle, and rigid. The stiffness and brittleness of pure piezoelectric ceramics limit the application of these materials as sensing elements, especially for fiber-reinforced-polymer (FRP) composite structures due to their flexibility and large strain at failure. The combination of polymer and ferroelectric ceramics to form piezoelectric composites offers the unique blending of the high piezoelectric properties of ferroelectric ceramics and the mechanical flexibility and formability of organic synthetic polymers. Piezoelectric composites can be classified according to the connectivity of piezoelectric ceramics and matrix phases; the piezoelectric paint under consideration has a 0-3 connectivity pattern. The "0-3" means that the ceramic particles are randomly dispersed in a polymer matrix. Conceivably, 0-3 composites can be more easily fabricated into complex shapes than other forms of composites. To overcome the technical hurdles associated with conventional fabrication methods, a novel *in-situ* fabrication technique for piezoelectric paint sensor has been developed at Lehigh University so that large areas of piezoelectric paint can be directly applied onto the host structure in an efficient manner.

The advantages of the piezoelectric paint for use as a sensor in structural health monitoring applications include: (i) it is a self-powered sensor; for applications where power consumption is a significant constraint, this can be very valuable; (ii) with the proposed in-situ fabrication method, the piezoelectric paint is directly deposited onto structural surfaces and thus conforms to curved surfaces and adheres well to the host structure surface; (iii) by choosing appropriate polymer materials for the matrix phase, the properties of piezoelectric paints can be tuned to optimum for a particular application; for example, with proper polymer materials, the paint can be made flexible and tough which is necessary for the monitoring of FRP structures undergoing large deformation; (iv) the ease of processing of the piezoelectric paint can be utilized to form complex sensor patterns.

Characteristics of piezoelectric paint strain sensor that need to be kept in mind for use in NEES-related experiments are listed as follows:

- The sensor can only measure vibration dynamic strain, that is, it will NOT respond to static load!
- Presently, the sensor is used as a surfaced-mounted sensor on test structures.
- The paint is compliant to structural surfaces with curved shapes or complex geometry such as bridge cables.
- It is a self-powered sensor, does not need external excitation power.
- The sensor has a broad frequency bandwidth and it can measure ultrasonic signal which is useful for wave-propagation-based non-destructive evaluation.
- With specially formulation for the paint composition, piezoelectric paint strain sensor can measure large strain on the order of 10%, for example, in FRP structures.
- The strain measurement is based on "1-3" mode of piezoelectric materials. The measured voltage signal reflects the total amount of the strains in the sensor plane. The sensor cannot distinguish between x and y direction strains and therefore it can only be used for measuring one-direction strain.
- The sensor output is AC voltage signal and is compatible with any data acquisition system capable of receiving AC voltage signals. Therefore, synchronization should not be an issue for the piezoelectric paint sensor. However, for low-impedance input, a charge amplifier needs to be used before the signal is fed into the data acquisition system.
- Although still under development, it is worth noting that a special technique has been proposed to use the piezoelectric paint sensor for surface crack detection in structural locations with complex geometry such as weld toes. This is especially important for real-time large-scale seismic testing, in

which there is a lack of effective instrumentation tools and test specimens can only be closely inspected before and after the test.

- It should always be kept in mind that piezoelectric paint strain sensors are developed primarily for challenging applications such as strain measurement in structural components with complex geometry or large deformation. For ordinary applications, use of metal foil strain gage is encouraged.

The effectiveness of piezoelectric paint sensors for dynamic strain measurement was examined using a test setup shown in Figure 1-27. A steel beam is mounted as a cantilever beam to a heavy steel block. The steel beam measures 33.5 inch x 2 inch x 0.25 inch. Piezoelectric paint sensors were applied on the top side of the beam (see Figure 1-27) along with metal foil resistive strain gages for comparative study. A vibration exciter (from MB Dynamic Modal 50A) was used to excite harmonic vibration of the beam. Two test series were performed to verify and calibrate the performance of piezoelectric paint strain sensor: forced harmonic vibration test and free vibration test. The output from the piezoelectric paint sensor was measured as a voltage signal using a SigLab 20-42 digital signal analyzer. Charge amplifier was not used in the test because the output voltage from the piezoelectric paint sensor was strong enough to drive the dynamic signal analyzer which has very high input impedance. The cable connecting the piezoelectric paint sensor to the dynamic signal analyzer was electrically shielded and has a length of 64 inches. The sampling frequency for the vibration tests was 2560 Hz. The response of the piezoelectric paint sensor under harmonic load (forcing frequency = 100 Hz) is shown in Figure 1-28. In Figure 1-29, the sensor response to free vibration of the steel cantilever beam is shown. As shown in these figures below, dashed lines are the responses of the metal foil strain gages for a side-by-side comparison. The effectiveness of piezoelectric paint sensors in measuring dynamic strains was demonstrated. The piezoelectric paint sensor was observed to have a good repeatability in its output signal when subjected to similar dynamic loading. The current specifications for piezoelectric paint sensor obtained from vibration tests are summarized in Table 1-16.

It should be noted that the development of piezoelectric paint sensor is still in its early stage and as research goes on its performance will be enhanced with improved paint composition formulation. Therefore, for each proposed application, arrangements can made between the project investigator and Lehigh University (contact person: Dr. Yunfeng Zhang, yuz8@lehigh.edu) to develop a special paint composition, sensor sensitivity calibration, mounting method, data acquisition and processing for its optimal performance in the application in question. For more detailed information on piezoelectric paint sensor, readers are referred to two recent publications (Zhang 2003, 2004).

Table 1-16 Summary of Current Piezoelectric Paint Strain Sensor Specifications

Item	Specification
Strain Measurement	> 8%

Range	
Sensitivity	843.3ue/Volt (calibrated at 100Hz)
Frequency Range	1 Hz to 200 kHz
Sampling Rate	No limit
Signal Conditioning Requirement	high input impedance (>1 M ohm) is required for data acquisition, otherwise a charge amplifier is needed to connect the sensor to data acquisition input channel
Sensor Output	AC voltage signal

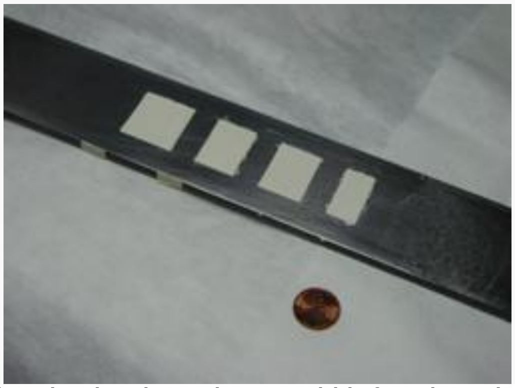


Figure 1-26 Close-up view of piezoelectric paint strain sensor (a) before electrode and wiring is applied; (b) after electroding and wiring

Figure 1-27 Sensor implementation test setup for piezoelectric paint strain sensor

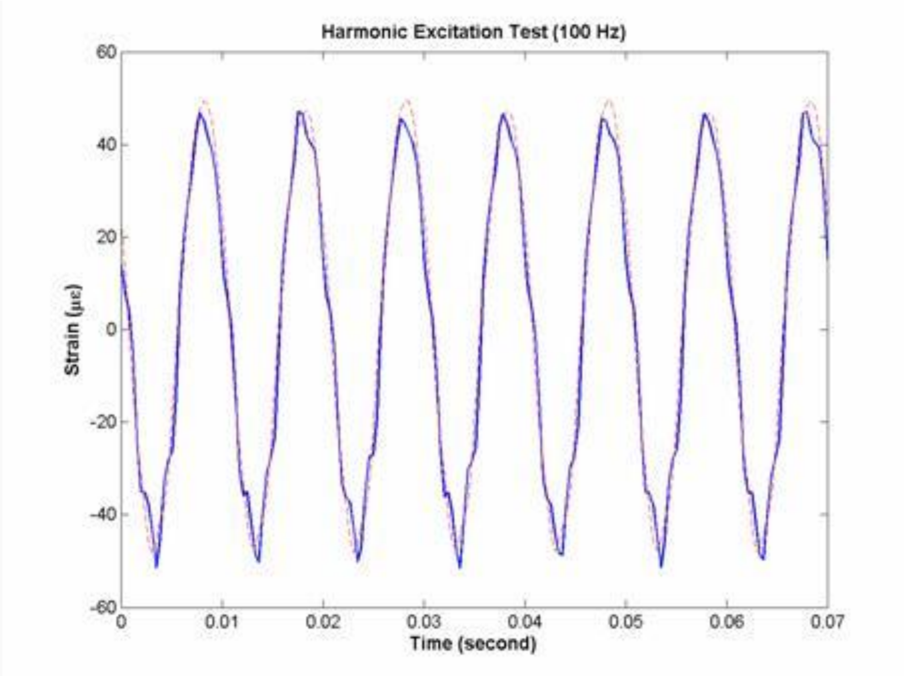


Figure 1-28 Harmonic vibration response data (solid line = piezoelectric paint strain sensor, red dashed line = metal foil resistive strain gage)

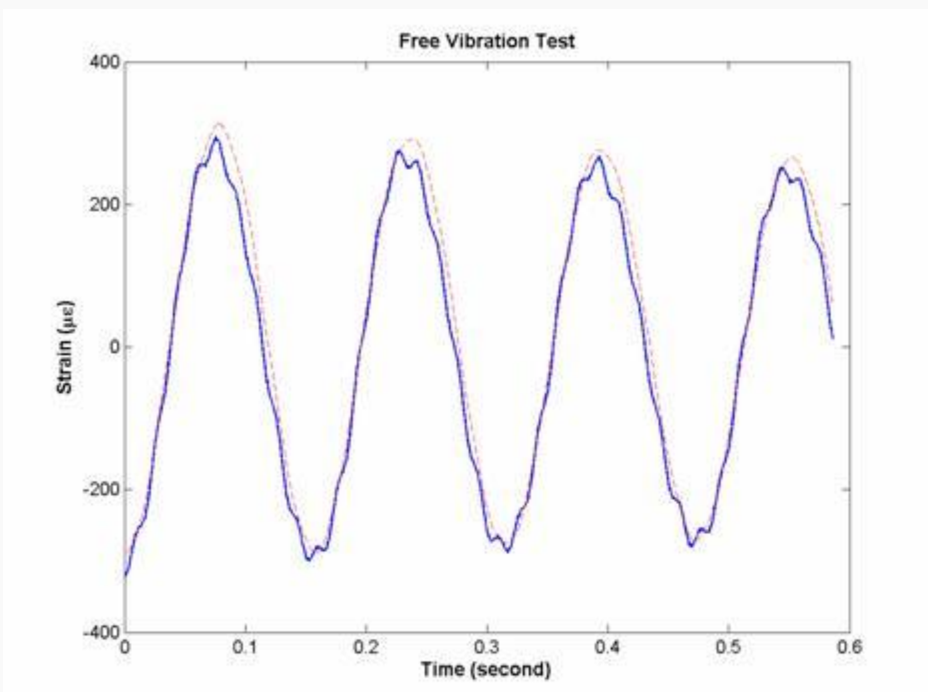


Figure 1-29 Free vibration response data (solid line = piezoelectric paint strain sensor, red dashed line = metal foil resistive strain gage)

1.9 ATLSS Facility Details

1.9.1 Reaction Wall Capacities

Concrete Strength 7,500 psi floor and walls

Table 1-17 Multi-directional reaction wall design capacity

Wall Height	Design Capacity (@base of wall)
(6.09m) 20ft	(2034 kN m) 1500ft-kips
(9.14m) 30ft	(3389 kN m) 2500ft-kips
(12.19m) 40ft	(6100 kN m) 4500ft-kips
(15.24m) 50ft	(6100 kN m) 4500ft-kips

1.9.2 Anchor Assembly Capacities Floor and Wall

Shear (2224 kN) 500 kips

Tension (1334 kN) 300 kips

1.9.3 Other Available Equipment

Table 1-18 ATLSS Existing Major Equipment

Equipment	Year Acquired
Multi-Directional Reaction Wall System	
15.2m to 6.1m tall L-shaped reaction wall	1989
30.5m x 12.2m strong test floor	1989
Hydraulic Equipment	
20.7 MPa (3000psi) Hydraulic power system with 2270 liters/min	1988,1992**
Central hydraulic distribution system	1988,1992**
6-Vickers Service hydraulic manifolds (1500 liters/min)	n/a
Hydraulic Loading Equipment	
Sactec 2670 kN universal test machine	1992
MTS 245 kN fatigue test machine	1992
Hydraulic Actuators	
3-2680kN Hanna, +-750 mm stroke, 20mm/sec max. velocity*	1997
2-2050kN Hanna, +-480 mm stroke, 25mm/sec max. velocity*	1988
4-1500kN Hanna, +-480 mm stroke, 35mm/sec max. velocity*	1988
2-150kN Hanna, +-125 mm stroke, 35mm/sec max. velocity*	1988
2-1050kN Hanna +-125 mm stroke, 50mm/sec max. velocity*	1988
2-607kN Hanna, +-300 mm stroke, 80mm/sec max. velocity*	1988
8-580kN Hanna, +-125 mm stroke, 60mm/sec max. velocity*	1992
2-1000kN Hanna, +-125 mm stroke, 35mm/sec max. velocity*	1992

2-130kN T/J, +-125 mm stroke, 320mm/sec max. velocity*	1995, 1998
Controllers	
4-Vickers controller systems	1994
1-Portable Vickers Controller System	1994
2-MTS 458 Controllers	1985
Data Acquisition Systems	
1-OPTIM Megadeck 2300 (256 channels)	1987
2-Keithley Instruments DAS1802HC (192 channels)	1995, 2001
200 channels of signal conditioners	1986, 2001
Overhead Crane Systems	
180 kN radio controlled	1989
90 kN radio controlled	1989
Special Equipment	
V-Notch Charpy testing machine	1992
SEM and Light Microscopy equipment	1992
Instrumentation: Sensors	
Displacement transducers: ranging from +/-6.4mm (LVDTs) to 1524mm (linear potentiometers). All transducers are calibrated to within +/-1% accuracy, with the LVDTs calibrated to within +/- 0.1%	n/a
Inclinometers: ranging up to +/-20 degrees with 1% accuracy	n/a
Strain gages: 150ohms to 350ohms; signal condition enables various ranges of accuracy to be achieved	n/a
Load cells: each hydraulic actuator (noted above) is equipped with a load cell. All load cells are calibrated to within +/-0.1% accuracy	n/a

based on standard 150 liters/min servo-valve

**hydraulic system upgraded in 1992

1.9.4 Schematics of ATLSS Multi-directional Reaction Wall and Strong Floor

Shown below are schematics of the multi-directional reaction wall and strong floor, which includes dimensions of the wall heights and length, and locations of the tie down points.

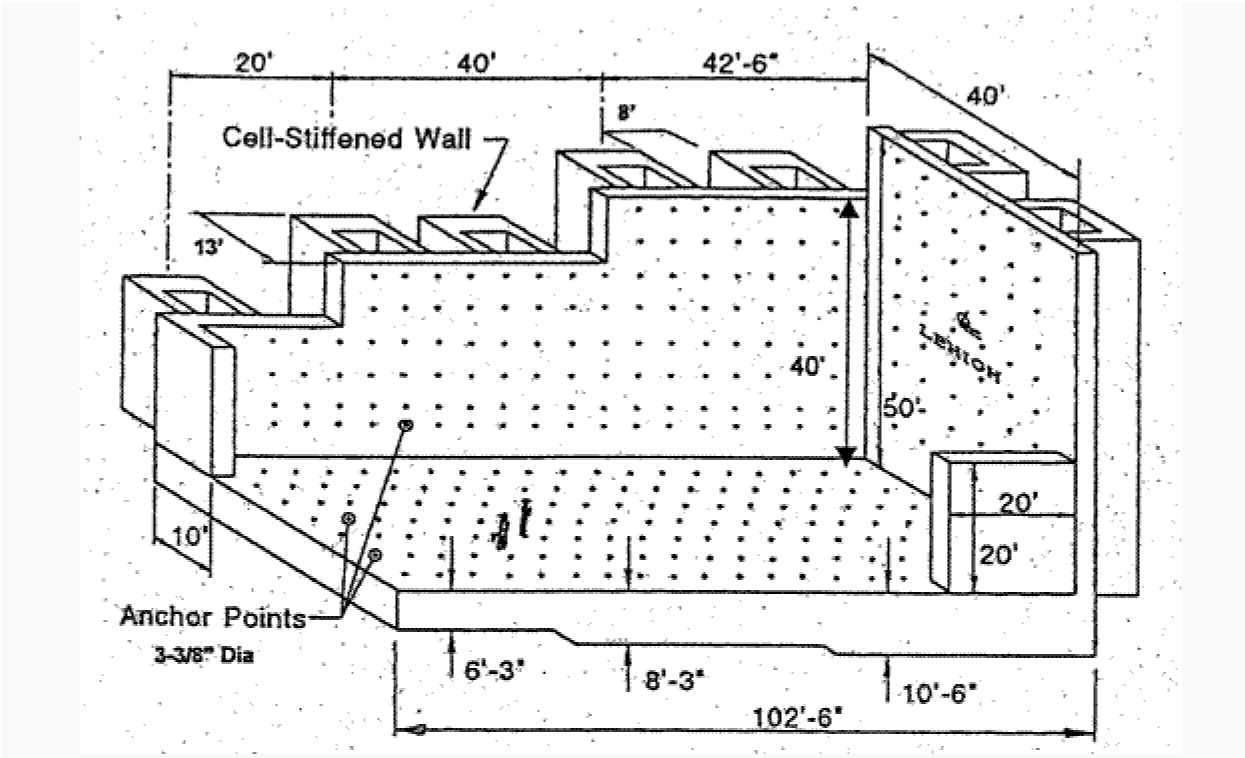


Figure 1-30 Multi-directional reaction wall and strong floor - isometric view

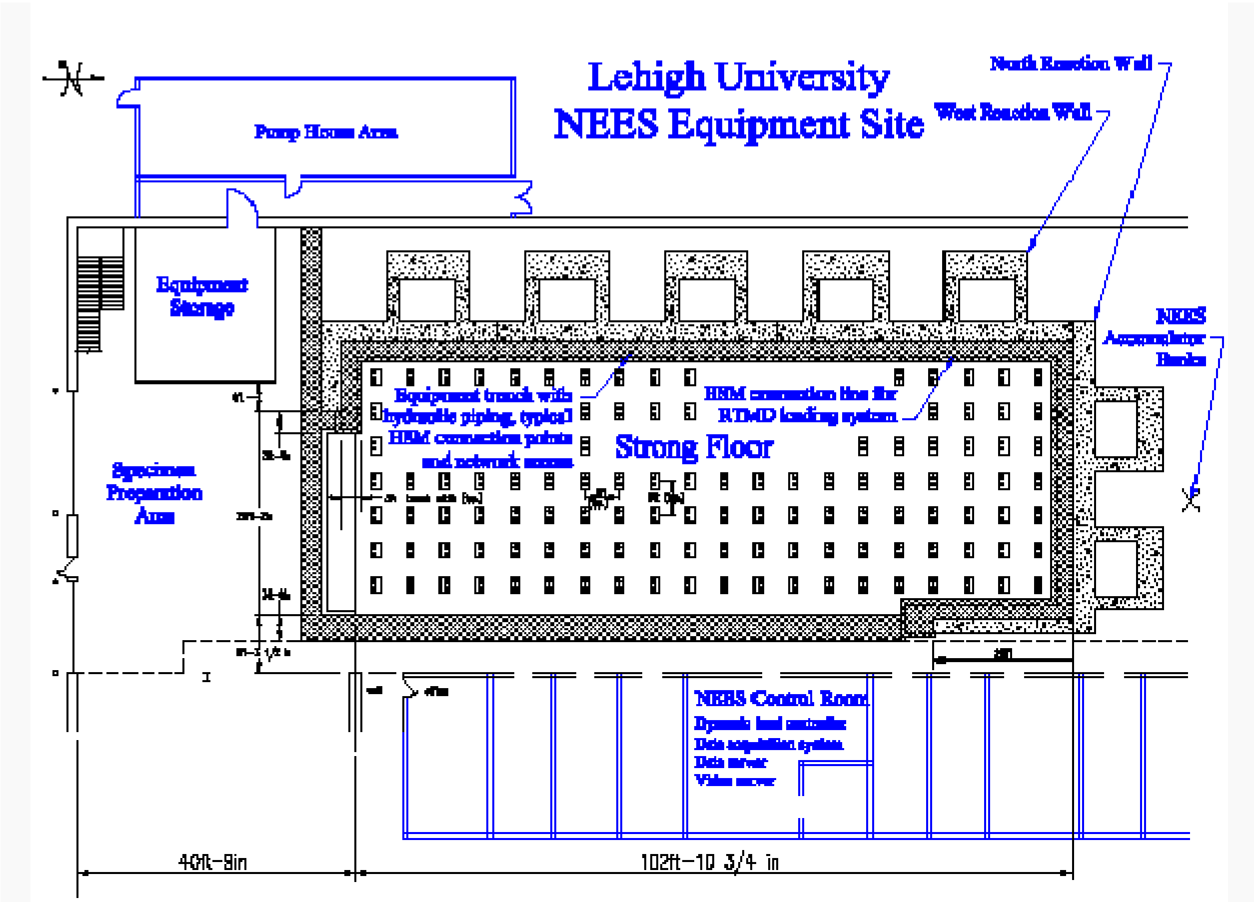


Figure 1-31 Floor Plan of RTMD Facility

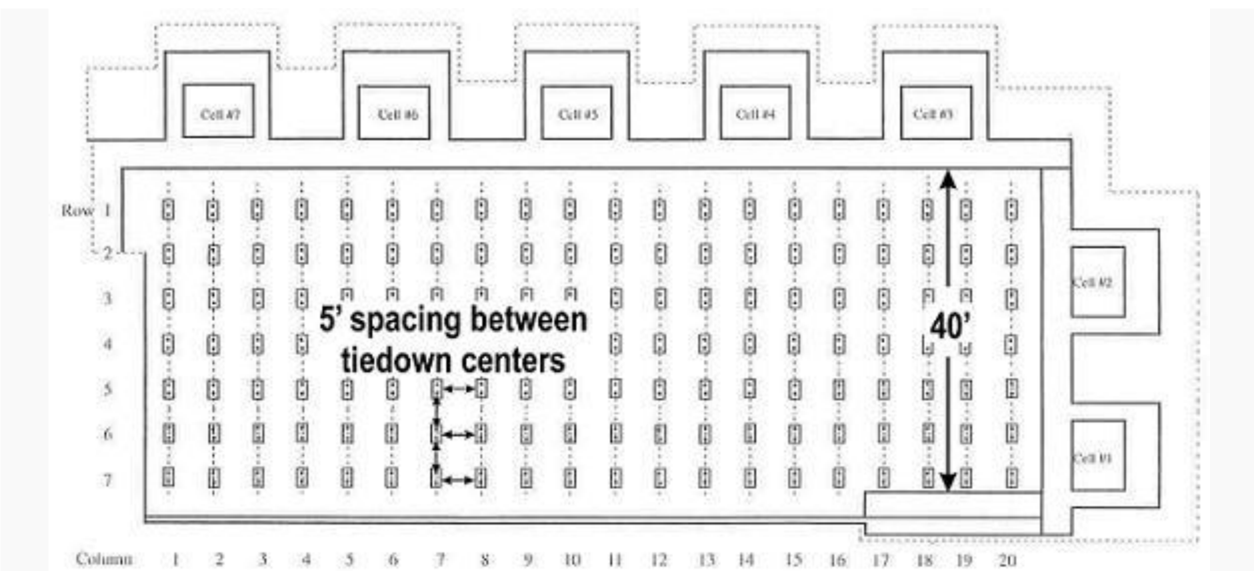


Figure 1-32 Floor Plan of Strong Floor

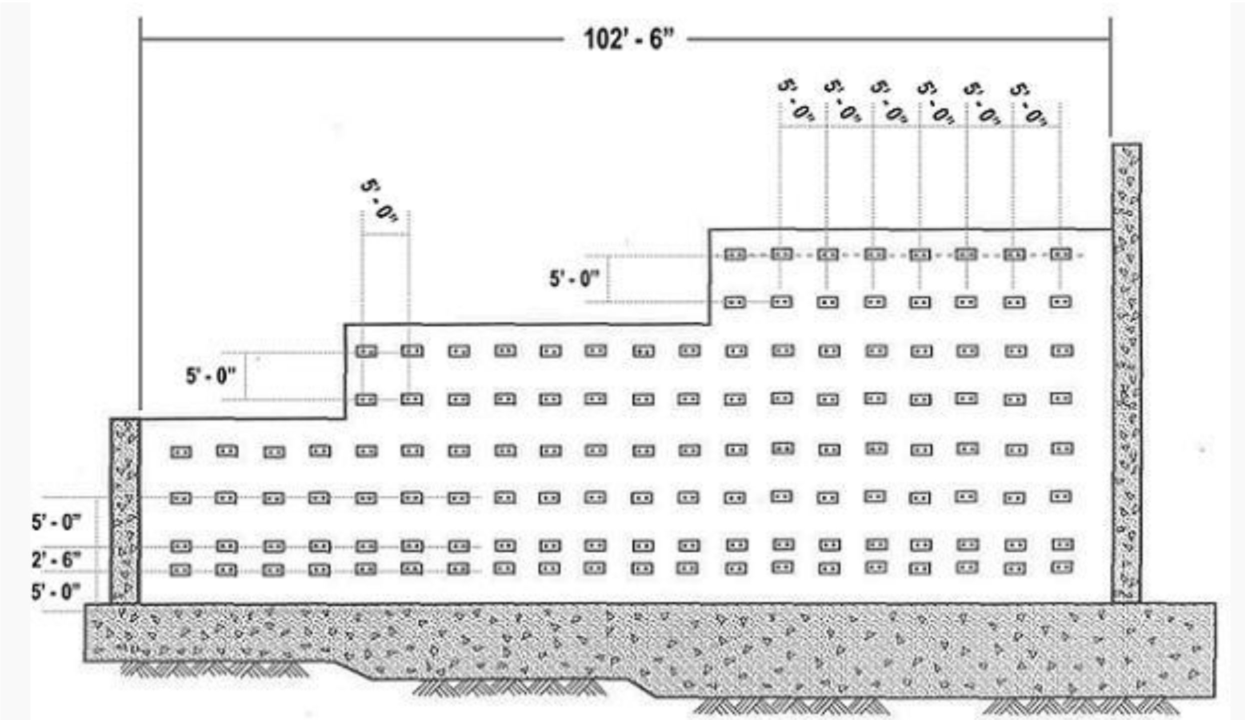


Figure 1-33 ATLSS West Reaction Wall Elevation

1.10 References

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2 Test Methods & Data Analysis

This chapter describes the test methods that are available at the RTMD earthquake simulation facility. These methods include: (1) quasi-static testing; (2) conventional pseudo-dynamic (PSD) testing; (3) real-time PSD testing; (4) real-time PSD hybrid testing; (5) real-time effective force testing; and (6) distributed hybrid PSD testing. The quasi-static method of testing is well understood, and is not discussed in this Manual. Aspects and an overview of the remaining test methods are given.

2.1 Dynamics of a Structure Subjected to Earthquake Motions

Figure 2-1 shows a simple example of a planar, which is a four-story shear building, structure subjected to an earthquake. The foundation of the four-story shear building is subjected to the ground acceleration history, $\ddot{x}_g(t)$. The equations of motion (Chopra, 2001) can be shown to be equal to:

$$Ma^t(t) + Cv(t) + Kd(t) = 0$$

(Equation 2-1)

where M, C, K, $a^t(t)$, $v(t)$, and $d(t)$ are the mass matrix, viscous damping matrix, stiffness matrix, total acceleration vector, relative velocity (to the foundation) vector, and relative displacement (to the foundation) vector. The total acceleration, $a^t(t)$, is related to the acceleration relative to the support, $a(t)$, and ground acceleration, $\ddot{x}_g(t)$.

$$a^t(t) = a(t) + i\ddot{x}_g(t)$$

(Equation 2-2)

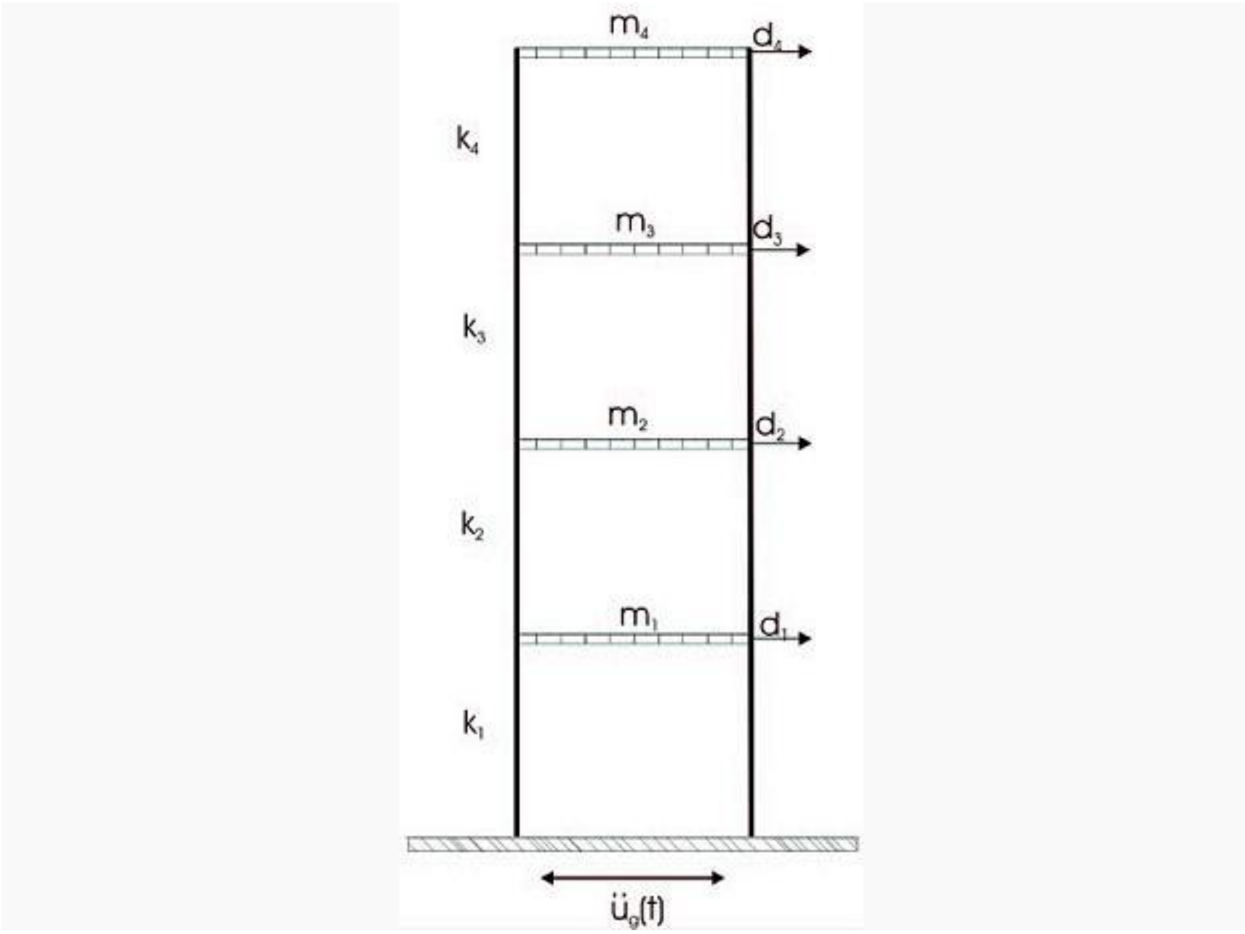

Figure 2-1 Shear building subjected to earthquake ground accelerations

In (Equation **2-2**), i is the influence vector representing the displacements of the mass of the structure resulting from the static application of a unit ground displacement.

Upon substituting (Equation 2-2) into (Equation 2-1):

$$Ma(t) + Cv(t) + Kd(t) = -Mi\ddot{x}_g(t)$$

(Equation 2-3)

(Equation **2-3**) implies that the structure can be analyzed as a structure that is supported on a fixed foundation and subjected to a effective force vector, $P_{eff}(t) = -Mi\ddot{x}_g(t)$ .If the restoring forces, represented by the third term on the right hand side of (Equation **2-3**), are replaced by a more general restoring force vector, $r(t)$, (which can include non-linearities) the equations of motion become:

$$Ma(t) + Cv(t) + r(t) = P_{eff}(t)$$

(Equation 2-4)

(Equation 2-4) is the basic set of equations of motion that the testing methods at the RTMD earthquake simulation facility are based upon. More complicated structures can be tested at the RTMD earthquake simulation facility than the one shown in Figure 2-1, including structures with rate-dependent components (e.g., semi-active MR dampers), multi-directional earthquake loading and geometric and material non-linearities.

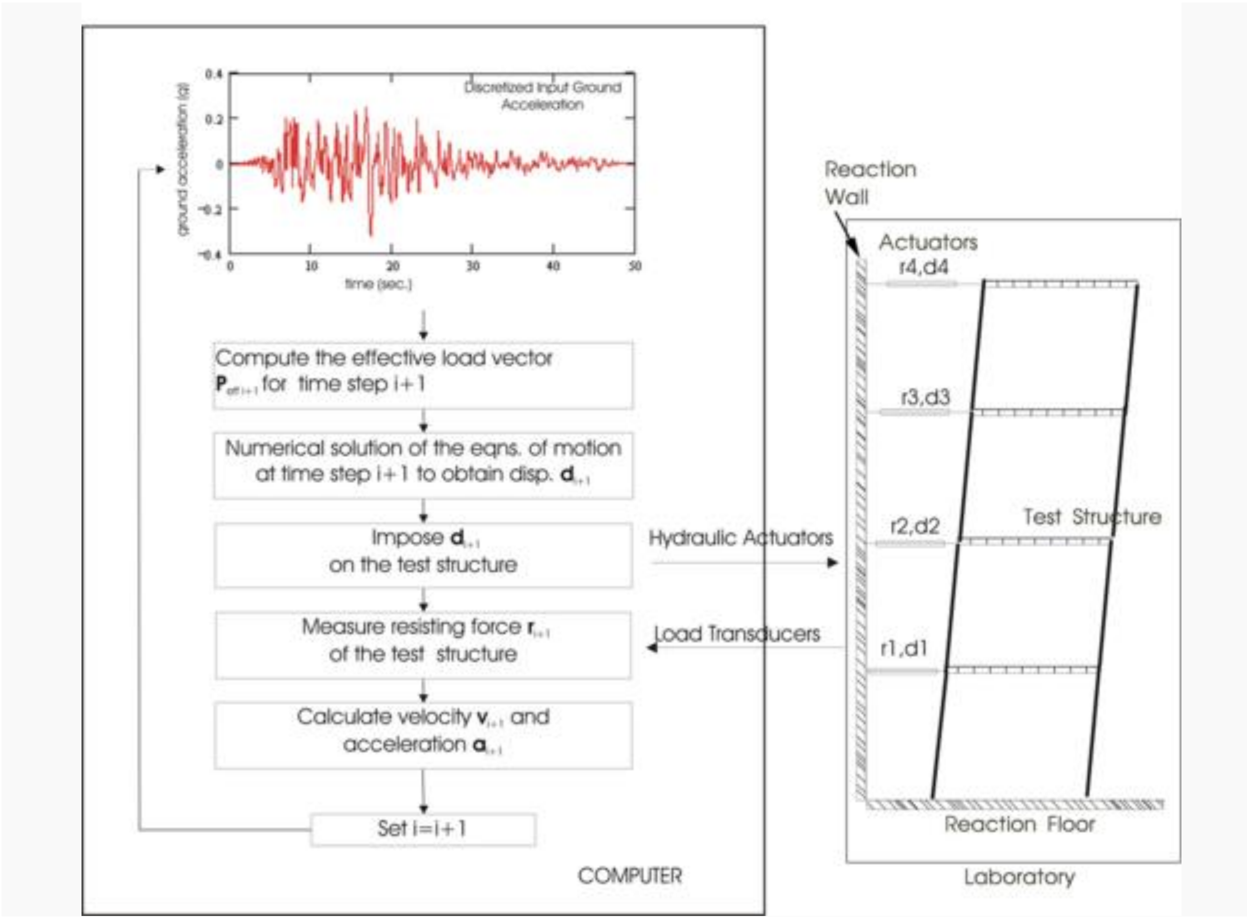

Figure 2-2 Conventional PSD test method scheme

2.2 PSD Test Method

The PSD test method overcomes the limitations of size and mass of a test structure present in a shaking table test by using the equipment similar to that for performing quasi-static testing (real-time PSD testing would however require dynamic actuators and a control system).

In the PSD method of testing, the equations of motion for the structure (i.e., (Equation 2-4)) are solved using either an explicit or implicit direct step-by-step integration method to obtain the response of the structure. The mass matrix M , viscous damping matrix C , and the excitation history $P_{eff}(t)$ are numerically specified. The step-by-step numerical integration is performed in conjunction with measured restoring forces $r(t)$ from a test structure. Depending on the rate the test structure is being loaded, PSD testing can be divided into two categories: (1) conventional PSD test method; and (2) real-time PSD test method. Structures with load-rate sensitive components are not likely able to have their response to seismic loading accurately captured by the conventional PSD test method, and should be tested using the real-time PSD test method.

Conventional PSD testing methods (Mahin and Shing, 1985) are based on a number of different integration schemes (e.g., Newark-Beta method), where the rate of loading is not of major concern. As shown in Figure 2-2, an explicit numerical integration scheme could be used to compute the displacement d_{i+1} for a time step, and the restoring force r_{i+1} measured resulting from the imposed displacement d_{i+1} to the test specimen. This is followed by the calculation of the corresponding velocity v_{i+1} and acceleration a_{i+1} based on the measured restoring force r_{i+1}. The process is repeated for each subsequent time step.

The RTMD earthquake simulation facility uses an implicit numerical integration scheme for conventional PSD testing called the Hilber α-method (Hilber et al., 1977). The method is unconditionally stable for linear structures. The details of the method are given below under Real-Time PSD Test Method. The rate of testing is controlled by a ramp generator which imposes command displacements to the test specimen over each time step. The user selects the duration of the ramp to suit the needs of the test.

The real-time PSD testing method implemented at the RTMD earthquake simulation facility is based on the procedures developed by Shing et al. (2002). As noted above, the integration procedure is based on the α-method. The algorithm for the real-time PSD testing method is illustrated in Figure 2-3. In the algorithm, a predictor displacement $\hat{d}_{i+1}$ is first computed, which is a function of the displacement d_i, velocity v_i, acceleration a_i, restoring force r_i, and the effective load $P_{eff}(t)$ from the prior time step i in addition to the effective load $P_{eff}(t)$ from the current time step $i+1$. A correction to achieve the correct displacement is then performed through a series of n substeps.

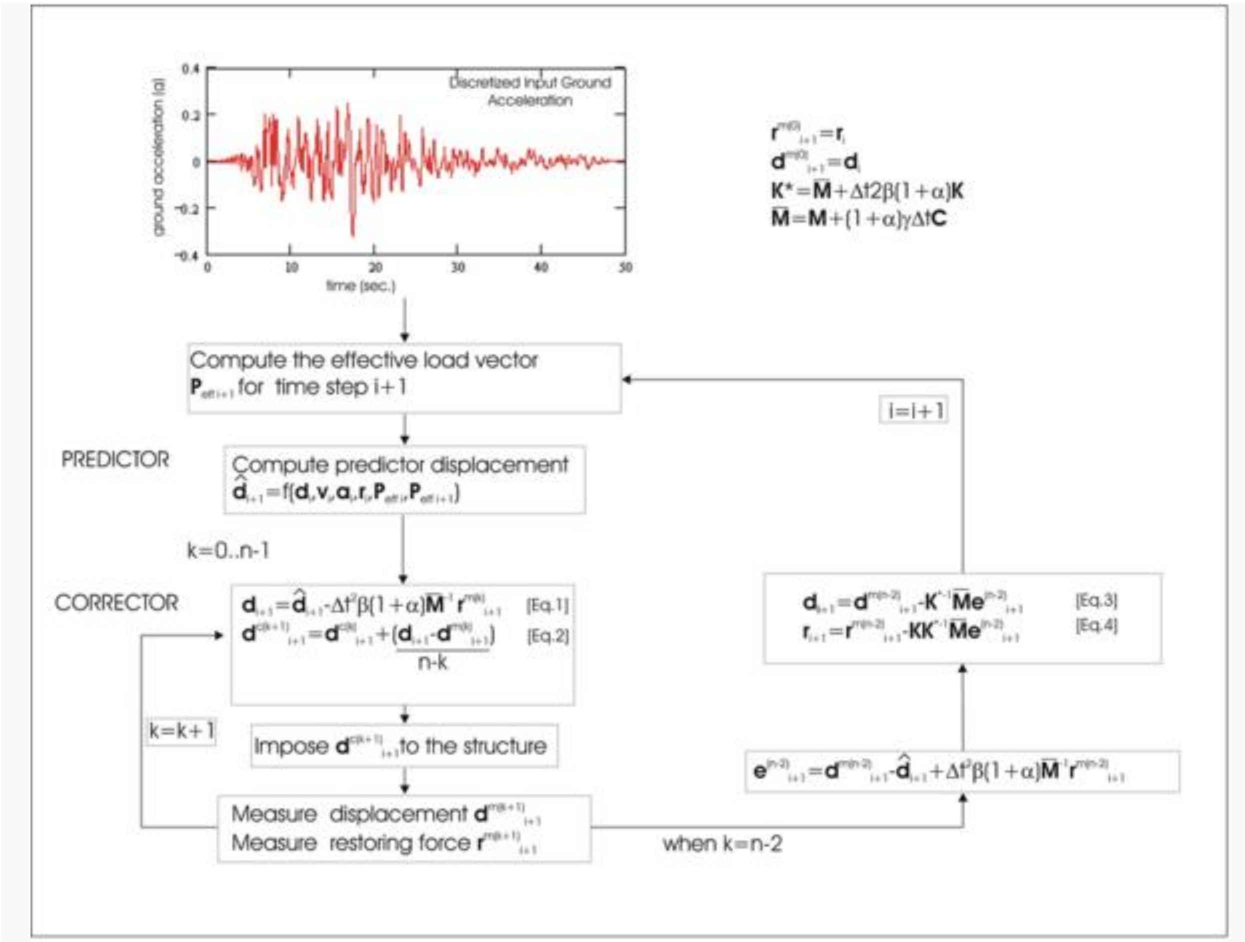

Figure 2-3 Real-Time PSD test method algorithm based on the α-method with a fixed number of correction sub steps

During the correction phase, in substep k the displacement d_{i+1} is calculated using the predictor displacement $\hat{d}_{i+1}$ and the measured restoring force $r_{i+1}^{m(k)}$ (Equation (1) in Figure 2-3). The corrected command displacement $d_{i+1}^{c(k)}$ is then determined using Equation (2) shown in Figure 2-3. For the first substep, where $k=0$, the measured restoring forces at the beginning of the time step, r_i^m, are used for $r_{i+1}^{m(k=0)}$. The quantity $n-k$ which appears in the denominator of the second term of Equation (2) leads to a more or less uniform incremental correction over each substep.

In the last substep during the correction phase, where $k=n-1$, an equilibrium error $e_{i+1}^{(n-2)}$ is simultaneously computed and an equilibrium correction is then performed using Equations (3) and (4) in Figure 2-3. This enables estimates for the displacement d_{i+1} and restoring force r_{i+1} corresponding to the end of the current time step $i+1$ to be available for the calculation of the predictor displacement $\hat{d}_{i+2}$ for the next time step $i+2$. Consequently, the structure is loaded without any pause between time steps $i+1$ and $i+2$.

More complete details about the algorithm for the real-time PSD testing method are given in Mercan and Ricles (2005).

2.3 Hybrid Test Method

To avoid fabrication and testing of an entire structure, the hybrid PSD test method (referred to herein as the hybrid test method) was developed (Dermitzakis and Mahin, 1985). In a hybrid PSD test, the structure is considered as an assembly of two distinct parts:

- Physical substructure (tested part of structure).
- Analytical substructure (numerically modeled part of structure).

The physical substructure is experimentally tested, where its degrees of freedom are coupled to the analytical substructure, which is the remaining part of the structure as shown in Figure 2-4. Figure 2-4 implies that the restoring forces r_{i+1} for time step $i+1$ are determined from the imposed displacements d_{i+1}^{E} to the physical substructure (i.e., the measured restoring forces r_{i+1}^{E}) and d_{i+1}^{A} to the analytical substructure (i.e., calculated restoring forces r_{i+1}^{A}).

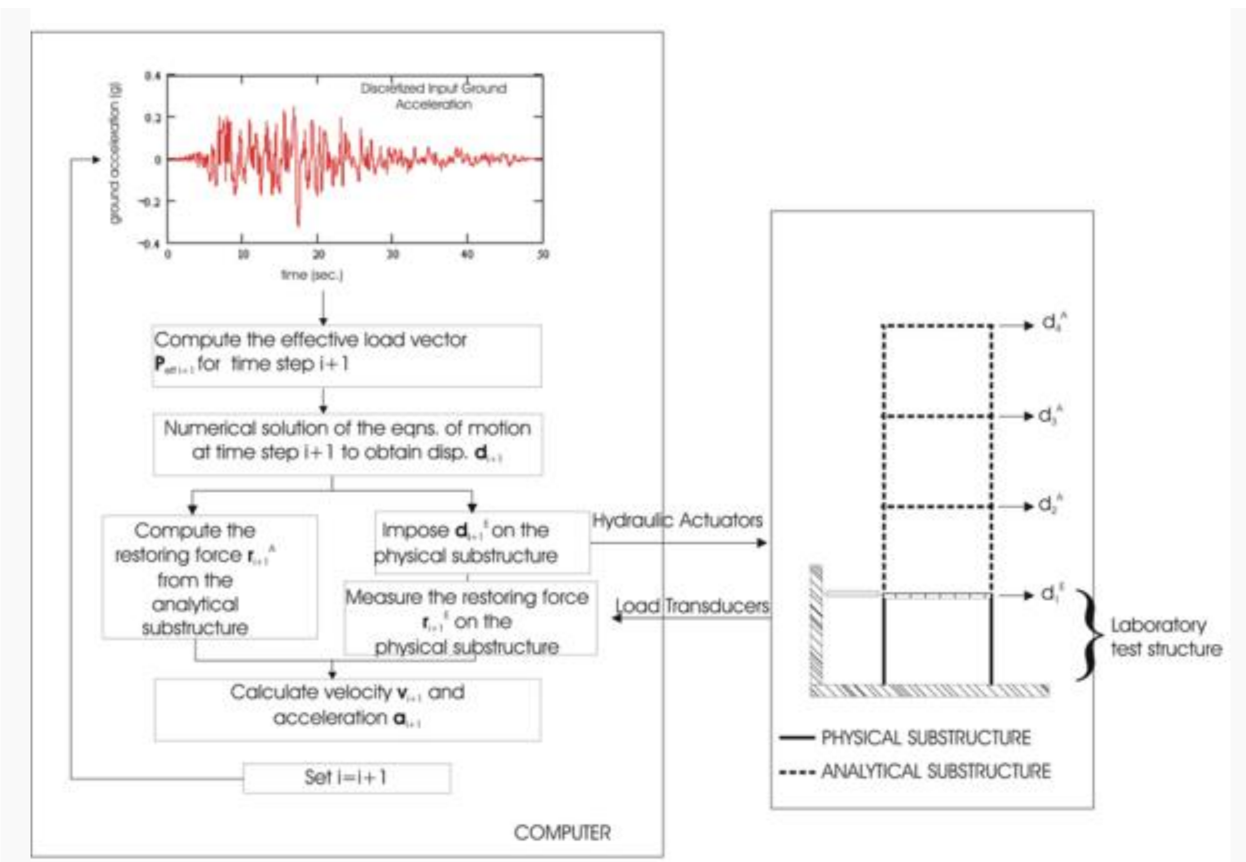

Figure 2-4 Real-time hybrid test method

Figure 2-5 shows the flowchart of the algorithm for the real-time hybrid test method employed at the RTMD earthquake simulation facility. The integration algorithm is similar to that used for the real-time PSD test method, and is based on the α-method with a fixed number of substeps during the correction phase. The displacement $\hat{d}_{i+1}$, d_{i+1}, $d_{i+1}^{c(k+1)}$ for all degrees of freedom (analytical and experimental substructures) are calculated in the same manner as in the real-time PSD test method. For each substep in the correction phase, the displacement commands for the physical substructure, $d_{i+1}^{c(k+1)E}$ are imposed on the test structure through the hydraulic actuators, and the resulting measured restoring forces $r_{i+1}^{m(k+1)E}$ and displacement $d_{i+1}^{m(k+1)E}$ are measured. Simultaneously, the restoring forces $r_{i+1}^{(k+1)A}$ corresponding to the displacements, $d_{i+1}^{c(k+1)A}$ for the analytical substructure are computed using a mathematical model. The restoring forces $r_{i+1}^{m(k+1)E}$ and $r_{i+1}^{(k+1)A}$ are subsequently combined to obtain the set of restoring forces $r_{i+1}^{(k+1)}$ for the complete structure. Care must be taken in dealing with the restoring forces at the degrees of freedom located at the interface of the analytical and physical substructure. At the interface, both $r_{i+1}^{m(k+1)E}$ and $r_{i+1}^{(k+1)A}$ contribute to the resistance $r_{i+1}^{(k+1)}$. The measured displacements $d_{i+1}^{m(k+1)E}$ are also combined with the displacements $d_{i+1}^{c(k+1)A}$ to form $d_{i+1}^{(k+1)}$. During the next correction cycle, $r_{i+1}^{(k+1)}$ becomes $r_{i+1}^{m(k)}$ in Equation (1) below.

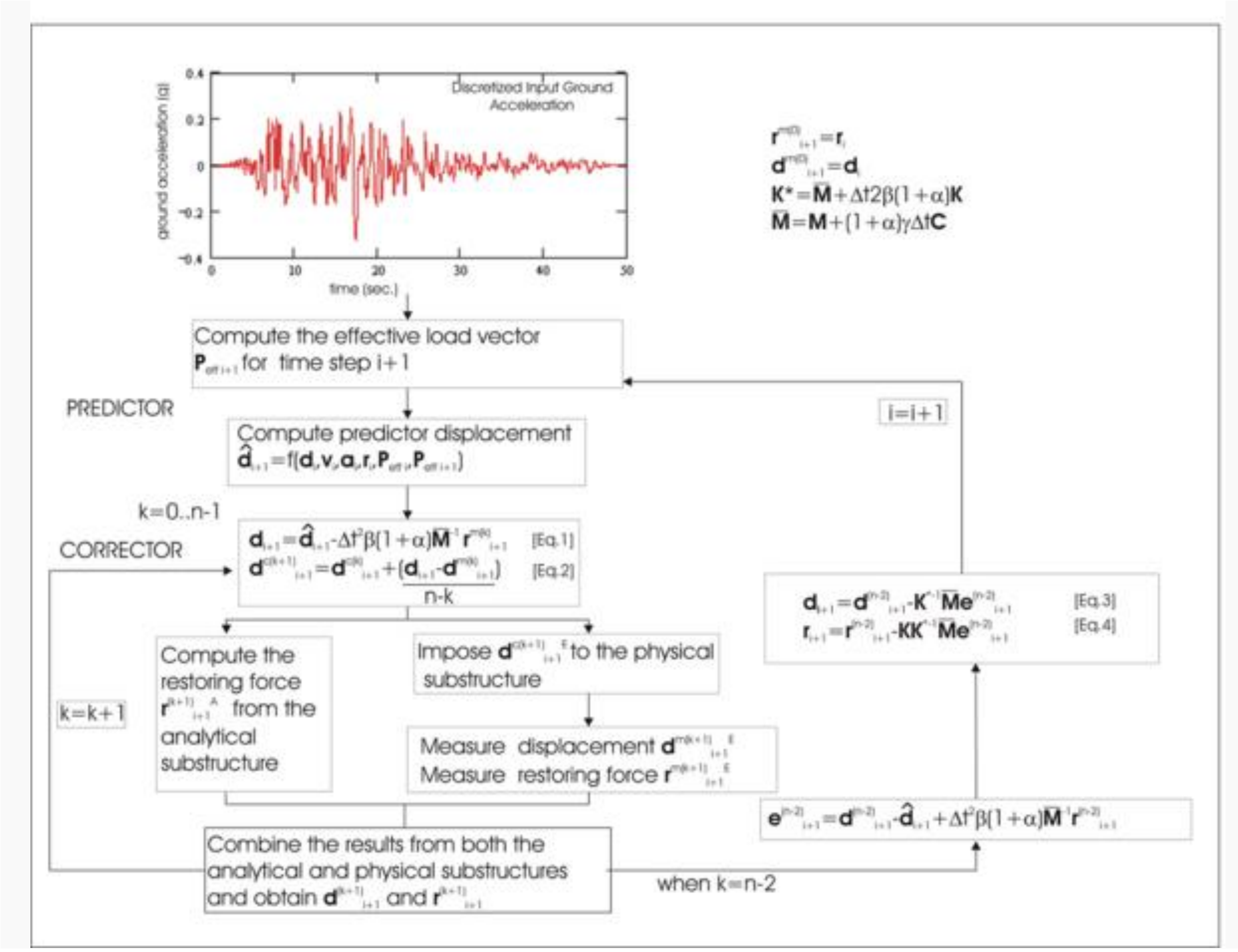

Figure 2-5 Real-time hybrid test method algorithm based on the α-method with a fixed number of iterations

After combining the results from the analytical and physical substructures to form $r_{i+1}^{(k+1)}$, and $d_{i+1}^{(k+1)}$, the algorithm continues with each subsequent substep in the correction phase. During the last substep the equilibrium correction is performed.

Multiple physical substructures of the prototype structure can also be defined in hybrid PSD testing at the RTMD earthquake simulation facility. Currently, the analytical substructure is defined by interfacing the integration algorithm with Matlab, Simulink or OpenSEES via OpenFresco.

2.4 Distributed Hybrid PSD Test Method

In distributed hybrid PSD testing, physical substructures are located at different geographical locations (i.e., experimental test facilities), with the analytical substructure located at either one of the experimental sites or at an independent site, as illustrated below in Figure 2-6. Distributed hybrid PSD testing thereby enables the capabilities of several experimental facilities and a computational facility to become engaged in the test. Figure 2-6 is a schematic describing the three sites that were involved in the NEES MiniMost experiment (Pearlman, et al. 2004), where the University of Illinois at Urbana, Champaign and the University of Colorado at Boulder participated as experimental sites, and National Center for Supercomputer Applications (NCSA) participated as a computational site. As shown in Figure 2-6, an experiment coordinator coordinates the test, using the Internet to receive control commands from the computational site, and then sending via the Internet each of the experimental sites their command displacement to be imposed to their physical substructure for a given time step (i.e., d_{i+1}^{E}, see Figure 2-4). The simulation coordinator receives back from each experimental site via the Internet the restoring forces corresponding to each physical substructure (i.e., r_{i+1}^{E}, see Figure 2-4). In the MiniMOST experiment, the NTCP protocol was used for communication between the coordinator and the sites.

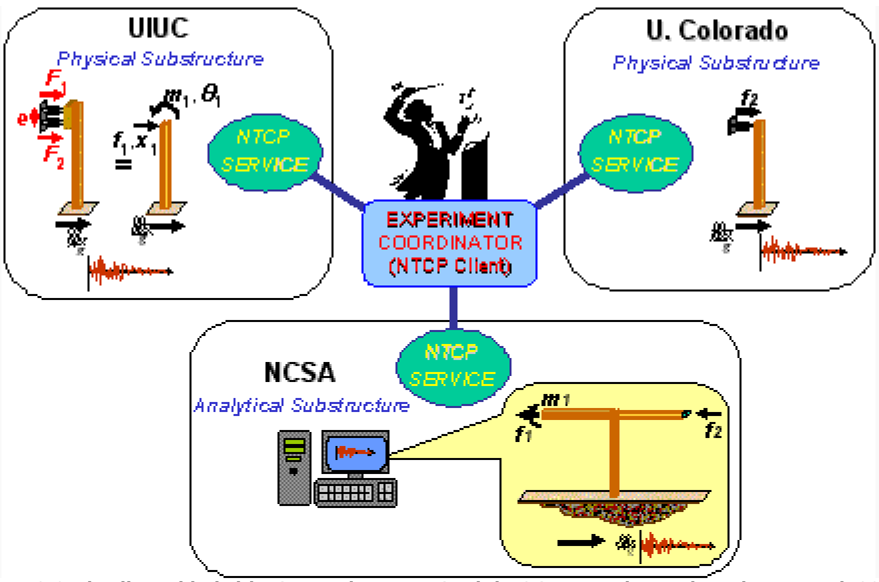

Figure 2-6 Distributed hybrid PSD testing: NEES MiniMOST experiment (Pearlman, et al. 2006)

The RTMD earthquake simulation facility can participate in distributed hybrid PSD testing with any computational or experimental facility that has the NTCP protocol. Figure 2-7 shows a schematic of the servo-hydraulic control and IT systems for the RTMD earthquake simulation facility. The systems include the RTMDtele (real-time telepresence server), RTMDsim (simulation coordinator), RTMDxPC (real-time simulation target), Controller (real-time controller), RTMDctrl (real-time control workstation), DAQ Mainframe (real-time data acquisition system), RTMDdaq (real-time data acquisition workstation), and RTMDrepos (RTMD local data repository). The RTMDctrl, RTMDsim and RTMDdaq are user interfaces with the Controller, RTMDxPC and the DAQ Mainframe, respectively.

When a distributed hybrid PSD test is performed, communication with each remote site is established through the NTCP protocol. When the RTMD earthquake simulation facility participates as an experimental site, the command received from a remote experiment coordinator is authenticated on the RTMDtele, and then passed to the RTMDsim. RTMDsim evaluates the command for conformance with equipment limits (e.g., maximum actuator forces, actuator maximum displacements), before transferring it to the Controller via the RTMDxPC and SCRAMNet. The Controller has active limits set in RTMDctrl before the test beings. These active limits are enforced as the command is received.

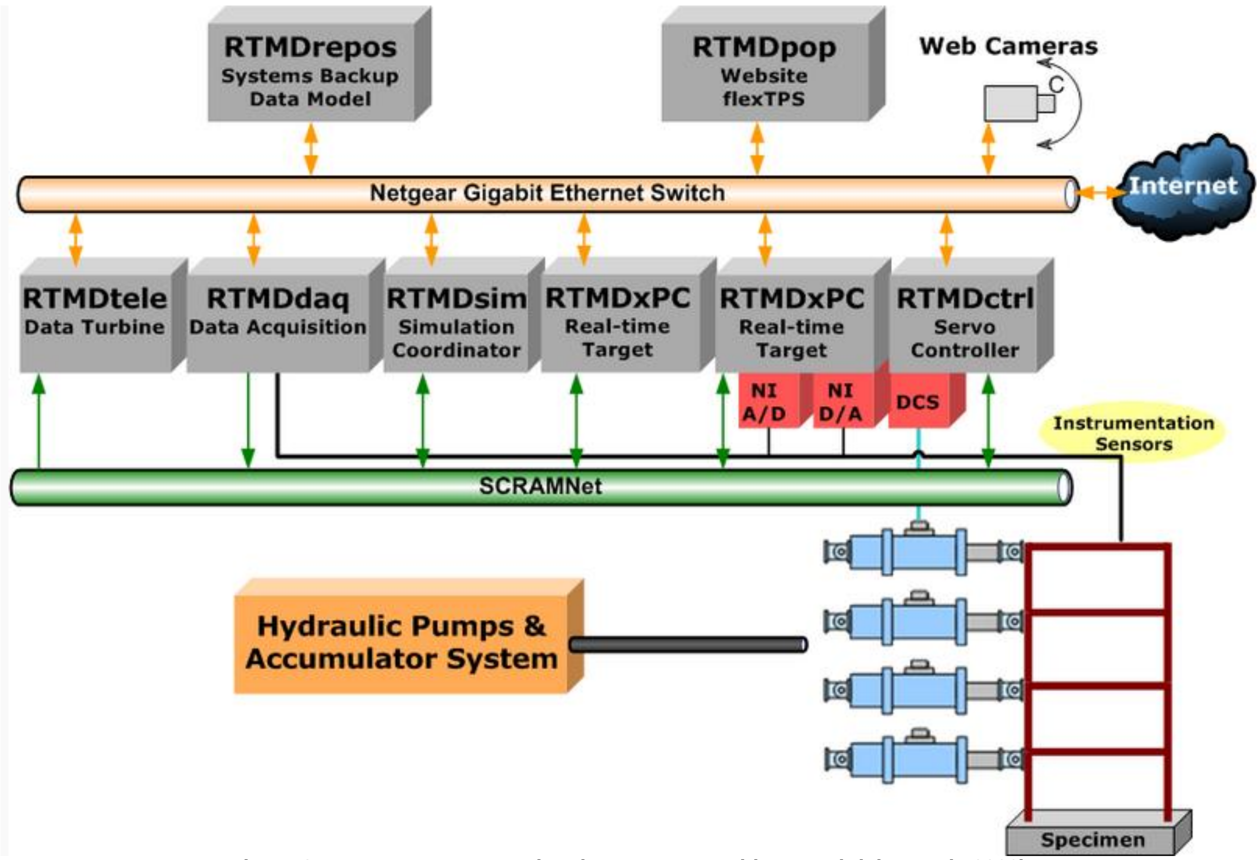

Figure 2-7 RTMD servo-control and IT systems architecture (Ricles et al., 2009)

2.5 Effects of Multi-directional DOFs

A variety of challenges arise when kinematics of the motion of the test specimen influences the actuators and instrumentation. A simple example is given in Figure 2-8, where x and y displacements of the test structure, shown in plan view, are controlled by the three actuators. The displaced configuration of the test structure results in transverse movement of the actuators and measurement sensors, introducing an error in the correct positioning of the specimen by the actuators and measurement sensors. The position of the test structure, actuators, and measurement devices must be accounted for during each time step of a test, using a kinematic correction procedure to ensure accurate test results.

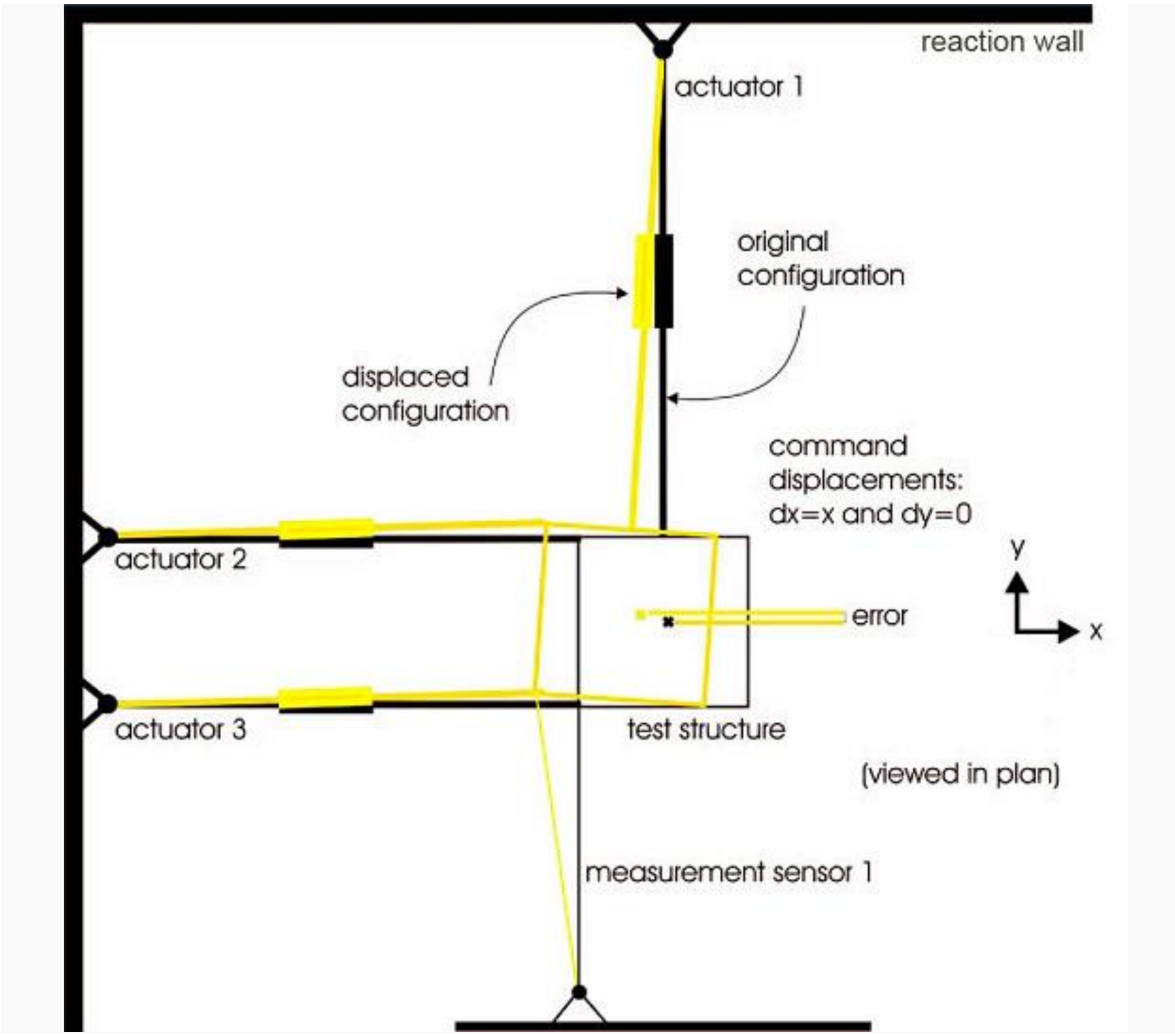

Figure 2-8 Geometrical inaccuracies due to test structure kinematics

The algorithm for multi-directional testing at the RTMD earthquake simulation facility includes a kinematic correction scheme, where the position of the test structure, actuators, and measurement devices is tracked during a test. For the general case involving 3-D motion, a total of eight displacement sensors (S1 through S8) are required to be arranged, as shown in Figure 2-9, where a rigid loading block is used in the test to control the degrees of freedom at the SPN (Structural Physical Node) shown. The instrumentation is attached to the structure at measurement structural nodes MSN1 and MSN2.

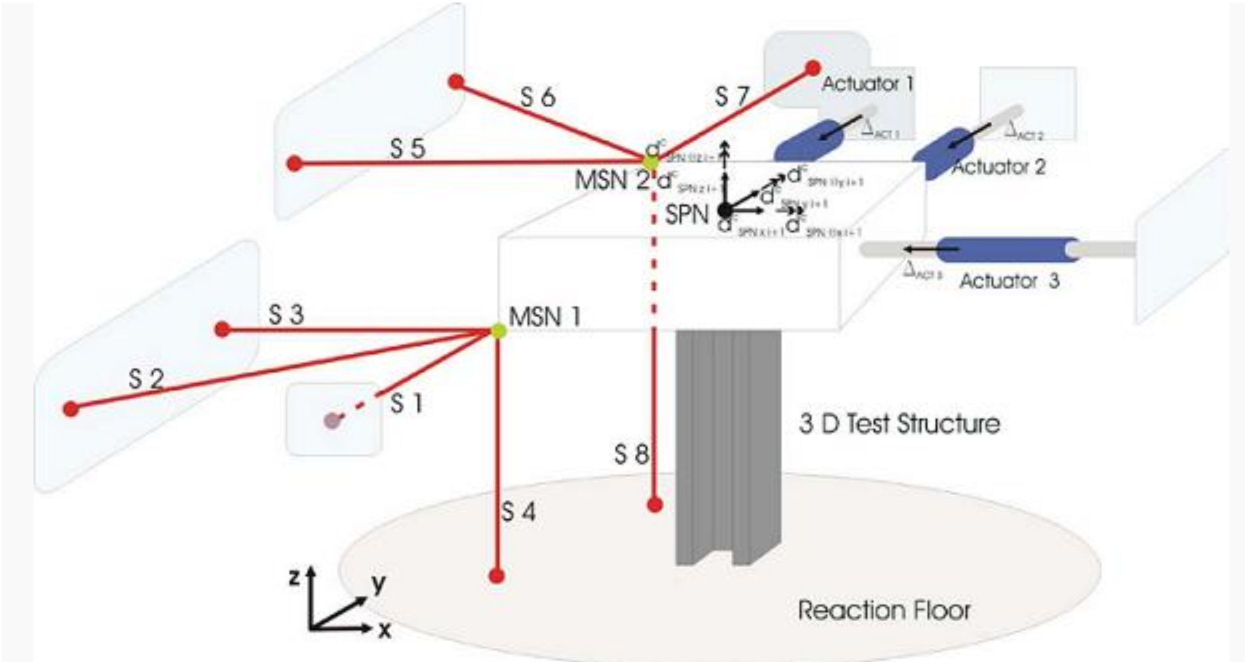

Figure 2-9 3-D test with displacement sensors arranged for tracking specimen position

The kinematic correction consists of the following steps:

(1) The extension or contraction ΔACT_j of each of the actuators j involved in the test is determined based on the command displacement $d^{c(k+1)}\mathrm{SPNp}_{i+1}$ to be imposed on the structure at the SPNp controlled by the actuators, where:

$$\Delta_{\mathrm{ACTj}} = f(d^{c(k+1)}_{\mathrm{SPNp}_{i+1}}, X^0_{\mathrm{SPNp}}, X^d_{\mathrm{SPNp}}, X^0_{\mathrm{ASNj}}, X^d_{\mathrm{ASNj}})$$

(Equation 2-5)

In (Equation **2-5**), $f()$ is a function that relates the extension or contraction of actuator j to the kinematics of the motion of the SPN, whose displacements are a subset of which contains the command displacements of all of the SPNs in the test structure. This function has as independent variables the command displacement to be imposed to the SPN, $d^{c(k+1)}_{\mathrm{SPNp}_{i+1}}$; the coordinates of the SPN in the undeformed geometry, X^0_{SPNp}; the coordinates of the SPN in the deformed geometry, X^d_{SPNp}; the coordinates of the actuator nodes (a node is defined at each end of the actuator) of actuator j in the undeformed geometry, X^0_{ASNj}; and the coordinates of the actuator nodes of actuator j in the deformed geometry, X^d_{ASNj}.

(2) As each of the actuators extends or contracts in accordance with (Equation **2-5**), the motion of each SPN, corresponding to the measured displacement is determined, where for SPNp the measured motion $d^{m(k+1)}_{\mathrm{SPNp}_{i+1}}$ corresponding to the displacement measurements is:

$$d_{\mathrm{SPNp}_{i+1}}^{m(k+1)} = f(X_{\mathrm{SPNp}}^{0}, X_{\mathrm{MSN1}}^{0}, X_{\mathrm{MSN2}}^{0}, X_{\mathrm{MSN1}}^{d}, X_{\mathrm{MSN2}}^{d})$$

(Equation 2-6)

In (Equation 2-6), $f()$ is a function that relates the motion of SPNp to the displacement transducer measurements for SPNp. This function has as independent variables the coordinates of the SPN in the undeformed geometry, X_{SPNp}^{0}; the coordinates of MSN1 in the undeformed geometry, X_{MSN1}^{0}; the coordinates of MSN2 in the undeformed geometry, X_{MSN2}^{0}; the coordinates of MSN1 in the deformed geometry, X_{MSN1}^{d}; and the coordinates of MSN2 in the deformed geometry, X_{MSN2}^{d}.

(3) The measured restoring forces at SPNp during substep k are:

$$r_{\mathrm{SPNp}_{i+1}}^{m(k+1)} = f(X_{\mathrm{SPNp}}^{d}, X_{\mathrm{ACT(i,m)}}^{d}, \mathrm{P}_{\mathrm{ACT(i,m)}})$$

(Equation 2-7)

Where in (Equation 2-7), $f()$ is a function that relates the restoring forces at SPNp to the load cell reading of the actuators associated with controlling the motion of SPNp. This function has as independent variables the coordinates of SPNp in the deformed geometry, X_{SPNp}^{d}; the coordinates of the nodes of the actuators in their deformed geometry, $X_{\mathrm{ACT(i,m)}}^{d}$, that are associated with SPNp; and the load cell reading of the actuators, $\mathrm{P}_{\mathrm{ACT(i,m)}}$, , associated with SPNp.

The above functions in each of (Equation 2-5) through (Equation 2-7) are developed on a case by case basis, and dependent on the geometry of the loading apparatus and stiffness. These functions are subsequently programmed as a module by the staff of the RTMD earthquake simulation facility, which is integrated into the control algorithms (on the RTMDxPC) to account for the kinematics of a test structure. The kinematic correction can be done based on either the incremental command displacements or the command of total displacements to each SPN in the test structure.

2.6 Effective Force Test Method

The concept of the Effective Force Test (EFT) method is that the response of a system to a given ground motion may be replicated by applying the effective force vector $P_{eff}(t)$ of (Equation 2-4) to the test structure. As noted in the development of (Equation 2-4), the effective force at each degree of freedom is equal to the product of the mass and ground acceleration in the direction of the degree of freedom. The concept of the EFT method is illustrated in Figure 2-10 for a single degree of freedom (SDOF) test structure. Actuators reacting off of a reaction wall are utilized to apply the effective force to the test structure.

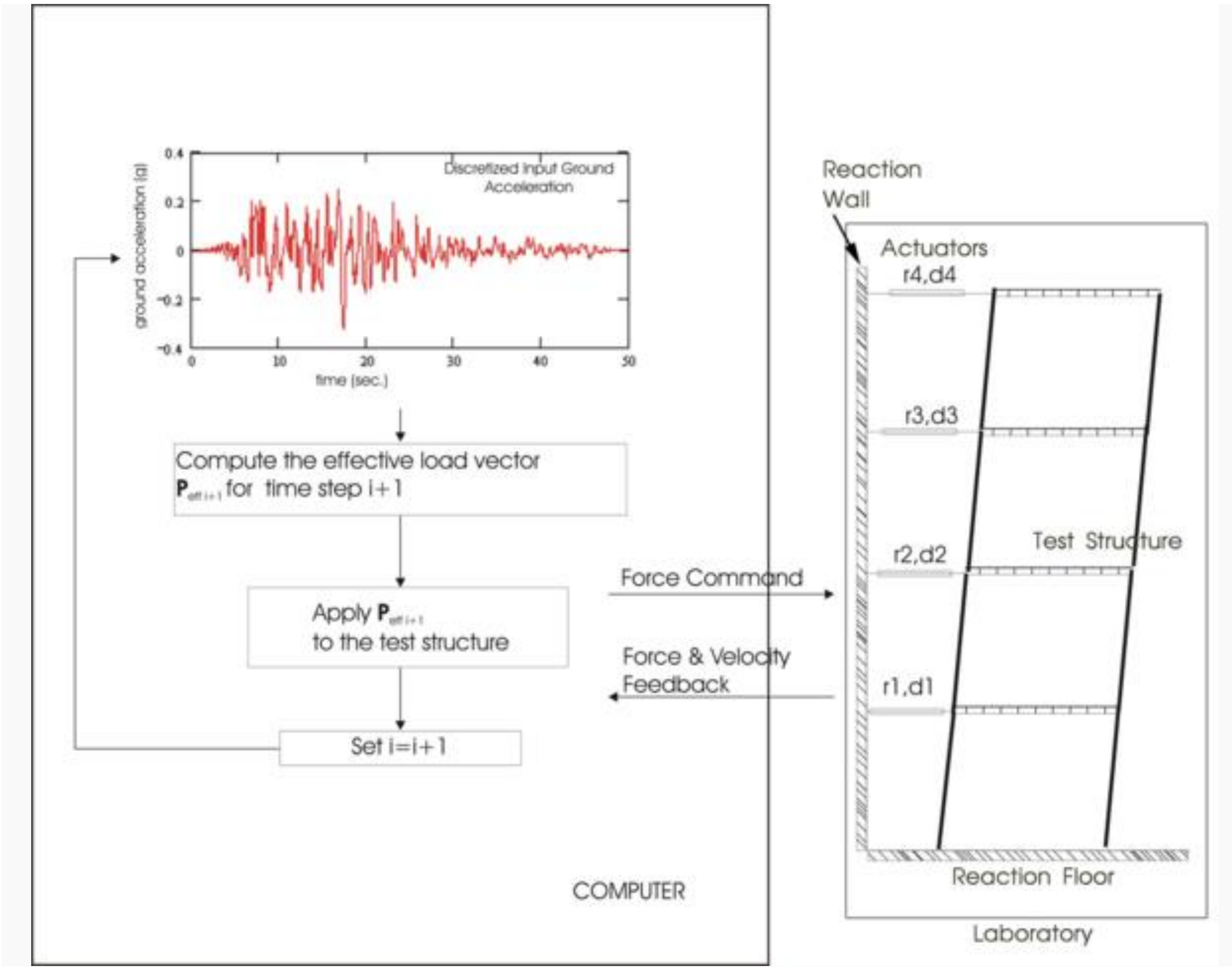

Figure 2-10 Effective Force Test Method

The key advantage of the EFT method is that the effective forces depend on only the ground acceleration record and the structural mass, and are independent of any nonlinear behavior of the structure such as stiffness and damping. They can therefore be calculated in advance of the test, and the need for online computations during testing is minimal.

The challenge of using the EFT method is to achieve accurate force control, whereby precise effective forces are applied to the test structure. To simulate the real-time effects of an earthquake on a structure, dynamic actuators a high quality servo-hydraulic control system are needed to accurately apply the effective forces. Dyke et al. (1995) found that there is an intrinsic property of hydraulic actuators, called natural velocity feedback, which restricts the ability of the actuators to apply an accurate force when the test structure is vibrating near one of its natural frequencies. Dimig et al. (1999) developed a method called natural velocity feedback negation to correct for the phenomenon associated with natural velocity feedback. This method is based on classical control theory and was successfully demonstrated for SDOF systems. Researchers at the RTMD earthquake simulation facility (Zhang et al., 2004) have successfully developed methods to negate the effects of natural velocity feedback in multi-degree of freedom (MDOF) test structures.

The main disadvantage of the EFT method is that the complete seismic mass of the structure must be included in the test structure. This may be difficult to achieve in all but the largest laboratories. Researchers at the RTMD earthquake simulation facility are currently developing an advanced EFT method that overcomes this problem.

2.7 RTMD Control System and IT System Architecture

A schematic of the servo-hydraulic control and IT systems for the RTMD earthquake simulation facility was presented in Figure 2-7.

The RTMD real-time testing architecture features a Real-Time Integrated Control System for real-time testing. Algorithms that enable real-time testing reside on the RTMDxPC, which is a dedicated real-time xPC kernel. These algorithms enable real-time pseudo dynamic testing, real-time hybrid testing, and real-time effective force testing. Multi-directional kinematics is accounted for by algorithms that also reside on the RTMDxPC or RTMDsim. All of the algorithms are implemented using MATLAB and SIMULINK from MathWorks, Inc. and are compiled onto the RTMDxPC for real-time testing. Lesser used options are to develop custom JAVA or MATLAB programs, C++ modules or LabVIEW VIs.

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 190 nanoseconds per channel, essentially enabling share 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 by the RTMDctrl 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.

For real-time hybrid testing, numerous options exist for modeling the analytical substructure. The preferred and primary method is to develop models with SIMULINK to describe the analytical substructure. 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 (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 simulation. Other tested programs and software environments which can be used include LabVIEW, NTCP, SimCor, ANSYS, and OpenFresco with OpenSEES.

2.8 Requirements for Users of the RTMD Facility

Researchers developing a proposal to use the RTMD earthquake simulation facility need to know the demand that their tests will impose on the equipment in order to ensure the equipment capacity of the facility is not surpassed. This will help to ensure that the test can be successfully completed. Equipment specifications were summarized in Chapter 1 of this manual, as well as in the NEES Equipment Site Specification Database.

It is recommended that researchers planning tests at the RTMD earthquake simulation facility consider the following:

1. Researchers must be aware that the maximum velocity that an actuator can achieve depends on the concurrent force in the actuator (i.e., hydraulic actuator power). Perform as accurate as possible time history analysis of the candidate test structure (nonlinear analysis may be needed) using the forcing function expected to be used during the test. Plot the ensuing force-velocity orbits associated with an actuator degree of freedom. Compare these orbits with the hydraulic actuator power envelop provided in Chapter 1 (see Figure 1-2) of this manual to check that the actuator power capacity is not surpassed, and that forces at the tie down points for the actuators and reactions of the test structure do not surpass their capacity (see Chapter 1), as well as the overturning moment capacity of the ATLSS multi-directional reaction wall.
2. From the time history results, determine the stroke range required of actuators and instrumentation, and check that the demand does not surpass the capacity summarized in Chapter 1.
3. If necessary, scale-down the test structure to avoid having the demand in (1) and (2) exceed the capacity of the equipment and instrumentation.

After the project is funded by the sponsor, the researchers will need to work with the research staff of the RTMD earthquake simulation facility to finalize the details of the test structure. This will include running the hydraulics off mode software to verify the demand on the equipment and instrumentation, as well as the functionality of any modifications made to the standard testing protocols in use at the RTMD earthquake simulation facility (e.g., using a new PSD integration algorithm defined by the researcher). More information on the hydraulics off software will be provided at scheduled RTMD training sessions.

2.9 Software Policies

The Real-Time Integrated Control System enables the real-time control of high speed, large capacity hydraulic actuators. These actuators pose a danger if not operated correctly because of user error or software generating incorrect actuator commands.

It is the policy of the RTMD, that in order to ensure the safety of the laboratory and prevent damage to equipment, software used for any form of testing at the RTMD earthquake simulation facility must be validated before placed on the Real-Time Integrated Control System. The algorithms which the software is based on must be shown to be stable. The user desiring to place the software on the Real-Time Integrated Control System must provide documented proof that the software has been validated and the algorithm is stable. The approval of the implementation of the software onto the Real-Time Integrated Control System will be at the discretion of the staff of the RTMD to ensure the safety of the laboratory and equipment.

It is strongly recommended that users make use of the existing software available on the Real-Time Integrated Control System in lieu of user developing their own software that requires validation and stability studies. A list of software for hybrid simulation available at the RTMD is given in Table 2-1.

Table 2-1 NEES@Lehigh Hybrid Simulation Software

Software	Version	Web Link for Documentation	Funding Agency	Availability
Matlab	R2010b and R2011a	http://www.mathworks.com/products/matlab/	NA	On-site license
Simulink	R2010b and R2011a	http://www.mathworks.com/products/simulink/	NA	On-site license
xPC Target	4.3 and 5.0	http://www.mathworks.com/products/xpctarget/	NA	On-site license
LabVIEW	2010	http://www.ni.com/labview/	NA	On-site license
OpenSEES	2.2.2	http://nees.org/resources/openseesbuild	NEES	Open source
OpenFresco	2.0	http://nees.org/resources/openfresco	NSF	Open source
HybridFEM	4.2.4 beta	http://www.nees.lehigh.edu/wordpress/uploads/reports/HybridFEM-2D_4.2.4_Users_Manual.pdf	PITA	In executable form
RDV	2.2.2	http://nees.org/resources/rdv	NEES	Open source
Data Turbine	3.1a	http://nees.org/resources/rbnb	NEES	Open source
Lehigh Data Model	n/a	http://www.nees.lehigh.edu/resources/lehigh-data-model	PITA	Open source
Inverse Compensation for Actuator control	n/a	http://www.nees.lehigh.edu/wordpress/uploads/reports/ASCE_Chen_Tracking_Error-Based_AIC_for_RT_testing.pdf	PITA; NEES O&M	Open source
Adaptive Inverse Compensation for Actuator control	n/a	http://www.nees.lehigh.edu/wordpress/uploads/reports/ASCE_Chen_Tracking_Error-Based_AIC_for_RT_testing.pdf	PITA; NEES O&M	Open source

Notes:

NA: Software developed by vendor

PITA: Pennsylvania Department of Community and Economic Development through Pennsylvania Infrastructure Technology Alliance

NSF = National Science Foundation

2.10 References

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3 Telepresence Capabilities

3.1 LAN Equipment and Computer Network

Shown below is a floor plan of the laboratory of the RTMD earthquake simulation facility, where the local area network (LAN) is identified. The laboratory of the RTMD earthquake simulation facility is supported by a switched gigabit copper network comprised of 16 independent connection ports on the laboratory floor, and an additional 8 connections in the control room to accommodate the control network, data acquisition, and RTMD servers. This network is operated as an independent subnet within the RTMD earthquake simulation facility, isolated from common network traffic, and managed as a secure subnet. The laboratory and control room network are connected through a managed gigabit switch to the university's main backbone. From the RTMD earthquake simulation facility switch through the campus backbone all traffic travels over gigabit fiber connections. All the network equipment is managed and monitored by Lehigh University's Library and Technology Services.

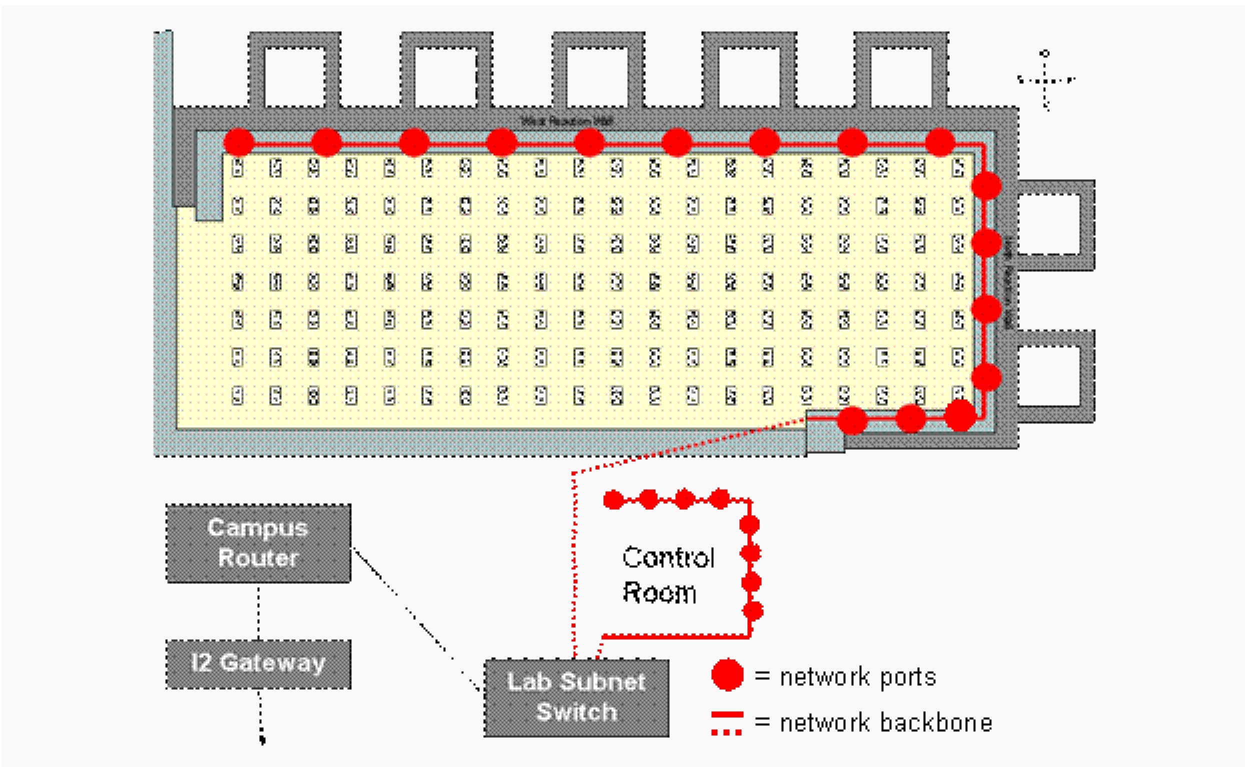


Figure 3-1 Local Area Network of the RTMD earthquake simulation facility

With the network isolated from the office network and the corresponding daily traffic, this allows greater flexibility and a larger pool of network addresses from which to assign computers, advanced sensors, and network cameras addresses, while making the maximum bandwidth available to the experimental and telepresence systems. The network switch allows the RTMD facility IT system to operate a VLAN for security purposes and effectively shield systems controlling the experiment from the outside world.

For on-site (local) participants, several network ports have been provided in the control room for laptops and portable computers. A wireless network and the general building 100 megabit network are available in this room for observers. Security on the wireless access point is enabled and arrangements for wireless access need to be obtained at the time of a visit to the RTMD earthquake simulation facility.

In addition to the equipment of the IT system described in Chapter 1, the system has several additional pieces of equipment. Network cameras are accessible through web interfaces on the RTMDpop system. Direct network access to these cameras is restricted in order to achieve optimal video streaming and ensure camera controls are not tampered with. As part of this network there are 6 cameras for laboratory use, 4 of which are permanently mounted cameras (2 Axis 205's and 2 Axis 2401+ PTZ cameras) installed in the laboratory, with the 2 remaining cameras (Sony SNC-RZ30N) having portable mounts for use in the laboratory. Video streams are managed through the telepresence system using flexTPS. Additional still cameras are available for use in the laboratory on a use fee basis at this time.

Two overhead video monitors exist in the control room, and are configured and maintained with real-time data and video content from active experiments. Local and remote participants will be able to view the displays via the network.

A portable videoconferencing system for use in the control room and laboratory is also available. It is capable of 4 point conferencing based on a H.323 protocol. A tethered camera is available for use in the laboratory with this system, providing researchers access to laboratory space during setup and configuration. Because of the harsh environment of the laboratory, use of the videoconferencing system in the laboratory is limited.

3.2 Telepresence

3.2.1 General

The implementation of the RTMD IT systems adheres to the protocols and implementations of the NEES software distribution. It is therefore recommended that potential participants and collaborators refer to NEES.org for a comprehensive list of systems requirements, steps for authentication, and details for using any NEES software.

Applications developed for use by experimental participants in the configuration of data acquisition, simulation, and control will be discussed in further detail at the end of this chapter. This includes applications and detailed instructions for use of the software for configuration of data and video streaming and remote experimental participation.

3.2.2 DataTurbine

DataTurbine® is a software server that provides a ring buffered network as a data path between suppliers and consumers of both static and dynamic information. Diverse distributed applications pool and share data using DataTurbine as a common intermediate point of contact. DataTurbine manages all aspects of inter-application data traffic, assimilating data acquisition and storage into the network itself.

The RTMD IT infrastructure implements a DataTurbine server on RTMDtele and sources it with data from RTMDdaq, RTMDsim, RTMDxPC and RTMDctrl via the SCRAMNet. A custom application exists which allows the administrator of the DataTurbine server to determine the rate the data is received off of the SCRAMNet, the rate the data is flushed across the network at and the size of the stored data archive.

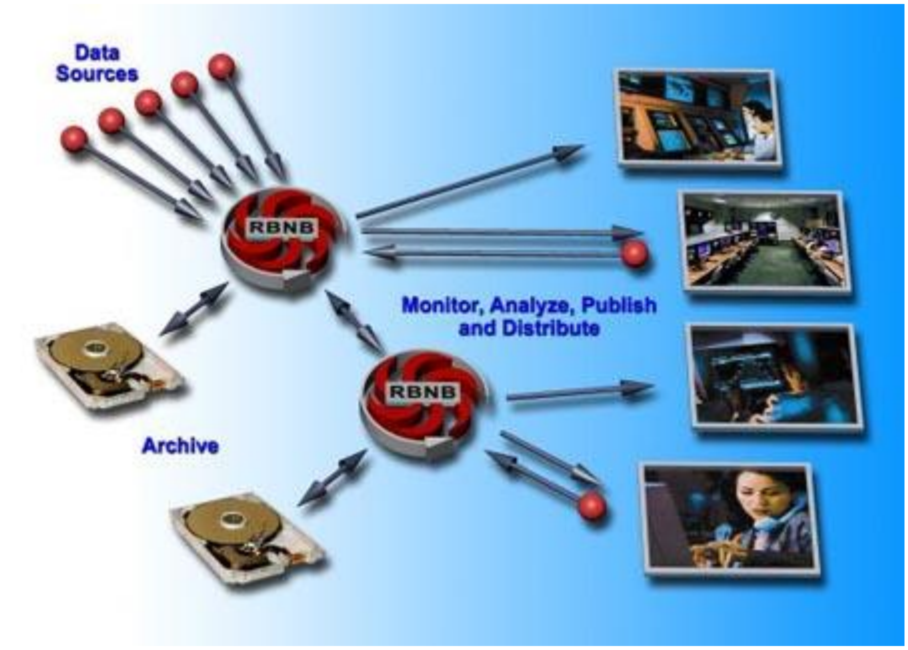


Figure 3-2 DataTurbine Architecture

3.2.3 Real-time Data Viewer (RDV)

The Real-time Data Viewer (RDV) provides an interface for viewing and analyzing live or archived time-synchronized data and video either locally or streamed across a network from a DataTurbine (RBNB) server. RDV is capable of displaying textual and numerical data, still images, and video. Users of RDV can access the RTMD DataTurbine server on an Internet-connected system running Java. This included Windows, Linux and Mac OSX systems. The features of RDV are listed below, including the 3D Model Panel developed at the RTMD facility.

- Synchronous display of numeric, textual, still images, and video data
- Monitor experimental data in real-time or playback from history at increased rates
- 2D time series or XY data plots
- Support for high- or low-resolution still-image and video data
- Multiple pages of data panels

- 3D visualization capability
- Support for visualization of large data sets (>1M samples)

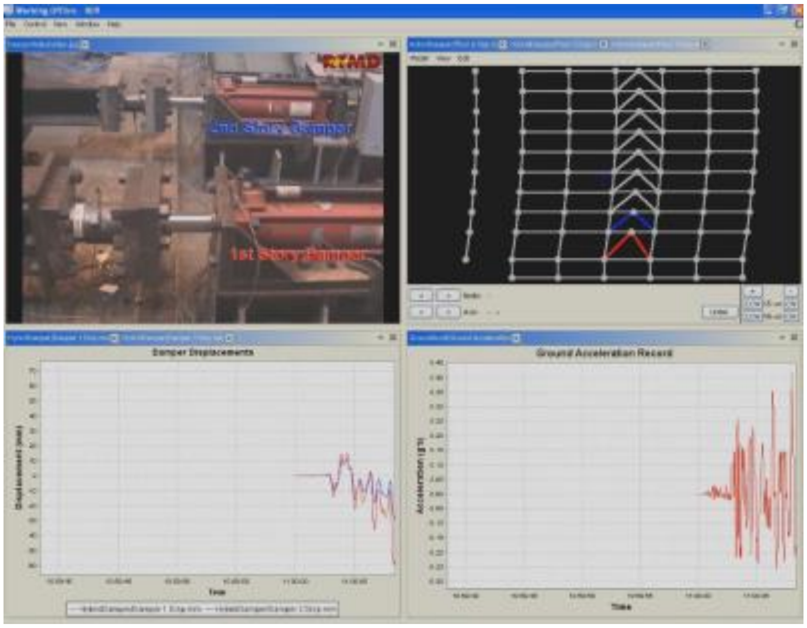


Figure 3-3 Screen capture of RDV showing live video, 3D model and plotting data

3.2.4 flexTPS

flexTPS (flexible TelePresence System) is a software system designed to enable the remote viewing and robotic control of live video over the internet without requiring any software beyond a web browser on the user's computer. In addition to viewing multiple video streams, robotic or PTZ (pan/tilt/zoom) enabled cameras can be manipulated by the user in real time. Multiple video sites can be linked through the Collaboration section allowing video streams from multiple associated flexTPS sites to be viewed in parallel.

The network cameras listed in Section 3.1 are configurable through the RTMDpop system and viewable and controllable using the flexTPS web application.

3.2.5 NTCP and NHCP

The RTMD IT systems support NTCP (NEES Telecontrol Protocol) and NHCP (NEES Hybrid Communications Protocol) to enable the direct participation between the RTMD facility and other experimental and analytical computational facilities. The implementation of these protocols has been developed to support the Distributed Hybrid Testing Method described in Chapter 2. A remote site interested in participating using this method must have the required protocols in place to provide authentication and data sharing using common NEES tools.

The RTMD protocol for distributed hybrid testing requires that some information be communicated prior to any access to the local RTMD server is granted. Limit states, limit response, test duration and expected command states must be clearly specified and communicated. The NTCP/NHCP service is only operational during experiments, at all other times the service is shut down for security.

The current implementation of this protocol utilizes an NTCP server on the RTMDsim which provides a bridge for command and feedback data to and from the RTMDxPC, RTMDctrl and RTMDdaq. Specification of the control points, command sets, and feedback requirements are necessary prior to experiment configuration. The diagram below shows the functionality of the protocol, and the basic elements that have been created to support its operation. A remote experimental participant would need to create an NTCP client.

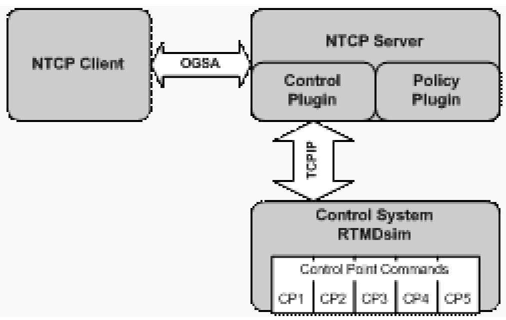


Figure 3-4 Basic functionality and elements to support NTCP

4 Education and Outreach

4.1 General

The vision of the Education, Outreach, and Training (EOT) program at Lehigh University Real-Time Multi-Directional (RTMD) Equipment Site can be outlined as follows:

1. Promote the discipline of earthquake engineering to a broad audience, including students (K-12, undergraduate, graduate) and professionals (practitioners, researchers, professors) through the utilization of Lehigh RTMD equipment, technology, and staff.
2. Enhance the awareness and utilization of Lehigh RTMD Equipment Site for earthquake engineering-related research projects.

The following section will illustrate the activities implemented by Lehigh RTMD staff to support its EOT vision.

4.2 Example Activities

4.2.1 Education

4.2.1.1 University Curriculum

The undergraduate and graduate teaching in Civil and Environmental Engineering (CEE) has been integrated into the activities of the RTMD earthquake simulation facility through curriculum. Numerous undergraduate and graduate courses have been augmented or developed to include subjects and/or experiments related to NEES activities. Such courses, along with whom they were offered, are provided below:

Undergraduate curriculum

- CEE 159 “Structural Analysis I”, Shamim Pakzad
- CEE 211 “Research Problems”, Instructor
- CEE 244 "Foundation Engineering", Sibel Pamukcu
- CEE 258 “Structural Laboratory”, Stephen Pessiki
- CEE 259 "Structural Analysis II", James Ricles
- CEE 352 "Structural Dynamics", Richard Sause
- CEE 361 “Bridge System Design”, Instructor
- CEE 363 "Building Systems Design", James Ricles

Graduate curriculum

- CEE 406 “Structural Reliability of Components and Systems”, James Ricles
- CEE 415 “Analysis and Design of Ductile Steel Systems”, James Ricles
- CEE 419 "Structural Behavior Laboratory", Stephen Pessiki
- CEE 441 “Dynamic Analysis in Geotechnical Engineering”, Instructor
- CEE 453 “Nonlinear Analysis of Structural Components and Systems”, James Ricles
- CEE 455 "Advanced Structural Dynamics", Richard Sause
- CEE 456 "Behavior and Design of Earthquake Resistant Structures", Peter Mueller
- CEE 455 "Advanced Structural Dynamics", Richard Sause

- CEE 467 “Advanced Topics in Structural Engineering", Shamim Pakzad

4.2.1.2 University Classroom Projects/Activities

Lehigh University has incorporated the earthquake engineering discipline into several classroom projects/activities as part of semester curriculum for the given course. Examples of the projects are provided below:

Seismic Testing of Model TV Tower

Under the direction of Professor Yungfeng Zhang, Co-PI on the Initial Equipment Site Construction Project at Lehigh, undergraduate (freshmen) students at Lehigh University participated in the design and creation of Model TV Towers that were subjected to subsequent testing on a shake table to understand structural performance under earthquake conditions. The course title is Engineering 5, "Introduction to Engineering Practice". This project was included as part of the course requirements during both the Fall 2005 and Spring 2006 semesters.

Seismic Testing of Pagoda Tower

Under the direction of Professor Yungfeng Zhang, Co-PI on the Initial Equipment Site Construction Project at Lehigh, students at Lehigh University participated in the design and creation of a Pagoda Tower that were subjected to subsequent testing on a shake table to understand structural performance under earthquake conditions. The goal of the project was to experimentally study the seismic behavior of a Japanese pagoda and base-isolation technology. Students in the course built a scaled version of the 5-story Japanese wood pagoda. The testing was held on April 24, 2006. The Course Title is CE 467-41, "Smart Structural Systems".

4.2.1.3 Research Experience for Undergraduates Program

Lehigh University RTMD Equipment Site has been selected by NEESinc as one of only four sites to participate in NEES inaugural Research Experience for Undergraduates (REU) Program. The RTMD Equipment Site operated the NEES REU program in conjunction with a summer REU program based out of the Advanced Technology for Large Structural Systems (ATLSS) Research Center at Lehigh University. This project was financed (in part) by a grant from the Commonwealth of Pennsylvania, Department of Community and Economic Development. The Summer 2006 program included a total of seven students, three of which participated through the NEES REU program and four of which participated through the ATLSS program.

Program Overview

As part of the program, undergraduate students from various universities and colleges spent 10 weeks conducting research under the direction of Lehigh University faculty and staff at the ATLSS Research Center, within which Lehigh RTMD Equipment Site is located. The NEES students conducted research in the area of earthquake engineering, while the ATLSS students researched under a broader Civil and Structural Engineering research area. At the conclusion of the program, students were required to submit a technical report and give a presentation on their findings. Additionally, throughout the program, the students participated in a series of workshops to enhance their professional skills and partook in a series of offsite tours that exposed the students to industrial environments. The Summer 2006 program included the following workshops and tours:

Workshops

1. ATLSS Safety Presentation/Laboratory Tour, presented by ATLSS staff
2. Laboratory Safety/Construction Safety, presented by Lehigh University Environmental Health and Safety Department
3. Library Search Training, presented by Lehigh University Library and Technology Services Department
4. Resume Building Workshop, presented by Lehigh University Career Services Department
5. Effective Presentations/Powerpoint Workshop, presented by Lehigh University Media Services DepartmentTechnical Report Workshop, presented by ATLSS staff

Tours

1. Susquehanna River Bridge
2. Dorney Park
3. High Steel Structures, Inc.
4. Carpenter Technology Corporation

4.2.2 Outreach

4.2.2.1 K-12 Activities

Lehigh RTMD staff has participated in several K-12 activities, targeted at supporting the site vision of promoting the earthquake engineering discipline to students. Any school districts, community programs, youth organizations, camps, etc. interested in discussing potential outreach programs available for their students are encouraged to contact the RTMD Equipment Site EOT Coordinator, whose contact information is provided in Section 4.3, EOT Coordinator Contact Information. Examples of K-12 activities that have been offered to date are summarized below:

S.T.A.R. Academies

RTMD staff, in conjunction with Professor Yungfeng Zhang, Co-PI on the Initial Equipment Site Construction Project at Lehigh, hosted Lehigh University S.T.A.R. (Students That Are Ready) Academies students on the following dates: January 28, 2006; March 18, 2006; April 22, 2006. S.T.A.R. Academies is an early intervention program designed to enrich and enhance the academic performance of economically and academically disadvantaged and/or at-risk elementary/middle/high school aged children. Student ages varied from 4th through 12th grade, and represented over five school districts (39 schools) in the Greater Lehigh Valley. The primary goals are to prepare and place these students in colleges and universities across the country in STEM and business majors. Activities included the following:

1. General discussion on earthquake engineering
2. Tours of the ATLSS Research Center and RTMD Equipment Site
3. Presentations on earthquakes in Pennsylvania
4. Demonstration of a small-shake table (seismic simulation) system and accompanying instrumentation (accelerometers) to illustrate how earthquake information is recorded
5. Student construction of structures using LEGOs that were subsequently subjected to earthquakes representative of those observed in Pennsylvania, California, and Alaska using a small-scale shake table (seismic simulation) system. Depending on the age group, design criteria were provided to the students.

The goal was to introduce students to earthquakes in Pennsylvania and basic earthquake engineering design considerations while providing a hands-on experience for the students. Due to the popularity of the activities with the students, the RTMD equipment site has been requested to participate again in the S.T.A.R. Academies program during the 2006-2007 academic year.

Centennial School

RTMD staff, in conjunction with Professor Yungfeng Zhang, Co-PI on the Initial Equipment Site Construction Project at Lehigh, hosted Centennial School of Lehigh University students on April 28, 2006. Centennial School of Lehigh University pursues a two-fold mission: (a) to serve children with disabilities and their families, and (b) to prepare high quality special education teachers and related service personnel to enter the workforce in Pennsylvania and beyond. Centennial School of Lehigh University is a special education day school that serves students, ages 6 through 21, who are classified under the Individuals with Disabilities Act (IDEA) as emotionally disturbed and/or autistic. The activity on this day included a brief presentation on earthquakes in Pennsylvania, followed by the construction of structures using LEGOs that were subsequently subjected to earthquakes representative of those observed in Pennsylvania, California, and Alaska using a small-scale shake table system. The goal was to introduce students to earthquakes in Pennsylvania and provide the students an opportunity to construct a building that will be subjected to earthquakes.

Mulberry Child Care Center

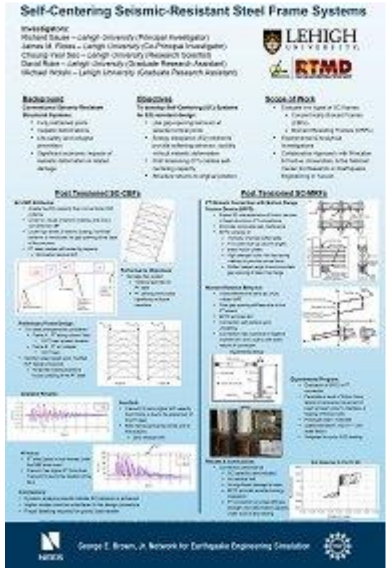
RTMD staff, in conjunction with Professor Yungfeng Zhang, Co-PI on the Initial Equipment Site Construction Project at Lehigh, hosted students from the Allentown Mulberry Child Care Center on July 18, 2006. On this day, 22 students, with ages ranging from 1st grade through 8th grade, participated in a series of earthquake engineering-related activities, including:

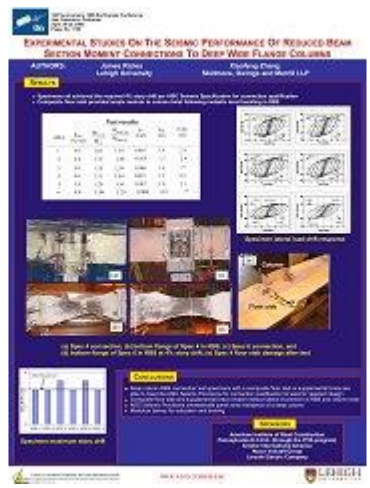
1. A general presentation on earthquakes, earthquake engineering, and Lehigh NEES RTMD site
2. A tour of the RTMD equipment site and control room
3. Seismic testing of a viscoelastic damper utilizing RTMD equipment
4. Hands-on input into Hybrid Viz seismic simulation software developed by NEES REU student Gabriel Valencia during Summer 2006 REU program
5. Limited hands-on control of RTMD equipment
6. A presentation on earthquakes in Pennsylvania
7. Student construction of structures using LEGOs that were subsequently subjected to earthquakes representative of those observed in Pennsylvania, California, and Alaska using a small-scale shake table (seismic simulation) system.

4.2.2.2 Posters

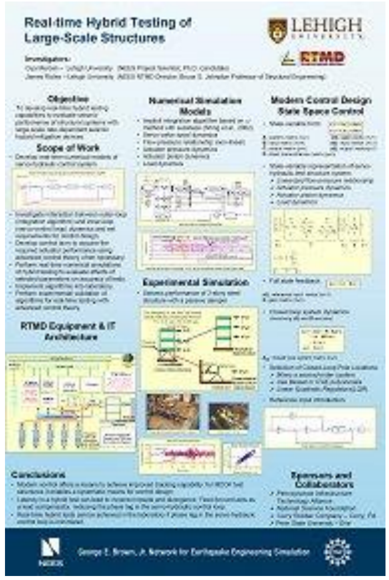
The RTMD Equipment Site has created posters for display at events such as the NEES Grand Opening in Davis, CA, the Earthquake Engineering Research Institute (EERI) Conference in San Francisco celebrating the 100th Anniversary of the 1906 San Francisco Earthquake, and NEES Annual Meetings. Examples of some of the posters are provided below for review:

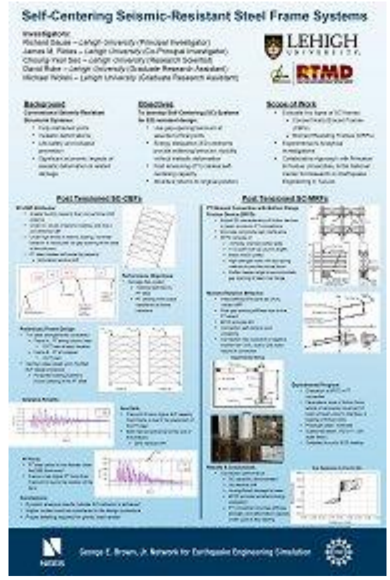
EERI Conference, April 2006





NEES Annual Meetings





4.2.2.3 Participation at Professional Conferences

Lehigh RTMD Faculty and Staff participate in various professional conferences related to seismic engineering. Participation may include, but is not limited to, technical presentations, poster development, proceedings development, and creation of display exhibits. A list of recent conference proceedings is included within the Publications section of this website. A list of posters developed for such conferences is available within the Posters section of this manual.

Lehigh RTMD staff created a site exhibit for the Earthquake Engineering Research Institute (EERI) Conference celebrating the 100th Anniversary of the 1906 San Francisco Earthquake in April 2006. The site developed the exhibit in order to promote the equipment site technical capabilities and current research projects. The exhibit was awarded the "Best NEES Exhibit at the Eighth National Conference on Earthquake Engineering" by NEESinc. Pictures of the exhibit are provided below:

4.2.2.4 Equipment Site Tours

Tours of the RTMD Equipment Site, scheduled and unscheduled, are available and can be coordinated through the RTMD Site Operations Manager. Tours have been provided to various groups, including domestic and international researchers, industrial organizations, and both K-12 and collegiate (undergraduate and graduate) students.

4.2.2.5 Equipment Site Activity Map

Lehigh RTMD staff regularly updates the NEES Equipment Site Activity Map with information regarding RTMD site activities through NEES.org. The site contains information on current research projects and provides video links to the RTMD Equipment Site. Snapshots from the Equipment Site Activity Map, indicating an active Lehigh research day in blue, are shown below:

4.2.2.6 Media Coverage

Activities of RTMD Equipment Site have been covered and subsequently reported on in both video and print media. Examples of the media coverage are provided below:

100th Anniversary of the 1906 San Francisco Earthquake

The following 3 news stations broadcast reports on Lehigh earthquake engineering research from the ATLSS research center, exhibiting RTMD Equipment Site capabilities:

- Channel 69 News (WFMZ TV) Lehigh Valley, April 18, 2006
- Fox29 News Philadelphia, April 17, 2006
- KYW CBS3 News Philadelphia, April 18, 2006.

An Associated Press report discussing earthquake engineering research being conducted at Lehigh University was published in the Express Times on April 18, 2006. A copy of the article is presented below:

RESEARCHING THE POWER OF NATURE

Research scientist Sougata Roy, seated, discusses procedures Monday in the control room of the ATLSS Engineering Research Center at Lehigh University. The center tests how structures hold up in earthquakes. Story and additional photo, Page B6.

The ATLSS Engineering Research Center's structural testing lab at Lehigh University is home to one of the largest structural testing facilities in the United States. Scientists here test new materials that will help buildings survive earthquakes with little damage.

Lehigh scientists shake up quake-proof structures

They say system using steel bands could be in commercial use in 10 to 15 years.

This Associated Press report was published locally, regionally, nationally, and internationally, at the following locations:

Local

- mcall.com (Lehigh Valley): "Engineers Work on Quake-Proof Buildings", April 18, 2006
- Express Times (Lehigh Valley): "Lehigh Scientists Shake Up Quake-Proof Structures", April 18, 2006
- wfmz.com (Lehigh Valley): "Earthquake Proof Buildings", April 18, 2006

Regional

- cbs3.com (Philadelphia): "Lehigh University Testing Earthquake Safety", April 17, 2006
- philly.com (Philadelphia): "Lehigh Engineers Working on An Earthquake-Proof Building", April 18, 2006
- phillyburbs.com (Philadelphia): "Engineers Work on Quake-Proof Buildings", April 18, 2006
- timesleader.com (Wilkes-Barre): "Engineers Working on an Earthquake-Proof Building", April 18, 2006
- whptv.com (Harrisburg): "Engineers Working on an Earthquake-Proof Building", April 18, 2006

National

- lasvegassun.com (national): "Engineers Work on Quake-Proof Buildings", April 18, 2006
- abcnews.com (national): "Engineers Work on Quake-Proof Buildings", April 18, 2006
- foxnews.com (national): "Engineers Try to Design 'Earthquake-Proof' Buildings", April 18, 2006
- insurancejournal.com (national): "Engineers Working, Stretching, Bending Toward Earthquake-Proof Building", April 18, 2006
- examiner.com (national): "Engineers Work on Quake-Proof Buildings", April 18, 2006

International

- canada.com (international): "Engineers Work on Next-Generation Quake-Proof Buildings", April 18, 2006

S.T.A.R. Academy Outreach Session

An article that discussed the April 22, 2006 outreach session with the S.T.A.R. Academy was published in The Morning Call on April 23, 2006. A copy of the article is provided below:

A new learning curve

PROGRAM
FROM PAGE B1

can be 'at-risk' regardless of color or economics."

In its 17 years, S.T.A.R. has grown, mostly from parental and student word of mouth. It started with 20 sixth- and seventh-graders from nearby Broughal. S.T.A.R. now has a parental advisory board and runs two programs for students in fourth through 12th grade from 30 schools across the Lehigh Valley region.

"Not every Lehigh student comes from a privileged background," said Henry Odi, Lehigh's executive director of academic outreach programs. "But it's really been a personal and professional joy to see how some of the Lehigh students have been transformed through their interactions by helping students develop and enhance their talents."

Chad Kusko, a research scientist at Lehigh's ATLSS Center, which is known for studying earthquakes, said the program allows students to experience other forms of science.

"This is a program for underrepresented and underprivileged children," he said after helping with an earthquake study involving Lego houses. "This is a chance for them to experience engineering and maybe it will pique someone's interest."

According to Henry Odi's statistics, nearly 98 percent of students stay for the whole program each year. 100 percent of students who have tried the program at some point graduate from high school, and 94 percent have gone onto higher education.

While growing up in north Bethlehem, Naomi Rivera said her son, Joshua, would look at Lehigh's stone buildings and grassy quads as a foreign place he would never reach. Next year, the Liberty senior will attend the $42,990-a-year university.

"S.T.A.R. has been a blessing," Naomi Rivera said.

Before traveling to ATLSS on Lehigh's Mountaintop Campus, the students gathered in auditorium for a group session. They recited the affirmation and then told the other students about positive things happening in their lives.

Angel Deat, 12, a seventh-grader at Bethlehem's East Hills Middle School, went from a C+ to an A in her science reports. Kalief Robinson, 15, made Liberty's honor roll and will become a lifeguard at Dorney Park & Wildwater Kingdom this summer. Giselle Brown, 15, a sophomore at Bethlehem's Liberty High School received straight As again, and she will start an internship at Air Products this summer.

"That's a paid internship doing research," Henry Odi boasted to Brown's fellow students. "She will not be running errands and doing mail. She will be using her brain."

"She's got it going on," his wife added.

So, too, do the Odis.

"They instill pride," parent Maria Sotbon said. "They are always telling the kids how important they are — I am loved. I am able. And I can make a difference."

STEVEN JONES (from left), a senior at Liberty High School; Liberty freshman Zachary Jones; and Bethlehem Catholic High School freshman Markus Matuszinski design a building to withstand an earthquake.

4.2.2.7 Research Workshops

RTMD staff assisted in the organization of and participated in a workshop entitled U.S.-Taiwan Workshop on Self-Centering Structural Systems, which was held June 6-7, 2005, at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. This workshop provided a forum to exchange information and ideas, and to formulate plans for future collaboration between the U.S. and Taiwan, with regard to a systematic investigation of post-tensioned self-centering structural systems for buildings. Presentations at the workshop included the seismic behavior of post-tensioned beam-to-column connections, column-to-base connections, frame systems, damage assessment and monitoring of self-centering frame systems, and analytical and experimental simulation methods for self-centering systems. A panel session was held at the end of the workshop to formulate bilateral collaborations and future perspectives of U.S. and Taiwan researchers. The workshop was sponsored by the National Science Council of Taiwan and NCREE. Future workshops are tentatively scheduled for October 2006 in Taiwan during the International Conference on Earthquake Engineering, January 2007 in the United States, and October 2007 in Taiwan.

4.2.3 Training

4.2.3.1 Seismic Testing Workshop

The RTMD Equipment Site held its first NEES@Lehigh: Real-Time Multi-Directional Seismic Testing Workshop on June 19, 2006 and a second one on November 12, 2007. Attendees were trained on the technical capabilities of the equipment site, provided with a review of current research projects and opportunities for future projects, challenged with a hands-on problem associated with control, presented hands-on participation activities related to hybrid simulation, and trained on proposal development utilizing the RTMD Equipment Site.

4.2.3.2 Website Training

The RTMD staff regularly updates the site training materials offered within the NEES@Lehigh website. Certain training modules are available to the public, while others require authorization from the RTMD staff. Parties interested in reviewing the training material requiring authorization are encouraged to contact the RTMD Systems Administrator.

4.3 EOT Coordinator Contact Information

Lehigh RTMD Equipment Site welcomes the opportunity to educate the community on earthquake engineering, develop outreach activities which involve the community, and train the community on how to best utilize the technical capabilities of the site. If you are interested in any of the activities noted above, or have an idea for an activity that you would like to discuss with the RTMD Equipment Site, we encourage you to contact the site EOT Coordinator:

Gary Novak
610-758-5488 (phone)

610-758-5902 (fax)
gsn207@lehigh.edu (e-mail)

5 Procedures & Policies

This chapter describes the procedures and policies for use of the NEES Real-Time Multi-Directional (RTMD) earthquake simulation facility at Lehigh University. The RTMD Facility NEES equipment is housed within the existing main laboratory of the Center for Advanced Technology for Large Structural Systems (ATLSS). The ATLSS facilities, including the RTMD Facility, are available for both academic/sponsored laboratory research and external (industrial) testing and use. As the ATLSS Lab now includes both NEES equipment and non-NEES equipment, every attempt will be made to accommodate concurrent use of the laboratory. For use of NEES equipment, priority will be given to NEES projects while priority will be given to the ATLSS Center faculty and staff for use of non-NEES equipment. For the purposes of this policy statement, NEES projects are defined as projects receiving funding through the NSF for use of the NEES equipment or projects that have received approval by NEEScomm for shared-use access, as per the NEEScomm Shared-Use Partnering Policy (SUPP), which is available on the NEES website (www.nees.org). The RTMD Facility will be responsible for maintaining NEES equipment, operating the equipment during the experiments, and providing basic training to collaborating researchers for use of the equipment.

NEES Projects

As previously noted, NEES projects are defined as projects receiving funding through the NSF for use of the NEES equipment or projects that have received approval by NEEScomm for shared-use access, as per the NEEScomm Shared-Use Partnering Policy. Equipment use fees are not applied to NEES equipment (equipment covered in Section 1.3, RTMD Equipment Specifications) that is utilized as part of a NEES project. Additionally for NEES projects, select services covered within the scope of the site's Operations and Maintenance Budget that are performed by site and laboratory personnel are not subject to use fees. NEES researchers will have the opportunity to utilize non-NEES equipment on a use-fee basis. Fee schedules are provided in Section 7.2, Rate Schedule for RTMD Facility, ATLSS, and Fritz Labs - NEES Projects, for NEES projects (Section 7.3, Rate Schedule for RTMD Facility, ATLSS, and Fritz Labs - non-NEES Projects, provides fee schedules for non-NEES projects). Regarding services, Section 7.1, Scope of Services Covered by the NEES Operations and Maintenance Budget, outlines both activities and services covered by Lehigh's RTMD facility under its Operations and Maintenance Budget and those activities and services that are to be covered by the research project. ***Thus, in summary, a researcher interested in developing costs associated with utilizing Lehigh's RTMD equipment site for a NEES project should reference Section 7.1 to understand the scope of services which are***

covered under the NEES Operations and Maintenance Budget and Section 7.2 to understand the cost structure associated with equipment and personnel required for the NEES project.

Note that all projects that utilize Lehigh's ATLSS Laboratory, whether NEES or non-NEES, is subject to an overall project fee, as outlined in Table 7.2-1, with the amount dependent on the project's budget specific to utilization of Lehigh's ATLSS Laboratory. The type of funding for the project, whether Academic/Sponsored or External Testing and Use, also determines the fee rate. The project fee will be applied to each project to cover the cost of maintaining ATLSS lab tools, miscellaneous equipment, and facilities, such as, but not limited to, hand tools, forklift, overhead crane, and hydraulic pumping systems that are non-NEES equipment. The fee will be assessed to each project for the time the project is active in the ATLSS Lab. This fee will be reviewed annually by ATLSS personnel and is subject to revision upon review. Finally, visiting researchers will be provided office space at the ATLSS Center for the duration of their project, and will have restricted access to the ATLSS Lab and Fritz Lab for NEES project related activities.

Non-NEES Projects

Non-NEES projects are considered those projects which are not sponsored by the National Science Foundation and which are not approved for shared-use access by NEEScomm, or those projects which are funded privately by industry with no intent of conforming to the requirements established in the NEES Facilities Users Guide. *Non-NEES project laboratory services and activities are not covered, in any manner, under the RTMD's NEES Operations and Maintenance Budget*. All laboratory activities are to be charged directly to the laboratory project. Additionally, equipment use fees for use of both NEES and non-NEES equipment are applied to these projects. Rates for use of this equipment are outlined in Section 7.3, Rate Schedule for RTMD Facility and ATLSS Lab. Note that each project is subject to an overall project fee, as outlined in Table 7.3-1, which is a function of the project's budget specific to utilization of the ATLSS Laboratory and is dependent on whether the project is Academic/Sponsored or External Testing and Use. The project fee will be applied to each project to cover the cost of maintaining ATLSS lab tools, miscellaneous equipment, and facilities, such as, but not limited to, hand tools, forklift, overhead crane and hydraulic pumping systems that are non-NEES equipment. The fee will be assessed to each project for the time the project is active in the ATLSS Lab. This fee will be reviewed annually by ATLSS personnel and is subject to revision upon review.

5.1 Guidelines for Proposal Preparation

Researchers interested in developing a proposal to utilize Lehigh's Equipment Site are referred to NEES Facilities Users Guide, which can be downloaded directly from the Policies section on NEES.org. Lehigh's site also recommends that contact be made early in the proposal process with Lehigh's Site

Operations Manager, in order to aid in planning, scheduling, cost development, etc. Lehigh also intends to offer an annual Seismic Testing Workshop (see Workshops heading at www.nees.lehigh.edu for more details) with the goal of training potential site users on the site's capabilities, equipment specifications, proposal development, etc. Researchers interested in utilizing the equipment site are strongly encouraged to attend the workshop.

5.2 Guidelines for Funded Projects

Researchers that have received funding to utilize Lehigh's Equipment Site are referred to the NEES Facilities Users Guide, which can be downloaded directly from the Policies section on NEES.org. This document includes a section entitled Guidelines for Funded Proposals. Among the topics covered in this section are Equipment Site Compliance Checks, Research Participation Agreements, and site scheduling. Researchers are strongly encouraged to review this section during the proposal development stage in order to understand the informational details that will be required by the equipment site upon funding of the project.

5.3 Required Documentation

Two primary documents ***must be completed prior to*** *the onset of any laboratory activity for an awarded research project*. The documents are outlined below:

1. Equipment Site Policies Compliance Check (ESPCC): To be completed by an equipment site representative, *with supporting information provided by the researcher*. The ESPCC assures policy compliance with respect to NEES Facilities Users Guide, experimental feasibility, safety, budget, schedule, and available data services. A copy of the ESPCC form is available at the NEES.org, under Policies.
2. Research Participation Agreement (RPA): *To be completed by the researcher*, with assistance from the equipment site staff. The RPA represents a contract between the Equipment Site and NEEScomm, detailing (but not limited to) sections including:

- Indemnification
- Insurance
- Payment terms
- Termination terms
- Intellectual Property rights
- Publication rights

- Change order procedures
- Conflict resolution procedures
- Scope of Work
- Project Description
- Project Schedule and Required Equipment
- Risk Mitigation Plan
- Safety Plan
- Data Sharing and Archiving Plan
- Budget for site activities
- Roles and Responsibilities for both researcher and equipment site

The RPA agreement template for Lehigh University is available on the NEES.org, under Research Sites, Lehigh University. Lehigh University reserves the right to deny the use of the RTMD Facility to visiting researchers for any reason if researcher actions are inconsistent with the goals and policies of the University.

5.4 Training

The RTMD Facility Training Plan intends to provide the level of information and training required for the following three user groups.

NEES Proposers

NEES Proposers are researchers developing NEES proposals that, if successful, would utilize the RTMD Facility. These researchers are expected to have basic understanding and some experience in laboratory experiments involving the dynamic effects of earthquakes on large structures and structural components. Two key components that provide the information required for NEES Proposers are the RTMD Facility Users Manual, available at www.nees.lehigh.edu and material at NEES.org. These components together provide the information required to understand the physical facilities and test equipment and the procedures and policies to be followed at the RTMD Facility. A third component of proposer training is the offering of Seismic Testing Workshops by RTMD staff at Lehigh's NEES equipment facility. Additional information on such workshops is available under the Workshops heading at the RTMD Facility website. Further clarifications and budget development assistance will be available through the RTMD Facility Operations Manager.

NEES On-Site Users

A formal on-site training program must be completed satisfactorily prior to any use of NEES or non-NEES equipment, including all of the ATLSS Lab equipment. RTMD Facility staff will provide training through regularly scheduled training workshops for all RTMD Facility users with awarded projects. For all projects, these training workshops will emphasize the safety procedures and policies described in the RTMD Facility Safety Manual. An overview of the RTMD Facility operations will also be provided. Additional training topics may include tasks specific to awarded projects, including instrumentation, data acquisition, control, and algorithm verification procedures. The duration of a training workshop will typically be 2 days and will be conducted at the RTMD Facility. Any additional training required for a specific project should be discussed in the proposal preparation process and the costs included in the proposal and testing plan. This additional training may be conducted utilizing teleconferencing, if appropriate. The NEES project PI, and students and staff from the project PIs home institution and from any project subcontractors must be authorized by the RTMD Facility Operations Manager to have access to the ATLSS Lab and any laboratory equipment. The staff of the RTMD Facility is available to assist and/or perform all functions related to the setup and operation of NEES and non-NEES equipment. All hydraulic actuators, hydraulic power systems, and control systems will be operated exclusively by RTMD Facility staff. These systems require extensive training and experience to operate properly. Improper operation poses significant risk to the facility and personnel in the ATLSS Lab. Additionally, trained members of the ATLSS staff will operate the ATLSS Labs forklift and overhead crane or other equipment requiring professional skill or operating certification.

NEES Observers

The third component of this Training Plan is educational in its focus and is intended to enhance the understanding of the effects of seismic events on structures for practicing engineers, interested graduate and undergraduate students, and K-12 teachers and students. Project summaries for each research project will be developed and posted on the RTMD Facility website (under Current Projects). It is the responsibility of the researcher to provide the RTMD Facility Staff with the project summary and any additional information required by the RTMD Facility Staff to post a project summary. Seminars will be conducted by the principal researcher or designate for each project. These seminars will be announced and open to the public.

5.5 Experiment Execution

Standard RTMD Facility and ATLSS Lab hours of operation are 7:00 am to 12:00 pm, and 12:30 pm to 3:00 pm local time. Exceptions to this policy must be made in writing in advance and agreed upon by the RTMD Facility Operations Manager and ATLSS Lab Manager. NEES projects are responsible for overtime hours incurred by RTMD Facility personnel during extended hours of operation. An exception to this policy might occur when extended hours of operation result from malfunction of the RTMD Facility equipment. The RTMD Facility Director and staff recognize the importance of opening the facility to all members of the earthquake engineering community for their research needs. Efforts have been made to maintain a safe, secure working environment for participants and visitors. There are, however, some areas within the ATLSS Lab that remain open to RTMD Facility and ATLSS Lab staff only. In general, these are consistent with standard safety practices and reflect a cautious approach in the interest of safety. As an example of such, the hydraulic pump house and electrical service equipment will remain closed to all visitors, including those working on NEES projects.

ATLSS Lab, which houses the RTMD Facility, is a ground level laboratory fully compliant with ADA requirements. Offices within and adjacent to the ATLSS Lab are also accessible. Special accommodations may be arranged with advance notice. The ATLSS Center offers office spaces with Ethernet access for visiting NEES project personnel. While the ATLSS Lab does not operate on a 24-hour basis, the ATLSS Center is accessible at all hours.

The control room for the RTMD Facility has a window facing the ATLSS Lab and is designed to accommodate up to 4 researchers with computer access available. During testing, researchers will be asked to refrain from entering the test area for safety reasons. The control room affords a limited view of the test area. Cameras focused on the test setup will provide more comprehensive views of the test. Video display screens will be available in the control room.

6 Cost Structure

NEES projects do not pay for use of NEES equipment or NEES-funded personnel for qualified activities. The RTMD facility will provide a baseline level of service to NEES projects at no cost to the researcher. This cost will be absorbed by Lehigh's NEES Operations and Maintenance budget. Section 6.1, Scope of Services Covered by the NEES Operations and Maintenance Budget, will provide a summary of these activities, developed from the Subaward Agreement for Operation and Maintenance of a NEES Equipment Site (OMSA-2004 v3.0). Additional levels of service beyond those noted in Section 6.1 will be subject to user fees or will be chargeable directly to the research project.

Section 6.2, Rate Schedule for RTMD Facility, ATLSS, and Fritz Labs - NEES Projects, outlines the fee structure currently being utilized to cover laboratory costs for **NEES projects only**. Section 6.3 outlines the fee structure for non-NEES projects. Fees will be charged for the use of non-NEES equipment by all projects and for the use of NEES equipment by non-NEES projects. *For this purpose, usage of the equipment is defined as the time during which the equipment is dedicated to a project, thereby, precluding that resource from being available to another project*. For example, an actuator being configured into an experimental setup is being "used" since it is unavailable to another project, and charges for use of that actuator will accrue to the particular project until the equipment is returned to the available equipment pool.

A project fee will be applied to all projects to cover the maintenance costs associated with ATLSS lab tools, miscellaneous equipment, and facilities, such as hand tools, forklift, overhead crane and hydraulic pumping systems that are non-NEES equipment. The standard fee, which is determined as a specific percentage of the project budget specific to utilization of Lehigh's ATLSS Laboratory, is outlined in Tables 6-2 and 6-7 (note the information is similar as the tables are duplicate). This fee will be reviewed annually by ATLSS personnel with the potential for revision.

Additional charges will be applied according to the attached tables in Section 6.2 (for NEES projects) and Section 6.3 (for non-NEES projects). The space use charges are intended to help cover the cost of maintaining the ATLSS Lab infrastructure, including, the strong floor and reaction walls. Other charges will allow recharging (e.g., for strain gages) or maintenance (e.g., non-NEES actuators) of the respective equipment.

In addition, NEES research projects are responsible for all fees and shipping costs from equipment and services provided by off-campus contractors. NEES projects are responsible for all travel costs associated with the project. This includes lodging, per diem, airline fares, rental cars, mileage reimbursement and parking fees.

6.1 Scope of Services Covered by the NEES Operations and Maintenance Budget

A basic scope of services is available to NEES projects through the NEES Operations and Maintenance budget. These services/activities are outlined in the table below. Specific questions regarding what is or is not covered under the Operations and Maintenance budget should be addressed to the NEES Facility Operations Manager.

Service/Activity Covered under NEES Operations and Maintenance
Maintaining fixtures related to NEES equipment
Providing safety and risk management for staff and visitors
Maintaining all NEES equipment at full function
Operation of NEES equipment during NEES-related activities*
Repair/replacement of failed or damaged NEES equipment, assuming damage was not caused specifically by a NEES research project (which could then be liable)
Reconfiguration of equipment for NEES-related activities*
Maintaining all NEES instrumentation at full function
Operation of NEES instrumentation during NEES-related activities*
Assisting researchers with NEES sensor/instrument installation+
Repair/replacement of failed or damaged NEES instrumentation, assuming damage was not caused specifically by a NEES research project (which could then be liable)

Reconfiguration of instrumentation for NEES-related activities*
All services associated with onsite NEES-related training activities
Assisting NEES researchers with laboratory cost estimation
Assisting NEES researchers with proposal development (laboratory, equipment, and infrastructure)
Assisting NEES researchers with post-award planning and design (laboratory, equipment, and infrastructure)
Training activities associated with equipment operation
Training activities associated with site safety
Video conferencing support
Data transfer to NEES data repository
Office space and Ethernet access
Liaison services with local contractors

* NEES-related activities include: NEESR or NEES-approved shared-use research projects, training, maintenance, calibration, safety, education, and outreach activities

+ O&M will burden the cost for application of NEES sensors only; research project is responsible for cost associated with installation of non-NEES instrumentation

Additional services and use of non-NEES equipment are available at additional costs. These are considered as research costs that are to be covered by NEES research projects. Costs for these services, as determined using the rate schedule in Section 6.2 for equipment and the table below for Services/Activities, will be billed to the individual NEES research projects.

Service/Activity Not Covered under NEES Operations and Maintenance
Construction of test specimens, including receiving, fabrication, assembly, demolition, and disposal
Construction of experiment-specific test fixtures, including labor and materials associated with receiving, fabrication, assembly, demolition, and disposal
Services associated with use of non-NEES facilities, equipment, or instrumentation (including machining, welding, universal testing machines, non-NEES actuators, etc.)
Time associated with purchases required to support specific research project
Acquisition of miscellaneous materials and supplies specific to the project, including consumables, special tools, wires and cables, strain gages, instruments not available at the RTMD Facility, and special instrument mounting devices.
Development of special instrumentation and data-acquisition capabilities that are not available in the existing NEES facility.
Special software development and integration
Modification of existing electronic system and network
Materials testing
Laboratory floor and wall space use
Space use for receiving, assembly, and storage of fixtures and specimens

6.2 Rate Schedule for RTMD Facility, ATLSS, and Fritz Labs - NEES Projects

Tables 6-1 through 6-6 apply to rates associated with **NEES projects only** (non-NEES projects are referred to Tables 6-7 through 6-12 for applicable costs). NEES projects are defined as projects receiving funding through the NSF for use of the NEES equipment or projects that have received approval by NEEScomm for shared-use access, as per the NEEScomm Shared-Use Partnering Policy.

Note: All costs in subsequent tables are direct cost only (personnel costs also include employee benefits as noted in Table 6-3). All costs will be subject to Lehigh University's current indirect cost rate. Contact RTMD Site Operations Manager for university's current indirect cost rate.

Table 6-1

ANNUAL PROJECT FEE			
Based on total test program budget (including indirect cost) for portion and time frame of research program that utilizes Lehigh University's ATLSS Laboratory			
Calculated by multiplying the total test program budget (attributed to activity within ATLSS Laboratory) * annual project fee percentage / 12 (for the number of months in one year) * the number of months utilizing the ATLSS Laboratory			
Example: Total budget for NEESR to utilize Lehigh's ATLSS laboratory = $50,000 and projects 3 months utilization of laboratory			
Project Fee = $50,000 * 1 % annual project fee / 12 months in year * 3 months in lab = $500/12*3 = $125			
	Unit of Measure	**Academic/ Sponsored**	**External Testing & Use**
Annual Project Fee	Per project	1 %	2 %

Table 6-2

FLOOR and WALL SPACE , and RED BRACING FRAME - ATLSS Laboratory			
** Note: Floor space/wall space charge is applicable to strong floor/reaction wall in laboratory's south bay (excluding red bracing frame fixture which is explained below) and to the steel test frame/wall grillage system in laboratory's north bay.*			
Floor Space* (excludes floor space within red bracing frame fixture)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Floor Space < 500 sq ft	Per day	$0	$50
Floor Space to 1000 sq ft	Per day	$50	$100
Floor Space to 1500 sq ft	Per day	$100	$200
Floor Space to 2000 sq ft	Per day	$150	$300
Floor Space to 2500 sq ft	Per day	$200	$400
Floor Space to 3000 sq ft	Per day	$250	$500
Floor Space to 3500 sq ft	Per day	$300	$600
Floor Space to 4000 sq ft	Per day	$400	$800
Wall Space			

Calculated by multiplying applicable floor space daily rate by wall space occupancy/ blockage factor (provided below)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Wall space < 30 sq ft	-----	1.0	1.0
Wall space to 30 sq ft	-----	1.3	1.3
Wall space to 40 sq ft	-----	1.6	1.6
Wall space to 50 sq ft	-----	2.0	2.0
ATLSS Red Bracing Frame**			
ATLSS Bracing Frame Fixture**	Per project per calendar year	$15,000	$15,000
*** Projects whose floor and/or wall plan footprint lie within the red bracing frame fixture are charged a $15,000 per project <u>per calendar year</u> usage fee in place of being charged per square foot for floor space and per foot for wall space for this area. Projects whose floor space footprint and wall space footprint fall outside of the red bracing frame but which utilize the outside of the red bracing frame as a support fixture are subject to the standard floor and wall space use fees as outlined above for projects whose footprint falls outside of the red bracing frame fixture.*			

Table 6-3

PERSONNEL – Labor			
ATLSS Staff (includes employee benefits, does not include indirect cost)			
Personnel	**Unit of Measure**	**Service/Activity covered under NEES O&M (per Section 6.1)**	**Service/Activity not covered under NEES O&M (per Section 6.1)**
ATLSS Laboratory Manager	Per hour	$0	$96
Laboratory Foreman	Per hour	$0	$43
Laboratory Technicians	Per hour	$0	$39
Instrumentation Leader	Per hour	$0	$58
Instrumentation Technicians	Per hour	$0	$53
ATLSS IT Manager	Per hour	$0	$62
Administrative Assistant	Per hour	$0	$35
NEES Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)			
Personnel	**Unit of Measure**	**Service/Activity covered under NEES O&M (per Section 6.1)**	**Service/Activity not covered under NEES O&M (per Section 6.1)**
NEES Operations Manager	Per hour	$0	$69
IT Systems Administrator	Per hour	$0	$68
Software Developer	Per hour	$0	$68

Table 6-4

NEES EQUIPMENT/NEES INSTRUMENTATION
NEES Equipment

Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NEES Hydraulic System (NEES actuators)	Setup project per year	$0	$0
- Static per actuator	Per day	$0	$0
- Dynamic per actuator	Per day	$0	$0
- Fatigue to 5M per actuator	Per M cycles	$0	$0
- Fatigue 5M-50M per actuator	Per M cycles	$0	$0
- Fatigue >50M per actuator	Per M cycles	$0	$0
NEES Accumulator System	Setup per project per year	$0	$0
- Accumulator discharge	Per discharge	$0	$0
NEES Control System (Pulsar)	Setup per project	$0	$0
- NEES Control System	Per test day	$150	$600
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate (based on cycle count) for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects (both Academic/Sponsored and External Use & Testing) will not be subject to static test charges for setting load limits for fatigue tests if the loads in such tests do not exceed the fatigue test load range. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day rate	2.5*day rate
- Monthly rate (>2 weeks/calendar month)		2.5*week rate	2.5*week rate
NEES Instrumentation (Charges per instrument, regardless of quantity)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NEES Data Acquisition System (Pacific Instruments)	Per day	$0	$0
NEES Accelerometers (monoaxial)	Per day	$0	$0
NEES Accelerometers (triaxial)	Per day	$0	$0
NEES Temposonics	Per day	$0	$0
NEES LVDTs	Per day	$0	$0
NEES Inclinometers	Per day	$0	$0
NEES Differential Pressure Transducers	Per day	$0	$0
Web Camera	Setup per camera per project	$0	$0
- Axis 2401 fixed network	Per test day	$0	$0
- Axis 205 fixed network	Per test day	$0	$0

- Sony SNC-RZ30N portable network	Per test day	$0	$0
Agilent Power Supply	Per instrument	$0	$0
Agilent Volt Meter	Per instrument	$0	$0
Note: Instrumentation subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day rate	2.5*day rate
- Monthly rate (>2 weeks/calendar month)		2.5*week rate	2.5*week rate

Table 6-5

Non-NEES EQUIPMENT/non-NEES INSTRUMENTATION			
ATLSS LABORATORY			
Non-NEES Equipment			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
ATLSS Hydraulic System (non-NEES actuators)	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600
- Dynamic per actuator*	Per test day	$250	$1000
- Fatigue to 5M per actuator	Per M cycles	$162	$650
- Fatigue 5M-50M per actuator	Per M cycles	$100	$400
- Fatigue 50M-200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Enerpac Pumping System	Per test day	$0	$0
Enerpac Jacks	Per test day	$0	$0
Manlift	Per test day	$0	$0
ATLSS Control System	Setup per project	$50	$200
- MTS Flex System*	Per test day	$20	$70
- MTS 458 System*	Per test day	$12	$45
- Wineman System*	Per test day	$12	$45
- Vickers System*	Per test day	$10	$40
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Non-NEES Instrumentation (Charges dependent on quantity of instrumentation utilized)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Trilion 3-D Image Correlation System	-----	-----	-----
- Static	Per test day (not subject to weekly and monthly rates)	$285	$1140
- Dynamic	Per test day (not subject to weekly and monthly rates)	$570	$2280
DaqScribe High Speed Data Acquisition System	Per test day (not subject to weekly and monthly rates)	$125	$500
Data Acquisition System	-----	-----	-----
- To 16 channels*	Per test day	$38	$150
- To 32 channels*	Per test day	$75	$300
- 33 - 64 channels*	Per test day	$100	$400
- 65 - 96 channels*	Per test day	$125	$500
- >96 channels*	Per test day	$150	$600
- CR9000 data logger*	Per test day	$81	$325
- CR5000 data logger*	Per test day	$56	$225
- Daytronics*	Per test day	$25	$100
Strain gage conditioners	Per test day	-----	-----
- 1 - 8 channels*	Per test day	$5	$20
- 9 - 16 channels*	Per test day	$10	$40
- 17 - 32 channels*	Per test day	$20	$80
- 33 - 64 channels*	Per test day	$30	$120
- > 64 channels*	Per test day	$40	$160
Strain Indicator	Per test day	$5	$20
Peak Reader	Per test day	$5	$20
Precision Voltmeter	Per test day	$10	$30
Power Supply	Per test day	$0	$0
LVDTs, Temposonics, Displacement Transducers	-----	-----	-----
- 1 - 8*	Per test day	$10	$40
- 9 - 16*	Per test day	$15	$60
- 17 - 24*	Per test day	$20	$80
- 25 - 32*	Per test day	$25	$100
- 33 - 40*	Per test day	$30	$120
- 41 - 48*	Per test day	$35	$140
- 49 - 56*	Per test day	$40	$160
- 57 - 64*	Per test day	$45	$180
- > 64*	Per test day	$50	$200
Plastic slides	-----	-----	-----
- 1 - 8*	Per test day	$5	$20
- 9 - 16*	Per test day	$10	$40
- > 16*	Per test day	$15	$60

String pots	-----	-----	-----
- 1 - 4*	Per test day	$10	$40
- 5 - 8*	Per test day	$15	$60
- 9 - 12*	Per test day	$20	$80
- > 12*	Per test day	$25	$100
Rotation meters, Inclinometers	-----	-----	-----
- 1 - 8*	Per test day	$10	$40
- 9 - 16*	Per test day	$15	$60
- > 16*	Per test day	$20	$80
Laser Displacement Sensors*	Per test day	$15	$60
Load cell*	Per test day	$10	$40
Calibration stand*	Per test day	$8	$30
Web Camera	Setup per camera per project	$15	$60
Nikon D-SLR Camera*	Per test day	$10	$40
Camcorder*	Per test day	$5	$20
DVR*	Per test day	$5	$20
Note: Instrumentation followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
FRITZ LABORATORY			
Non-NEES Equipment			
Amsler Hydraulic System	Setup per project per year	$125	$500
- Static per actuator*	Per test day	$75	$300
- Fatigue to 5M per actuator	Per M cycles	$75	$300
- Fatigue 5M-50M per actuator	Per M cycles	$50	$200
- Fatigue 50M-200M per actuator	Per M cycles	$25	$100
- Fatigue >200M per actuator	Per M cycles	$10	$40
MTS/Vickers Hydraulic	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600
- Fatigue to 5M per actuator	Per M cycles	$150	$600
- Fatigue 5M-50M per actuator	Per M cycles	$100	$400
- Fatigue 50M-200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Amsler Alternating Stress Machine	Per M cycles	$75	$300
Baldwin 5000 kip Universal*	Per test day	$250	$1000
Baldwin 5000 kip Universal*	Overnight	$100	$400
Riehle 800 kip Universal*	Per test day	$150	$600

Southwark Emery 300 kip Universal	Per test day	$75	$300
Drop Weight Tester	Per test day	$15	$60
Rexroth Pumping System	Per test day	$100	$400
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Table 6-6

ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT			
ATLSS LABORATORY			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Large Scale Furnace	Per test day	$50	$200
Materials Testing	-----	-----	-----
- Welding equipment	Per hour	$5	$10
- Heat treating furnace	Per hour	$10	$20
Mechanical Testing	-----	-----	-----
- 2670 kN (600 kip) Universal	Per day	$200	$400
- 267 kN (60 kip) Universal	Per day	$50	$100
245 kN Servo	-----	-----	-----
- Static	Per hour	$10	$15
- < 5 M cycles	Per M cycles	$25	$75
- 5 - 50 M cycles	Per M cycles	$25	$35
- > 50 M cycles	Per M cycles	$10	$15
Charpy V-notch Test Machine	Per day	$50	$100
Metallography Laboratory	-----	-----	-----
- Sample preparation	Per sample	$5	$10
- Hardness: Rockwell and Vickers	Per hour	$10	$15
- Optical microscope	Per hour	$10	$15

Additional Notes:

1. The 22,242 kN testing machine at Fritz Laboratory is also available for use by NEES researchers. Costs will be developed on a per test basis, based on the complexity of the test

setup. The Manager, Structural Testing will assist in developing estimates for the use of this machine.

2. All costs require indirect cost to be applied to the stated rates (stated rates are only direct cost, with the exception of personnel which also includes employee benefits). Contact the RTMD site operations manager for current Lehigh University indirect cost rates.
3. Space rates (both floor and wall) are applicable for total calendar days associated with a given project. Such rates are not subject to the special weekly and monthly rates noted above for select equipment and instrumentation.

6.3 Rate Schedule for RTMD Facility, ATLSS, and Fritz Labs - Non-NEES Projects

Tables 6-7 through 6-12 apply to rates associated with **non-NEES projects only** (NEES projects are referred to Tables 6-1 through 6-6 for applicable costs). NEES projects are defined as projects receiving funding through the NSF for use of the NEES equipment or projects that have received approval by NEEScomm for shared-use access, as per the NEEScomm Shared-Use Partnering Policy. Non-NEES projects are projects that do not qualify per the definition above.

Note: All costs in subsequent tables are direct cost only (personnel costs also include employee benefits as noted in Table 6-9). All costs will be subject to Lehigh University's current indirect cost rate. Contact RTMD Site Operations Manager for university's current indirect cost rate. For use fees assessed per day, the charges will be applied in either half day or full day increments.

Table 6-7

ATLSS PROJECT FEE			
The ATLSS Project Fee is assessed as a *one-time* charge at the onset of a project at the percentages noted below. The fee is assessed *on the total test program* budget. The fee is assessed to cover costs associated with forklifts, cranes, hydraulic pumps, tools, filters, etc. required for daily operation at ATLSS.			
	Unit of Measure	**Academic/ Sponsored**	**External Testing & Use**
ATLSS Project Fee	Per project	1%	2%

Table 6-8

FLOOR and WALL SPACE, and RED BRACING FRAME - ATLSS Laboratory			
** Note: Floor space/wall space charge is applicable to strong floor/reaction wall in laboratory's south bay (excluding red bracing frame fixture which is explained below) and to the steel test frame/wall grillage system in laboratory's north bay.*			
Floor Space* (excludes floor space within red bracing frame fixture)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing &**

			Use
Floor Space < 500 sq ft	Per calendar day	$0	$50
Floor Space to 1000 sq ft	Per calendar day	$50	$100
Floor Space to 1500 sq ft	Per calendar day	$100	$200
Floor Space to 2000 sq ft	Per calendar day	$150	$300
Floor Space to 2500 sq ft	Per calendar day	$200	$400
Floor Space to 3000 sq ft	Per calendar day	$250	$500
Floor Space to 3500 sq ft	Per calendar day	$300	$600
Floor Space to 4000 sq ft	Per calendar day	$400	$800
Wall Space* (excludes wall space within red bracing frame fixture)			
Calculated by multiplying applicable floor space daily rate by wall space occupancy/blockage factor (provided below)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Wall space < 30 sq ft	-----	1.0	1.0
Wall space to 30 sq ft	-----	1.3	1.3
Wall space to 40 sq ft	-----	1.6	1.6
Wall space to 50 sq ft	-----	2.0	2.0
ATLSS Red Bracing Frame**			
ATLSS Bracing Frame Fixture**	Per project per calendar year	$15,000	$15,000
*** Projects whose floor and/or wall plan footprint lie within the red bracing frame fixture are charged a $15,000 per project <u>per calendar year</u> usage fee in place of being charged per square foot for floor space and per foot for wall space for this area. Projects whose floor space footprint and wall space footprint fall outside of the red bracing frame but which utilize the outside of the red bracing frame as a support fixture are subject to the standard floor and wall space use fees as outlined above for projects whose footprint falls outside of the red bracing frame fixture.*			

Table 6-9

PERSONNEL - Labor			
ATLSS Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)			
Personnel	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Manager, Structural Testing	Per hour	$94	$96
Laboratory Operations Manager	Per hour	$42	$43
Laboratory Technicians	Per hour	$38	$39
Instrumentation Leader	Per hour	$57	$58
Instrumentation Technicians	Per hour	$52	$53
ATLSS IT Manager	Per hour	$61	$62
Administrative Assistant	Per hour	$34	$35
NEES Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)			

Personnel	Unit of Measure	Academic/ Sponsored	External Testing & Use
NEES Operations Manager	Per hour	$67	$69
IT Systems Administrator	Per hour	$67	$68
Software Developer	Per hour	$67	$68

Table 6-10

NEES EQUIPMENT/NEES INSTRUMENTATION			
NEES Equipment			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NEES Hydraulic System (NEES actuators)	Setup per project per year	$250	$1000
- Static per actuator	Per test day	$200	$800
- Dynamic per actuator	Per test day	$300	$1200
- Fatigue to 5M per actuator	Per M cycles	$200	$800
- Fatigue 5M-50M per actuator	Per M cycles	$150	$600
- Fatigue 50M-200M per actuator	Per M cycles	$100	$400
- Fatigue >200M per actuator	Per M cycles	$50	$200
NEES Accumulator System	Setup per project per year	$150	$600
- Accumulator discharge	Per discharge	$100	$400
NEES Control System (Pulsar)	Setup per project	$200	$600
- NEES Control System	Per test day	$150	$600
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate (based on cycle count) for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects (both Academic/Sponsored and External Use & Testing) will not be subject to static test charges for setting load limits for fatigue tests if the loads in such tests do not exceed the fatigue test load range. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
NEES Instrumentation (Charges per instrument, regardless of quantity)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NEES Data Acquisition System (Pacific Instruments)	Per test day	$150	$600
NEES Accelerometers (monoaxial)	Per test day	$15	$60

NEES Accelerometers (triaxial)	Per test day	$20	$80
NEES Temposonics	Per test day	$15	$60
NEES LVDTs	Per test day	$10	$40
NEES Inclinometers	Per test day	$15	$60
NEES Differential Pressure Transducers	Per test day	$15	$60
Web Camera	Setup per camera per project	$15	$60
- Axis 2401 fixed network	Per test day	$10	$40
- Axis 205 fixed network	Per test day	$10	$40
- Sony SNC-RZ30N portable network	Per test day	$10	$40
Agilent Power Supply	Per instrument	$10	$40
Agilent Volt Meter	Per instrument	$15	$60
Note: Instrumentation subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Table 6-11

Non-NEES EQUIPMENT/non-NEES INSTRUMENTATION			
ATLSS LABORATORY			
Non-NEES Equipment			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
ATLSS Hydraulic System (non-NEES actuators)	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600
- Dynamic per actuator*	Per test day	$250	$1000
- Fatigue to 5M per actuator	Per M cycles	$162	$650
- Fatigue 5M-50M per actuator	Per M cycles	$100	$400
- Fatigue 50M-200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Enerpac Pumping System	Per test day	$0	$0
Enerpac Jacks	Per test day	$0	$0
Manlift	Per test day	$0	$0
ATLSS Control System	Setup per project	$50	$200
- MTS Flex System*	Per test day	$20	$70
- MTS 458 System*	Per test day	$12	$45
- Wineman System*	Per test day	$12	$45
- Vickers System*	Per test day	$10	$40
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			

Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
Non-NEES Instrumentation (Charges dependent on quantity of instrumentation utilized)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Trilion 3-D Image Correlation System	-----	-----	-----
- Static	Per test day (not subject to weekly and monthly rates)	$285	$1140
- Dynamic	Per test day (not subject to weekly and monthly rates)	$570	$2280
DaqScribe High Speed Data Acquisition System	Per test day (not subject to weekly and monthly rates)	$125	$500
Data Acquisition System	-----	-----	-----
- To 16 channels*	Per test day	$38	$150
- To 32 channels*	Per test day	$75	$300
- 33 - 64 channels*	Per test day	$100	$400
- 65 - 96 channels*	Per test day	$125	$500
- >96 channels*	Per test day	$150	$600
- CR9000 data logger*	Per test day	$81	$325
- CR5000 data logger*	Per test day	$56	$225
- Daytronics*	Per test day	$25	$100
Strain gage conditioners	Per test day	-----	-----
- 1 - 8 channels*	Per test day	$5	$20
- 9 - 16 channels*	Per test day	$10	$40
- 17 - 32 channels*	Per test day	$20	$80
- 33 - 64 channels*	Per test day	$30	$120
- > 64 channels*	Per test day	$40	$160
Strain Indicator	Per test day	$5	$20
Peak Reader	Per test day	$5	$20
Precision Voltmeter	Per test day	$10	$30
Power Supply	Per test day	$0	$0
LVDTs, Temposonics, Displacement Transducers	-----	-----	-----
- 1 - 8*	Per test day	$10	$40
- 9 - 16*	Per test day	$15	$60
- 17 - 24*	Per test day	$20	$80

- 25 - 32*	Per test day	$25	$100
- 33 - 40*	Per test day	$30	$120
- 41 - 48*	Per test day	$35	$140
- 49 - 56*	Per test day	$40	$160
- 57 - 64*	Per test day	$45	$180
- > 64*	Per test day	$50	$200
Plastic slides	-----	-----	-----
- 1 - 8*	Per test day	$5	$20
- 9 - 16*	Per test day	$10	$40
- > 16*	Per test day	$15	$60
String pots	-----	-----	-----
- 1 - 4*	Per test day	$10	$40
- 5 - 8*	Per test day	$15	$60
- 9 - 12*	Per test day	$20	$80
- > 12*	Per test day	$25	$100
Rotation meters, Inclinometers	-----	-----	-----
- 1 - 8*	Per test day	$10	$40
- 9 - 16*	Per test day	$15	$60
- > 16*	Per test day	$20	$80
Laser Displacement Sensors*	Per test day	$15	$60
Load cell*	Per test day	$10	$40
Calibration stand*	Per test day	$8	$30
Web Camera	Setup per camera per project	$15	$60
Nikon D-SLR Camera*	Per test day	$10	$40
Camcorder*	Per test day	$5	$20
DVR*	Per test day	$5	$20
Note: Instrumentation followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
FRITZ LABORATORY			
Non-NEES Equipment			
Amsler Hydraulic System	Setup per project per year	$125	$500
- Static per actuator*	Per test day	$75	$300
- Fatigue to 5M per actuator	Per M cycles	$75	$300
- Fatigue 5M-50M per actuator	Per M cycles	$50	$200
- Fatigue 50M-200M per actuator	Per M cycles	$25	$100
- Fatigue >200M per actuator	Per M cycles	$10	$40
MTS/Vickers Hydraulic	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600

- Fatigue to 5M per actuator	Per M cycles	$150	$600
- Fatigue 5M-50M per actuator	Per M cycles	$100	$400
- Fatigue 50M-200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Amsler Alternating Stress Machine	Per M cycles	$75	$300
Baldwin 5000 kip Universal*	Per test day	$250	$1000
Baldwin 5000 kip Universal*	Overnight	$100	$400
Riehle 800 kip Universal*	Per test day	$150	$600
Southwark Emery 300 kip Universal	Per test day	$75	$300
Drop Weight Tester	Per test day	$15	$60
Rexroth Pumping System	Per test day	$100	$400
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Table 6-12

ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT			
ATLSS LABORATORY			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Large Scale Furnace	Per test day	$50	$200
Materials Testing	-----	-----	-----
- Welding equipment	Per hour	$5	$10
- Heat treating furnace	Per hour	$10	$20
Mechanical Testing	-----	-----	-----
- 2670 kN (600 kip) Universal	Per day	$200	$400
- 267 kN (60 kip) Universal	Per day	$50	$100
245 kN Servo	-----	-----	-----
- Static	Per hour	$10	$15
- < 5 M cycles	Per M cycles	$25	$75
- 5 - 50 M cycles	Per M cycles	$25	$35
- > 50 M cycles	Per M cycles	$10	$15

Charpy V-notch Test Machine	Per day	$50	$100
Metallography Laboratory	-----	-----	-----
- Sample preparation	Per sample	$5	$10
- Hardness: Rockwell and Vickers	Per hour	$10	$15
- Optical microscope	Per hour	$10	$15

Additional Notes:

4. The 22,242 kN testing machine at Fritz Laboratory is also available for use by NEES researchers. Costs will be developed on a per test basis, based on the complexity of the test setup. The Manager, Structural Testing will assist in developing estimates for the use of this machine.
5. All costs require indirect cost to be applied to the stated rates (stated rates are only direct cost, with the exception of personnel which also includes employee benefits). Contact the RTMD site operations manager for current Lehigh University indirect cost rates.
6. Space rates (both floor and wall) are applicable for total calendar days associated with a given project. Such rates are not subject to the special weekly and monthly rates noted above for select equipment and instrumentation.

7 Facility Organization

This chapter describes the staff organization and capabilities of the RTMD earthquake simulation facility at Lehigh University.

7.1 Overview

It is important to understand that the RTMD earthquake simulation facility is not a stand-alone facility. The RTMD facility is a component of the existing ATLSS Center at Lehigh. All NEES experiments are expected to require the use of both ATLSS and RTMD facility components. The ATLSS Center consists of the strong floor/reaction wall/hydraulic pump system/multi-directional laboratory that are utilized by the RTMD facility. The RTMD facility adds a significant enhancement to the ATLSS hydraulic system capability through the installation of the 3030 liters (800 gallons), 24 MPa (3500 psi) hydraulic oil accumulator, and the high load rate actuators and servo-valves. Additional enhancements include the 8 channel controller and the 264 channel data acquisition system. All of these components are described in detail in Section 1 of this manual. Thus, the RTMD facility and ATLSS share many common components, not all of which were funded by the NSF NEES Program. Likewise, the staff of the RTMD facility cannot be separated from that of the ATLSS Center. Many of the laboratory functions overlap both the NEES and ATLSS programs at Lehigh University. The responsibilities of the staff thereby overlap both research programs. NEES operation and maintenance (O&M) funding reflects this overlap for both staff and facilities. Neither the staff costs nor the facility maintenance costs are fully funded by the O&M. Thus, NEES projects may be required to cover a portion of the costs of both the staff and the facility maintenance if project costs exceed the O&M allocation for NEES projects.

As an example of this functional overlap for the staff, the ATLSS Laboratory Manager is responsible for all tests conducted in the lab - both NEES and non-NEES. The Lab Manager is not fully funded by the NEES O&M. This is typical for all personnel.

Following are listings of the key personnel at both the RTMD facility and ATLSS Center. Groupings are according to the primary source of support.

7.2 RTMD Organization

Principal Investigator	James M. Ricles, Ph.D., P.E. (jmr5@lehigh.edu)
Co-Principal Investigator	Richard Sause, Ph.D., P.E. (rs0c@lehigh.edu)
Operations Manager	Gary Novak (gsn207@lehigh.edu)
Systems Administrator	Thomas M. Marullo (tmm3@lehigh.edu)
Software Developer	Thomas M. Marullo (tmm3@lehigh.edu)

7.3 ATLSS Organization

Director	Richard Sause, Ph.D. (rs0c@lehigh.edu)
Deputy Director	James M. Ricles, Ph.D. (jmr5@lehigh.edu)
Administrative Director	Chad S. Kusko, Ph.D. (chk205@lehigh.edu)
Administrative Assistant	Elizabeth MacAdam (es00@lehigh.edu)
Accounts Manager	Doris Oravec (dao1@lehigh.edu)
Manager Structural Testing	Frank E. Stokes (fes2@lehigh.edu)
Laboratory Operations Manager	John P. Hoffner (jph3@lehigh.edu)
Instrumentation Manager	Edward A. Tomlinson (eat2@lehigh.edu)
Instrumentation Manager	Carl Bowman (cab6@lehigh.edu)
Materials Program Manager	Eric Kaufmann, Ph.D. (ek02@lehigh.edu)
Infrastructure Monitoring Program Manager	Richard Sause, Ph.D., P.E. (rs0c@lehigh.edu)
IT Systems Manager	Peter Bryan (pb02@lehigh.edu)
Web Developer	Peter Bryan (pb02@lehigh.edu)

7.4 ATLSS Research Center Facilities

The following describes the resources available to NEES researchers at the ATLSS Center.

7.4.1 Laboratory Technician Staff

The ATLSS Center maintains a staff of Laboratory Technicians to support the setup and removal of large scale experiments, and to maintain the hydraulic supply system and reaction wall facility. These technicians operate all of the lab mobile equipment: forklifts and overhead crane: for all functions. They also have the capability to form and pour concrete and fabricate reinforcing. They are skilled in steel fabrication and erection with significant experience in layout, fitting, burning welding, heat straightening and erection of both fixtures and specimens. Additional capabilities include hydraulic systems operation and maintenance. These technicians average 25 years experience in these construction related and maintenance functions. This staff works under the direction of the Laboratory Foreman.

7.4.2 Instrumentation Technician Staff

The ATLSS Center maintains a staff of Instrumentation Technicians to support the data acquisition and control functions for all experiments. Their functions include the maintenance and setup of the DAS control system computers, the installation of all instrumentation as required by individual experiments, and the maintenance of all electronic equipment required for large scale experimentation. These technicians have been trained in the use of all the newly acquired NEES equipment, including the Pacific Instruments DAS, Wineman servo controller system and the Servotest servo controller system. They are experienced in the application of all instrumentation used in structural experiments involving concrete, steel, fiber reinforced polymers, and composite materials. The average experience for these technicians is over 15 years. The Instrumentation Technicians are directed by the Instrumentation Manager.

7.4.3 ATLSS Structural Testing Lab

Accommodates both small scale and full size test structures composed of all materials, facilitated by a test floor measuring 40' by 102', and fixed reaction walls up to 50' high encircling three corners of the test floor. Multidirectional loads and motions can be applied allowing the study of the behavior of complete structures under a wide variety of load conditions.

Contact: Frank Stokes, fes2@lehigh.edu, (610) 758-5498

7.4.4 Fritz Engineering Lab

Features 800,000 lb and 5,000,000 lb universal testing machines, and a dynamic test bed with broad fatigue-testing capabilities, and a wide range of instrumentation. Founded in 1909 and enlarged to the present capacity in 1954. Designated as an ASCE Civil Engineering Landmark Structure.

Contact: Frank Stokes, fes2@lehigh.edu, (610) 758-5498

7.4.5 Mechanical Testing Laboratory

Capable of standard mechanical property tests of metallic, cementitious and composite construction materials. Features 60,000 and 600,000 lb universal testing machines, and Charpy V-Notch fracture toughness testing machine.

Contact: Dr. Eric Kaufmann, ek02@lehigh.edu, (610) 758-4250

7.4.6 Robert E. Stout Welding and Heat Treating Laboratory

The Robert D. Stout Welding and Joining Laboratory is equipped to produce test weldments by the shielded-metal-arc, gas-metal-arc, gas-tungsten-arc, and submerged-arc processes under accurately controlled parameters of voltage, current, and travel speed. In addition, the Laboratory has facilities for preparing specimens by sawing and flame-cutting and by heating and quenching for various tests that include slow-notch-bend, hardenability, fracture-toughness, weld-restraint-cracking, implant, tension, and creep-rupture testing.

Contact: Dr. John Gross, jhg5@lehigh.edu, (610) 758-5952

7.4.7 Metallography and Microscopy Laboratories

This facility 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.

Contact: Dr. Eric Kaufmann, ek02@lehigh.edu, (610) 758-4250

7.4.8 Computational Laboratory for Life-Cycle Structural Engineering

This facility is equipped with several high performance computer desktops providing a large number of advanced Life-Cycle, Reliability, Risk, Optimization, and Structural Engineering software applications. These applications are also available on the Laboratory's 64-bit quad core computational server, which is capable of speedily performing heavy-duty computational tasks.

Contact: Dr. Dan M. Frangopol, dmf206@lehigh.edu, (610) 758-6103

7.4.9 Laboratory of Advanced Integrated Technology for Intelligent Structures (LAITIS)

The Laboratory of Advanced Integrated Technology for Intelligent Structures (LAITIS) is focused on research and education in the areas of wireless sensor networks, structural health monitoring, advanced information technology for enhancement of civil infrastructure performance, structural dynamics and vibration. The lab is equipped with state-of-the-art vibration testing, sensor networks development and calibration equipments. In addition, the lab has a small-scale shaking table (18"x18"), which is used to simulate dynamic response of civil structures and prototype testbed experiments.

Contact: Dr. Shamim N. Pakzad, snp208@lehigh.edu, (610) 758-3566

7.4.10 Nondestructive Evaluation (NDE) 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 for both undergraduate and graduate research, and undergraduate instruction.

Contact: Dr. Stephen Pessiki, spp1@lehigh.edu, (610) 758-3494

7.4.11 ATLSS Infrastructure Monitoring Program Vehicle

The vehicle is used to increase the productivity and the safety of those involved with the Infrastructure Monitoring Program. The vehicle provides space for storing and transporting equipment, and for working in the field.

Contact: Ian Hodgson, ich2@lehigh.edu, (610) 758-6105