NHERI Lehigh EF Large-Scale Testing and Real-time Hybrid Simulation

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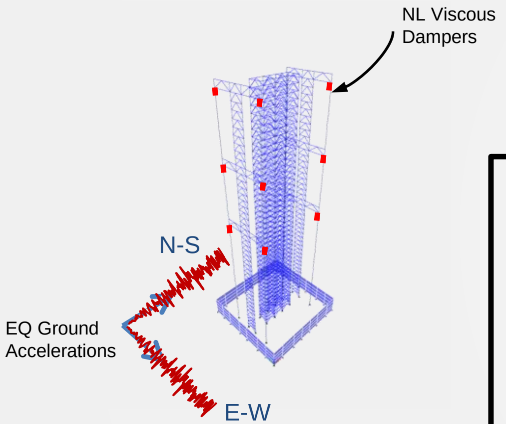
Overall Concept of Real-time Hybrid Simulation: Structural System Subject to Multi-Natural Hazards

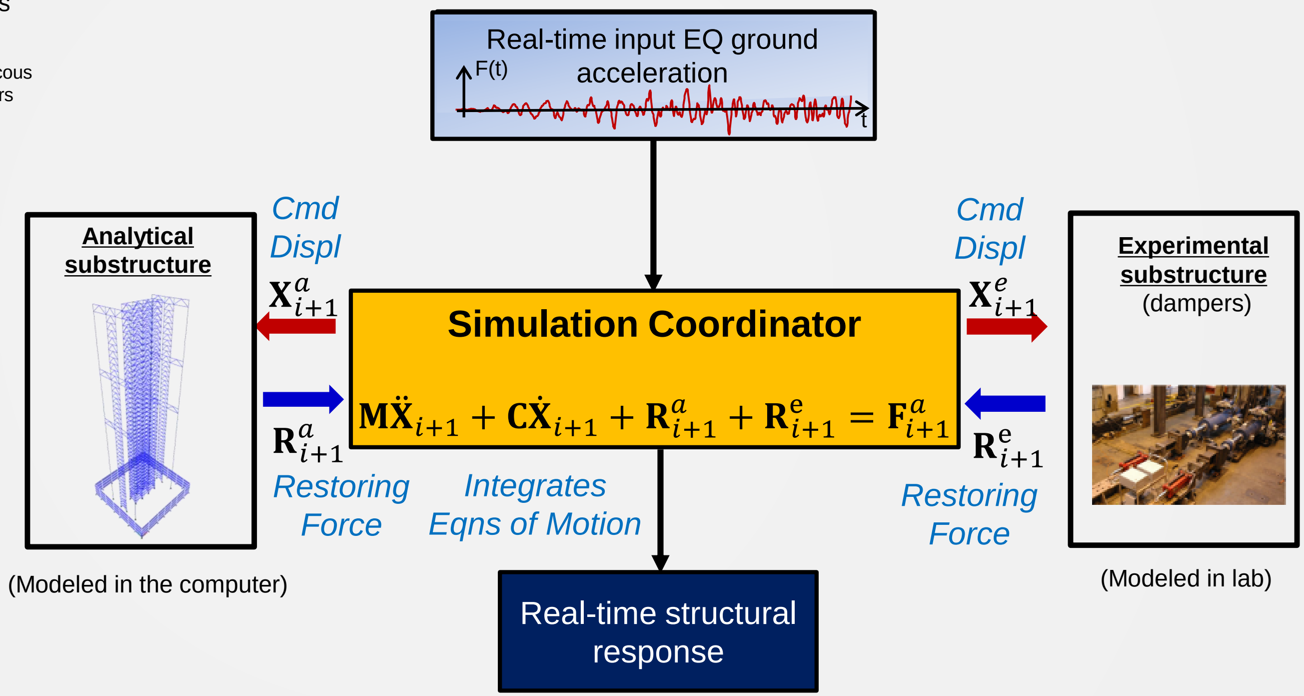
Structural System

40-Story Building with Outriggers
and Supplemental Dampers



Wind Tunnel Tests NHERI@FIU
Wind Load Determination

Hybrid Earthquake Simulation Experiments



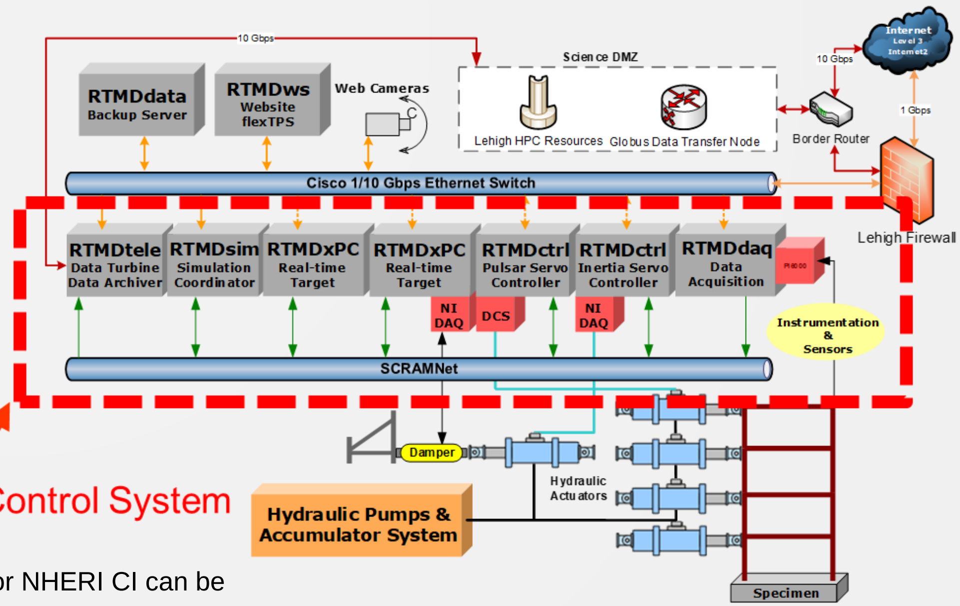
LEHIGH UNIVERSITY ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

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

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



Real-Time
Integrated Control System

NHERI Lehigh EF Experimental Protocols

- **Real-time 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; Al-Subaihawi 2021*)
  - Multi-directional actuator control: Multi-directional Kinematic Compensation (*Mercan et al. 2009*)
  - Explicit-formulated computational modeling element (*Kolay et al. 2018)*

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.

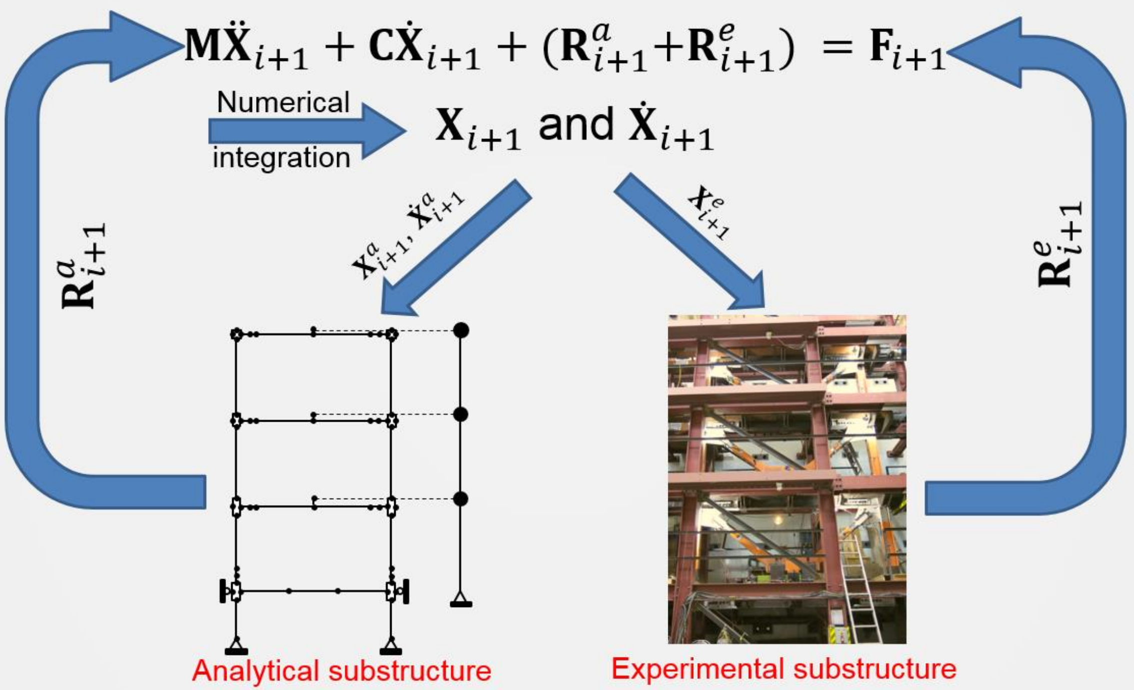
Al-Subaihawi, Safwan. (2021) "Real-time hybrid simulation of large structural systems under multi-natural hazards." *PhD dissertation, Lehigh University, Bethlehem, PA*.

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.

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.

NHERI Lehigh EF Experimental Protocols

- **Real-time Hybrid Simulation**
  - Hybrid simulation analytical substructure created by either
    - HyCom-3D
    - OpenSees with OpenFresco interface



Schematic of hybrid simulation

HyCom-3D: 3-D Real-time Computational Modeling

- MATLAB and Simulink based 3-D 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

HyCom-3D: 3-D Real-time Computational Modeling

Configuration Options:

- Three-dimensional analysis
- Coordinate system of nodes
- Boundary, constraint and restraint conditions
- **3-D 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
    - Co-Rotational force and displacement-based fiber elements
    - Gap elements
- Geometric nonlinearities
- Steel wide flange sections (link to AISC Database)
- Reinforced concrete sections
- Structural mass & inherent damping properties
- Adaptable dissipative, explicit-based integration methods
- Real-time online model updating
- Neural Network Modeling
- Nonlinear static analysis (load or displacement control)
- Transient multi-natural hazard analysis
- Restart feature for sequential analysis of hazards
- **Materials**
    - Elastic
    - Bilinear elasto-plastic
    - Hysteretic
    - Bouc-Wen
    - Trilinear
    - Stiffness degrading
    - Concrete
    - Steel
    - Fracture
    - Initial stress
    - Tension-only
    - Compression-only
    - SMA

RTHS: Implementation issues and challenges

Simulation coordinator

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

Preferred

- ❑ Fast communication

Experimental substructure

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

Analytical substructure

- ❑ Fast and accurate state determination procedure for complex, nonlinear 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
  - $\rho_\infty =$ 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

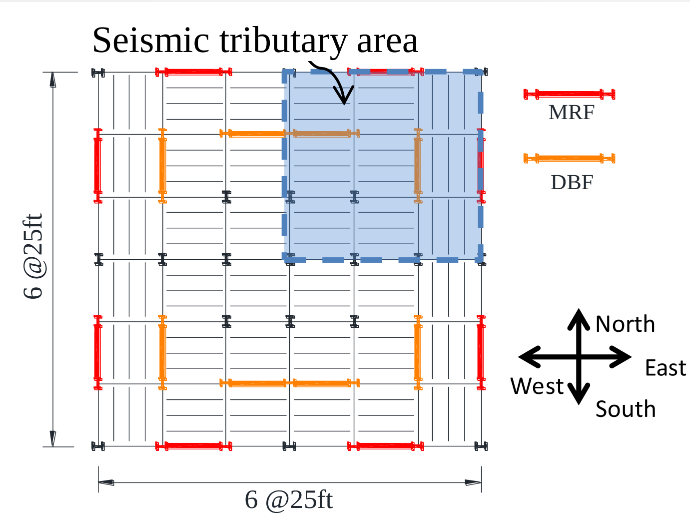
Controlled Numerical Damping

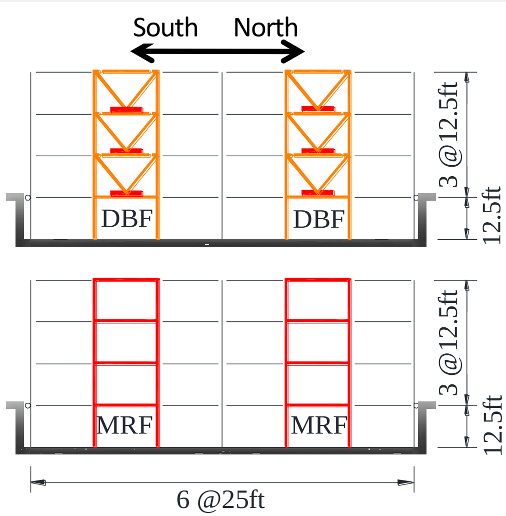
Kolay, C., and J.M. Ricles (2014). Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation. *Earthquake Engineering and Structural Dynamics*, 43(9), 1361–1380. http://doi.org/10.1002/eqe.2401

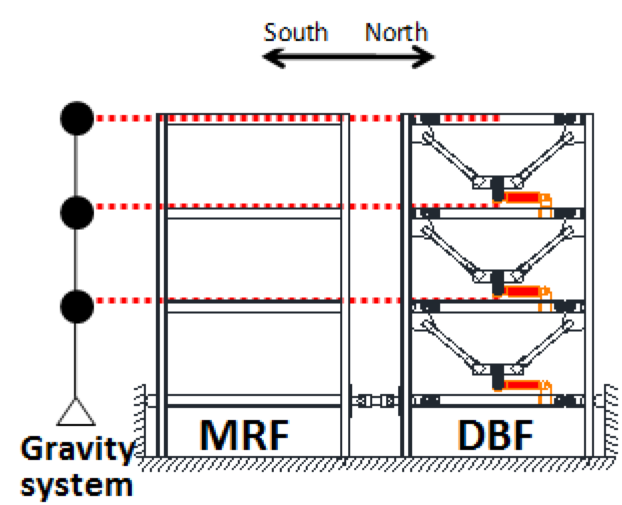
Kolay, C., and J.M. Ricles (2019) "Improved Explicit Integration Algorithms for Structural Dynamic Analysis with Unconditional Stability and Controller Numerical Dissipation," *Journal of Earthquake Engineering*, http://dx.doi.org/10.1080/13632469.2017.1326423.

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**

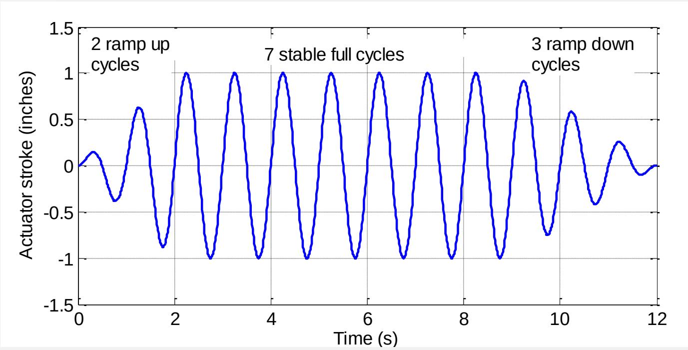
Dong, B., Sause, R., and J.M. Ricles, (2015) "Accurate Real-time Hybrid Earthquake Simulations on Large-scale MDOF Steel Structure with Nonlinear Viscous Dampers," Earthquake Engineering and Structural Dynamics, 44(12) 2035–2055, https://DOI.org/10.1002/eqe.2572.

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.

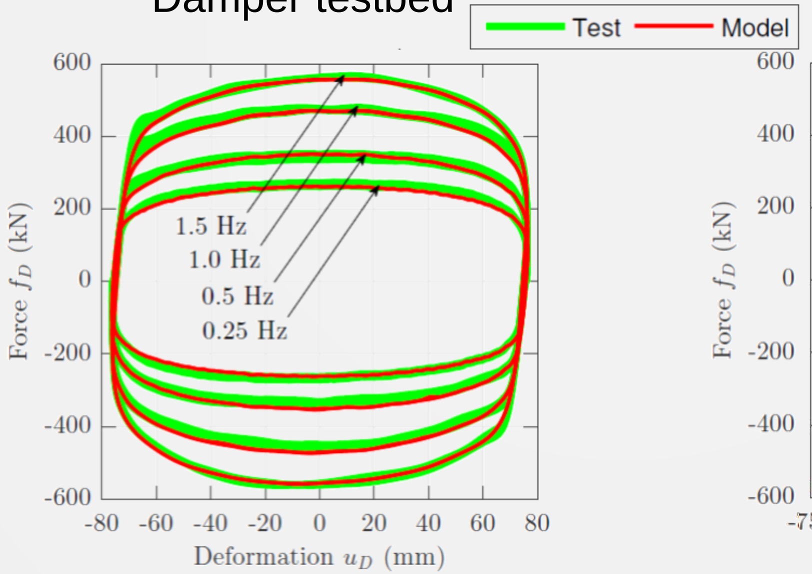
Nonlinear Viscous Dampers

Characterization testing

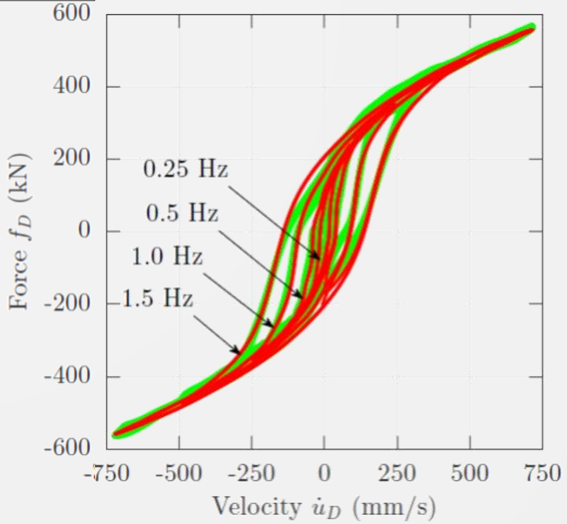
Damper testbed



Loading Protocol



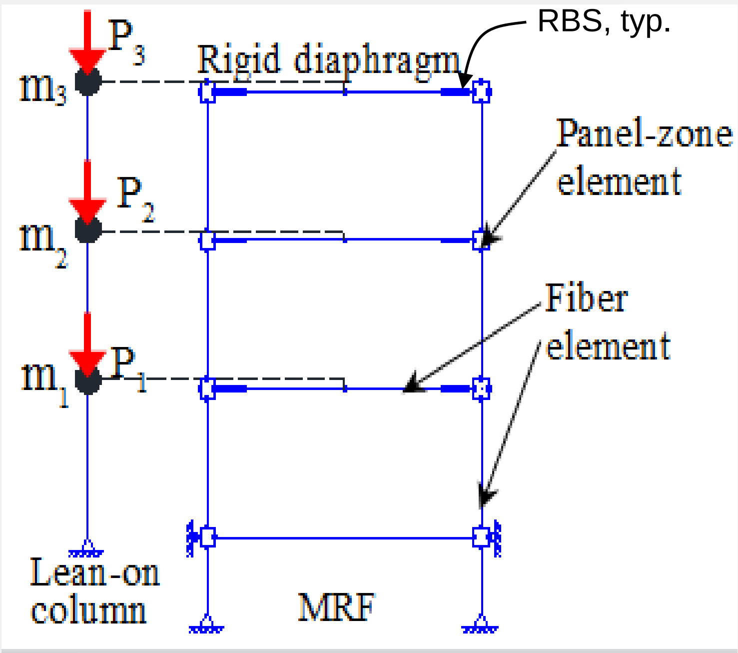
Damper force - deformation



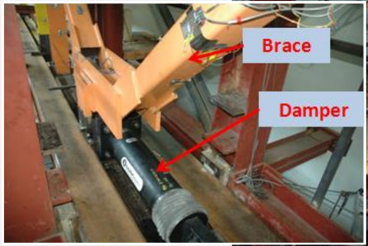
Damper force - velocity

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

Substructures for RTHS Phase-1



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

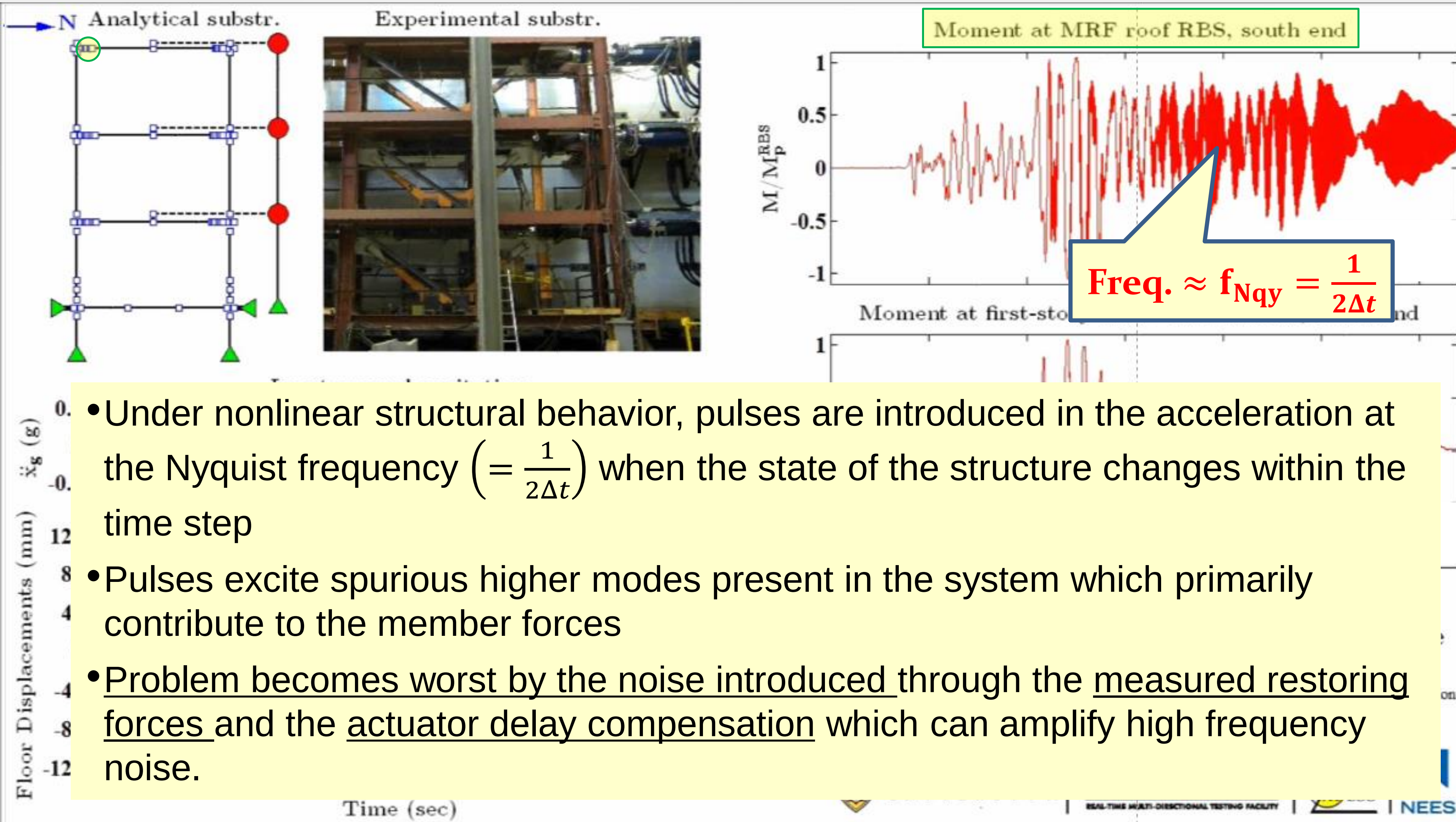


Experimental substructure (0.6-scale DBF)

<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.

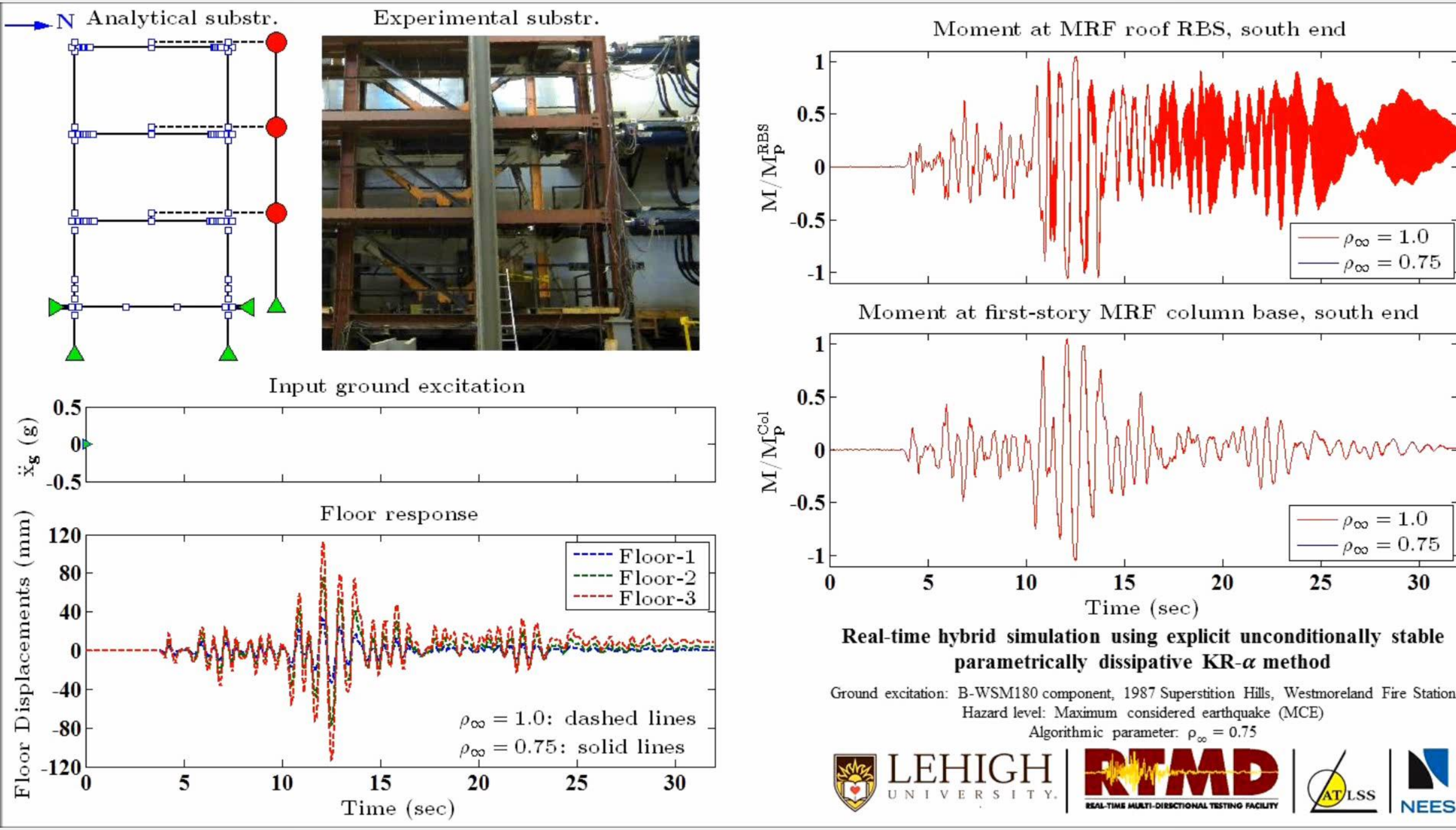
MCE level RTHS using $\rho_\infty = 1.0$



- 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
- Problem becomes worst by the noise introduced through the measured restoring forces and the actuator delay compensation 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 $\rho_\infty = 0.75$



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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

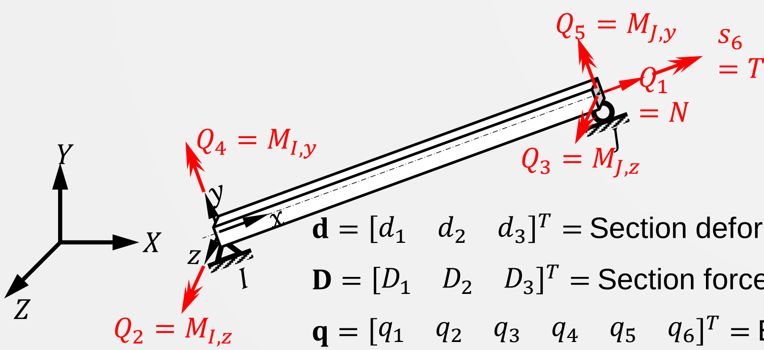
Displacement-based fiber elements

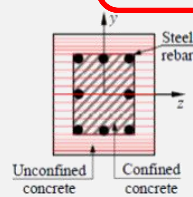
- ❑ Curvature varies linearly
  - ➢ Requires numerous elements per structural member to model nonlinear response
  - ➢ Increases number of DOFs
- ❑ State determination is straight forward

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

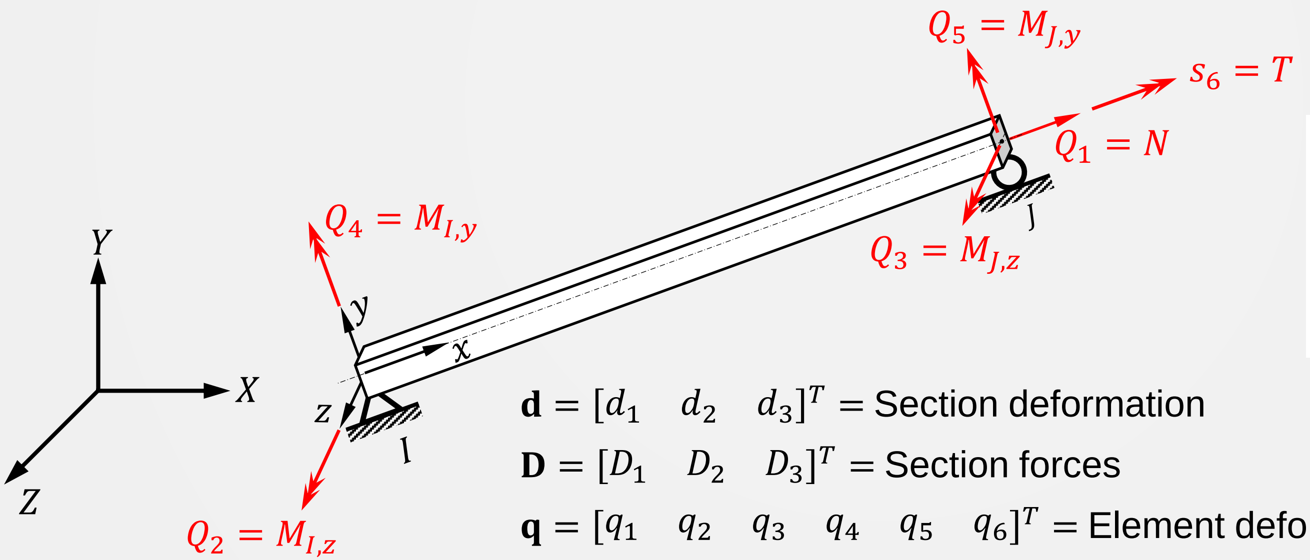
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T =$ Element deformations

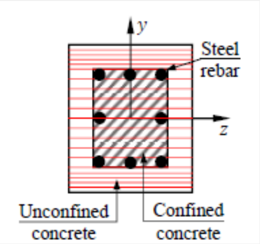
$\mathbf{Q} = [Q_1 \quad Q_2 \quad Q_3 \quad Q_4 \quad Q_5 \quad Q_6]^T =$ Element forces

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

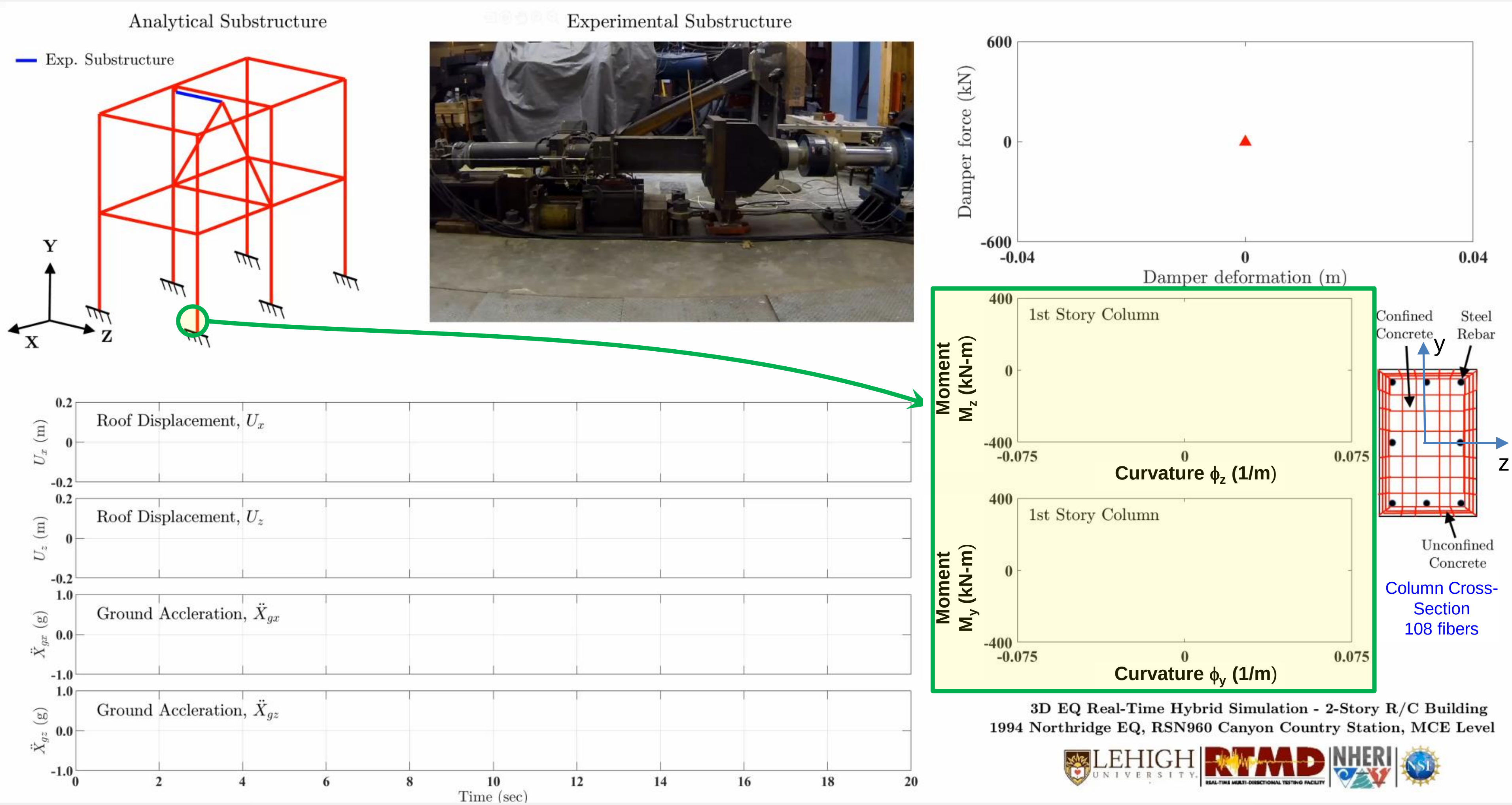
$\mathbf{q} = [q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6]^T$ = Element deformations

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

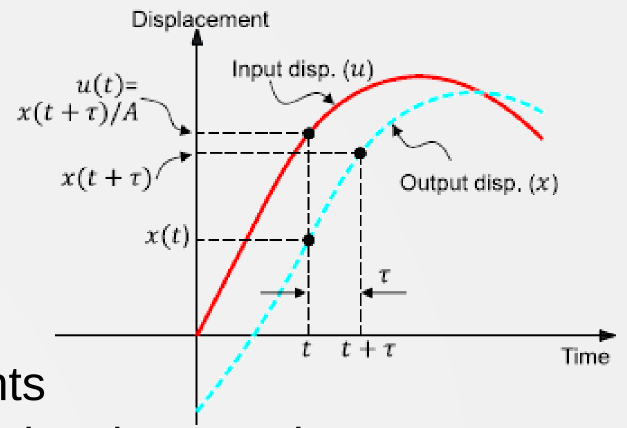
- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause instability

It is important to compensate

Servo Hydraulic Actuator Control - Actuator Delay Compensation

Adaptive Time Series (ATS) compensator

$$u_k^c = a_{0k} x_k^t + a_{jk} \dot{x}_k^t + a_{2k} \ddot{x}_k^t + a_{3k} \dddot{x}_k^t$$



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.

Al-Subaihawi, Safwan. (2021) "Real-time hybrid simulation of large structural systems under multi-natural hazards." *PhD dissertation, Lehigh University, Bethlehem, PA*.

Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator

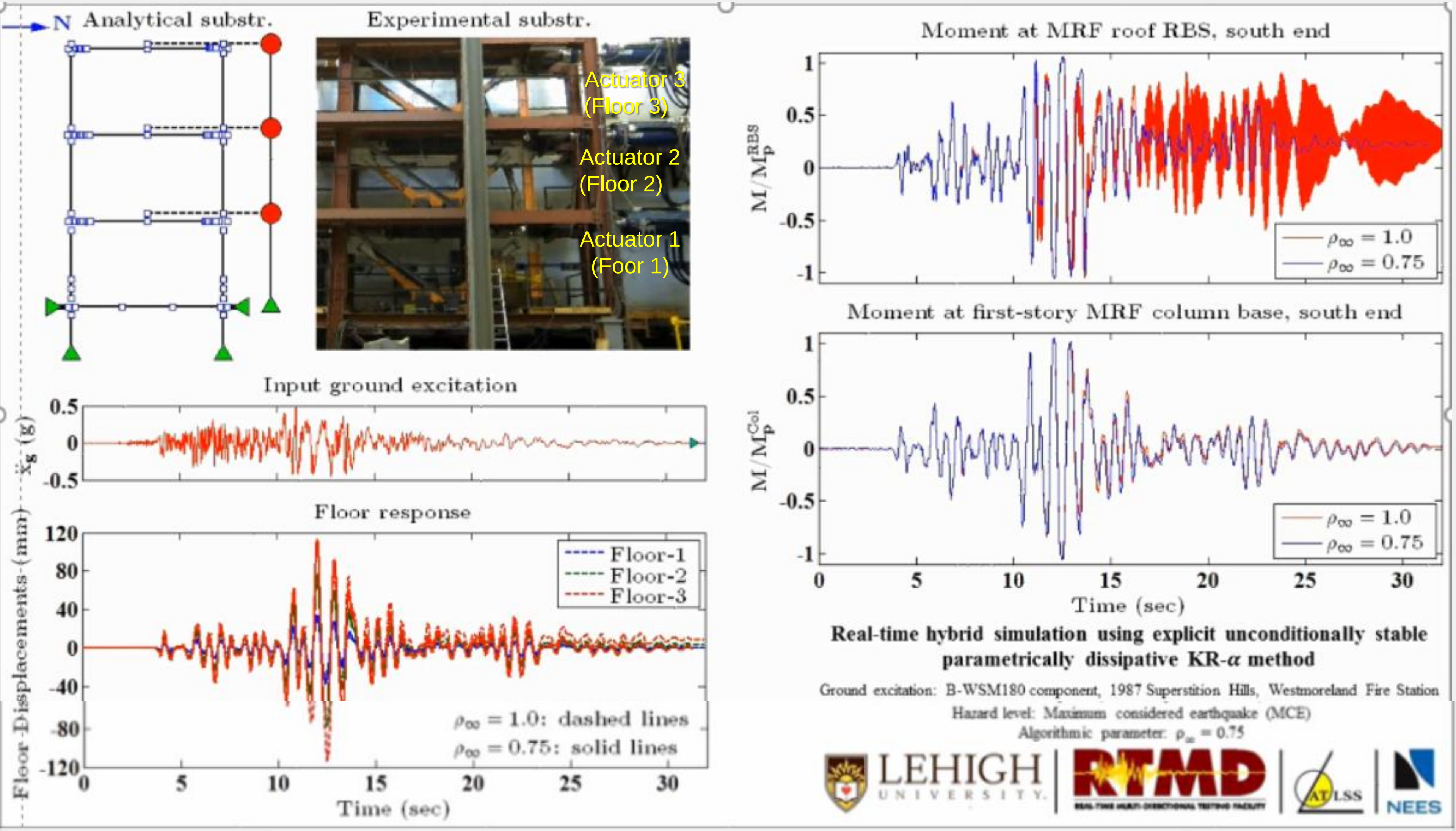
- No user-defined adaptive gains ➔ applicable for large-scale structures susceptible to damage (i.e., concrete structures)
- Negates both variable time delay and variable amplitude error response
- Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients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

Time Step k

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

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

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



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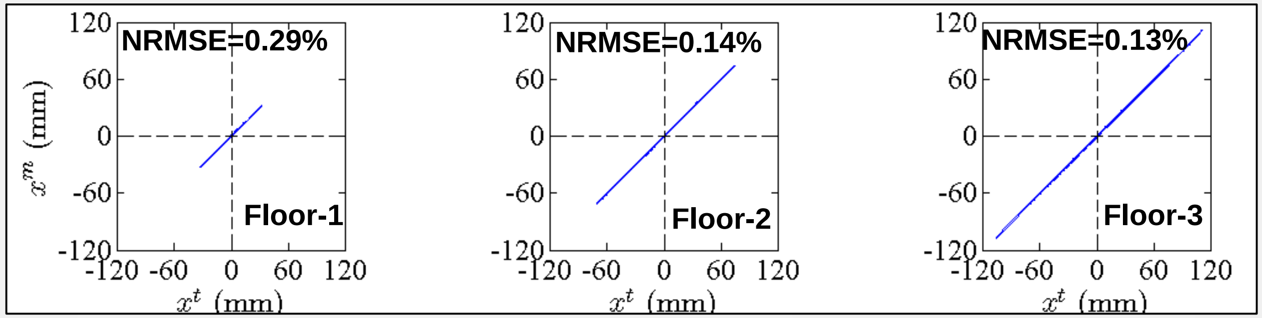
Actuator control: Typical MCE level RTHS & $\rho_\infty = 0.75$

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

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



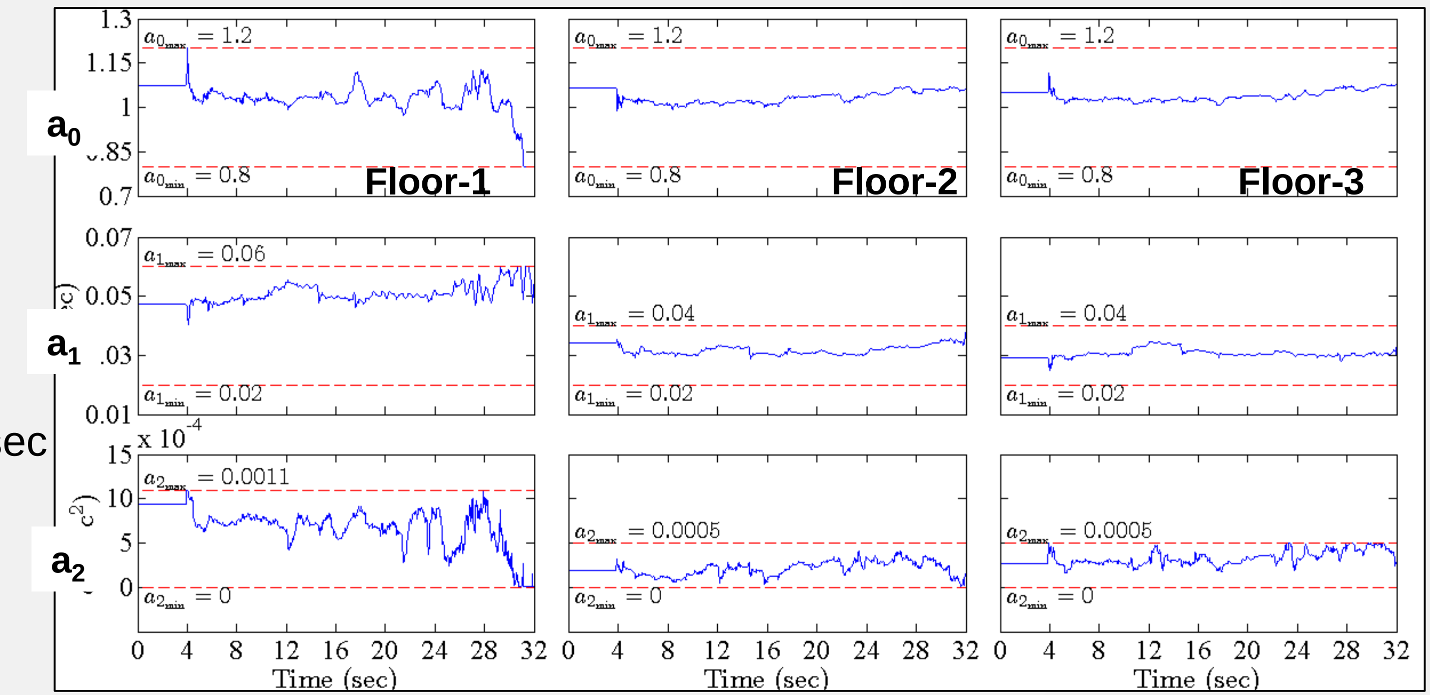
Time History of Adaptive Coefficients

Amplitude Correction

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

Delay Compensation

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



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RTMD
REAL-TIME MULTI-DIRECTIONAL SIMULATION
NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE
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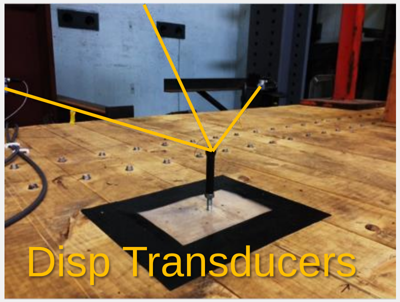
A NATURAL HAZARDS ENGINEERING COMMUNITY

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

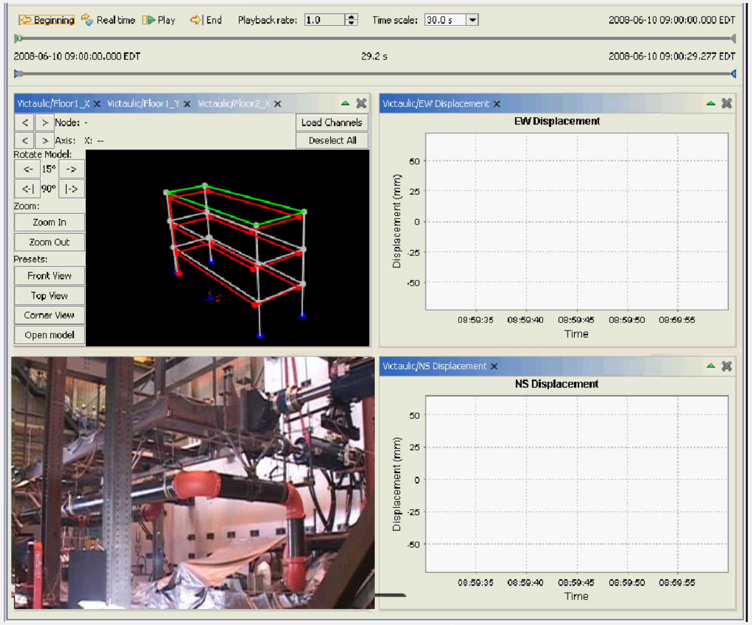


$$(M_i SNxL_{new}, M_i SNyL_{new}) = (-LMa_{inew}\sin(\Theta_2 + \phi_i), LMa_{inew}\cos(\Theta_2 + \phi_i))$$

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

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

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



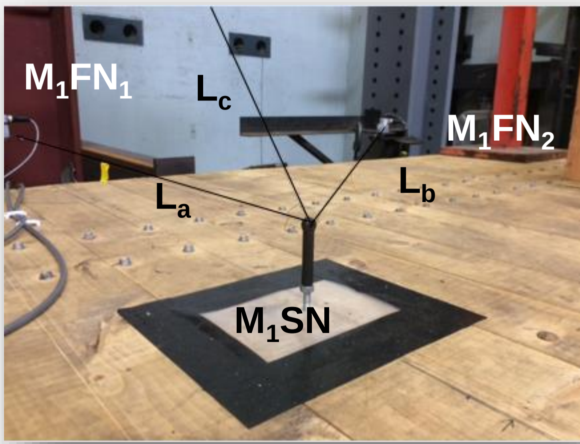
Multi-directional Real-time Hybrid Simulation

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.

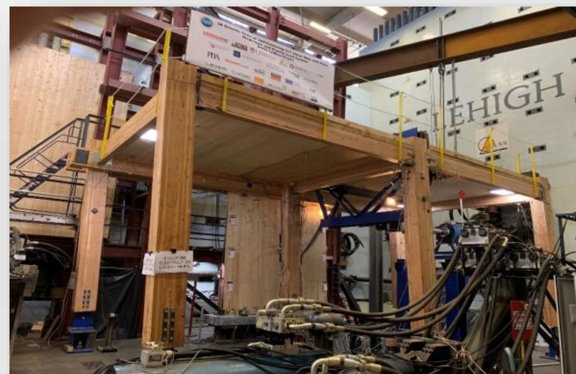
Actuator Kinematic Compensation

3D Directional Loading of Large-scale Timber Structural Subassemlages Development and Validation of Resilience-Based Seismic Design

- Testing Protocol
  - 3-D motions: bi-directional story drift combined with vertical motion of test specimen
  - Adapt actuator kinematic control algorithm to 3-D motion of flexible diaphragm



Instrumentation for measuring 3D motion



3D motions of test specimen

$$(M_iSNxL_{new}, M_iSNyL_{new}) = (-LMa_{inew}\sin(\Theta_2+\phi_i), LMa_{inew}\cos(\Theta_2+\phi_i))$$

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

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

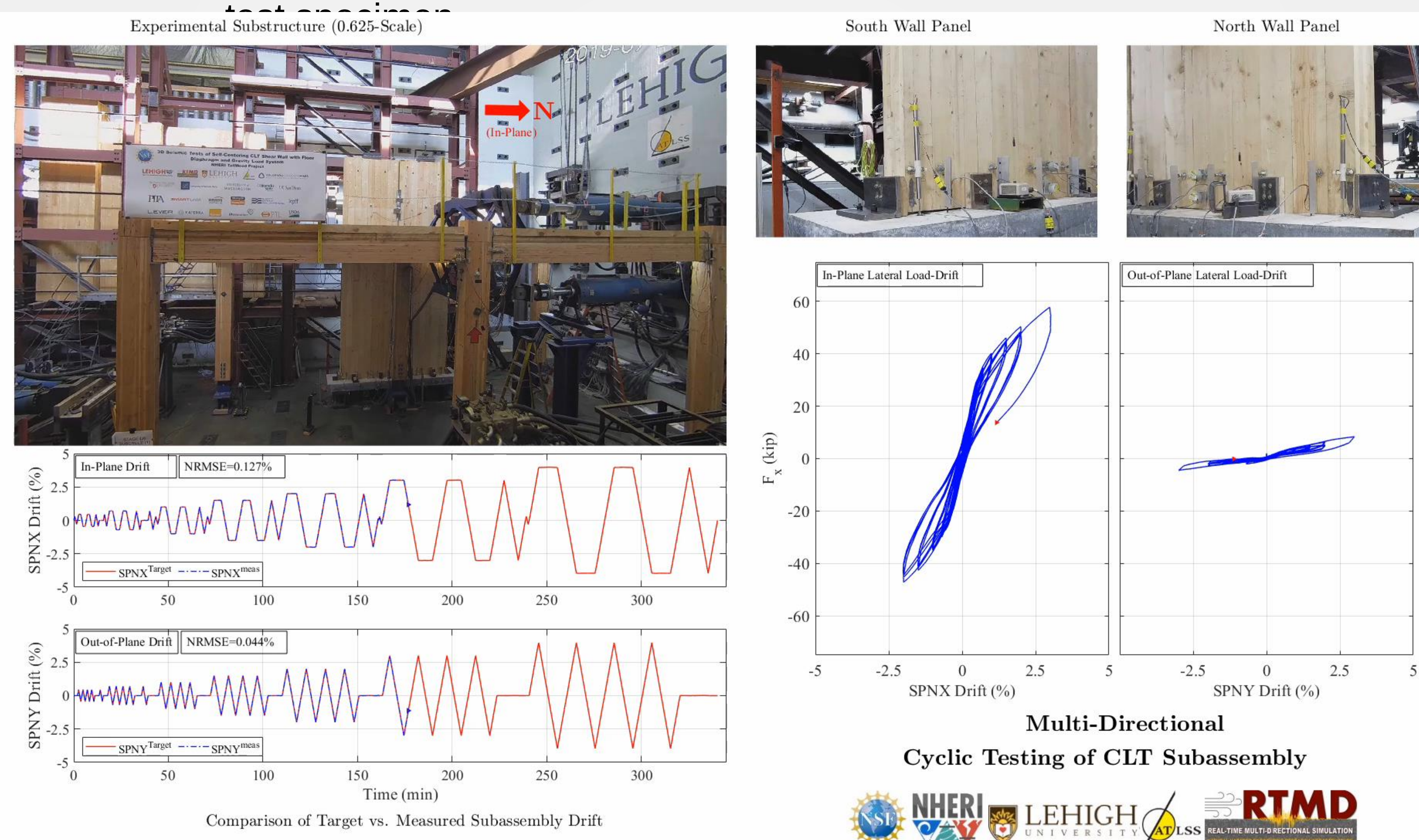
$$(SPN^m x_{new}, SPN^m y_{new}) = (M_1SN^m x_{new} - \left|\overrightarrow{VM_1}\right|\cos(\Theta M_{1,0} + d^m SPN\Theta), M_1SN^m y_{new} - \left|\overrightarrow{VM_1}\right|\sin(\Theta M_{1,0} + d^m SPN\Theta))$$

Amer, A. (2022) "Performance of CLT Systems Subject to Multi-Directional Loading Effects." PhD dissertation, Lehigh University, Bethlehem, PA

Actuator Kinematic Compensation

3D Directional Loading of Large-scale Timber Structural Subassemlages
Development and Validation of Resilience-Based Seismic Design

- Testing Protocol
  - 3-D motions: bi-directional story drift combined with vertical motion of



Is Multi-Directional Loading and Large-Scale Testing Important?

Scale Effects:

- Heat Transfer:
  - Thermal Effects, Residual Stresses in Welded Structures
  - Heat Dissipation in Response Modification Devices (e.g., dampers)
- Material Characterization at Reduced Scale:
  - Timber, concrete, soil, etc.
- Compliance with Similitude Laws

Is Multi-Directional Loading and Large-Scale Testing Important?

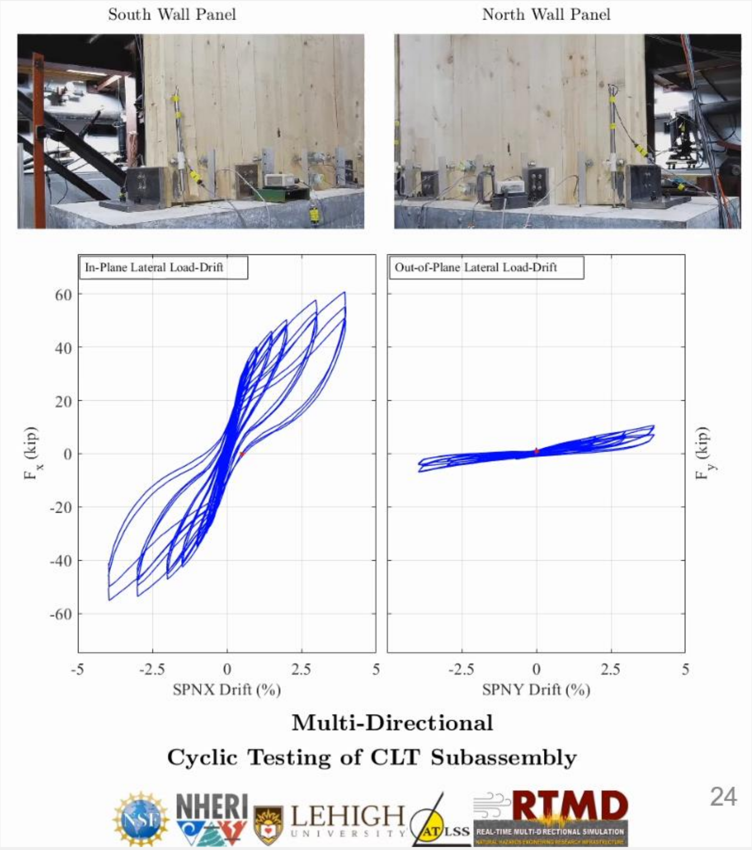
Multi-directional Effects:

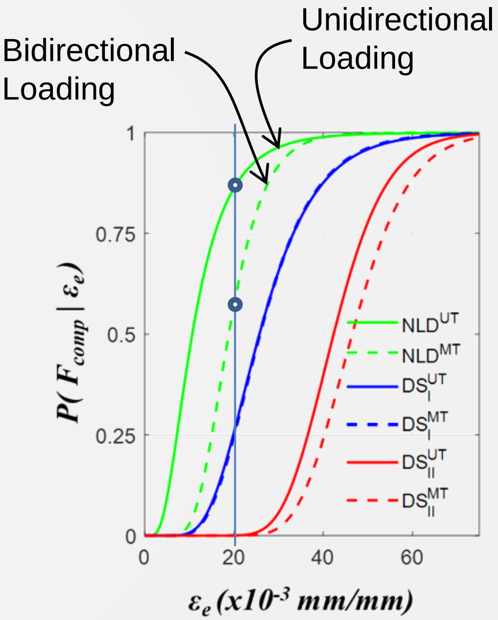
- Out of plane Loading on Lateral-force Resisting Systems Causes Damage and Effects Resiliency

Is Multi-Directional Loading and Large-Scale Testing Important?

Multi-directional Effects:

- Out of plane Loading on Lateral-force Resisting Systems Causes Damage and Effects Resiliency





Fragility Functions of CLT Shear Walls Associated with Damage States, Subject to Unidirectional (UT) and Bidirectional (MT) Lateral Loads

Amer, A. (2022) “Performance of CLT Systems Subject to Multi-Directional Loading Effects." PhD dissertation, Lehigh University, Bethlehem, PA

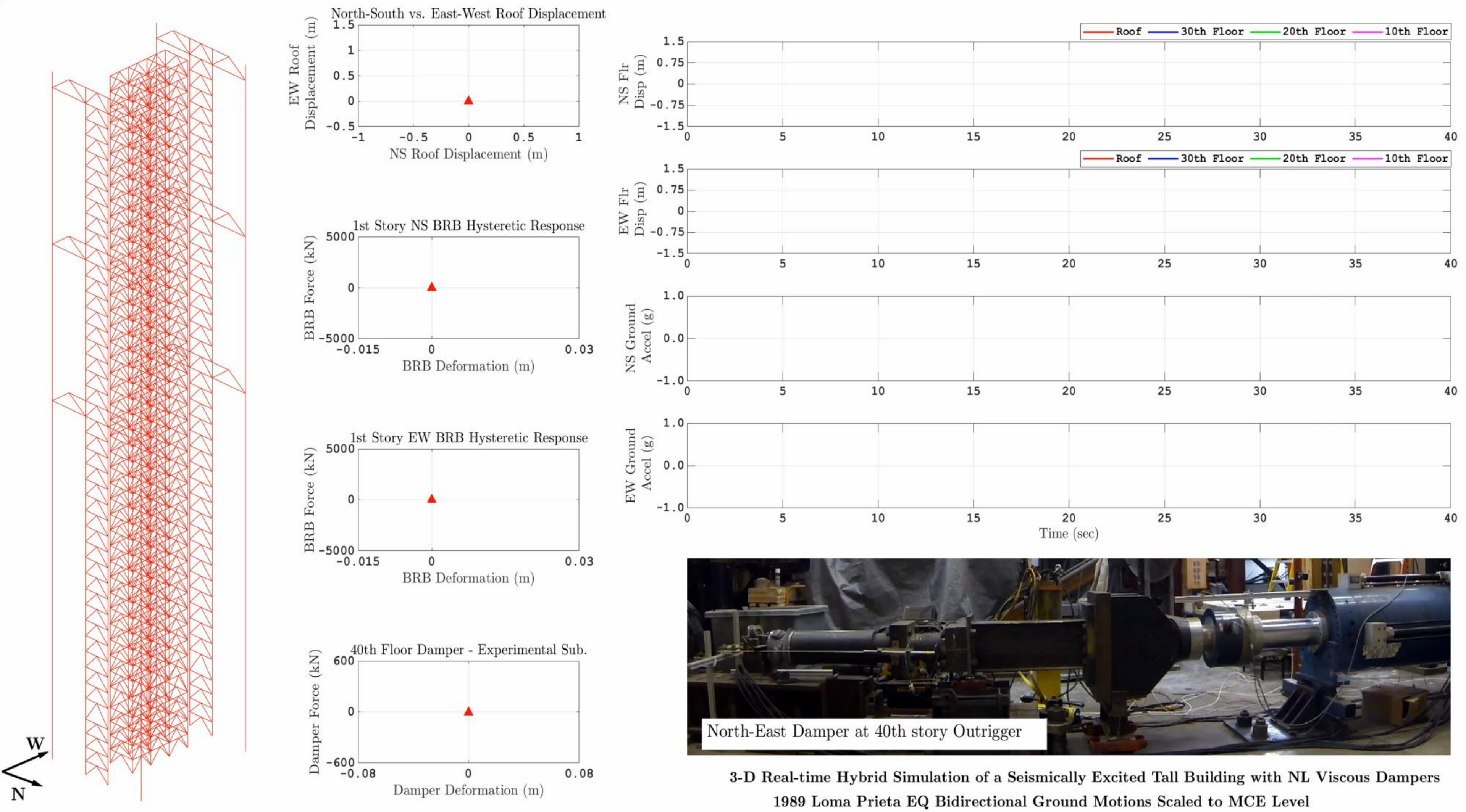
Is Multi-Directional Loading and Large-Scale Testing Important?

Multi-directional Effects:

- Members Subjected to Biaxial Bending and Larger Axial forces, Effecting Their Strength and Structural Resiliency
- Greater Demand on Response Modification Devices (e.g., NL Viscous Dampers)

Al-Subaihawi, Safwan. (2021) “Real-time hybrid simulation of large structural systems under multi-natural hazards." *PhD dissertation, Lehigh University, Bethlehem, PA*.

3-D Real-time Hybrid Simulation
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE



Motions scaled by factor of 5 in animation

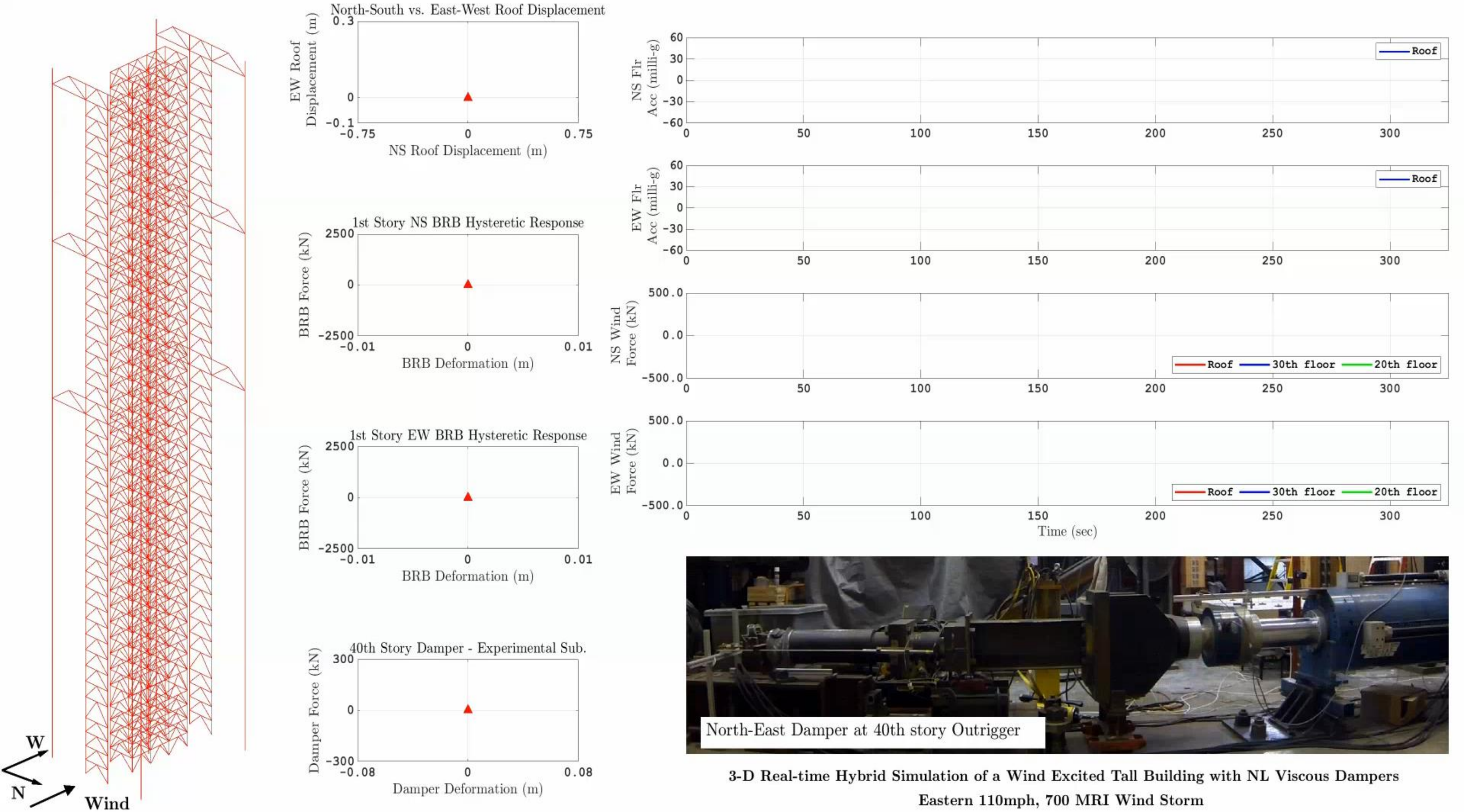
Al-Subaihawi, Safwan. (2021) “Real-time hybrid simulation of large structural systems under multi-natural hazards." *PhD dissertation, Lehigh University, Bethlehem, PA*.

Is Multi-Directional Loading and Large-Scale Testing Important?

- Bidirectional Wind Leads to Torsion, Resulting in Greater Structural Accelerations
- Cross Wind Effects with Vortex Shedding Can Cause Large Out-of-Plane Motions and Accelerations
- Greater Demand on Response Modification Devices (e.g., NL Viscous Dampers)

Al-Subaihawi, Safwan. (2021) “Real-time hybrid simulation of large structural systems under multi-natural hazards." *PhD dissertation, Lehigh University, Bethlehem, PA*.
Al-Subaihawi, S., Kolay, C., Thomas Marullo, Ricles, J. M. and S. E. Quiel. (2020) “Assessment of Wind-Induced Vibration Mitigation in a Tall Building with Damped Outriggers Using Real-time Hybrid Simulations,” *Engineering Structures*, 205, art. no. 110044, https://doi.org/10.1016/j.engstruct.2019.110044.
Kolay, C., Al-Subaihawi, S., Thomas Marullo, Ricles, J. M. and S. E. Quiel, (2020) “Multi-Hazard Real-Time Hybrid Simulation of a Tall Building with Damped Outriggers*,” International Journal of Lifecycle Performance Engineering*, Vol. 4, Nos. 1/2/3, pp.103–132, https://doi.org/10.1504/IJLCPE.2020.108937.

3-D Real-time Hybrid Simulation
110 mph, 700 MRI Wind Storm (EW Windward Direction)



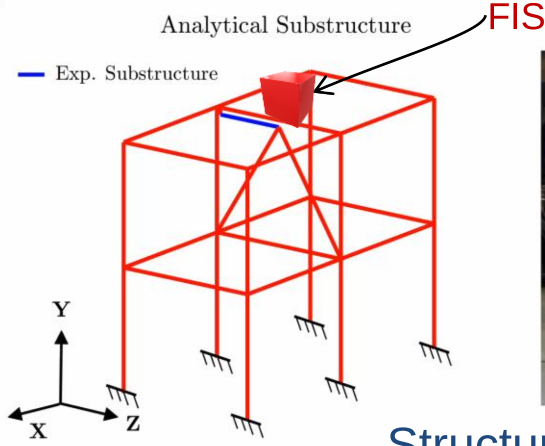
Motions scaled by factor of 20 in animation

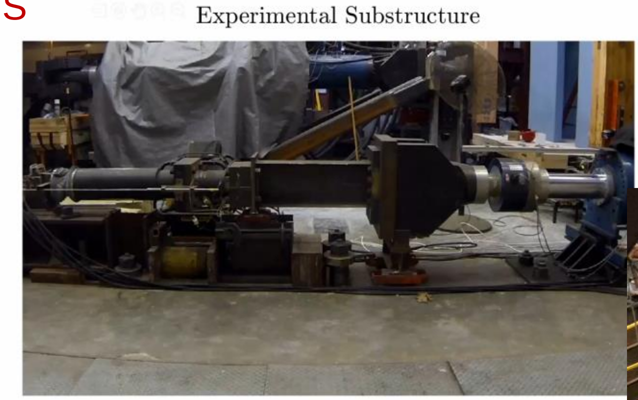
Kolay, C., Al-Subaihawi, S., Thomas Marullo, Ricles, J. M. and S. E. Quiel, (2020) “Multi-Hazard Real-Time Hybrid Simulation of a Tall Building with Damped Outriggers,” *International Journal of Lifecycle Performance Engineering*, Vol. 4, Nos. 1/2/3, pp.103–132, https://doi.org/10.1504/IJLCPE.2020.108937.

Is Multi-Directional Loading and Large-Scale Testing Important?

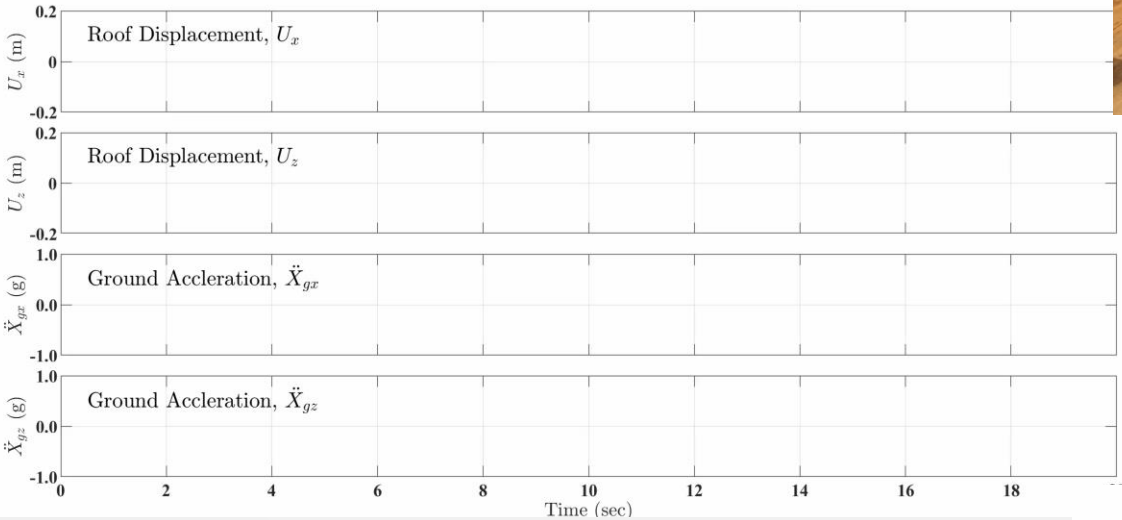
- Yes!
- Quality NSF proposals: Large-scale simulations that accountant for multi-directional effects
- The NHERI Lehigh EF provides the resources to enable researchers to investigate these effects

Integration of Resources to Perform Real-time EQ Hybrid Simulation Floor Isolation System at Roof of R/C Structure





Structural System



Equipment Floor Isolation System (FIS) at Roof

RTHS of Floor Isolation System using Multi-directional Shake Table

PI - Scott Harvey, University of Oklahoma

3D EQ Real-Time Hybrid Simulation - 2-Story R/C Building
1994 Northridge EQ, RSN960 Canyon Country Station, MCE Level

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

Thank you