National Science Foundation

University of California at San Diego NHERI Natural Hazards Engineering Research Infrastructure

UC San Diego JACOBS SCHOOL OF ENGINEERING Structural Engineering

NHERI Lehigh Experimental Facility Description, Experimental Capabilities and Protocols

James Ricles, NHERI Lehigh PI
Lehigh University

Joint Researcher Workshop
UC San Diego, Lehigh & SimCenter

December 16-17, 2019
University of California, San Diego

LEHIGH NHERI Real-Time Multi-Directional Testing Facility

University of California at San Diego NHERI Natural Hazards Engineering Research Infrastructure

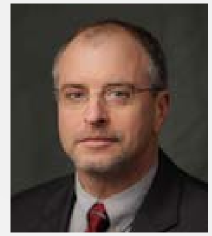
SIMCENTER COMPUTATIONAL MODELING AND SIMULATION CENTER

Outline

- NHERI Staff
- Experimental Capabilities
- Real-time Hybrid Simulation: Overview, NHERI Lehigh Developments
- Test Beds
- Equipment
- Experimental Protocols
- Telepresence and Data Management
- User Training

NHERI Lehigh EF Team

James Ricles, PI



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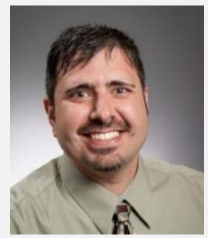
Liang Cao
Research Engr



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Capacity Building Partners

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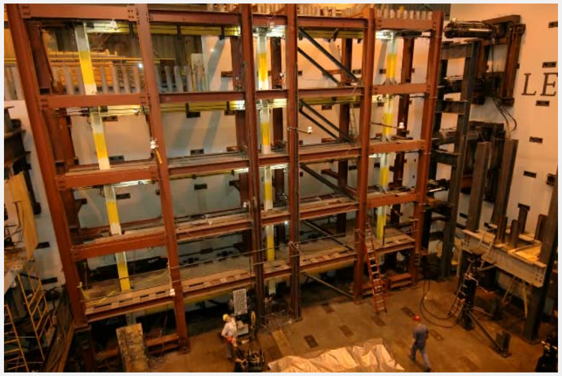
Adv. Sensors, Structural Monitoring
Lehigh Univ

Muhannad Suleiman
Soil-Structure Interaction
Lehigh Univ

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

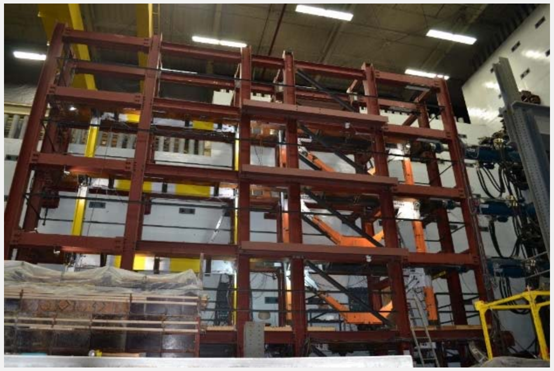
- Large-Scale Hybrid Simulation



HS EQ Simulation of Buildings with SC-MRF

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

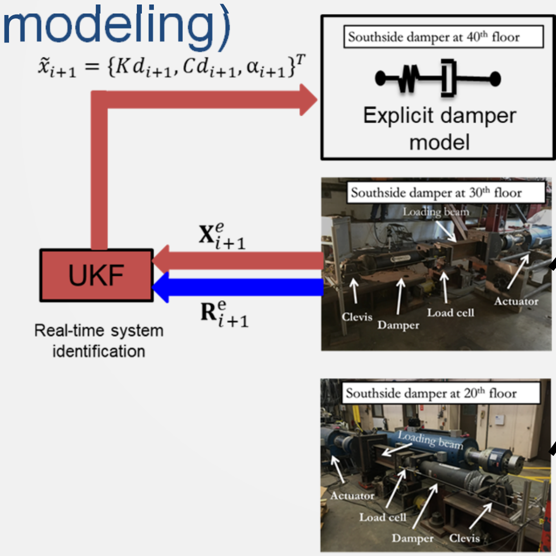
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation

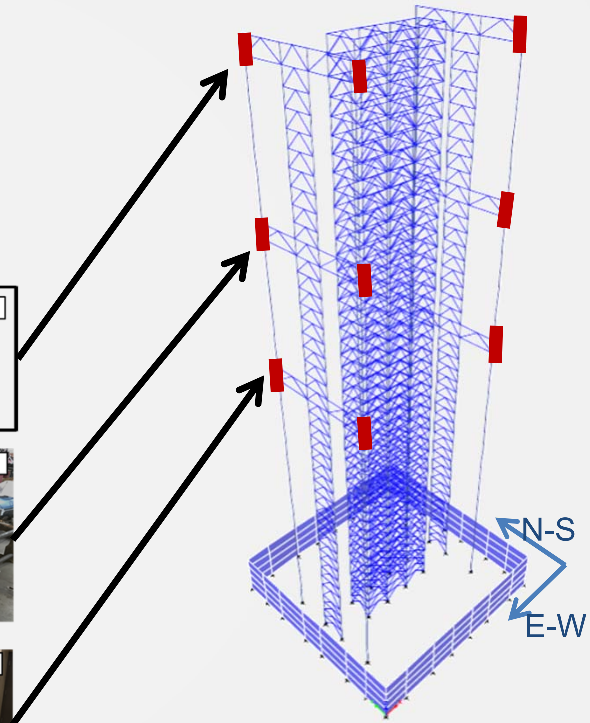


RTHS EQ Simulation of Buildings with Dampers

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)





RTHS Wind and EQ Simulation of Tall Buildings with Dampers

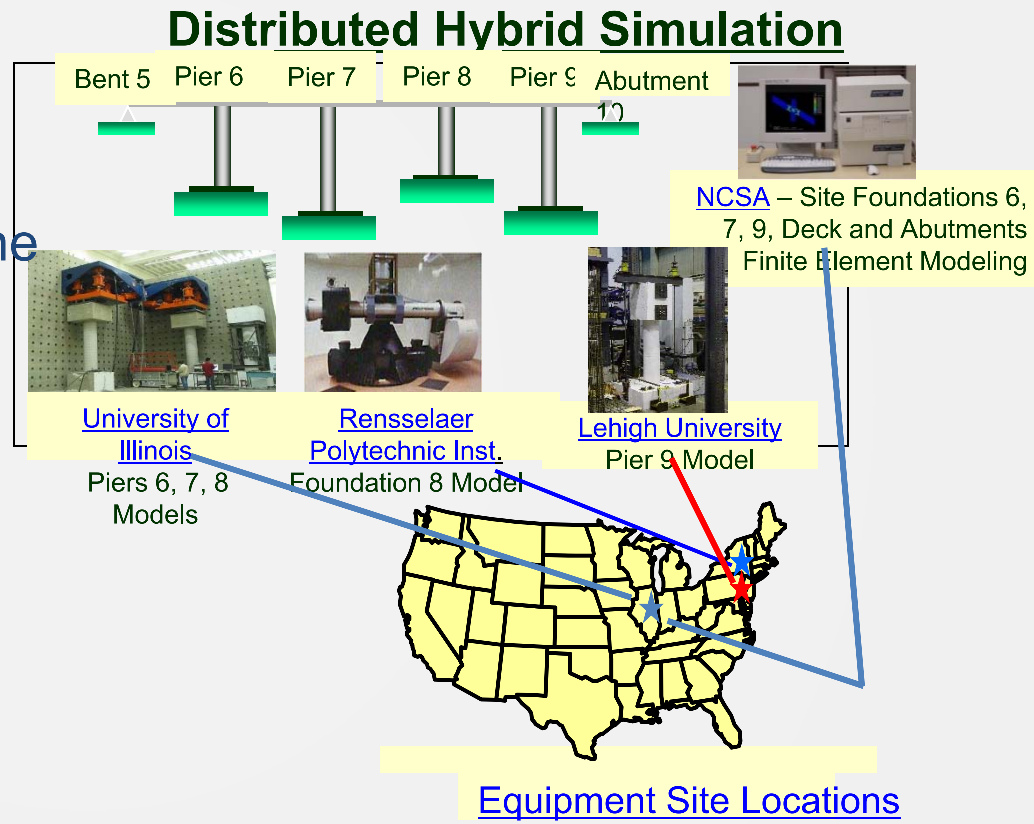
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures

RTHS EQ Simulation of Building with Multiple Dampers

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation

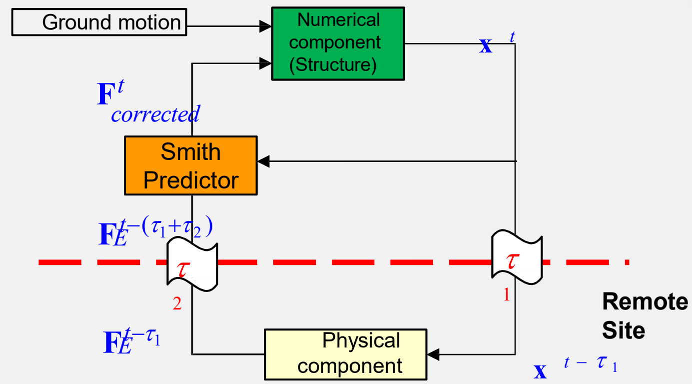


Distributed RTHS EQ Simulation of I-10 Collector Bridge

LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

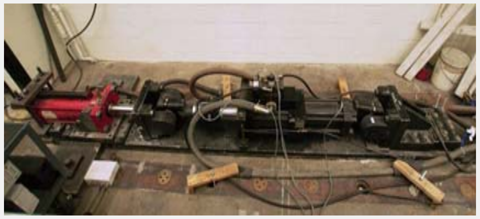
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation



Lehigh

UIUC



RTHS EQ Simulation of Building with MR Dampers (Kim, Christenson)

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)

Temperature Control Chamber

Characterization of Full-scale Semi-active and Passive Dampers

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)

Characterization of Large-scale RC Coupled Shear Wall System

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

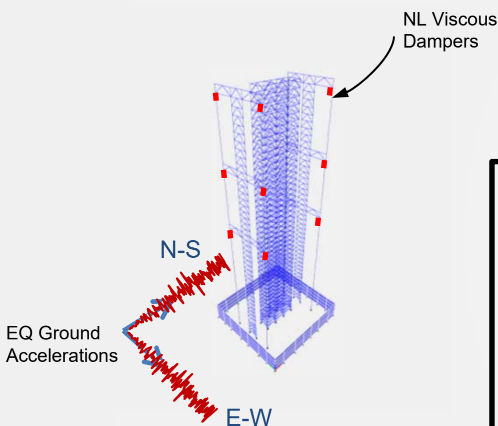
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating, Machine Learning-based modeling)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)
- Dynamic testing

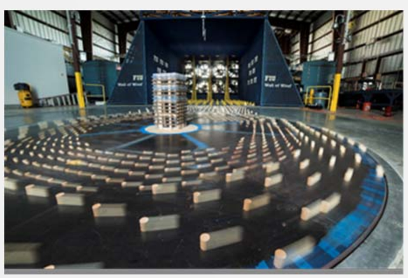
Multi-directional Dynamic Testing of Pipe Couplers

Overall Concept of Real-time Hybrid Simulation: Structural System Subject to Multi-Natural Hazards

Structural System

40-Story Building with Outriggers and Supplemental Dampers

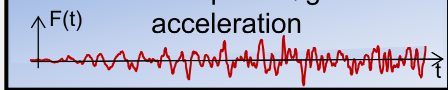




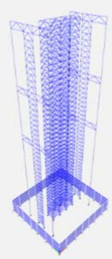
Wind Tunnel Tests NHERI@FIU
Wind Load Determination

Hybrid Earthquake Simulation Experiments

Real-time input EQ ground acceleration



Analytical substructure



(Modeled in the computer)

Cmd Displ $\mathbf{X}^{a}_{i+1}$

$\mathbf{R}^{a}_{i+1}$ *Restoring Force*

Simulation Coordinator

$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{R}^{a}_{i+1} + \mathbf{R}^{e}_{i+1} = \mathbf{F}^{a}_{i+1}$$

Integrates Eqns of Motion

Cmd Displ $\mathbf{X}^{e}_{i+1}$

$\mathbf{R}^{e}_{i+1}$ *Restoring Force*

Experimental substructure (dampers)

(Modeled in lab)

Real-time structural response

LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

RTHS: Implementation issues and challenges

Simulation coordinator

- ❑ Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative

  Preferred
- ❑ Fast communication

Analytical substructure

- ❑ Fast and accurate state determination procedure for complex, nonlinear structures

Experimental substructure

- ❑ Large capacity hydraulic system and dynamic actuators required
- ❑ Actuator kinematic compensation
- ❑ Robust control of dynamic actuators for large-scale structures

RTHS: Implementation solutions

Simulation coordinator

- ❑ Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative
- ❑ Fast communication

NHERI Lehigh Solutions

Explicit model-based integration algorithms

Numerical Integration Algorithms

Explicit Modified KR-α (MKR-α) Method

- Explicit Integration of Equations of Motion, Model-based
- Unconditionally Stable
- Controlled Numerical Damping – eliminate spurious high frequency noise

$\boldsymbol{\alpha_1}$, $\boldsymbol{\alpha_2}$, and $\boldsymbol{\alpha_3}$: model-based integration parameters

Velocity update: $\dot{\mathbf{X}}_{n+1} = \dot{\mathbf{X}}_n + \Delta t \boldsymbol{\alpha_1} \ddot{\mathbf{X}}_n$

Displacement update: $\mathbf{X}_{n+1} = \mathbf{X}_n + \Delta t \dot{\mathbf{X}}_n + \Delta t^2 \boldsymbol{\alpha_2} \ddot{\mathbf{X}}_n$

MKR-α: One parameter (ρ_∞) family of algorithms

- ρ_∞, Parameter controlling numerical energy dissipation
  - ρ_∞ = spectral radius when $\Omega = \omega \Delta t \rightarrow \infty$
  - varies in the range $0 \leq \rho_\infty \leq 1$
  - $\rho_\infty = 1$: No numerical energy dissipation
  - $\rho_\infty = 0$: Asymptotic annihilation

Stability: Root-Loci

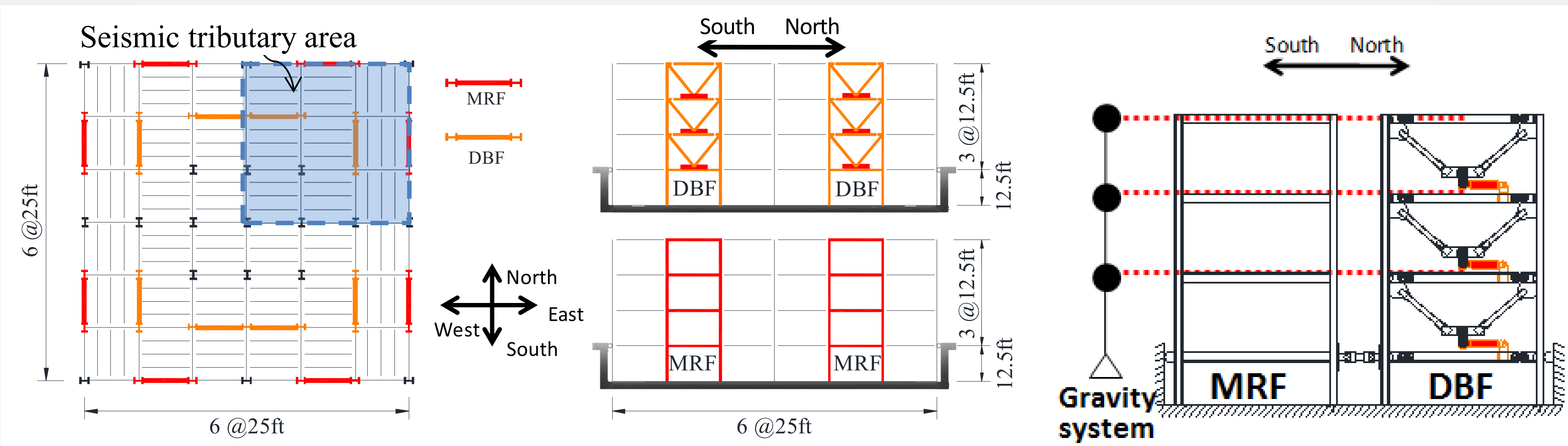
Controlled Numerical Damping

Kolay, C., and J.M. Ricles (2014). Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation. *Earthquake Engineering and Structural Dynamics*, 43(9), 1361–1380. http://doi.org/10.1002/eqe.2401

Kolay, C., and J.M. Ricles (2017) "Improved Explicit Integration Algorithms for Structural Dynamic Analysis with Unconditional Stability and Controller Numerical Dissipation," *Journal of Earthquake Engineering*, http://dx.doi.org/10.1080/13632469.2017.1326423.

Steel Structure with Nonlinear Viscous Dampers Studied using Large-scale RTHS

- **Prototype building**
  - 3-story, 6-bay by 6-bay office building located in Southern California
  - Moment resisting frame (MRF) with RBS beam-to-column connections, damped brace frame (DBF), gravity load system, inherent damping of building



Plan view of prototype building **Section view of prototype building** **Test structure**

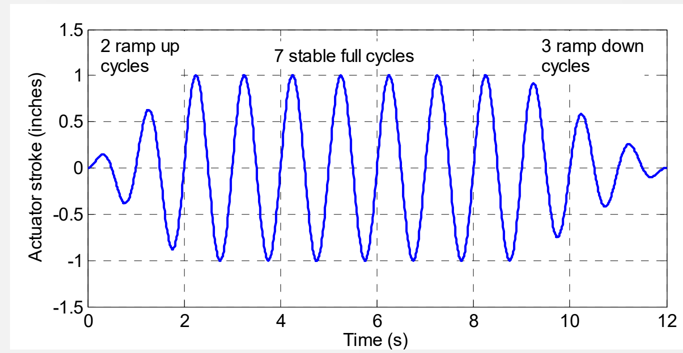
Dong, B., Sause, R., and J.M. Ricles, (2015) "Accurate Real-time Hybrid Earthquake Simulations on Large-scale MDOF Steel Structure with Nonlinear Viscous Dampers," Earthquake Engineering and Structural Dynamics, 44(12) 2035–2055, https://DOI.org/10.1002/eqe.2572.

Dong, B., Sause, R., and J.M. Ricles, (2016) "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 142(6) https://DOI.org/10.1061/(ASCE)ST.1943-541X.0001482.

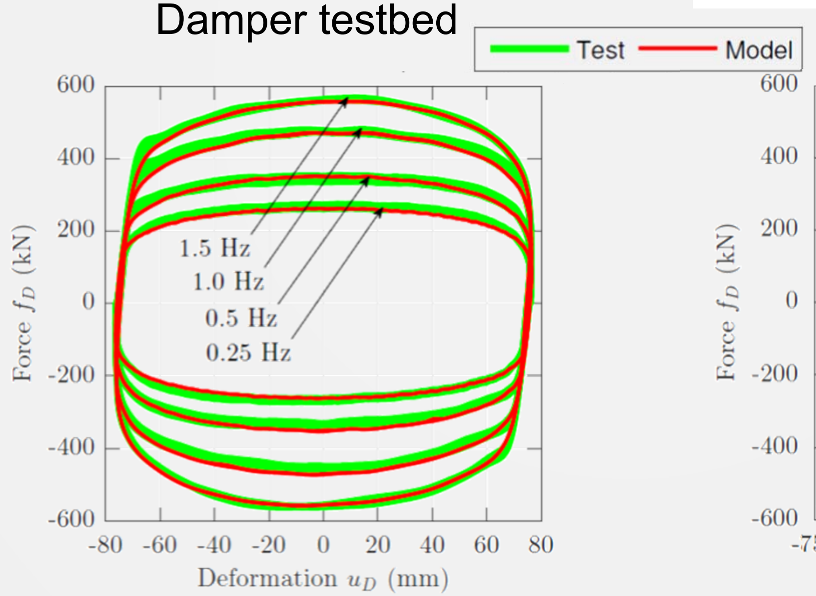
Nonlinear Viscous Dampers

Characterization testing

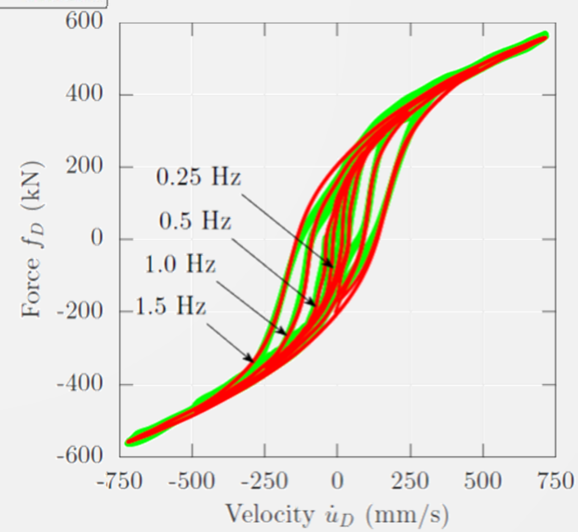
Damper testbed



Loading Protocol



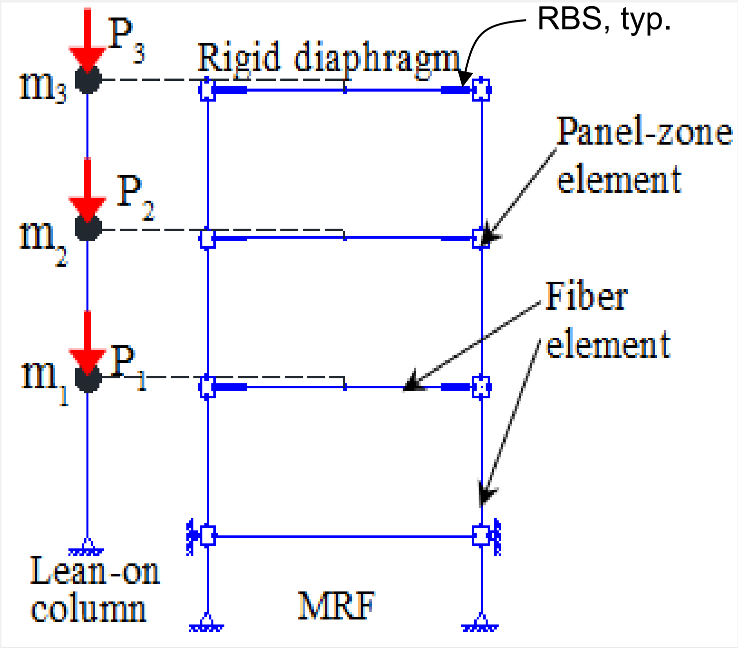
Damper force - deformation



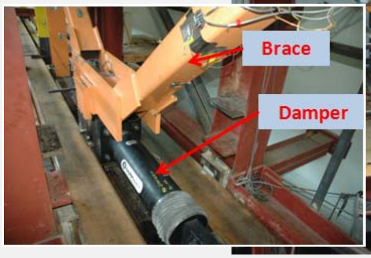
Damper force - velocity

Large-scale RTHS on Structure with Nonlinear Viscous Dampers: Substructures

Substructures for RTHS Phase-1



Analytical substructure (MRF, mass, gravity system, inherent damping)

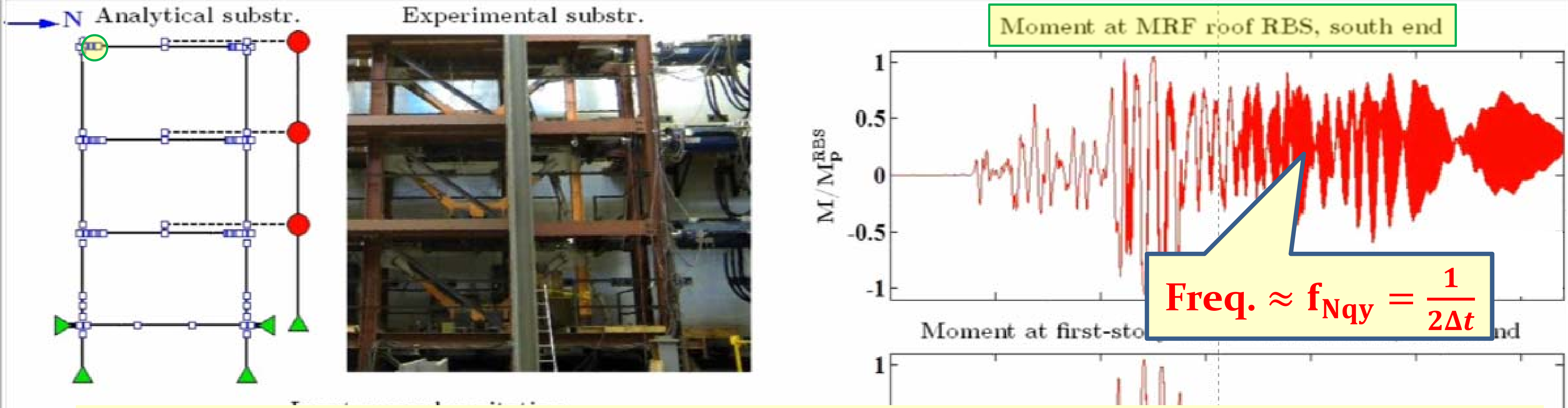


Experimental substructure (0.6-scale DBF)

Real-time state determination

- Analytical substructure has 296 DOFs and 91 elements;
- Nonlinear fiber elements for beams, columns, and RBS;
- Nonlinear panel zone elements for panel zone of beam-column connection;
- Elastic beam-column element for the lean-on column;
- P-delta effects included in the analytical substructure.

MCE level RTHS using $\rho_\infty = 1.0$

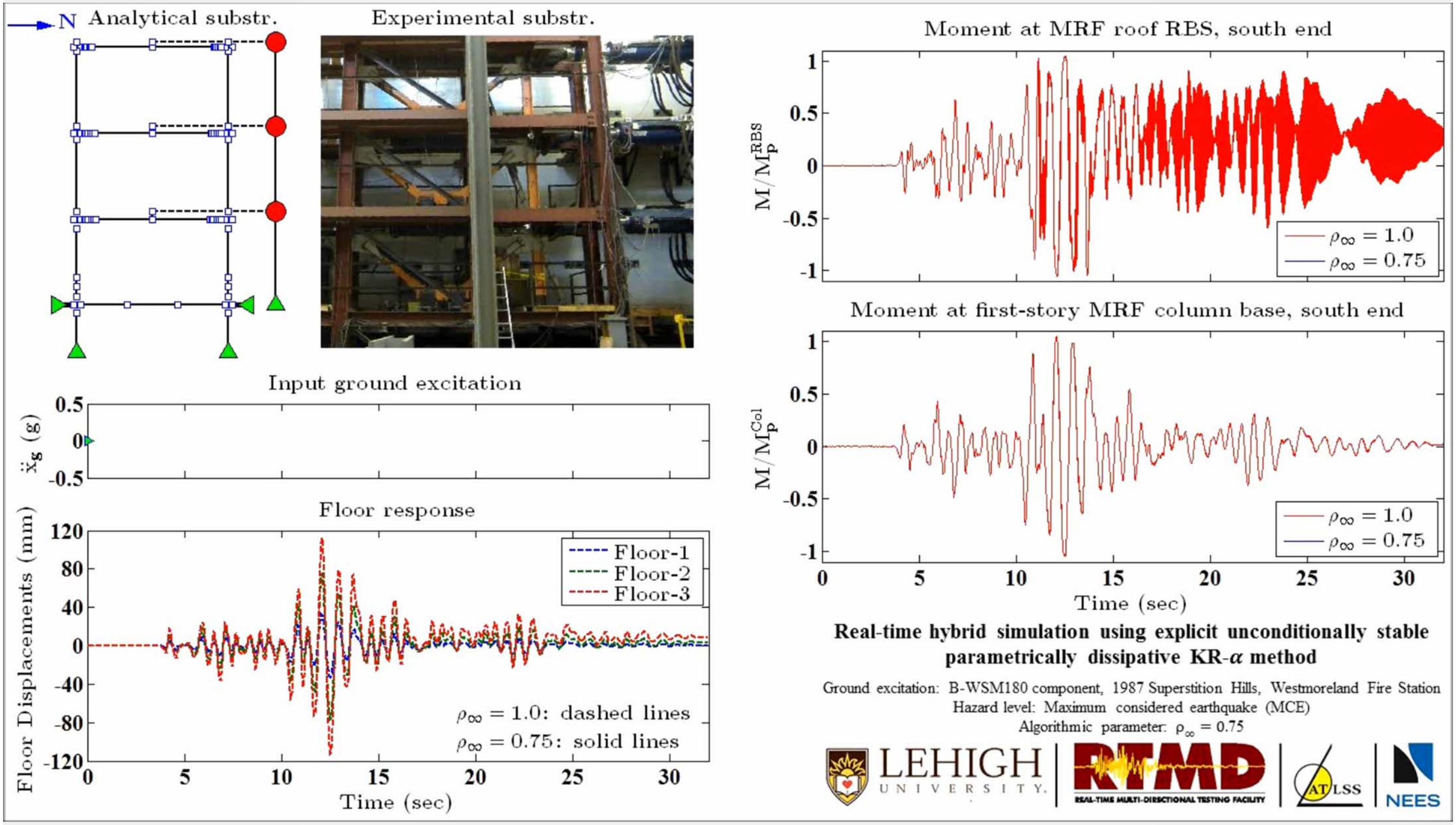


- Under nonlinear structural behavior, pulses are introduced in the acceleration at the Nyquist frequency $\left(= \frac{1}{2\Delta t}\right)$ when the state of the structure changes within the time step
- Pulses excite spurious higher modes present in the system which primarily contribute to the member forces
- Problem becomes worst by the noise introduced through the measured restoring forces and the actuator delay compensation which can amplify high frequency noise.

Time (sec)

Kolay, C., Ricles, J., Marullo, T., Mahvashmohammadi, A., and Sause, R. (2015). Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*. 44, 735-755, doi:10.1002/eqe.2484.

3-story Steel Frame Building with NL Viscous Dampers MCE level RTHS using $\rho_\infty = 0.75$



Kolay, C., Ricles, J., Marullo, T., Mahvashmohammadi, A., and Sause, R. (2015). Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*. 44, 735-755, doi:10.1002/eqe.2484.

RTHS: Implementation solutions

Analytical substructure

- Fast and accurate state determination procedure

NHERI Lehigh Solutions

Explicit force-based fiber elements

Fiber Element State Determination

FE Modeling of Analytical Substructure

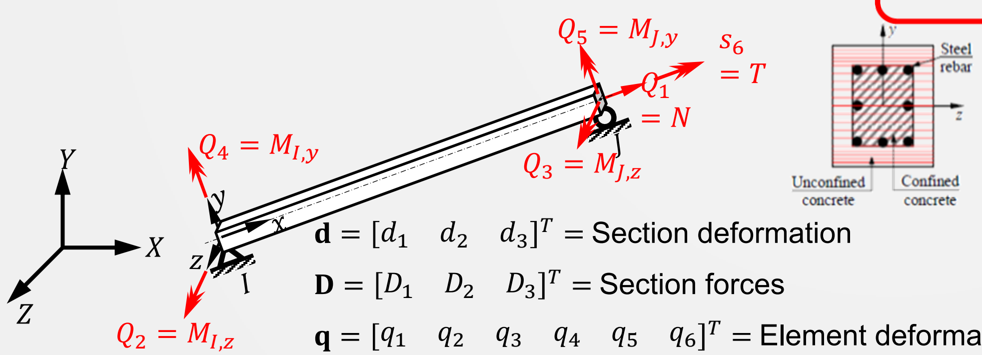
Displacement-based fiber elements

- ❑ Curvature varies linearly
  - ➢ Requires numerous elements per structural member to model nonlinear response
  - ➢ Increases number of DOFs
- ❑ State determination is straight forward

Force-based fiber elements

- ❑ Equilibrium is strictly enforced
  - ✓ Material nonlinearity can be modeled using a single element per structural member
  - ✓ Reduces number of DOFs
- ❑ Requires iterations at the element level

Jeopardizes explicit integration



$\mathbf{d} = [d_1 \quad d_2 \quad d_3]^T$ = Section deformation

$\mathbf{D} = [D_1 \quad D_2 \quad D_3]^T$ = Section forces

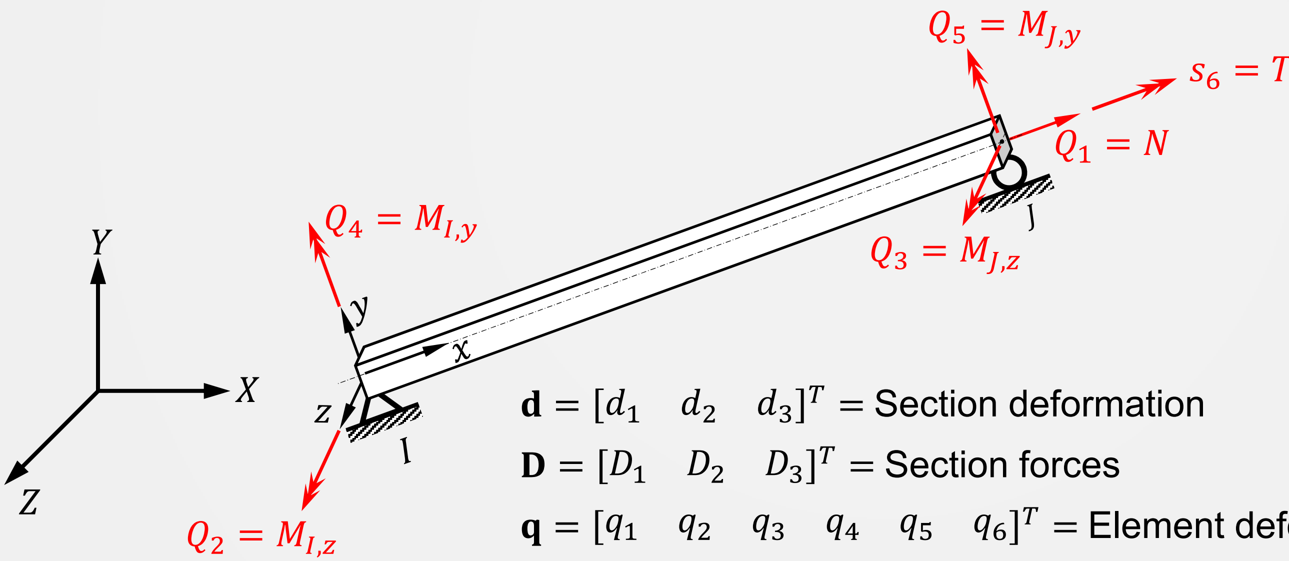
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T$ = Element deformations

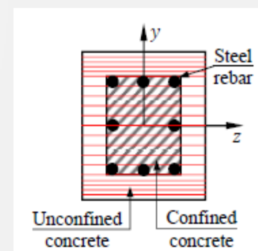
$\mathbf{Q} = [Q_1 \quad Q_2 \quad Q_3 \quad Q_4 \quad Q_5 \quad Q_6]^T$ = Element forces

3-D Fiber element

Explicit-formulated Force-Based Fiber Element

- Used with explicit integration algorithm
- Material nonlinearity
- Equilibrium is strictly enforced along element
- Reduced DOFs in system modeling
- Fixed number of iterations during state determination with carry-over and correction of unbalanced section forces in next time step





$\mathbf{d} = [d_1 \quad d_2 \quad d_3]^T$ = Section deformation

$\mathbf{D} = [D_1 \quad D_2 \quad D_3]^T$ = Section forces

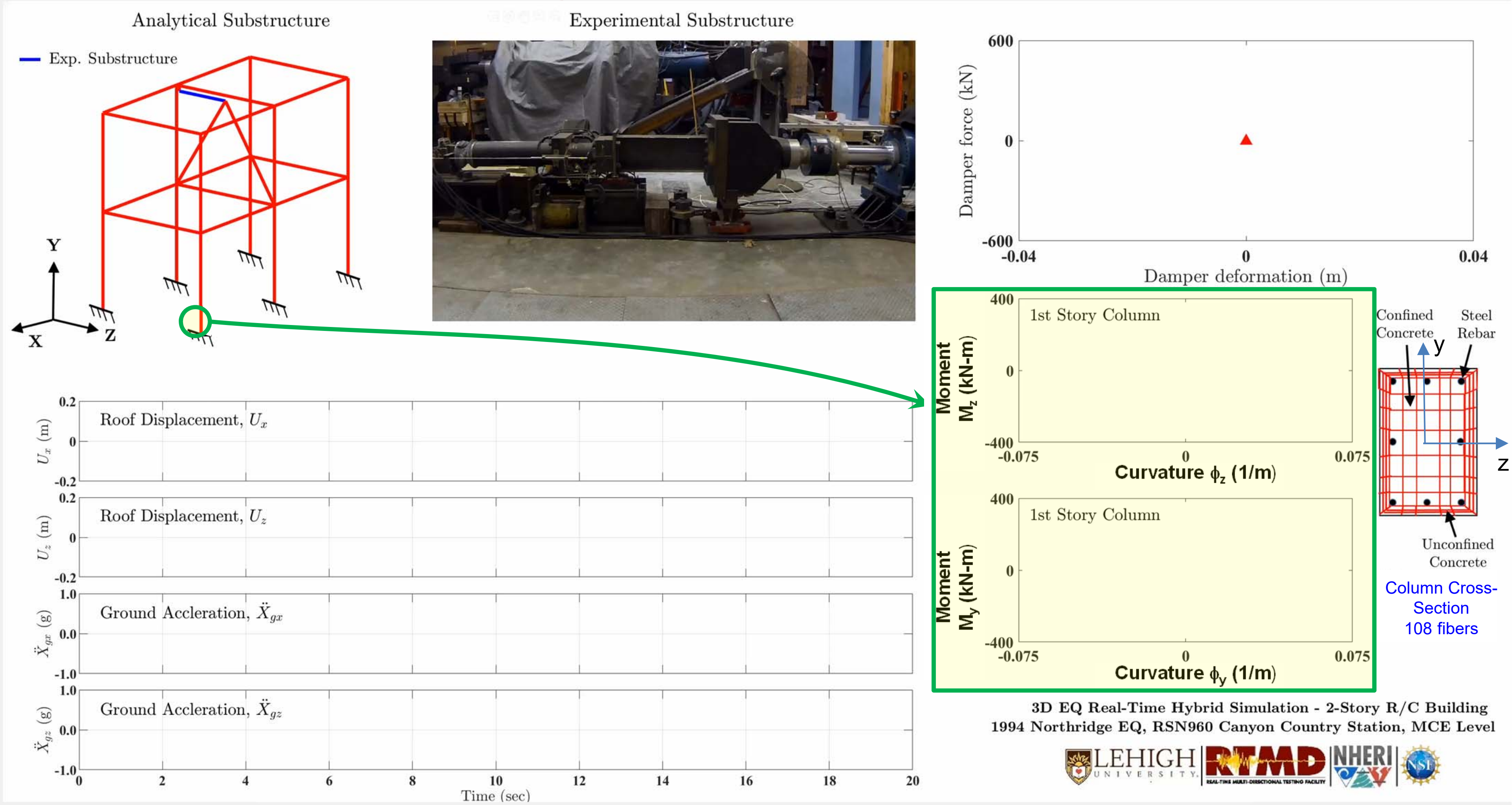
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T$ = Element deformations

$\mathbf{Q} = [Q_1 \quad Q_2 \quad Q_3 \quad Q_4 \quad Q_5 \quad Q_6]^T$ = Element forces

3-D Fiber element – Deformation Modes

Kolay, C. and J.M. Ricles, (2018). Force-Based Frame Element Implementation for Real-Time Hybrid Simulation Using Explicit Direct Integration Algorithms. *Journal of Structural Engineering*, 144(2) http://dx.doi.org/10.1080/13632469.2017.1326423.

3-D EQ RTHS of RC Structure: Fiber Element Real-time State-Determination



Al-Subaihawi, S., Marullo, T., Cao, L., Kolay, C., and J.M. Ricles, (2019). 3-D Real-time Hybrid Earthquake Simulation of RC Buildings.

Column develops inelastic behavior with cyclic strength and stiffness deterioration, and hysteretic pinching in force-deformation response

RTHS: Implementation solutions

Experimental substructure

- Large capacity hydraulic system and dynamic actuators required
- Actuator kinematic compensation
- Robust control of dynamic actuators for large-scale structures

NHERI Lehigh Solutions

- Large hydraulic power supply system
- Large capacity dynamic actuators
- Servo hydraulic actuator control: Adaptive Time Series Compensator (ATS)
- Development of actuator kinematic compensation

Servo Hydraulic Actuator Control

- Nonlinear servo-valve dynamics
- Nonlinear actuator fluid dynamics
- Test specimen material and geometric nonlinearities
- Slop, misalignment, deformations in test setup

- Variable amplitude error and time delay in measured specimen displacement

- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause instability

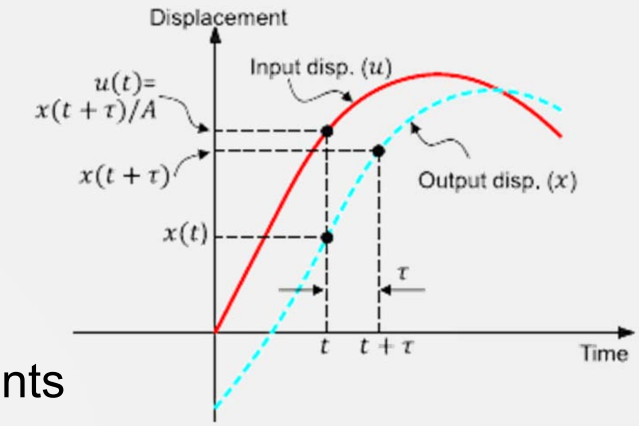
It is important to compensate

NHERI Lehigh Solutions to RTHS Challenges

Servo Hydraulic Actuator Control - Actuator Delay Compensation

Adaptive Time Series (ATS) compensator

$$u_k^c = a_{0k}x_k^t + a_{jk}\dot{x}_k^t + a_{2k}\ddot{x}_k^t$$



u_k^c: compensated input displacement into actuator

x_k^t: target **specimen** displacement a_{jk}: adaptive coefficients

Adaptive coefficients are optimally updated to minimize the error between the specimen target and measured displacements using the **least squares** method

$$\mathbf{A} = \left(\mathbf{X}_\mathbf{m}^\mathbf{T}\mathbf{X}_\mathbf{m}\right)^{-1}\mathbf{X}_\mathbf{m}^\mathbf{T}\mathbf{U}_\mathbf{c}$$

$$\mathbf{A} = \left[a_{0k}\; a_{1k} \cdots a_{nk}\right]^T \qquad \mathbf{X}_\mathbf{m} = \left[\mathbf{x}^\mathbf{m}\; \dot{\mathbf{x}}^\mathbf{m} \cdots \frac{d^n}{dt^n}\left(\mathbf{x}^\mathbf{m}\right)\right]^T$$

$$\mathbf{x}^\mathbf{m} = \left[x_{k-1}^m\; x_{k-2}^m \cdots x_{k-q}^m\right]^T$$ (Output (measured) specimen displacement history)

$$\mathbf{U}_\mathbf{c} = \left[u_{k-1}^c\; u_{k-2}^c \cdots u_{k-q}^m\right]^T$$ (Input actuator displacement command history)

Chae, Y., Kazemibidokhti, K., and Ricles, J.M. (2013). “Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation”, *Earthquake Engineering and Structural Dynamics,* DOI: 10.1002/ eqe.2294.

Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator

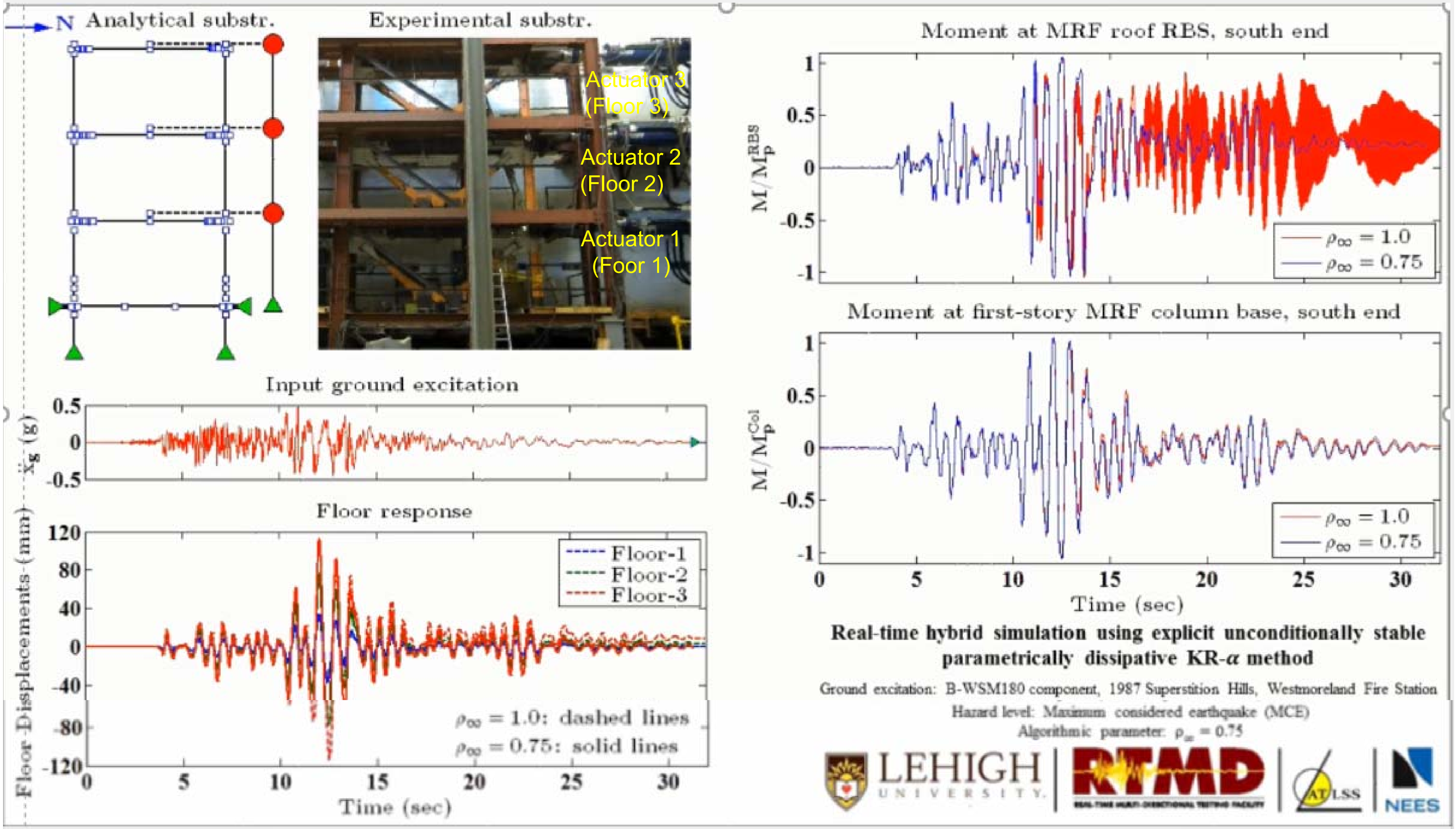
- No user-defined adaptive gains ➔ applicable for large-scale structures susceptible to damage (i.e., concrete structures)
- Negates both variable time delay and variable amplitude error response
- Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients
- Use specimen feedback

Time Step k

Amplitude error: $A_k = \dfrac{1}{a_{0k}}$

Time delay: $\tau_k = \dfrac{a_{1k}}{a_{0k}}$

MCE level RTHS using $\rho_\infty = 0.75$

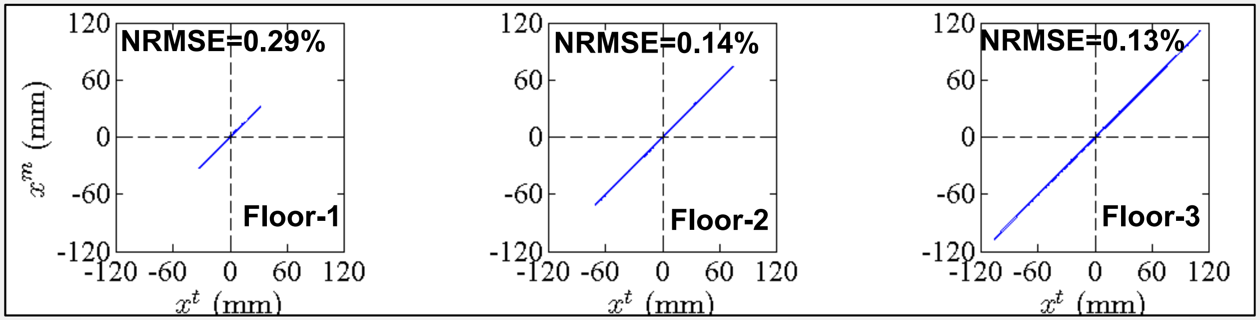


Kolay, C., Ricles, J., Marullo, T., Mahvashmohammadi, A., and Sause, R.. (2015). Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*. 44, 735-755, doi:10.1002/eqe.2484.

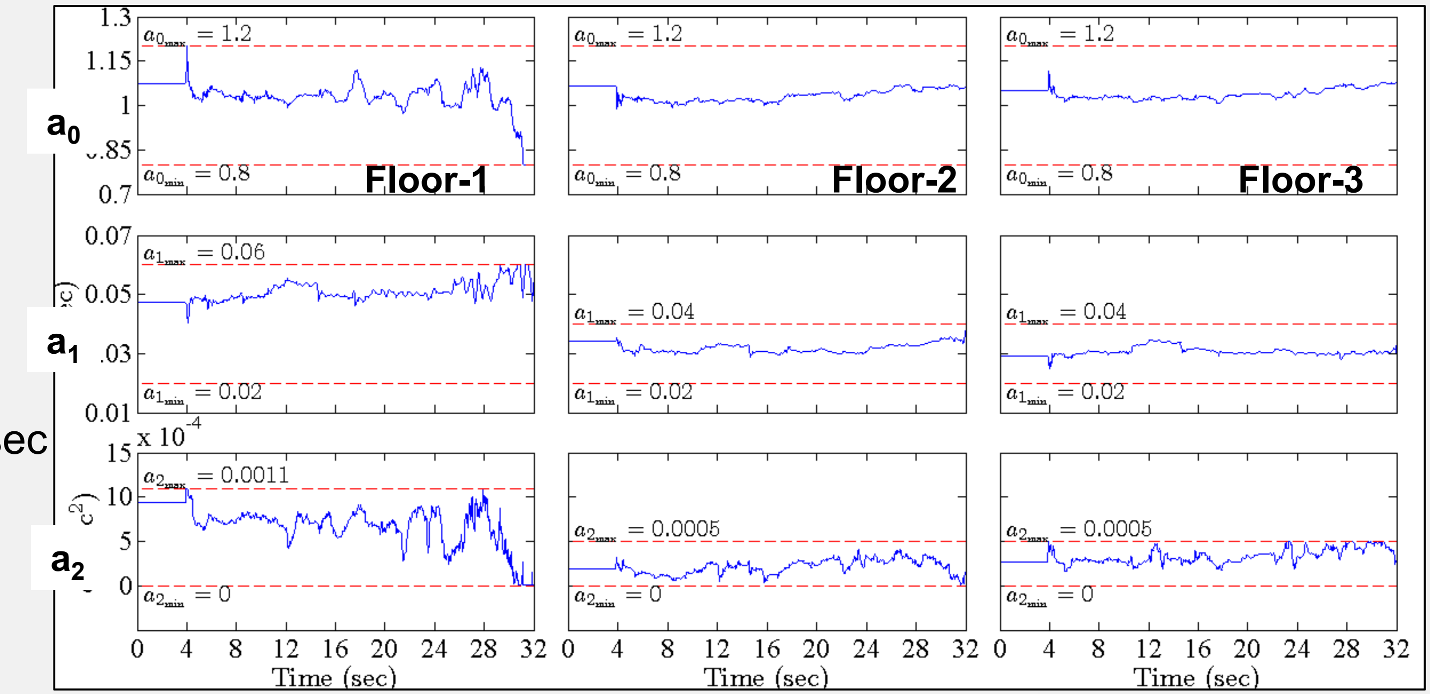
Actuator control: Typical MCE level RTHS & $\rho_\infty = 0.75$

x^t : targeted specimen displacement
x^m : measured specimen displacement

Synchronized Subspace Plots: x^t vs. x^m



Time History of Adaptive Coefficients



Amplitude Correction

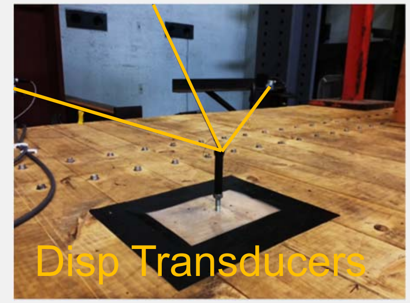
$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 0.83 \sim 1.25$$

Delay Compensation

$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 18 \sim 75 \text{ msec}$$

Actuator Kinematic Compensation

- Kinematic compensation scheme and implementation for RTHS (Mercan et al. 2009)
  - Kinematic correction of command displacements for multi-directional actuator motions
  - Robust, avoiding accumulation of error over multiple time steps; suited for RTHS
  - Exact solution

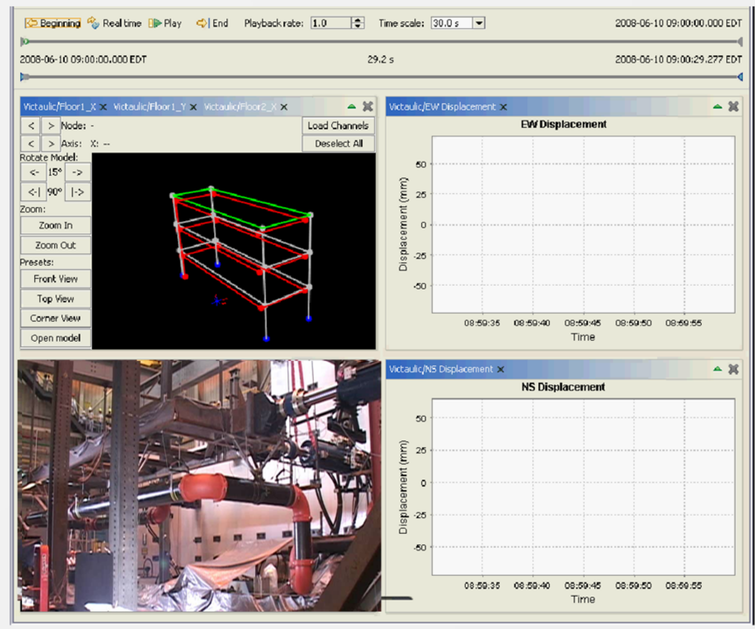


$$(M_i SNxL_{new}, M_i SNyL_{new}) = (-LMa_{inew} sin(\Theta_2 + \phi_i), LMa_{inew} cos(\Theta_2 + \phi_i))$$

$$\Theta_2 = \arcsin\left[\frac{LMb_{inew}}{yF_i/cos\phi_i} \sin\Theta_3\right]$$

$$\Theta_3 = \arccos\left[\frac{LMa_{inew}{}^2 + LMb_{inew}{}^2 - (yF_i/cos\phi_i)^2}{2LMa_{inew}LMb_{inew}}\right]$$

$$(SPN^m x_{new}, SPN^m y_{new}) = (M_1 SN^m x_{new} - \left|\overrightarrow{VM}_1\right| cos(\Theta M_{1,0} + d^m SPN\Theta), M_1 SN^m y_{new} - \left|\overrightarrow{VM}_1\right| sin(\Theta M_{1,0} + d^m SPN\Theta))$$



Multi-directional Real-time Hybrid Simulation

Mercan, O, Ricles, J.M., Sause, R, and M. Marullo, (2009). “Kinematic Transformations in Multi-directional Pseudo-Dynamic Testing,” *Earthquake Engineering and Structural Dynamics*, Vol. 38(9), pp. 1093-1119.

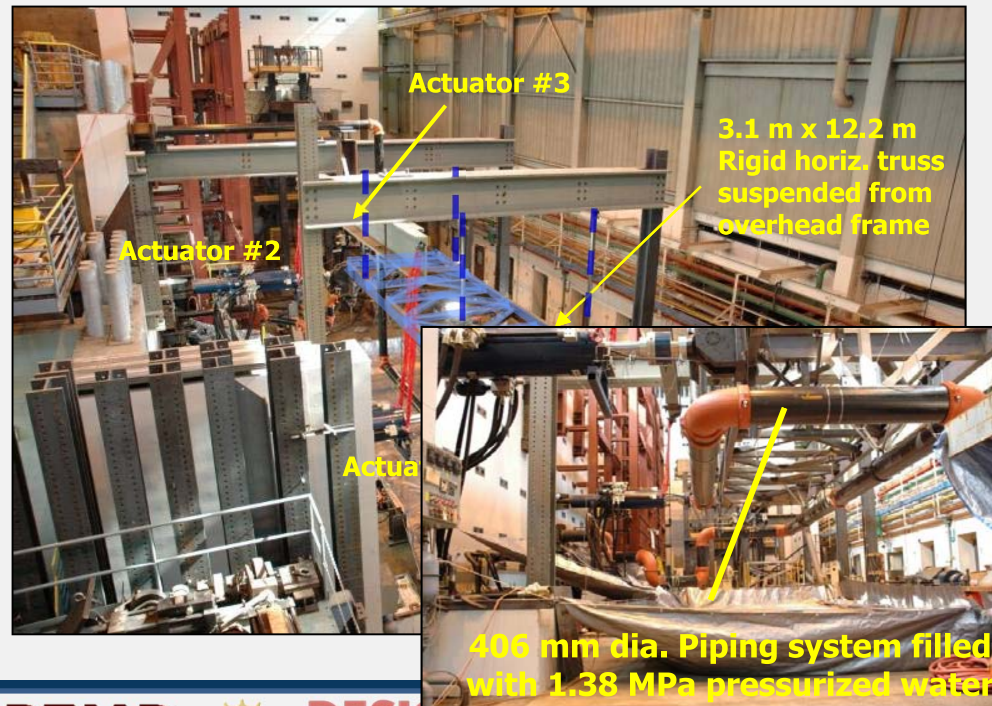
NHERI Lehigh EF/ATLSS Testbeds

- **Bracing Frame**
  - Perform experiments on test frame specimens of:
    - ➢Up to 13.7 m (45 ft) in height
    - ➢Up to 11 m (36 ft) in width

NHERI Lehigh EF/ATLSS Testbeds

- **Non-Structural Component Seismic Simulator**
  - Enables multi-directional real-time hybrid simulation of non-structural components and systems:
    - ➢ Up to 12.2 m (40 ft) in length
    - ➢ Up to 3.1 m (10 ft) in width

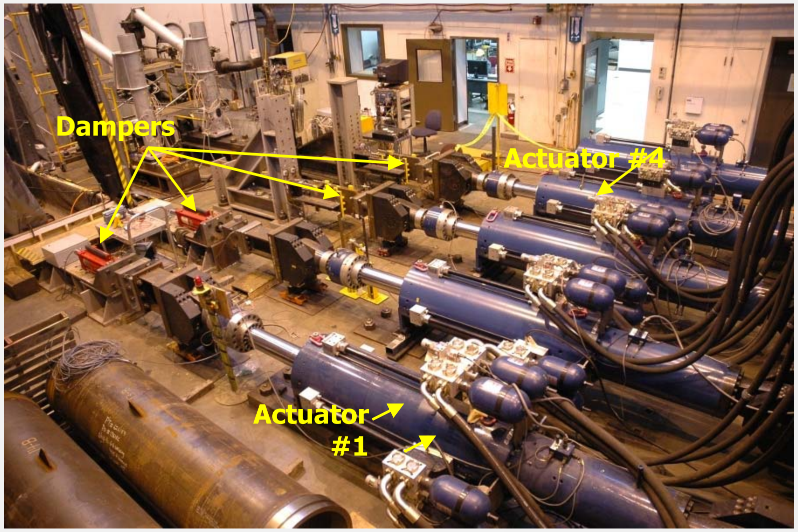
Multi-directional Real-time hybrid simulation of building piping system



NHERI Lehigh EF/ATLSS Testbeds

- **Full-scale Damper Testbeds**
  - Enables full-scale damper tests:
    - ➢ Damper characterization tests
    - ➢ Real-time hybrid simulations
  - Stoke, velocity, and force capacity:
    - ➢ +/- 500 mm (20 in.) stroke
    - ➢ 1140 mm/s (45 in/s) for 1700 kN actuators
    - ➢ 840 mm/s (33 in/s) for 2300 kN actuators

Real-time hybrid simulation of building with four passive dampers



NHERI Lehigh EF/ATLSS Testbeds

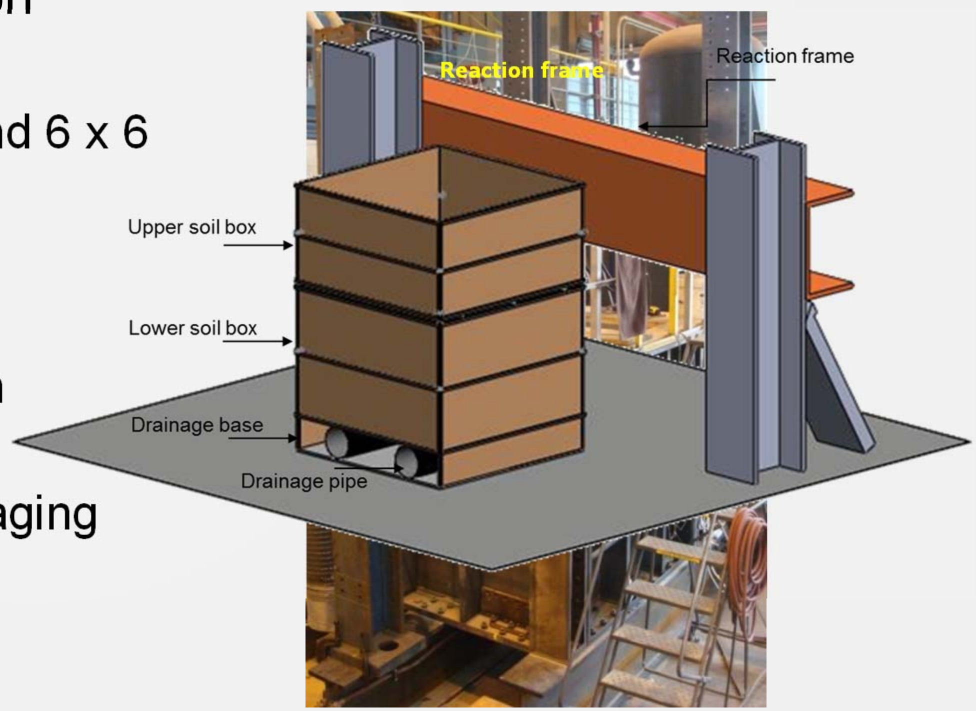
- **Tsunami Debris Impact Force Testbed**
  - Enables full-scale debris impact tests:
    - ➢ High speed DAQ; high speed 5000 fps cameras
    - ➢ High bandwidth, resolution load cells
    - ➢ Accelerometers, laser-displacement transducers

Real-time simulation of impact forces from tsunami shipping container debris

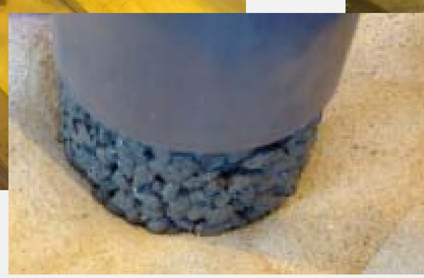
NHERI Lehigh EF/ATLSS Testbeds

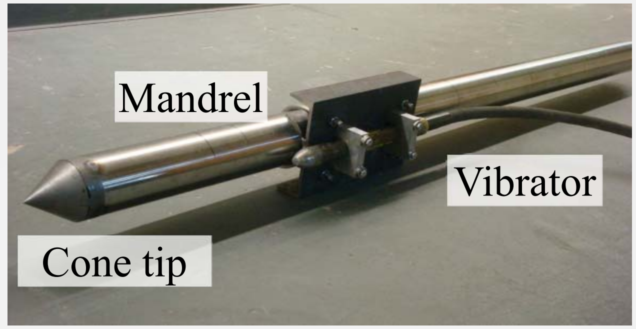
- **Reduced-scale Soil Box**
  - Enables soil-structure interaction research
    - ➢ Flexible designs (6 x 6 x 6 ft and 6 x 6 x 3 ft in size)
    - ➢ Actuators with load cells; data acquisition system
    - ➢ Sensors for soil and foundation response measurements
    - ➢ Advanced sensors - Digital Imaging Correlation

<u>Soil-foundation structure interaction testbed</u>



Soil-Structure Interaction Testbed

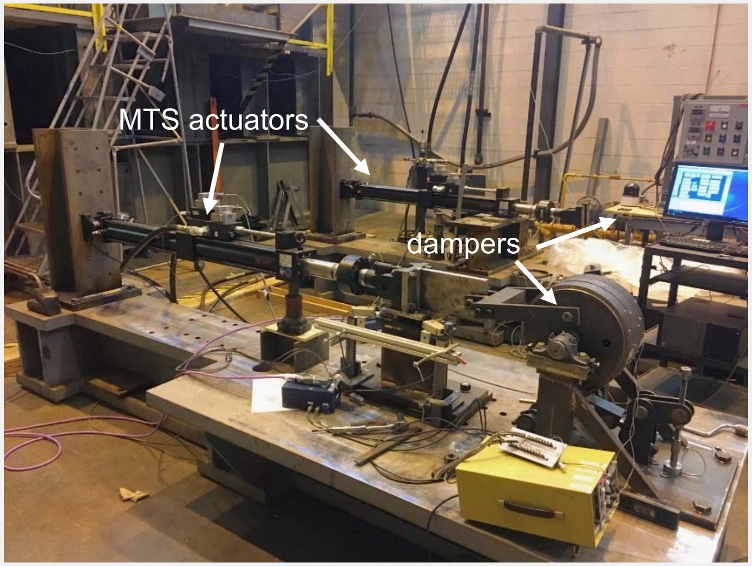




LEHIGH UNIVERSITY · ATLSS · RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION · NSF · DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

Lehigh Real-time Cyber-Physical Structural Systems Laboratory

- Purpose
  - Education & Training
  - Small-scale Testing
- Five MTS Actuators:
  - 2 - Model 244.21G2
  - 1 - Model 244.20G2S
  - 2 - Model 244.22



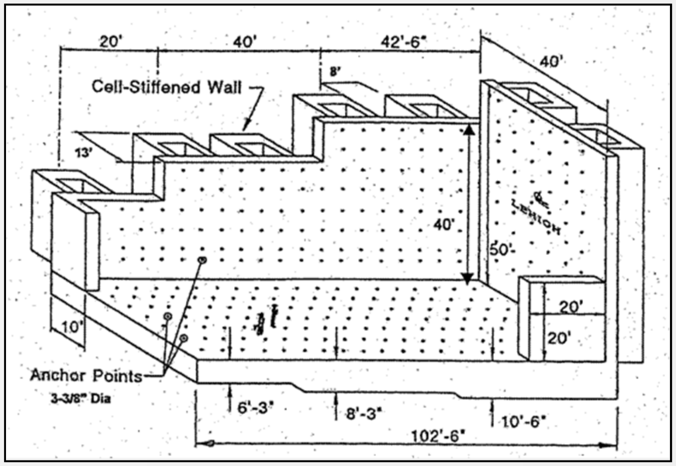
Actuator Specifications

	244.21G2	244.20G2s	244.22
Max Force	50 kN (11 kips)	82 kN (18.5 kips)	100 kN (22 kips)
Max displacement	±254 mm (±10 in)	±177 mm (±7 in)	±75 mm (±3 in)
Max velocity	0.74 m/s (29 in/s)	0.43 m/s (17 in/s)	0.39 m/s (15 in/s)
Servo Valve	30 gpm	90 gpm	30 gpm

LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

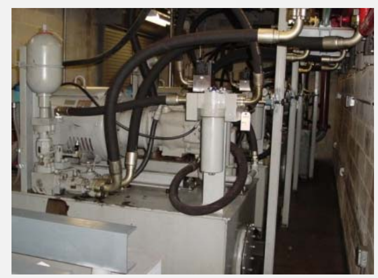
Existing ATLSS Infrastructure

- **3-D Multi-directional reaction wall facility**
  - 3-dimensional
  - Up to 15.2 m (50 ft) height
  - 1.5 m (5 ft) anchor point grid
- **Strong floor**
  - 12.2 m by 30.5 m (40 ft by 100 ft)
  - Anchor assembly capacity
    - 2,224 kN (500 kips) shear
    - 1,334 kN (300 kips) tension
- **Hydraulic Supply System**
- **Over 30 Hydraulic Actuators**
- **Large array of Conventional Sensors**
- **Crane**
- **Skilled staff**



NHERI Lehigh EF Hydraulic Equipment and Power

- **Enables real-time EQ large scale demand to be imposed for up to 30 seconds**
- **Hydraulic supply system (ATLSS)**
  - 5-120 gal/min variable axial piston pumps
- **Accumulator System (NHERI)**
  - 16 piston accumulators
    - 50.2 gal each
- **5 dynamic hydraulic actuators (NHERI)**
  - Maximum load capacity
    - 2 actuators: 517 kips at 3000 psi
    - 3 actuators: 382 kips at 3000 psi
  - Stroke
    - +/- 19.7 in
  - Maximum velocity
    - 45 in/s for 382 kip actuators
    - 33 in/s for 517 kip actuators
- **10 3-stage 550 gal/min Servovalves and HSMs (NHERI)**



Other NHERI Lehigh EF Equipment

- High Speed 300+ Channel Data Acquisition System
- 3 Real-Time Targets for simulation coordination, including additional DAQ
- Three real-time servo-hydraulic controllers
- Sensors (displacement, accelerometers, inclinometers)
- Telepresence webcams
- Specs for all equipment found in NHERI Lehigh User's Guide

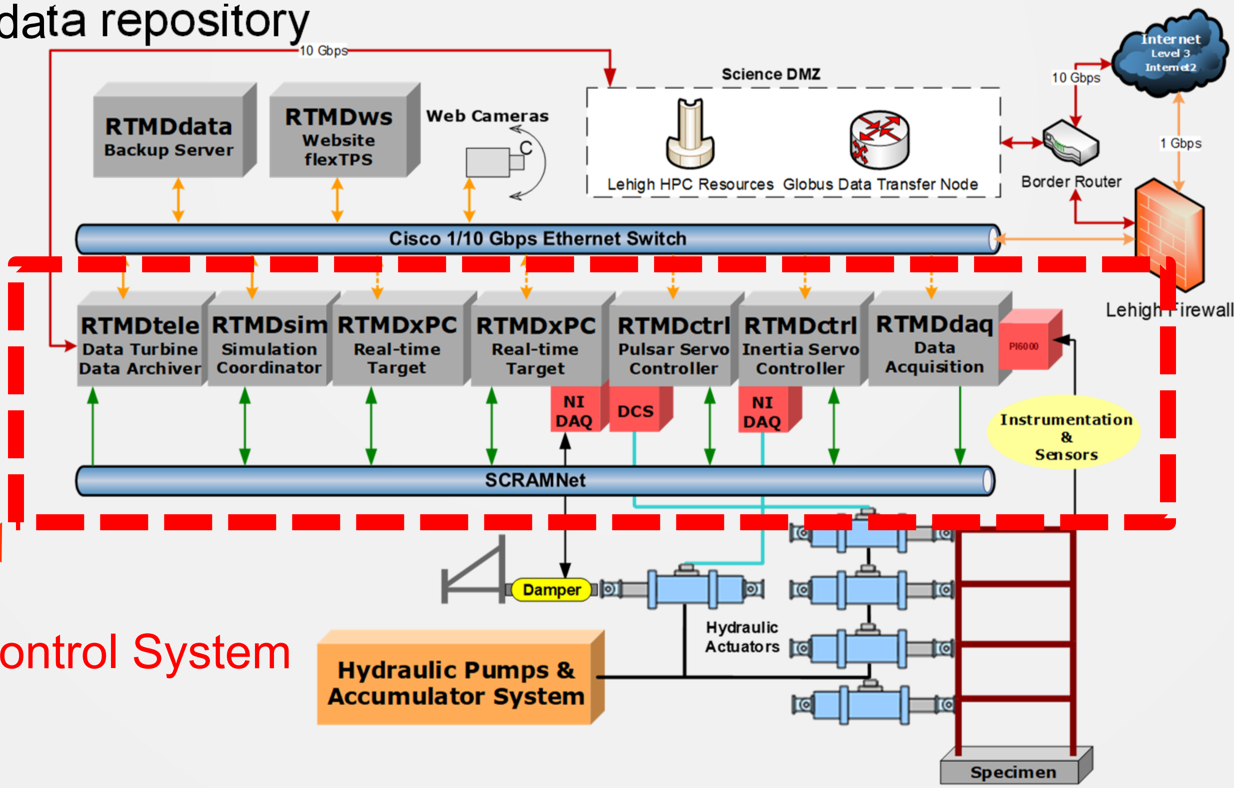
https://lehigh.designsafe-ci.org/resources

Instrumentation

- Displacement transducers
  - Strokes ranging from ±6.4mm (LVDTs) to 1524mm (linear potentiometers).
  - Temposonic position sensors with a ±760 mm stroke, to a ±1100 mm stroke.
  - All transducers are calibrated to within ±1% accuracy, with the LVDTs calibrated to within ±0.1%.
- Inclinometers ranging up to ±20 degrees with 1% accuracy.
- Each hydraulic actuator is equipped with a load cell.
  - All load cells are calibrated to within ±0.1% accuracy.

Other Major NHERI Lehigh EF Equipment

- Real-time Integrated Control System
  - Multiple Real-Time targets for simulation coordination with additional DAQ
  - Three real-time servo-hydraulic controllers
  - High Speed 300+ Channel Data Acquisition System
  - Web and Data telepresence system
  - Local data repository

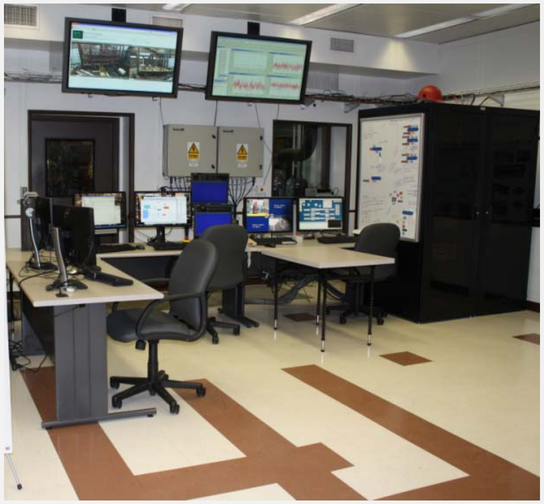


Real-Time
Integrated Control System

NHERI Lehigh EF Control Room

Control Center

- Houses Real-time Integrated Control System
- Camera Control
- Data Acquisition System and Server
- Data Streaming System
    - Video
    - Sensors
- Video Displays
- Local Repository



NHERI Lehigh EF non-NHERI Equipment

- Site leverages Non-NHERI equipment to provide capability, improve capacity and maintain throughput.
  - 30 Actuators
  - ATLSS Wineman Controller
  - 2 MTS 458 Controllers
  - MTS FlexTest 100 Controller
  - DAQ systems
  - Trilion System for Digital Image Correlation - full field displacement and strain
  - Transducers - over 96 LVDTs, 62 load cells, Temposonics (12 ATLSS)
  - SSI instrumentation
- Users Guide - Available ATLSS Equipment

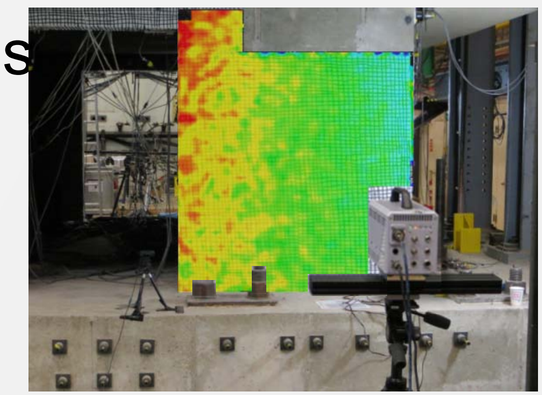
https://lehigh.designsafe-ci.org/resources

Instrumentation

- Digital imaging correlation (DIC) systems.
  - Utilizes 3D im… …nod.
  - Works on bot… …r pattern, thus simplifying sa…
  - Same sensor… …neasure small and large objects… …nd s… range of 0.05… …%.

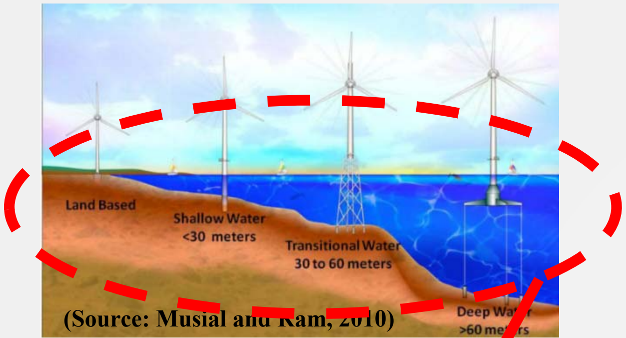
Figure F.4 DIC System

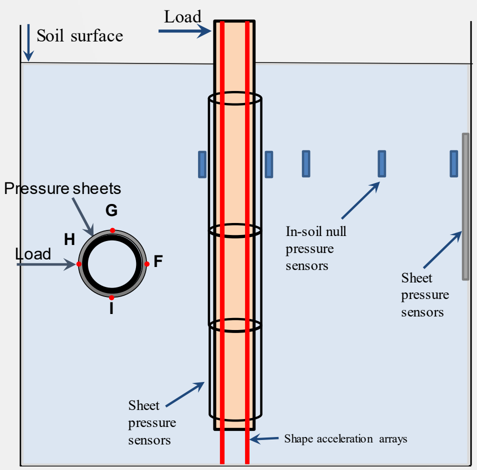
NEES@Lehigh Coupled Shear Wall Test Specimen with Multi-Directional Loading



Digital Imaging Correlation System: reinforced concrete coupled-shear wall test specimen measured pier vertical displacements (courtesy M. McGinnis)

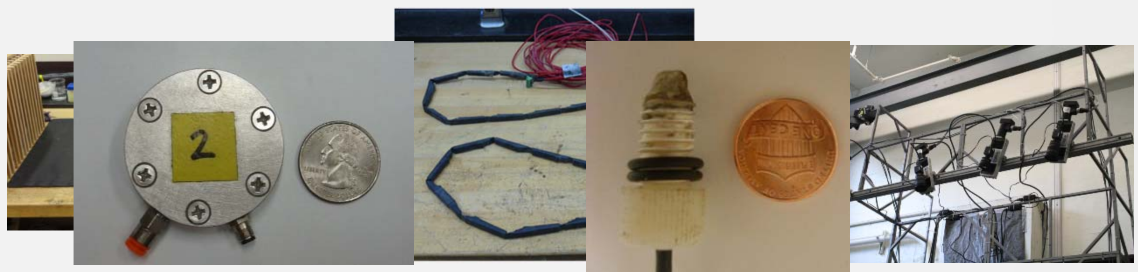
Soil-Structure Interaction Instrumentation

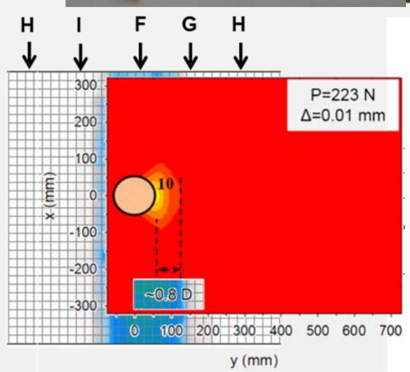


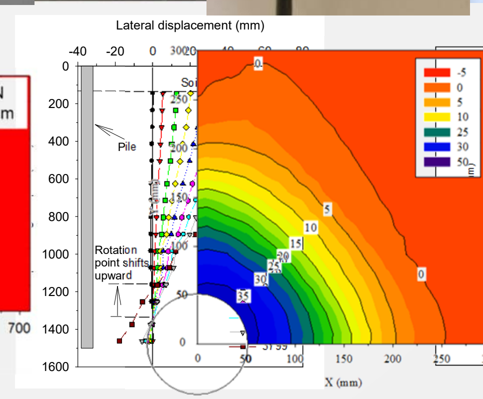


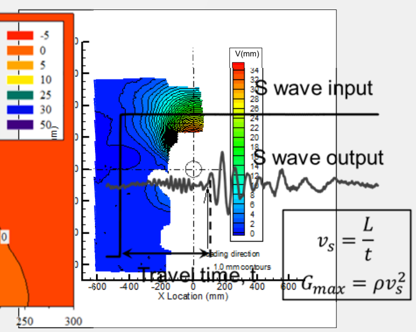
Test Setup and instrumentation

- Advanced instrumentation to understand SSI of foundation systems under different loading conditions
- Combine with hybrid simulation to improve analytical substructure models, or
- Hybrid simulation with soil included in experimental substructure









Soil-pile interaction pressure sensors

Pressure sensors

Shape acceleration arrays

Shear wave sensors

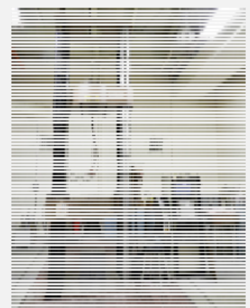
Digital image correlation

NHERI Lehigh EF - ATLSS Space and Resources

- **Specimen Prep**
  - Staging Areas
  - Machine Shop
- **Laboratories**
  - Intelligent Structures
  - Mechanical Testing
  - Welding and Joining
  - Materials
  - Microscopy
- **Offices**: Faculty; Staff; Visiting Researchers
- **Meeting Rooms**: Auditorium; Conference Room
- **Storage Areas**
- **Secure Facility**


Specimen preparation staging area

Mechanical testing



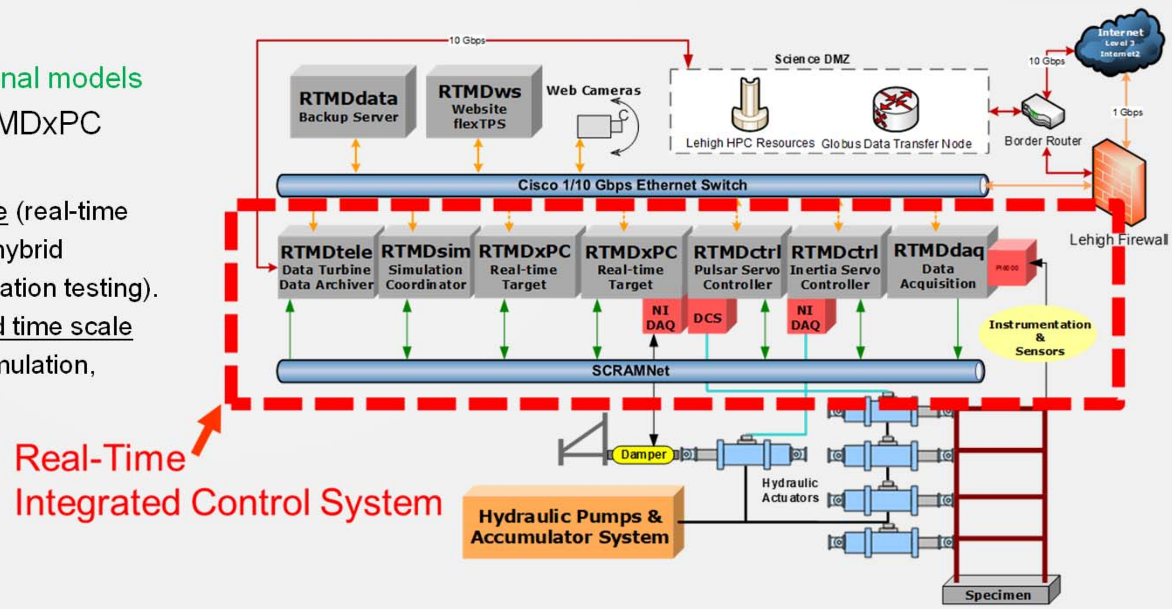
Auditorium – ECO Activities

NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Configured with experimental protocol required by user to perform test
    - Large-Scale Hybrid Simulation
    - Large-Scale Real-time Hybrid Simulation
    - Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
    - Geographically Distributed Hybrid Simulation
    - Geographically Distributed Real-time Hybrid Simulation
    - Predefined load or displacements (Quasi-static testing or characterization testing)
    - Dynamic testing
    - Semi-active controlled devices
    - On-line real-time model updating
    - Machine learning-based computational models

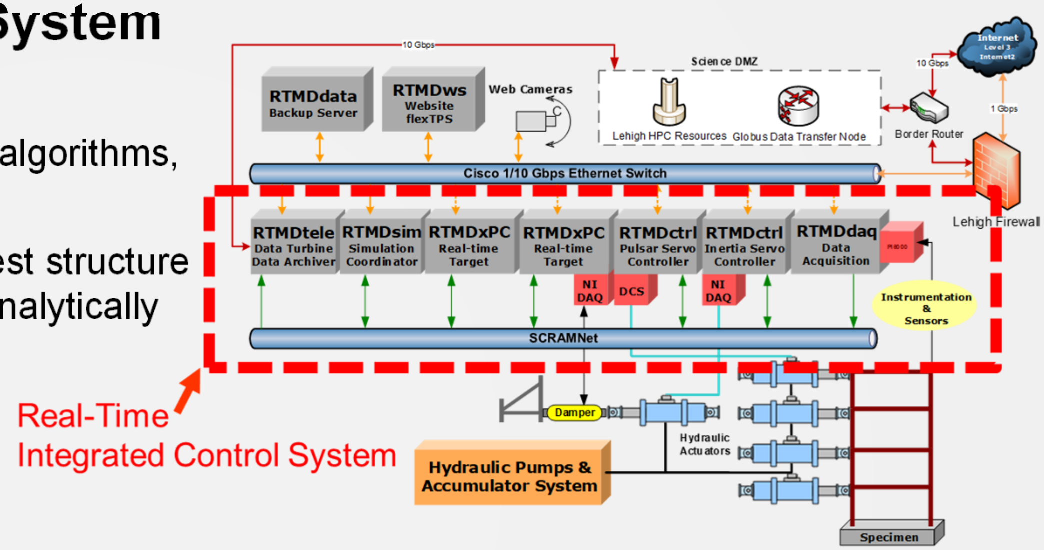
https://lehigh.designsafe-ci.org/protocols/experimental-protocol/

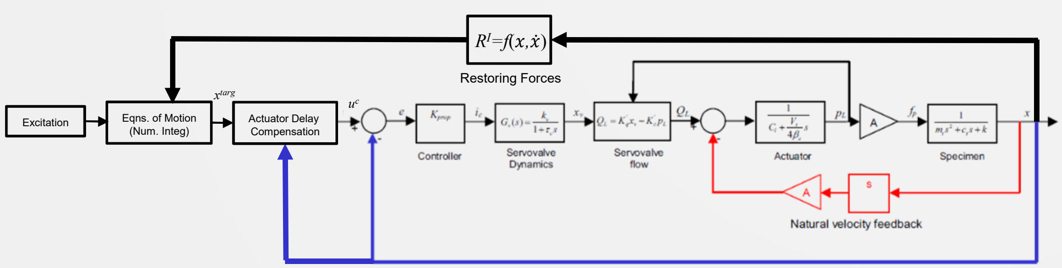
  - Testing algorithms reside on an RTMDxPC and run in real time
    - Experiments can be run in true real-time (real-time hybrid simulation, real-time distributed hybrid simulation, dynamic testing, characterization testing).
    - Experiments can be run at an expanded time scale (hybrid simulation, distributed hybrid simulation, quasi-static testing).
  - Distributed hybrid simulation via:
    - OpenFresco
    - Simcor
    - Custom software
  - Flexible-designed system
    - Software and middleware packages developed by users or NHERI CI can be plugged in and utilized for testing

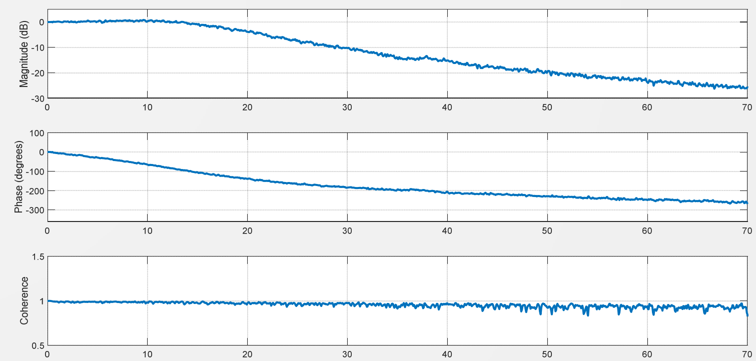


NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hydraulics-off mode
    - Used for validation of testing methods/algorithms, training, education
    - Both servo-hydraulic control system, test structure and numerical substructure modeled analytically



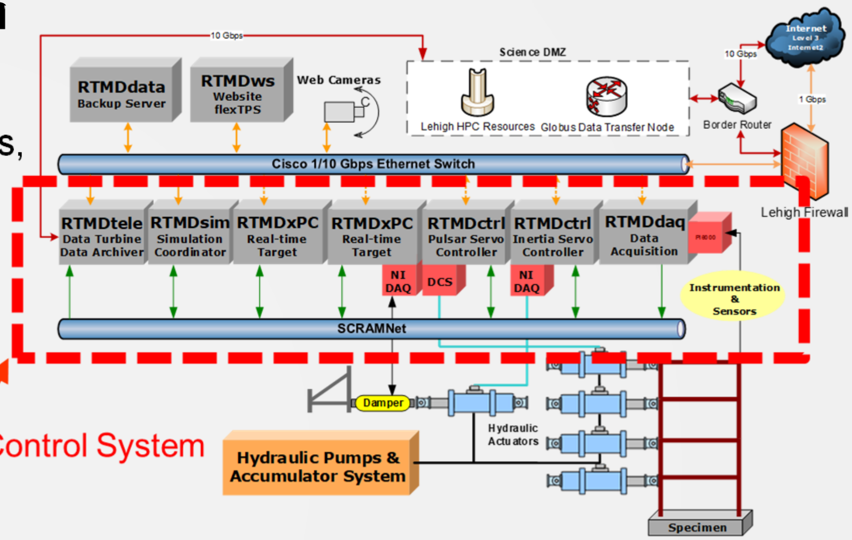




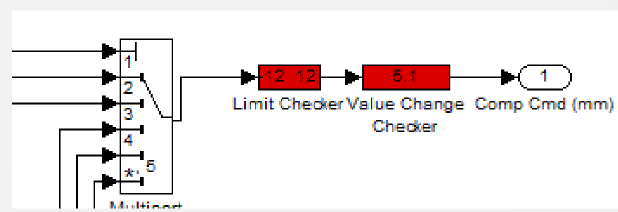
$$G_{x^{targ}x} = \frac{0.009086z^2 - 0.02565z + 0.0023}{z^3 - 2.243z^2 + 1.568z - 0.3195}$$

NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hydraulics-off mode
    - Used for validation of testing methods/algorithms, training, education
    - Both servo-hydraulic system, test structure and any analytical substructure modeled analytically
  - Safety
    - Software limits are enabled on the System.
    - Hardware actuator positon stroke and test specimen displacement limit switches placed.
    - Emergency stop system activated throughout laboratory



Real-Time Integrated Control System



NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hybrid simulation:
    - Robust integration algorithms: Explicit MKR-α Integration Algorithm - Explicit unconditionally stable integration algorithm with controlled numerical energy dissipation and controlled overshoot (*Kolay and Ricles, 2014, 2017*)
    - Adaptive actuator control: Adaptive Time Series (ATS) Compensator (*Chae et al. 2013*)
    - Multi-directional actuator control: Multi-directional Kinematic Compensation (*Mercan et al. 2009*)

Kolay, C., & Ricles, J. (2014). "Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation." *Earthquake Engineering & Structural Dynamics*, *43*(9), 1361–1380. DOI:10.1002/eqe.2401

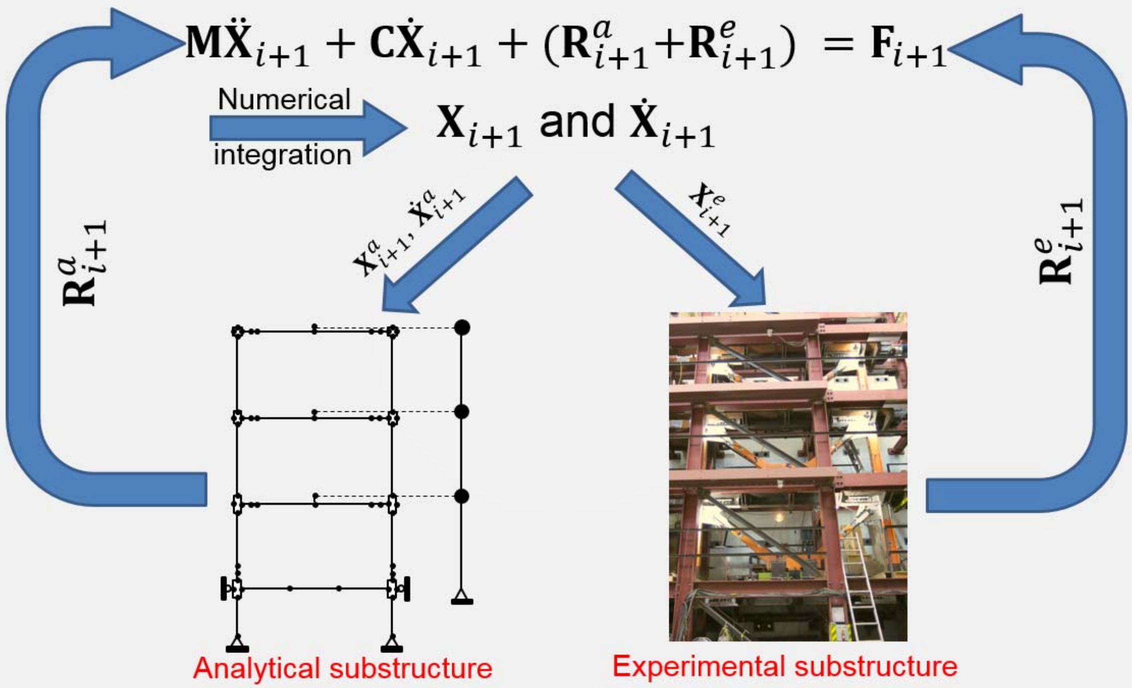
Kolay, C., and J.M. Ricles (2017). "Improved Explicit Integration Algorithms for Structural Dynamic Analysis with Unconditional Stability and Controllable Numerical Dissipation," Journal of Earthquake Engineering, http://dx.doi.org/10.1080/13632469.2017.1326423

Chae, Y., Kazemibidokhti, K., and Ricles, J.M. (2013). "Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation." Earthquake Engineering and Structural Dynamics, 42(11), 1697–1715, DOI: 10.1002/ eqe.2294.

Mercan, O, Ricles, J.M., Sause, R, and M. Marullo, (2009). "Kinematic Transformations in Multi-directional Pseudo-Dynamic Testing," Earthquake Engineering and Structural Dynamics, Vol. 38(9), pp. 1093-1119.

NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hybrid simulation analytical substructure created by either
    - HybridFEM
    - OpenSees via OpenFresco interface
    - User-defined



Schematic of hybrid simulation

HybridFEM

- MATLAB and Simulink based computational modeling and simulation coordinator software for dynamic time history analysis of inelastic-framed structures and performing real-time hybrid simulation
- Simulink architecture facilitates real-time testing through multi-rate processing
- Run Modes
  - MATLAB script for numerical simulation
  - Simulink modeling for Real-Time Hybrid simulation with experimental elements via Real-Time Targets, and hydraulics-off for training and validation of user algorithms.
- User's Manual for training

JR5 JR6

NHERI Lehigh HybridFEM

Configuration Options:

- Coordinate system of nodes
- Boundary, constraint and restraint conditions
- Explicit-formulated Elements
  - Elastic beam-column
  - Elastic spring
  - Inelastic beam-column stress resultant element
  - Non-linear spring
  - NL Displacement-based beam-column fiber elem
  - NL Force-based beam column fiber element
  - Zero-length
  - NL planar panel zone
  - Elastic beam-column element with geometric stiffness
  - User-defined Reduced Order Modeling elements
- Geometric nonlinearities
- Steel wide flange sections (link to AISC shapes Database)
- Reinforced concrete sections
- Structural mass & inherent damping properties
- Adaptable integration methods
- Real-time online model updating
- Machine learning-based computational modeling
- Semi-active control laws

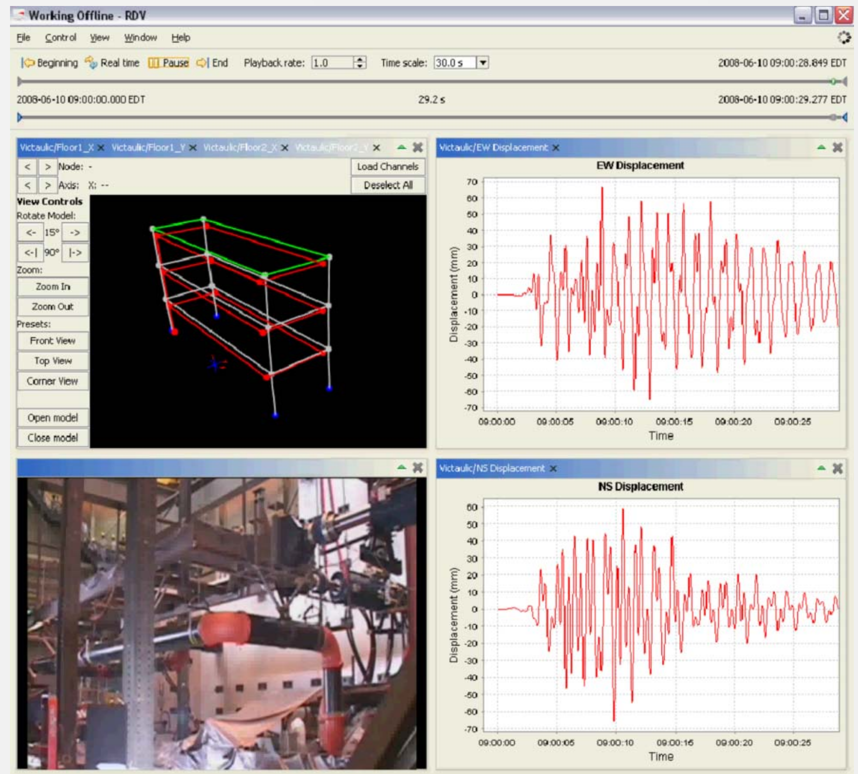
- Materials
  - Elastic
  - Bilinear elasto-plastic
  - Hysteretic
  - Bouc-Wen
  - Trilinear
  - Stiffness degrading
  - Concrete
  - Steel
  - Fracture
  - Initial stress
  - Prestress/Posttensioning

Telepresence

- Data Turbine (RBNB) (dataturbine.org)
  - Aggregates data from SCRAMNet using RTMD tools to define channel list, sample rate and duration
  - Streaming of data and images locally and remotely
  - Additional storage archive of test data

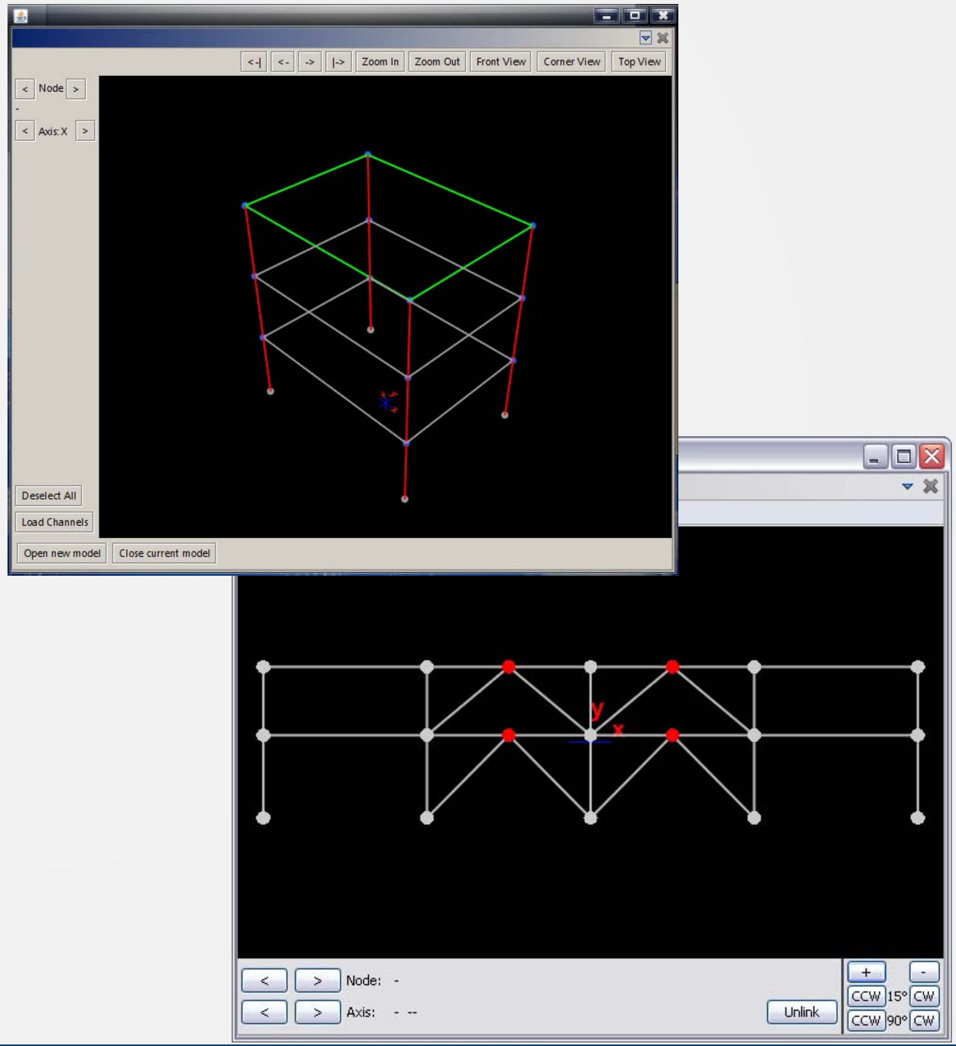
Real-Time Data Viewer

- Real-Time Data Viewer (RDV)
  - Connect from anywhere on any system
  - Invaluable tool for visualizing Real-Time Hybrid Simulations



3D Model Panel for RDV

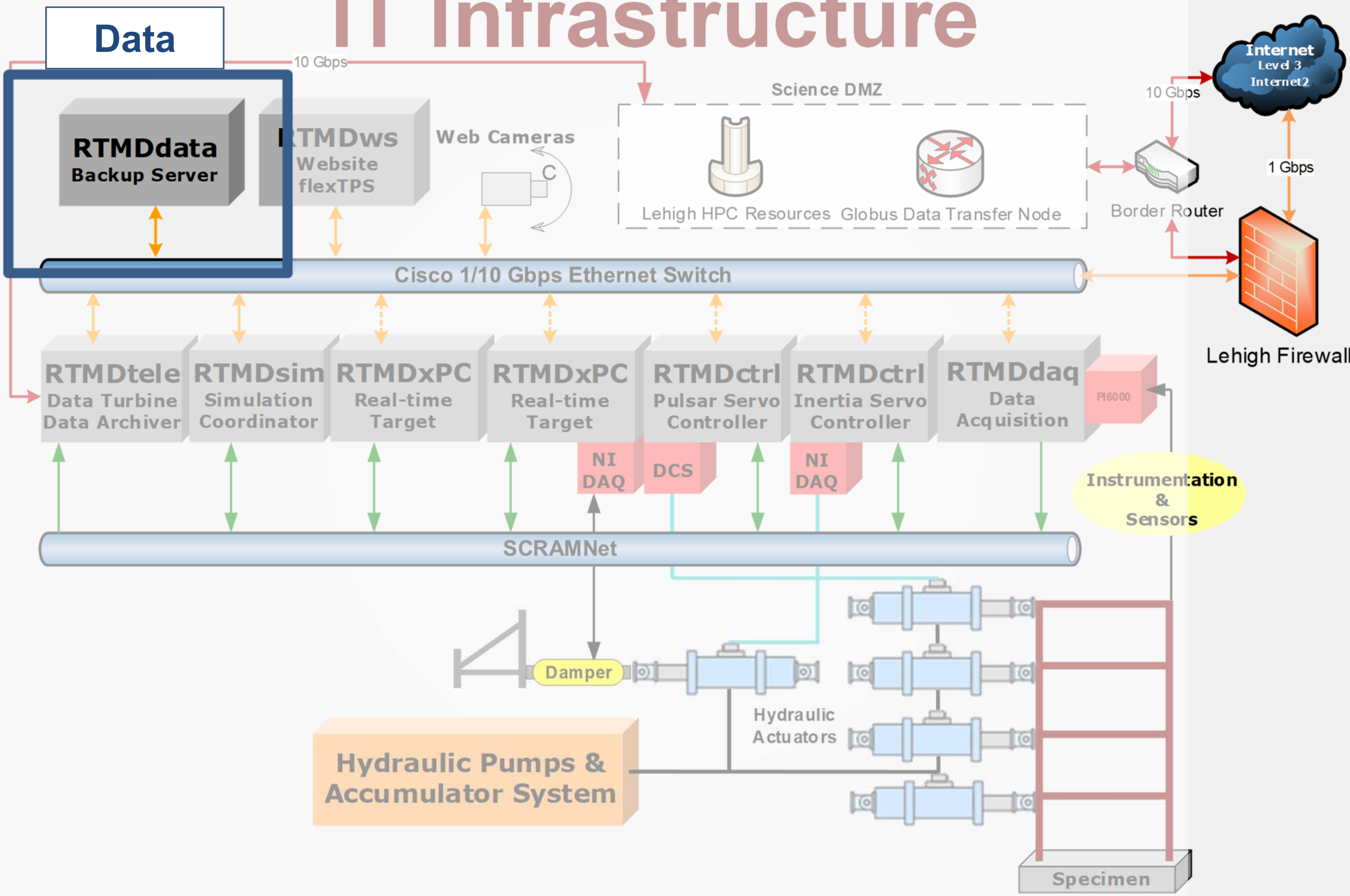
- 3D Modeling for RDV
- Real-time visualization complete structural system in hybrid simulation



Video

- Video/Imaging systems
  - (24) Amcrest Bullet/PTZ IP Cameras (up to 8k)
  - (4) Sony SNC-EP550 HD (720p HD)
  - (9) GoPro Hero 3 Black camcorders (1080p60 HD)
  - (2) Sony SNC-RZ30N network cameras (SD Security)
  - Nikon D70 D-SLR camera
  - HD camcorders available upon request through Lehigh
- Blue Iris Servers
  - Portal for all users to access and control web cameras
  - Archived video available for previous experiments

IT Infrastructure



RTMDdata

- Synology DS 1817
  - 8 hard drive slots, 96 TB capacity up to 216 TB
  - 10Gb Connection
- Dual-disk Redundancy
- Network Attached Storage
- Public and Private storage

Data Management Plan

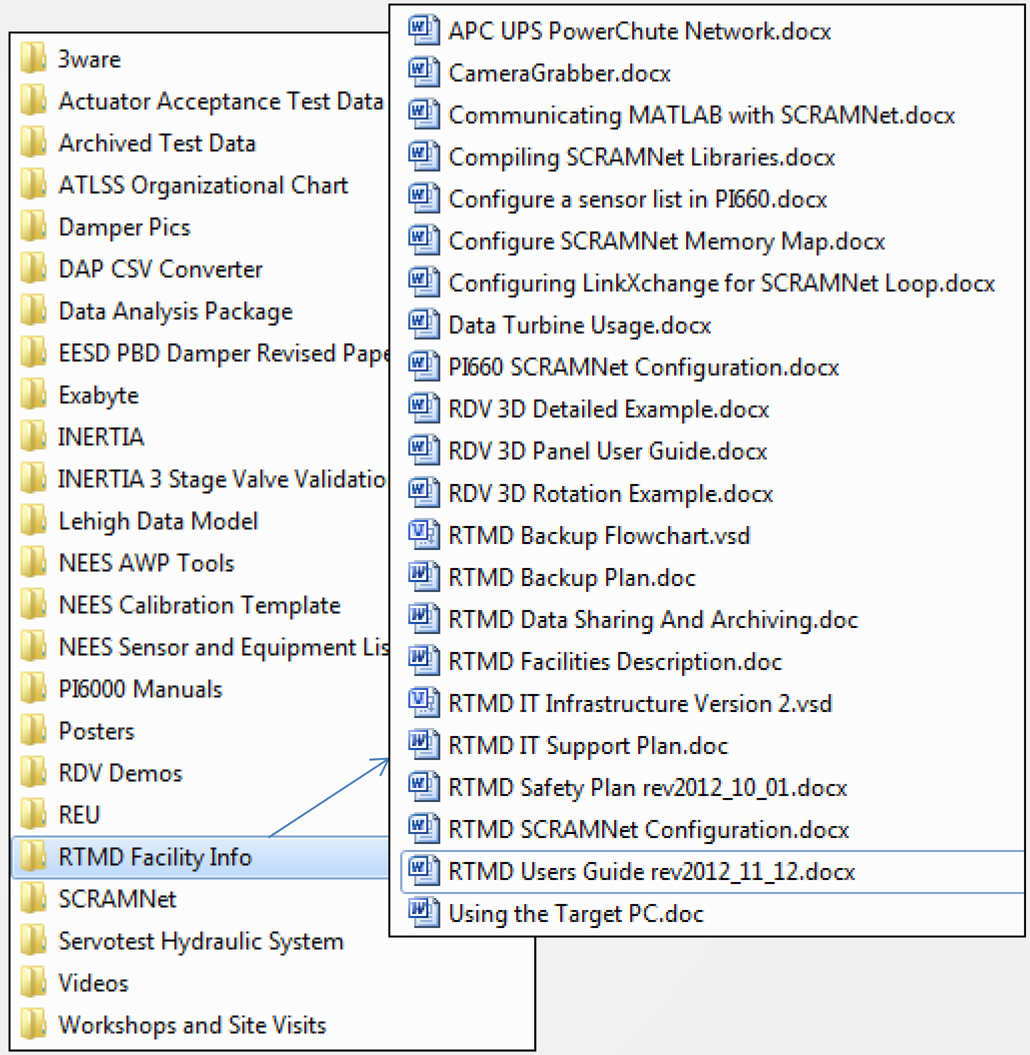
- Local repository for data storage managed by NHERI Lehigh with offsite backup risk mitigation through DesignSafe-CI
- Unlimited Google Drive space through Lehigh University
- Locally stored data adheres to the Lehigh University records retention policy or extended by the ATLSS Center IT management
- Included under NHERI Lehigh data management umbrella:
  - Unprocessed and RAW data from experiments
  - Converted and derived data sets using computational software
  - Experimental photos and videos
  - Computational models and analytical data sets
  - Scripts and software developed for project tasks
- Local curation utilizing folder/file structure
  - Project/Date/Task Description/Data Set; format “testname_date”
- Automated Globus Project data upload
- DesignSafe-CI curation through Data Depot and Data Model

Training: Hands on

- Familiarize users with testing methodologies and IT equipment
- Introduce users to software and user tools
- Describe all safety requirements
- Perform validation studies on physical test bed
- Demonstrate various simulation techniques

Training: Documentation

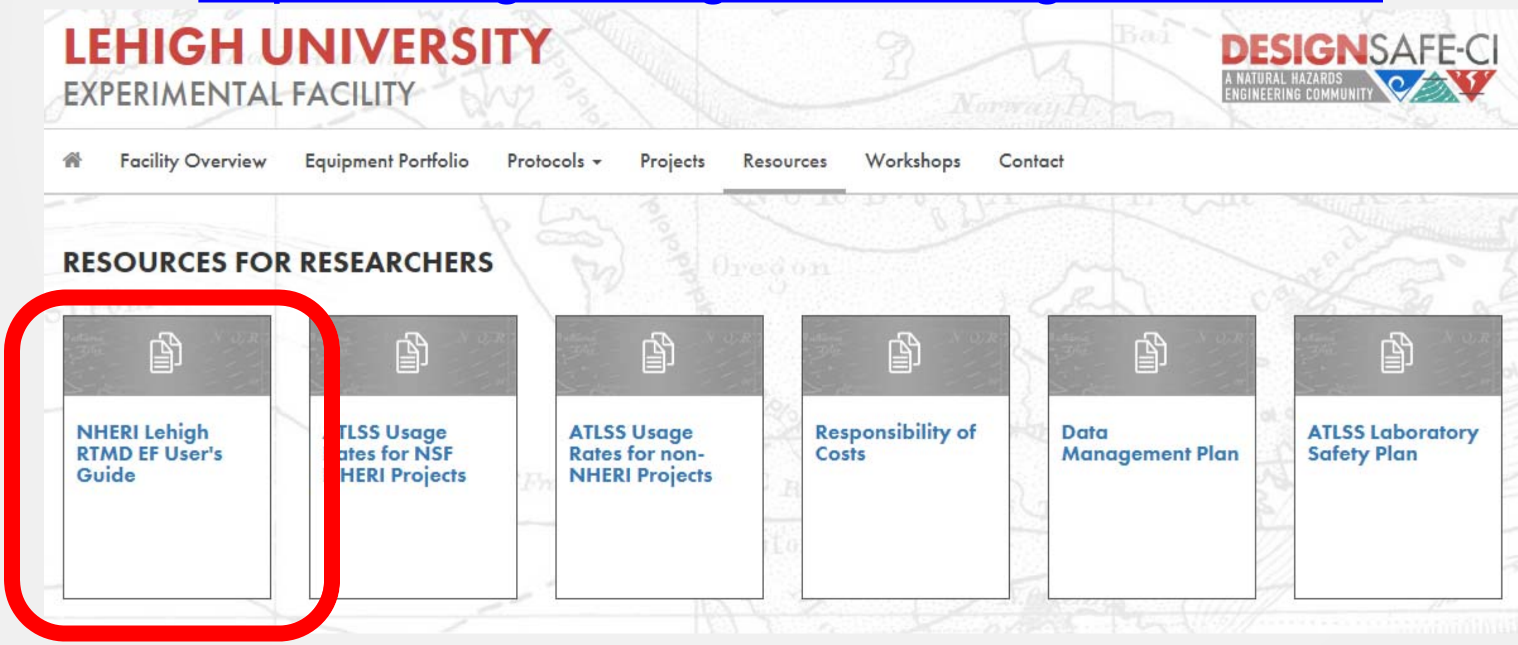
- User's Guide
- Repository of technical documents, demos and video tutorials
- Available to all users



Users Guide

- Details of the Equipment Specifications, Experimental Protocols, and Equipment Inventory are given in the User's Guide

https://lehigh.designsafe-ci.org/resources/



Thank you