NHERI Lehigh Project Portfolio

James Ricles
NHERI Lehigh Director

NHERI Lehigh EF

NHERI Lehigh EF Capabilities for Natural Hazards Engineering Research

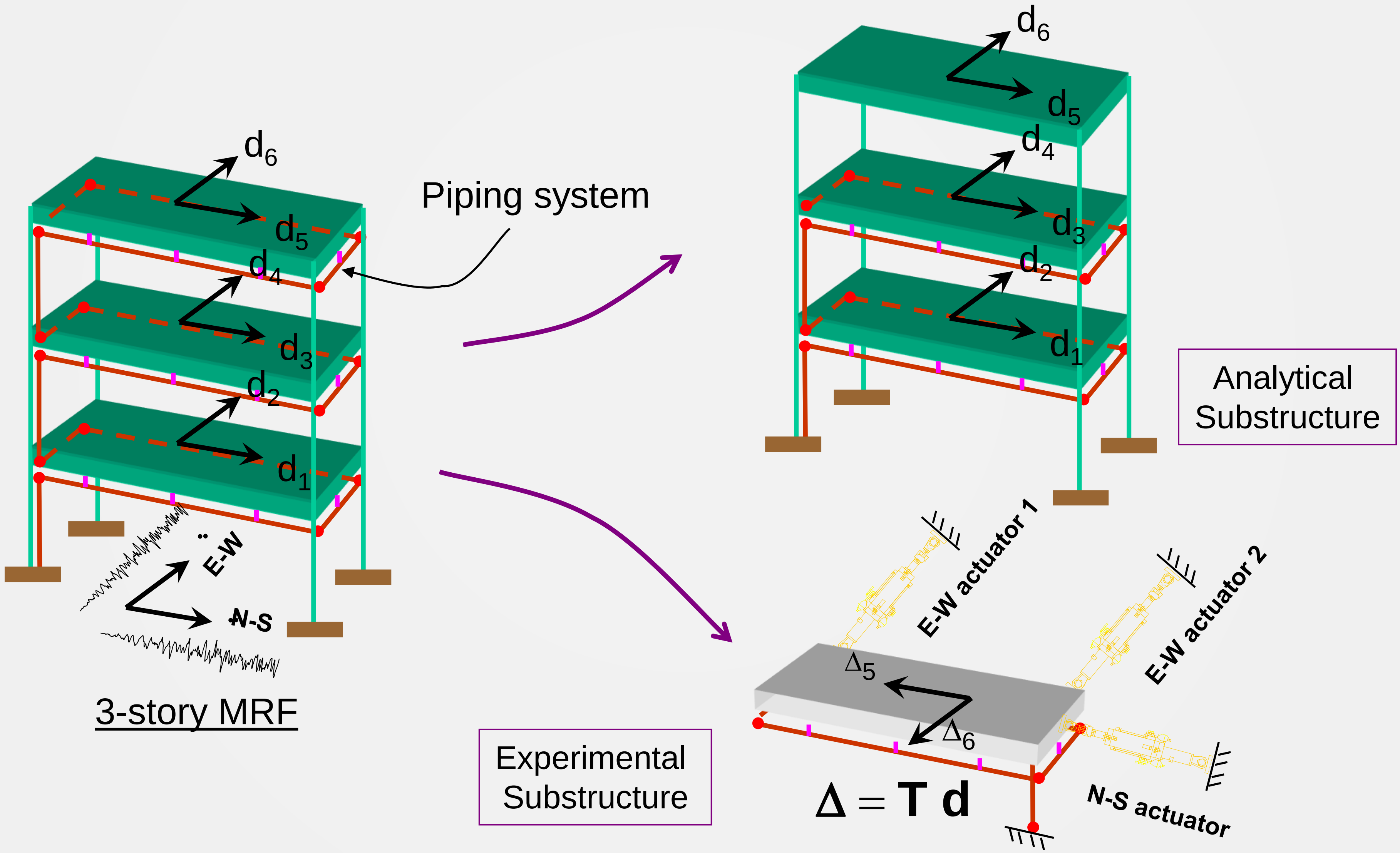
- Large-Scale Hybrid Simulation
- Large-Scale Real-Time Hybrid Simulation
- Large-Scale Real-Time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined Load or Displacement (Quasi-Static or Dynamic) Testing
- Dynamic Testing

Example Past Projects

Experiment	Capability
3-story building with piping system	Multi-directional real-time hybrid simulation
Self-centering moment-resisting frame (SC-MRF)	Large-scale hybrid simulation
Self-centering concentrically-braced frame (SC-CBF)	Large-scale hybrid simulation
Real-time testing of structures with dampers	Large-scale real-time hybrid simulation with multiple experimental substructures
Seismic hazard mitigation using passive damper systems	Predefined displacement dynamic testing (for characterization)
Seismic hazard mitigation using passive damper systems (steel MRF building with passive dampers)	Large-scale real-time hybrid simulations
Tsunami-driven debris	Dynamic testing (impact loading)
Post-tensioned coupled shear wall system	Complex large-scale multi-directional predefined force and displacement quasi-static testing
Inertial force-limiting floor anchorage systems for buildings	Predefined displacement dynamic testing (for characterization)
Cross-Laminated Rocking Wall-Floor Diaphragm Systems	Multi-directional quasi-static and hybrid simulation

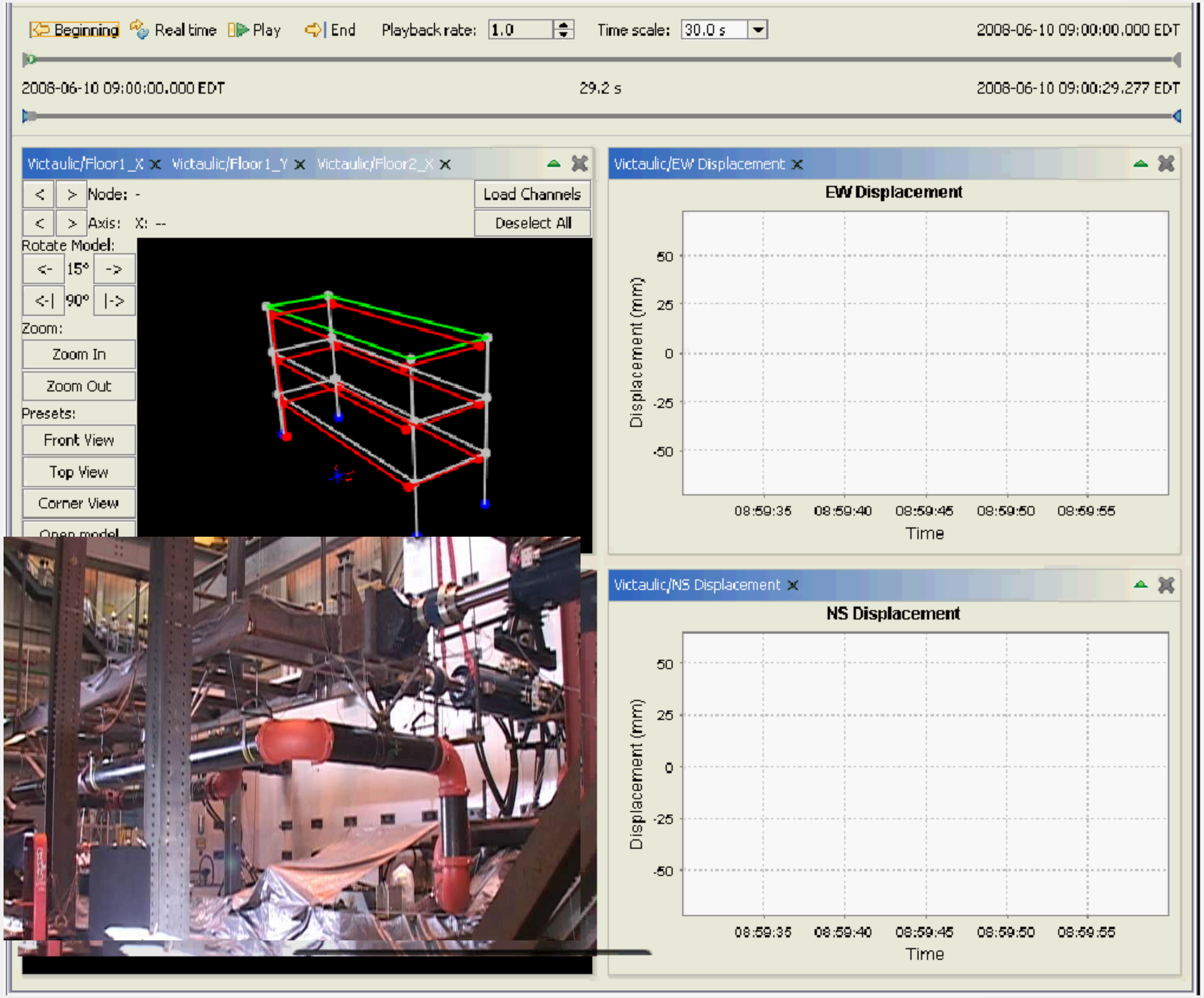
Multi-Directional Large-Scale Real-Time Hybrid Simulation of 3-story Building with Piping System

Multi-Directional Large-Scale Real-Time Hybrid Simulation



Multi-Directional Large-Scale Real-Time Hybrid Simulation of 3-story Building with Piping System

RTHS: 1994 Northridge EQ, Canogo Park (MCE)

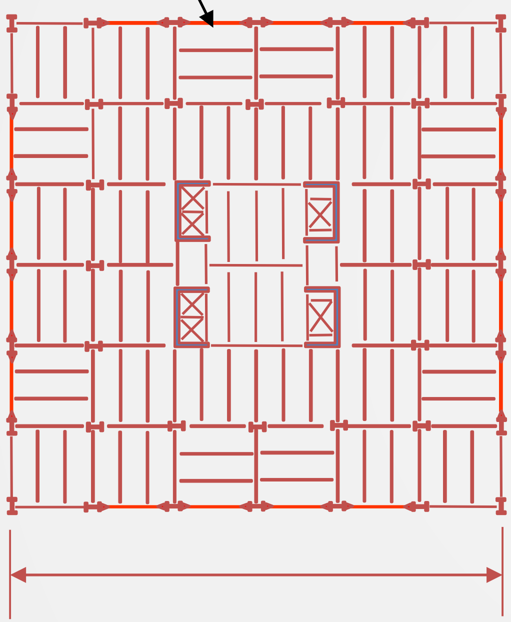


NEES

Self Centering Steel Moment-Resisting Frame (SC-MRF) Systems
Princeton, Purdue, Lehigh, NCREE

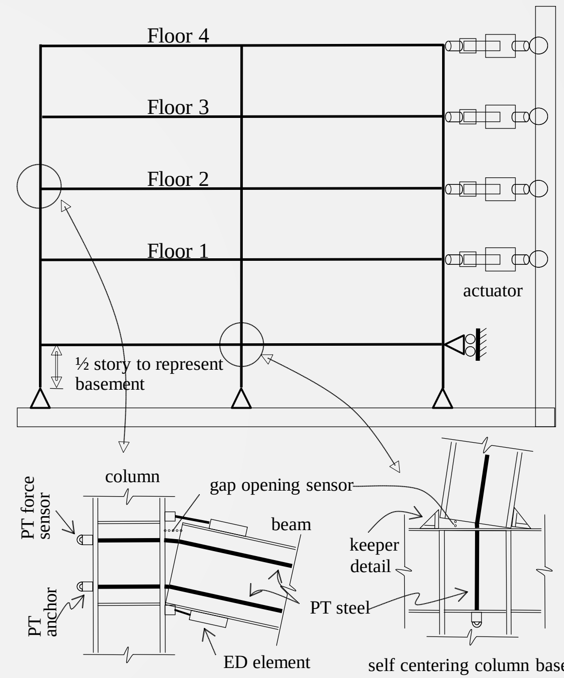
Large-Scale Hybrid Simulation

SC-MRF



6-story : 6 bays @ 30 ft = 180 ft

Plan of Prototype Building

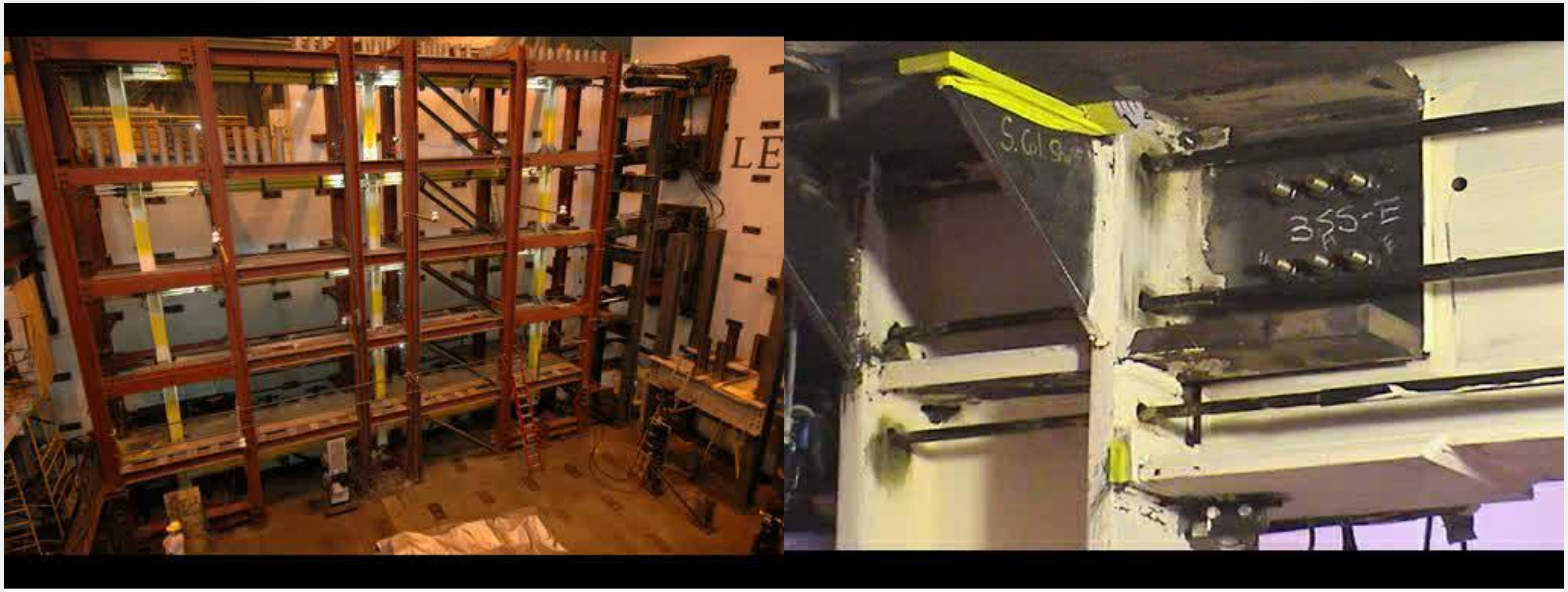


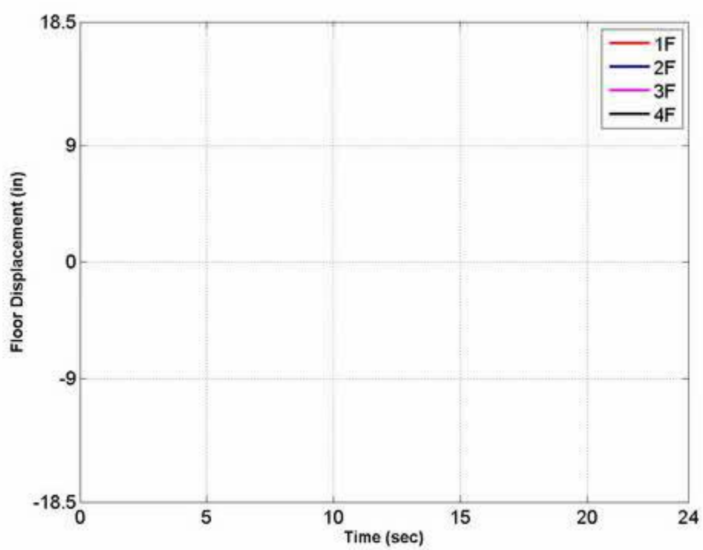
SC-MRF Experimental Substructure
(Floor Diaphragm, Gravity System, Mass, Inherent Damping in Analytical Substructure)

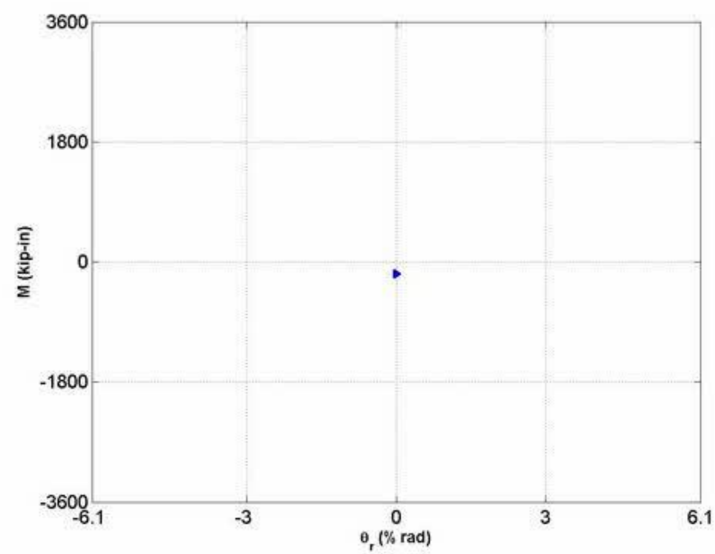
NEES

Self Centering Steel Moment-Resisting Frame (SC-MRF) Systems
Princeton, Purdue, Lehigh, NCREE

Large-Scale Hybrid Simulation (SC-MRF)



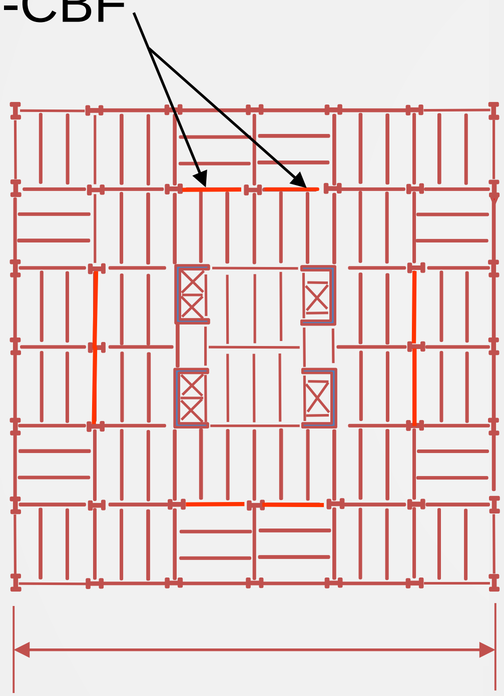




Self Centering Steel Concentrically-Braced Frame (SC-CBF) Systems
Princeton, Purdue, Lehigh, NCREE

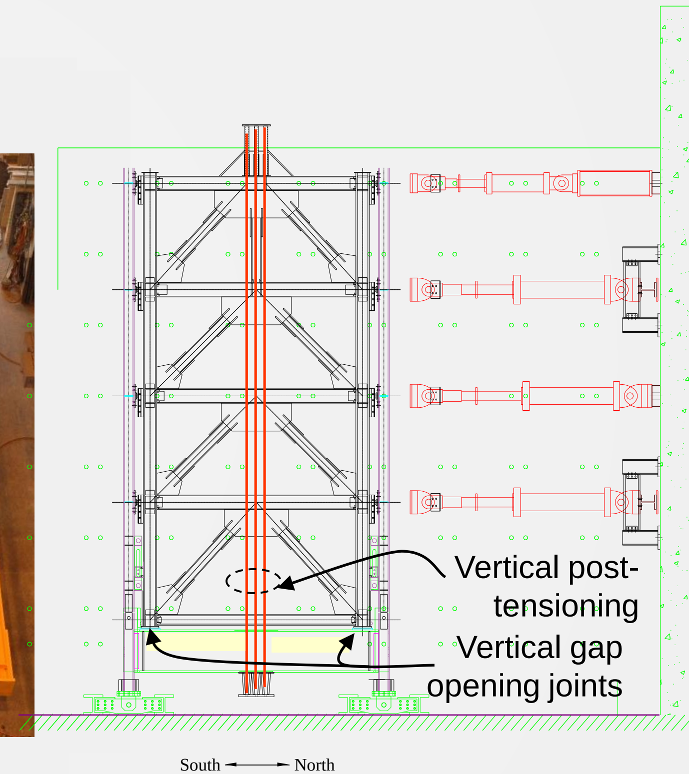
Large-Scale Hybrid Simulation

SC-CBF



6-story : 6 bays @ 30 ft = 180 ft

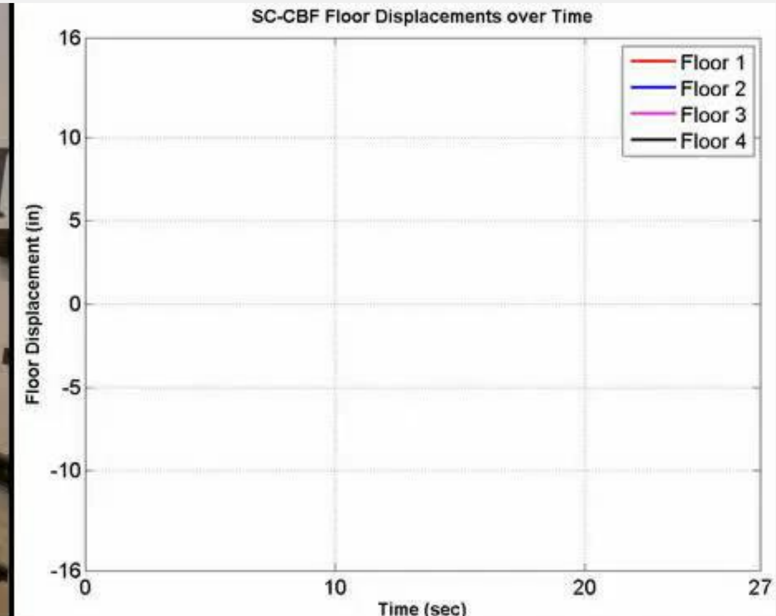
Plan of Prototype Building



SC-CBF Experimental Substructure
(Floor Diaphragm, Gravity System, Mass, Inherent Damping in Analytical Substructure)

NEES

Large-Scale Hybrid Simulation (SC-CBF)

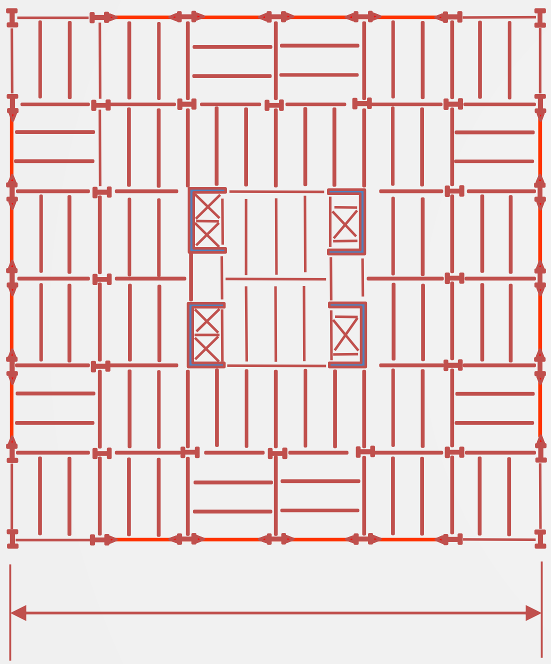


South Base

North Base

Test Bed For Real-Time Testing of Structures with Dampers

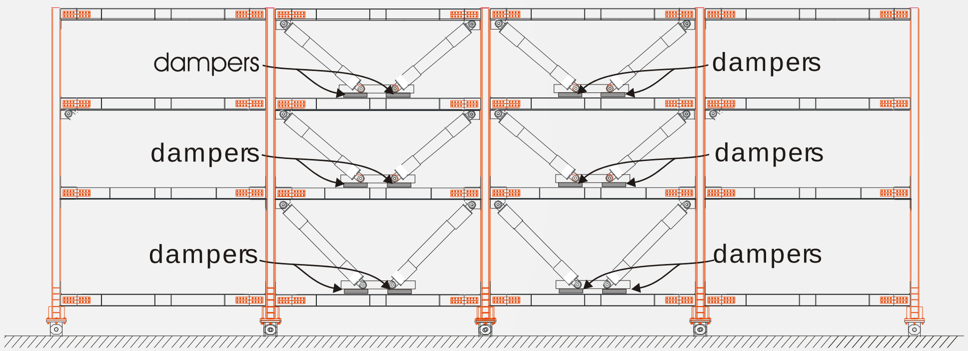
Large-Scale Real-Time Hybrid Simulation, Multiple Experimental Substructures



Steel MRF with Passive Dampers

6-story : 6 bays @ 30 ft = 180 ft

Plan of Prototype Building

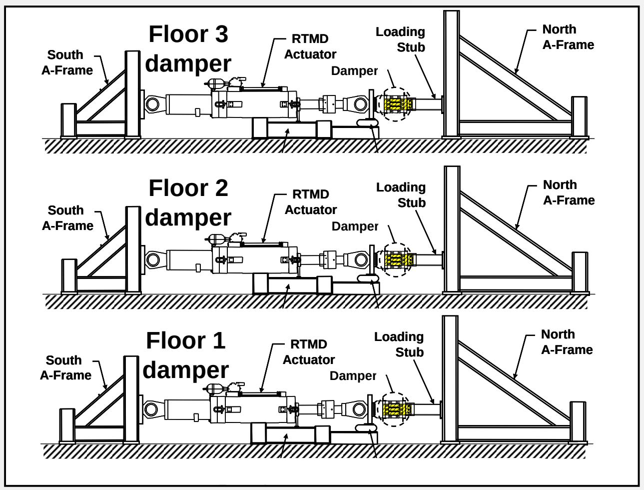


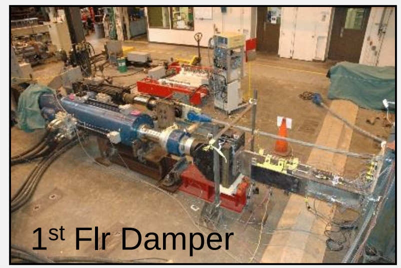
Elevation of MRF with Passive Dampers

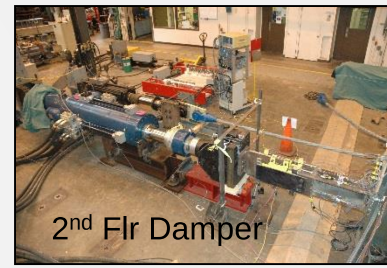
NEES

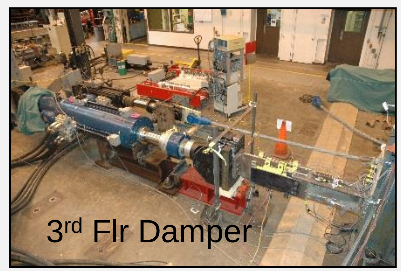
Test Bed For Real-Time Testing of Structures with Dampers

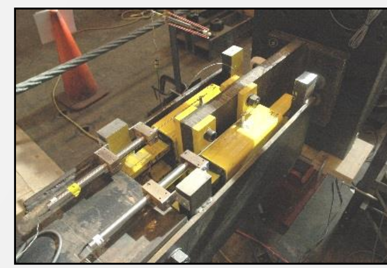
Large-Scale Real-Time Hybrid Simulation, Multiple Experimental Substructures









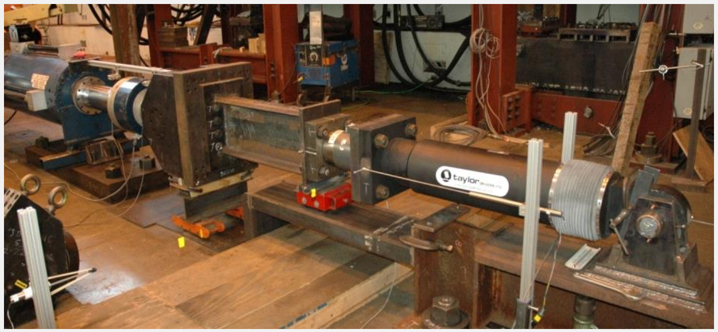


Experimental Substructures
(MRF, Floor Diaphragm, Gravity System, Mass, Inherent Damping in Analytical Substructure)

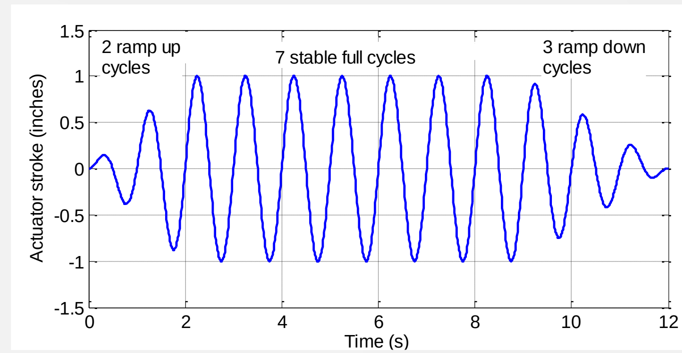
Close up view of damper

Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems
Cal State Pomona, Cal State Northridge, Lehigh

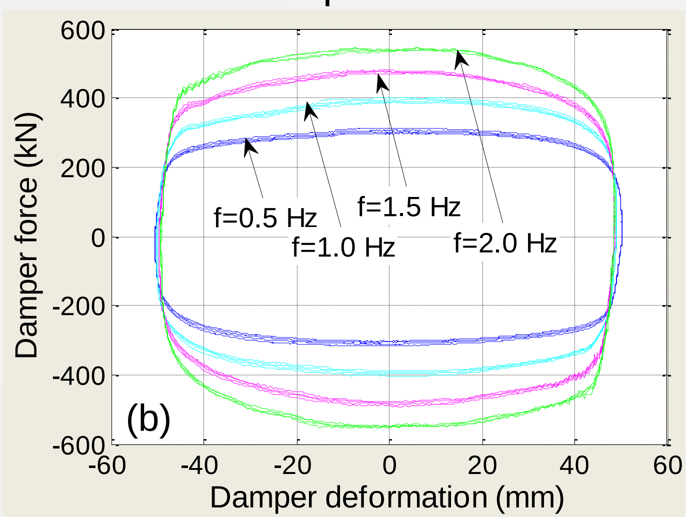
Predefined Displacement Dynamic Testing for Characterization



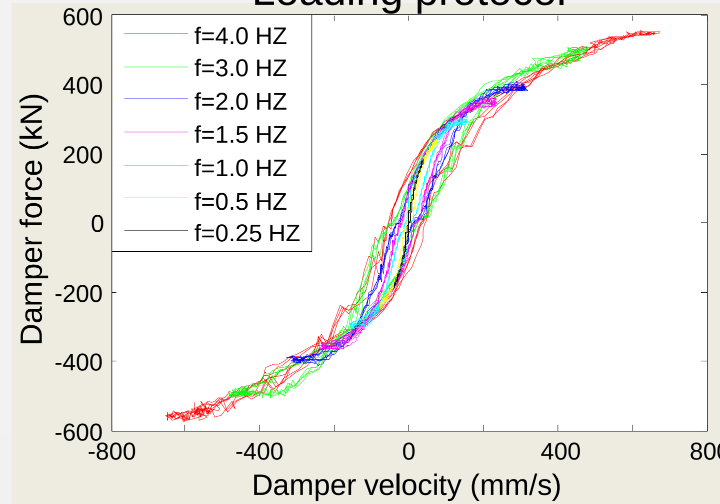
Damper testbed



Loading protocol



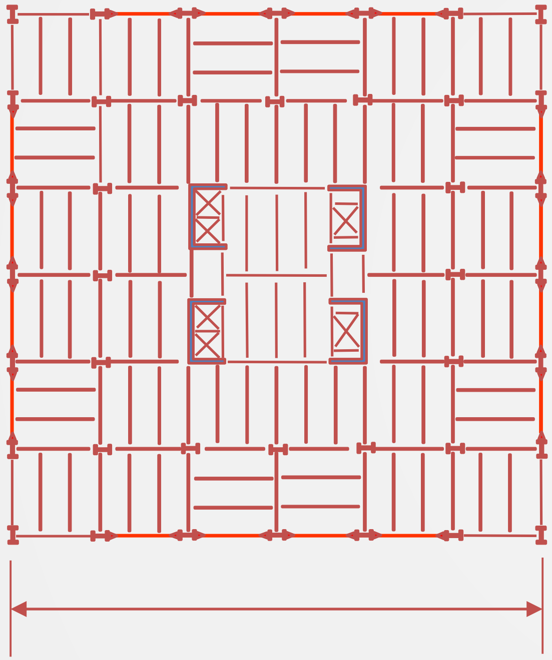
Damper force - deformation



Damper force - velocity

Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems
Cal State Pomona, Cal State Northridge, Lehigh

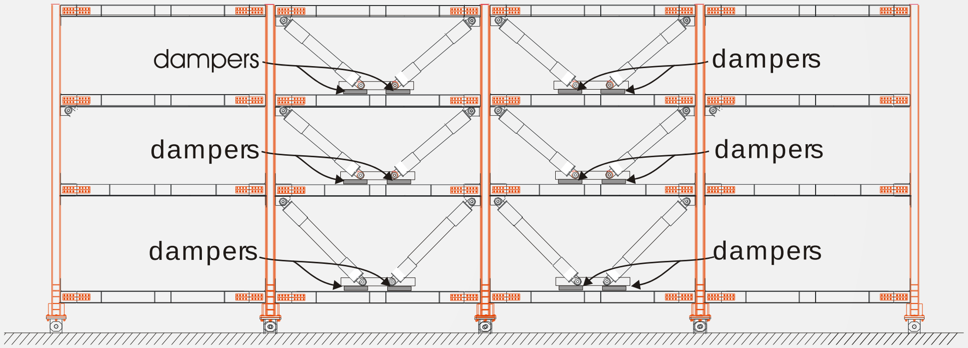
Large-Scale Real-Time Hybrid Simulation



Steel MRF with Passive Dampers

6-story : 6 bays @ 30 ft = 180 ft

Plan of Prototype Building

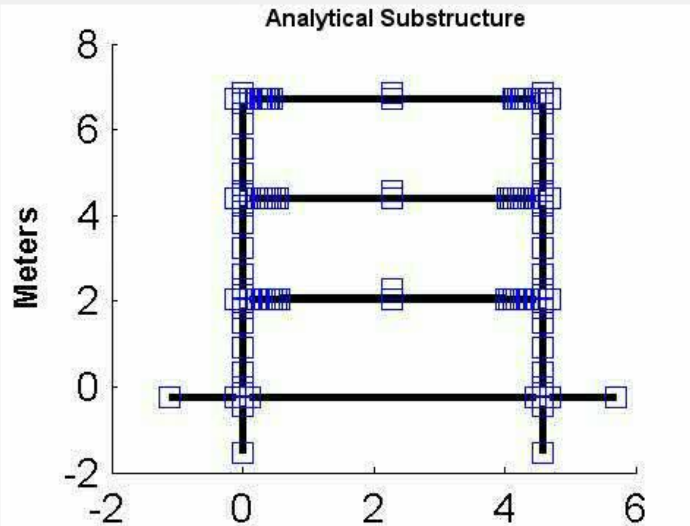


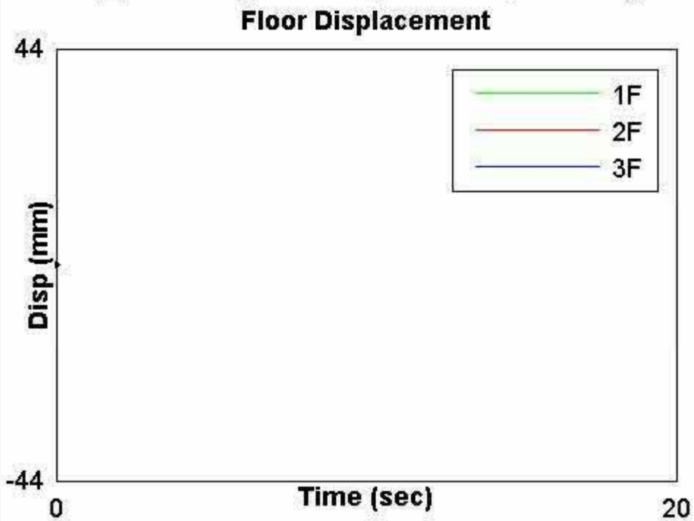
Elevation of MRF with Passive Dampers

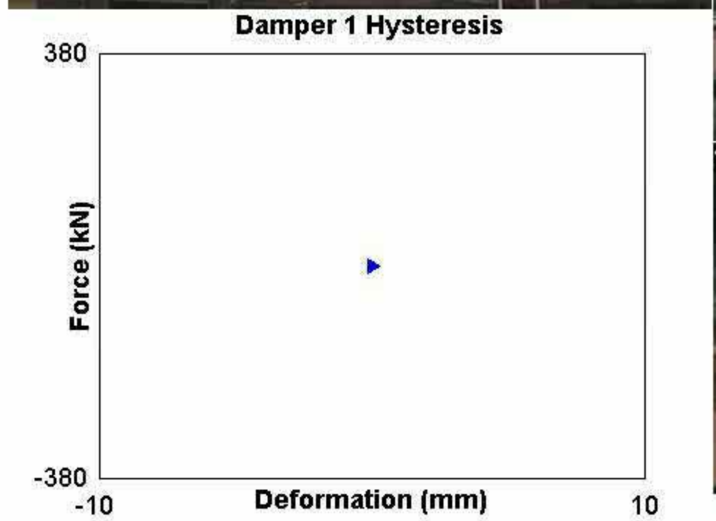
Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems
Cal State Pomona, Cal State Northridge, Lehigh

Large-Scale Real-Time Hybrid Simulation

(MRF, Floor Diaphragm, Gravity System, Mass, Inherent Mass in Analytical Substructure)







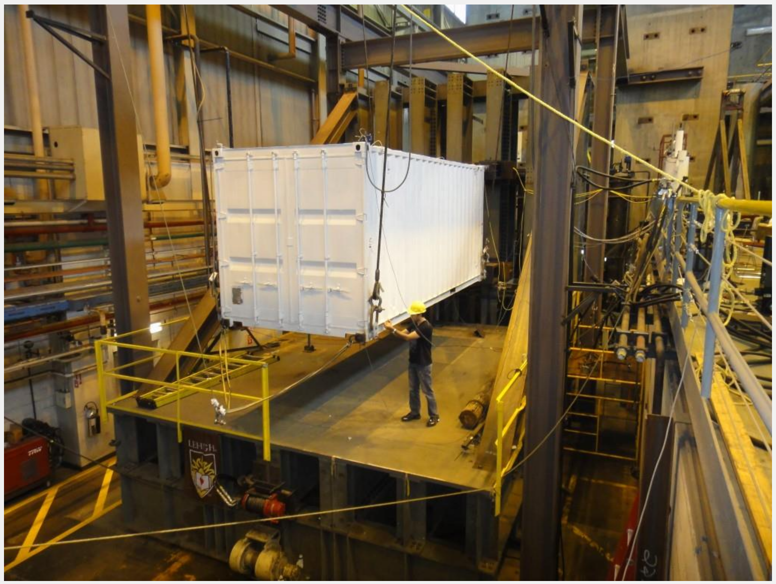
Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems
Cal State Pomona, Cal State Northridge, Lehigh

Large-Scale Real-Time Hybrid Simulation
(Floor Diaphragm, Gravity System, Mass, Inherent Mass in Analytical Substructure)

Experimental Substructure: MRF and Braced Frame with Dampers

Impact Forces from Tsunami-Driven Debris
University of Hawaii, Oregon State University, Lehigh

Dynamic Testing (Impact Loading)

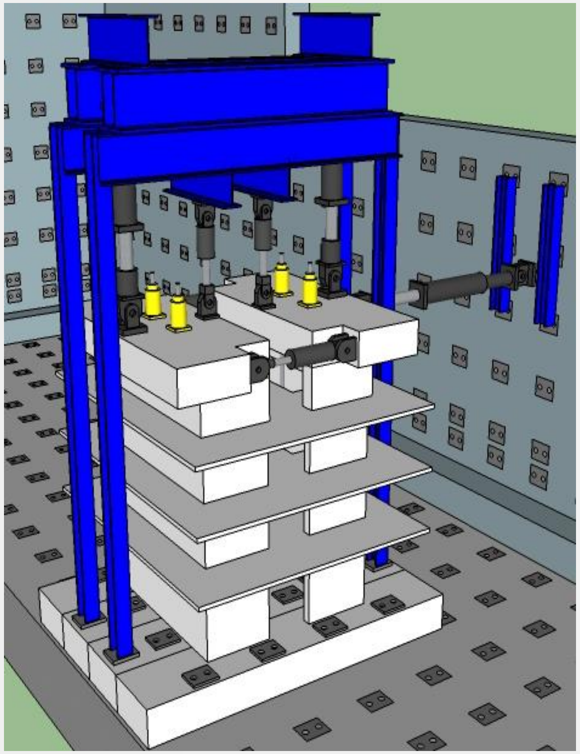


Test Setup with Cargo Shipping Container Debris

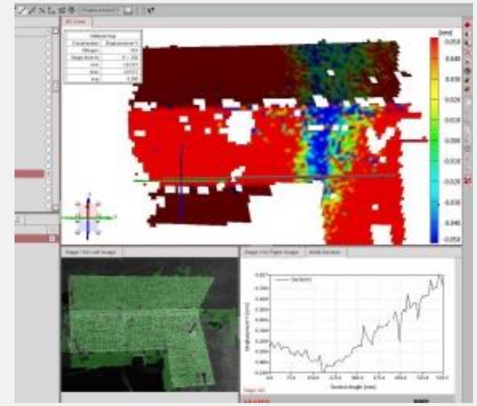
High Speed Video of Impact of Cargo Shipping Container on Structure

Post-Tensioned Coupled Shear Wall System
Notre Dame, University of Texas at Tyler

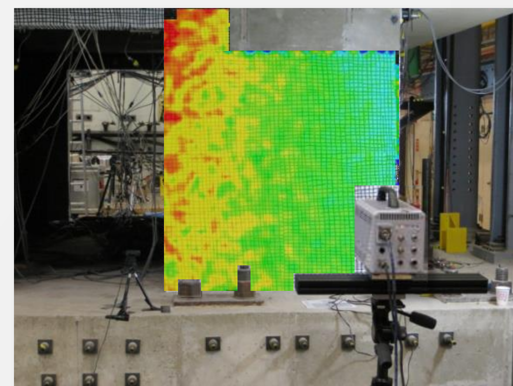
Complex Large-Scale Predefined Multi-Directional Force & Displacement (Quasi-Static) Testing



RC coupled shear wall test specimen with multi-directional loading. Upper 5 stories of 8-story building simulated with vertical force-controlled actuators. 1 displacement-controlled and 10 force-controlled (11 total) used for test.



Joint strains measured by DIC (S. Pakzad)



RC coupled shear wall pier vertical deformation measured by Digital Image Correlation (DIC) (M. McGinnis)

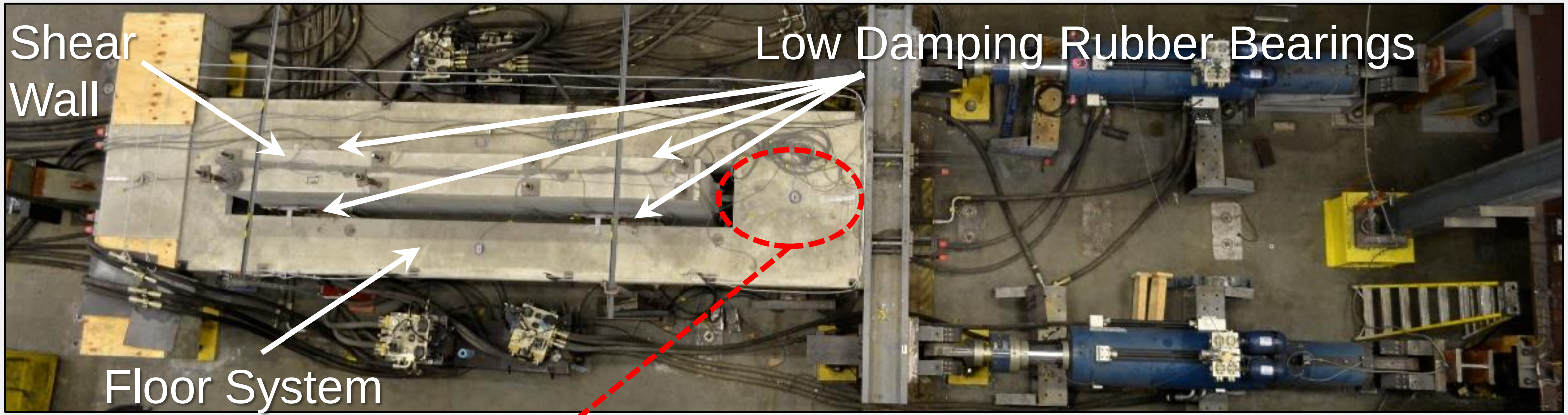
NEES

Post-Tensioned Coupled Shear Wall System
Notre Dame, University of Texas at Tyler

Complex Large-Scale Predefined Multi-Directional Force & Displacement (Quasi-Static) Testing

Inertial Force Limiting Floor Anchorage Systems for Buildings
University of Arizona, UCSD, Lehigh

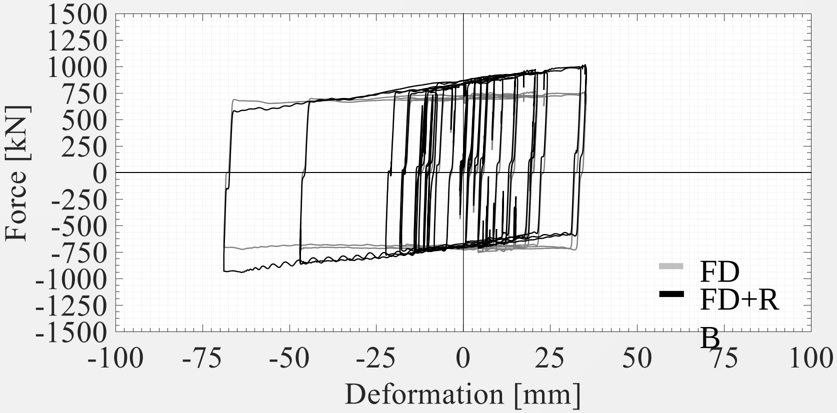
Predefined Displacement Dynamic Testing for Characterization



Friction Device for Floor Anchorage

BRB was also Studied

Floor Anchorage Hysteretic Response

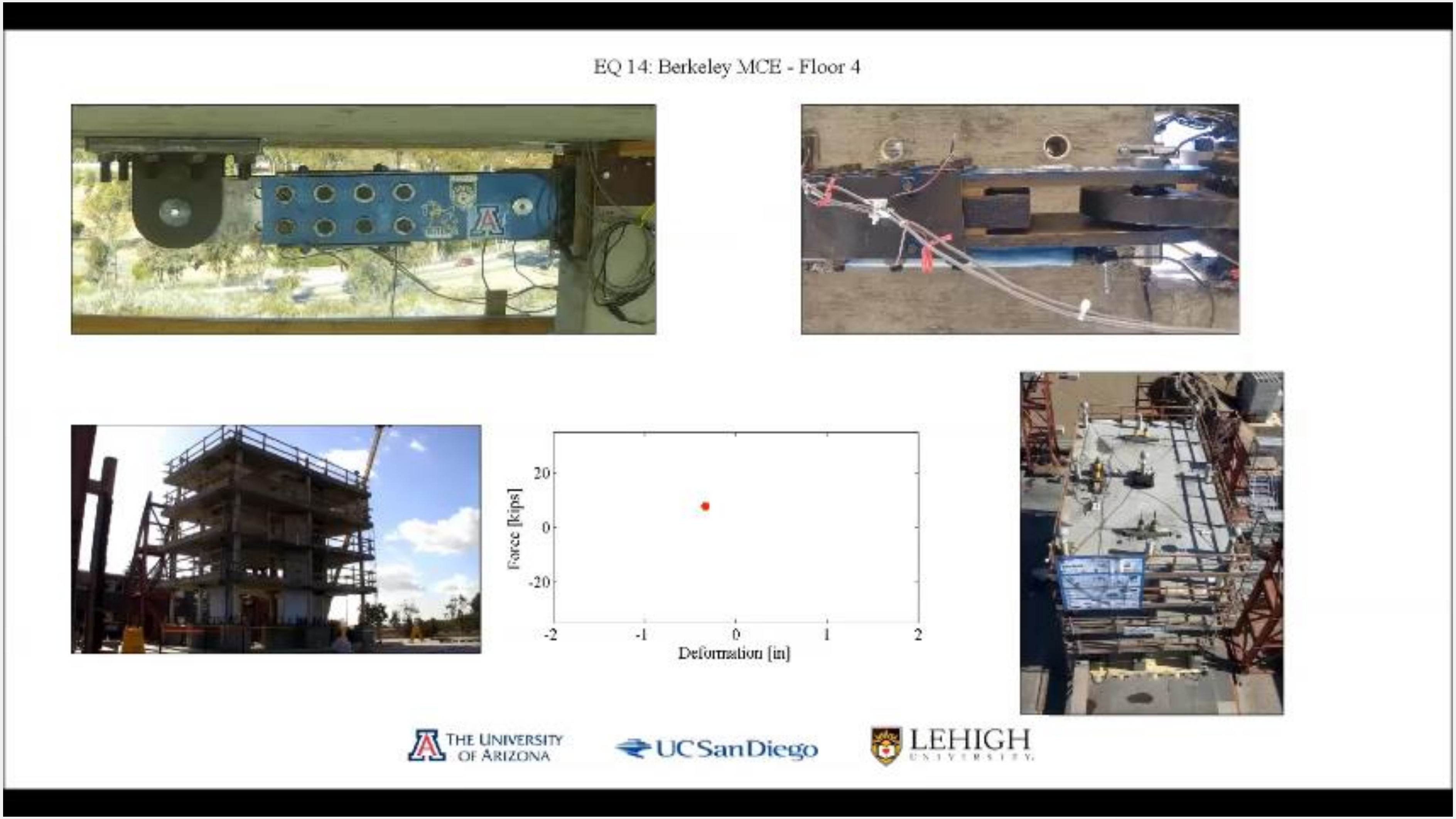


Inertial Force Limiting Floor Anchorage Systems Buildings
University of Arizona, UCSD, Lehigh

Predefined Displacement Dynamic Testing for Characterization

Inertial Force Limiting Floor Anchorage Systems Buildings
University of Arizona, UCSD, Lehigh

[Complimentary Shake Table Tests at NHERI UCSD]



Current Projects at NHERI Lehigh EF

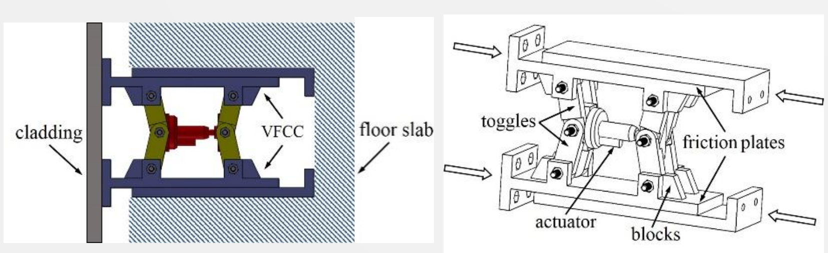
Project	Capability
Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards: Iowa State University (S. Laflamme)	Real-time hybrid simulation
Passive Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards: Lehigh University (J. Ricles, S. Quiel)	Real-time hybrid simulation
Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings (*Non-Structural System*): University of Nevada, Reno (Keri Ryan)	Complex predefined multi-directional displacement quasi-static testing
Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings (*Structural System*): Lehigh University (J. Ricles, R. Sause)	Complex predefined multi-directional displacement quasi-static testing; multi-directional hybrid simulation
Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures: University of Arizona (R. Fleischman (PI) with C.-M. Uang (UCSD), J. Ricles, R. Sause (Lehigh University))	Complex large-scale predefined force and displacement quasi-static testing
Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic-Resilient Buildings: University Illinois Urbana-Champaign (L. Fahnestock (PI), B. Simpson (OSU), R. Sause, J. Ricles (Lehigh University))	Multi-directional quasi-static and hybrid simulation
Multi-Hazard RTHS Studies of Tall Buildings with Response Modification Devices – NHERI Lehigh Capacity Building (NHERI Lehigh Staff)	Multi-directional Real-time hybrid simulation, online real-time model updating

Current Projects at NHERI Lehigh EF

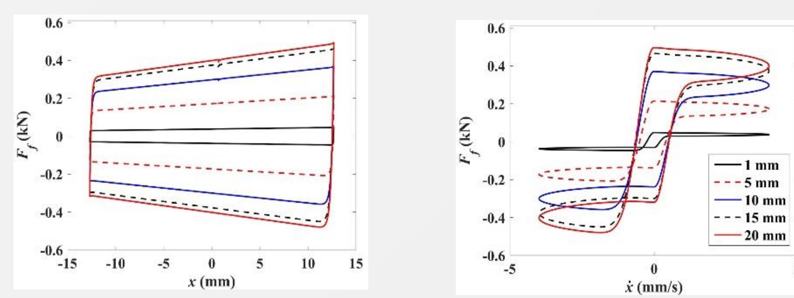
Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards: (CMMI 1463252) **Iowa State University (Simon Laflamme)**

Features Using NHERI Lehigh Underlined

- Project Overview
  - Improve performance of buildings for multiple hazards using <u>semi-active controlled variable friction cladding panel connectors</u>
  - Hazards: Earthquake, Wind (NHERI UF), Blast Loading
- Project Scope
  - Design cladding connectors and control laws
  - Construct prototype connector, perform characterization testing
  - Perform l<u>arge-scale RTHS</u> to validate numerical models and results (450 data sets from RTHS uploaded to DesignSafe to date)



Semi-Active Controlled Variable Friction Cladding Connector



Dynamic Numerical Models

Current Projects at NHERI Lehigh EF

Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards: (CMMI 1463497) **Lehigh University (James Ricles, Spencer Quiel)**

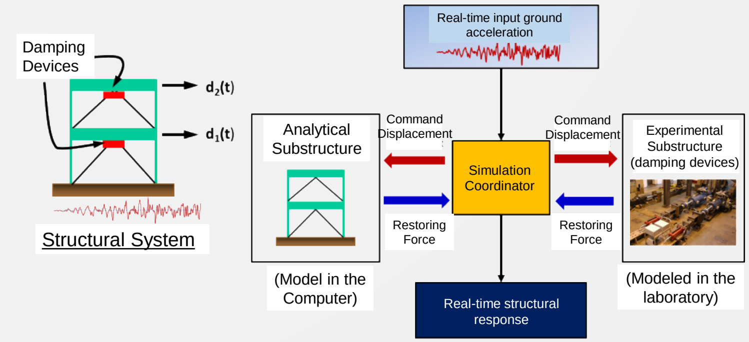
<u>Features Using NHERI Lehigh Underlined</u>

- Project Overview
  - Improve performance of buildings under multiple hazards using <u>passive energy dissipating cladding panel connectors</u>
  - Hazards: Earthquake, Wind (NHERI UF), Blast Loading
- Project Scope
  - Design prototype buildings of various heights
  - Perform nonlinear time history analysis to assess performance
  - Perform <u>large-scale RTHS</u> to validate numerical models and results (450 data sets from RTHS uploaded to DesignSafe to date)

Test Matrix: Passive Control Connectors

HAZARD	METHODOLOGY	HAZARD LEVEL
WIND	Real Time Hybrid Simulation	700- and 1700- years return period per wind speeds & hurricane
SEISMIC	Real Time Hybrid Simulation	DBE and MCE ground motions
BLAST	Shock Tube	GSA Medium and High Design basis blast threat

Seismic Hybrid Simulation Experiments



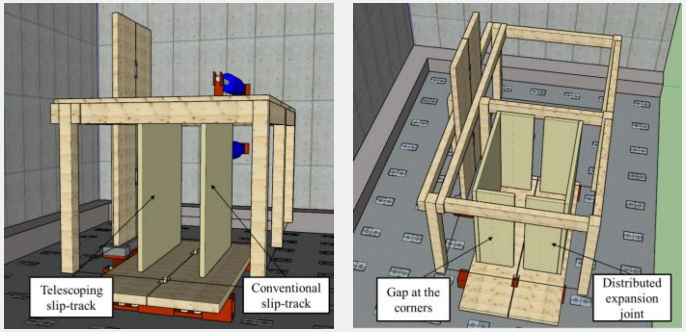
Current Projects at NHERI Lehigh EF

Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings: (CMMI 1635363)

University of Nevada, Reno (Keri Ryan)

Features Using NHERI Lehigh Underlined

- Project Overview
  - Develop seismic design methodology for tall wood buildings with high-performance structural and non-structural systems
  - Determine partition wall configurations for large lateral drift with minimized partition damage
- Project Scope
  - Conduct large-scale tests of partition wall systems under in-plane & out-of-plane (bi-directional) loading (& associated vertical motion)
  - Consider different partition slip track and other details to minimize damage

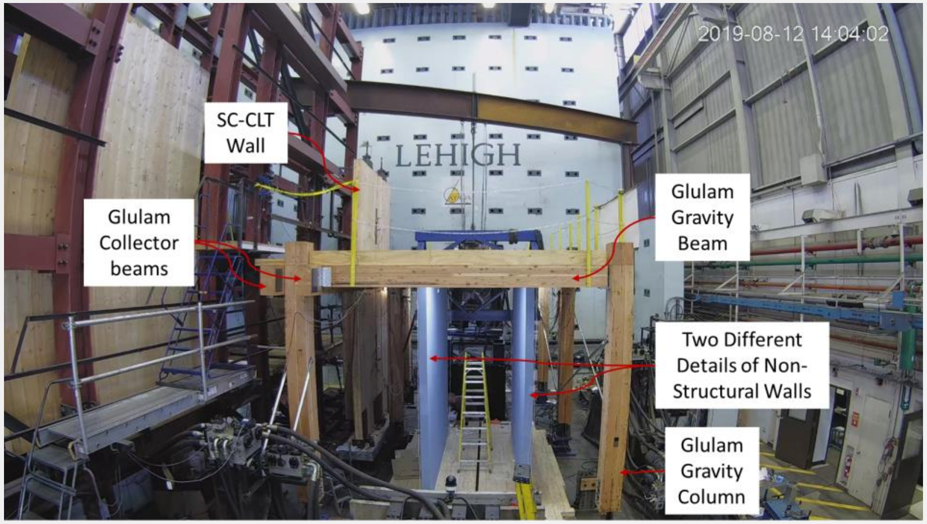


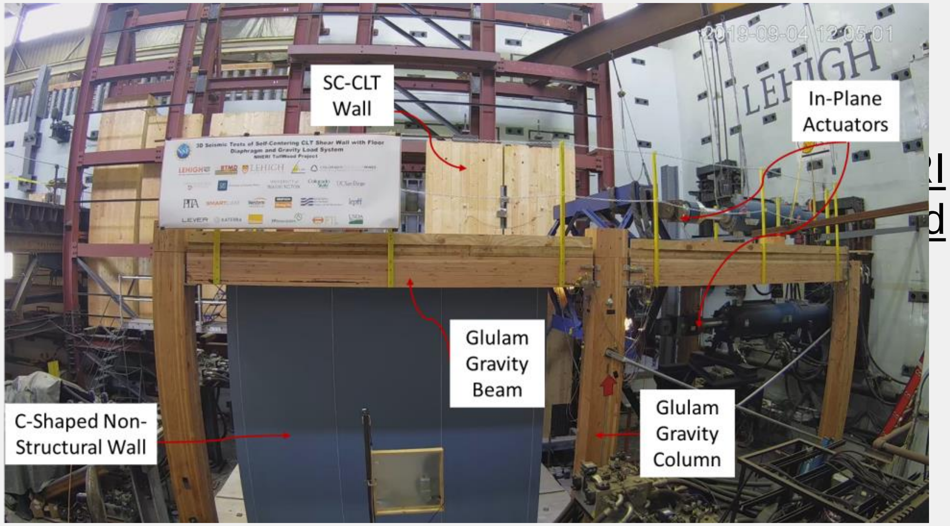
Test setup for partition wall testing

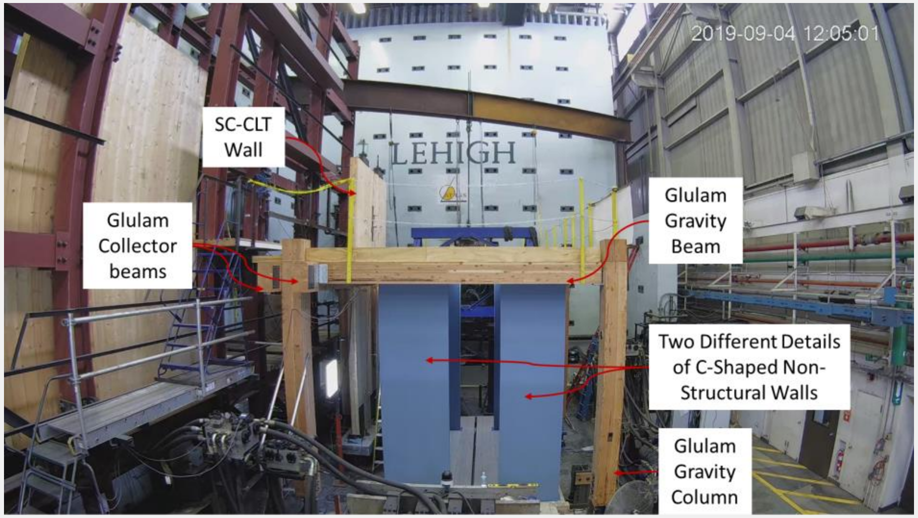
Test Phases	Objectives
Phase I.1-NS	Two independent flat partition walls tested to characterize slip behavior of different slip track details and measure forces in walls under bidirectional loading
Phase I.2-NS	Two independent C-shaped partition walls tested to characterize deformability with different details and measure forces in walls under bidirectional loading
Phase III-NS	Partition walls with dense layout tested under bidirectional loading

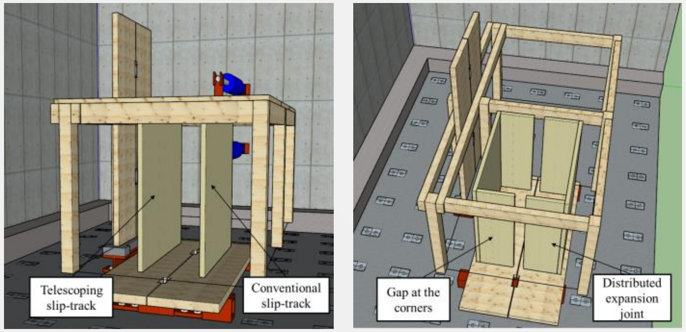
Test plan for partition wall testing

Current Projects at NHERI Lehigh EF









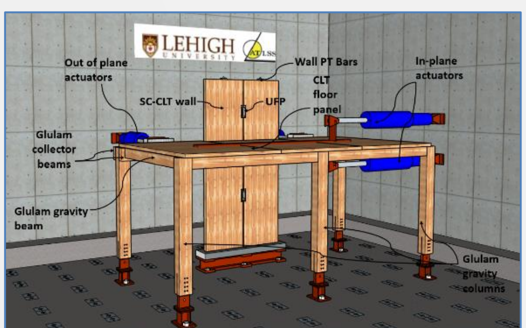
Test setup for partition wall testing

Current Projects at NHERI Lehigh EF

Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings: (CMMI 1635227) **Lehigh University (James Ricles, Richard Sause)**

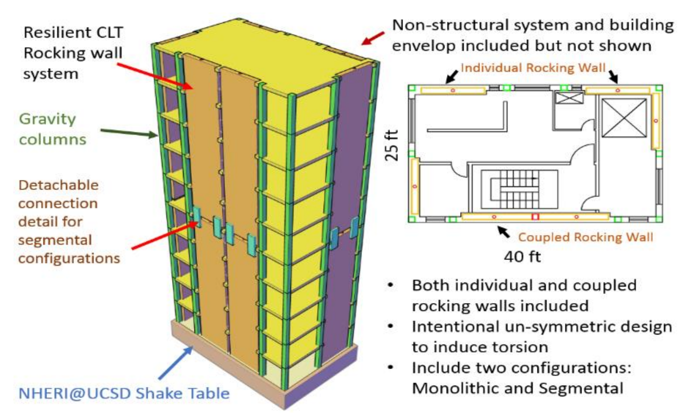
Features Using NHERI Lehigh Underlined

- Project Overview
  - ➢ Develop seismic design methodology for tall wood buildings with high-performance structural and non-structural systems
  - ➢ Study self-centering rocking cross-laminated timber (SC-CLT) wall with diaphragm and gravity load system
- Project Scope
  - ➢ Conduct large-scale tests
    out-of-plane (bi-direction
  - ➢ Project is supporting wor
    table tests (CSM, S. Pei)



Test setup for subassembly testing

Test Phase
Phase I
Phase I.1-S
Phase I.2-S
Phase II
Phase II.1-S
Phase II.2-S
Phase III



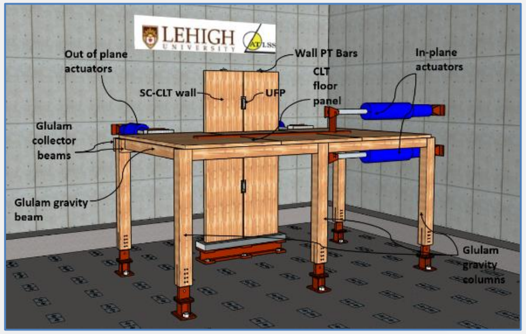
- ➢ **Results of test specimen components are used for design of 10-Story CLT building shake table test specimen at University of California San Diego (UCSD) – led by Shiling Pei, University of Colorado School of Mines**

Current Projects at NHERI Lehigh EF

Collaborative Research: Developm
Based Seismic Design Methodolog
1635227) **Lehigh University (Jam**

HERI
rlined

- Project Overview
  - Develop seismic design met... n
    high-performance structural
  - Study self-centering rockin...)
    wall with diaphragm and gra
- Project Scope
  - Conduct large-scale tests of subassemblies under in-plane &
    out-of-plane (bi-direction
  - Project is supporting wo
    table tests (CSM, S. Pei



Test setup for subassembly testing

Test Phase
Phase I
Phase I.1-S
Phase I.2-S
Phase II
Phase II.1-S
Phase II.2-S
Phase III

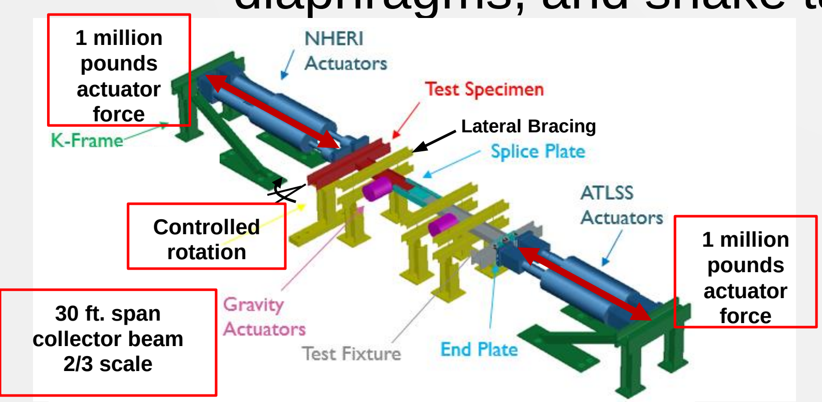
Test plan for subassembly testing

Current Projects at NHERI Lehigh EF

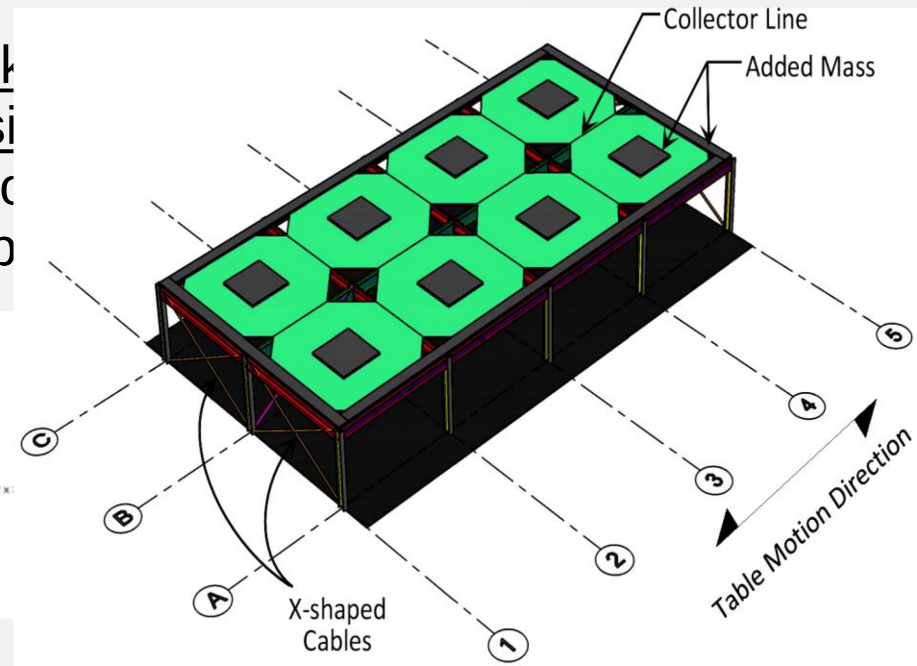
Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures: (CMMI 1662816) **University of Arizona (Robert Fleischman (PI), Chia-Ming Uang, James Ricles, Richard Sause)**

<u>Features Using NHERI Lehigh Underlined</u>

- Project Overview
  - Investigate failure-critical yet poorly understood component of steel seismic force resisting system, the seismic collector
  - FE analyses, <u>large-scale tests</u> and shake-table tests of floor diaphragms and collectors
- Project Scope
  - Conduct <u>large-scale (1000k</u> … n collector connections (<u>tensi</u> …
  - Project is supporting FE mo … diaphragms, and shake tab …



Test setup for collector connection testing



Collector connection details

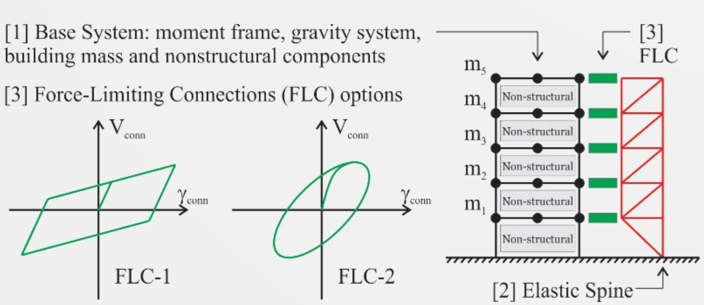
FE analyses

Current Projects at NHERI Lehigh EF

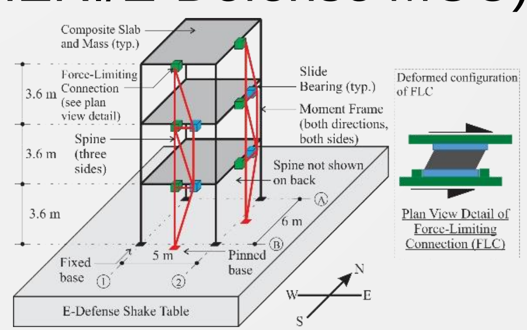
Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic-Resilient Buildings: **University of Illinois (Larry Fahnestock (PI), OSU (Barbara Simpson), Lehigh (Richard Sause and James Ricles)**

Features Using NHERI Lehigh Underlined

- Project Overview
  - Develop novel steel frame-spine lateral-force-resisting system with force-limiting connections to protect building from damaging lateral drift and accelerations, providing resilient structural and non-structural building performance
  - FE analyses, large-scale tests and shake-table tests of floor diaphragms and collectors
- Project Scope
  - Conduct large-scale tests on connections
  - Project is supporting FE models at OSU, design studies at UIUC, and shake table tests at E-Defense (NHERI/E-Defense MOU).



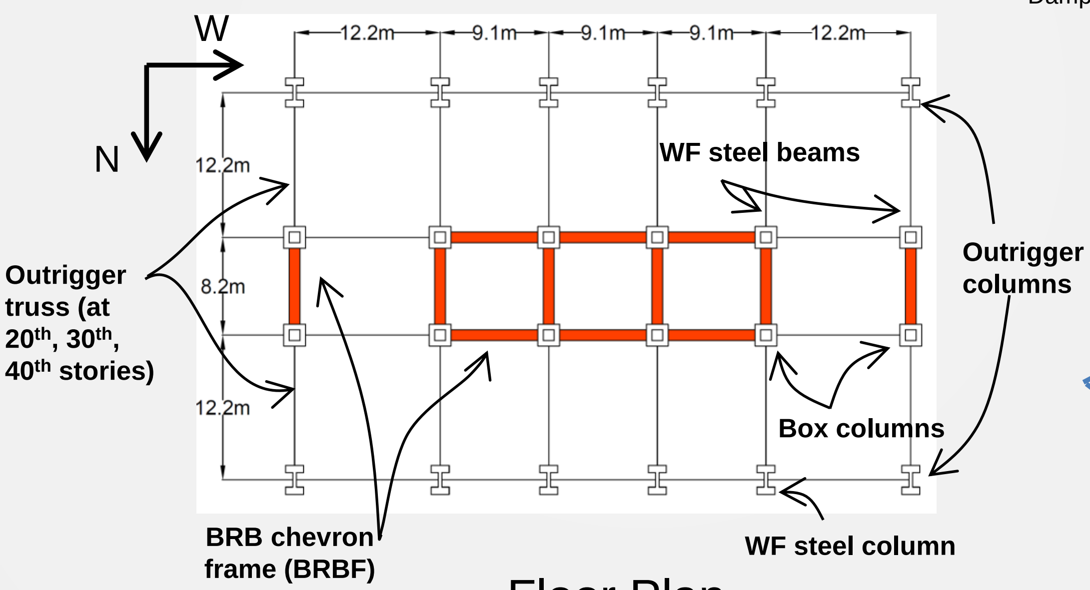
Connection Component Testing at NHERI Lehigh



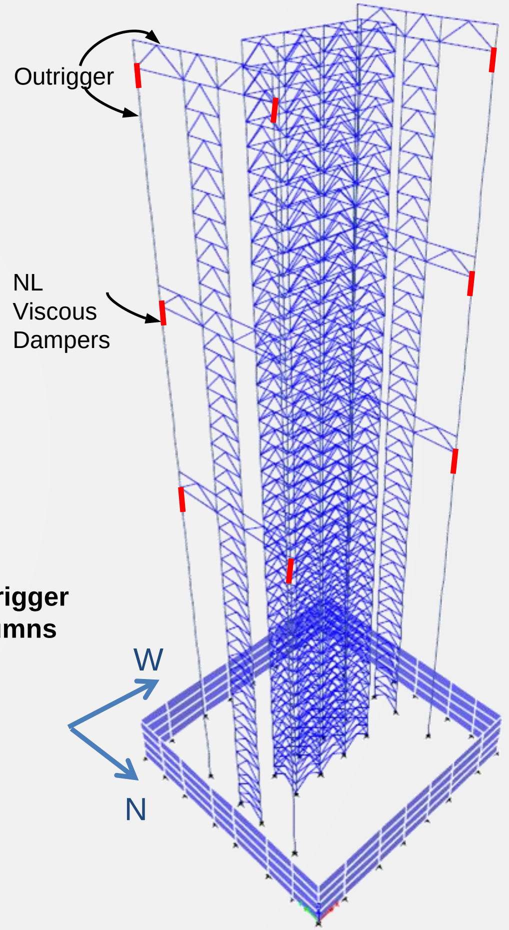
E-Defense Shake Table Testing

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 wind natural hazard
- Online model updating – explicit-based NL Maxwell model



Floor Plan



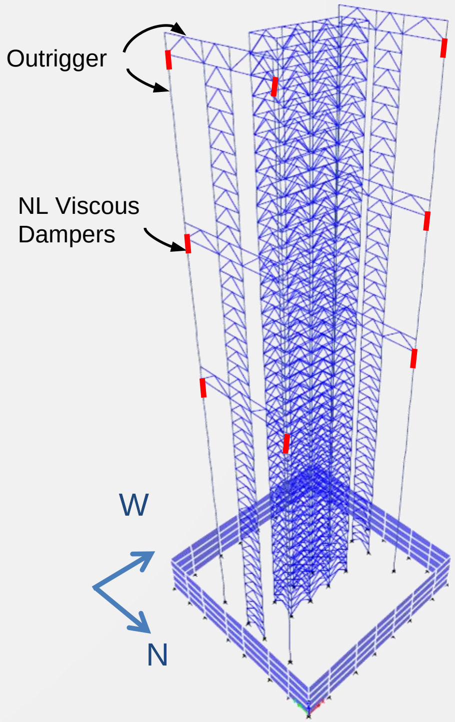
[1] Moehle et al., PEER 2011/05

Al-Subaihawi, S., Kolay, C., Thomas Marullo, Ricles, J. M. and S. E. Quiel, "Assessment of Wind-Induced Vibration Mitigation in a Tall Building with Damped Outriggers Using Real-time Hybrid Simulations," *Engineering Structures*, submitted for preparation, 2019.

Kolay, C., Al-Subaihawi, S., Thomas Marullo, Ricles, J. M. and S. E. Quiel, "Multi-Hazard Real-Time Hybrid Simulation of a Tall Building with Damped Outriggers," *International Journal of Lifecycle Performance Engineering*, submitted for preparation, 2019.

Multi-Hazard RTHS of Tall Building – EQ & Wind

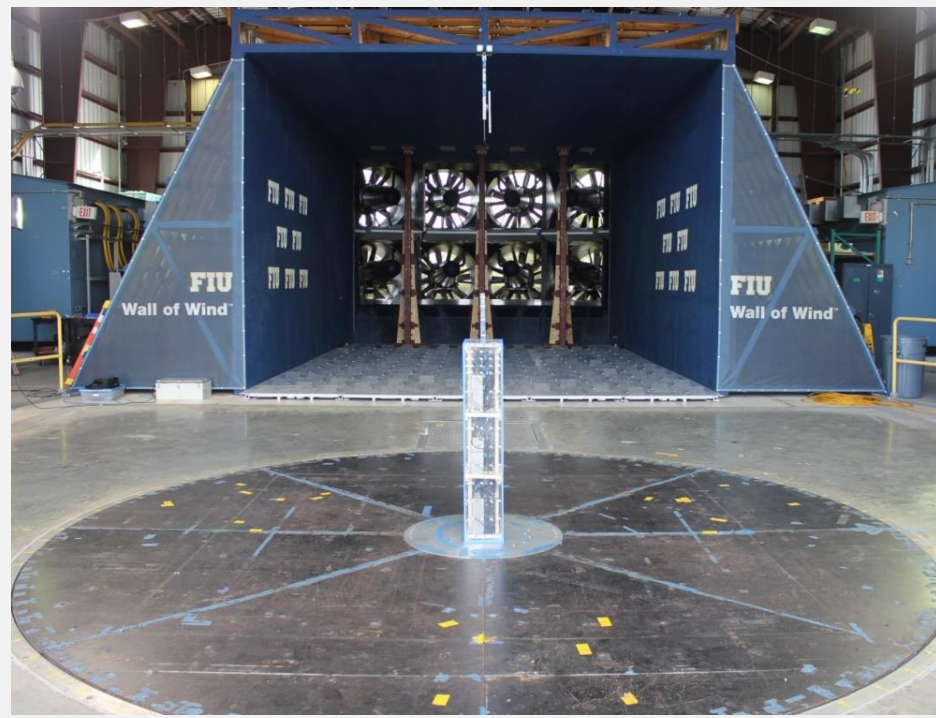
- Bidirectional EQ ground motions
  - ➢ 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to MCE (2500 year return period) hazard level
- Bidirectional wind loading
  - ➢ Wind speed of 110 mph, 700 MRI
  - ➢ Exposure B



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



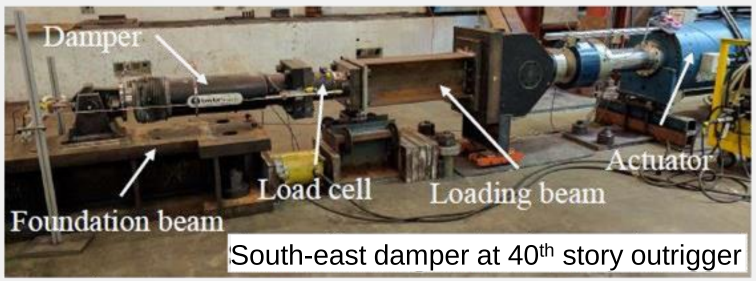
RTHS Configuration

- 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

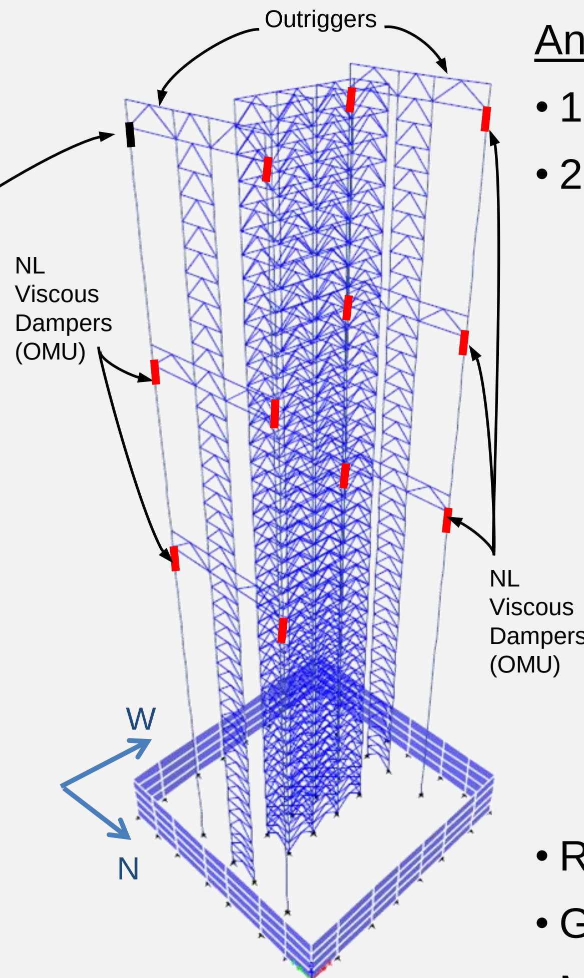
MKR-α parameter and ATS coefficients

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

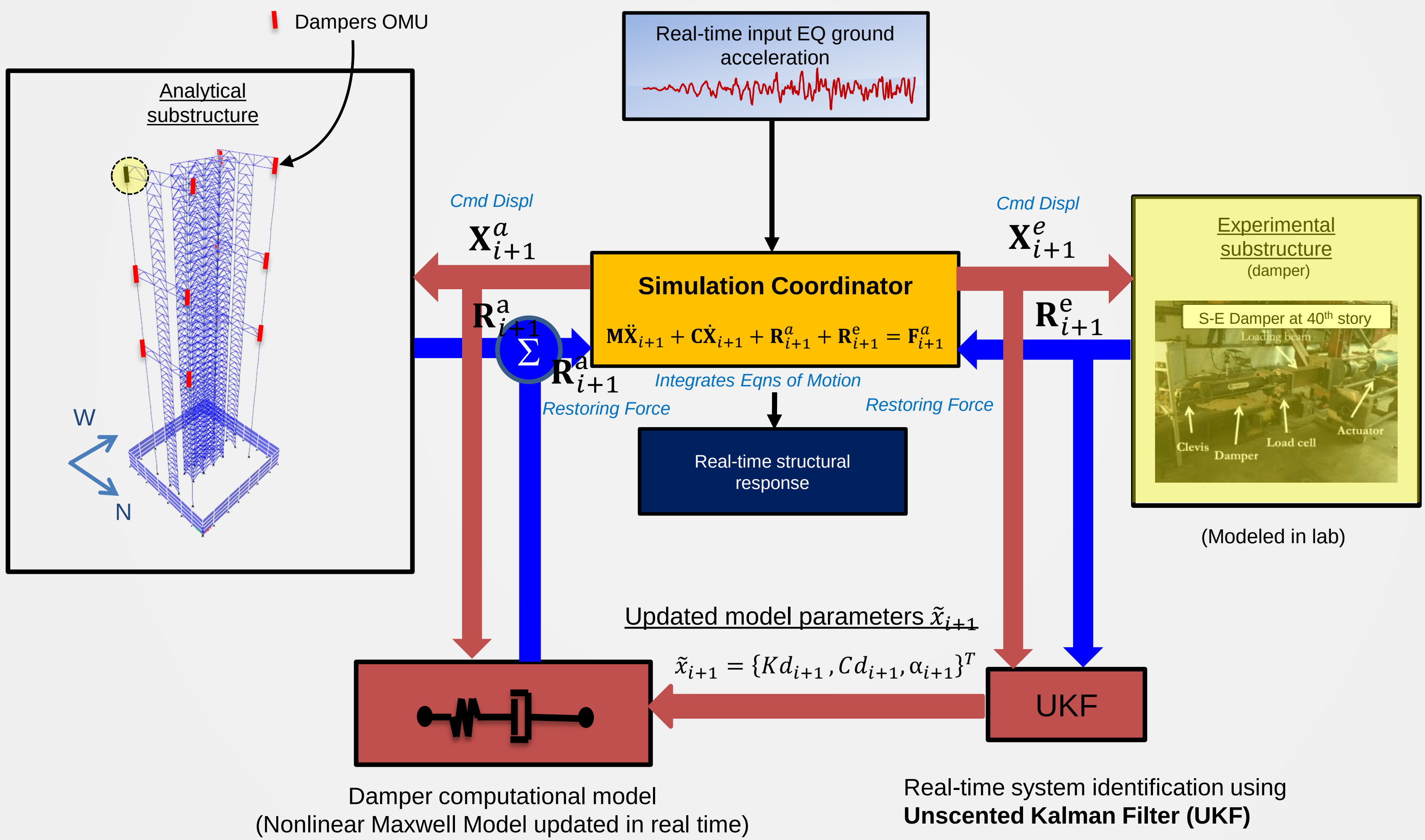
[1] Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

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

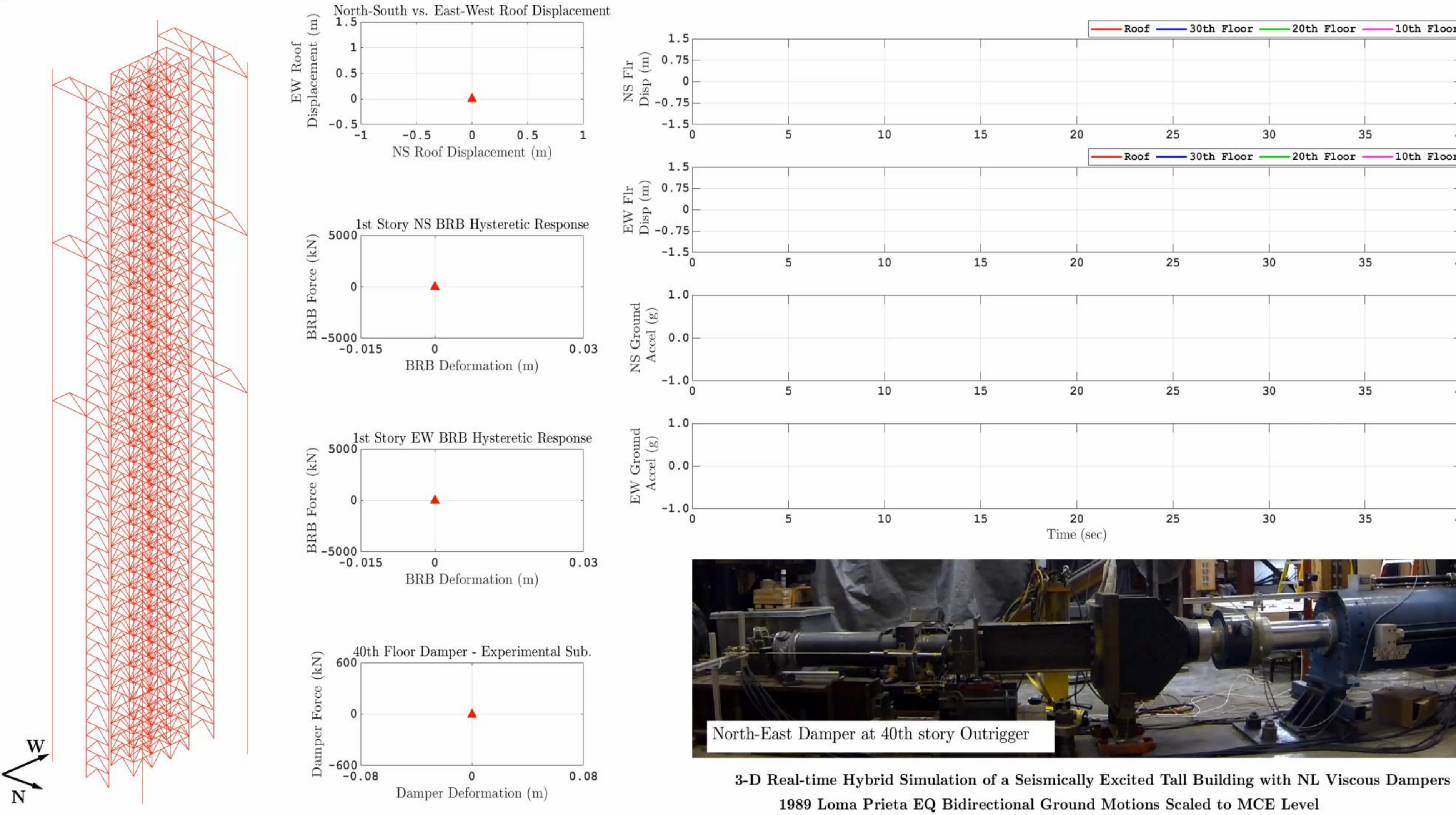
- Real-time Model Updating
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via Unscented Kalman Filter (UFK) to numerically model the 11 dampers
    - Development 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, CEE Dept., Lehigh University.

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



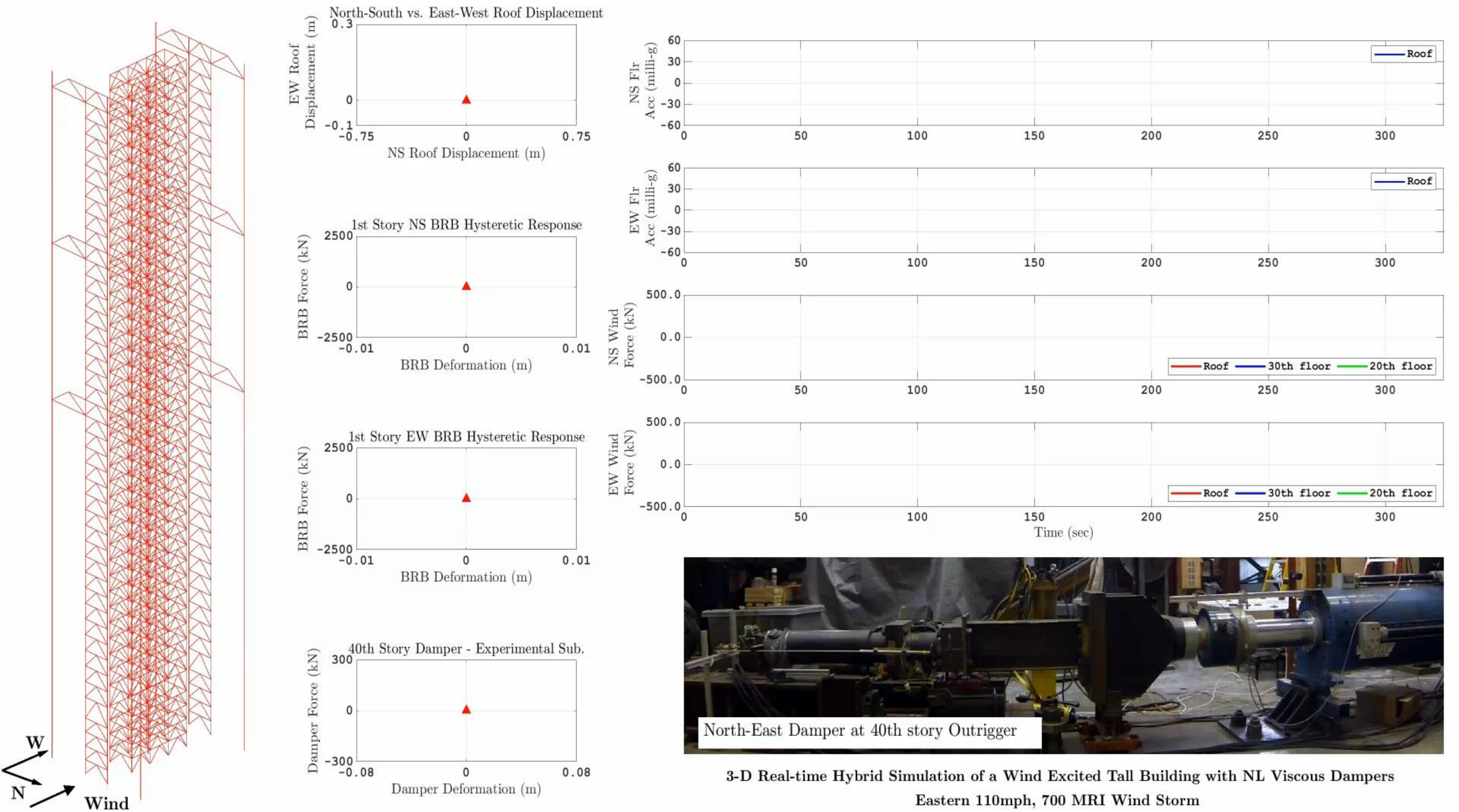
3-D Real-time Hybrid Simulation
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE



Motions scaled by factor of 5 in animation

Al-Subaihawi, S., Marullo,T., Cao, L., Kolay, C. and J.M. Ricles, (2019) "3D Multi-Hazard Real-Time Hybrid Simulation Studies of a Tall Building with Damped Outriggers".

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., Marullo,T., Cao, L., Kolay, C. and J.M. Ricles, (2019) “3D Multi-Hazard Real-Time Hybrid Simulation Studies of a Tall Building with Damped Outriggers”.

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 20^{th}, 30^{th}, 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

3-D RTHS Results: BRB Maximum Ductility

1989 Loma Prieta EQ Scaled to MCE

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

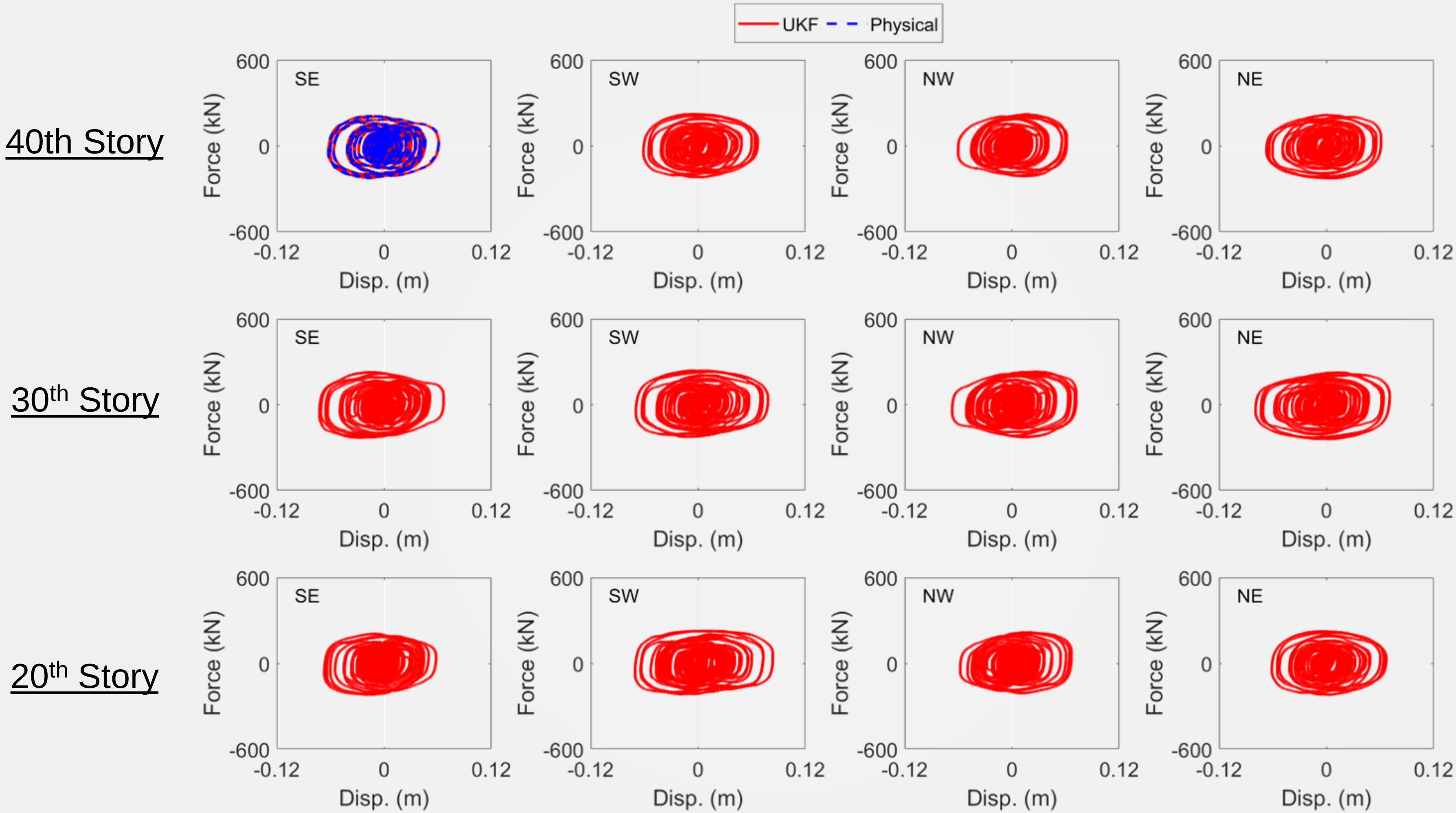
Story	No Dampers		With Dampers	
	EW	NS	EW	NS
1	3.2	3.0	3.2	2.1

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

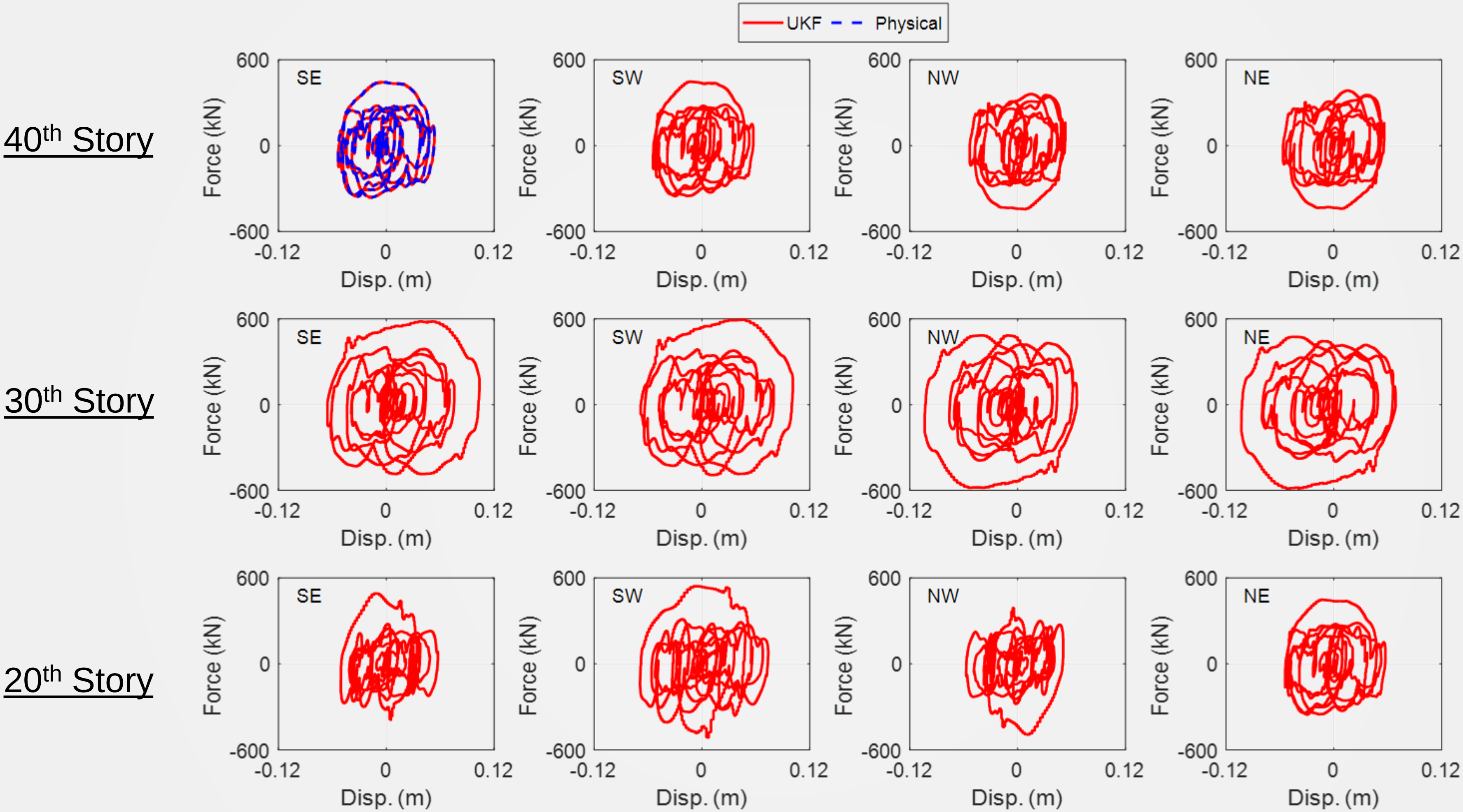
Damper Hysteretic Response – 700 MRI Wind



40th Story @ SE: Experimental Substructure

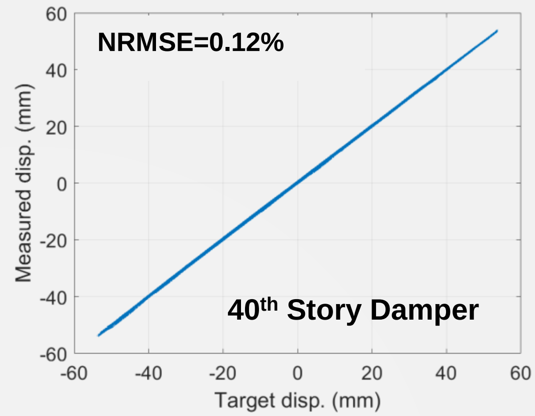
All other dampers: Real-time Model Updating is UKF

Damper Hysteretic Response – EQ MCE Level



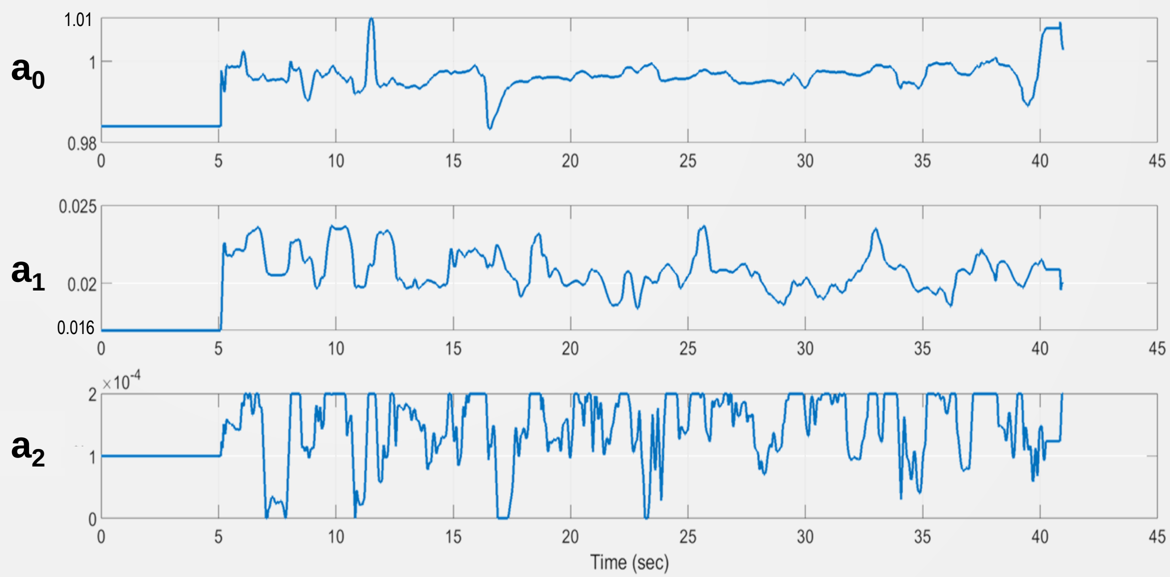
40^{th} Story @ SE: Experimental Substructure
All other dampers: Real-time Model Updating is UKF

Actuator Control – Loma Prieta EQ @ MCE RTHS



Synchronized Subspace Plots:
Target vs. *Measured Displacement*

Time History of Adaptive Coefficients – 40th Story Damper



Amplitude Correction

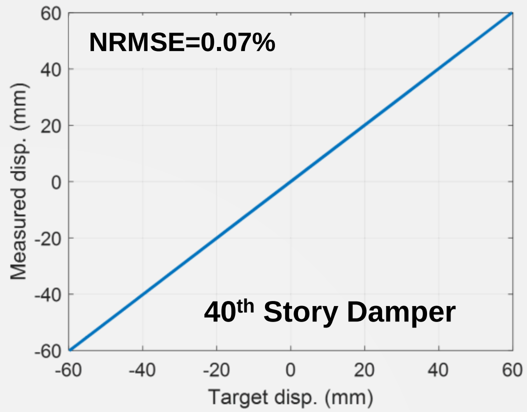
$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 0.982 \sim 1.01$$

Delay Compensation

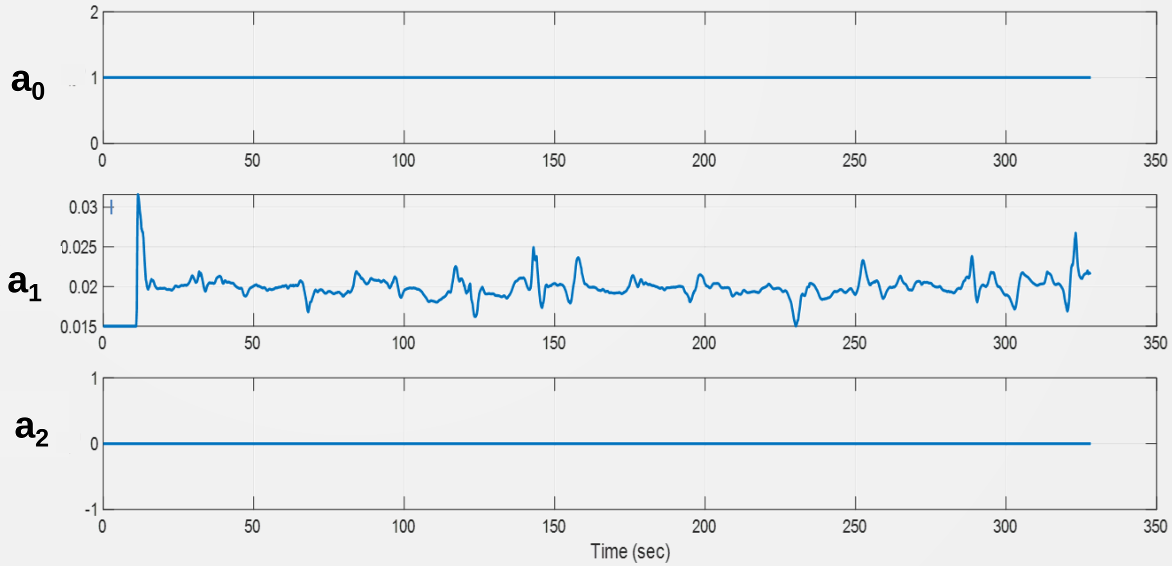
$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 16 \sim 53 \text{ msec}$$

Actuator Control – 700 MRI Wind RTHS

Synchronized Subspace Plots:
Target vs. *Measured Displacement*



Time History of Adaptive Coefficients – 40th Story Damper



Amplitude Correction

$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 1.0$$

Delay Compensation

$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 15 \sim 32 \text{ msec}$$

LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE NSF LEHIGH NHERI Real-Time Multi-Directional Testing Facility

Thank You