NHERI Lehigh Experimental Facility Description, Experimental Capabilities and Protocols

James Ricles
NHERI Lehigh Director

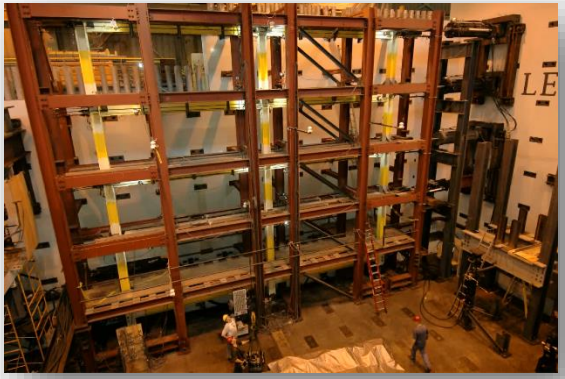
NHERI Lehigh EF

Outline

- Experimental Capabilities
- Real-time Hybrid Simulation: Overview, NHERI Lehigh Developments
- Test Beds
- Equipment
- Experimental Protocols

NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation



HS EQ Simulation of Buildings with SC-MRF

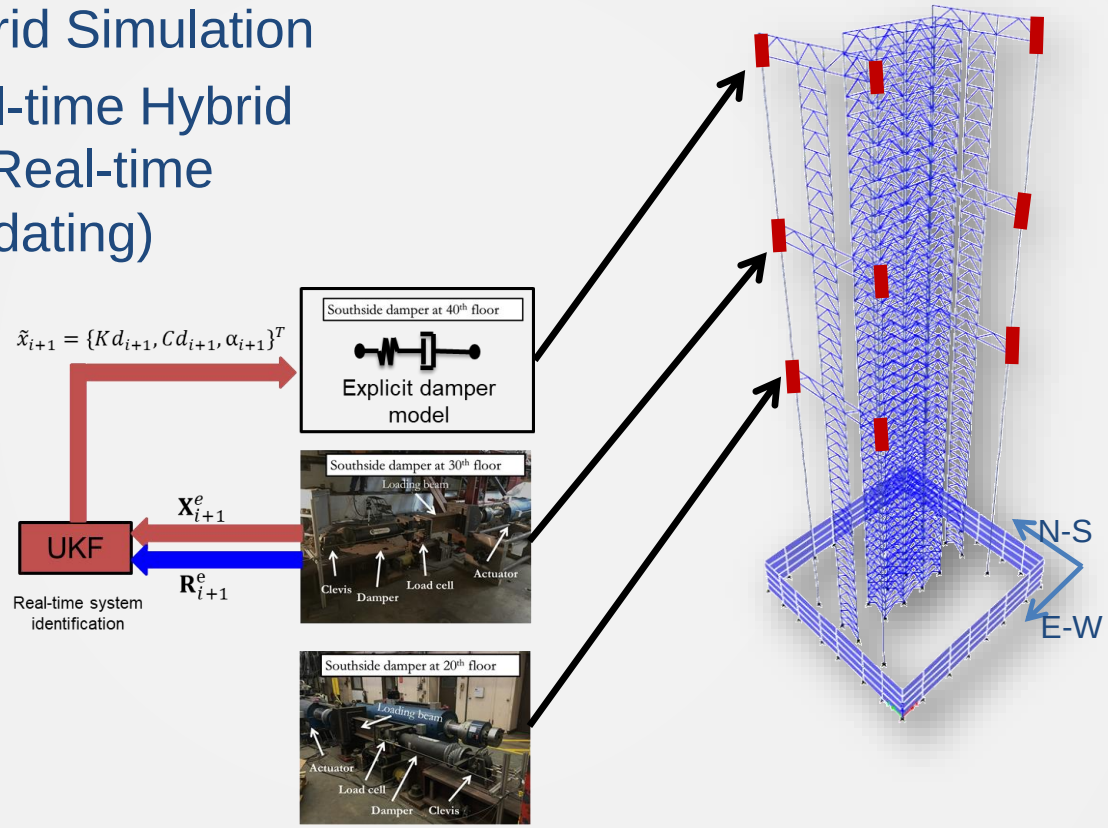
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- 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)



RTHS Wind and EQ Simulation of Tall Buildings with Dampers

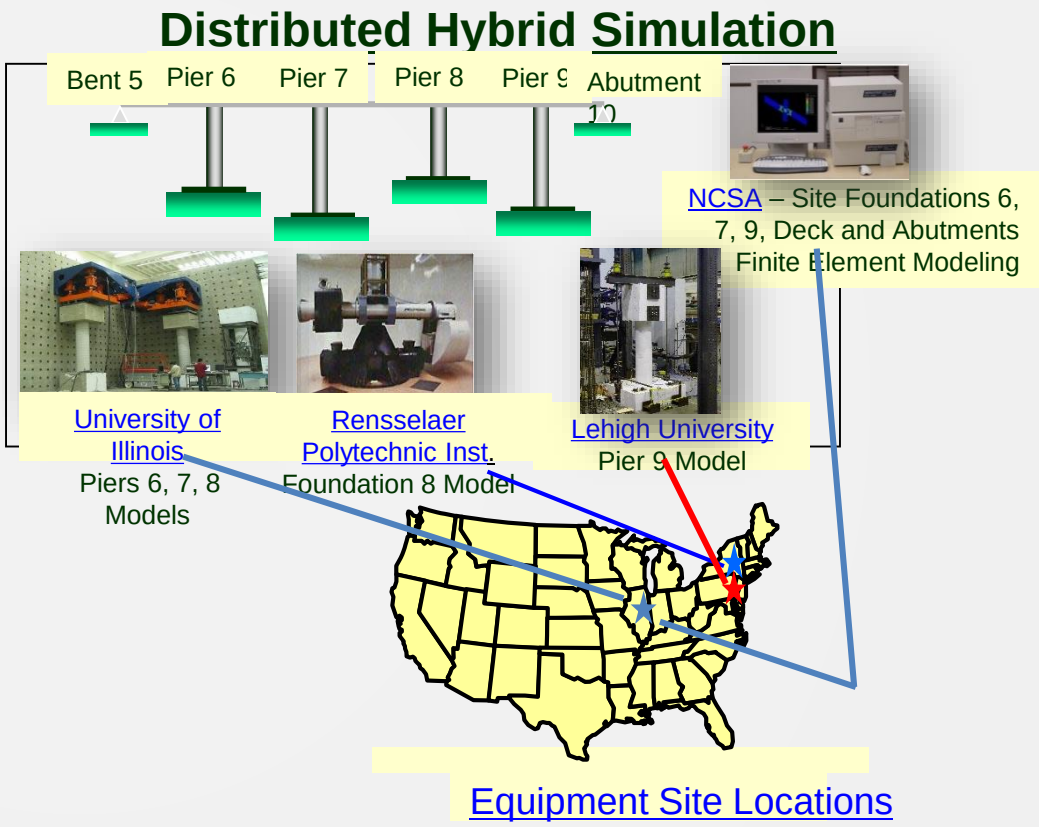
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)
- 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

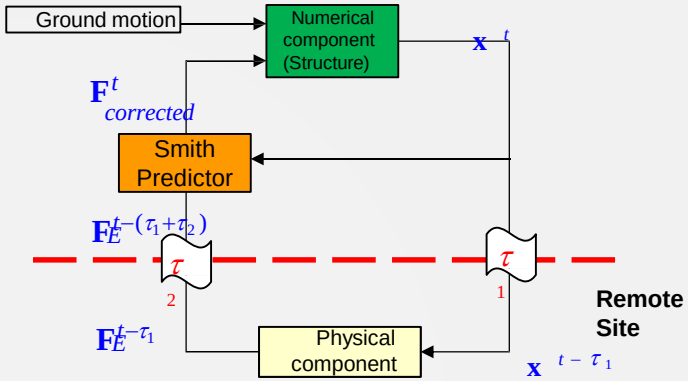
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation



Distributed RTHS EQ Simulation of I-10 Collector Bridge

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)
- 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)
- 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)
- 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

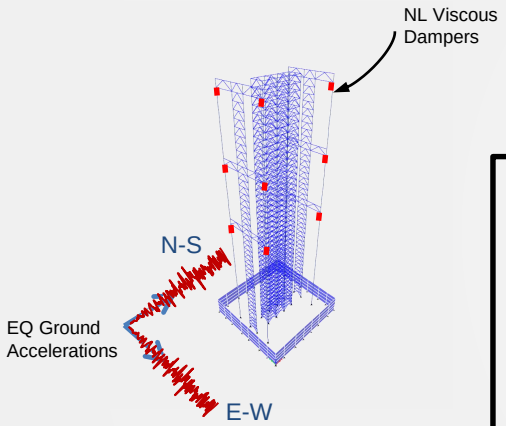
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- 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

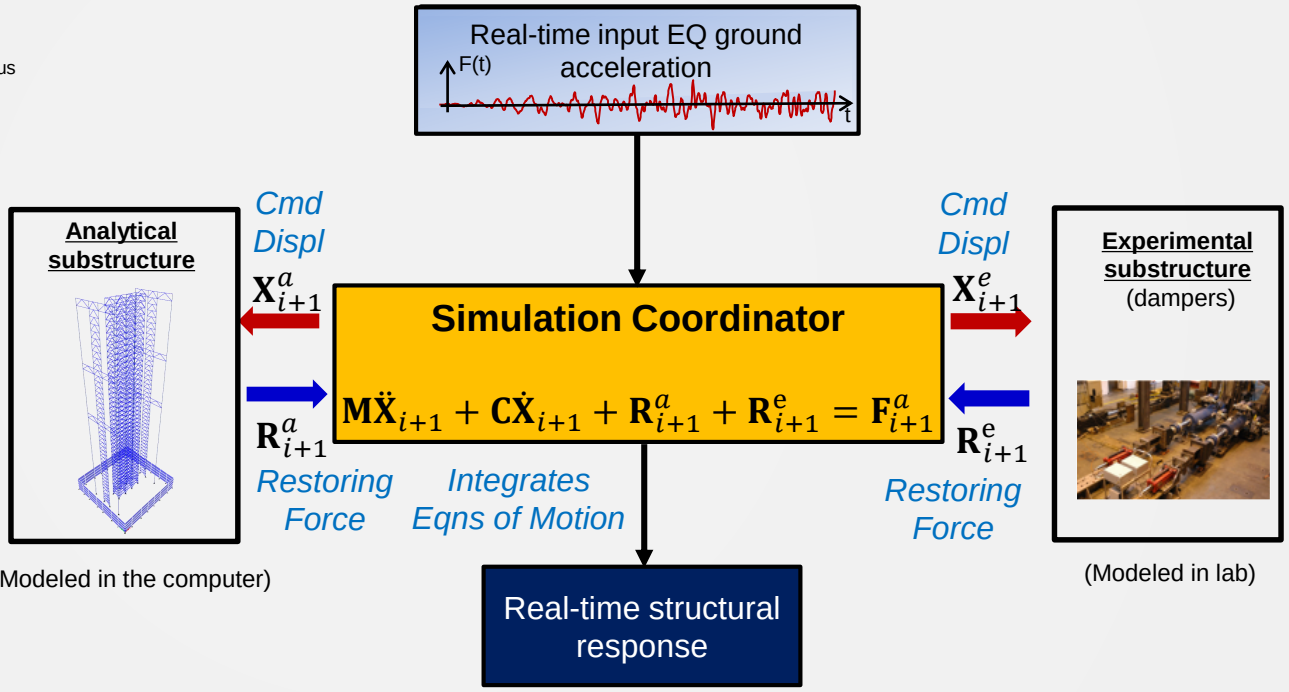
Structural System

40-Story Building with Outriggers and Supplemental Dampers



Wind Tunnel Tests NHERI@FIU
Wind Load Determination

Hybrid Earthquake Simulation Experiments



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 $\Omega = \omega \Delta t \to \infty$
  - varies in the range $0 \le \rho_\infty \le 1$
  - $\rho_\infty = 1$: No numerical energy dissipation
  - $\rho_\infty = 0$: Asymptotic annihilation

Stability: Root-Loci

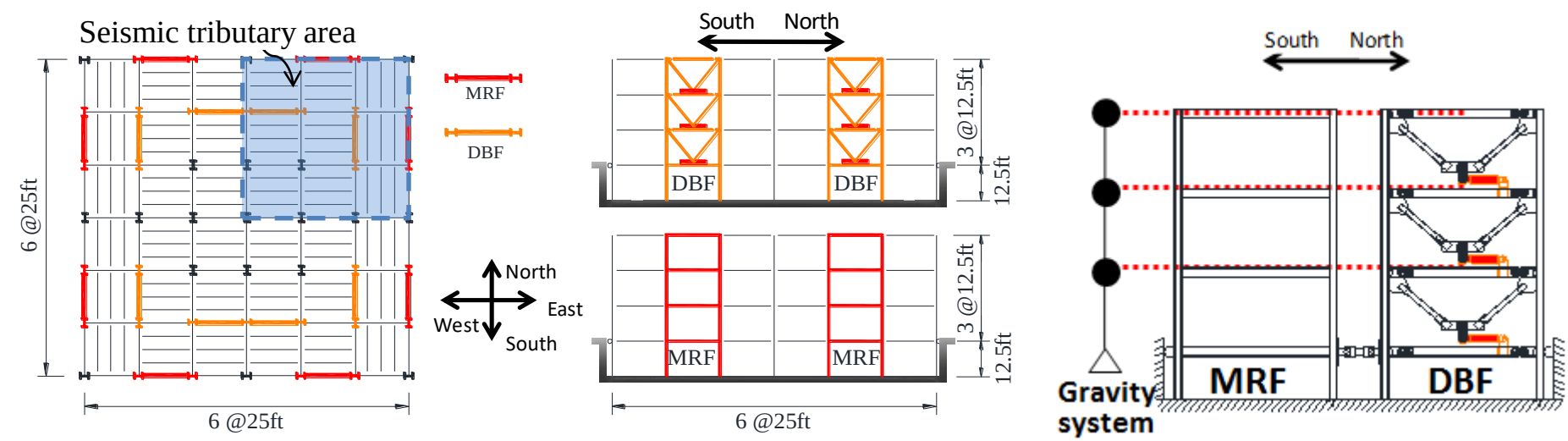
Controlled Numerical Damping

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) <u>with RBS beam-to-column connections</u>, damped brace frame (DBF), gravity load system, inherent damping of building



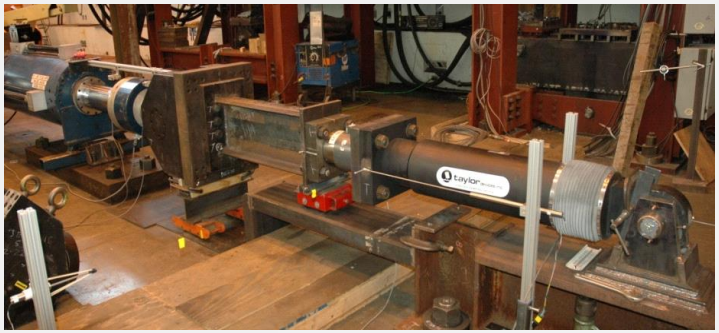
Plan view of prototype building **Section view of prototype building** **Test structure**

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.

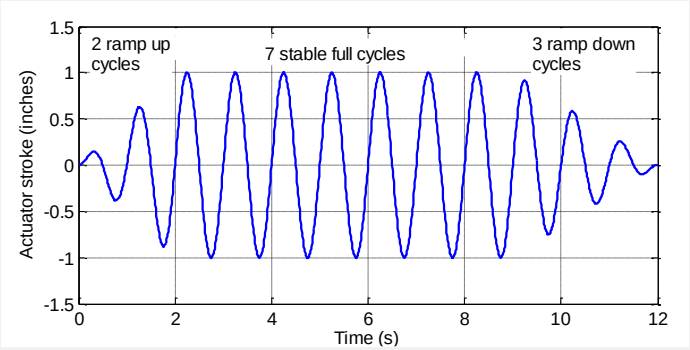
Dong, B., Sause, R., and J.M. Ricles, (2016) "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 142(6) https://DOI.org/10.1061/(ASCE)ST.1943-541X.0001482.

Nonlinear Viscous Dampers

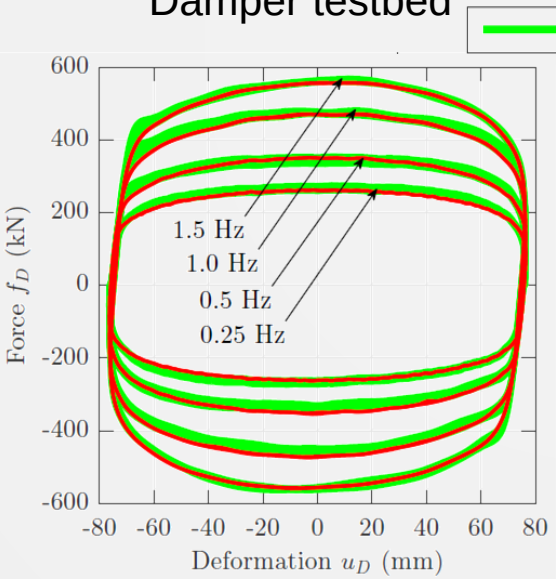
Characterization testing



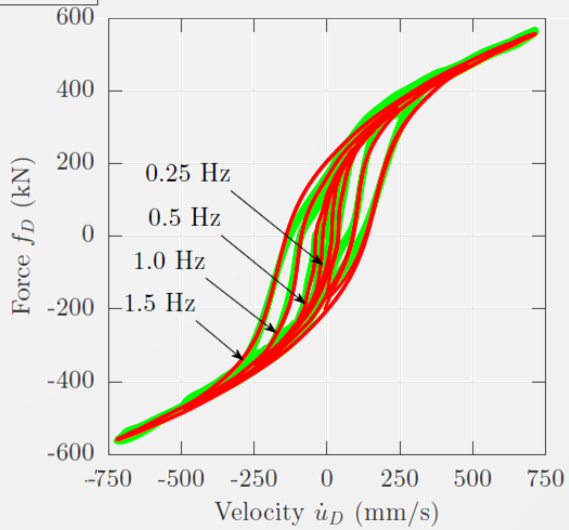
Damper testbed



Loading Protocol



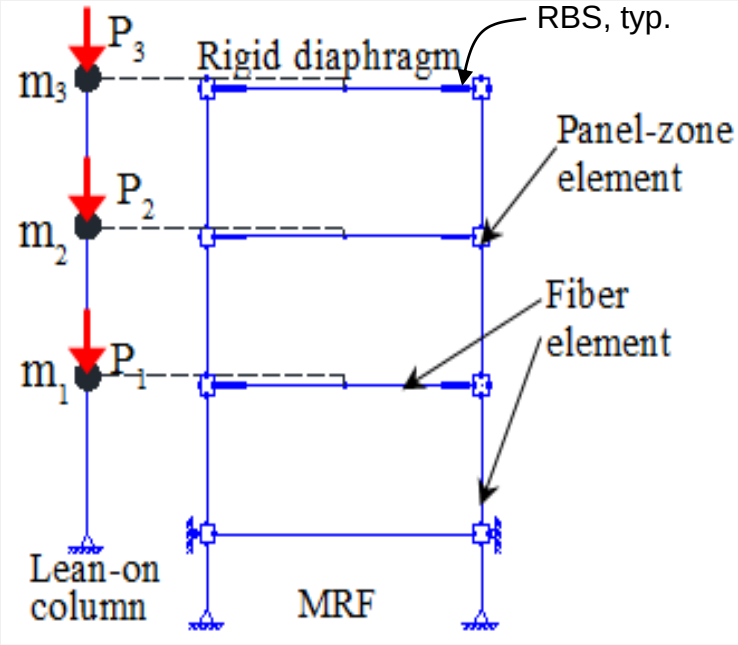
Damper force - deformation



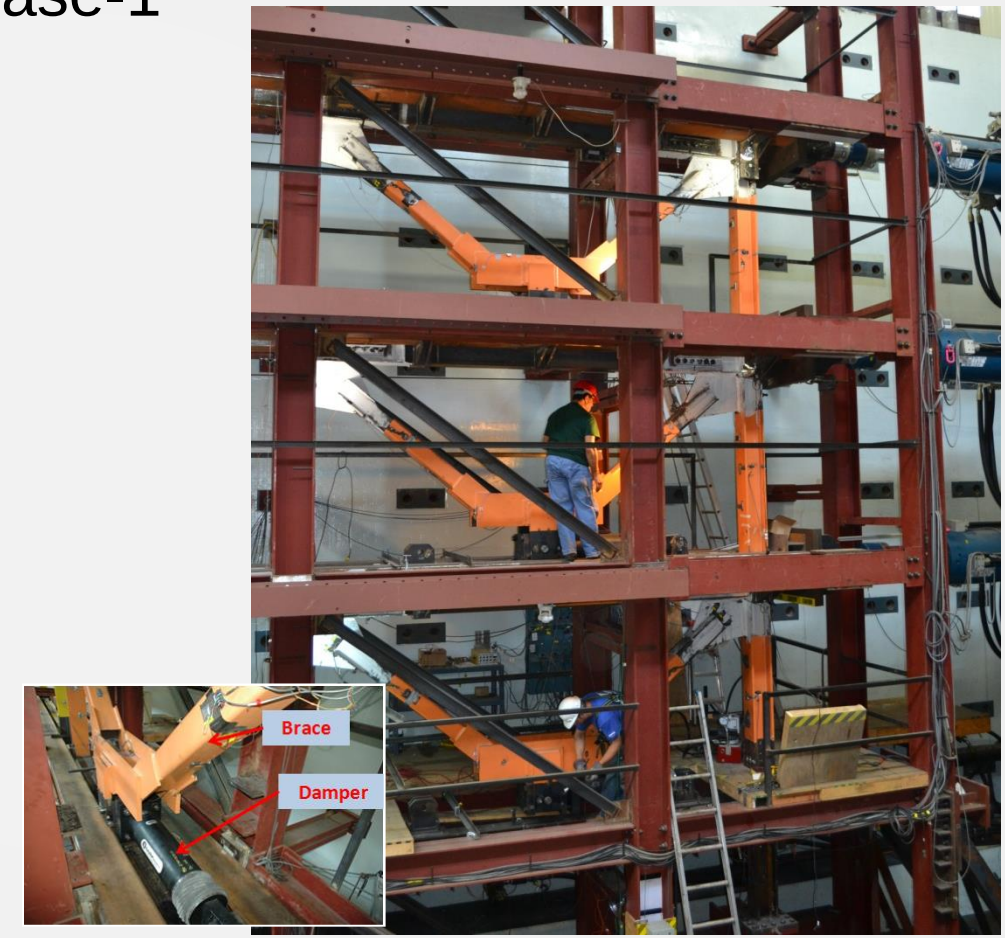
Damper force - velocity

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

Substructures for RTHS Phase-1



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

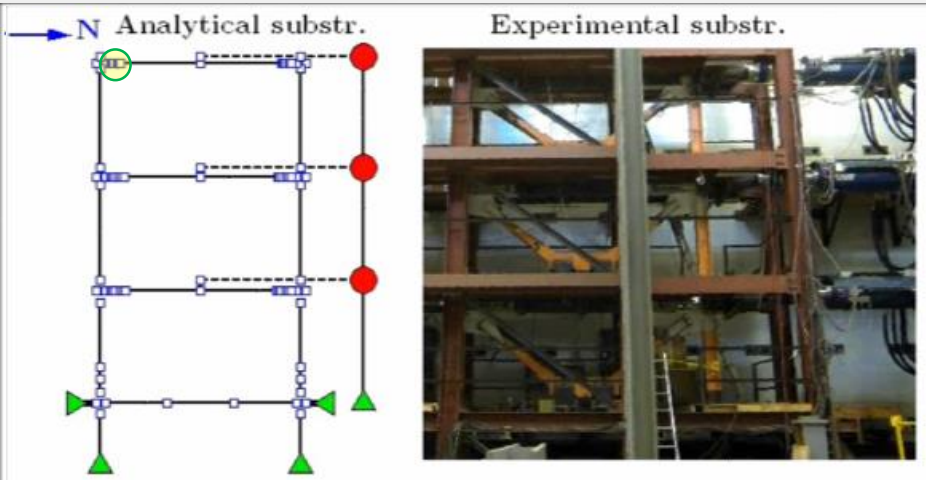


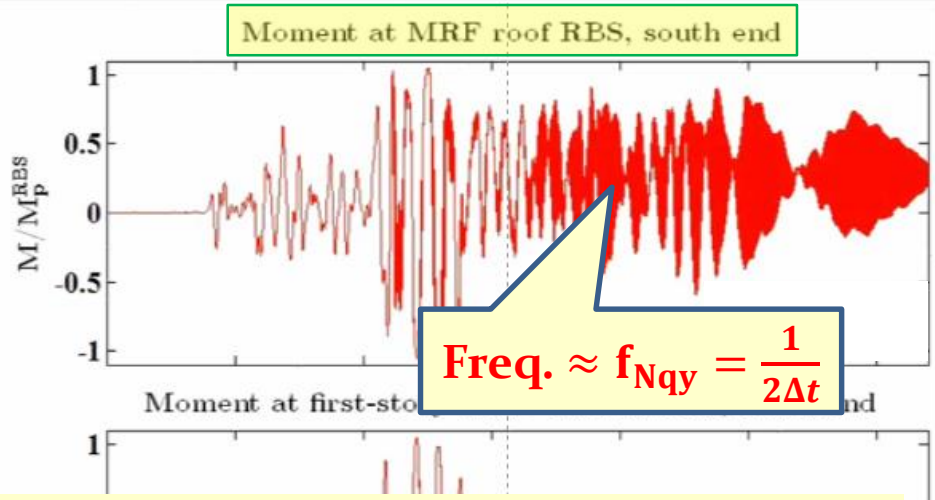
Experimental substructure (0.6-scale DBF)

<u>Real-time state determination</u>

- 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 $\rho_\infty = 1.0$

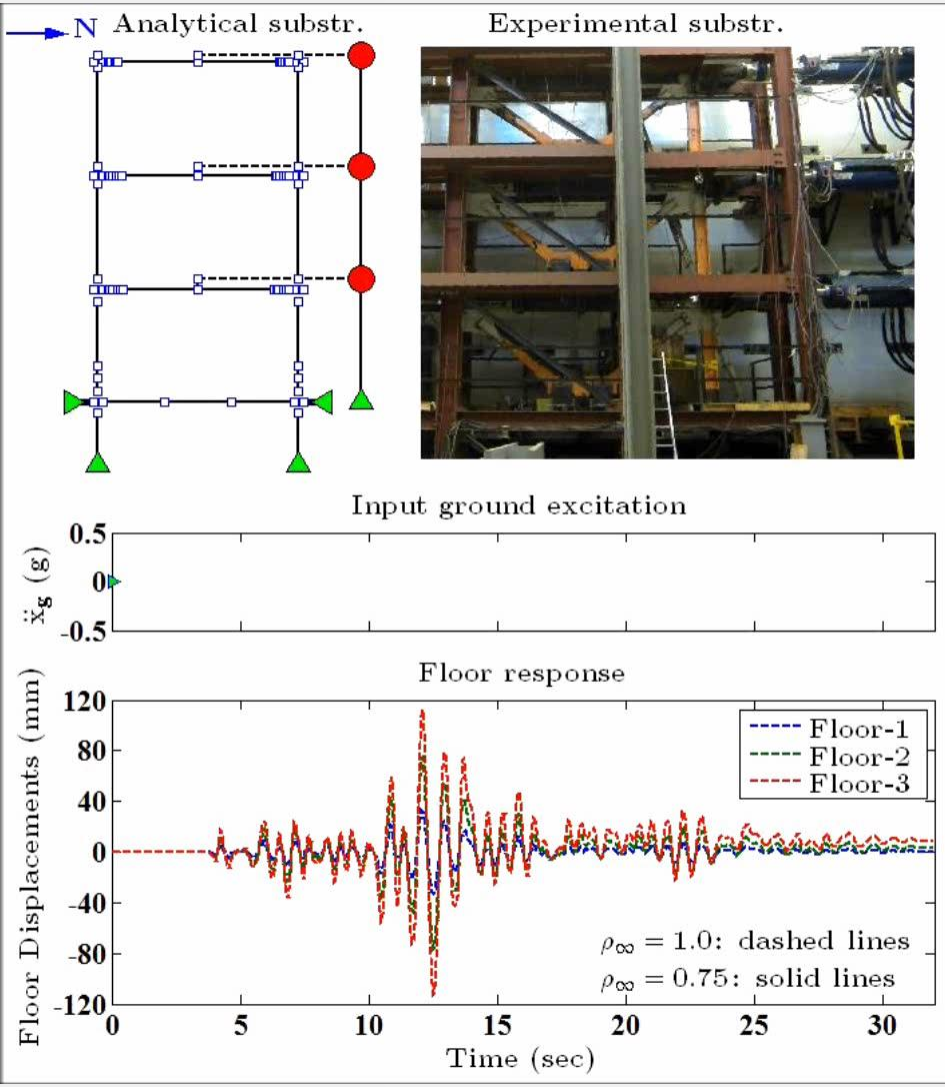


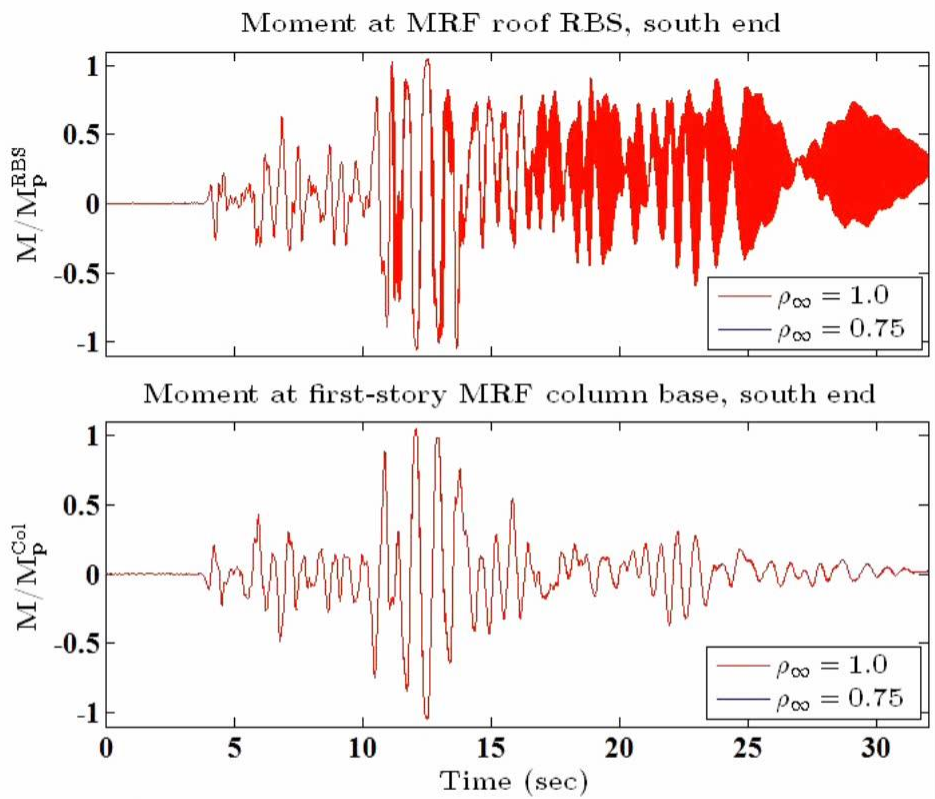


- Under nonlinear structural behavior, pulses are introduced in the acceleration at the Nyquist frequency $\left(= \frac{1}{2\Delta t}\right)$ when the state of the structure changes within the time step
- Pulses excite spurious higher modes present in the system which primarily contribute to the member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

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 $\rho_\infty = 0.75$





Real-time hybrid simulation using explicit unconditionally stable parametrically dissipative KR-α method

Ground excitation: B-WSM180 component, 1987 Superstition Hills, Westmoreland Fire Station
Hazard level: Maximum considered earthquake (MCE)
Algorithmic parameter: $\rho_\infty = 0.75$

LEHIGH UNIVERSITY | RTMD REAL-TIME MULTI-DIRECTIONAL TESTING FACILITY | ATLSS | NEES

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

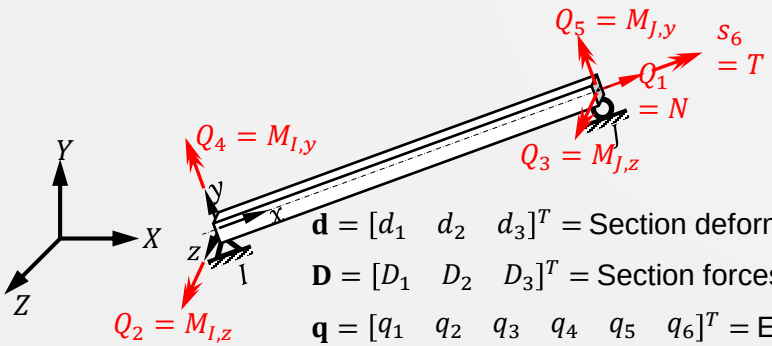
Displacement-based fiber elements

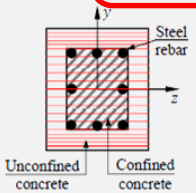
- ❑ Curvature varies linearly
  - ➢ Requires numerous elements per structural member to model nonlinear response
  - ➢ Increases number of DOFs
- ❑ State determination is straight forward

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

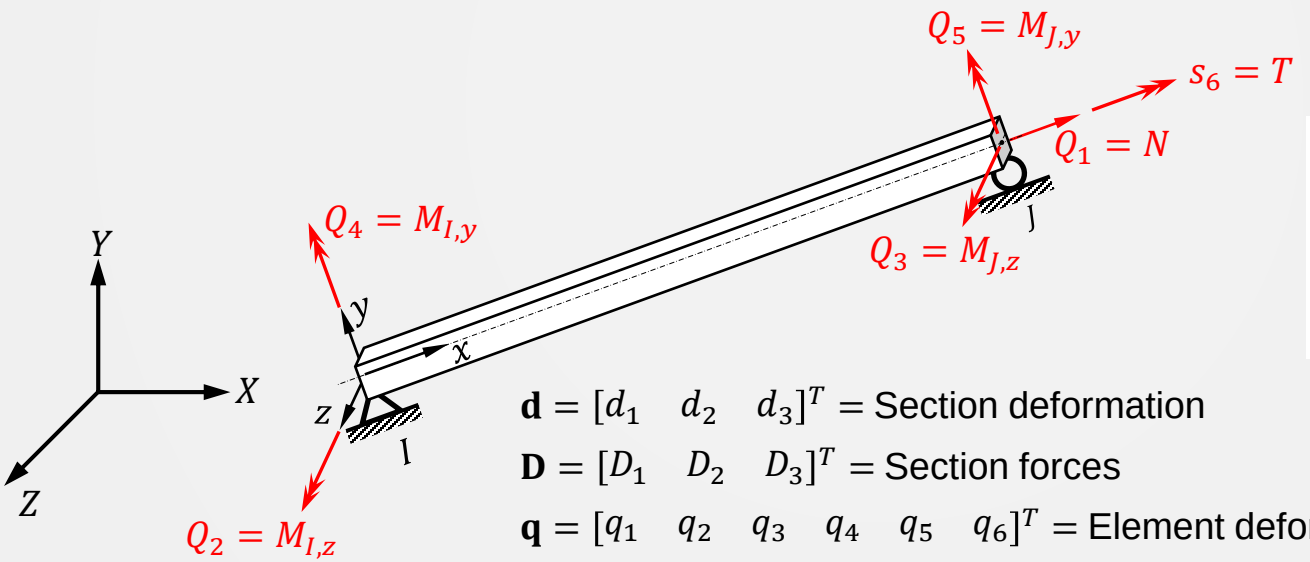
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T$ = Element deformations

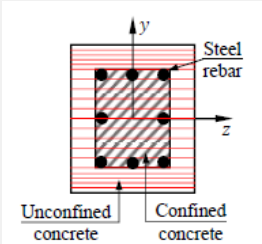
$\mathbf{Q} = [Q_1 \quad Q_2 \quad Q_3 \quad Q_4 \quad Q_5 \quad Q_6]^T$ = Element forces

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

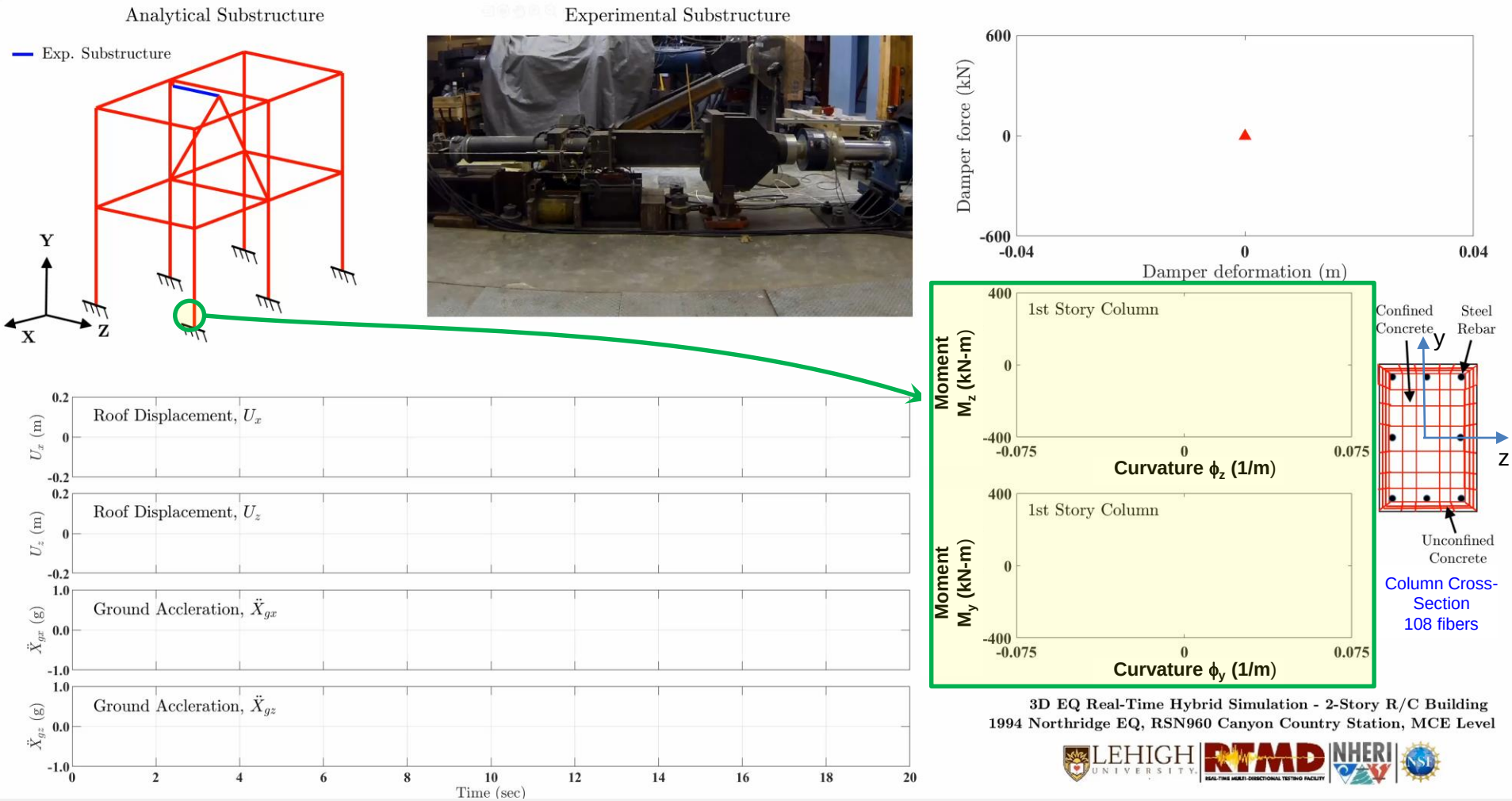
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T$ = Element deformations

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

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

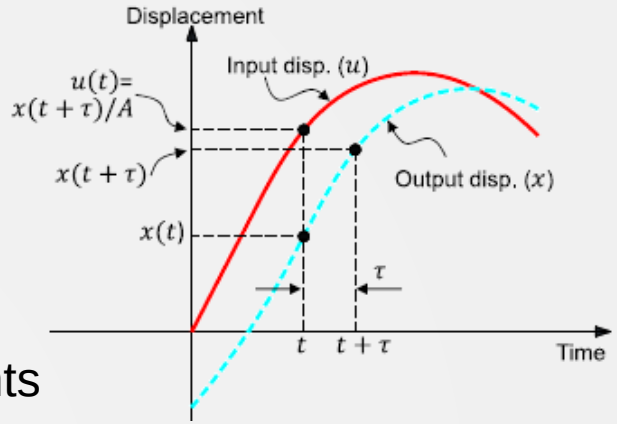
- Variable amplitude error and time delay in measured specimen displacement

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

It is important to compensate

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

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

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

$$\mathbf{x}^\mathbf{m} = \begin{bmatrix} x_{k-1}^m\ x_{k-2}^m \cdots x_{k-q}^m \end{bmatrix}^T$$ (Output (measured) specimen displacement history)

$$\mathbf{U}_\mathbf{c} = \begin{bmatrix} u_{k-1}^c\ u_{k-2}^c \cdots u_{k-q}^m \end{bmatrix}^T$$ (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

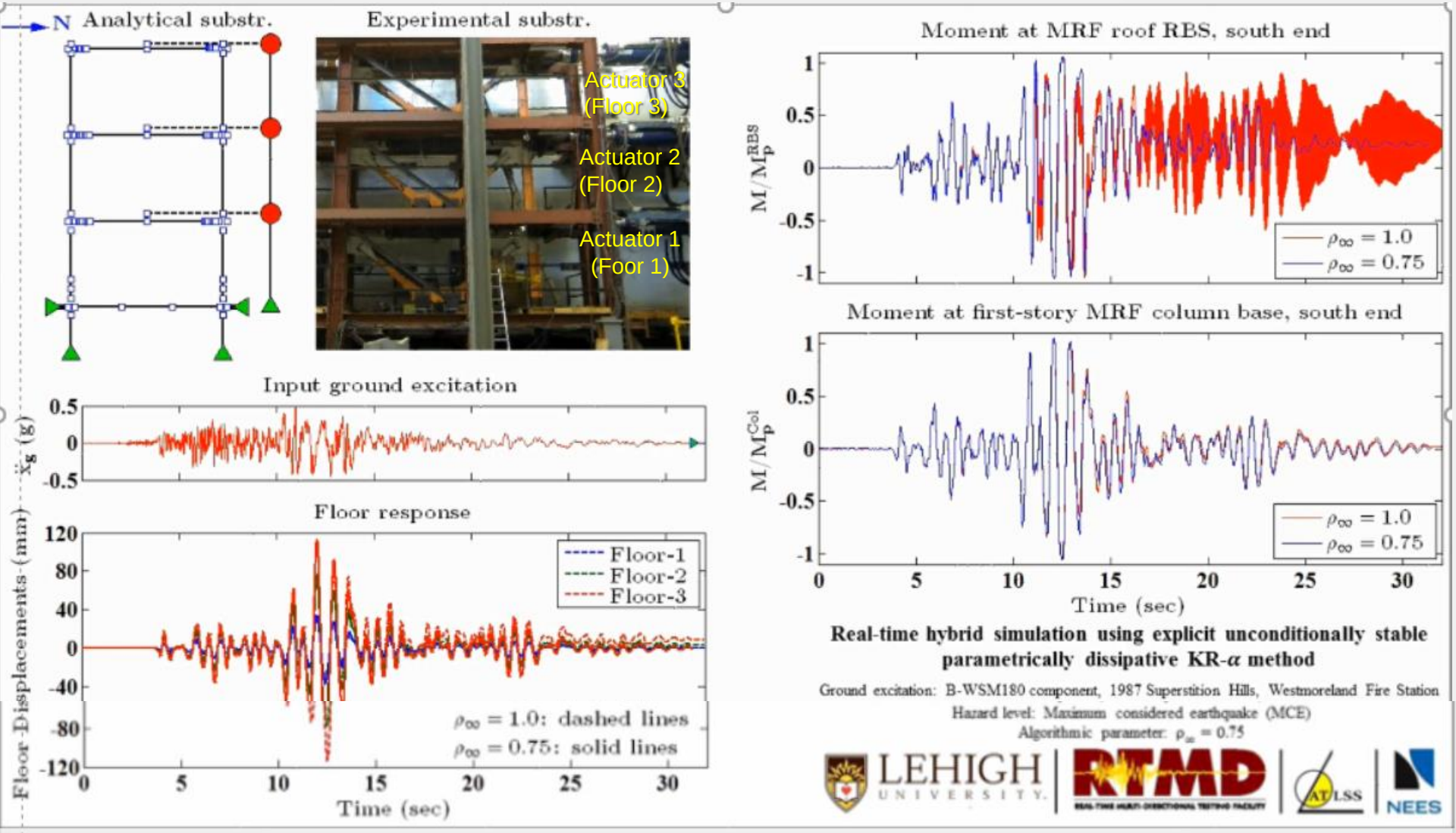
- No user-defined adaptive gains ➔ applicable for large-scale structures susceptible to damage (i.e., concrete structures)
- Negates both variable time delay and variable amplitude error response
- Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients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

Time Step k

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

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

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



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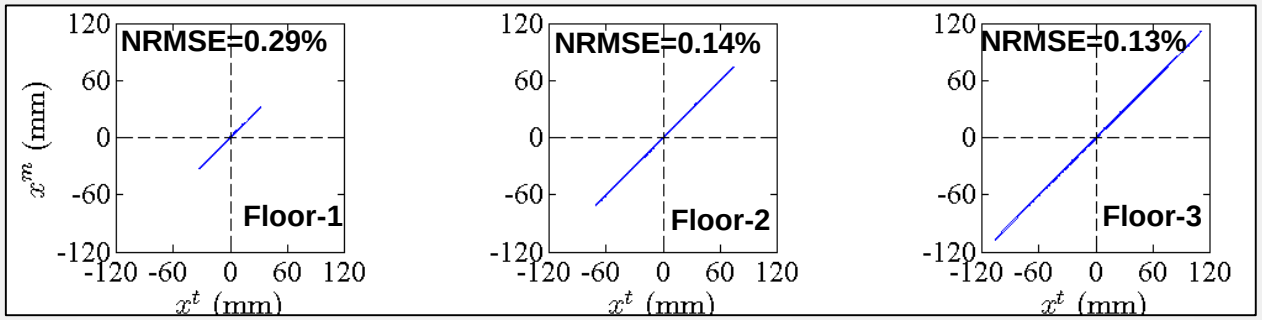
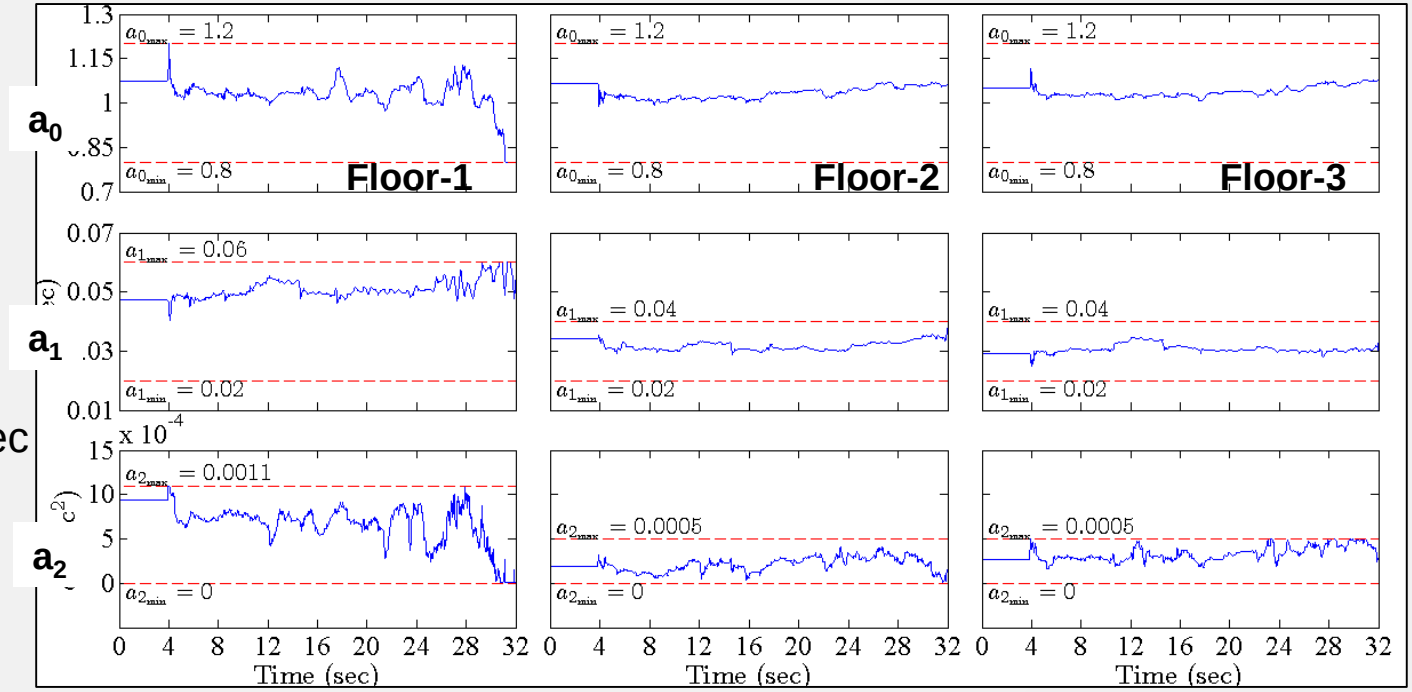
Actuator control: Typical MCE level RTHS & $\rho_\infty = 0.75$

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

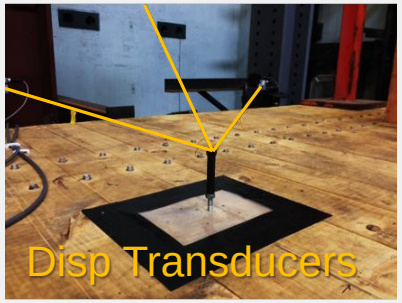
$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 0.83 \sim 1.25$$

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

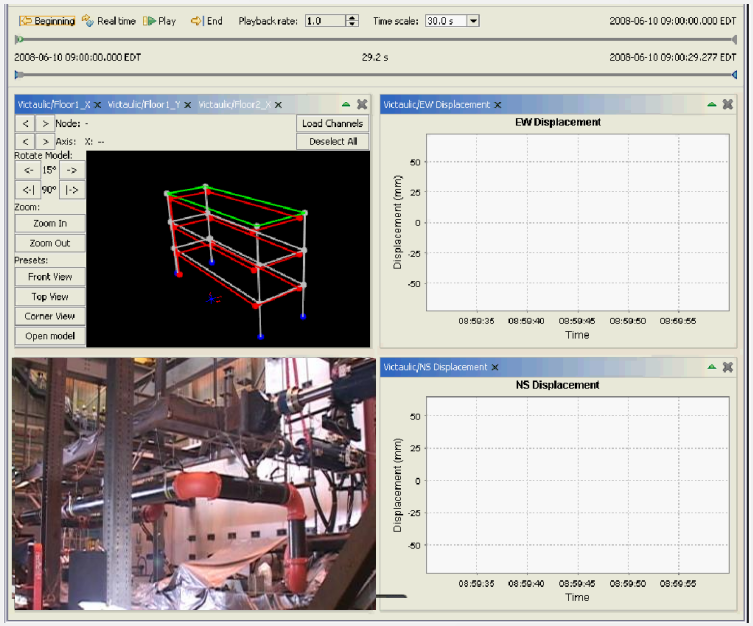


$$(M_i SNxL_{new}, M_i SNyL_{new}) = (-LMa_{inew} sin(\Theta_2 + \phi_i), LMa_{inew} cos(\Theta_2 + \phi_i))$$

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

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

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



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.

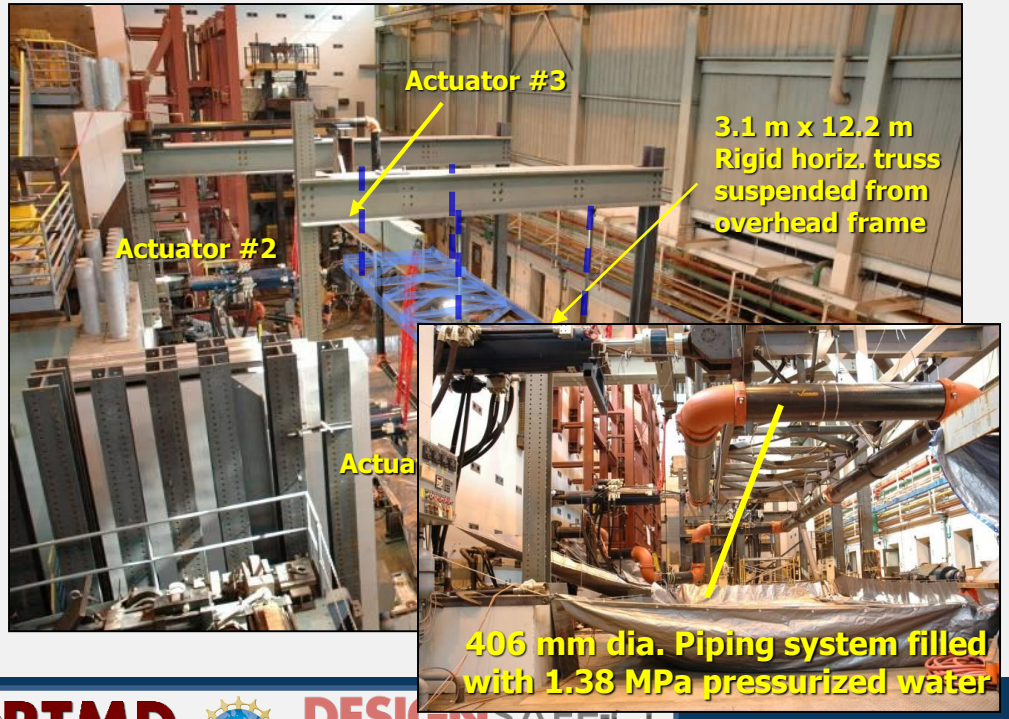
NHERI Lehigh EF/ATLSS Testbeds

- **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

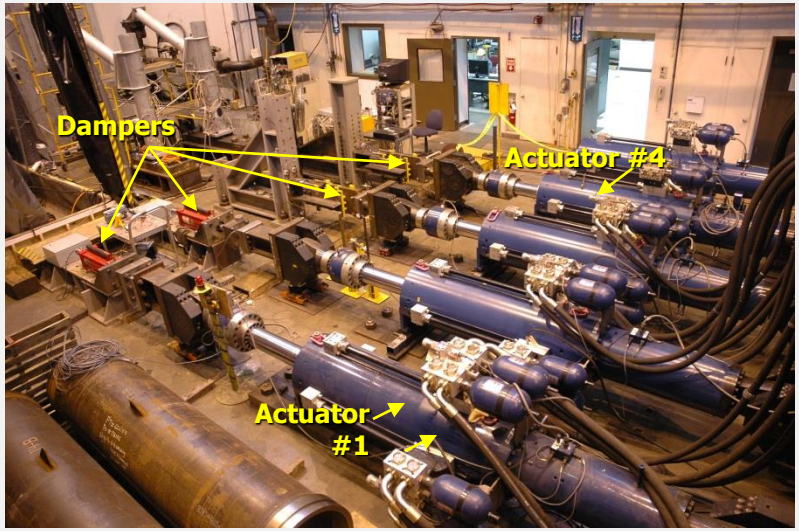
Multi-directional Real-time hybrid simulation of building piping system



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

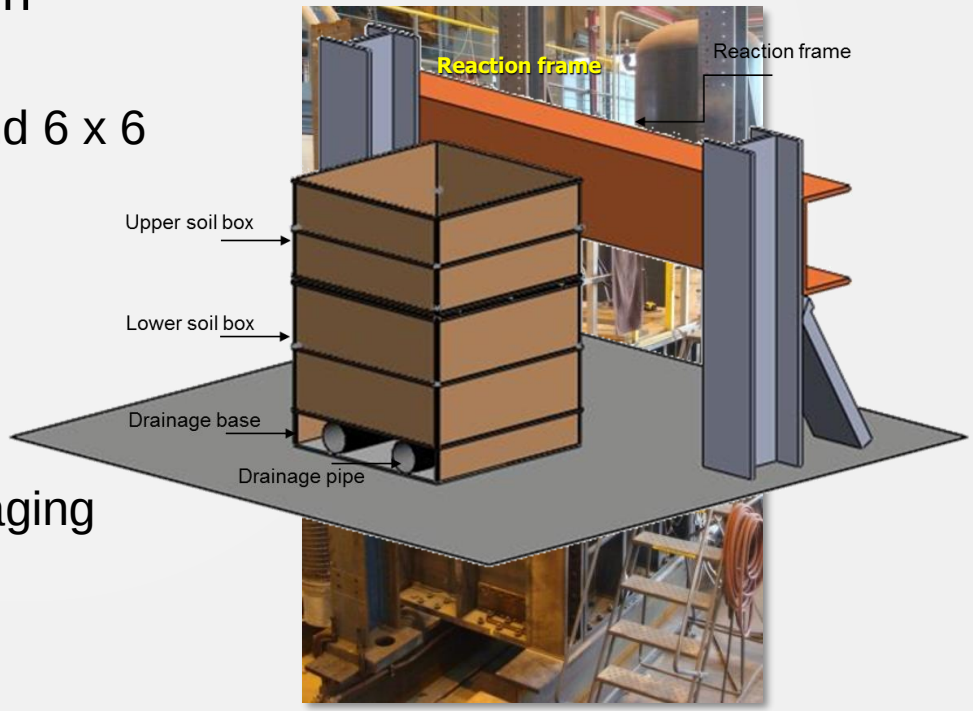
- **Tsunami Debris Impact Force Testbed**
  - Enables full-scale debris impact tests:
    - High speed DAQ; high speed 5000 fps cameras
    - High bandwidth, resolution load cells
    - Accelerometers, laser-displacement transducers

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

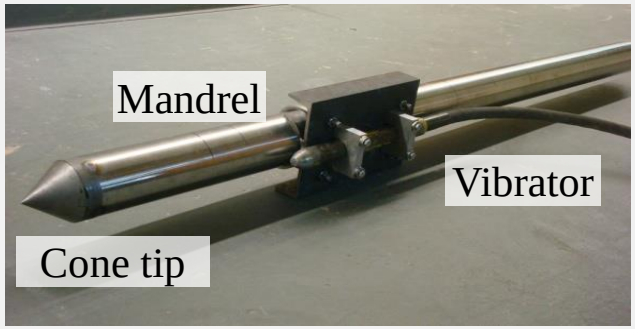
NHERI Lehigh EF/ATLSS Testbeds

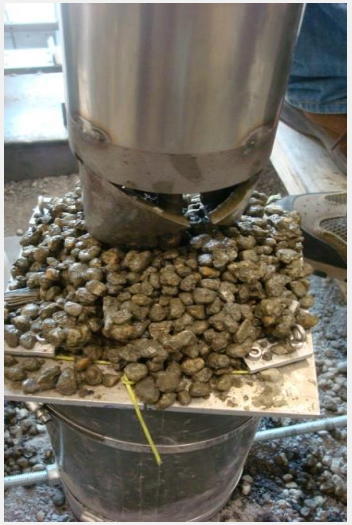
- **Reduced-scale Soil Box**
  - Enables soil-structure interaction research
    - Flexible designs (6 x 6 x 6 ft and 6 x 6 x 3 ft in size)
    - Actuators with load cells; data acquisition system
    - Sensors for soil and foundation response measurements
    - Advanced sensors - Digital Imaging Correlation

Soil-foundation structure interaction testbed



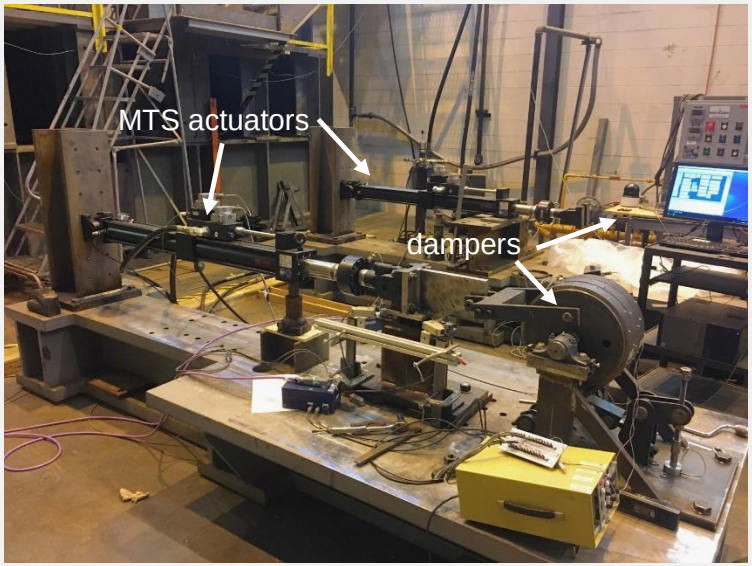
Soil-Structure Interaction Testbed





Lehigh Real-time Cyber-Physical Structural Systems Laboratory

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

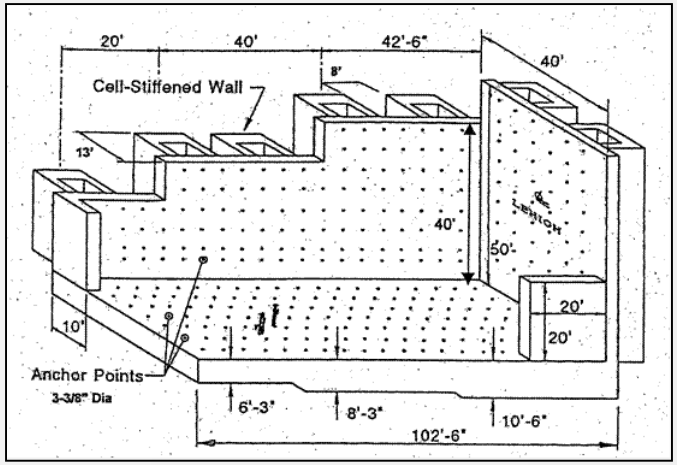


Actuator Specifications

	244.21G2	244.20G2s
Max Force	50 kN (11 kips)	82 kN (18.5 kips)
Max displacement	± 254 mm (± 10 in)	± 177 mm (± 7 in)
Max velocity	0.74 m/s (29 in/s)	0.43 m/s (51 in/s)
Servo Valve	30 gpm	90 gpm

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

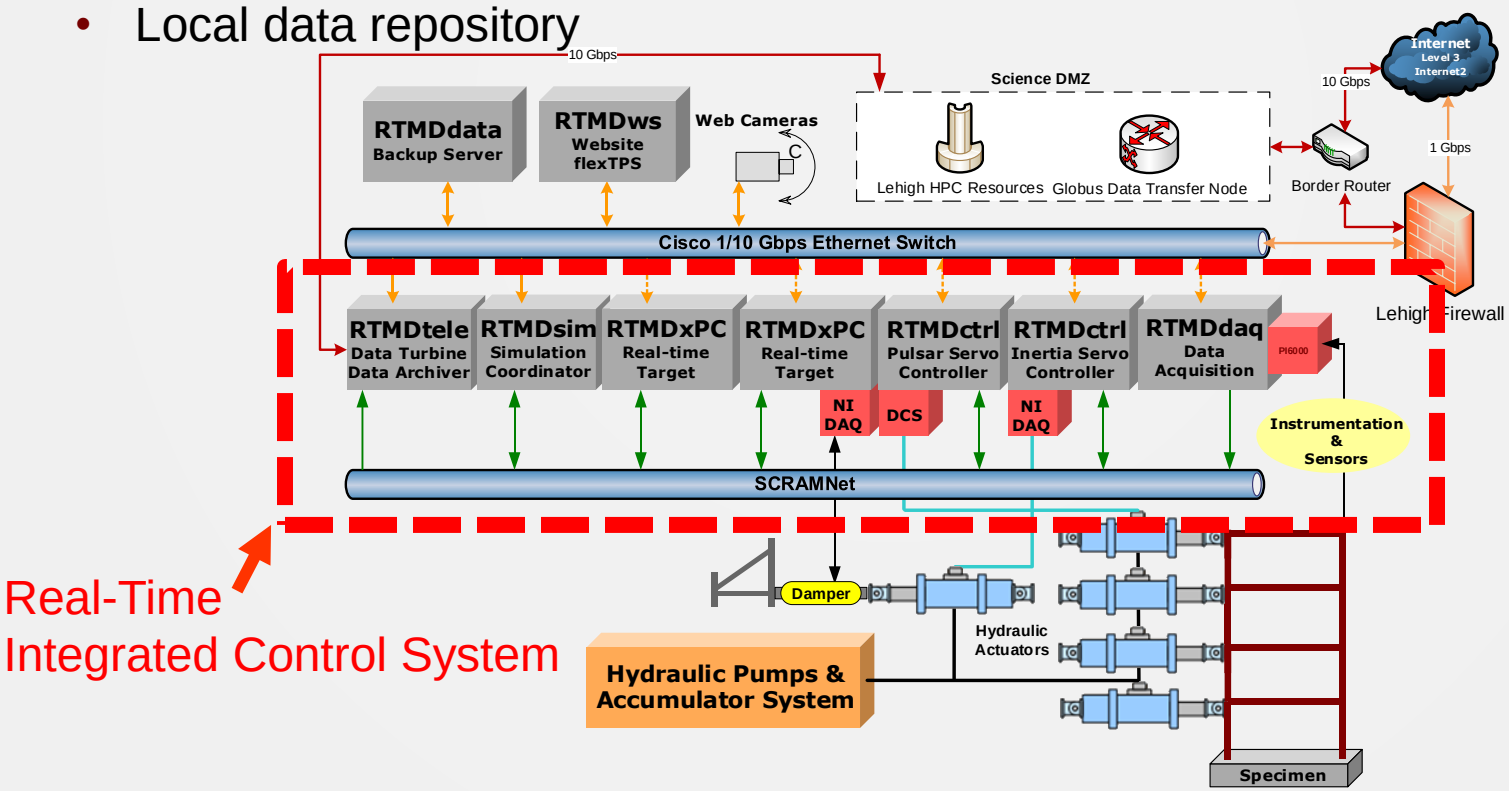
- High Speed 300+ Channel Data Acquisition System
- 3 Real-Time Targets for simulation coordination, including additional DAQ
- Three real-time servo-hydraulic controllers
- Sensors (displacement, accelerometers, inclinometers)
- Telepresence webcams
- Specs for all equipment found in User's Guide

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

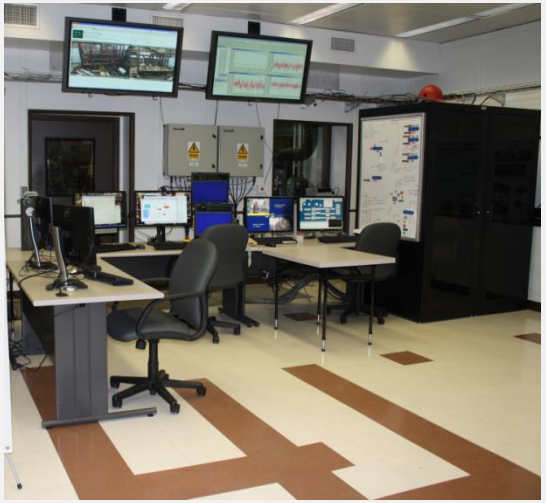
- Real-time Integrated Control System
  - Multiple Real-Time targets for simulation coordination with additional DAQ
  - Three real-time servo-hydraulic controllers
  - High Speed 300+ Channel Data Acquisition System
  - Web and Data telepresence system
  - Local data repository



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

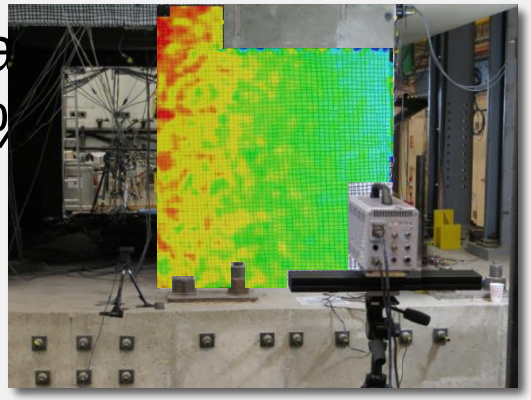
https://lehigh.designsafe-ci.org/resources

Instrumentation

- Digital imaging correlation (DIC) systems.
  - Utilize the 3D ethod.
  - Works on bot r pattern, thus simplifying sa
  - The same se to measure small and large obj m) a the range of (100%

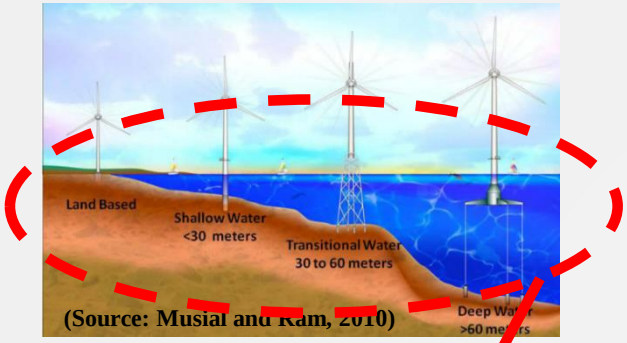
Figure F.4 DIC System

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

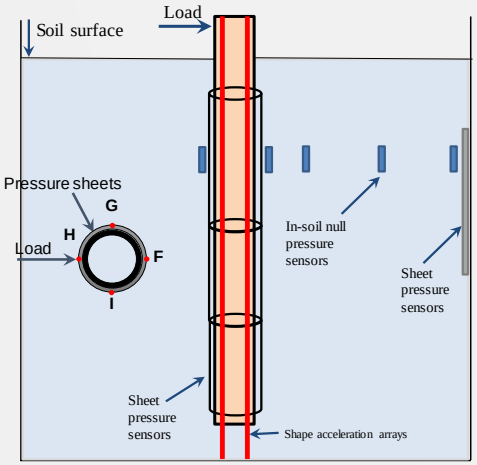


Digital Imaging Correlation System: reinforced concrete coupled-shear wall test specimen measured pier vertical displacements (courtesy M. McGinnis)

Soil-Structure Interaction Instrumentation

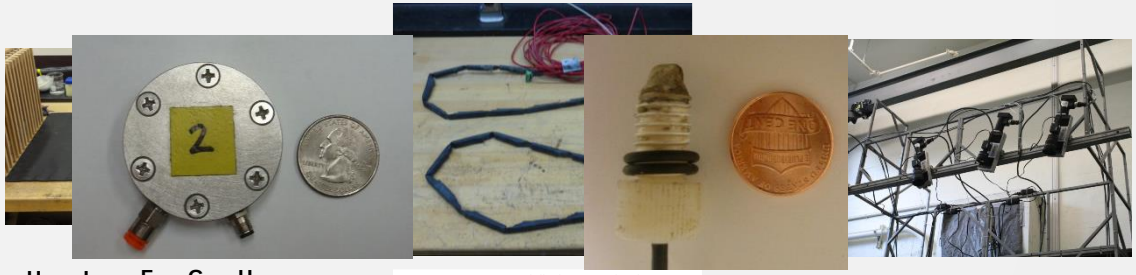


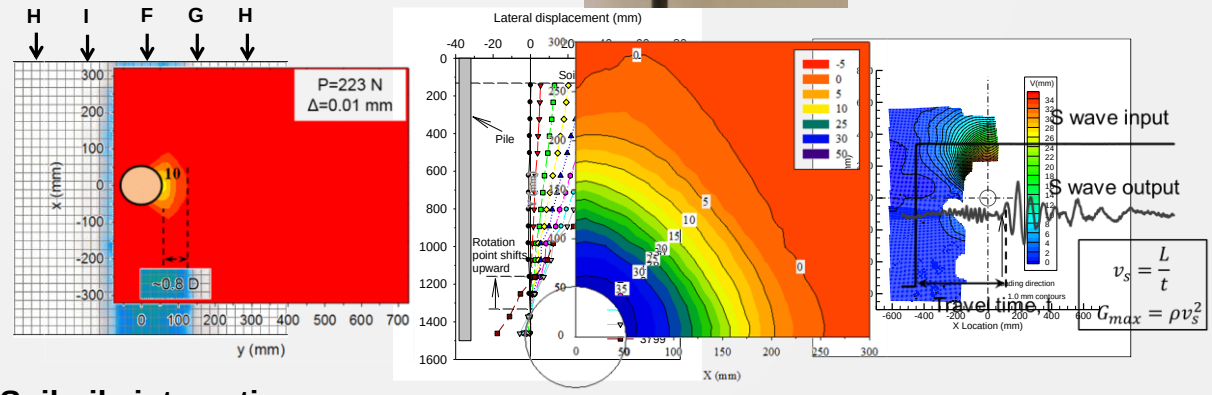
(Source: Musial and Ram, 2010)



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

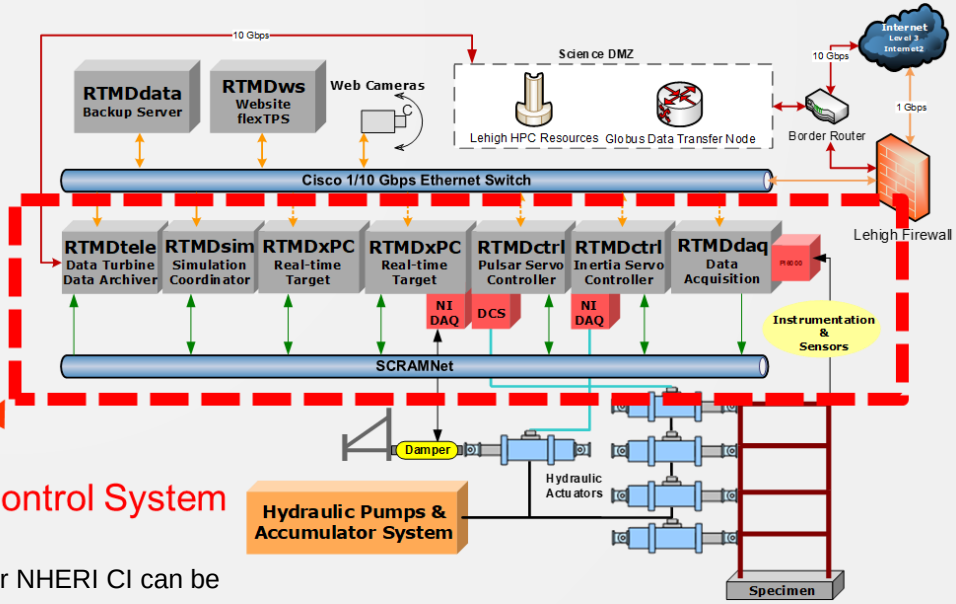
Mechanical testing

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
  - 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

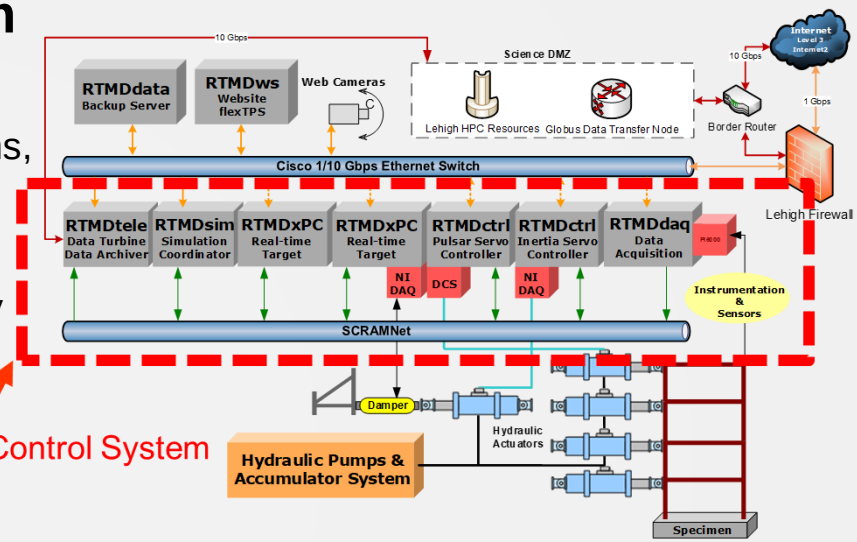
https://lehigh.designsafe-ci.org/protocols/experimental-protocol/

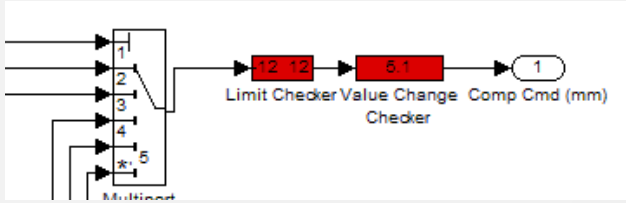


Real-Time
Integrated Control System

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





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

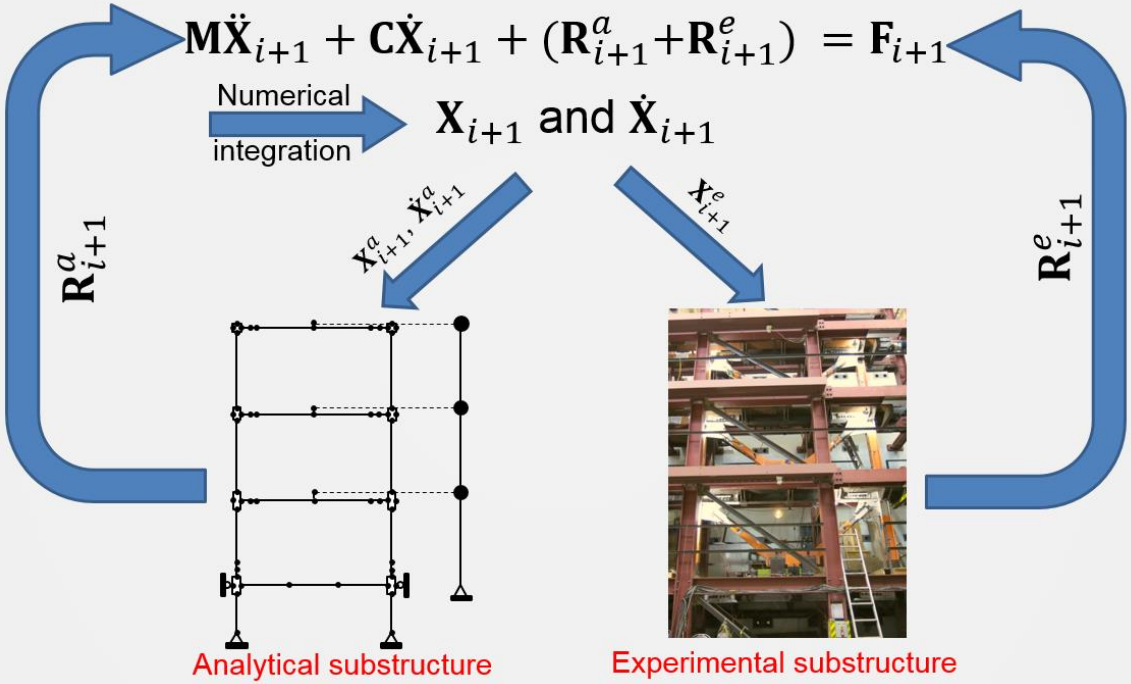
Kolay, C., and J.M. Ricles (2017). "Improved Explicit Integration Algorithms for Structural Dynamic Analysis with Unconditional Stability and Controllable Numerical Dissipation," Journal of Earthquake Engineering, http://dx.doi.org/10.1080/13632469.2017.1326423

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 with OpenFresco interface



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

HybridFEM

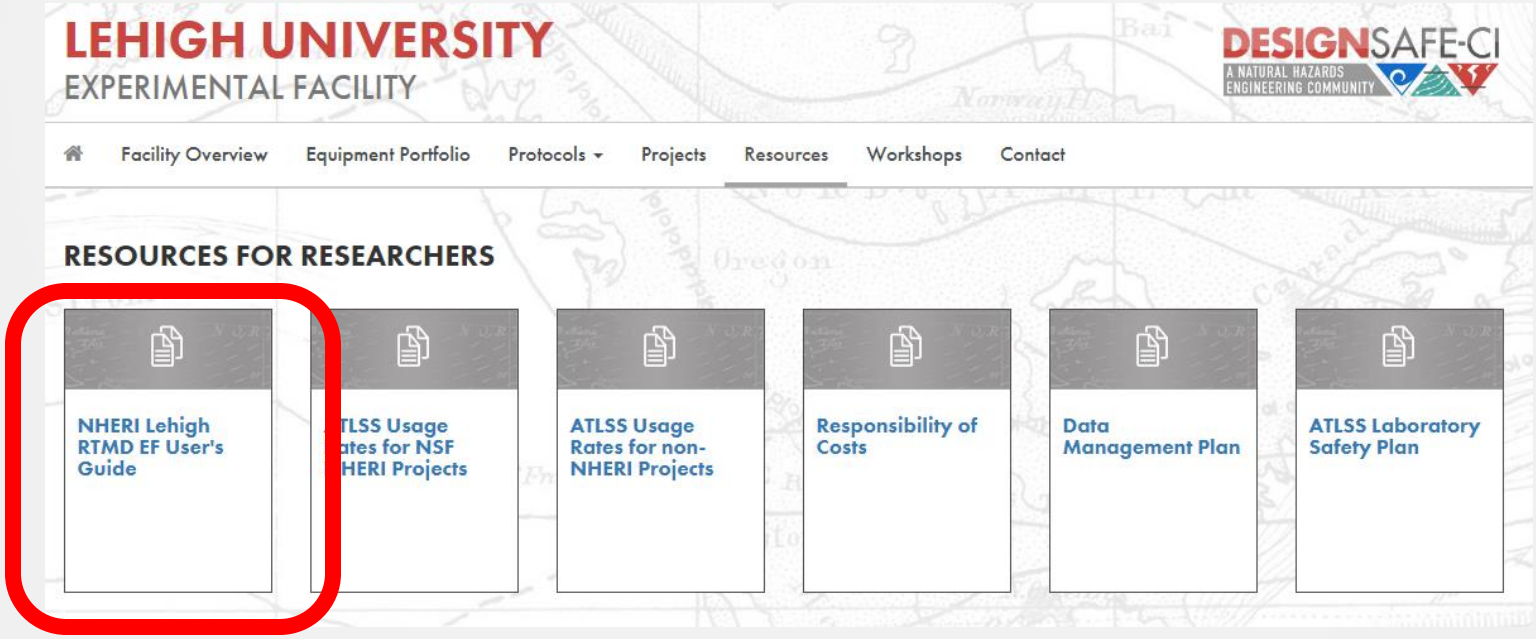
Configuration Options:

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

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