Hybrid Simulation: Framework, Hardware & Software Capabilities

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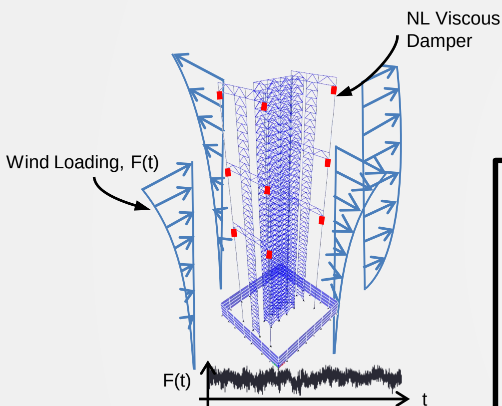
Overall Concept of Real-time Hybrid Simulation (RTHS): Structural System Subject to Predefined Wind Loading

NSF CMMI: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings

- S. Laflamme (Iowa State), J. Ricles (Lehigh University), S. Quiel (Lehigh University)

Structural System

40-Story Building with Outriggers and Supplemental Dampers



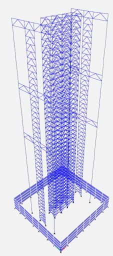
Wind Tunnel Tests NHERI@FIU
Wind Load Determination

Hybrid Wind Simulation Experiments

Real-time input (Forcing Function): Wind Tunnel Data

$\mathbf{F}_{i+1}^{a}$

Analytical substructure



(Modeled in the computer)

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

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

Simulation Coordinator

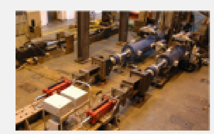
$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{R}_{i+1}^{a} + \mathbf{R}_{i+1}^{e} = \mathbf{F}_{i+1}^{a}$$

Integrates Eqns of Motion

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

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

Experimental substructure (dampers)



(Modeled in lab)

Real-time structural response

Why Real-Time Hybrid Simulation?

- **Enables cost-effective large-scale dynamic tests**
  - ➢ Low experimental cost compared to a full shake table test
  - ➢ Various analytical substructures can be used for a given experimental substructure, enabling extensive and comprehensive experimental studies
  - ➢ Meets the need of the natural hazards engineering community of providing experimental validation of concepts for natural hazards mitigation
- **Accounts for rate-dependency of physical specimens**
  - Rate-dependent structures (frictional devices, dampers, base-isolators, tuned mass damper, etc.) can be investigated with RTHS

  ➔ not possible with conventional, slow hybrid simulation

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

- Advanced experimental techniques in NHERI Lehigh EF:
  - ✓ Unconditionally stable explicit integration algorithms with minimal overshooting and controlled numerical damping for HS and RTHS

Velocity update: $\dot{\mathbf{X}}_{n+1} = \dot{\mathbf{X}}_n + \Delta t \boldsymbol{\alpha}_1 \ddot{\mathbf{X}}_n$

Displacement update: $\mathbf{X}_{n+1} = \mathbf{X}_n + \Delta t \dot{\mathbf{X}}_n + \Delta t^2 \boldsymbol{\alpha}_2 \ddot{\mathbf{X}}_n$

$\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, and $\boldsymbol{\alpha}_3$: model-based integration parameters

Weighted equations of motion: $\mathbf{M}\hat{\ddot{\mathbf{X}}}_{n+1} + \mathbf{C}\dot{\mathbf{X}}_{n+1-\alpha_f} + \mathbf{K}\mathbf{X}_{n+1-\alpha_f} = \mathbf{F}_{n+1-\alpha_f}$

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

Kolay, C., Ricles, J., Marullo, T., Mahvashmohammadi, A., and R. Sause, (2015) “Implementation and Application of the Unconditionally Stable Explicit Parametrically Dissipative KR-α Method for Real-Time Hybrid Simulation,” *Earthquake Engineering and Structural Dynamics*, 44(5), 735-755, https://DOI.org/10.1002/eqe.2484

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*, 23(5), pp 771-792, http://dx.doi.org/10.1080/13632469.2017.1326423.

RTHS Implementation solutions

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  - ✓ Explicit force-based nonlinear fiber element for NLTHA, HS and RTHS

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.

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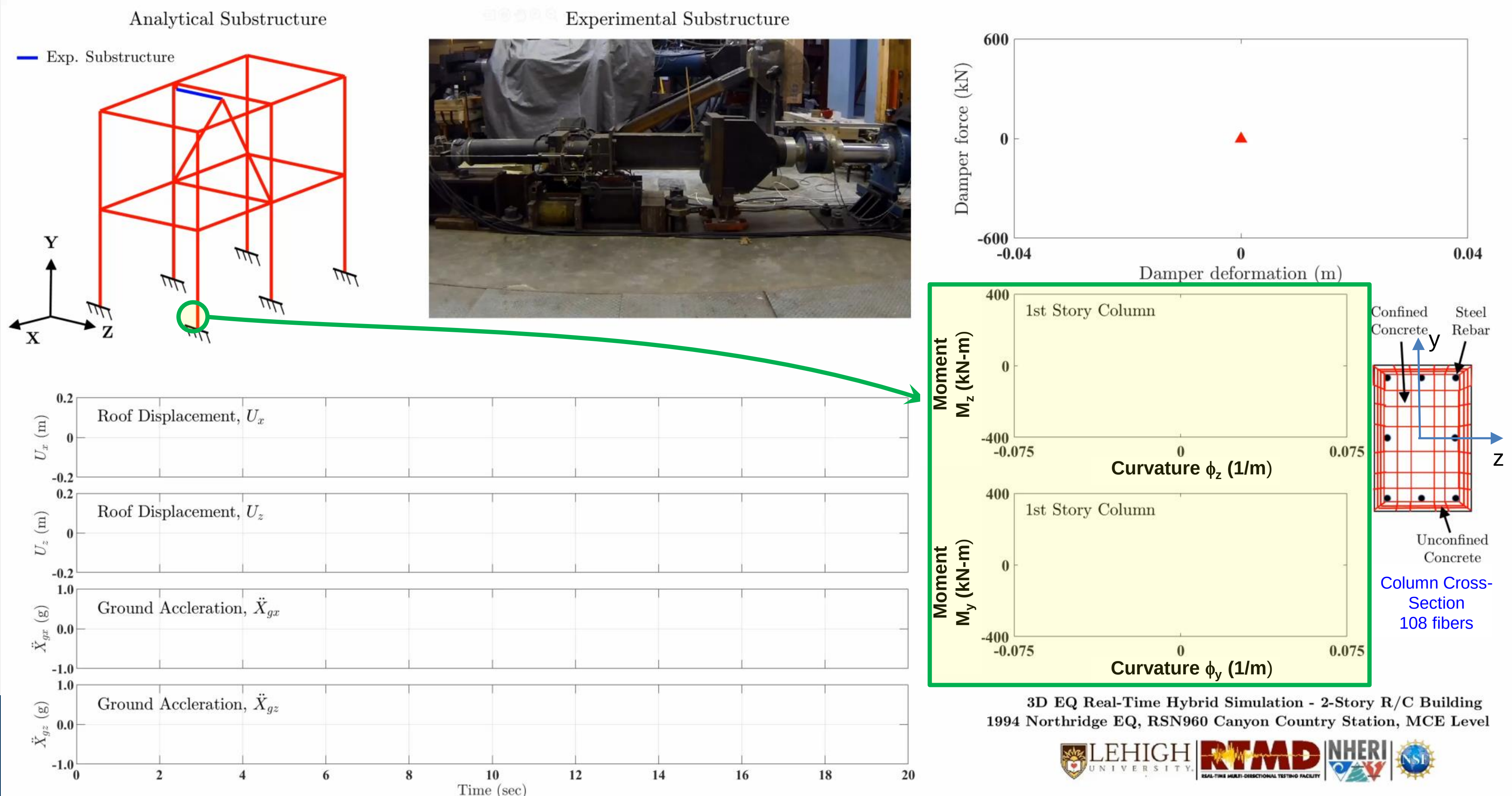

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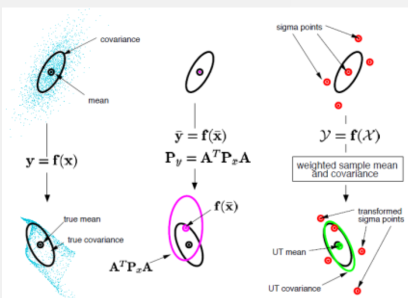
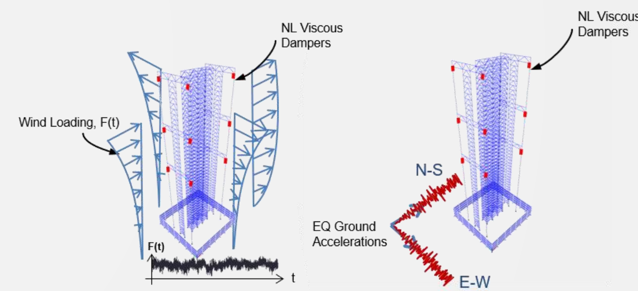
  - ✓ <u>Explicit force-based nonlinear fiber element</u> for NLTHA, HS and RTHS
  - ✓ Development and implementation of <u>real-time nonlinear model updating</u> for HS and RTHS





40 story building 3D multi-hazard RTHS, modified KR- α method with online model updating

$$f_{d_{i+1}} = f_{d_i} + K_d \Delta t \left|\frac{f_{d_i}}{C_d}\right|^{\frac{1}{\alpha}} sign(f_{d_i}) + K_d(u_{d_{i+1}} - u_{d_i})$$

Nonlinear real-time model updating –
Explicit nonlinear viscous damper model

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, Department of Civil and Environmental Engineering, Lehigh University.

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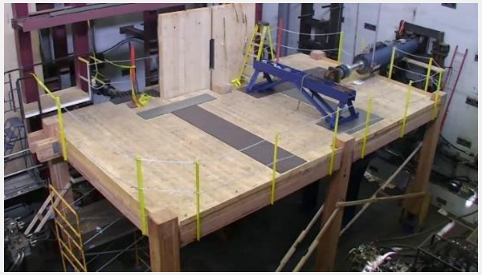
  - ✓ Development and implementation of real-time nonlinear model updating for HS and RTHS
  - ✓ Development and implementation of 3-D kinematic compensation actuator control algorithm

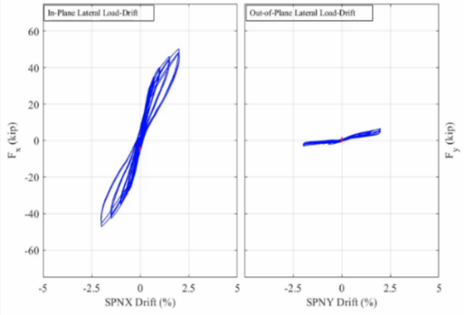
$$(M_i SNxL_{new}, M_i SNyL_{new}) = (-LMa_{inew} sin(\Theta_2 + \phi_i), LMa_{inew} cos(\Theta_2 + \phi_i))$$

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

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

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





3D Multi-directional loading of CLT Shear Wall-Floor Diaphragm-Gravity Load System Subassembly

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

Amer, A., Sause, R., Ricles, J, and T. Marullo, (2020) “Multi-Directional Cyclic Testing of Cross-Laminated Timber Rocking Wall-Floor Diaphragm Sub-Assemblies,” *Proceedings of the 17th World Conference on Earthquake Engineering*, September 13-18, Sendai, Japan

RTHS Implementation solutions

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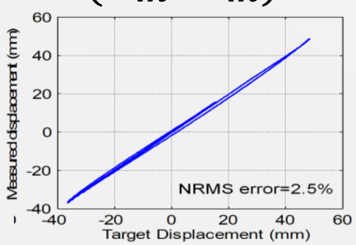
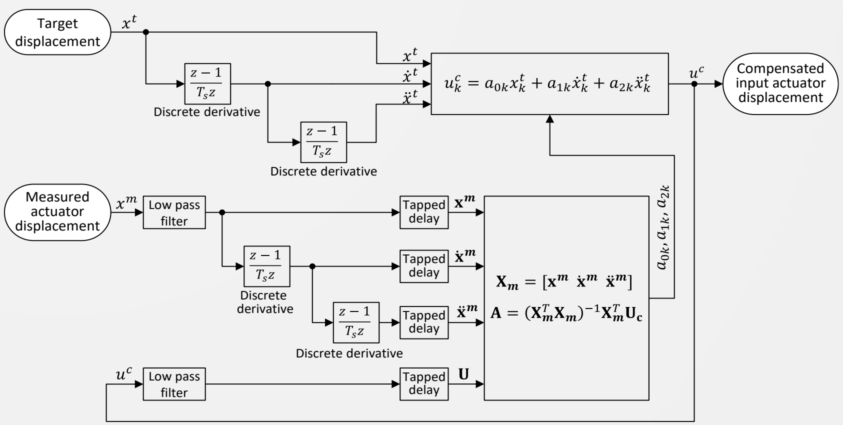
  - ✓ <u>Explicit force-based nonlinear fiber element</u> for NLTHA, HS and RTHS
  - ✓ Development and implementation of <u>real-time nonlinear model updating</u> for HS and RTHS
  - ✓ Development and implementation of <u>3-D kinematic compensation actuator</u> control algorithm
  - ✓ Development and implementation of <u>real-time adaptive servo-hydraulic control</u> for delay compensation

$$u_k^c = a_{0k}x_k^t + a_{1k}\dot{x}_k^t + a_{2k}\ddot{x}_k^t$$

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





Real-time Adaptive Time Series Delay Compensation

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.

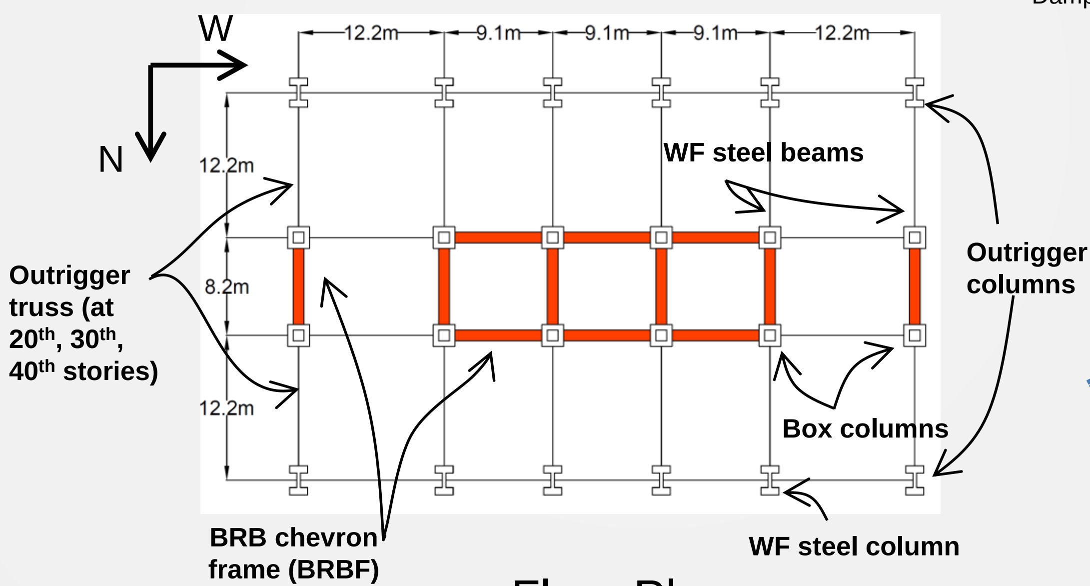
Summary of Advancements in Experimental Methods

3-D large-scale multi-directional RTHS:

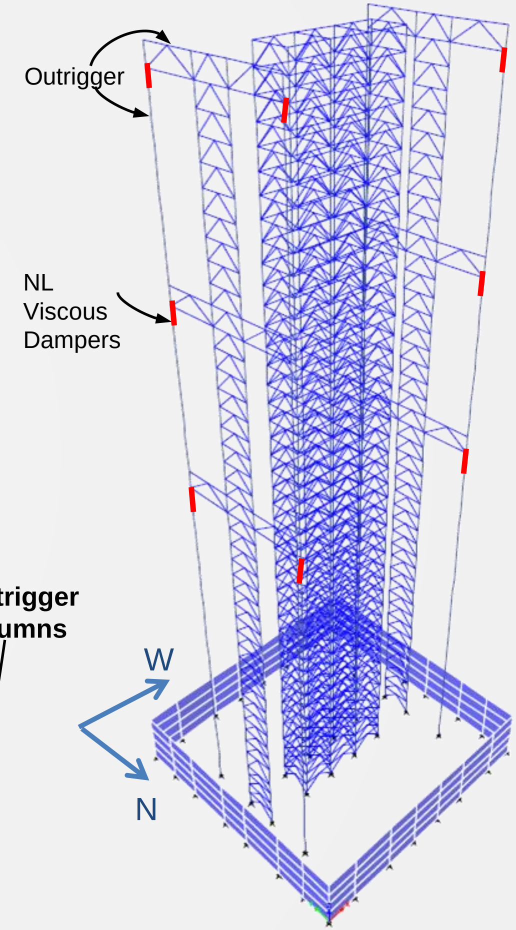
- ✓ Unconditionally stable explicit integration algorithms
- ✓ Explicit force-based nonlinear fiber element
- ✓ Real-time nonlinear model updating for HS and RTHS
- ✓ 3-D kinematic compensation actuator control
- ✓ Real-time adaptive servo-hydraulic control

Example: Multi-hazard RTHS of a Tall Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH[1] for PEER Tall Building Initiative case studies – BRBFs with Outriggers
- Objectives of study
  - Improve performance using nonlinear fluid viscous dampers with outriggers
  - Assess performance of structure under multi-hazards using RTHS
- Extend MKR-α integration algorithm and ATS actuator control to multi-hazards
- Online model updating – explicit-based NL Maxwell model



Floor Plan



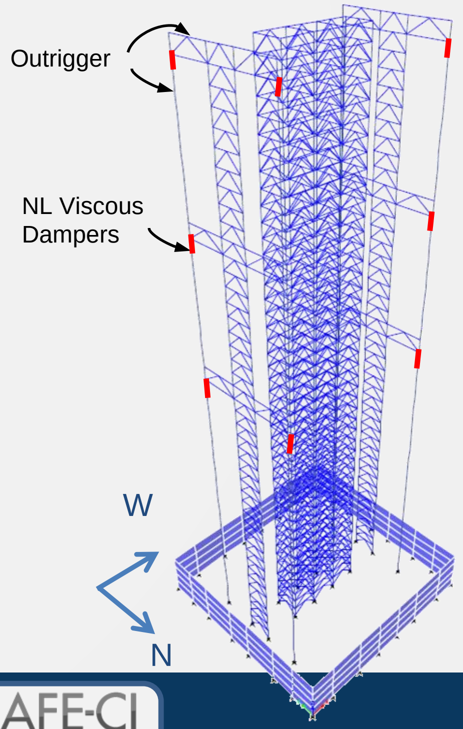
[1] Moehle et al., PEER 2011/05

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, 110044. DOI: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*, 4.1-3, 103-132. DOI: IJLCPE.2020.108937

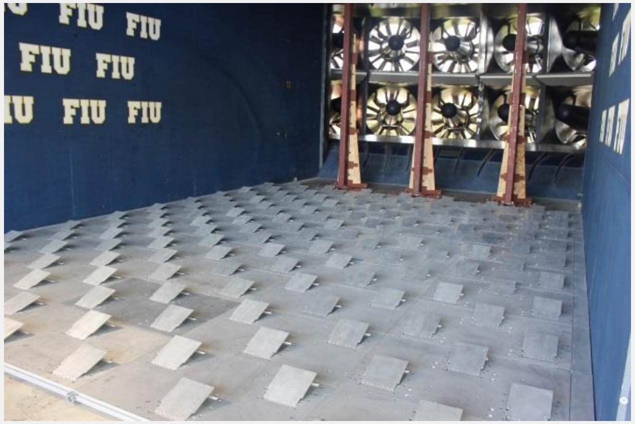
Multi-Hazard RTHS of Tall Building – EQ & Wind

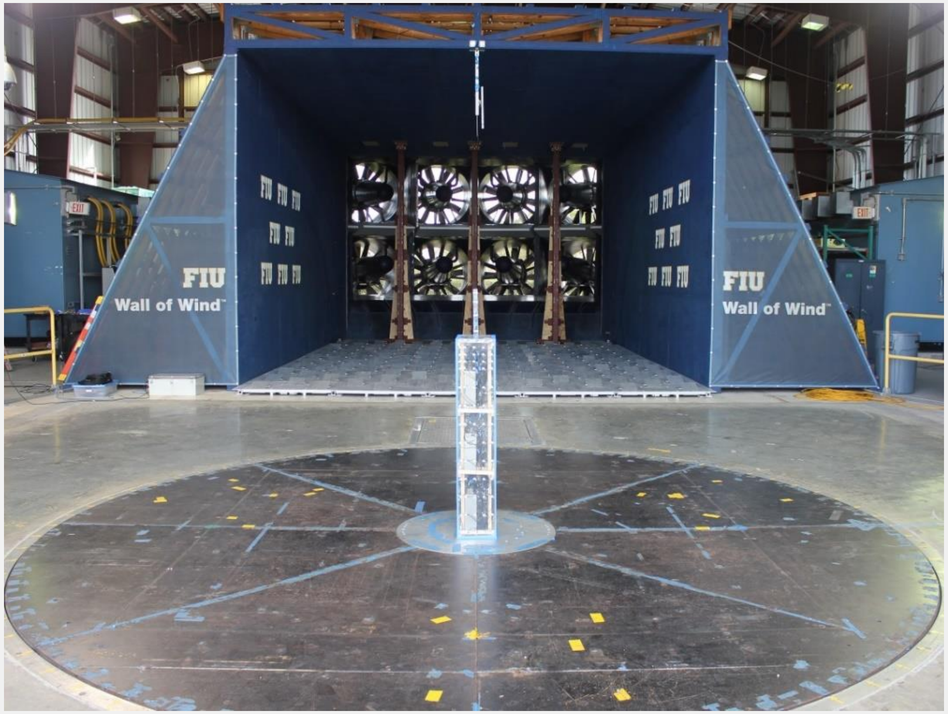
- Bidirectional EQ ground motions
  - 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to MCE (2500 year return period) hazard level
- Bidirectional wind loading
  - Wind speed of 110 mph, 700 MRI
  - Exposure B



Wind Loading
Aerodynamic Wind Testing @ FIU WOW

- Aerodynamic wind testing at the NHERI FIU WOW to obtain wind pressure time histories distributed on the building.





Courtesy: Amal Elawady
and Arindam Chowdhury, FIU

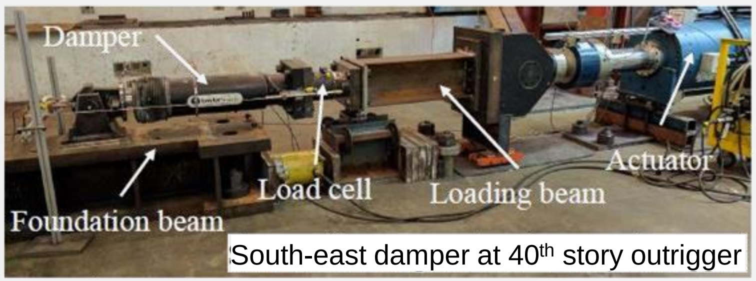
RTHS Configuration

- Use of:
  - ➢ Explicit MKR-α Integration Algorithm
  - ➢ Explicit Force-based Nonlinear Fiber Element – Analytical Substructure
  - ➢ Adaptive Time Series Compensator for Actuator Control
  - ➢ Online Model Updating (OMU) – explicit-based NL Maxwell model

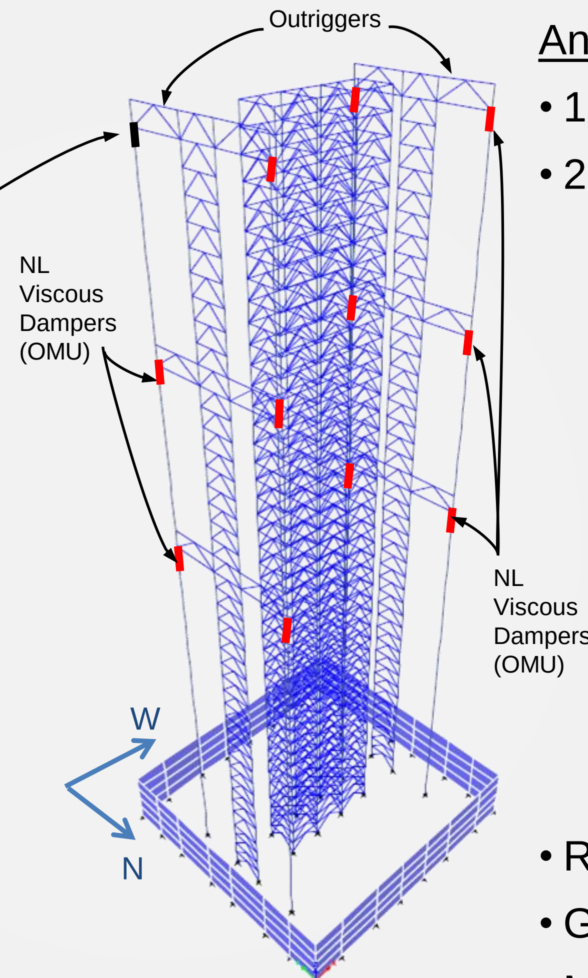
MKR-α parameter and ATS coefficients

Natural Hazard	Time Step, Δt (sec)	ρ_∞	ATS Coefficients			Comments
			a_{0k}	a_{1k}	a_{2k}	
Wind	$\frac{6}{1024}$	0.866	Fixed	Adaptive	Fixed	Wind: static component with dynamic gusts - 1st mode linear response
EQ	$\frac{6}{1024}$	0.50	Adaptive	Adaptive	Adaptive	EQ: Multi-mode non-linear response

RTHS Substructures



Experimental Substructure –
NL Fluid Viscous Damper



Analytical Substructure

<u>Analytical Sub. Key features</u>:

- 1317 Nodes
- 2974 Elements
  - ➢ 2411 Nonlinear Explicit Force-based fiber elements
  - ➢ 11 Nonlinear Explicit Maxwell Elements(1) with real-time model updating (dampers placed in each outrigger at 20th, 30th, & 40th floors)
  - ➢ 552 Nonlinear truss elements
- Reduced Order Modeling
- Geometric nonlinearities
- Mass
- Inherent damping of building

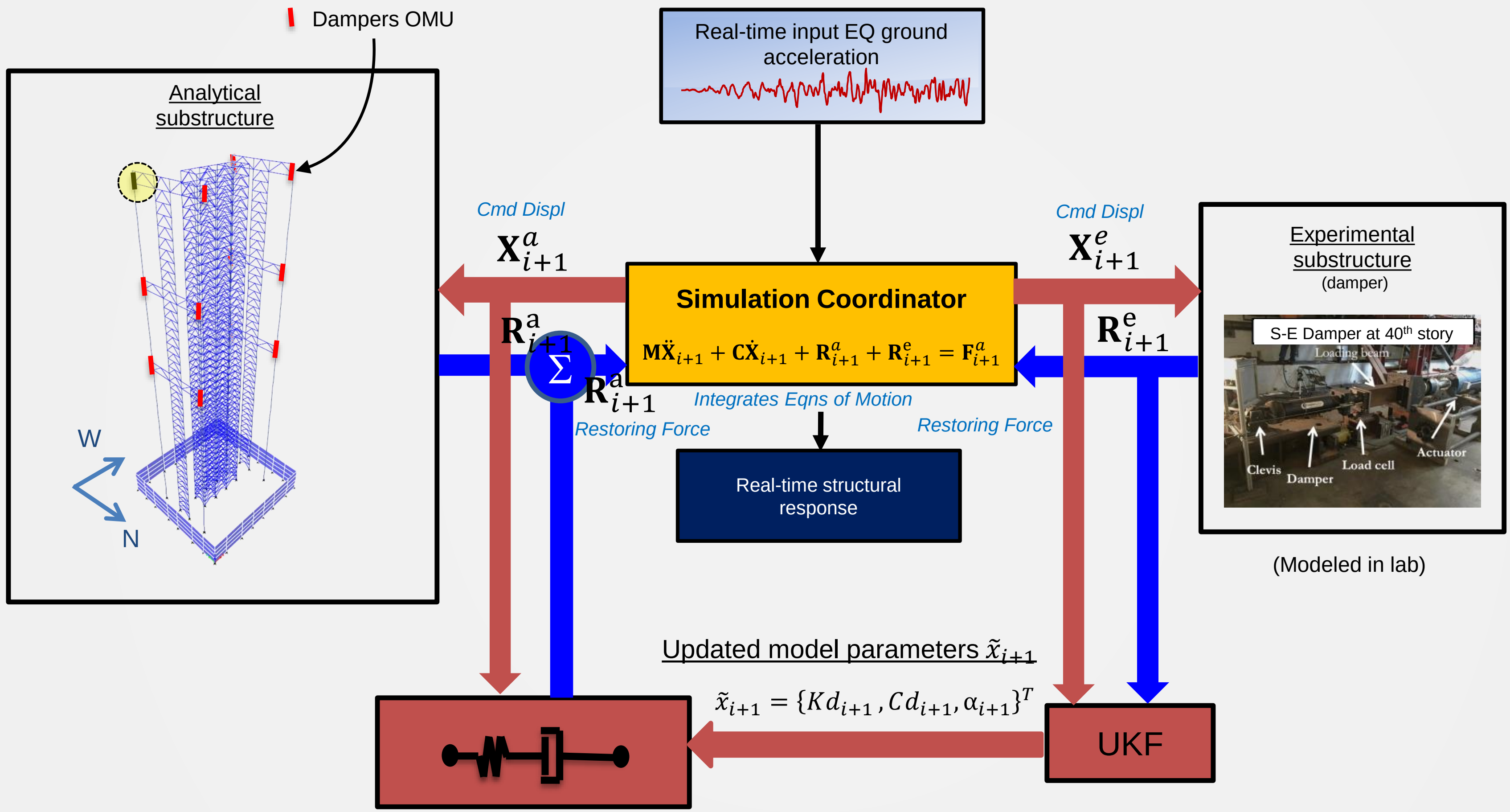
Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, Department of Civil and Environmental Engineering, Lehigh University.

Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

- Real-time Model Updating
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via Unscented Kalman Filter (UFK) to numerically model the 11 dampers
    - Development of explicit, non-iterative Nonlinear Maxwell Damper Model for real-time hybrid simulation
    - Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, Department of Civil and Environmental Engineering, Lehigh University.

Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

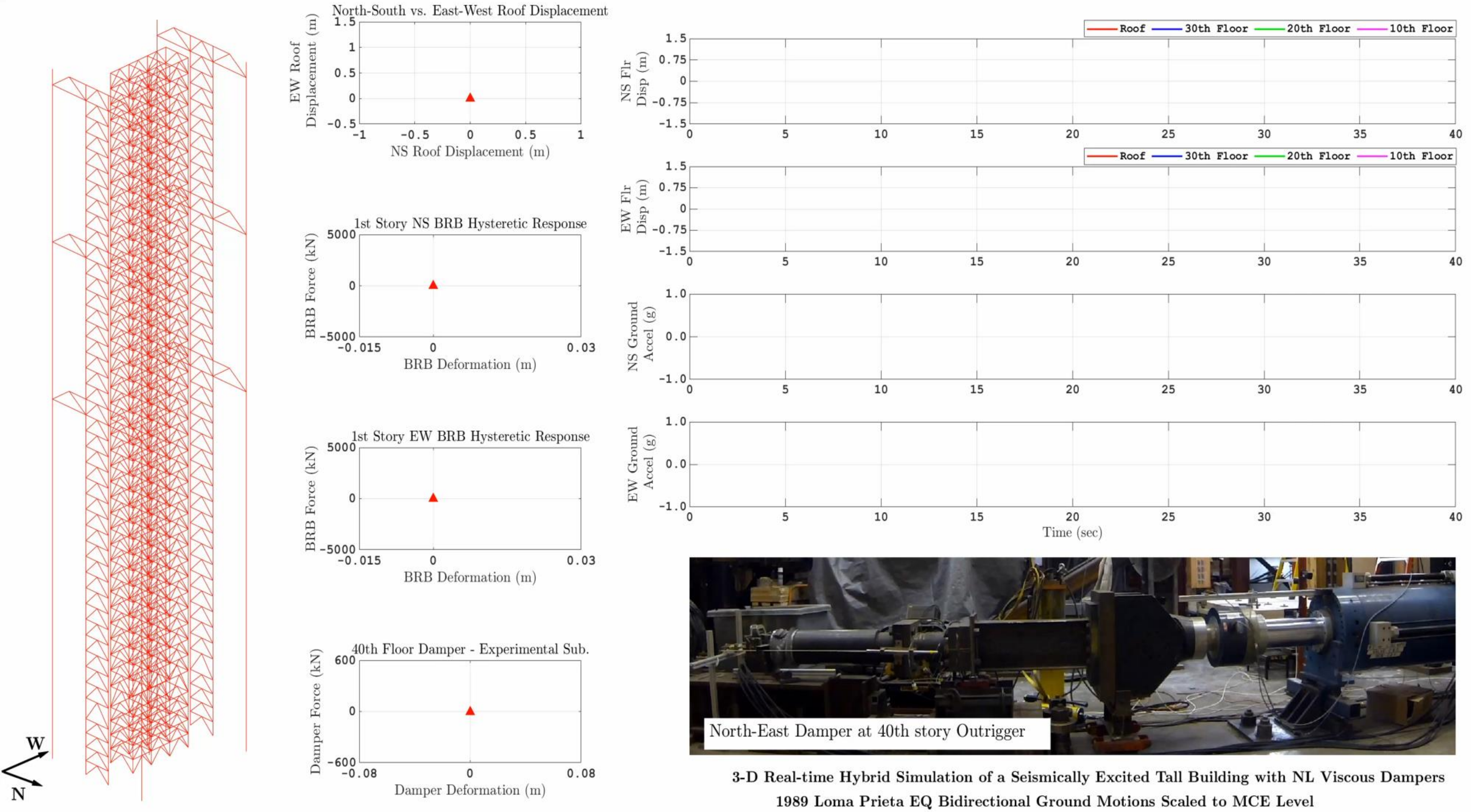


Damper computational model
(Nonlinear Maxwell Model updated in real time)

Real-time system identification using **Unscented Kalman Filter (UKF)**

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, Department of Civil and Environmental Engineering, Lehigh University.

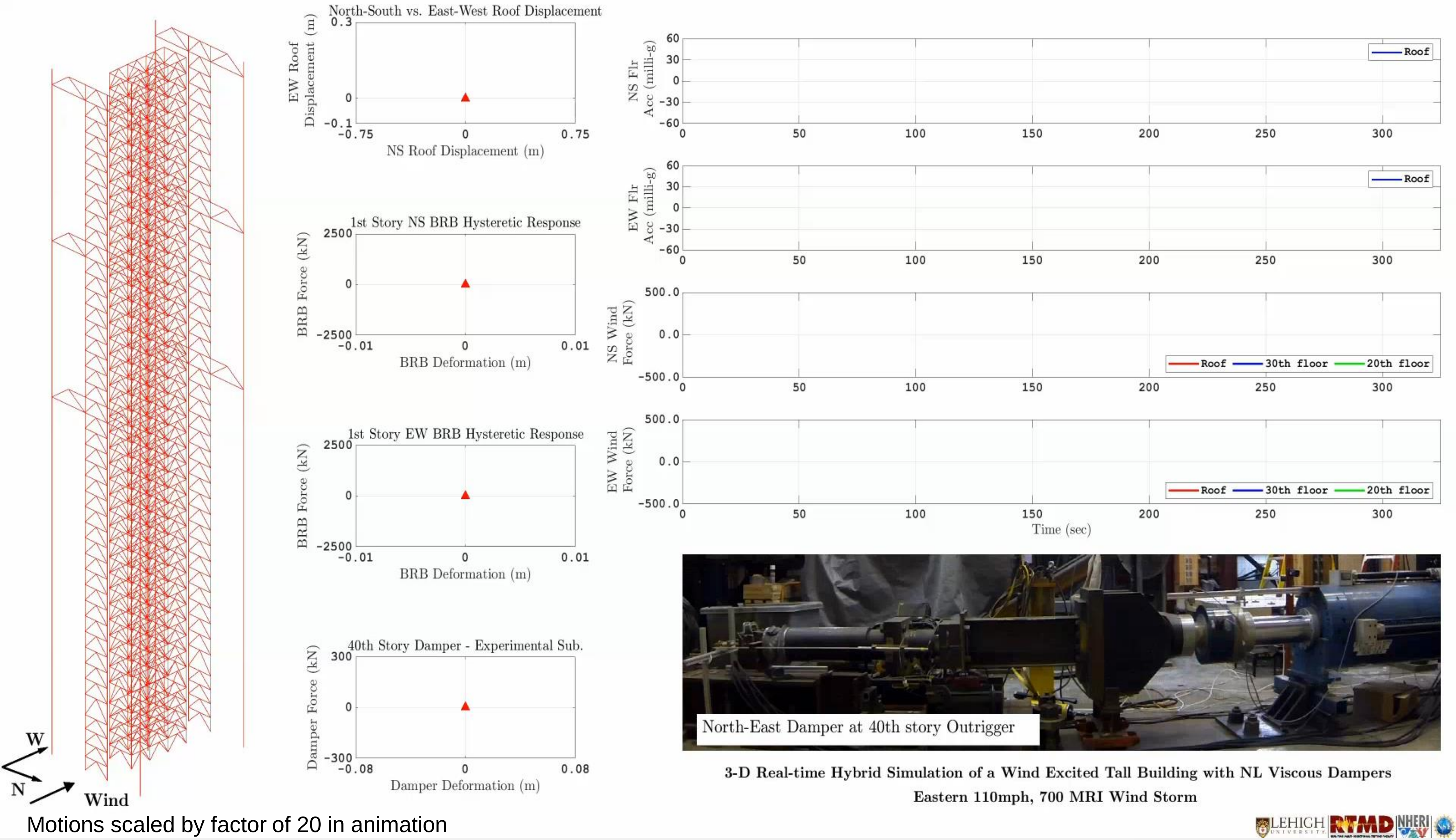
3-D Real-time Hybrid Simulation
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE



Motions scaled by factor of 5 in animation

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

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



Motions scaled by factor of 20 in animation

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

3-D RTHS Results: BRB Maximum Ductility
1989 Loma Prieta EQ Scaled to MCE

BRB Maximum Ductility Demand (Δ_b^{max}/Δ_y)

Story	No Dampers		With Dampers	
	EW	NS	EW	NS
1	3.2	3.0	3.2	2.1

Dampers added to outriggers at 20th, 30th, and 40th stories:

- BRB ductility demand: Minimal reduction in EW, 30% reduction in NS

  Note: Outrigger frames are in NS direction

3-D RTHS Results: Roof RMS Lateral Accelerations

East to West 110 mph, 700 Year MRI Wind

RMS Roof Accelerations (mG)

Floor	No Dampers		With Dampers	
	EW	NS	EW	NS
40	7.0	31.5	6.9	16.2

Peak Roof Accelerations (mG)

Floor	No Dampers		With Dampers	
	EW	NS	EW	NS
40	28.8	90.3	25.8	59.0

Dampers added to outriggers at 20th, 30th, and 40th stories:

- RMS Acceleration: 2% reduction in EW, 49% reduction in NS
- Peak Acceleration: 10% reduction in EW, 35% reduction in NS

Note: Outrigger frames are in NS direction