NHERI Lehigh EF Example Research Projects

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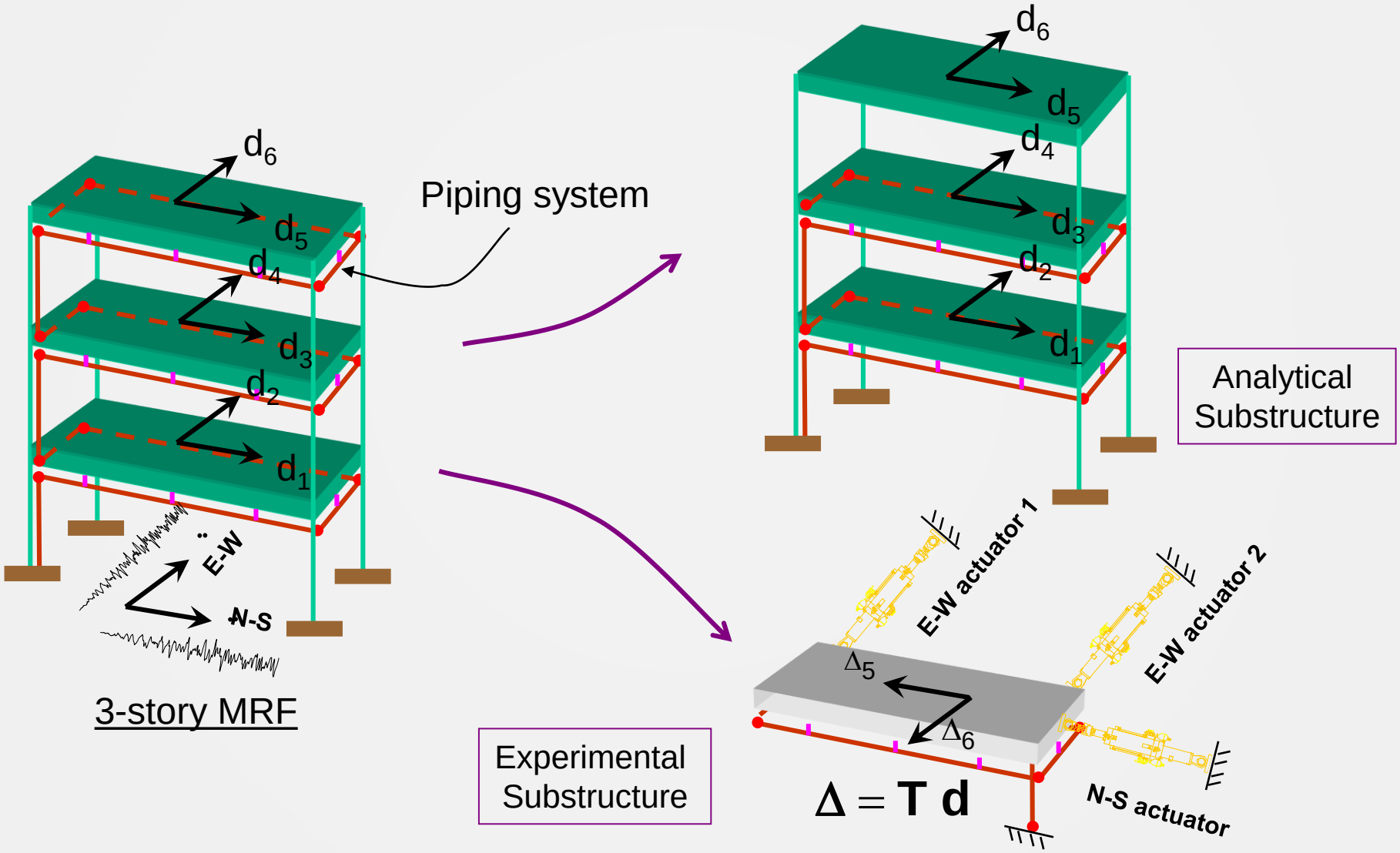
NHERI Lehigh EF Research Scientist

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) 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

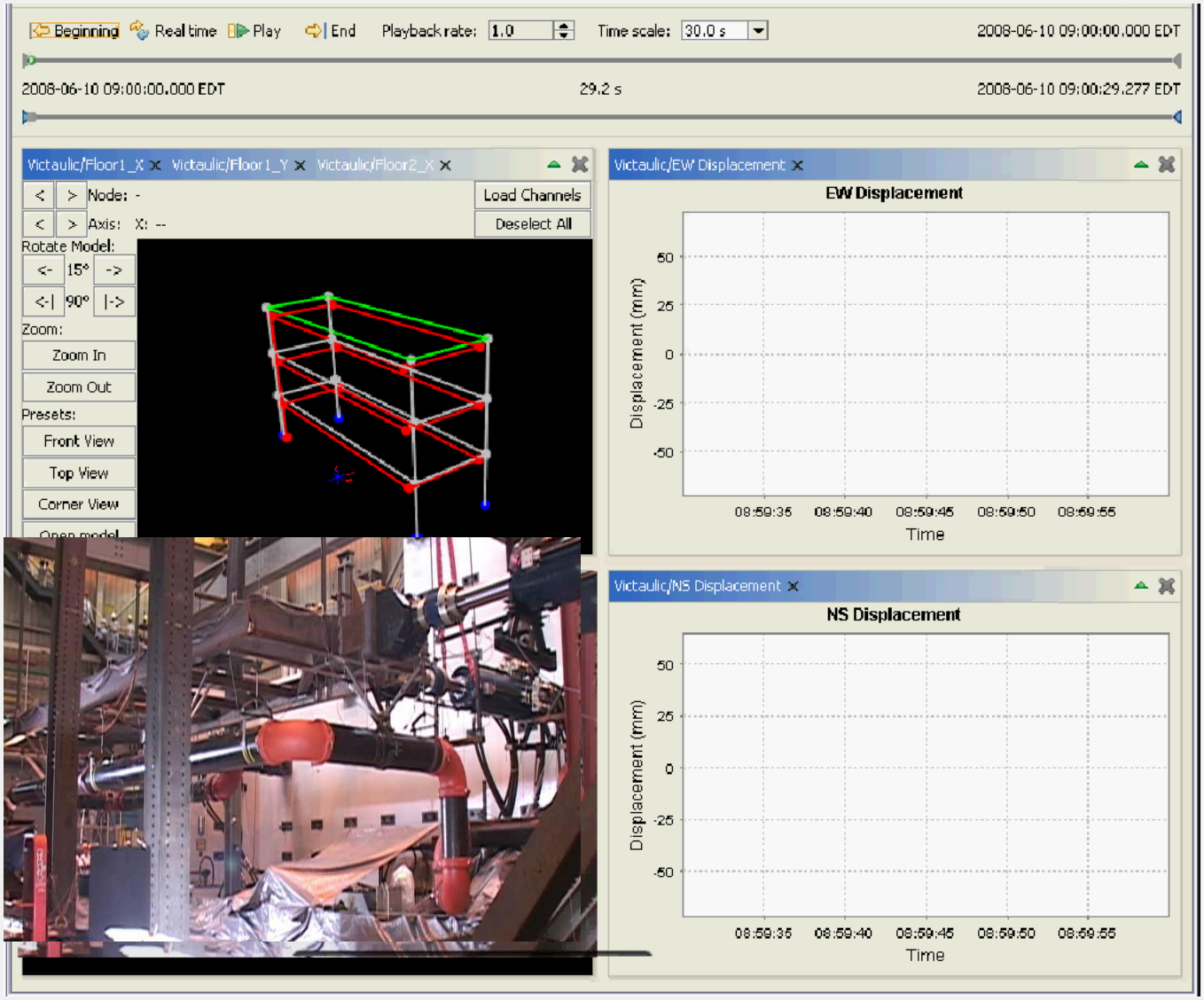
Multi-Directional Large-Scale Real-Time Hybrid Simulation of 3-story Building with Piping System

Multi-Directional Large-Scale Real-Time Hybrid Simulation



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

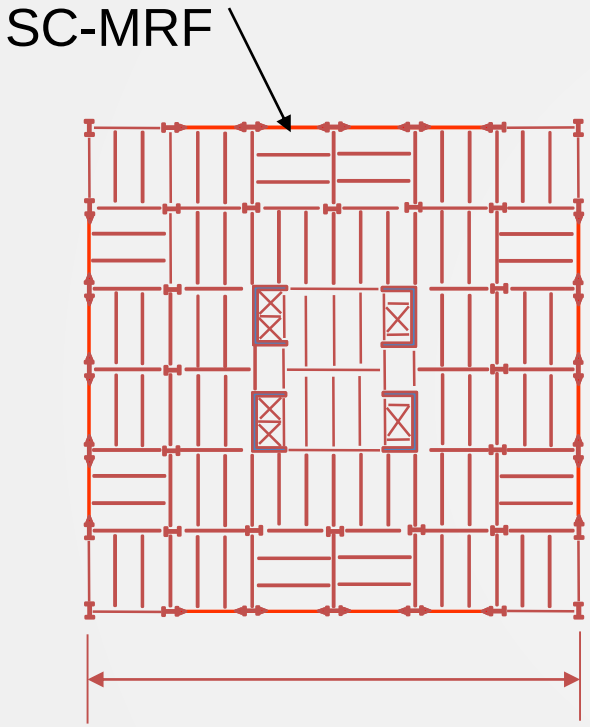
RTHS: 1994 Northridge EQ, Canogo Park (MCE)



NEES

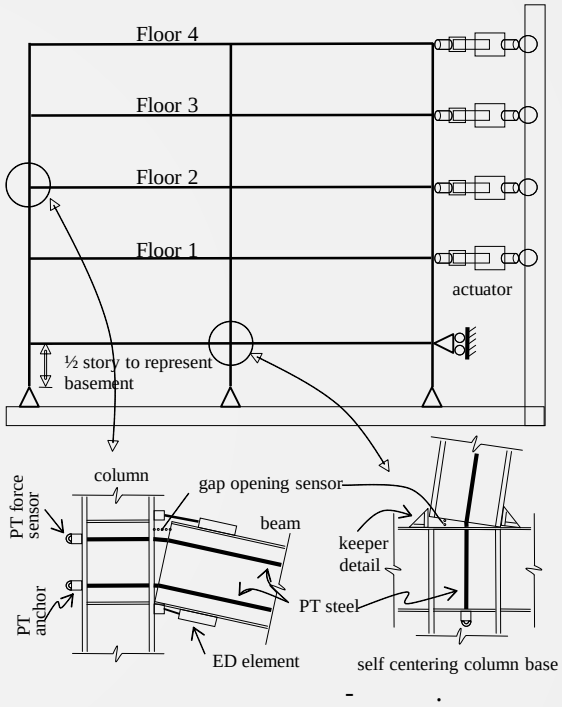
Self Centering Steel Moment-Resisting Frame (SC-MRF) Systems
Princeton, Purdue, Lehigh, NCREE

Large-Scale Hybrid Simulation



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

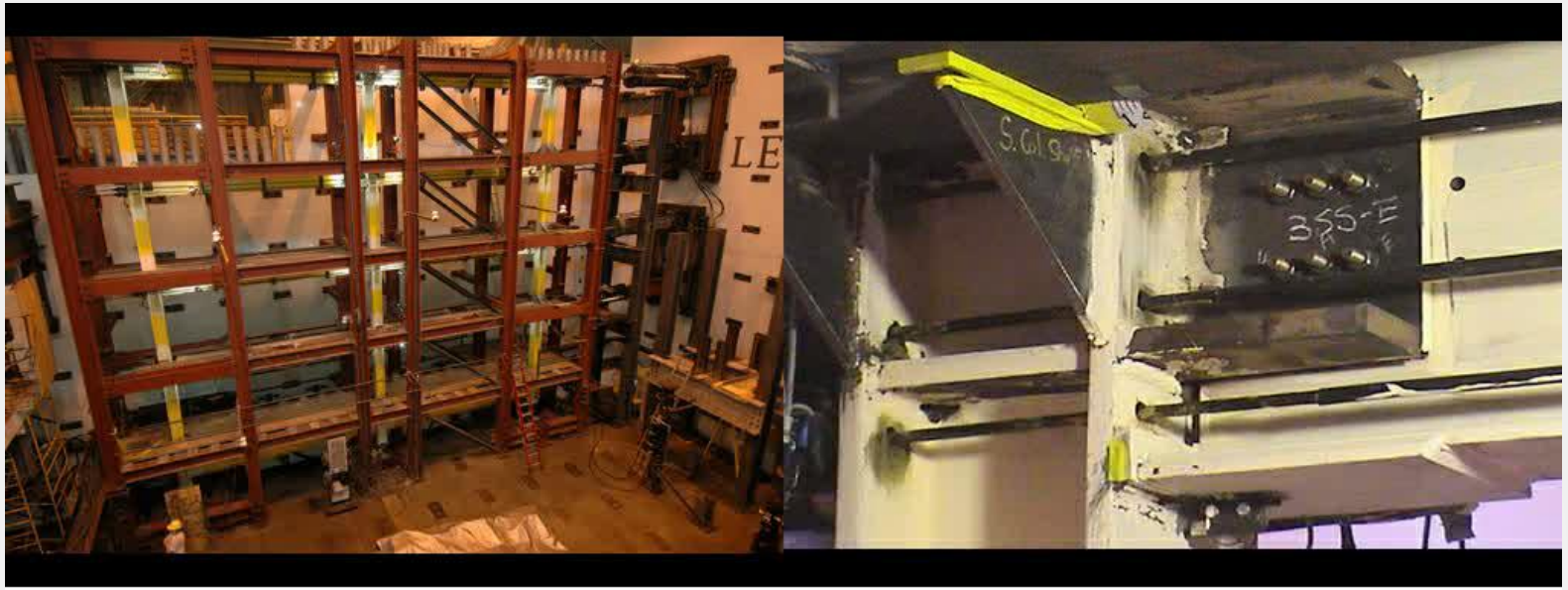
Plan of Prototype Building

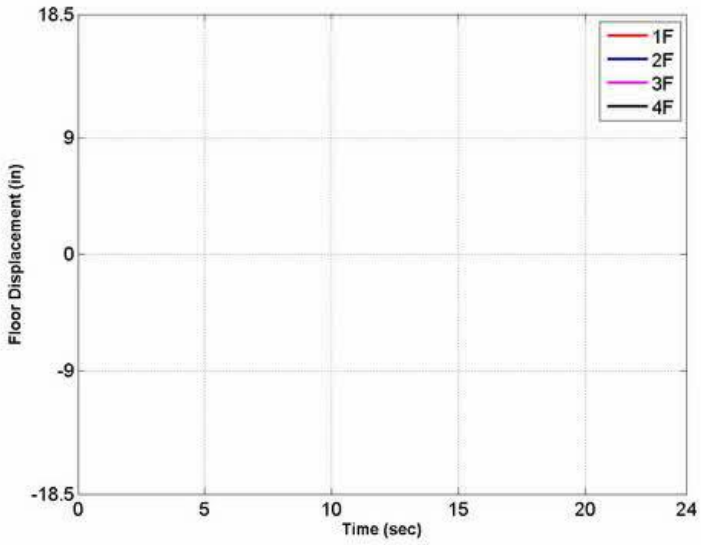


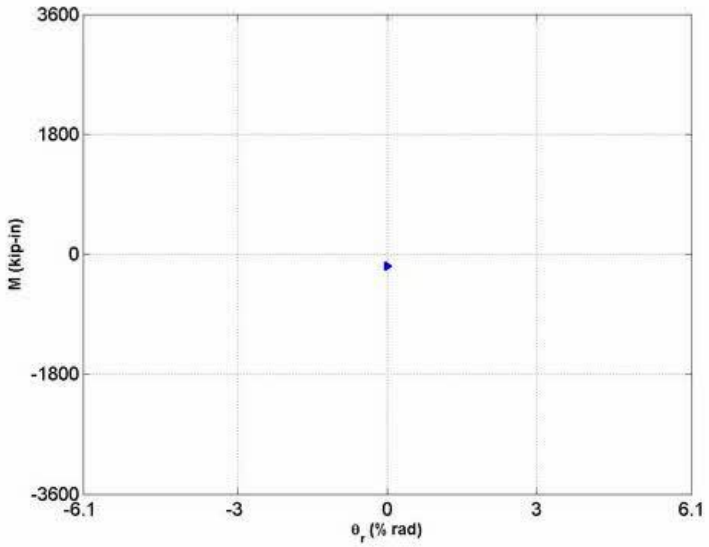
SC-MRF Experimental Substructure
(Floor Diaphragm, Gravity System, Mass, Inherent Damping in Analytical Substructure)

NEES

Large-Scale Hybrid Simulation (SC-MRF)

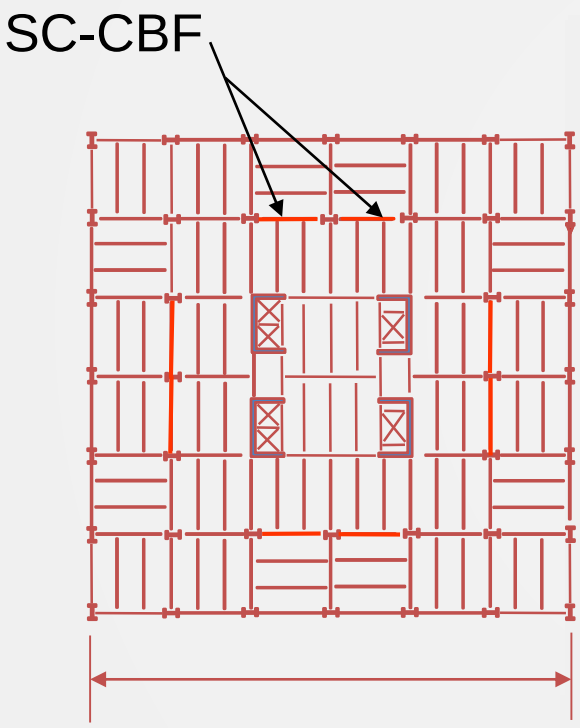






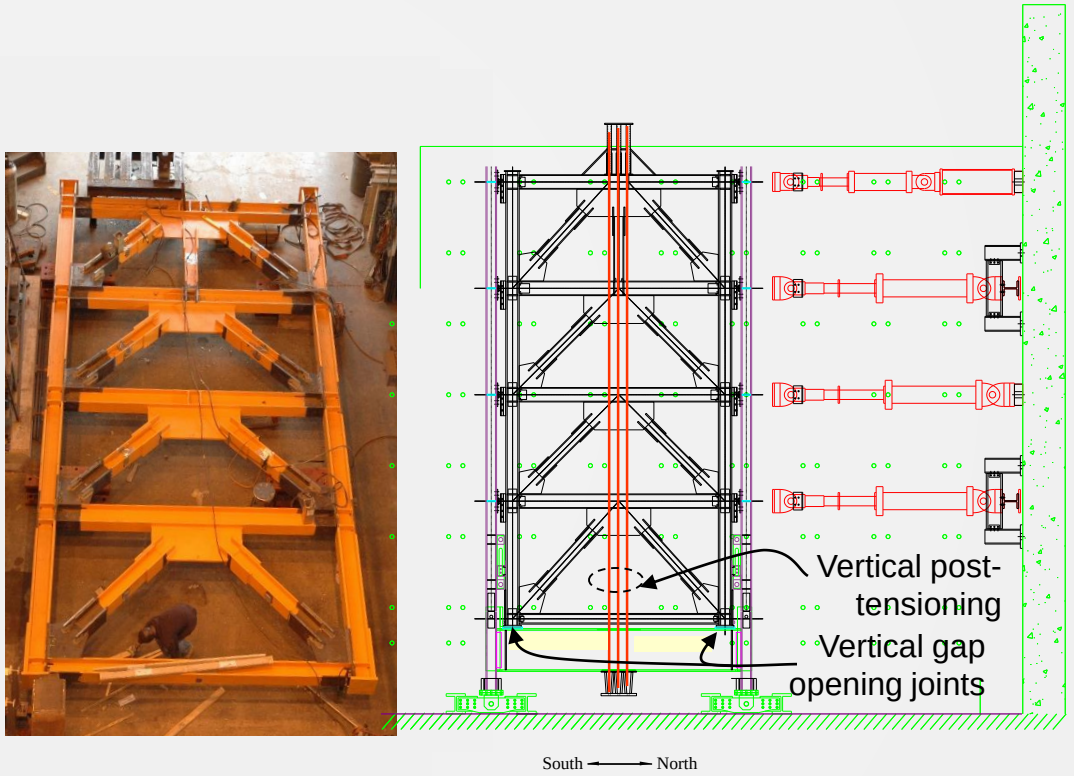
Self Centering Steel Concentrically-Braced Frame (SC-CBF) Systems
Princeton, Purdue, Lehigh, NCREE

Large-Scale Hybrid Simulation



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

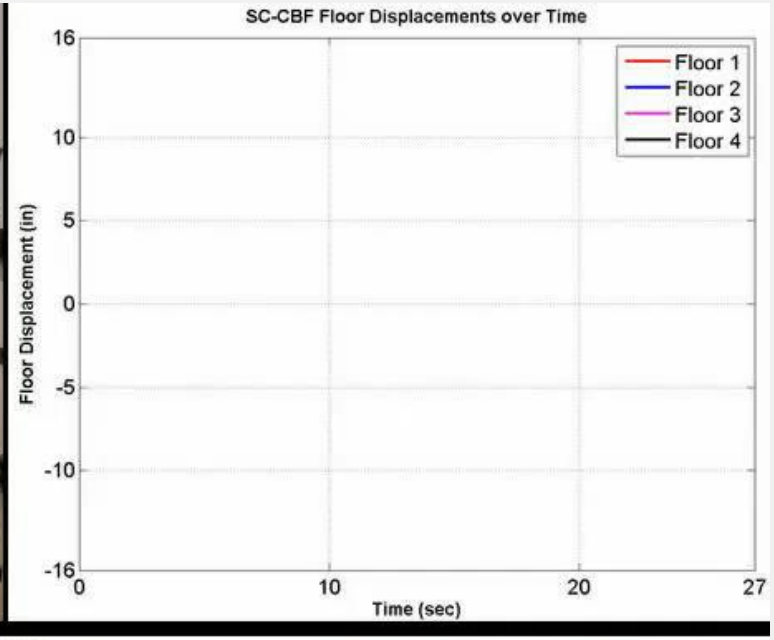
Plan of Prototype Building



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

NEES

Large-Scale Hybrid Simulation (SC-CBF)

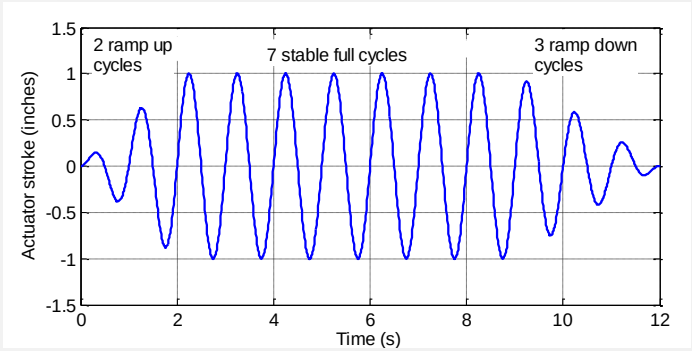


Seismic Hazard Mitigation in New Buildings Using Supplemental Passive (Nonlinear Viscous) Damper Systems

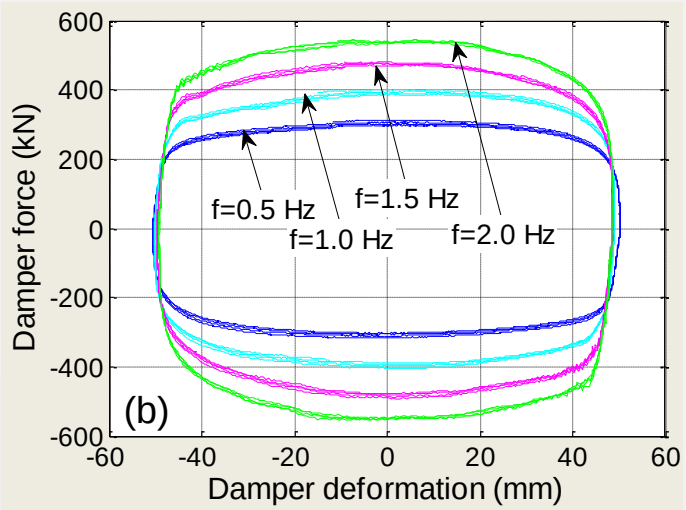
Cal State Pomona, Cal State Northridge, Lehigh

Predefined Displacement Dynamic Testing for Characterization

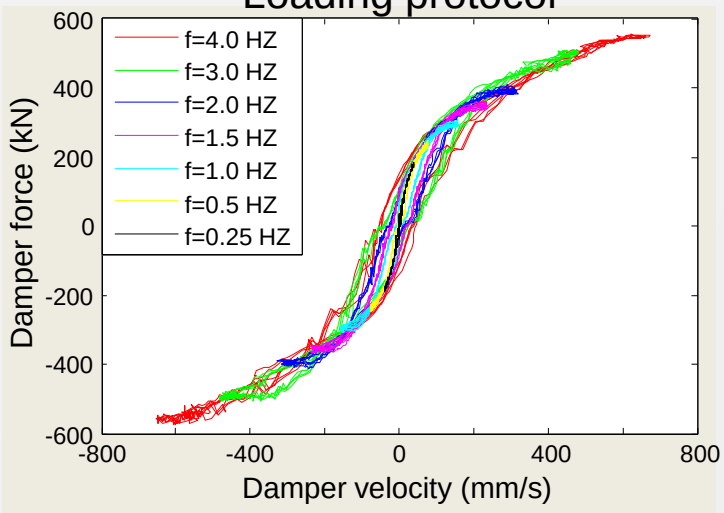
Damper testbed



Loading protocol



Damper force - deformation

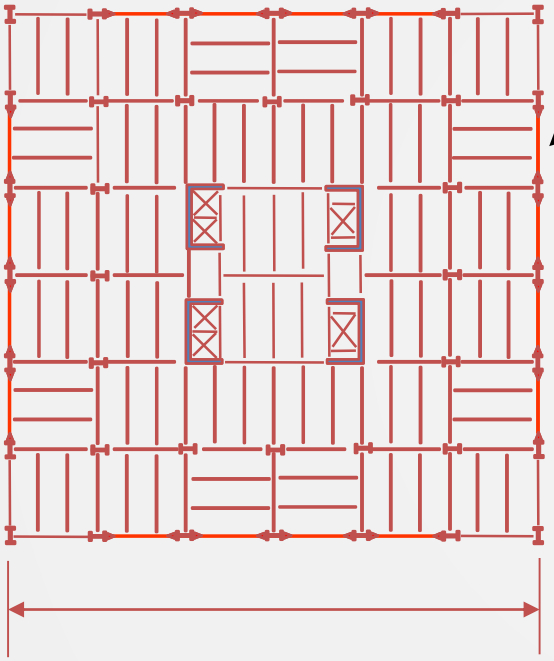


Damper force - velocity

Seismic Hazard Mitigation in New Buildings Using Supplemental Passive (Nonlinear Viscous) Damper Systems

Cal State Pomona, Cal State Northridge, Lehigh

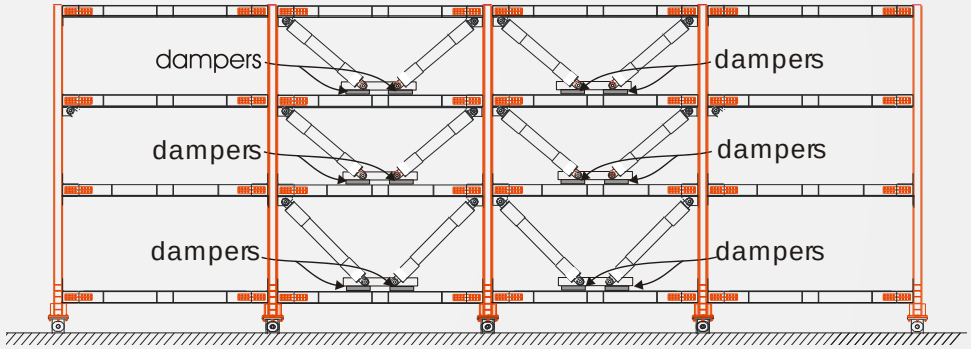
Large-Scale Real-Time Hybrid Simulation



Steel MRF with Passive Dampers

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

Plan of Prototype Building



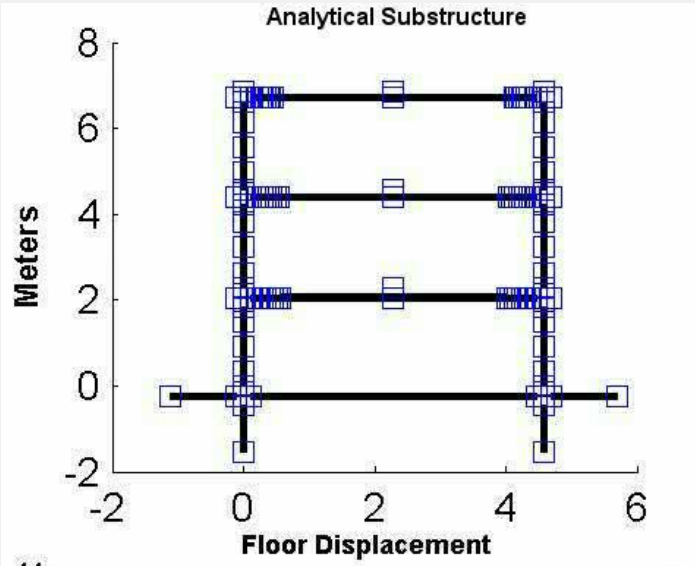
Elevation of MRF with Passive Dampers

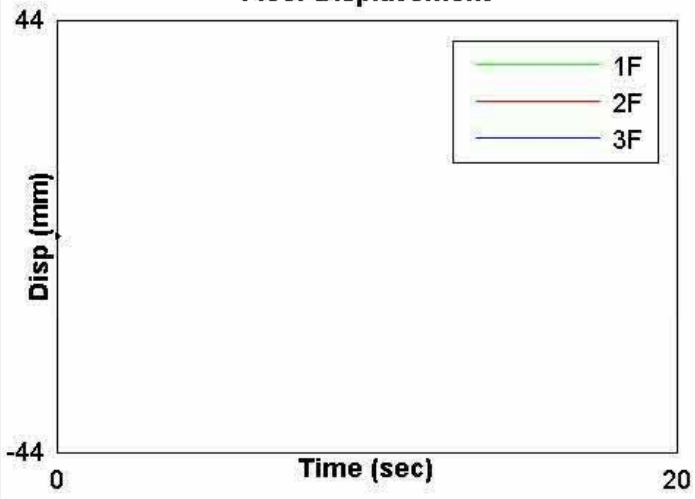
Seismic Hazard Mitigation in New Buildings Using Supplemental Passive (Nonlinear Viscous) Damper Systems

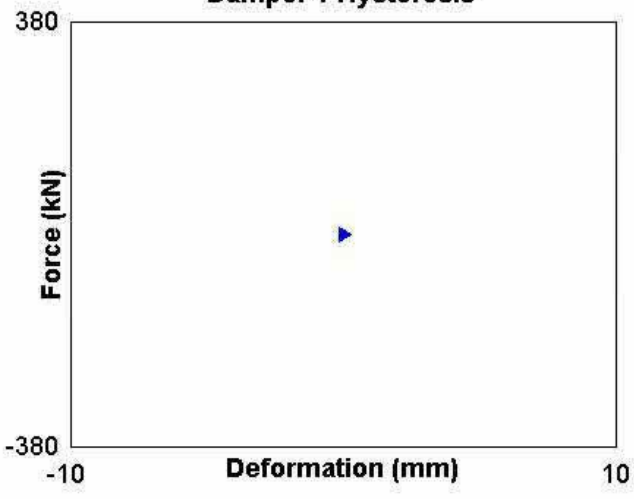
Cal State Pomona, Cal State Northridge, Lehigh

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 (Nonlinear Viscous) 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)

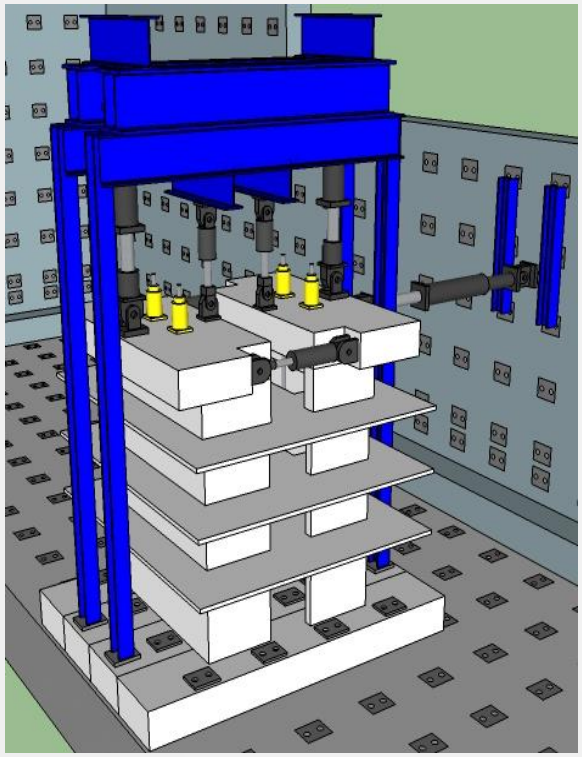
Test Setup with Cargo Shipping Container Debris

High Speed Video of Impact of Cargo Shipping Container on Structure

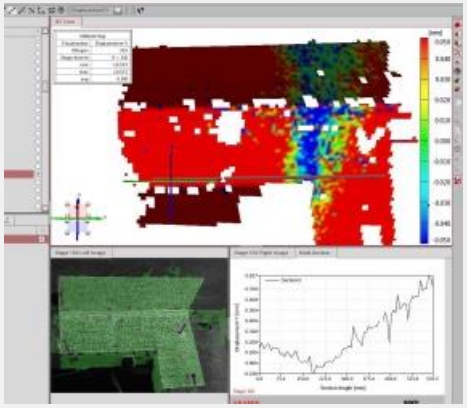
NEES

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

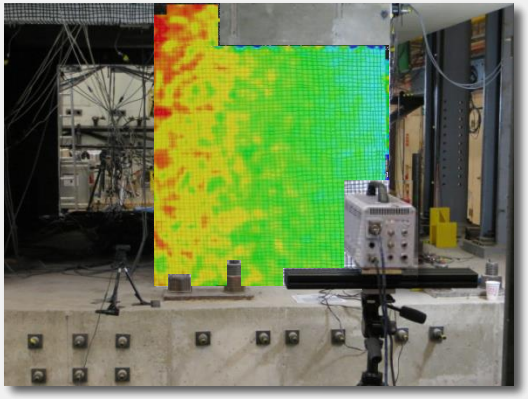
Complex Large-Scale Predefined Multi-Directional Force & Displacement (Quasi-Static) Testing



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

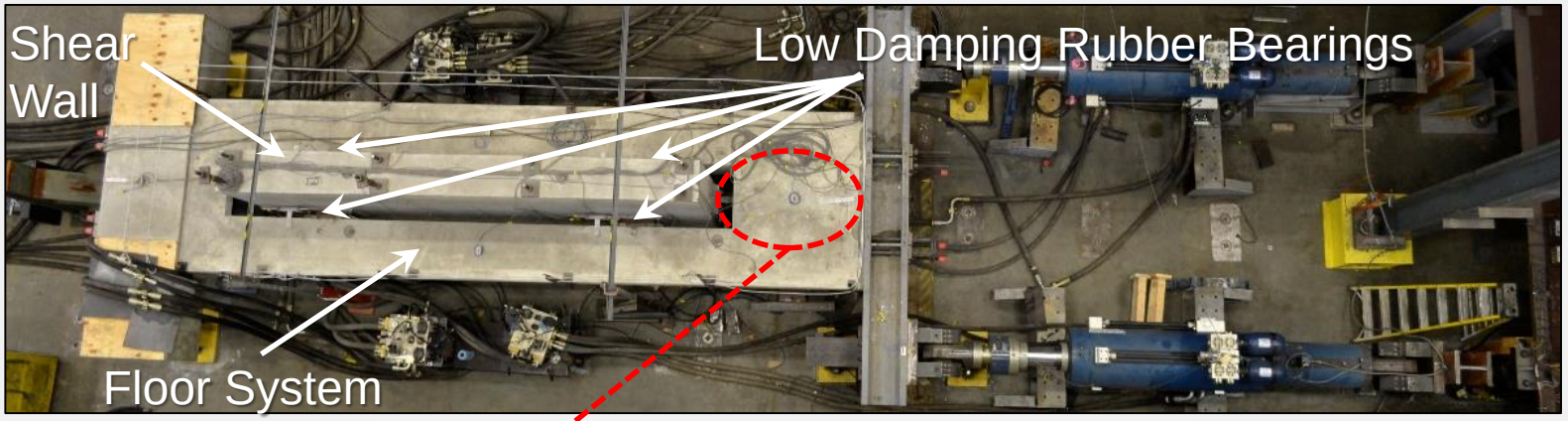
Post-Tensioned Coupled Shear Wall System
Notre Dame, University of Texas at Tyler

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

NEES

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

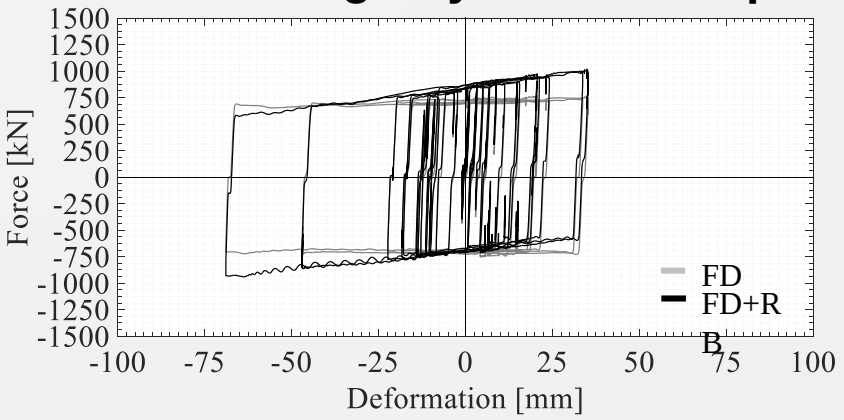
Predefined Displacement Dynamic Testing for Characterization



Friction Device for Floor Anchorage

BRB was also Studied

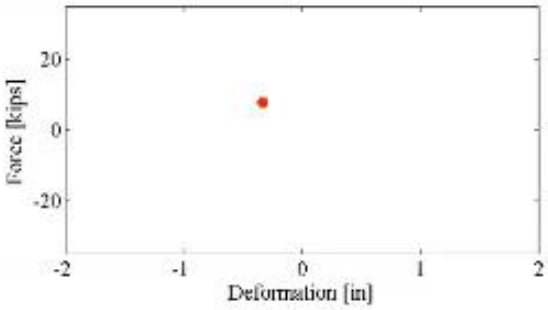
Floor Anchorage Hysteretic Response



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

Complimentary Shake Table Tests at NHERI UCSD

EQ 14: Berkeley MCE - Floor 4



THE UNIVERSITY OF ARIZONA UCSanDiego LEHIGH UNIVERSITY

Recent and 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, Soil-structure interaction
Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing, University of Oklahoma, Scott Harvey (PI)	Multi-directional Shake Table Real-time hybrid simulation; characterization testing

Recent and Current Projects at NHERI Lehigh EF

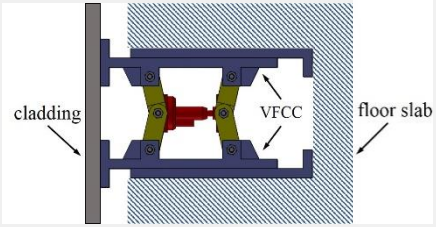
Project	Capability
Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing, University of Oklahoma, Scott Harvey (PI)	Multi-directional Shake Table Real-time hybrid simulation; characterization testing
Shear-Buckling Mechanics for Enhanced Performance of Thin Plates, PIs - Maria Garlock, Princeton University; Spencer Quiel, Lehigh University.	Large-scale quasi-static plate girder testing, digital image correction measurements
Investigation of a Novel Pressurized Sand Damper for Sustainable Seismic and Wind Protection of Buildings, PI – Nicos Makris, Southern Methodist University.	Quasi-static and dynamic characterization testing, real-time hybrid simulation; effects of temperature on damper performance
OIA 2040665 NSF Convergence Accelerator Track D: Intelligent Surveillance Platform for Damage Detection and Localization of Civil Infrastructure, PI – Claudia Marin, Howard University	Nonlinear transient analysis computational modeling, quasi-static and dynamic testing with photo imaging measurements

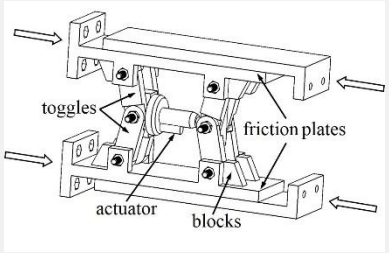
Recent Projects at NHERI Lehigh EF

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

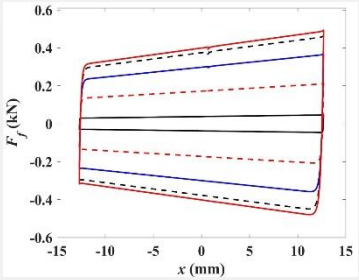
Features Using NHERI Lehigh Underlined

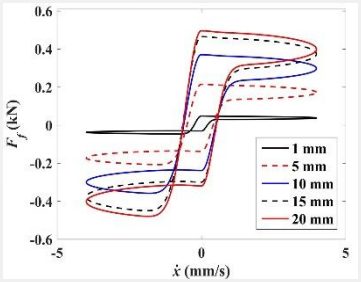
- Project Overview
  - Improve performance of buildings for multiple hazards using semi-active controlled variable friction cladding panel connectors
  - Hazards: Earthquake, Wind (NHERI UF), Blast Loading
- Project Scope
  - Design cladding connectors and control laws
  - Construct prototype connector,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





Semi-Active Controlled Variable Friction Cladding Connector





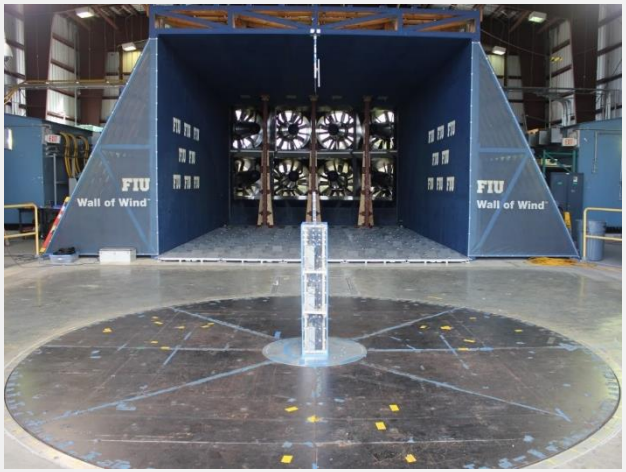
Dynamic Numerical Models

Research Projects

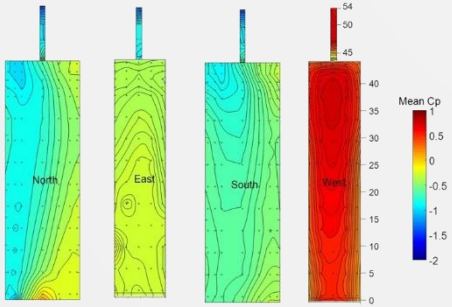
Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards

(CMMI 1463497) Lehigh University (James Ricles)

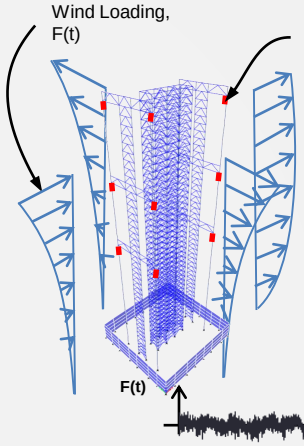
- Multiple NHERI facilities: NHERI EF at Florida; NHERI WOW EF at FIU; and NHERI EF at Lehigh

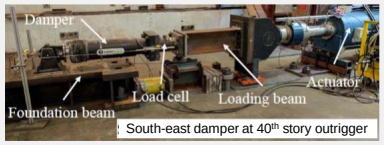


FIU wind tunnel aerodynamic model



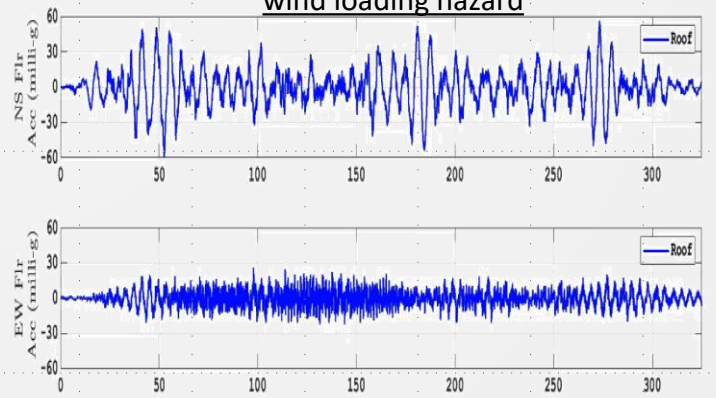
Measured mean wind pressure coefficients for 0° winds





Experimental Substructure – NL Fluid Viscous Damper

3D real-time hybrid simulation of 40-story building subject to wind loading hazard



Real-time hybrid wind simulation – roof accelerations

Research Projects

Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards

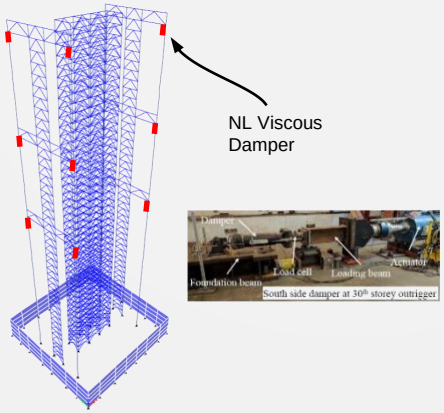
(CMMI 1463497) Lehigh University (James Ricles)

With Supplemental Dampers in Outrigger Systems for Tall Buildings

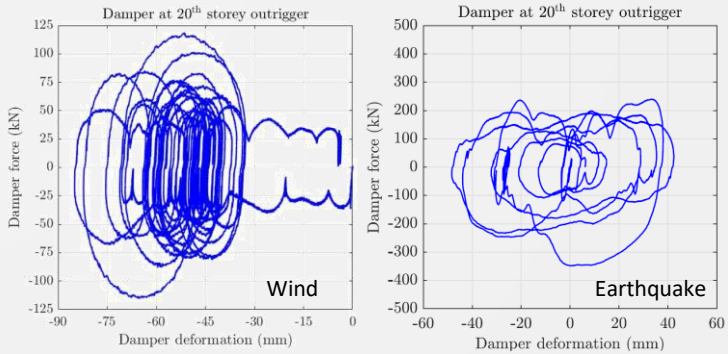
- Major Findings
  - ➢ Nonlinear viscous dampers in outrigger systems can be effective in improving multi-hazard performance of tall buildings.

Response Quantity	Reduction using passive controlled damped outriggers	
	Wind	EQ
Maximum story drift	10%	22%
Maximum absolute acceleration	35%	25%

Prototype 40-story building



3D Real-time hybrid simulation with on-line model updating



Damper force-deformation response

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, No. 2/3, pp.103–132.

Research Projects

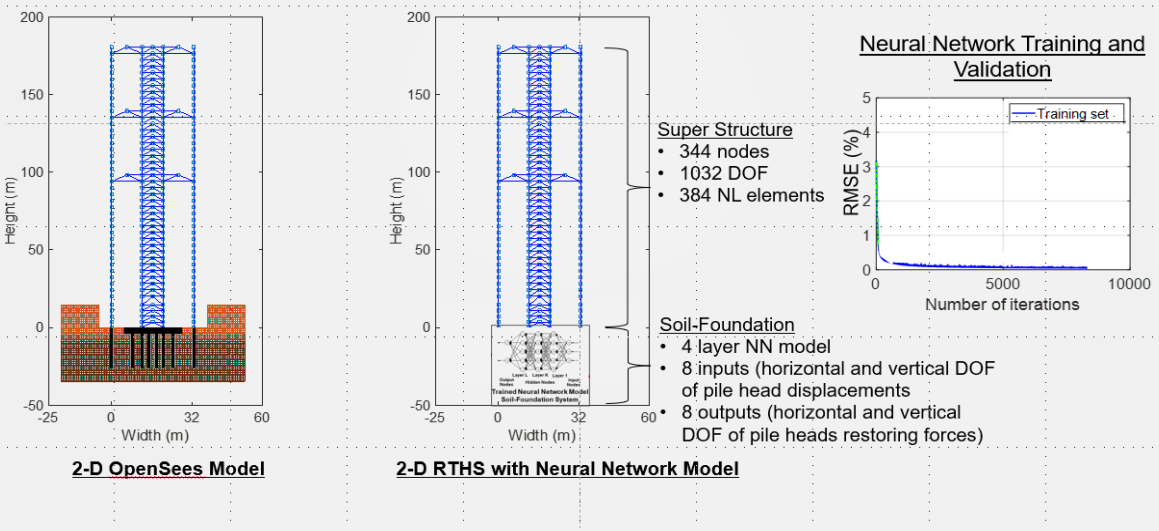
Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards

(CMMI 1463497) Lehigh University (James Ricles)

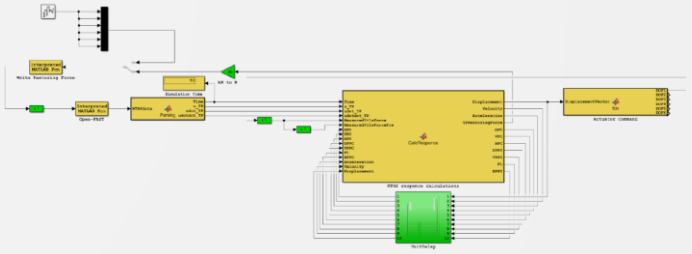
RTHS with Soil-Foundation-Structure Interaction Effects

- A neural network-based method trained using machine learning to include soil-foundation-structure interaction effects of systems in a hybrid simulation involving natural hazards has been developed to support the project.
- Overcomes the computational barrier of modeling soil and the foundation using conventional FEA (1000's DOF) in a real-time hybrid simulation.
- Performed 9 real-time hybrid simulations of a 40-story building with soil-foundation-structure interaction effects included in the experiment. Excellent results were achieved
- Outcomes include creation of tool for users; collaborating with TACC.

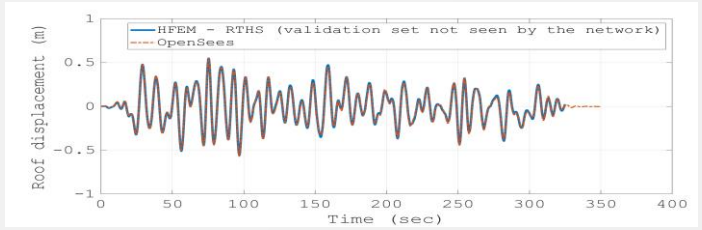
RTHS with Soil-Foundation-Structural System Interaction



Neural Network Model of Soil Training



Simulink Block – User Tool



Comparison with OpenSees

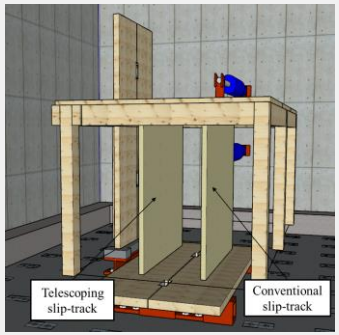
Current Projects at NHERI Lehigh EF

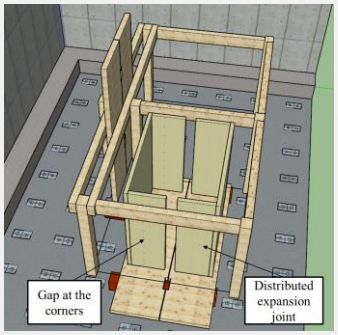
Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings

(CMMI 1635363) University of Nevada, Reno (Keri Ryan), (CMMI 1634204) University of Washington (Jeff Berman), (CMMI 1634628) Colorado State (John van de Lindt)

- 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
- Scope
  - Conduct large-scale tests of partition wall systems under in-plane & out-of-plane (bi-directional) loading (with associated vertical motion)
  - Consider different partition slip track and other details to minimize damage

Features Using NHERI Lehigh Underlined





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

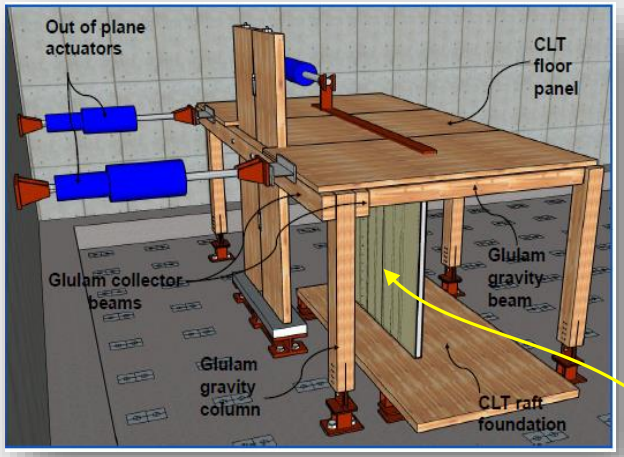
Research Projects

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

(CMMI 1635363) University of Nevada, Reno (Keri Ryan), (CMMI 1634204) University of Washington (Jeff Berman), (CMMI 1634628) Colorado State (John van de Lindt)

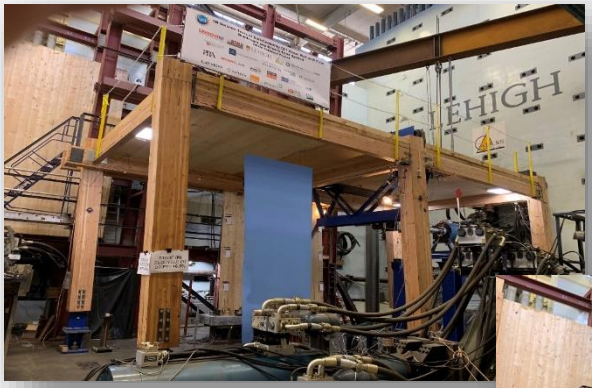
- Overview
  - Develop seismic design methodology for tall wood buildings with high-performance structural and non-structural systems
  - Determine partition wall configurations for large lateral drift with minimized partition damage
- Scope
  - Conduct large-scale tests of partition wall systems under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

Features Using NHERI Lehigh Underlined

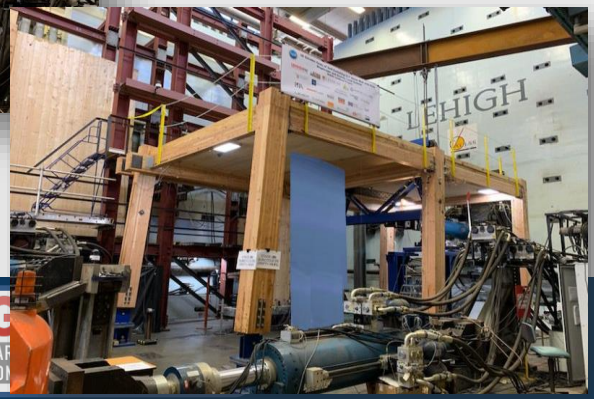


Multi-directional loading test setup

Partition wall



3D motions of subassembly



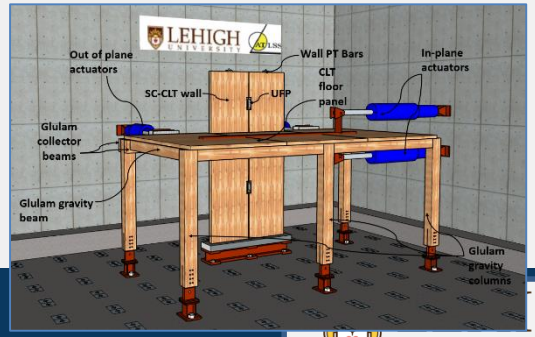
LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NSF DESIG A NATURAL HAZA ENGINEERING CO

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)**

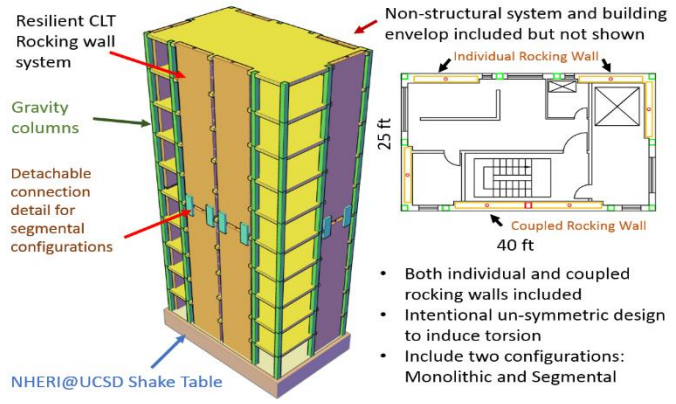
Features Using NHERI Lehigh Underlined

- 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-directiona
  - 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**

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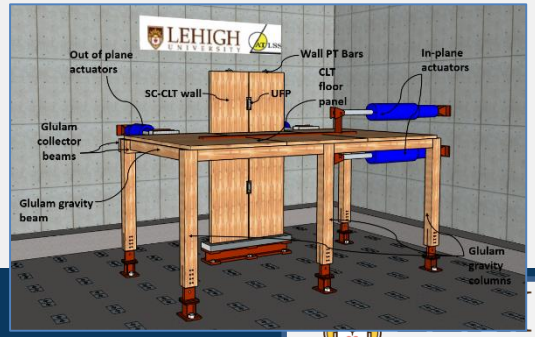
)

- Project Overview
  - Develop seismic design met
    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-directior
  - Project is supporting wo
    table tests (CSM, S. Pei



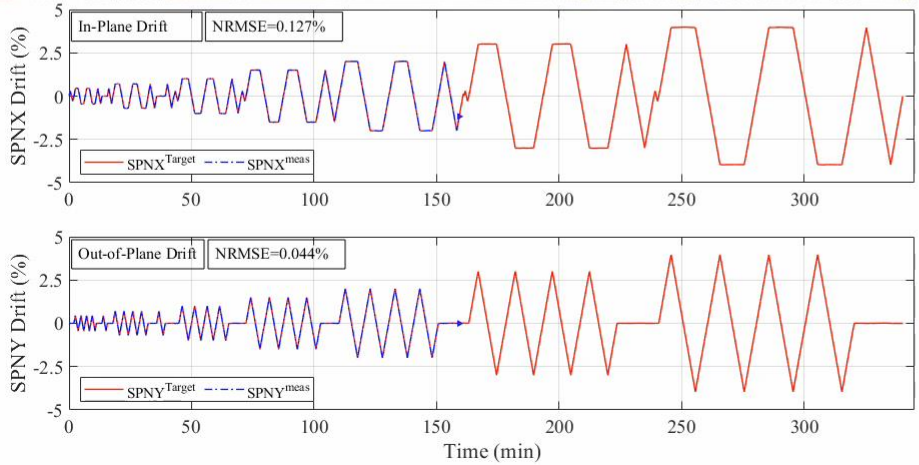
Test Phase
Phase I
Phase I.1-S
Phase I.2-S
Phase II
Phase II.1-S
Phase II.2-S
Phase III

Test setup for subassembly testing

Test plan for subassembly testing

Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings

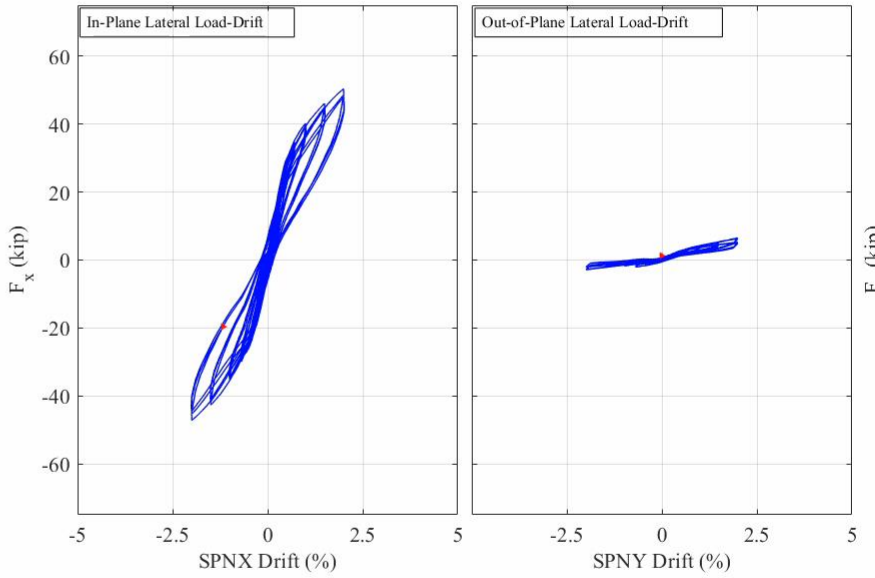
Experimental Substructure (0.625-Scale)



Comparison of Target vs. Measured Subassembly Drift

South Wall Panel

North Wall Panel



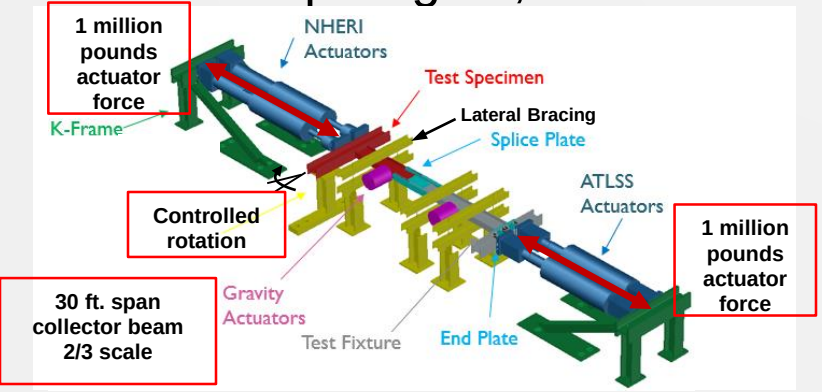
Multi-Directional Cyclic Testing of CLT Subassembly

Current Projects at NHERI Lehigh EF

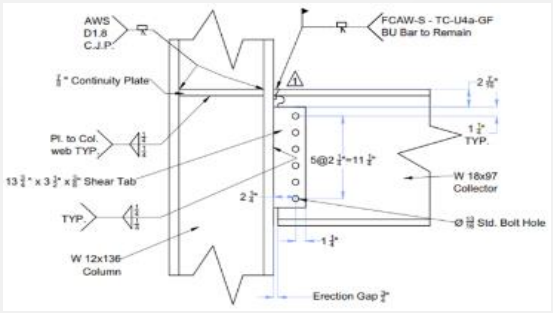
Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures: (CMMI 1662816) **University of Arizona (Robert Fleischman (PI), Chia-Ming Uang, James Ricles, Richard Sause)**

Features Using NHERI Lehigh Underlined

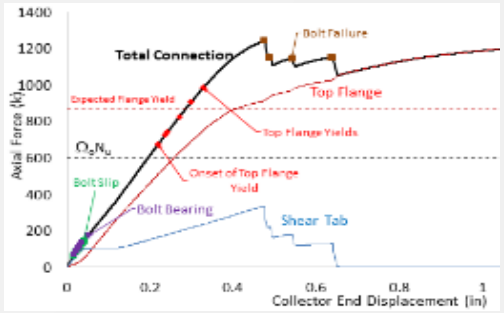
- Project Overview
  - Investigate failure-critical yet poorly understood component of steel seismic force resisting system, the seismic collector
  - FE analyses, large-scale tests and shake-table tests of floor diaphragms and collectors
- Project Scope
  - Conduct large-scale (1000k axial force plus simulated drift) tests on collector connections (tension/compr.) and members (compr.)
  - Project is supporting FE models and studies of collectors and floor diaphragms, and shake table tests at NHERI UCSD EF



Test setup for collector connection testing



Collector connection details



FE analyses

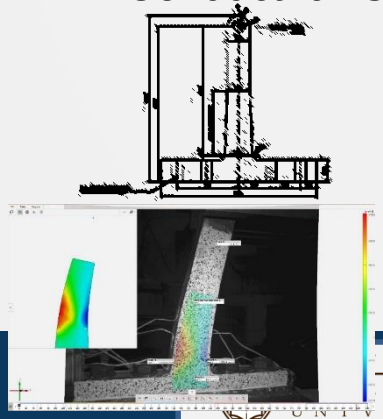
Research Projects

Collaborative Research: Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings

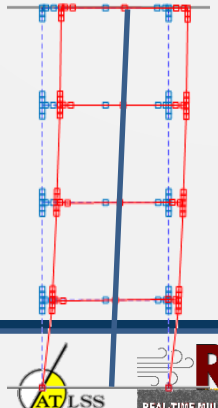
(CMMI 1928906) Univ Illinois (Larry Fahnestock), (1926365) Oregon State (Barbara Simpson), (1926326) Lehigh University (Richard Sause and James Ricles)

- Overview
  - Develop novel steel frame-spine lateral-force-resisting system with force-limiting connections to control multi-modal seismic response and protect building from damaging lateral drift and accelerations, providing resilient structural and non-structural building performance
  - International collaboration with researchers at Japanese universities and E-Defense
- Scope
  - Conduct full-scale experiments on force limiting connections
  - Develop design procedure for resilient building performance
  - Perform hybrid simulations to assess system performance and design procedure
  - Numerical studies of system to validate performance and design procedure
  - Conduct full-scale building shaking table tests at E-Defense

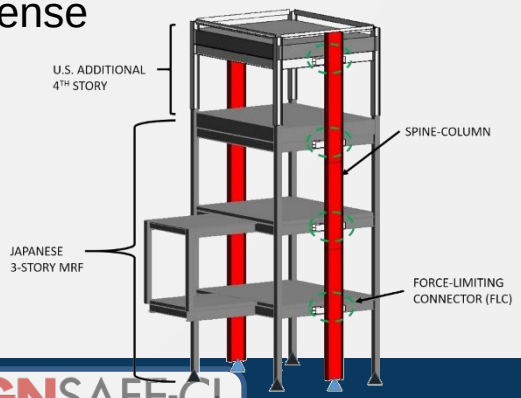
US-Japan research meetings



Lehigh EF testing of force-limiting connector



Lehigh EF Hybrid Simulations of system



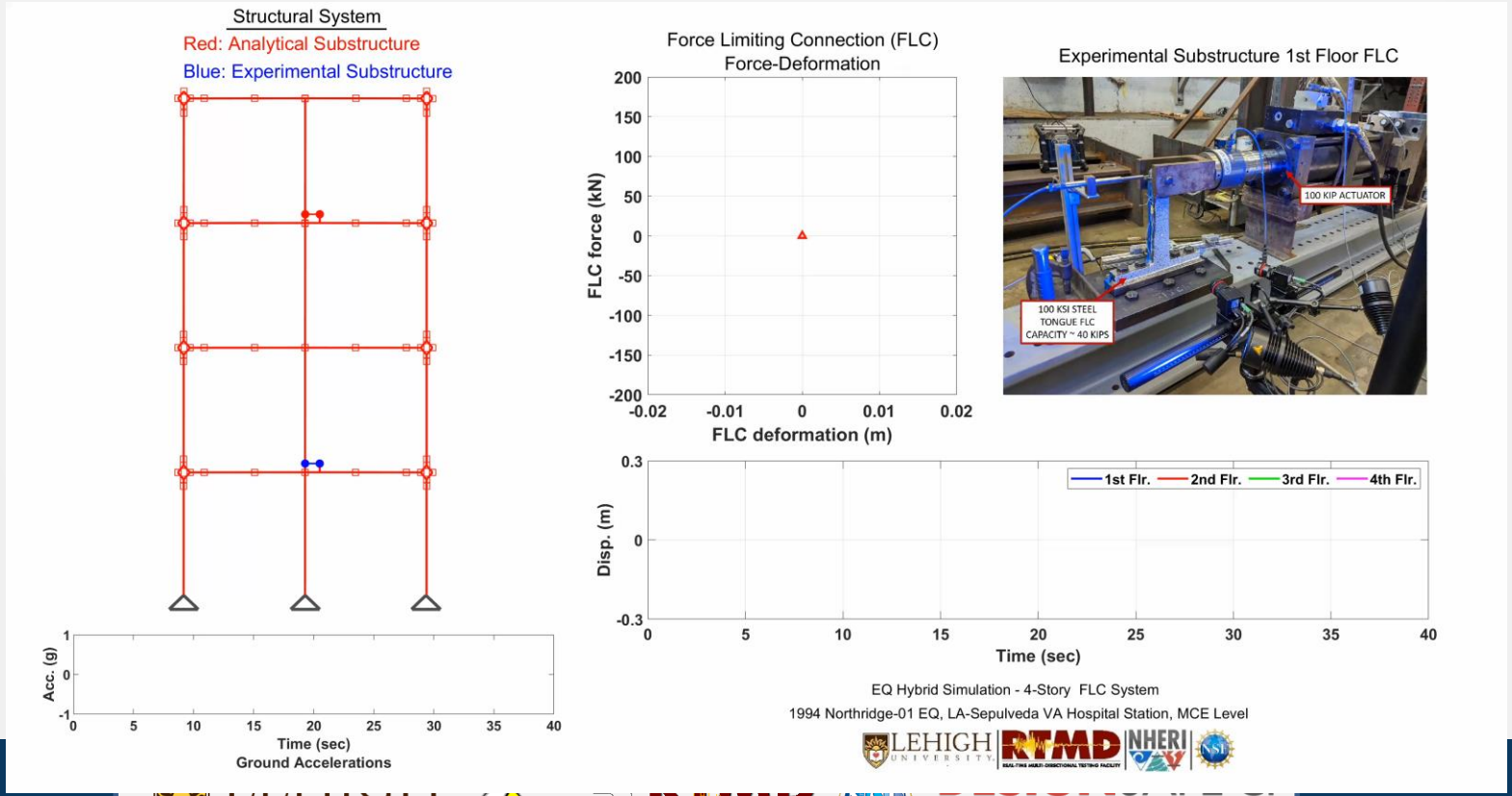
E-Defense Shake table testing of system

Research Projects

Collaborative Research: Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings

(CMMI 1928906) Univ Illinois (Larry Fahnestock), (1926365) Oregon State (Barbara Simpson), (1926326) Lehigh University (Richard Sause)

Hybrid Simulation: E-Defense MRF test structure with spine + FLCs subject to 1994 Northridge EQ, scaled to MCE level

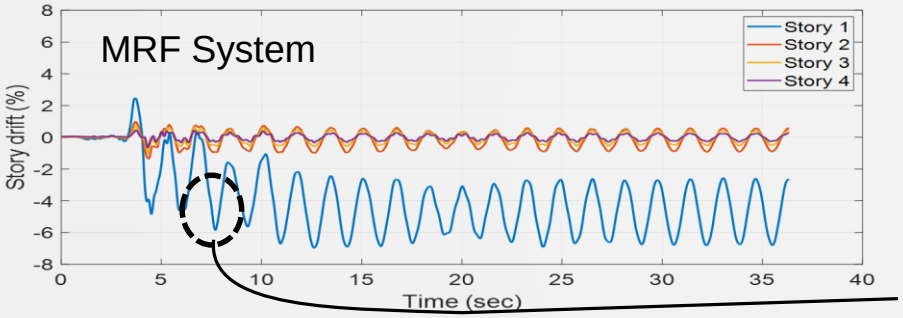


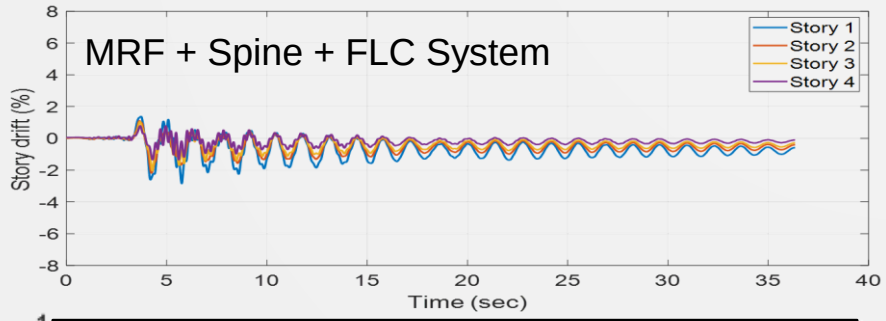
Research Projects

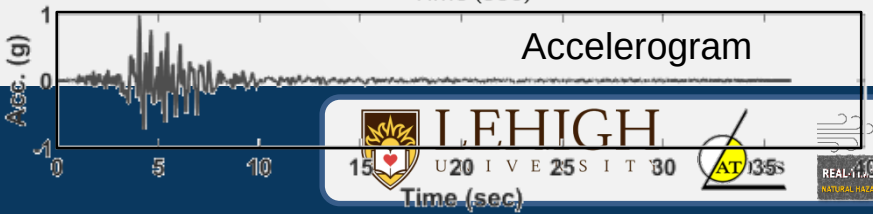
Collaborative Research: Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings

(CMMI 1928906) Univ Illinois (Larry Fahnestock), (1926365) Oregon State (Barbara Simpson), (1926326) Lehigh University (Richard Sause)

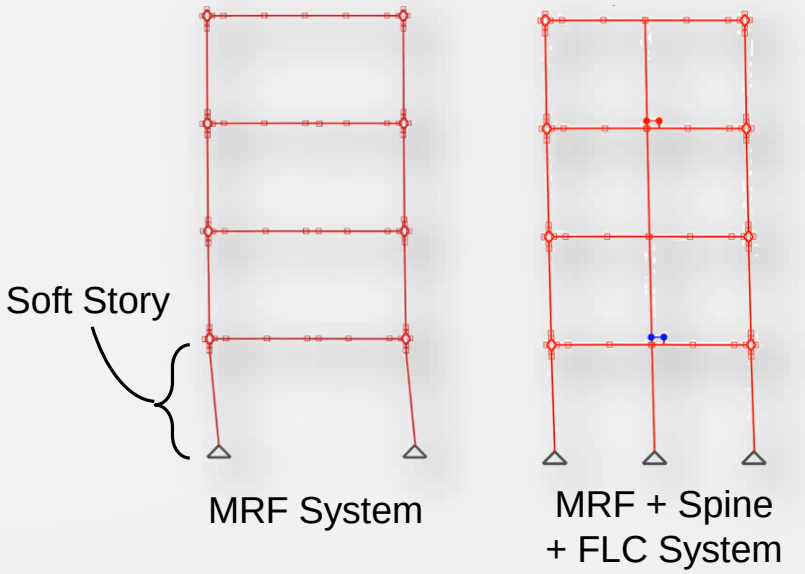
- Major Findings
  - ➢ Adding spine with FLCs to MRF:
    a. Eliminates the formation of a soft story, reducing drift and damage.
    b. Reduces lateral accelerations from higher modes.







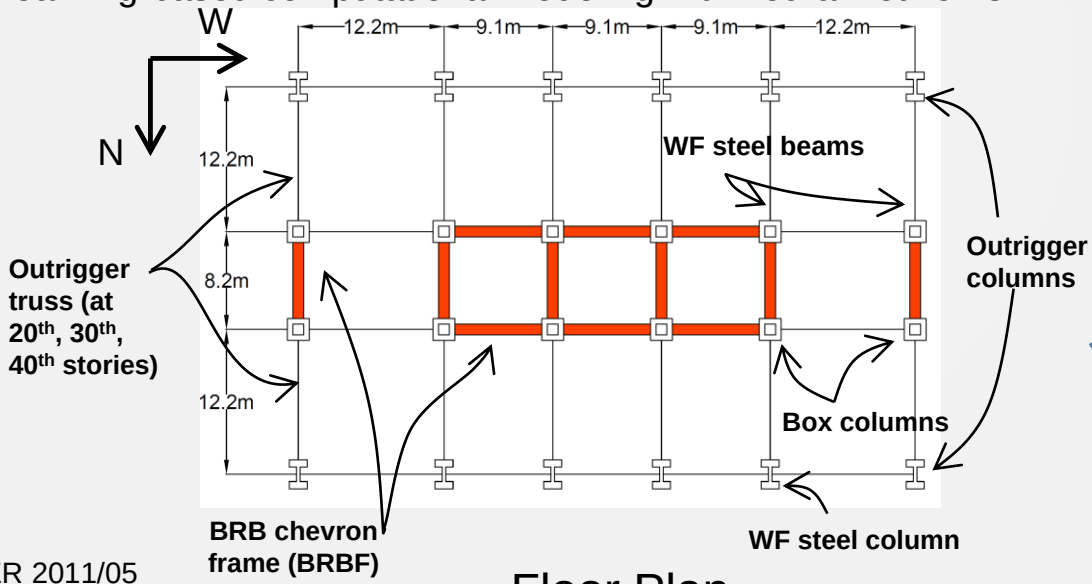
Displaced shape at maximum roof displacement



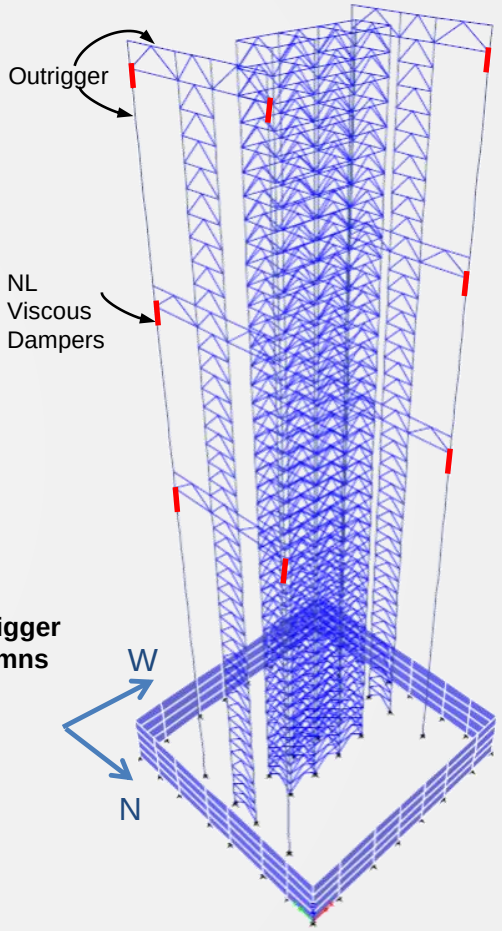
Case	Max Story Drift (% rads.)	Max Roof Accel (g)
MRF alone	6.5	1.25
MRF + spine	2.0	1.95
MRF + spine + FLC	1.9	1.62

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
- Real-time Online model updating – explicit-based NL Maxwell model
- Machine Learning-based computational modeling with neural networks



Floor Plan



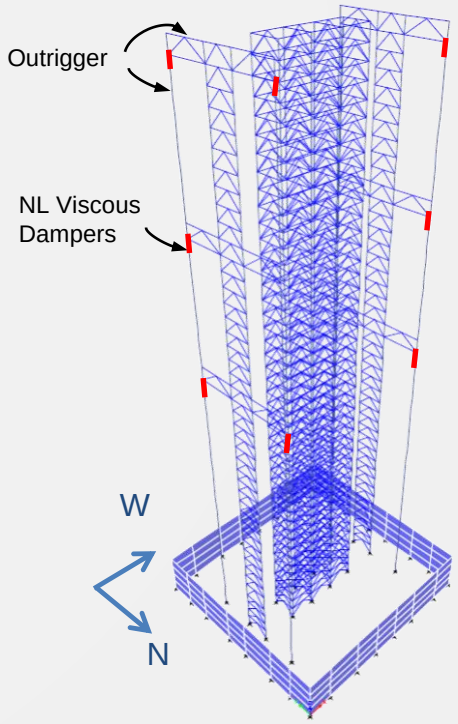
(1) Moehle et al., PEER 2011/05

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*, accepted 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*, accepted for preparation, 2019.

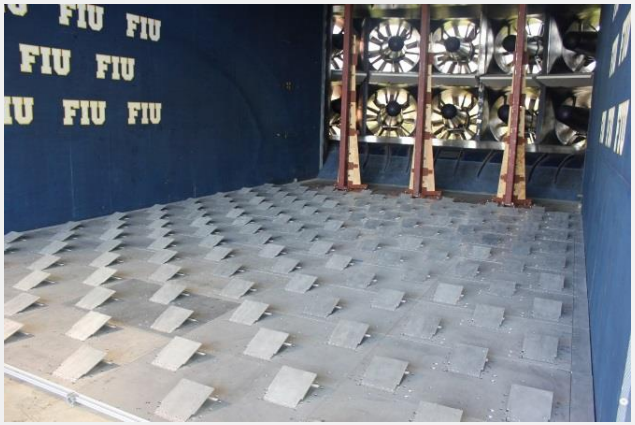
Multi-Hazard RTHS of Tall Building – EQ & Wind

- 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

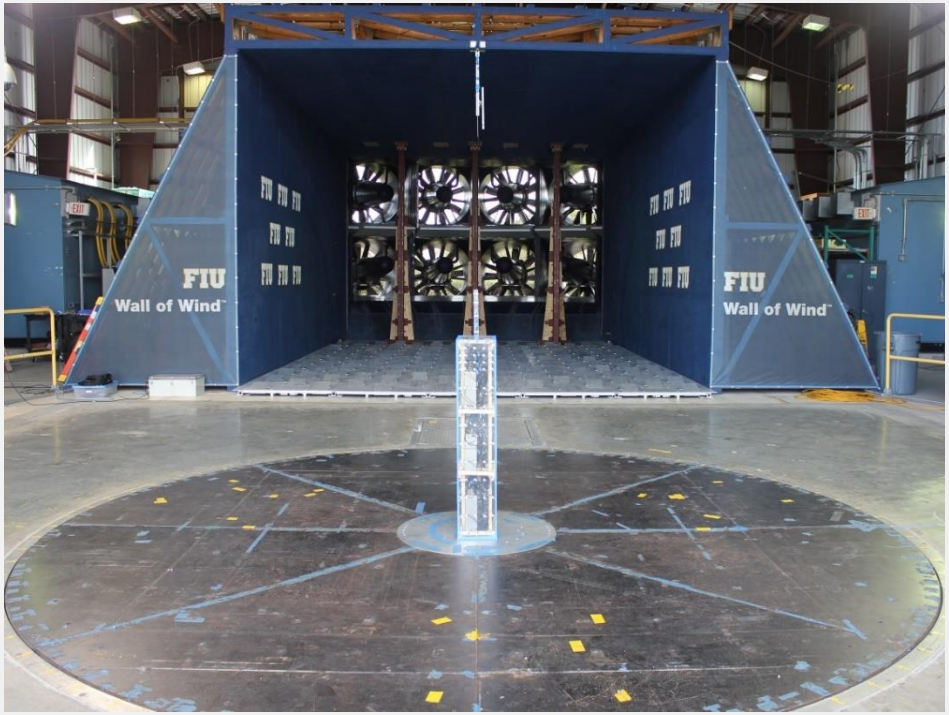


Wind Loading
Aerodynamic Wind Testing @ FIU WOW

- 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



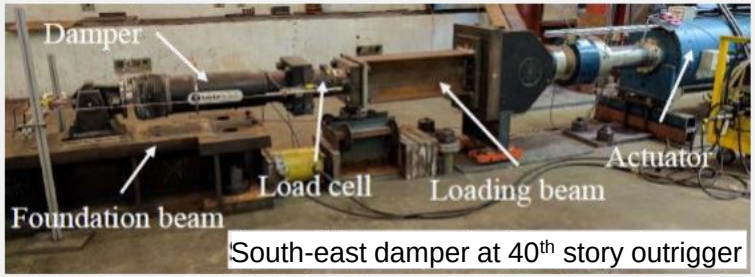
RTHS Configuration

- 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

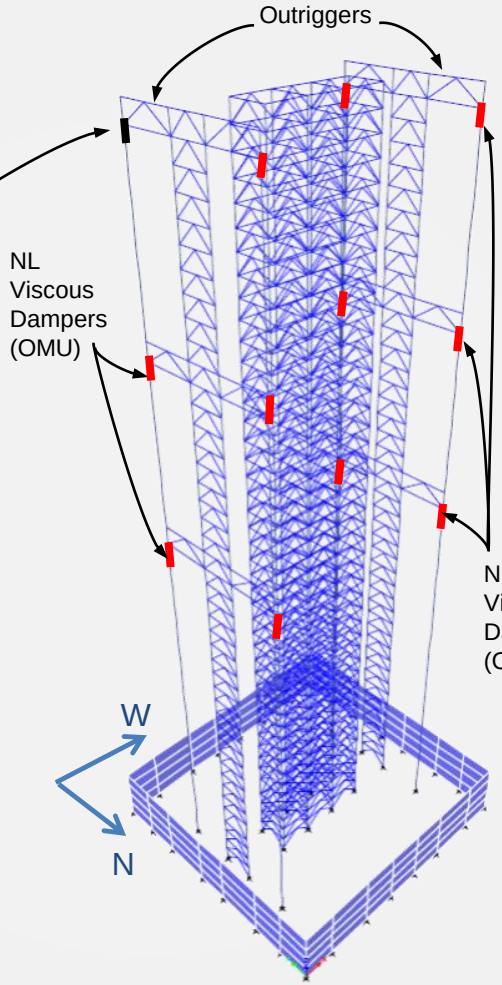
MKR-α parameter and ATS coefficients

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

Analytical Sub. Key features:

- 1317 Nodes
- 2974 Elements
  - 2411 Nonlinear Explicit Force-based fiber elements
  - 11 Nonlinear Explicit Maxwell Elements[1] with real-time on-line 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

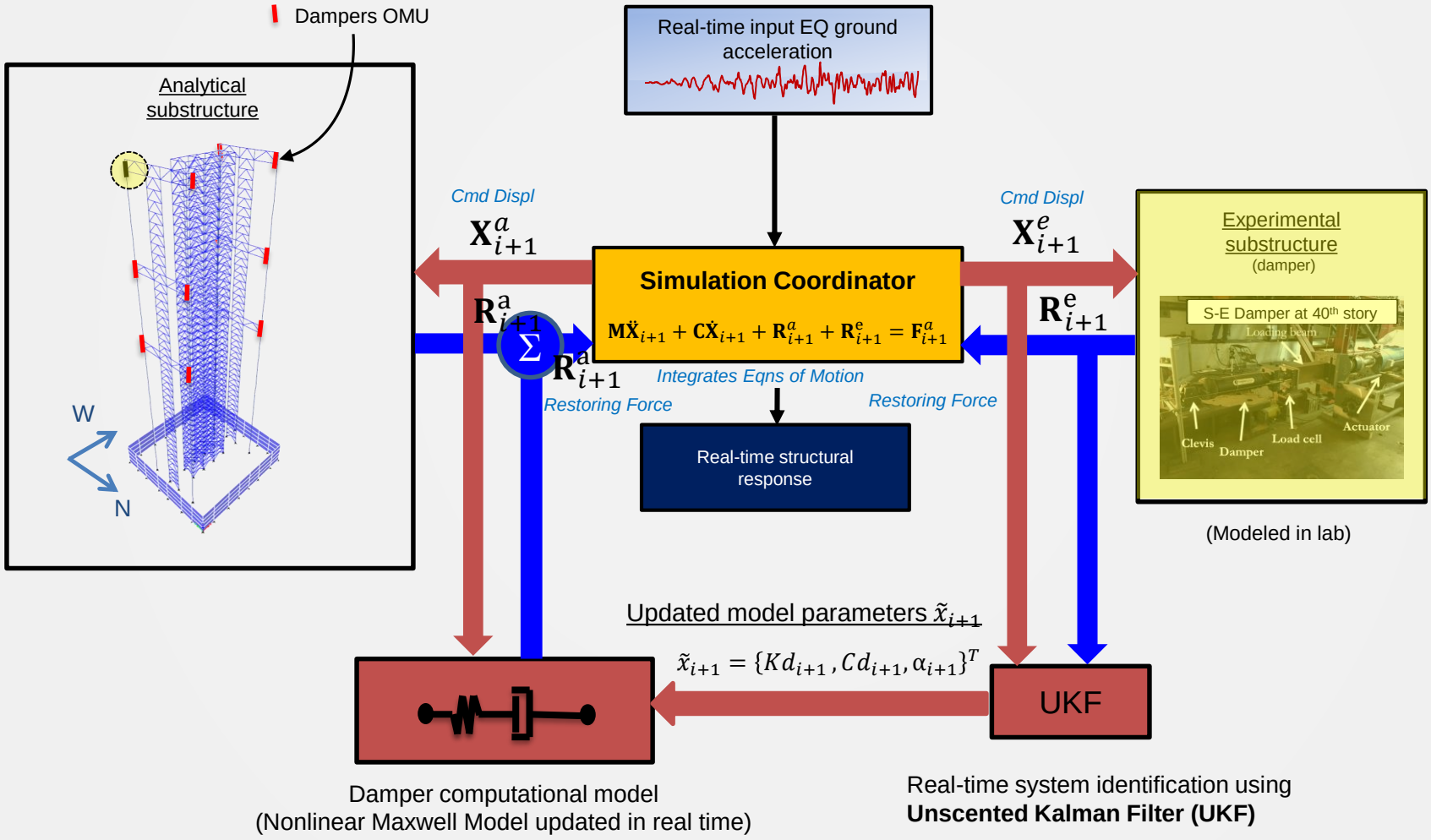
[1] Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

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

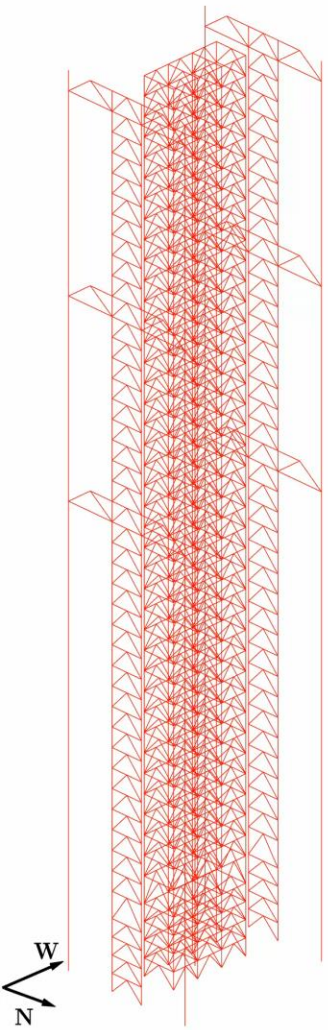
- Real-time Model Updating
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via Unscented Kalman Filter (UFK) to numerically model the 11 dampers
    - Development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

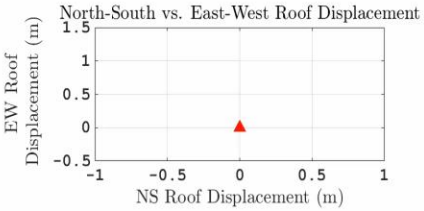
Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

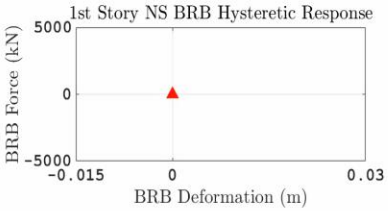
Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

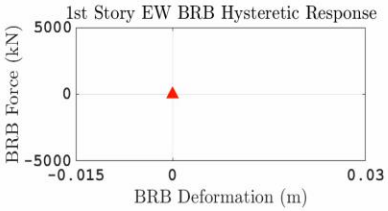


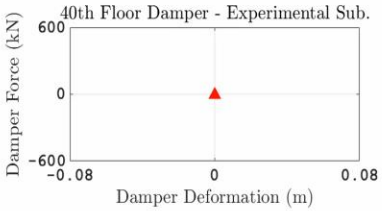
3-D Real-time Hybrid Simulation
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE

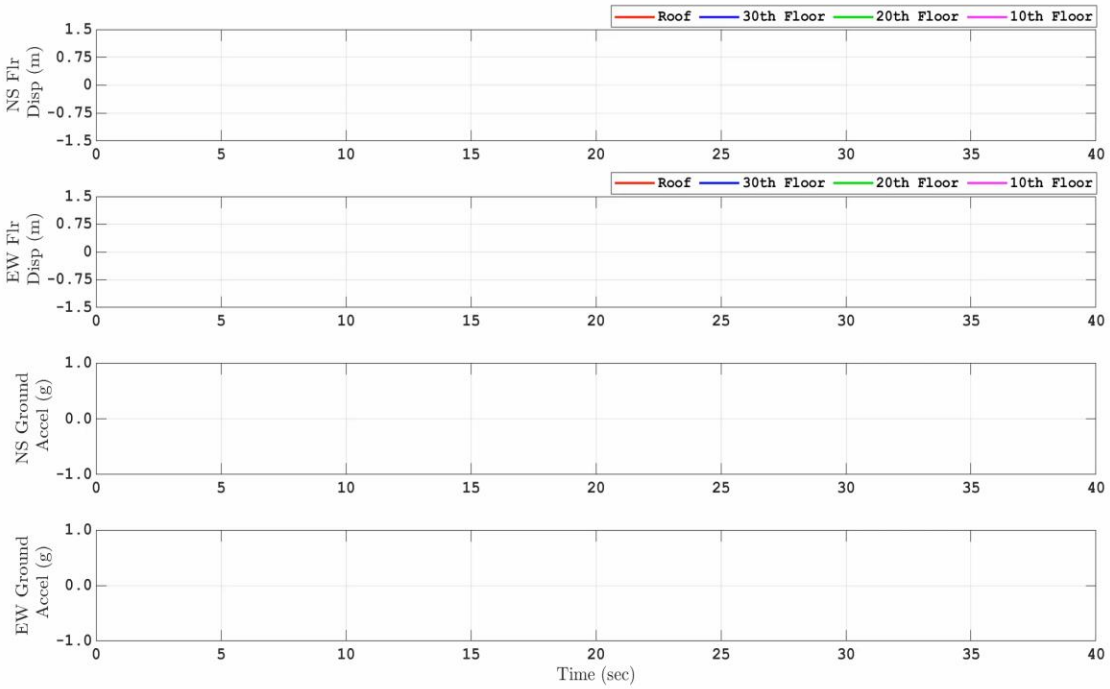


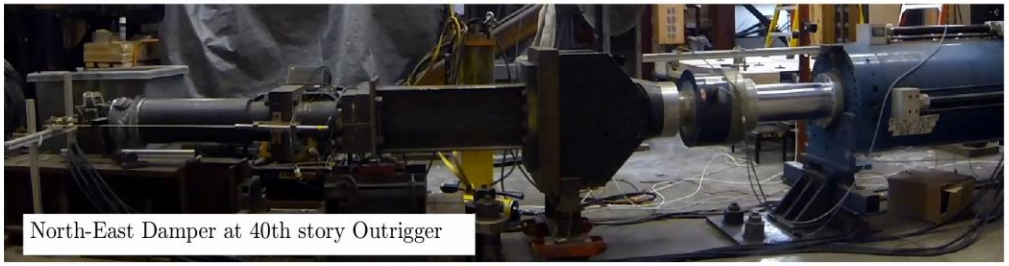










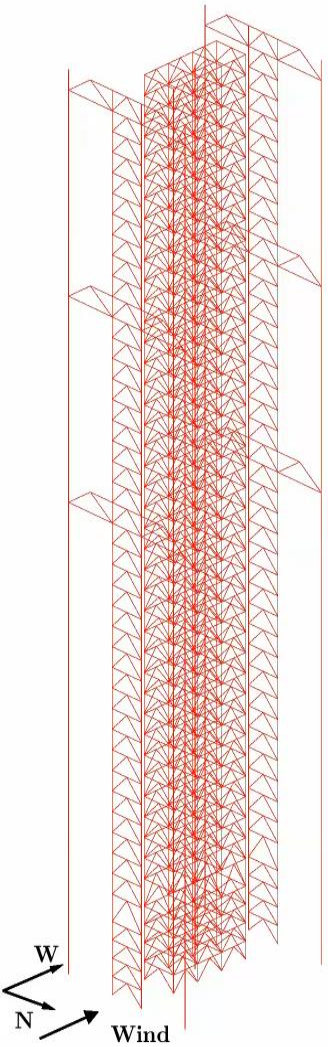


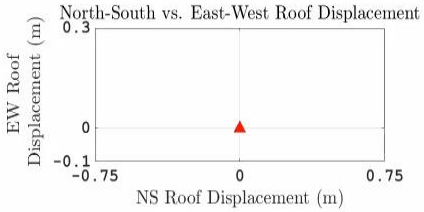
3-D Real-time Hybrid Simulation of a Seismically Excited Tall Building with NL Viscous Dampers
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE Level

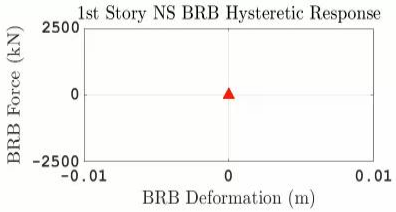
Motions scaled by factor of 5 in animation

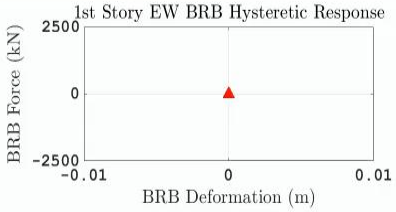
Al-Subaihawi, S., Marullo,T., Cao, L., Kolay, C. and J.M. Ricles, (2019) “3D Multi-Hazard Real-Time Hybrid Simulation Studies of a Tall Building with Damped Outriggers”.

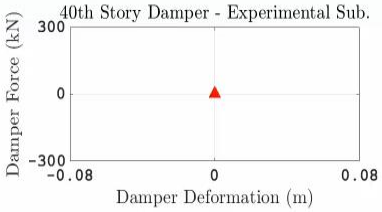
3-D Real-time Hybrid Simulation
110 mph, 700 MRI Wind Storm (EW Windward Direction)

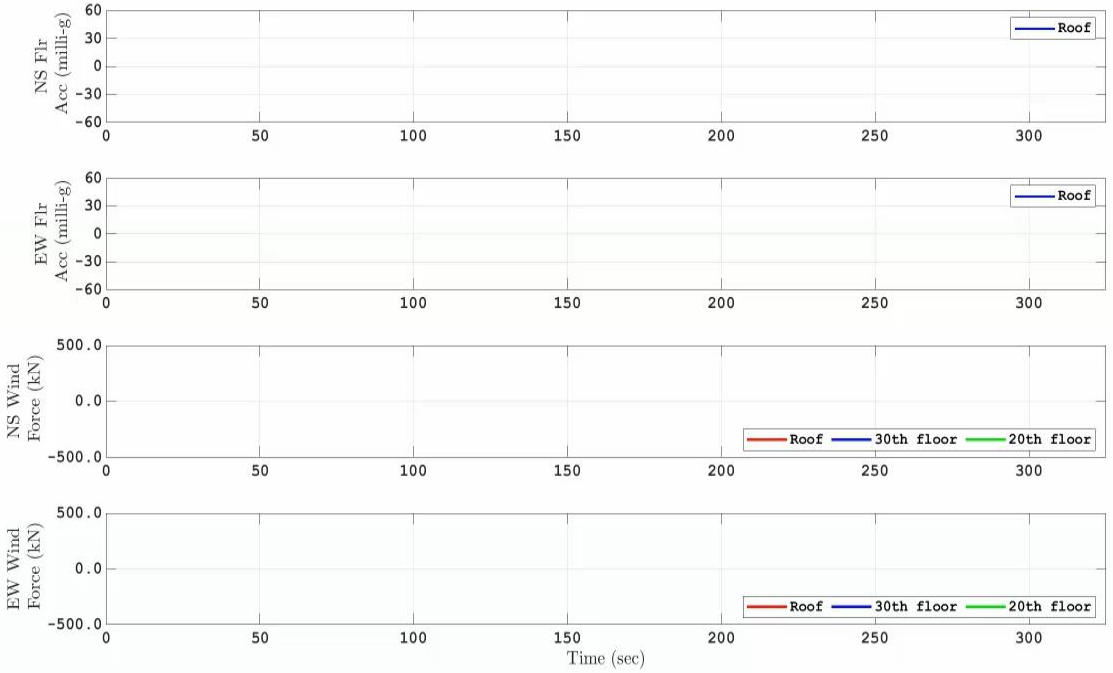












3-D Real-time Hybrid Simulation of a Wind Excited Tall Building with NL Viscous Dampers
Eastern 110mph, 700 MRI Wind Storm

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 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

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

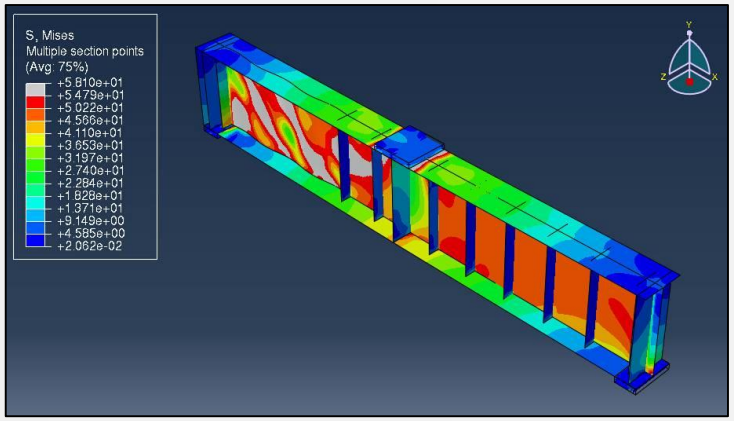
Research Projects

CMMI 1662886 and 1662964 Collaborative Research: Shear-Buckling Mechanics for Enhanced Performance of Thin Plates, PIs - Maria Garlock, Princeton University; Spencer Quiel, Lehigh University.

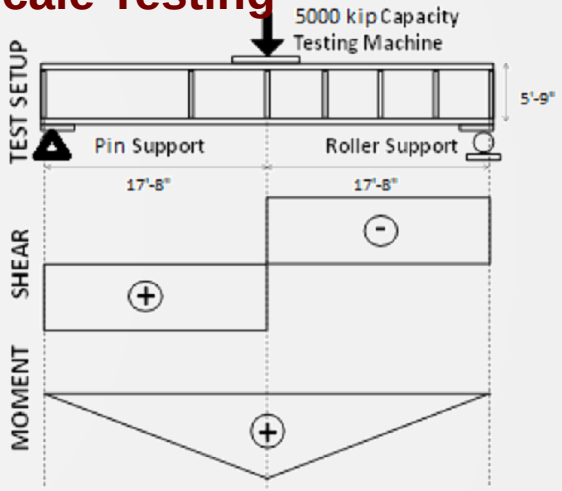
Large-scale Thin-walled Plate Girder Testing

- NHERI Lehigh staff assisted researchers to prepare data for archiving in DesignSafe.
- NHERI Lehigh staff assisted researchers to develop setup for Phase II testing.

Finite Element Analysis and Large-Scale Testing

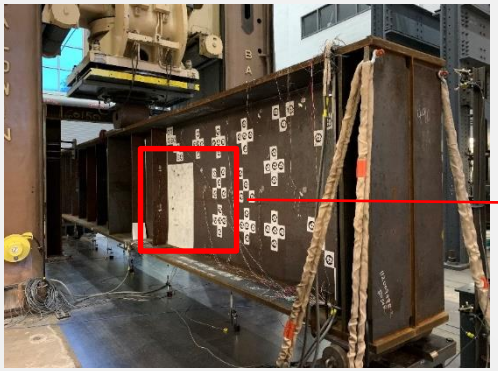


Finite Element Model Prediction

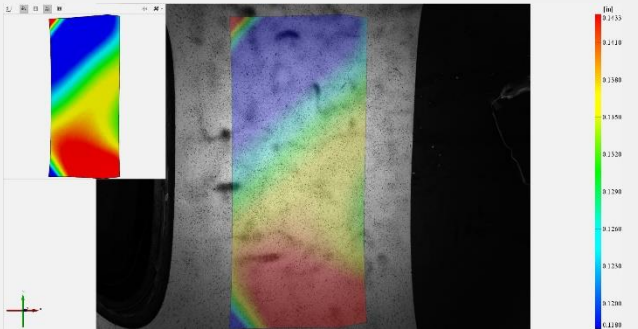


Planned Phase II Test Setup

Structural Testing



Horizontal strain measured from DIC

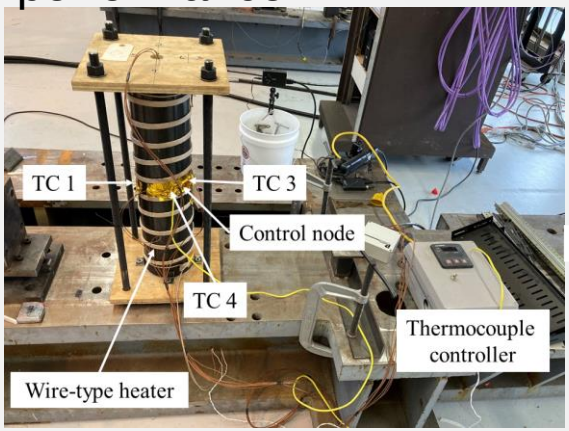


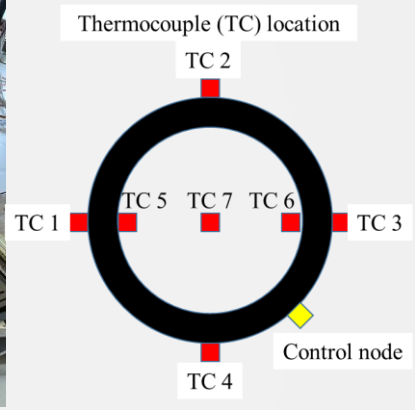
Research Projects

Investigation of a Novel Pressurized Sand Damper for Sustainable Seismic and Wind Protection of Buildings: (CMMI 2036131) **Southern Methodist University (Nicos Makris(PI))**

Features Using NHERI Lehigh Underlined

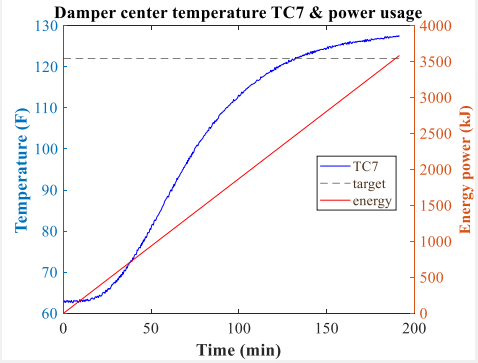
- Characterize dynamic behavior under various temperatures
- Perform RTHS to validate mitigation performance





Damper mockup and heating setup

Pressurized Sand-Damper (1)



(1) Makris, N., Palios, X., Moghimi, R. and Bousias, S. Pressurized sand damper for earthquake and wind engineering: Design, testing and characterization. Journal of Engineering Mechanics, ASCE, 2021, 147(4): 04021014

Thank You