Example Research Projects at NHERI Lehigh

Liang Cao

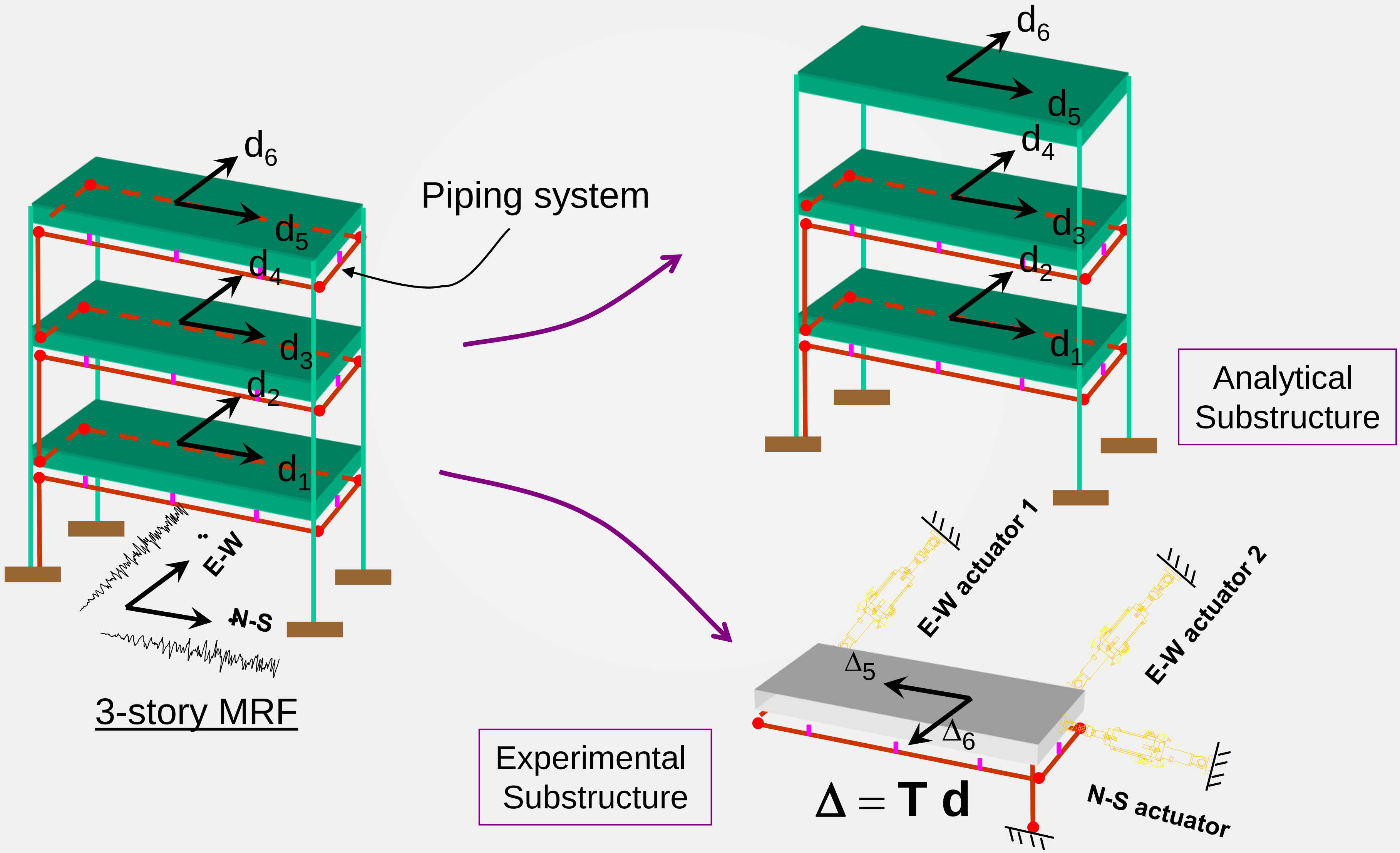
NHERI Lehigh EF Research Scientist

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)

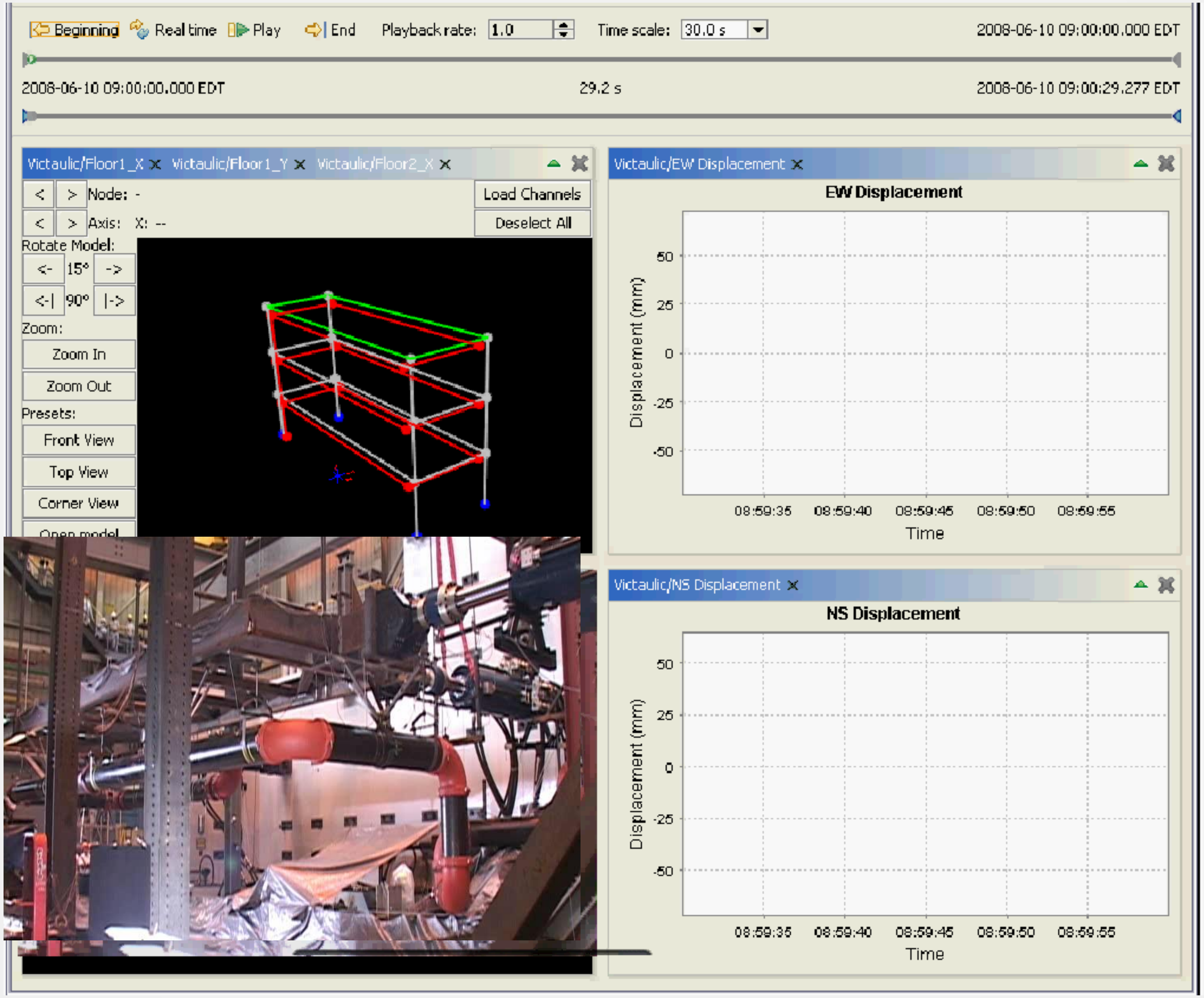
Multi-Directional Large-Scale Real-Time Hybrid Simulation of 3-story Building with Piping System

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)

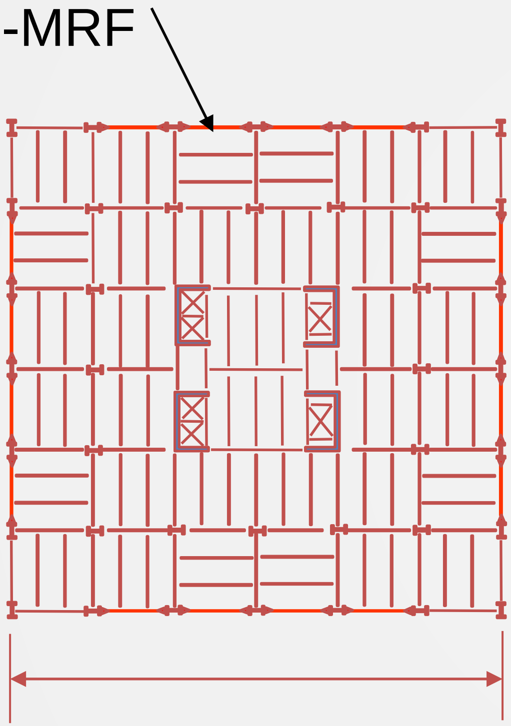


NEES

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

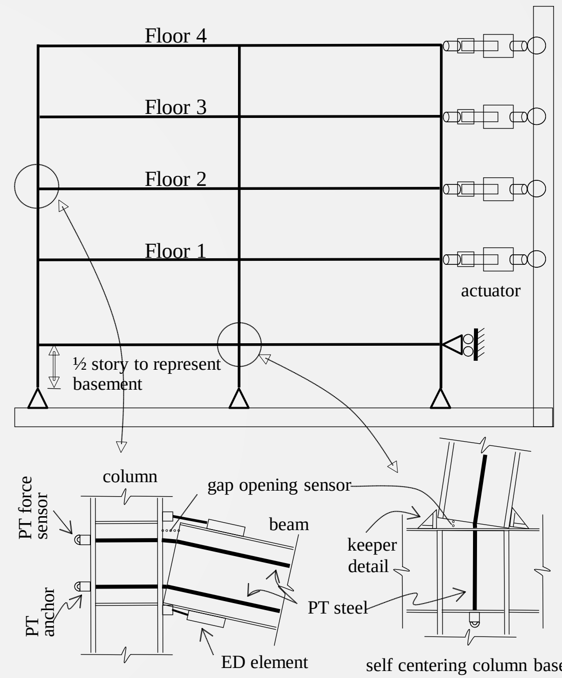
Large-Scale Hybrid Simulation

SC-MRF



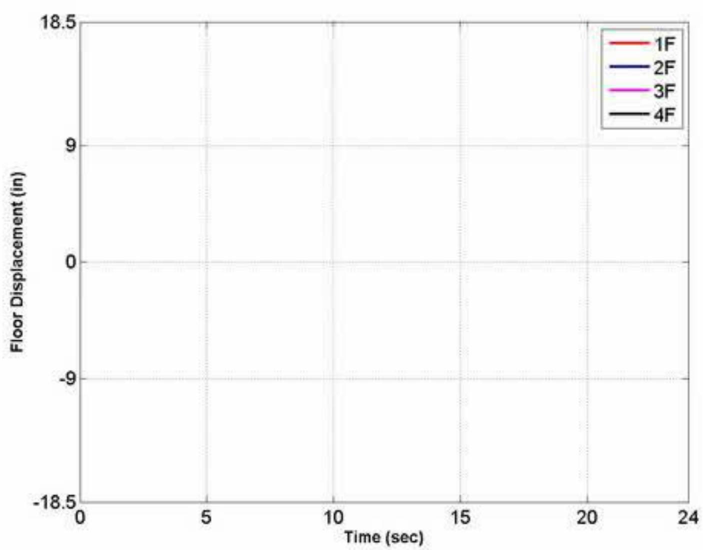
6-story : 6 bays @ 30 ft = 180 ft

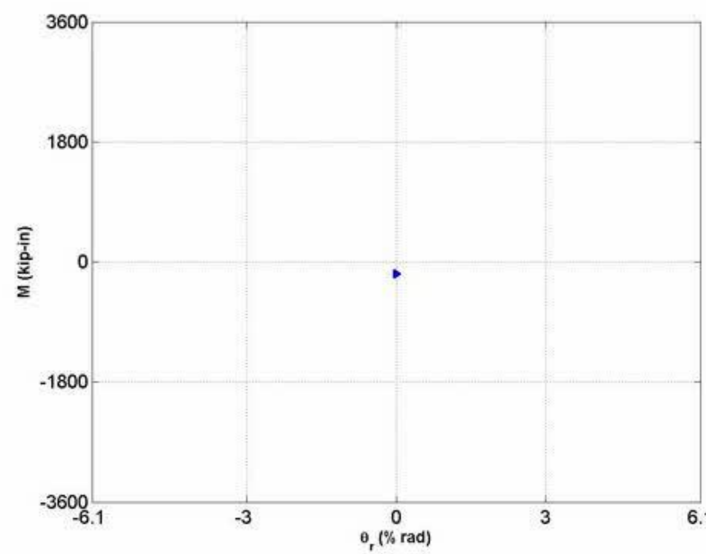
Plan of Prototype Building



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

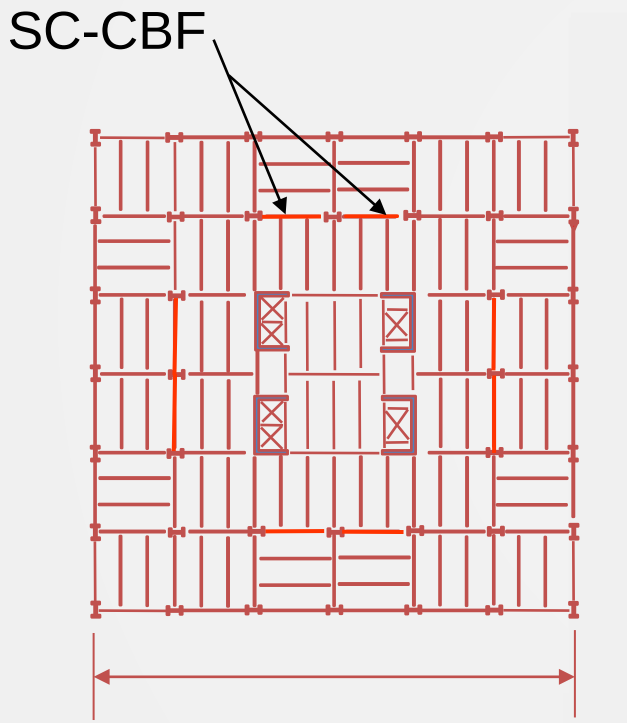
Large-Scale Hybrid Simulation (SC-MRF)





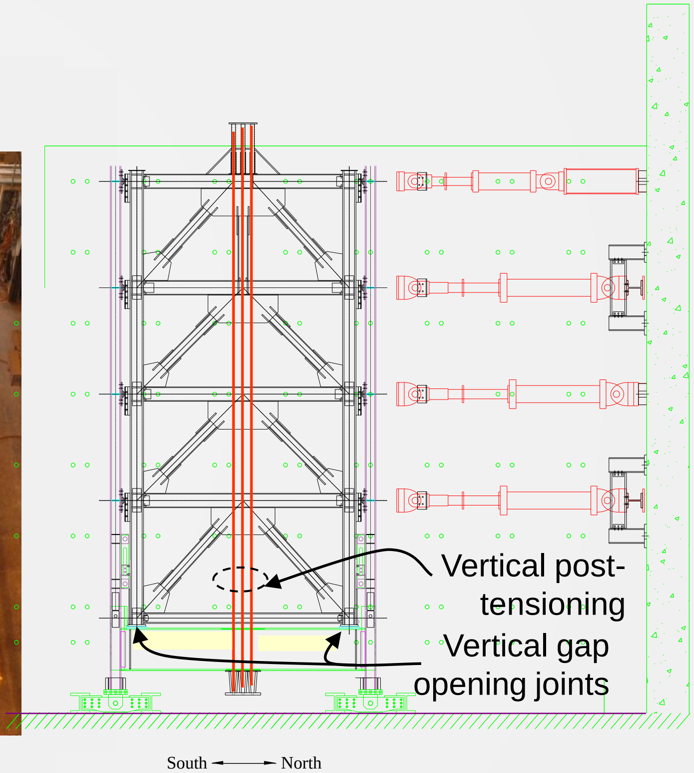
Self Centering Steel Concentrically-Braced Frame (SC-CBF) Systems
Princeton, Purdue, Lehigh, NCREE

Large-Scale Hybrid Simulation



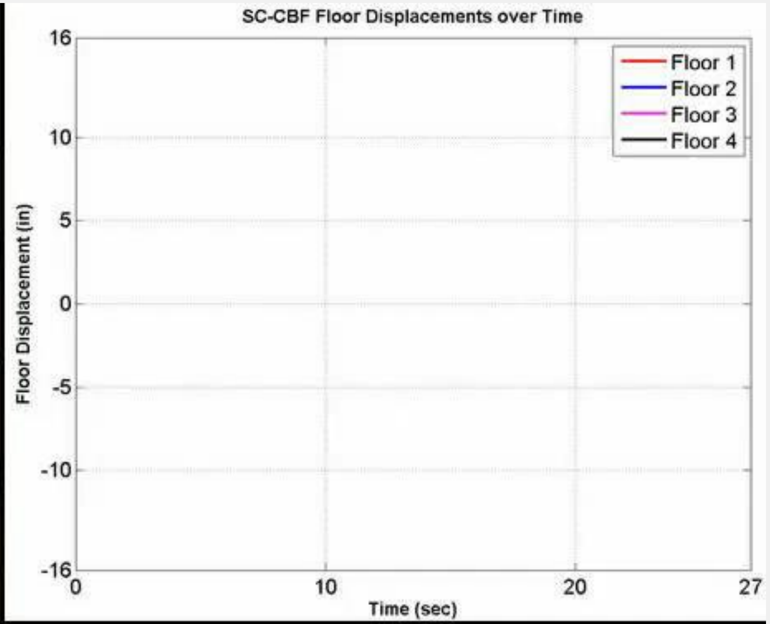
6-story : 6 bays @ 30 ft = 180 ft

Plan of Prototype Building



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

Large-Scale Hybrid Simulation (SC-CBF)



South Base

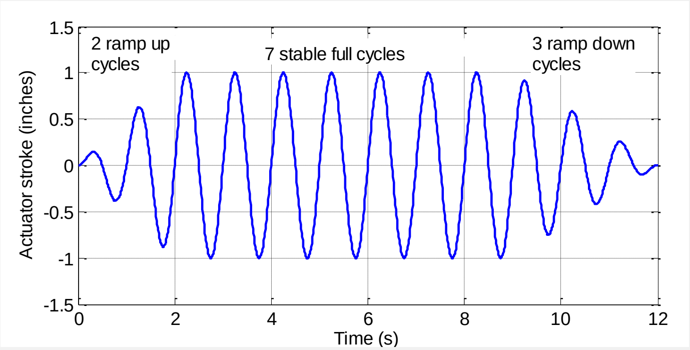
North Base

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

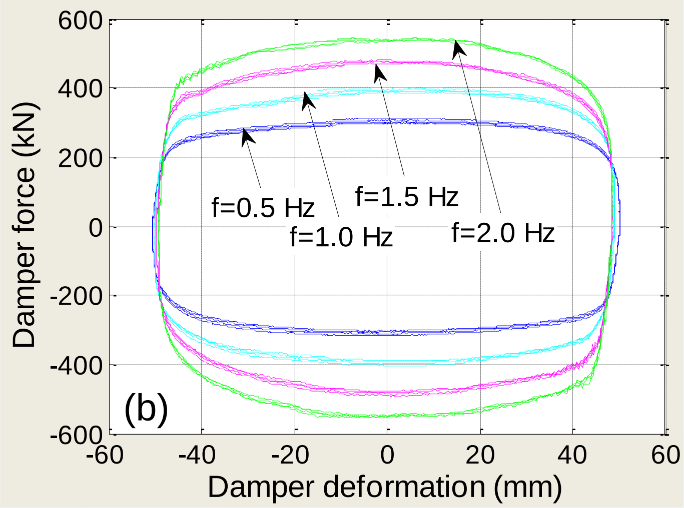
Cal State Pomona, Cal State Northridge, Lehigh

Predefined Displacement Dynamic Testing for Characterization

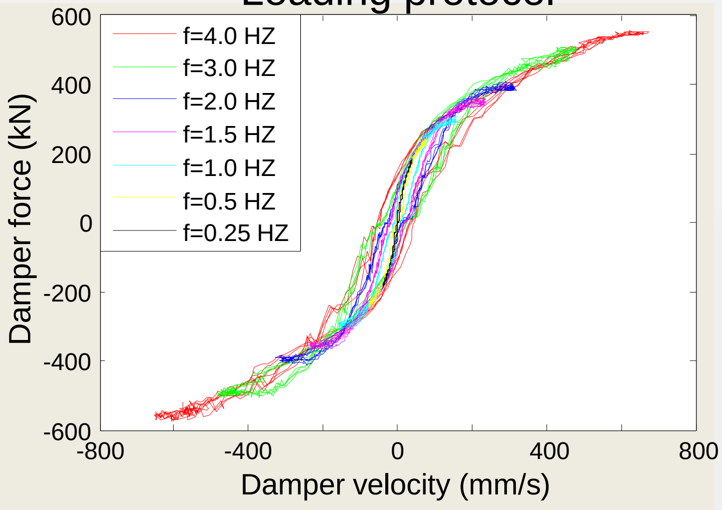
Damper testbed



Loading protocol



Damper force - deformation



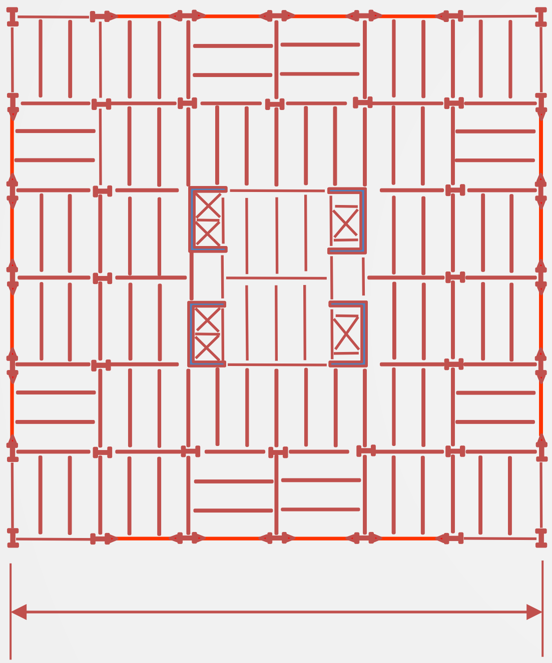
Damper force - velocity

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

Cal State Pomona, Cal State Northridge, Lehigh

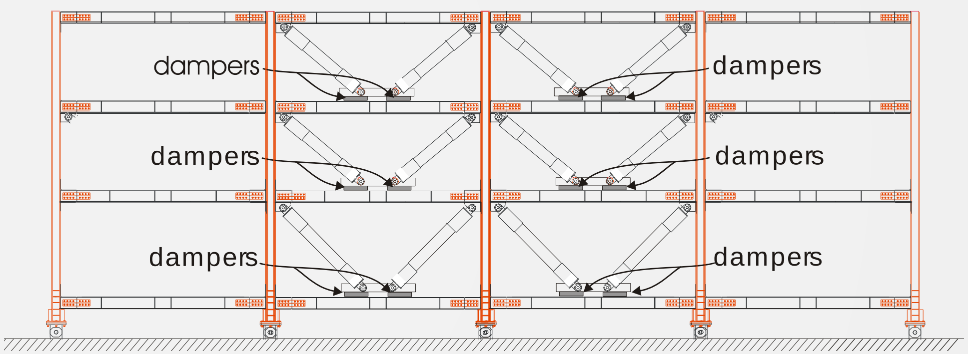
Large-Scale Real-Time Hybrid Simulation

Steel MRF with Passive Dampers



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

Plan of Prototype Building

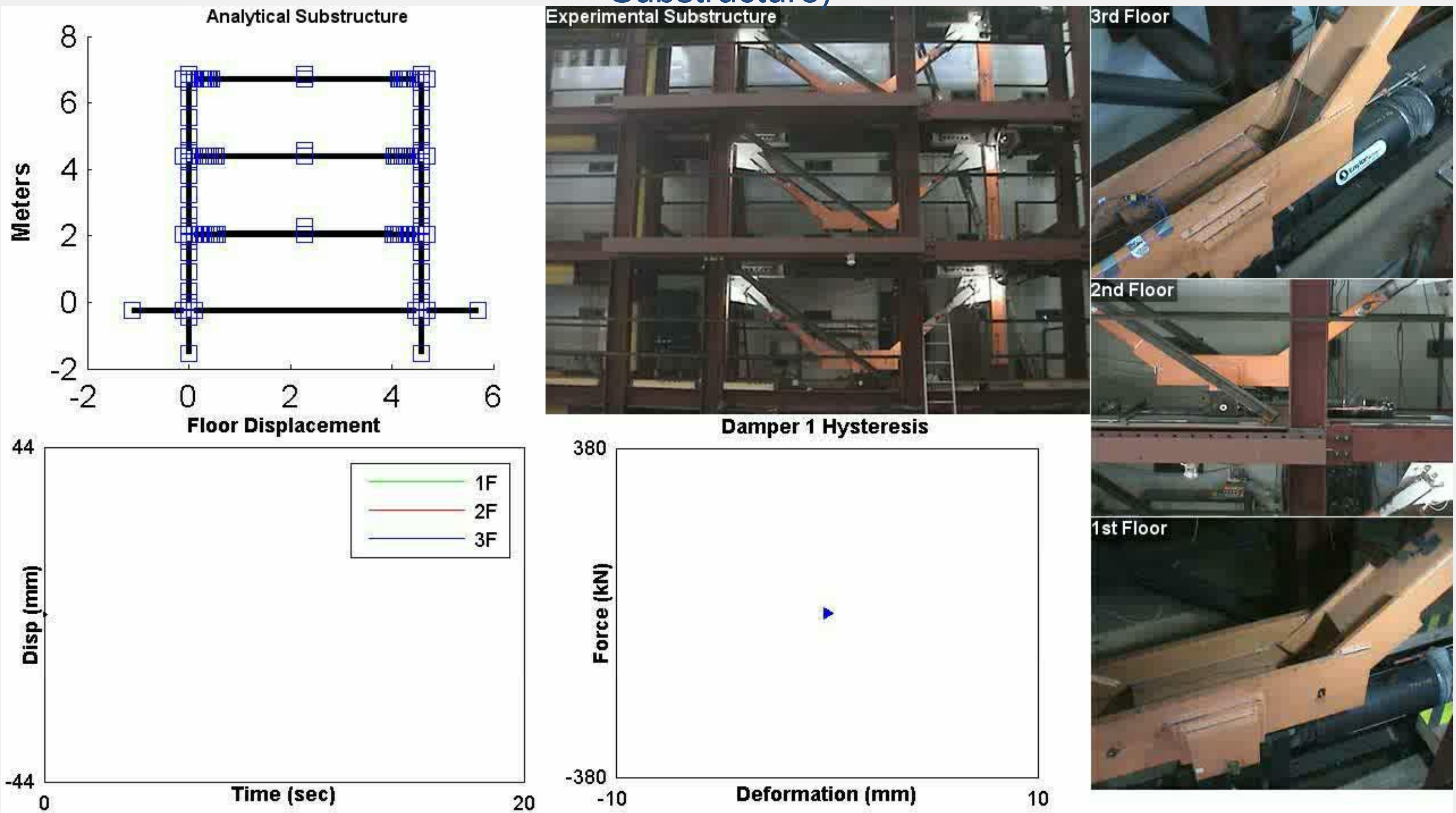


Elevation of MRF with Passive Dampers

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 Damping in Analytical Substructure)



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

Cal State Pomona, Cal State Northridge, Lehigh

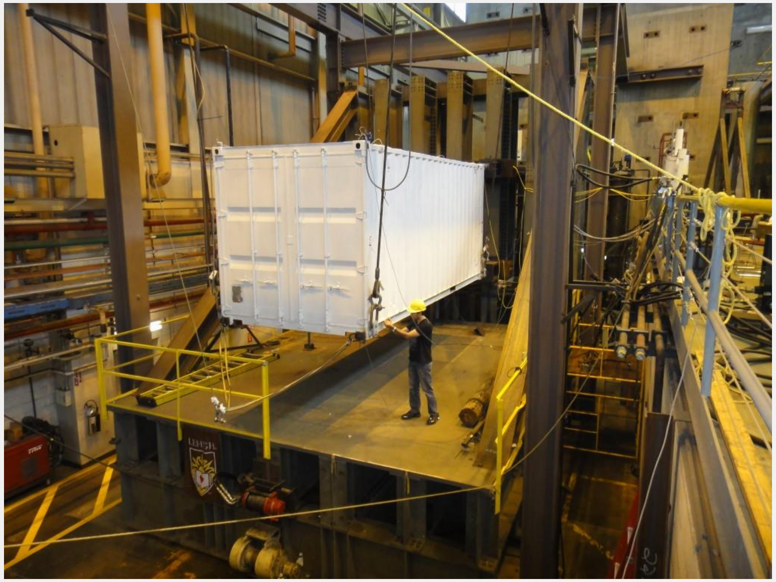
Large-Scale Real-Time Hybrid Simulation

(Floor Diaphragm, Gravity System, Mass, Inherent Damping 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)

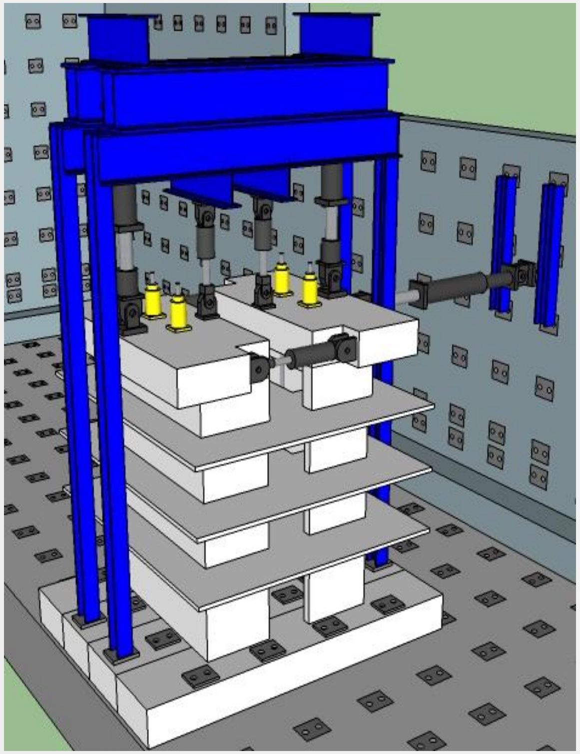


Test Setup with Cargo Shipping Container Debris

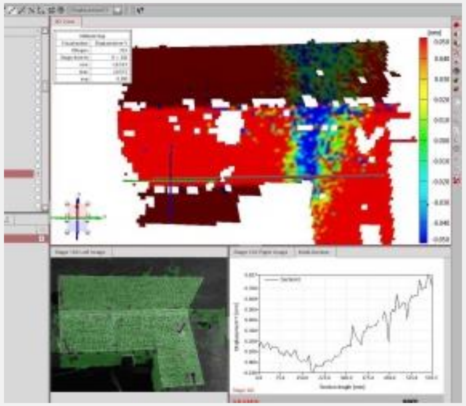
High Speed Video of Impact of Cargo Shipping Container on Structure

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

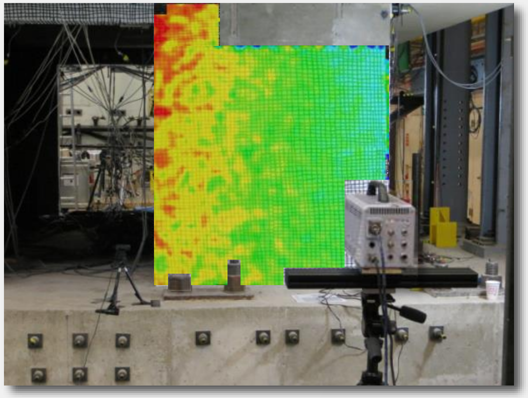
Complex Large-Scale Predefined Multi-Directional Force & Displacement (Quasi-Static) Testing



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)

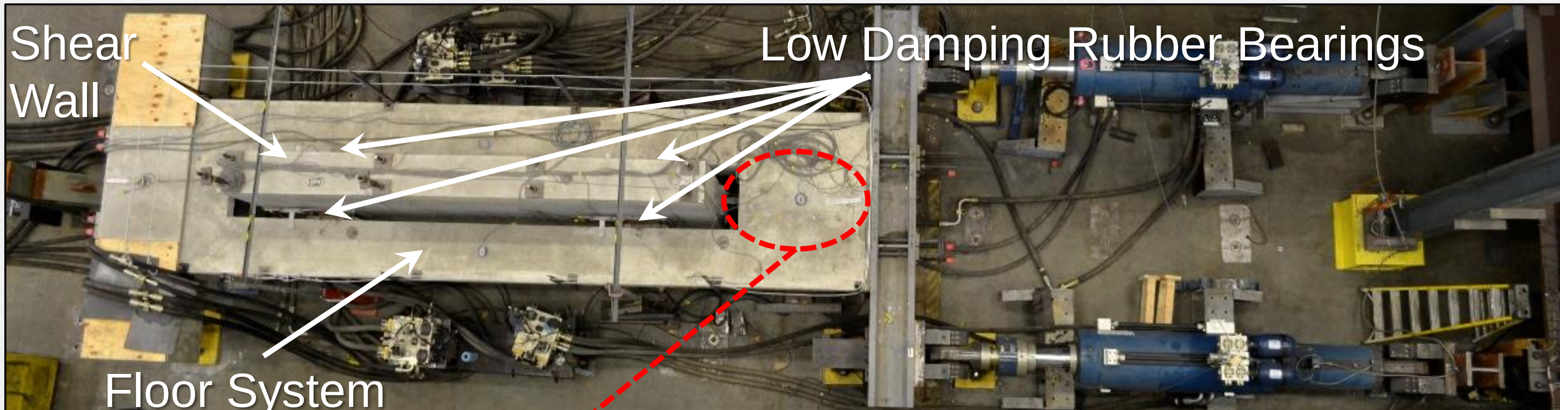
ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE LEHIGH UNIVERSITY NSF NSF NHERI CYBER-PHYSICAL SIMULATION

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

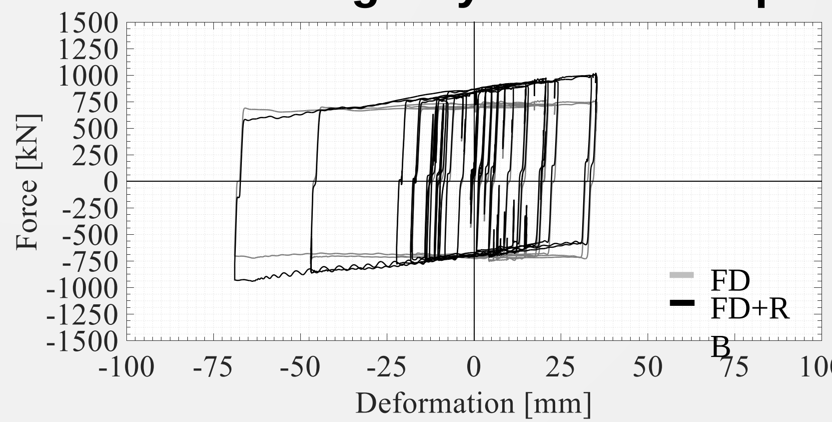
Predefined Displacement Dynamic Testing for Characterization



Friction Device for Floor Anchorage

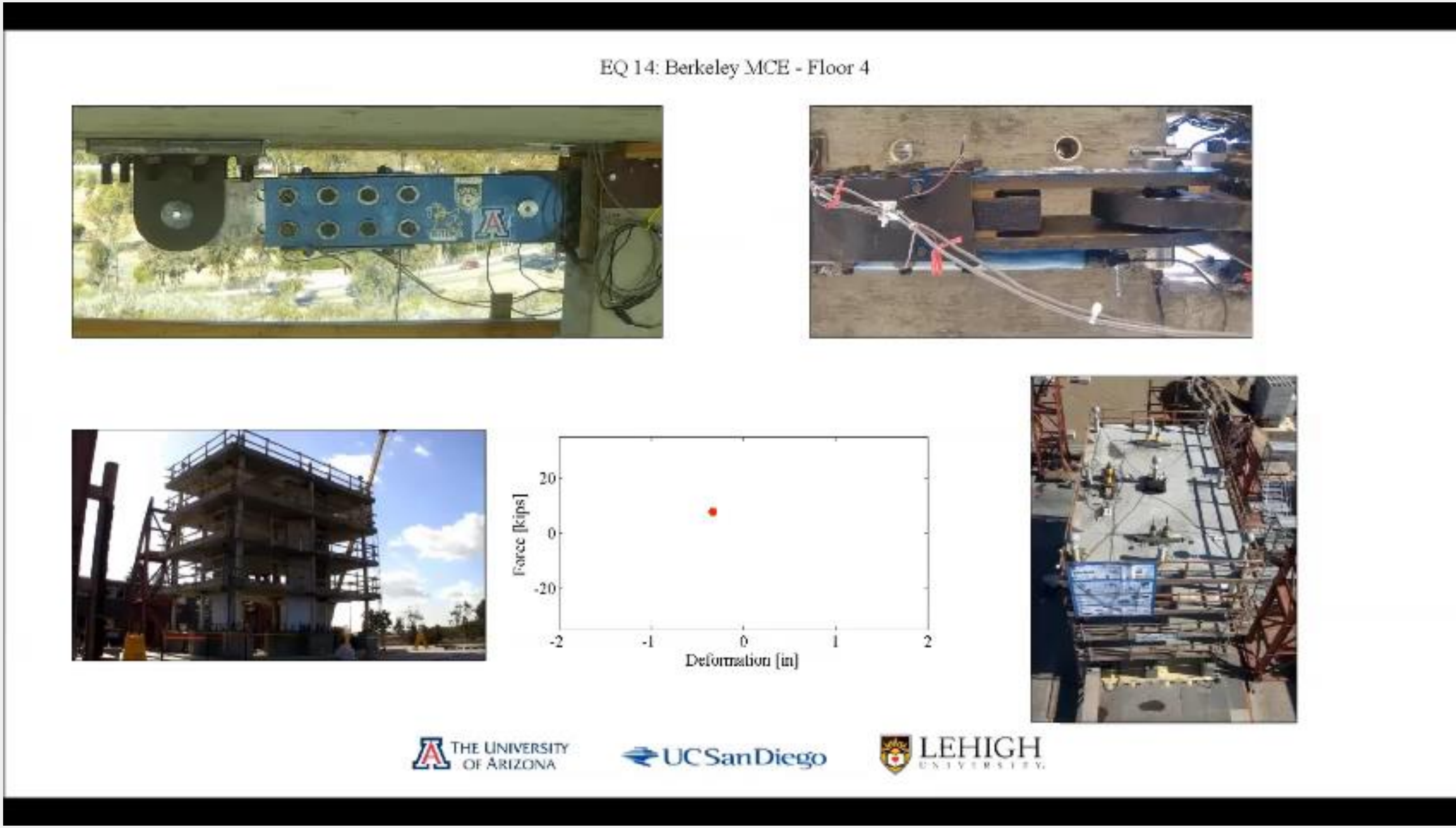
BRB was also Studied

Floor Anchorage Hysteretic Response



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

[Complimentary Shake Table Tests at NHERI UCSD]



Recent and Current Projects at NHERI Lehigh EF

Project	Resource,Testing Method	PI	Institution of PI
CMMI 1463252, 1463497: Collaborative Research: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings	Damper test beds, CPSSL; characterization testing, RTHS	Simon Laflamme, James Ricles	Iowa State University Lehigh University
CMMI 1636164, 1635156 and 1635227: Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings	High bay lab, DIC; multi-directional quasi-static cyclic testing, hybrid simulation	Shiling Pei, James Dolan, James Ricles	Colorado School of Mines, Washington State Univ Lehigh University
CMMI 1662886 and 1662964: Collaborative Research: Shear-Buckling Mechanics for Enhanced Performance of Thin Plates	High bay lab, DIC; quasi-static testing	Maria Garlock, Spencer Quiel	Princeton University Lehigh University
CMMI 1662816: Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures	high bay lab, DIC; mixed-mode control quasi-static cyclic testing, hybrid simulation	Robert Fleischman	University of Arizona
CMMI 1926326: Collaborative Research: Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings	High bay lab, damper test beds, CPSSL, DIC; quasi-static cyclic testing, hybrid simulation, RTHS	Larry Fahnestock Richard Sause	University Illinois Lehigh University
RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing	High-bay lab, damper test beds, CPSSL; characterization testing, RTHS	Scott Harvey	University of Oklahoma
CMMI 2036131: Investigation of a Novel Pressurized Sand Damper for Sustainable Seismic and Wind Protection of Buildings	High-bay lab, damper test beds, CPSSL; characterization testing, RTHS	Nicos Makris	Southern Methodist University
RTHS of Soil-Structure-Foundation Systems Using Neural Networks (1)	High-bay lab, damper test beds, CPSSL; high performance computing, RTHS	James Ricles	Lehigh University
Real-Time Hybrid Simulation of Wind-induced Aerodynamic Vibrations (1)	WOW FIU Wind Tunnel, High-bay lab, damper test beds, CPSSL, RTHS	Arindam Chowdhury & Amal Elawady, James Ricles & Liang Cao	Florida International University Lehigh University
TI 2222232: STTR Phase I: Development of an Innovative Ultra High Performance Concrete Foundation System with Bio-inspired Surfaces to Support Renewable Offshore Wind Turbines	CPSSL; reduced-scale Soil-Foundation-Structure Interaction, characterization testing, RTHS	JP Binard, Muhannad Suleiman, Clay Naito	Precast Systems Engineering, LLC Lehigh University

(1) Capacity Building Projects

REAL-TIME MULTI-DIRECTIONAL SIMULATION
NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

LEHIGH UNIVERSITY

NSF NHERI CYBER-PHYSICAL SIMULATION

Recent and Current Projects at NHERI Lehigh EF

Project	Resource,Testing Method	PI	Institution of PI
TI 2141073: PFI-TT: Self-Centering Seismic Dampers for Resilience-Based Earthquake Design of Buildings	High-bay lab, damper test beds, CPSSL; characterization testing, RTHS	Osman Ozbulut	University of Virginia
CMMI 2040665: NSF Convergence Accelerator Track D: Intelligent Surveillance Platform for Damage Detection and Localization of Civil Infrastructure	High bay lab, DIC; quasi-static testing	Claudia Marin	Howard University
CMMI 1943917: CAREER: Mitigation of Seismic Risk to Critical Building Contents via Optimum Nonlinear 3D Isolation	High-bay lab, damper test beds, CPSSL; characterization testing, RTHS	Scott Harvey	University of Oklahoma
CMMI 2237696: CAREER: Data-Driven Control of High-Rate Dynamic Systems	High-bay lab, damper test beds, CPSSL; characterization testing, RTHS	Austin Downey	University of South Carolina
CMMI 2145665: CAREER: Accelerating Real-time Hybrid Physical-Numerical Simulations in Natural Hazards Engineering with a GPU-driven Paradigm	High-bay lab, damper test beds, CPSSL, RTHS	Barbara Simpson	Oregon State University
CBET 2401005: RAISE: CET: Coupled Aero-Hydro-Geotechnical-Mechanical Interaction and Control of Floating Offshore Wind Turbines Subjected to Extreme Loading Conditions	High-bay lab, Soil-Foundation-Structure Interaction, RTHS	Muhannad Suleiman, James Ricles, Richard Sause, Keith Moored	Lehigh University

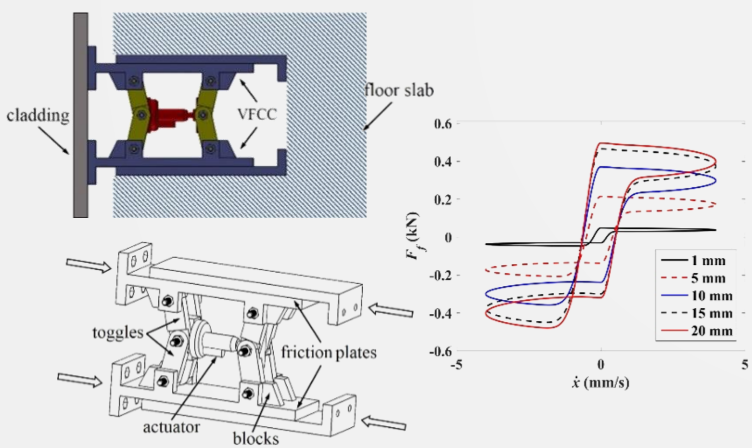
15 of 20 funded projects are from external researchers, including 3 recent CAREER awards!

Research Projects

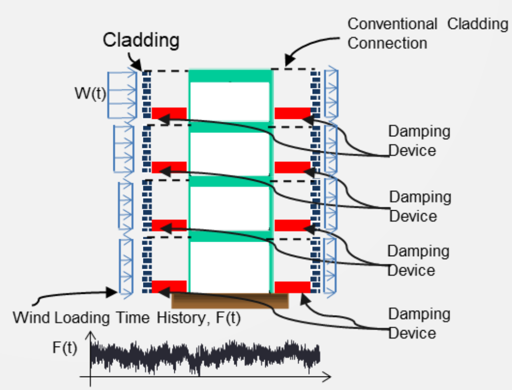
Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards

(CMMI 1463252) Iowa State University (Simon Laflamme)

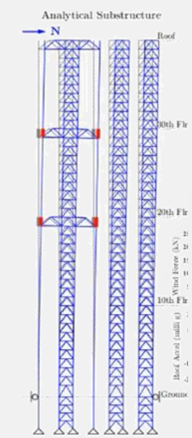
- Overview
  - ➢ Improve performance of buildings for multiple hazards <u>using controlled variable friction cladding panel connectors</u>
  - ➢ Hazards: Earthquake, Wind (NHERI UF and NHERI FIU)
- Scope
  - ➢ Design cladding connectors and control laws
  - ➢ Construct prototype connector, perform characterization testing
  - ➢ Perform <u>large-scale RTHS</u> to validate numerical models and results



<u>Variable friction connecting device</u>



<u>4-story building with friction connectors</u>



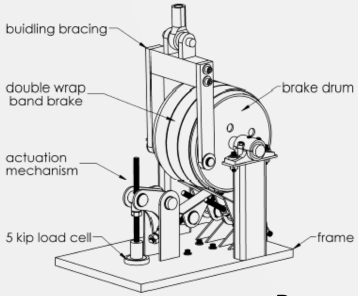
<u>40-story building with friction connectors</u>

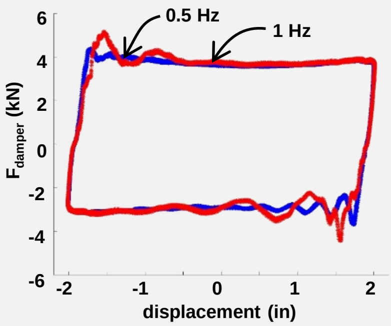
Research Projects

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

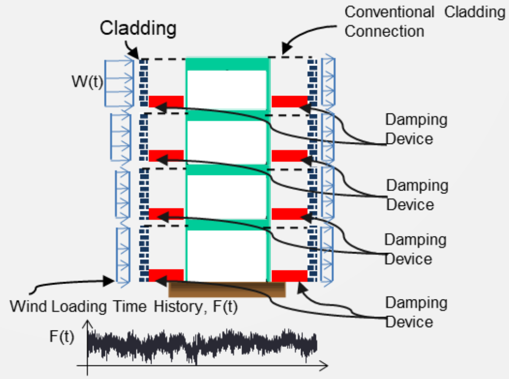
(CMMI 1463497) Lehigh University (James Ricles)

- Overview
  - ➢ Improve building performance for multiple hazards using passive energy dissipating cladding connectors combined with supplemental damper systems
  - ➢ Hazards: Earthquake, Wind (NHERI UF and NHERI FIU)
- Scope
  - ➢ Design prototype buildings of various heights
  - ➢ Perform nonlinear time history analysis to assess performance
  - ➢ Perform large-scale RTHS to validate numerical models and results

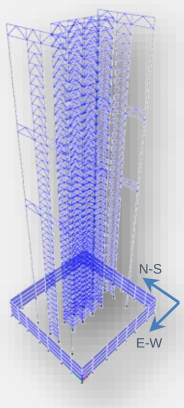


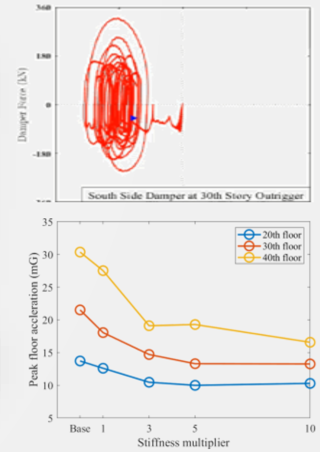


Rotary friction damper



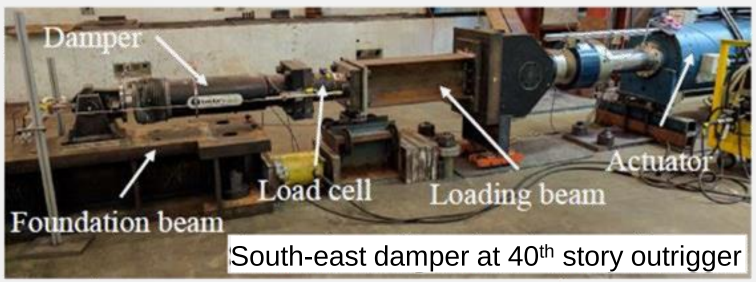
4-story building with friction connectors



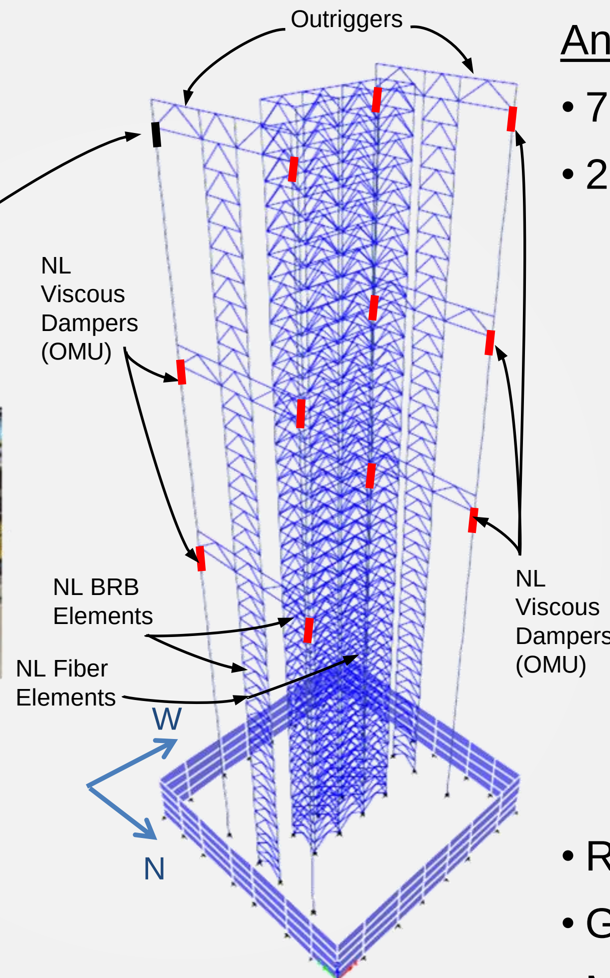


40-story building with nonlinear viscous dampers

RTHS Substructures: Tall Building Subjected to Multi-Natural Hazards



Experimental Substructure – NL Fluid Viscous Damper



Analytical Substructure

Analytical Sub. Key features:

- 7902 DOF
- 2974 Elements
  - 2411 Nonlinear Explicit Force-based fiber elements
  - 11 Nonlinear Explicit Maxwell Elements(1,2) 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

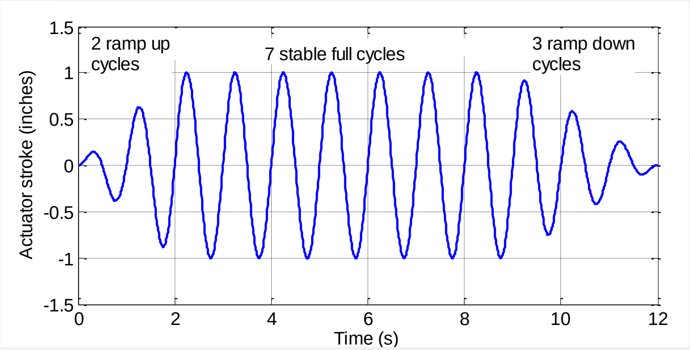
(1) Al-Subaihawi, S. (2022). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

(2) Al-Subaihawi, S., Ricles, J., and S. Quiel. "Online Explicit Model Updating of Nonlinear Viscous Damper for Real Time Hybrid Simulation," *Earthquake Engineering and Soil Dynamics*, Vol. 154, https://doi.org/10.1016/j.soildyn.2021.107108, 2022.

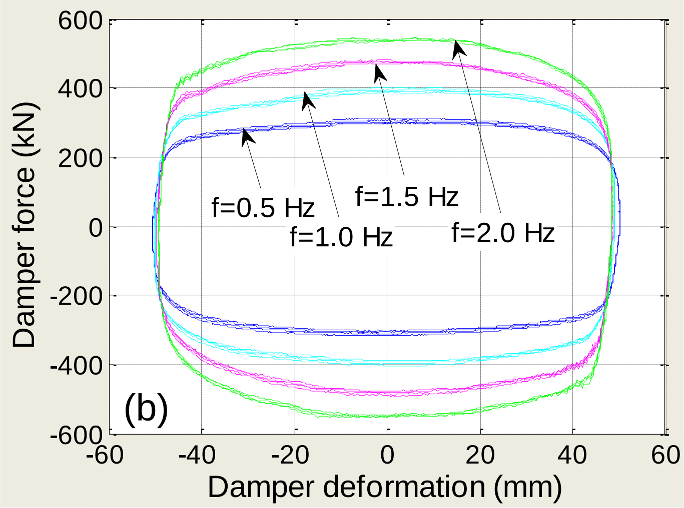
Full-Scale Nonlinear Viscous Dampers

Characterization testing

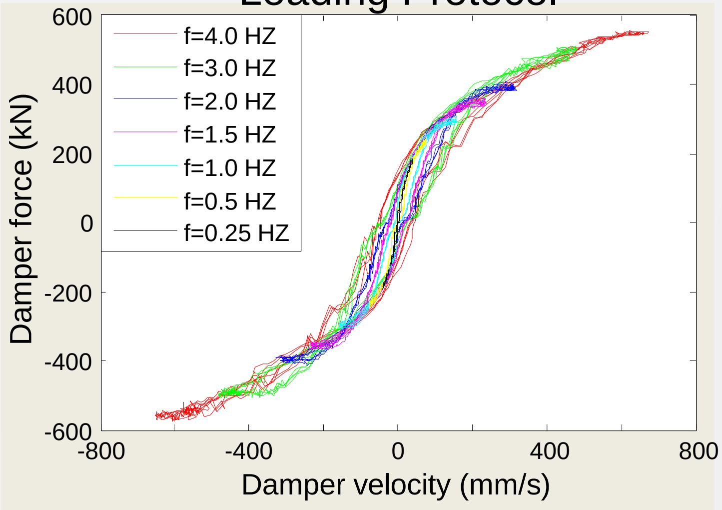
Damper testbed



Loading Protocol

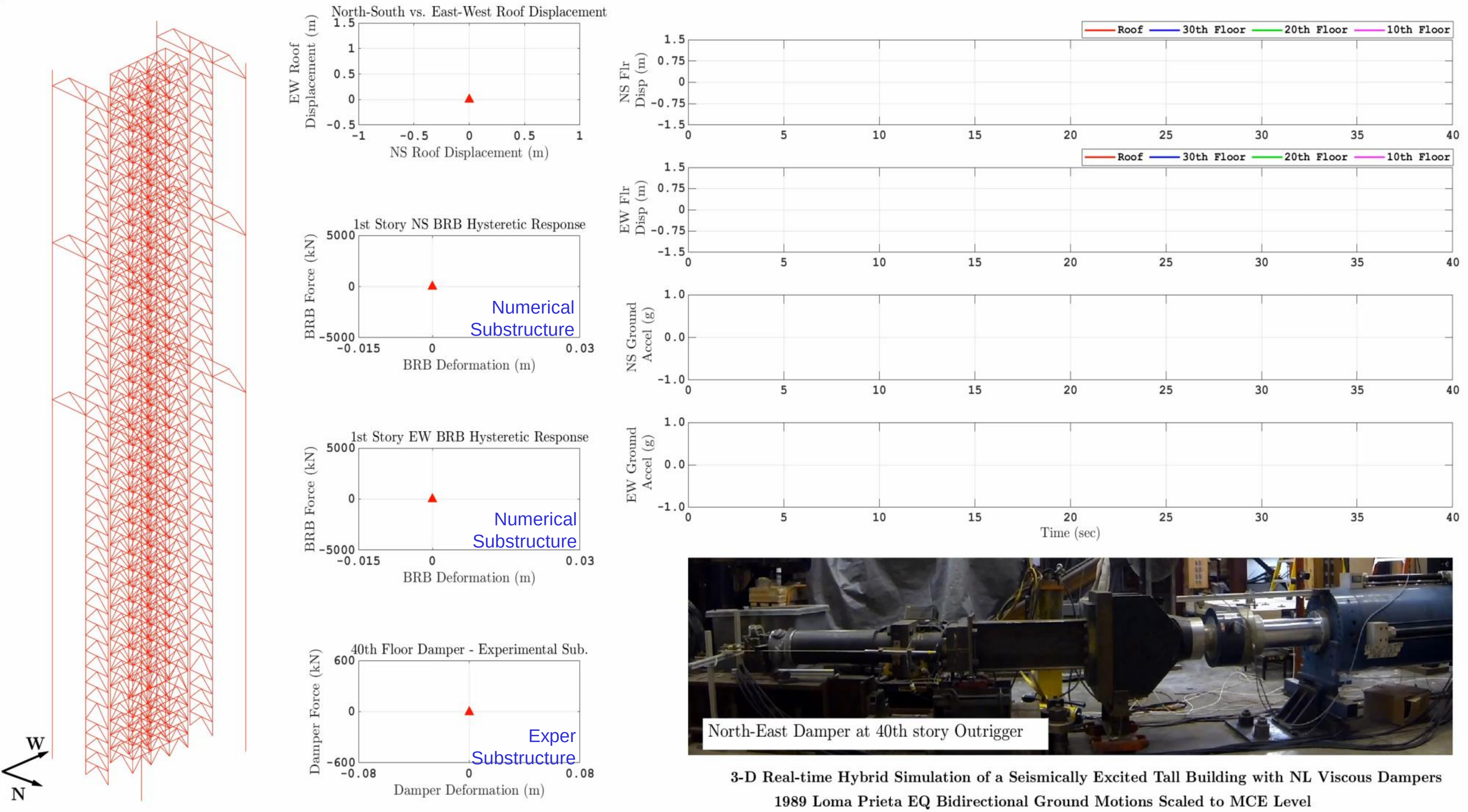


Damper force - deformation



Damper force - velocity

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



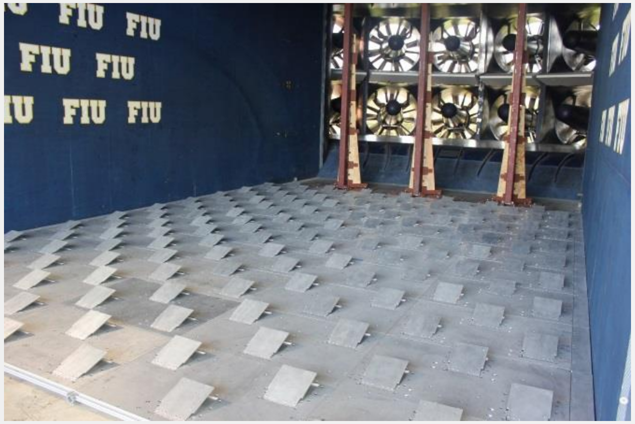
Motions scaled by factor of 5 in animation

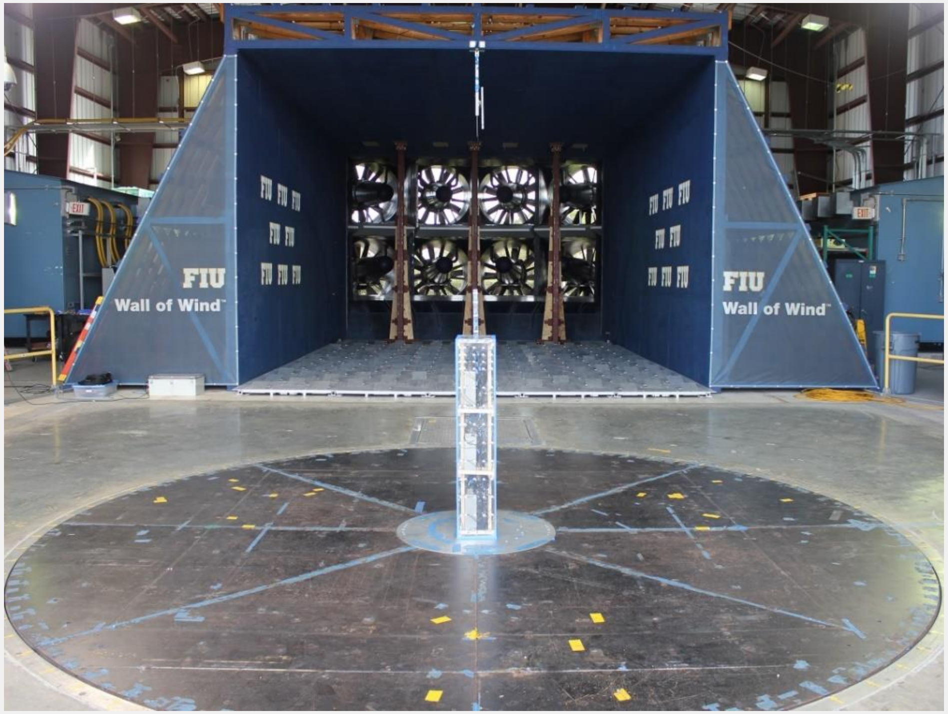
Caption: *Response of building to seismic loading from 3D RTHS involving Maximum Considered Earthquake (MCE) hazard.* VIDEO 2: https://www.youtube.com/watch?v=IaX0A1aIRBo

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”.

Wind Loading
Aerodynamic Wind Testing @ FIU WOW

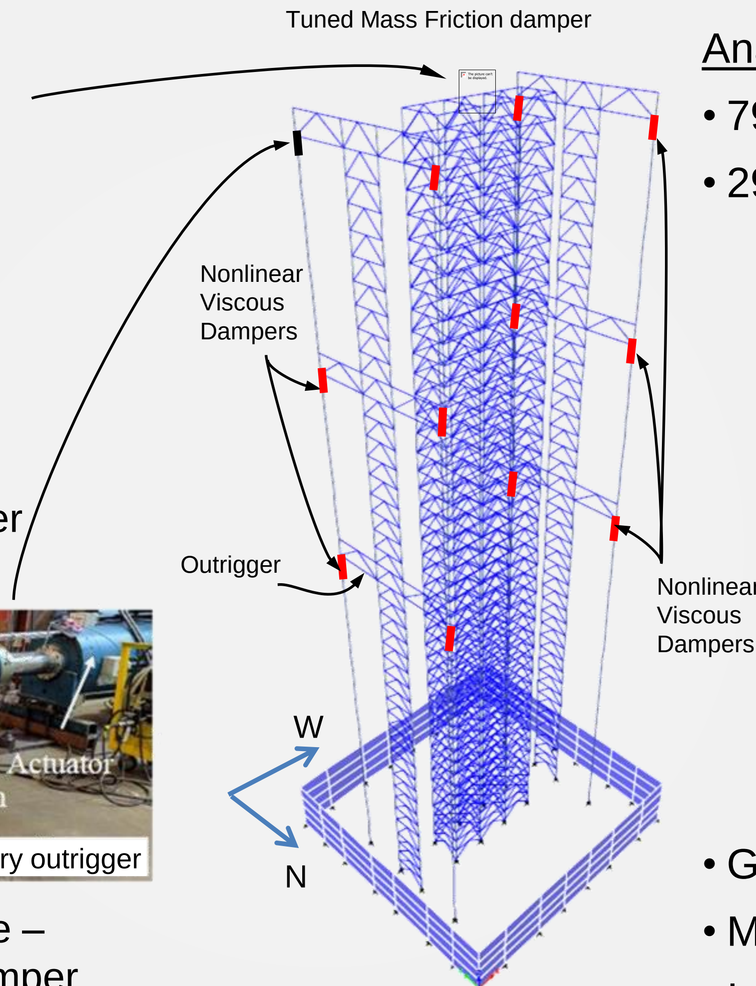
- Aerodynamic wind testing at the NHERI FIU WOW to obtain wind pressure time histories distributed on the building.





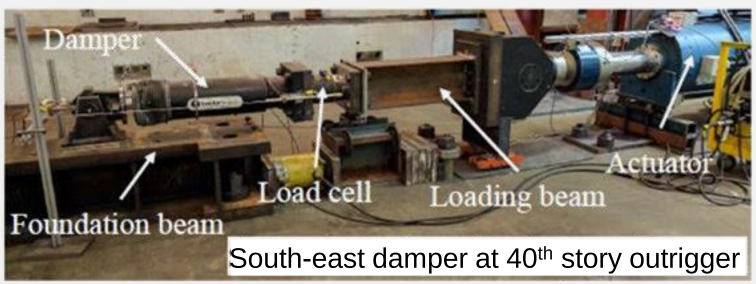
Courtesy: Amal Elawady
and Arindam Chowdhury, FIU

RTHS Substructures



Analytical Substructure

Experimental Substructure – Banded Rotary Friction Damper



Experimental Substructure – Nonlinear Fluid Viscous Damper

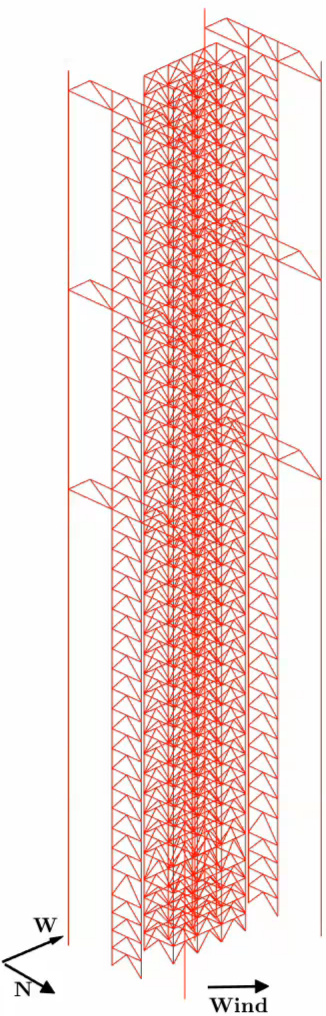
<u>Analytical Sub. Key features</u>:

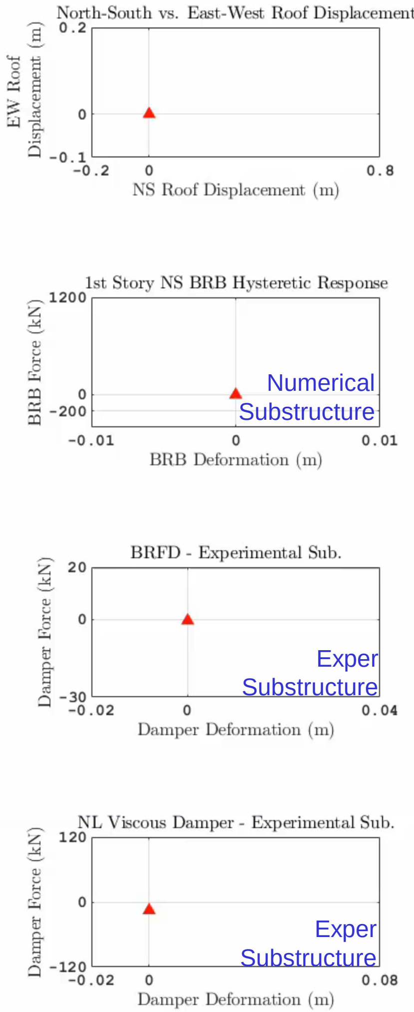
- 7903 DOF
- 2975 Elements
  - ➢ 2411 Nonlinear Explicit Force-based fiber elements
  - ➢ 11 Nonlinear Explicit Maxwell Elements[1] with real-time model updating (dampers placed in each outrigger at 20th, 30th, & 40th floors)
  - ➢ 553 Nonlinear truss elements
- Geometric nonlinearities
- Mass
- Inherent damping of building

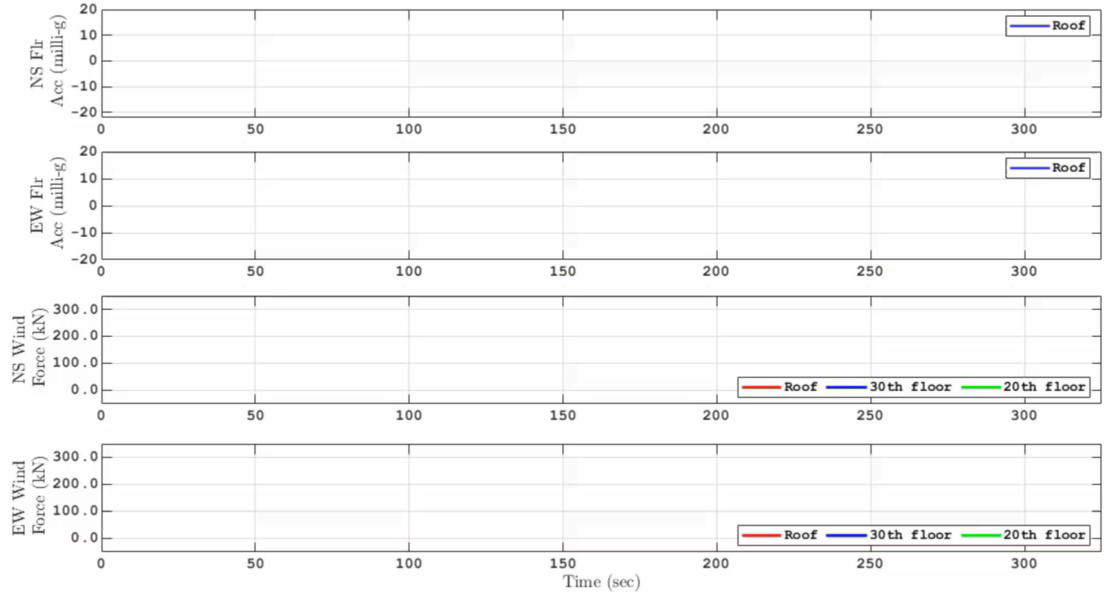
3-D Real-time Hybrid Simulation

110 mph, 700 MRI Wind Storm (Northwestern Windward Direction)

Multiple Experimental Substructures; Multi-natural Hazards







Friction TMD @ Roof

NL Viscous Dampers - Outrigger

3-D Real-time Hybrid Simulation of a Wind Excited Tall Building with Banded Rotary Friction Damper and NL Viscous Dampers

Southeastern 110mph, 700 MRI Wind Storm

Motions scaled by factor of 20 in animation

Research Projects

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

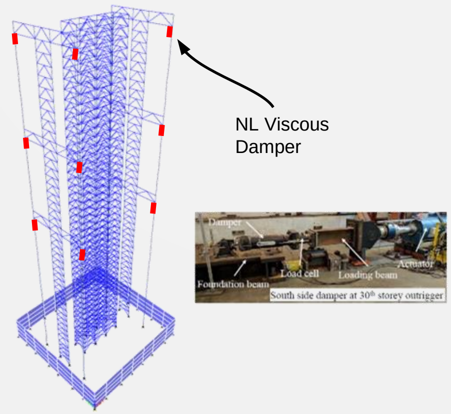
(CMMI 1463497) Lehigh University (James Ricles)

<u>With Supplemental Dampers in Outrigger Systems for Tall Buildings</u>

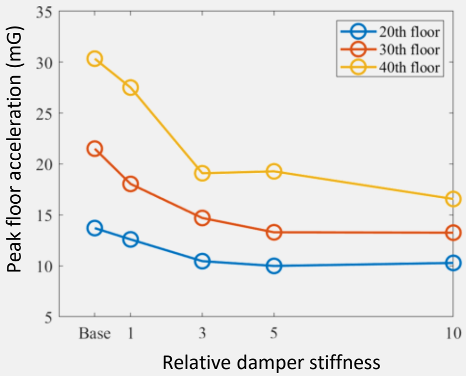
- Major Findings
  - Nonlinear viscous dampers in outrigger systems combined with a TMD can be effective in improving multi-hazard performance of tall buildings.
  - Attention must be given to prescribing sufficient damper stiffness relative to that of members in load path.

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

<u>Prototype 40-story building</u>



<u>3D Real-time hybrid simulation with on-line model updating</u>



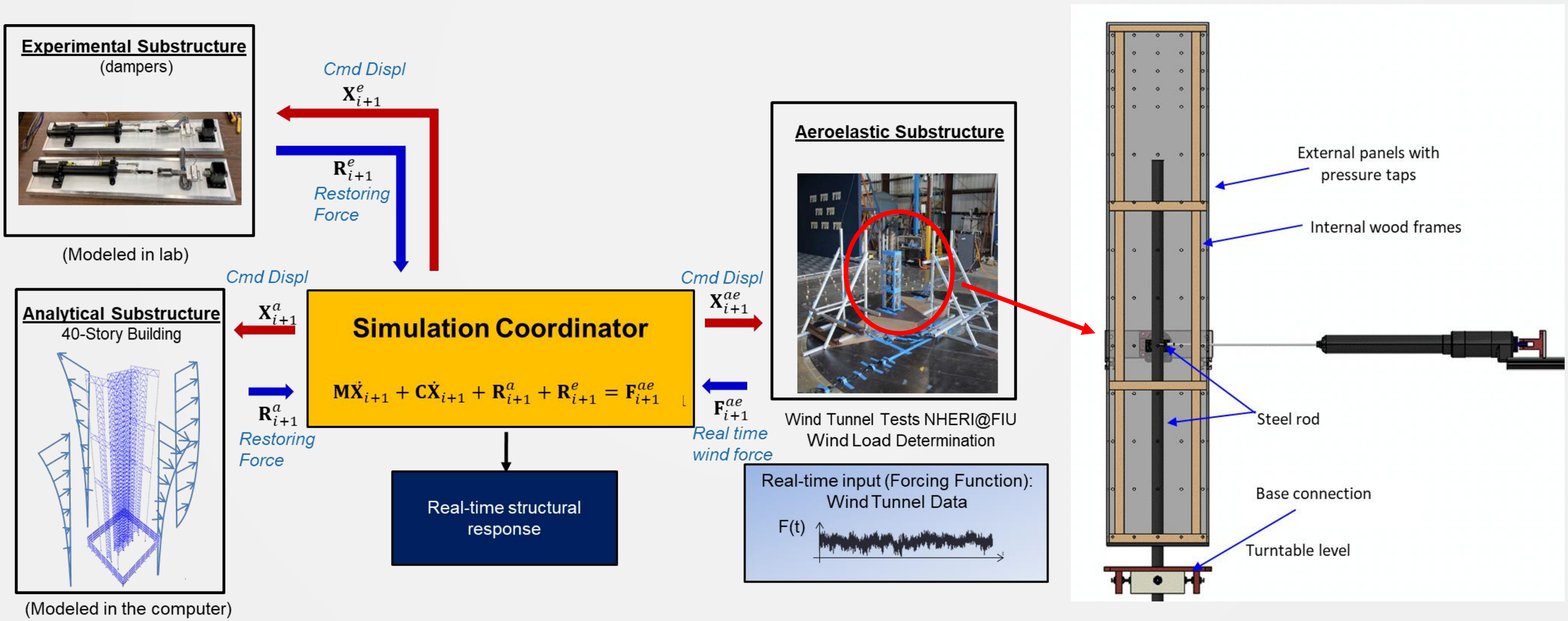
Al-Subaihawi, S., Kolay, C., Thomas Marullo, Ricles, J. M. and S. E. Quiel. (2020) "Assessment of Wind-Induced Vibration Mitigation in a Tall Building with Damped Outriggers Using Real-time Hybrid Simulations," *Engineering Structures*, 205, <u>https://doi.org/10.1016/j.engstruct.2019.110044</u>.

Research Projects

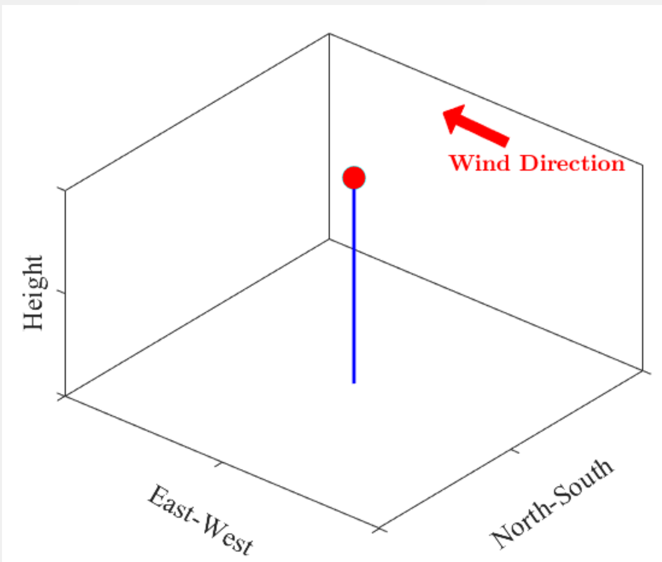
Collaborative Research: 3D Real-time Aeroelastic Hybrid Simulation of Wind-induced Vibrations on a Tall Building

(CMMI 2037899) Florida International University (Amal Elawady, Arindam Chowdhury), (2037771) Lehigh University (James Ricles)

- Overview
  - ➢ Develop novel 3D real-time aeroelastic hybrid simulation technologies to accurately assess wind-induced aeroelastic response of civil structures
  - ➢ Understand the effect of wind-structure interaction
  - ➢ Provide experimental validation of concepts for wind hazards mitigation



RTAHS Substructure



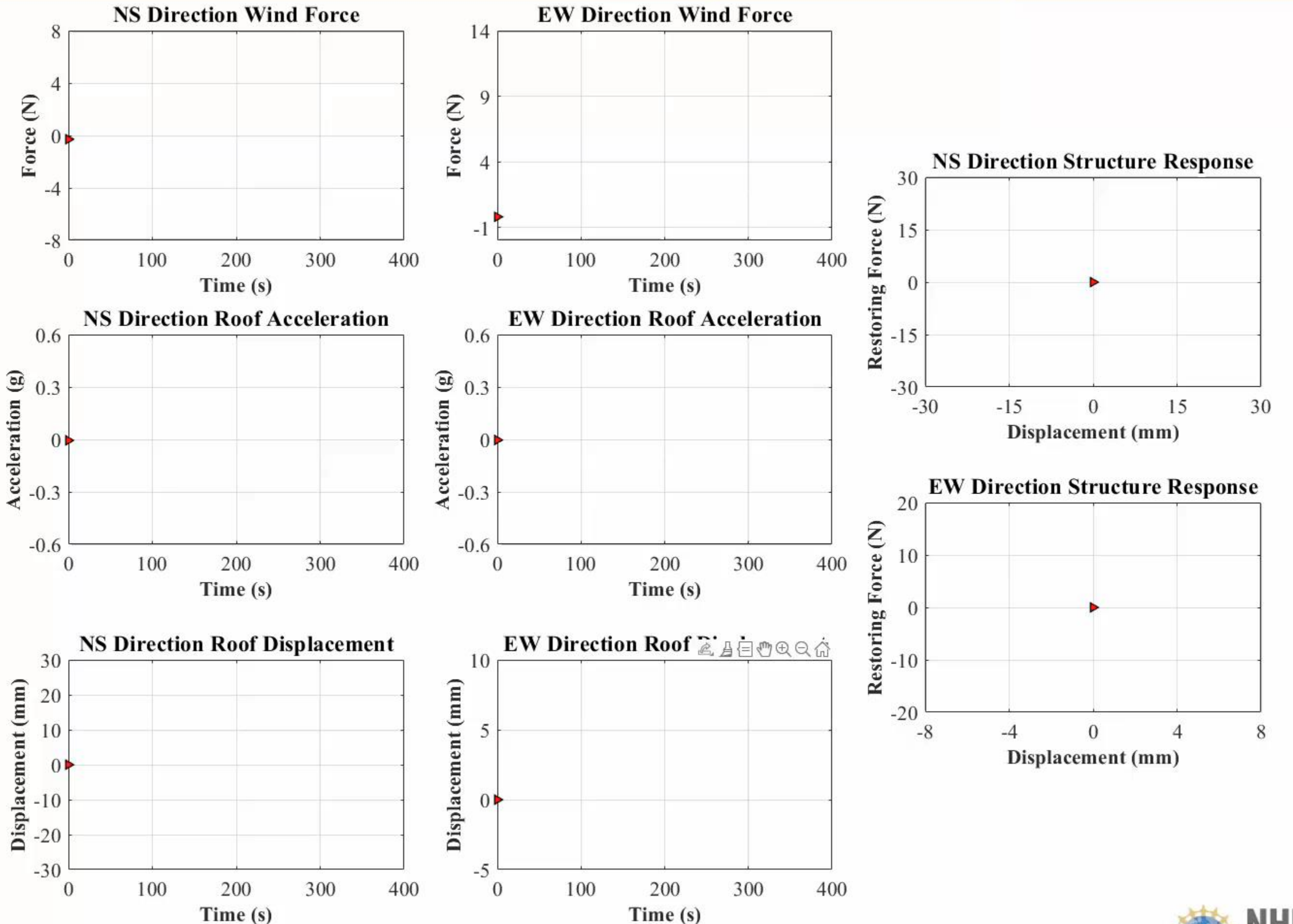
336 total number of pressure taps

Analytical Substructure
Determines restoring forces of structure based on displaced position obtained from integration algorithm

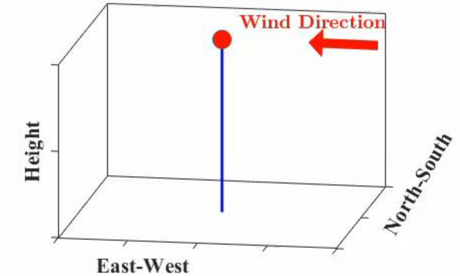
Aeroelastic Substructure
(Aeroelastic @1:150 scale): Measure wind pressures based on displaced position obtained from integration algorithm

3D RTAHS Application – Test 1: Linear model

3D Real-time Aeroelastic Hybrid Simulation of a 1:150 Scale Wind Excited Building (210 mph Western Wind)
40-Story As-Built Structure, Linear Model



Analytical Substructure



Experimental Substructure - RTAHS Building Model

NHERI LEHIGH UNIVERSITY FIU FLORIDA INTERNATIONAL UNIVERSITY

ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION LEHIGH UNIVERSITY NSF NSF NHERI CYBER-PHYSICAL SIMULATION

3D RTAHS Application – Test 1: Linear model

3D Real-time Aeroelastic Hybrid Simulation of a 1:150 Scale Wind Excited Building (210 mph Western Wind)
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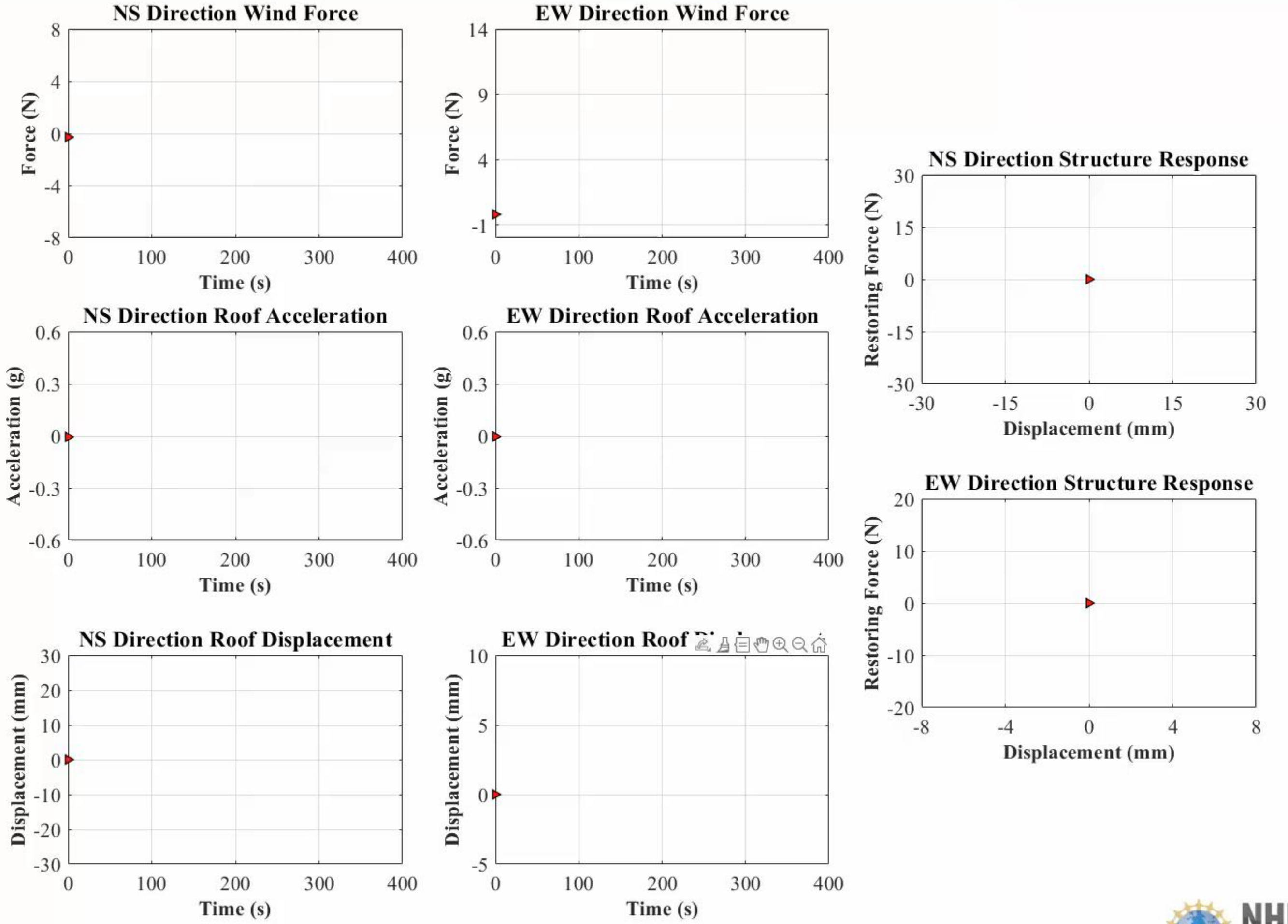
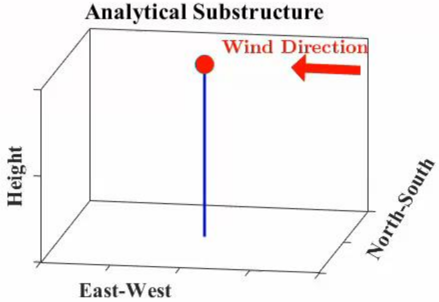
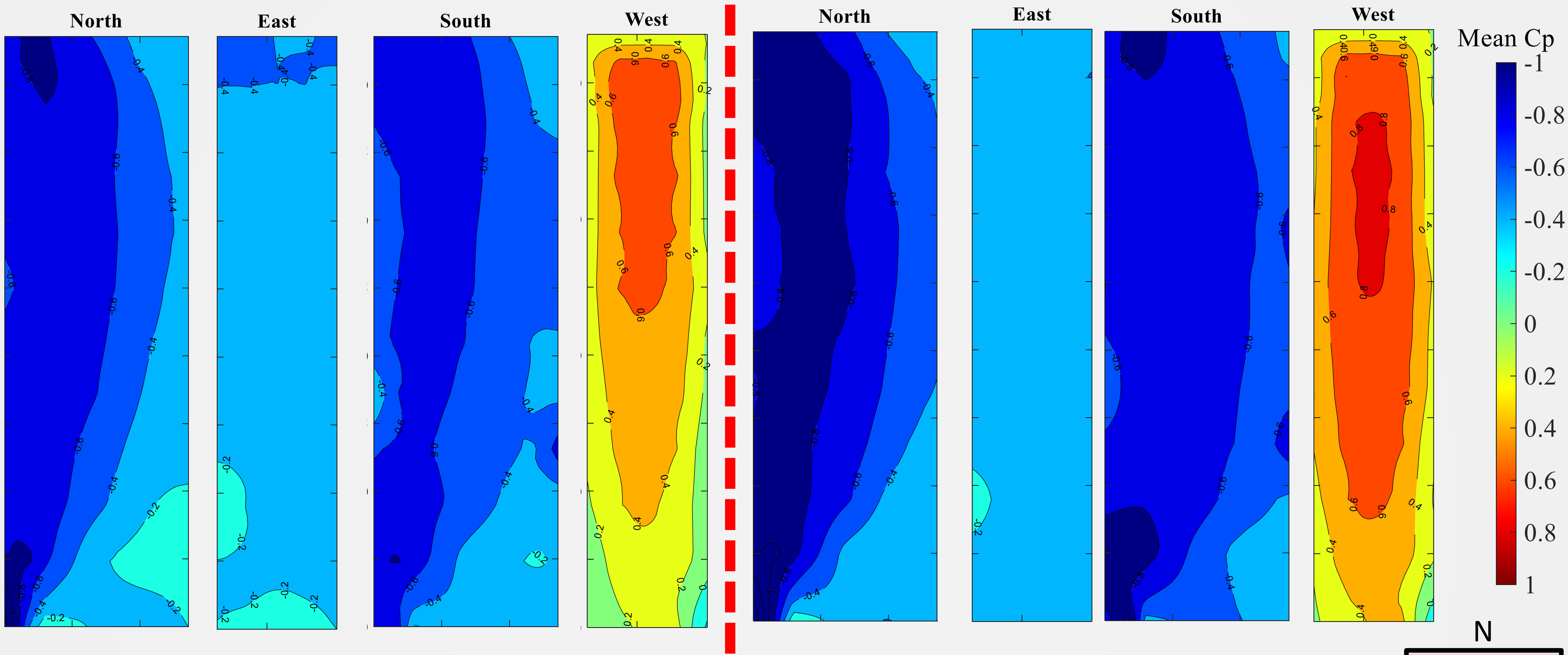




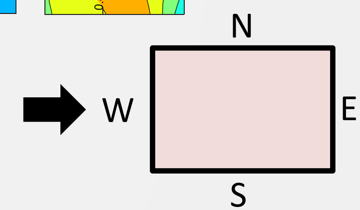
Experimental Substructure - RTAHS Building Model

3D RTAHS Results: Aeroelastic Effect



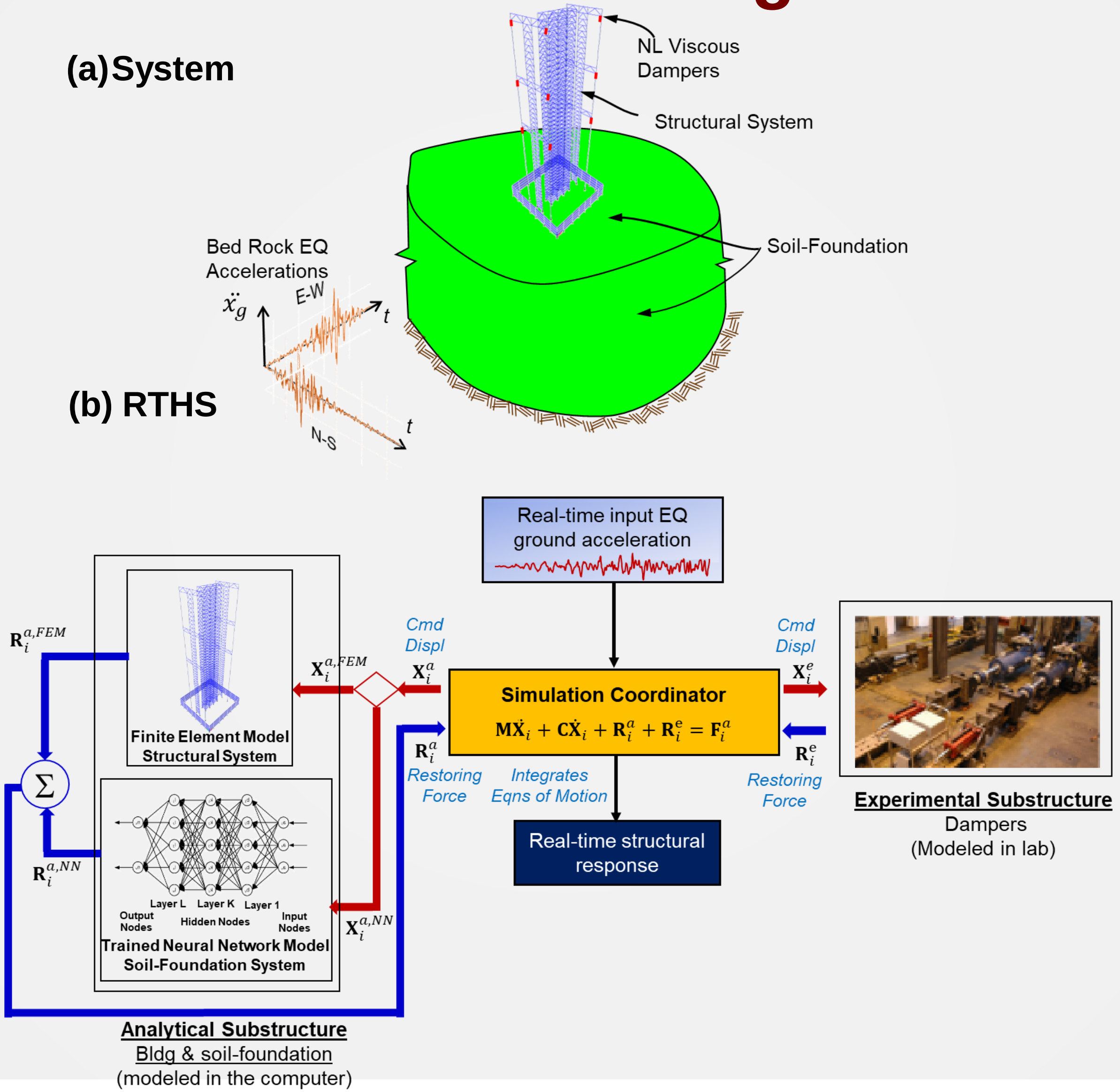
(a) Aerodynamic Model

(b) RTAHS Model



Some cases showed significant change (up to 40%) in the mean Cp after considering the aeroelastic effect.

RTHS of Soil-Structure-Foundation Systems Using Neural Networks – Lehigh University, MTS



3-D RTHS of Multi-Story Building Soil-Structure-Foundation System: (a) System; and, (b) RTHS Framework with Analytical Substructure Comprised of FEM and Neural Network Model.

Research Projects

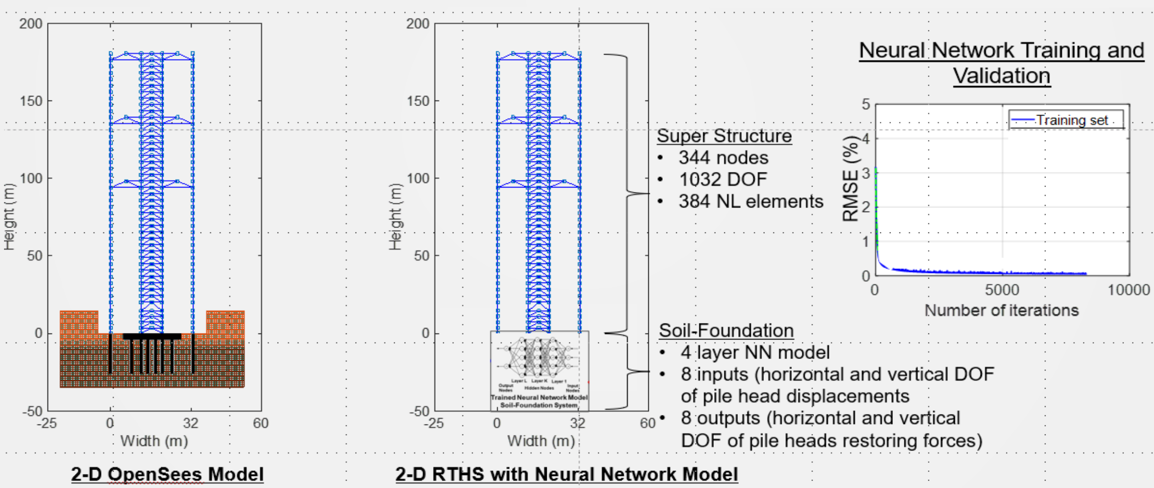
Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards

(CMMI 1463497) Lehigh University (James Ricles)

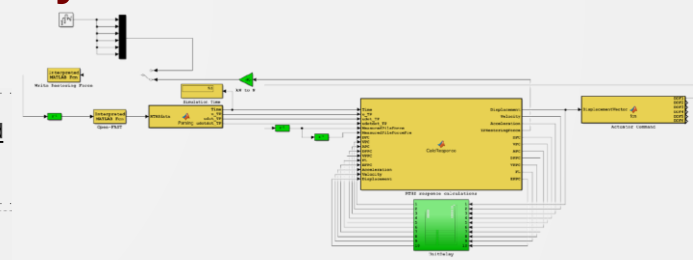
RTHS with Soil-Foundation-Structure Interaction Effects

- 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.

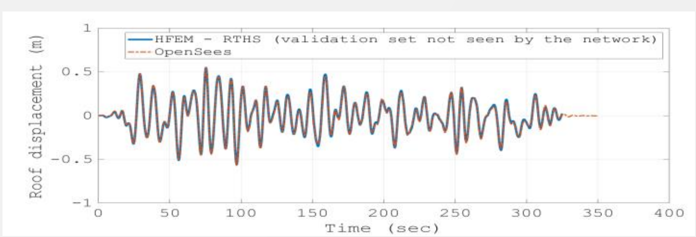
RTHS with Soil-Foundation-Structural System Interaction



Neural Network Model of Soil Training

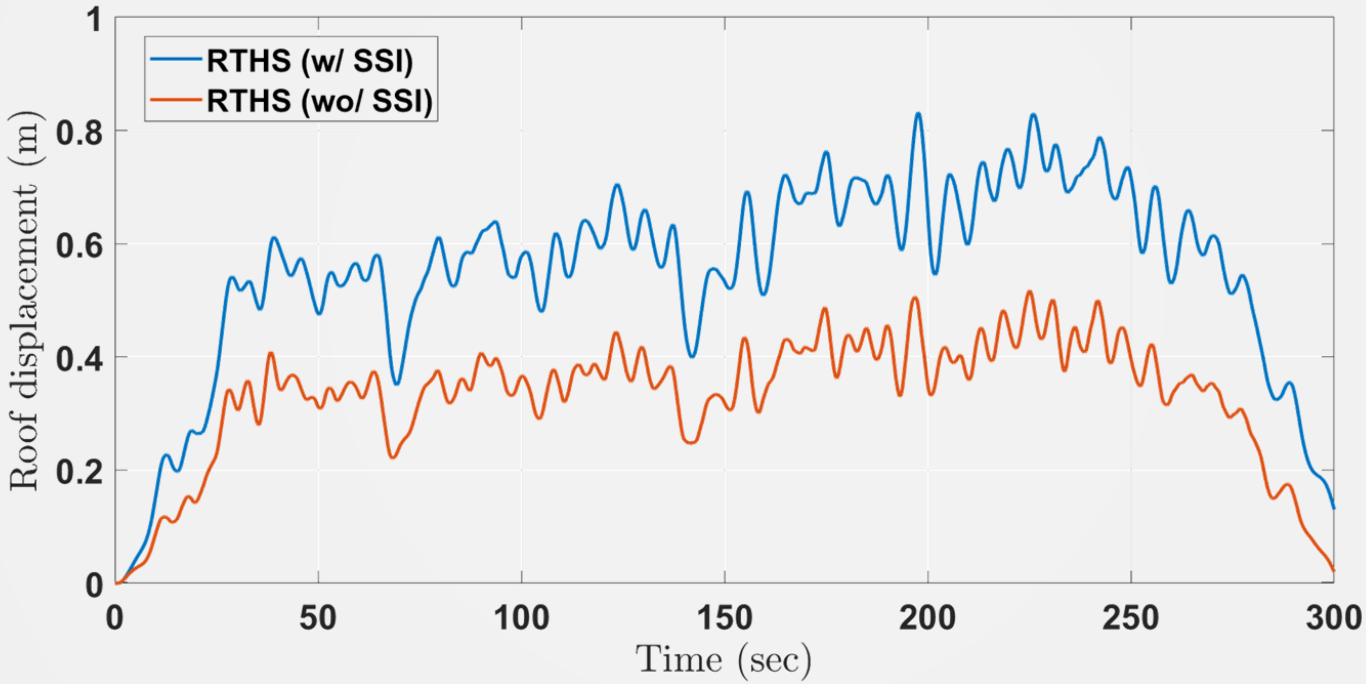


Simulink Block – User Tool



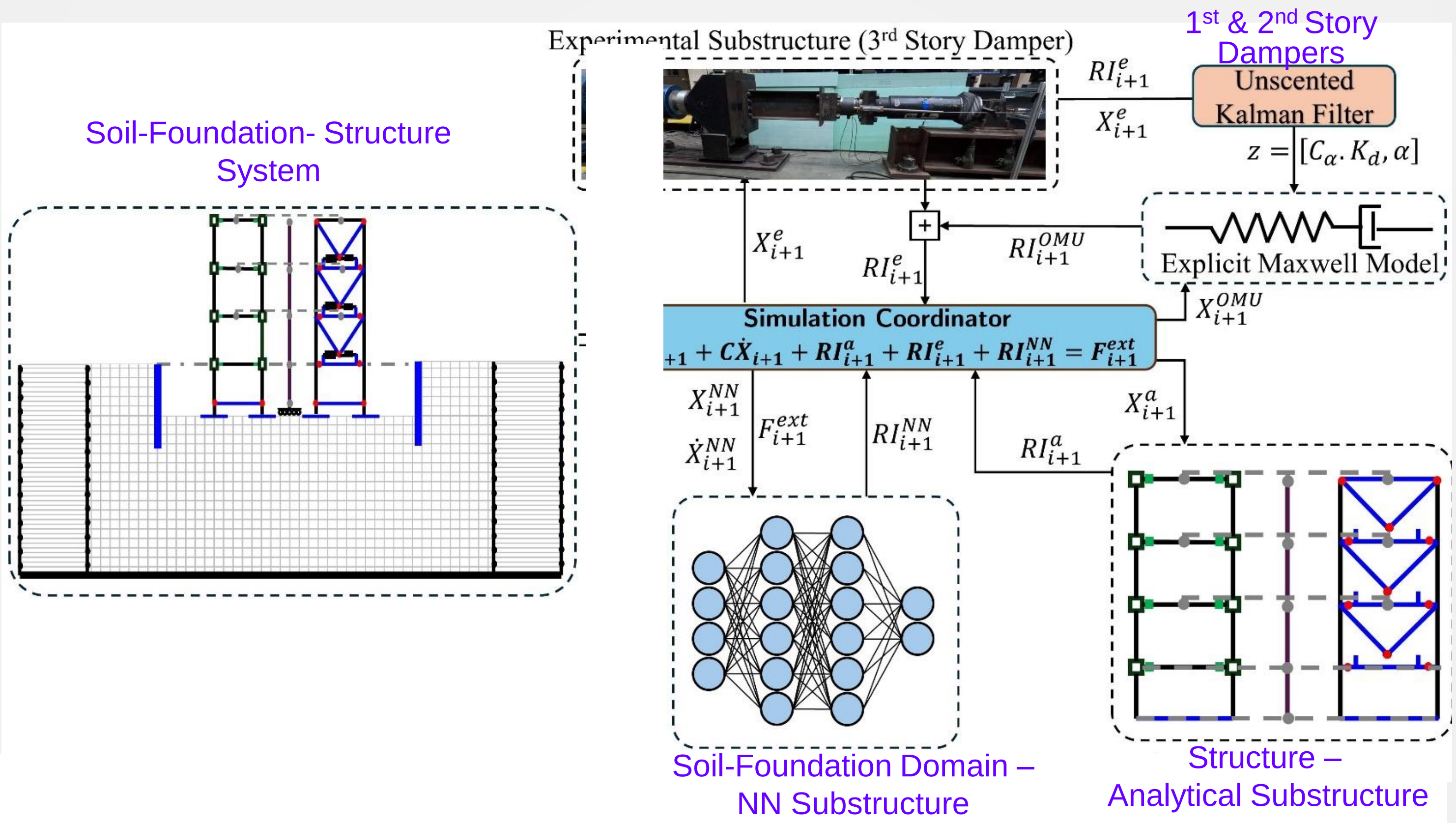
Comparison with OpenSees

RTHS of Soil-Structure-Foundation System
Roof Displacement Time History- Windward Direction



Multi-physics RTHS: Seismic Real-time Hybrid Simulation with Soil-Foundation-Structure Interaction Using Neural Networks

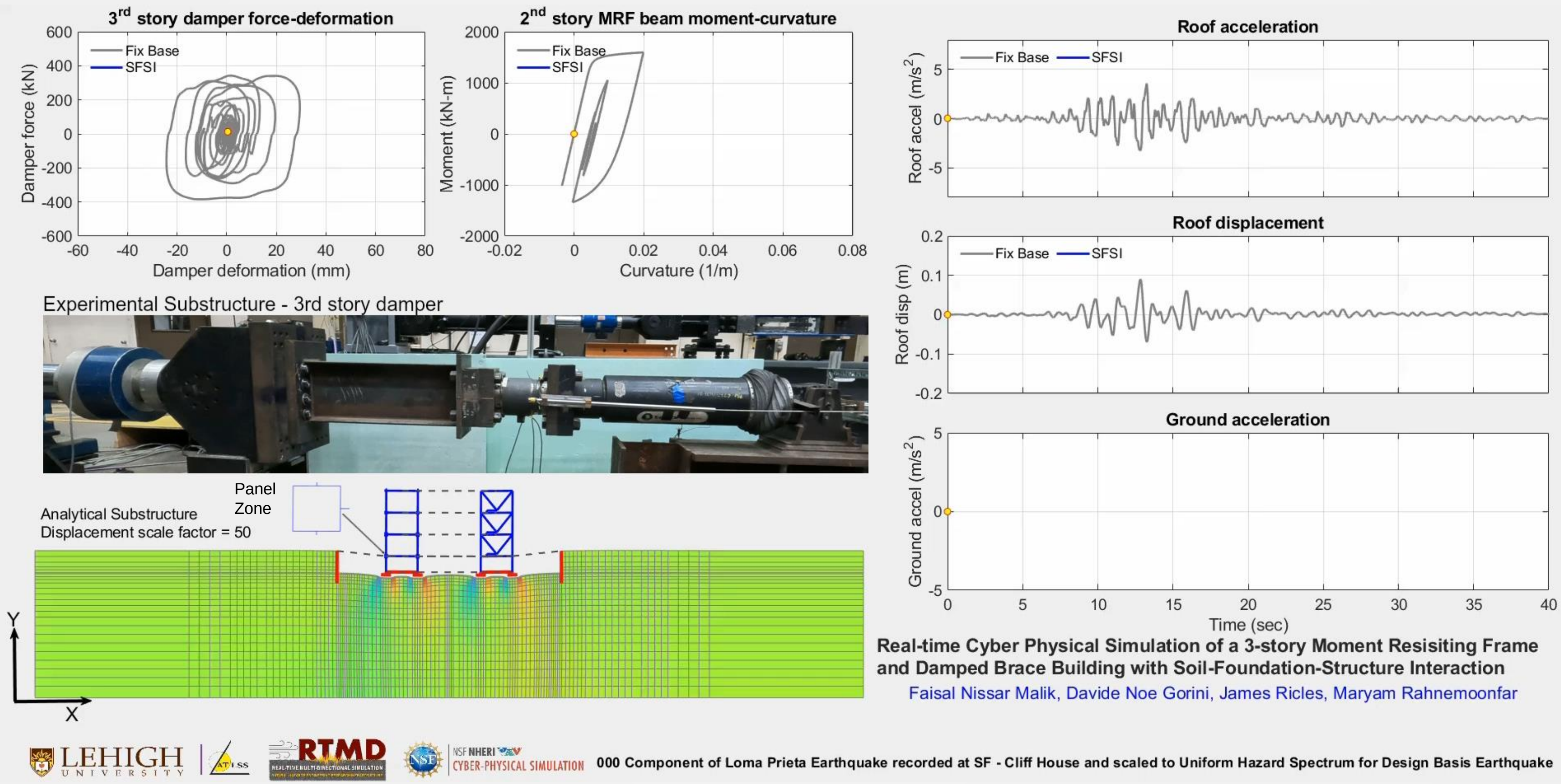
Faisal Malik, Davide Noe Gorini, James Ricles, and Maryam Rahnesmoonfar
Lehigh University & Trento University



Malik, F. “Multi-Physics Real-Time Cyber-Physical Simulation of Complex Nonlinear Structural Systems with Soil-Foundation-Structure Interaction,“ PhD Dissertation, Lehigh Univ., in progress

Malik, F. Gorini, D,N, Ricles, J., and M. Rahnesmoonfar, (2024). “Multi-Physics Framework for Seismic Real-time Hybrid Simulations with Soil-Foundation-Structure Interaction,” *Engineering Structures*, in preparation

Multi-physics RTHS: Seismic Real-time Hybrid Simulation with Soil-Foundation-Structure Interaction Using Neural Networks



Malik, F. “Multi-Physics Real-Time Cyber-Physical Simulation of Complex Nonlinear Structural Systems with Soil-Foundation-Structure Interaction,“ PhD Dissertation, Lehigh Univ., in progress.

Malik, F. Gorini, D,N, Ricles, J., and M. Rahnesmoonfar, (2024). “Multi-Physics Framework for Seismic Real-time Hybrid Simulations with Soil-Foundation-Structure Interaction,” *Engineering Structures*, in preparation.

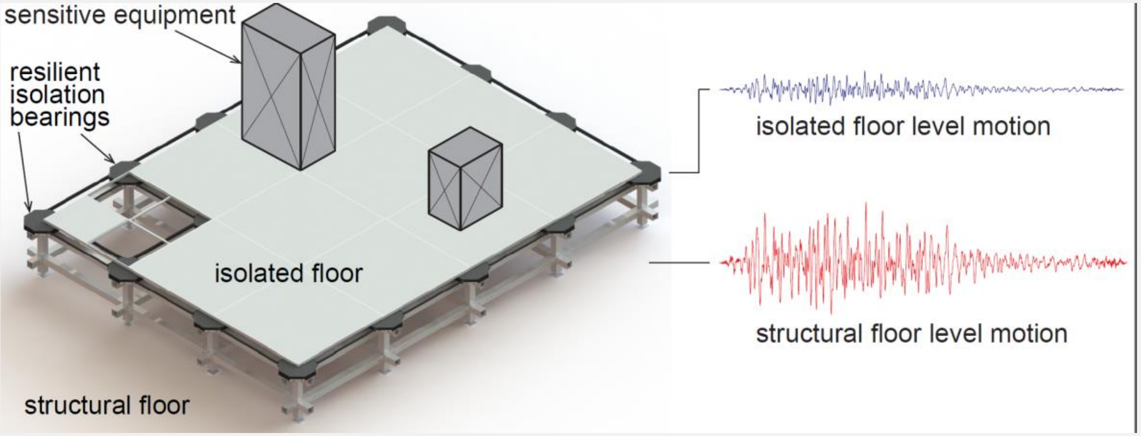
Research Projects

RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing

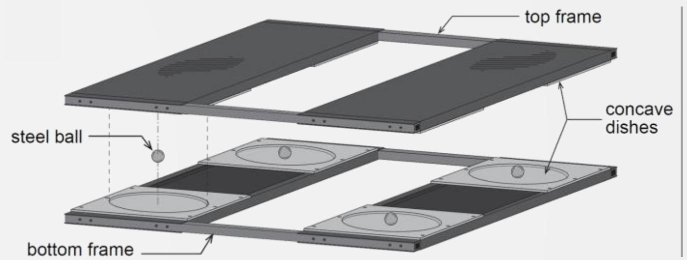
(OIA 1929151) University of Oklahoma (Scott Harvey)

Overview

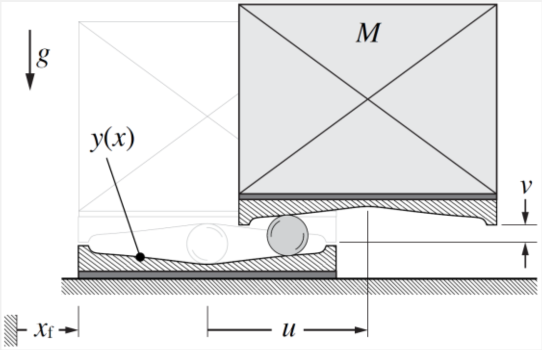
- Investigate the multi-directional nonlinear dynamics of floor isolation systems (FISs) used to reduce seismic force demand and protect vital building contents.
- Rigorously evaluate a design methodology for multi-functional FISs incorporating building-FIS interactions.



Floor isolation of critical building contents



Floor isolation system



Rolling Pendulum (RP) bearing system

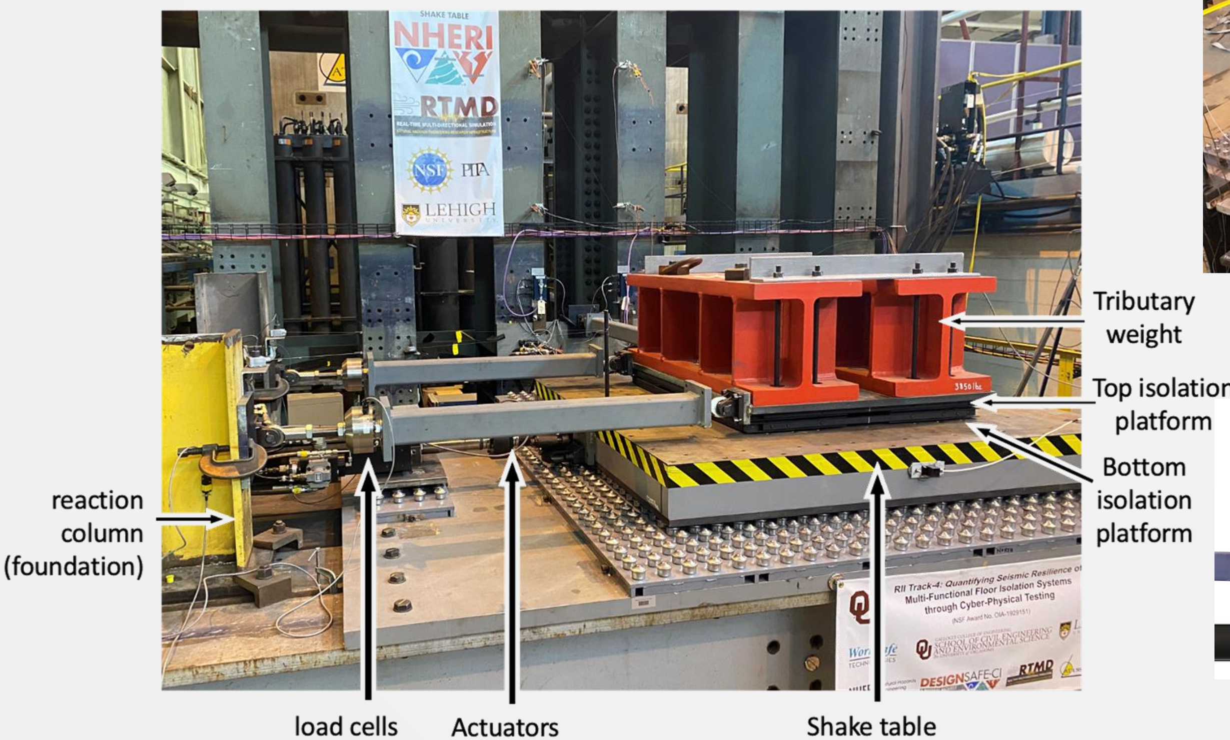
Research Projects

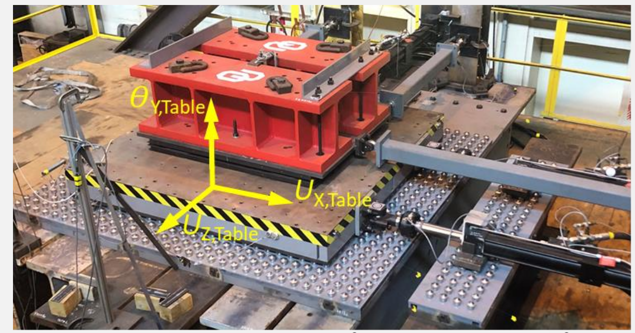
RII Track-4: Quantifying Seismic Resilience of Multi-Functional Floor Isolation Systems through Cyber-Physical Testing

(OIA 1929151) University of Oklahoma (Scott Harvey)

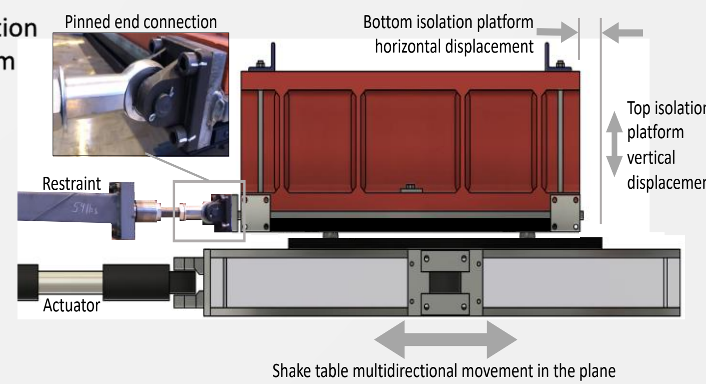
Scope

- Perform large-scale FIS characterization tests to experimentally validate physics-based mathematical models.
- Perform large-scale real-time hybrid simulations to quantify the performance of FISs which incorporate multi-scale building-FIS interactions.
- Use of NHERI Lehigh Multidirectional Shake Table





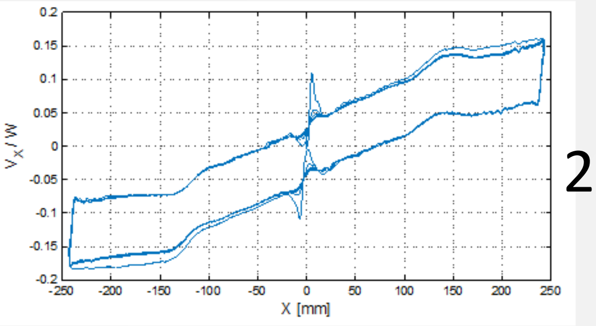
South-West top general view



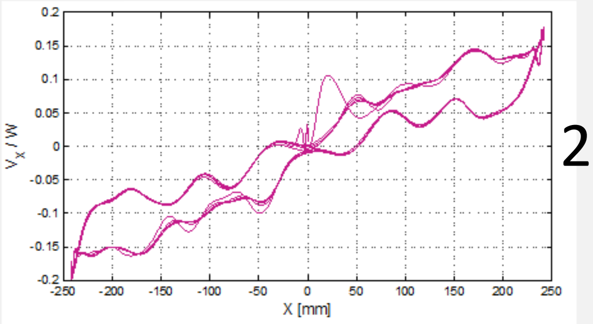
Floor isolation of critical building contents

Characterization Tests

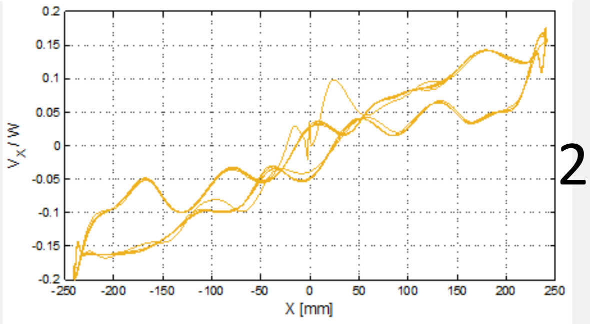
Normalized shear vs displacement in X –direction: Multi-directional and rate dependency



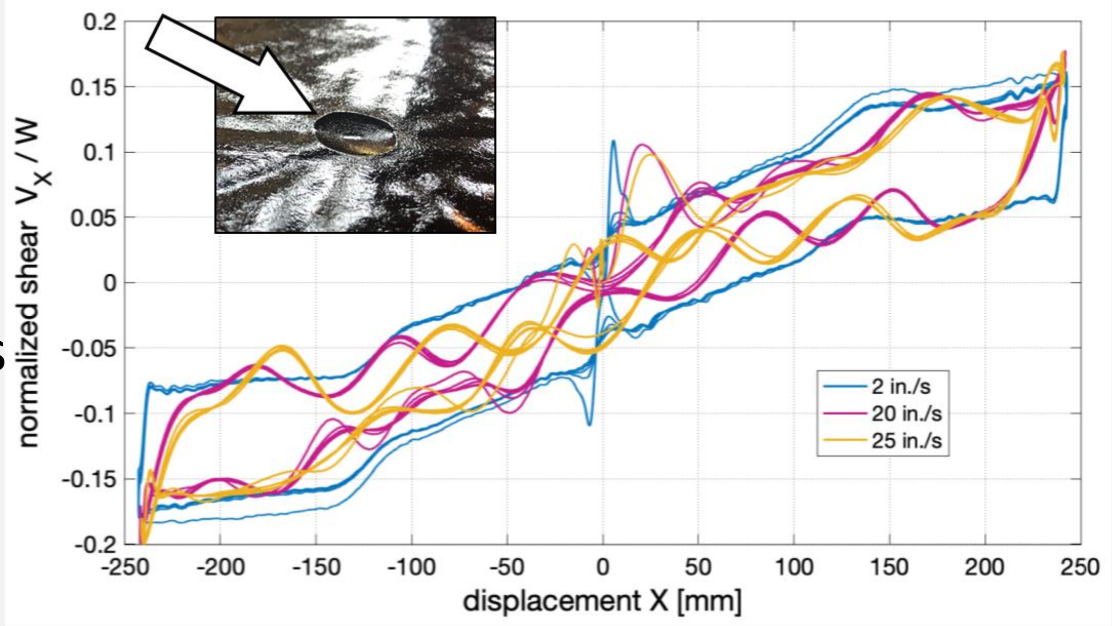
2 in./s



20 in./s



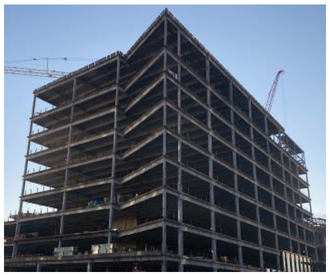
25 in./s



With increasing velocity, higher frequencies have a predominant effect on the response

Base Isolation of Server Cabinets – Rolling Pendulum Bearings

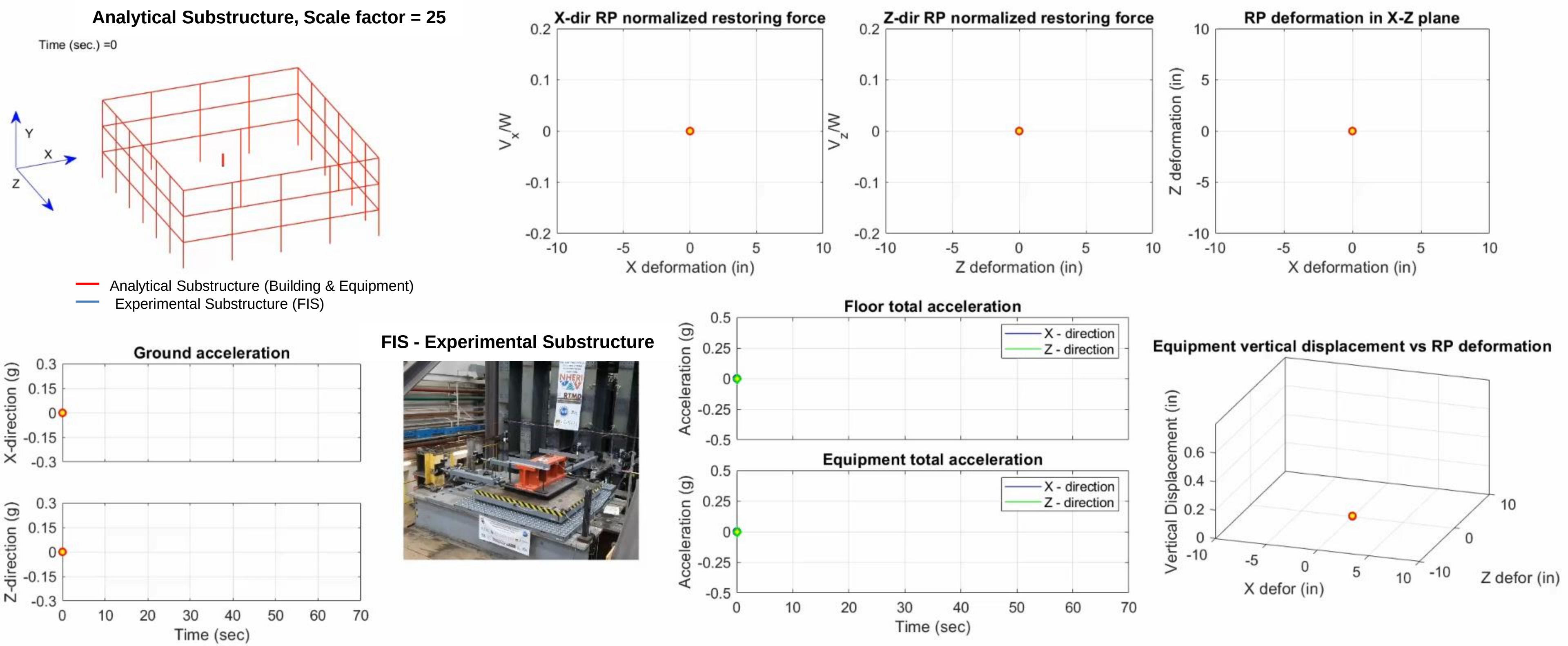
Multi-directional RTHS Scheme


Structure of interest


Server cabinet on top of RP isolation system

3-D Real-time Hybrid Simulation

SMRF with RP Isolation System (FIS) @ 2nd Floor, Coalinga EQ Scaled to SLE



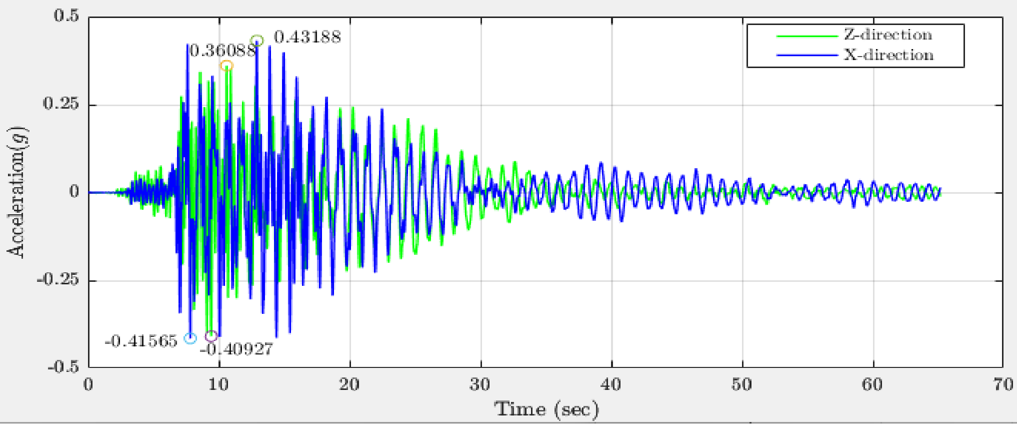
X-direction = 270 component, Z-direction = 360 component

3-D Real-time Hybrid Simulation of a 3-Story SMRF with 2nd Floor Rolling Pendulum Equipment Isolation System: 1983 Coalinga EQ Bidirectional Ground Motions Recorded at Cantua Creek School and Scaled to SLE Hazard Level.

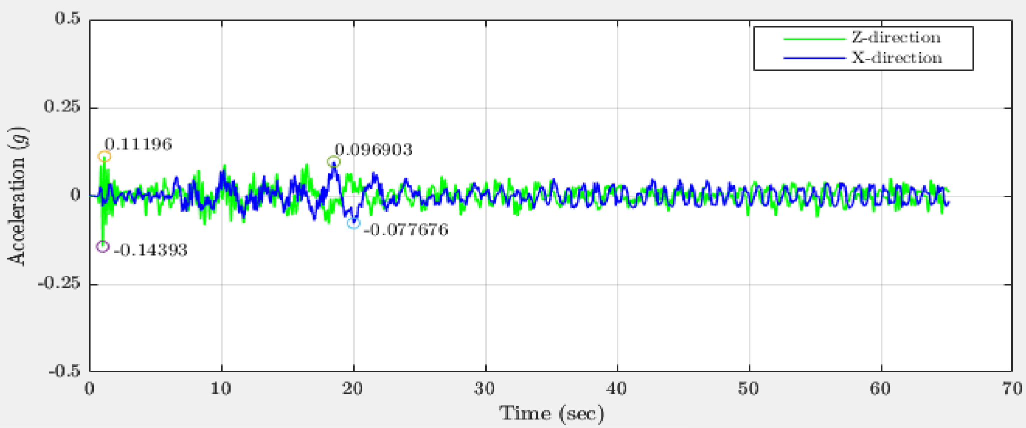
Equipment Acceleration
SMRF with RP Isolation System @ 2nd Floor

Reduction in Equipment Total Acceleration	
X-Direction	Z-Direction
81.3%	68.9%

SMRF 2nd Floor Total Acceleration



Equipment Total Acceleration



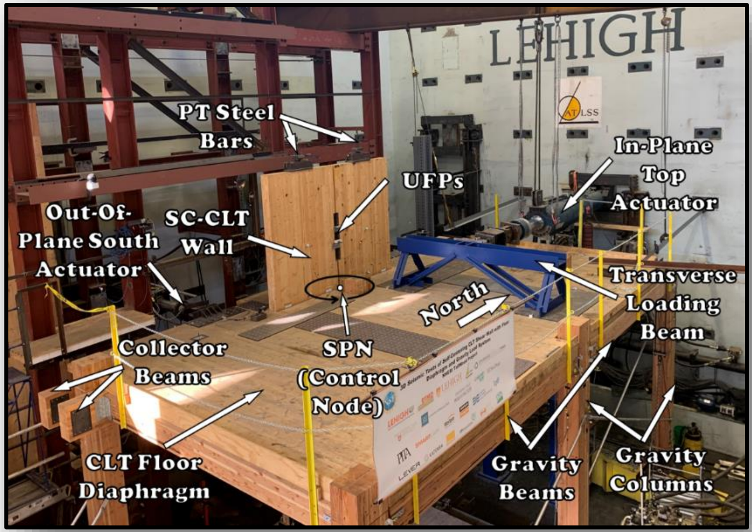
Research Projects

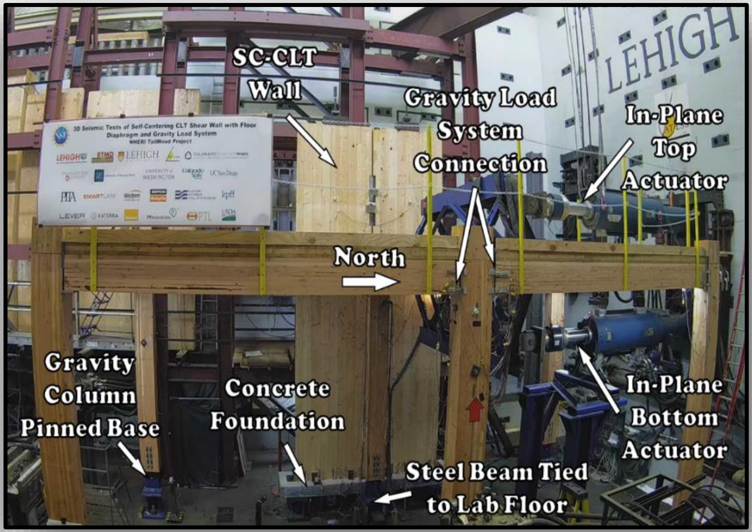
Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings

(CMMI 1636164) Colorado School Mines (Shiling Pei), (CMMI 1635156) Washington State (James Dolan), (CMMI 1635227) Lehigh University (James Ricles)

- Overview
  - Design and construct a low-damage, resilient 3-D CLT building sub-assembly
  - Investigate the lateral-load response and damage of SC-CLT walls under multidirectional loading
  - Investigate the associated response of the CLT floor diaphragm, collector beams, and gravity load system within this 3-D sub-assembly under multidirectional loading

Isometric and long-side view of 0.625-scale test sub-assembly





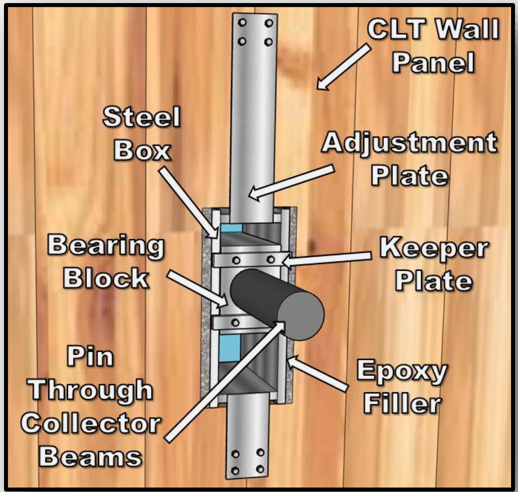
Amer, A., Sause, R., and Ricles, J. (2023) "Experimental Response and Damage of SC-CLT Shear Walls under Multidirectional Cyclic Lateral Loading." Journal of Structural Engineering. 10.1061/JSENDH/STENG-12576.

Research Projects

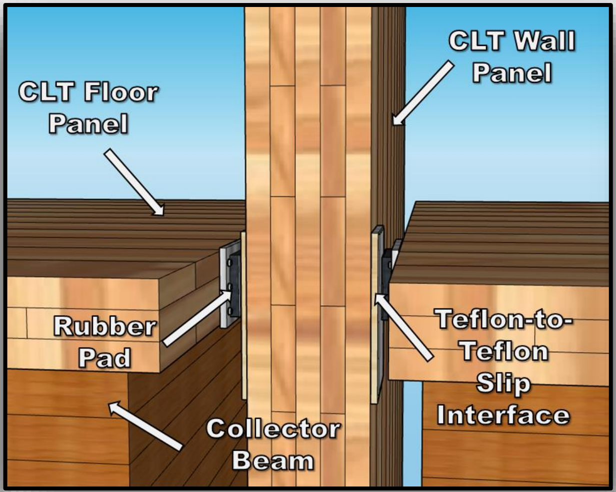
Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings

(CMMI 1636164) Colorado School Mines (Shiling Pei), (CMMI 1635156) Washington State (James Dolan), (CMMI 1635227) Lehigh University (James Ricles)

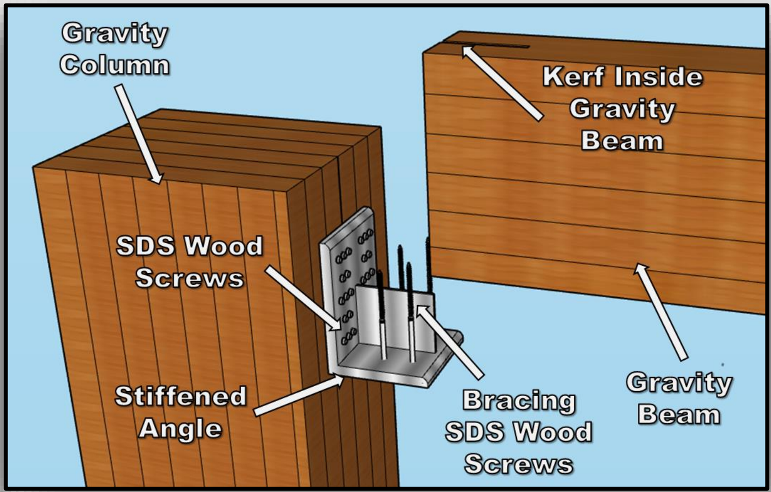
- Test Sub-Assembly Components and Connection Details
  - Design considering force and/or deformation demands expected during the multidirectional lateral-load tests
  - 3.0% story-drift as performance objective for damage initiation to sub-assembly components and connection details



Collector-beam-to-SC-CLT-wall connection details



CLT-floor-diaphragm-to-SC-CLT-wall connection details



Gravity-beam-to-gravity-column connection details

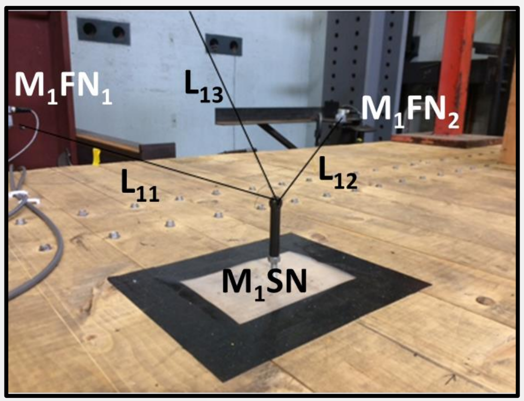
Amer, A. (2023) “Multidirectional Experimental Performance of a Seismically Resilient Self-Centering Cross-Laminated Timber Shear Wall System.” PhD Dissertation, Lehigh University, Bethlehem, PA.

Research Projects

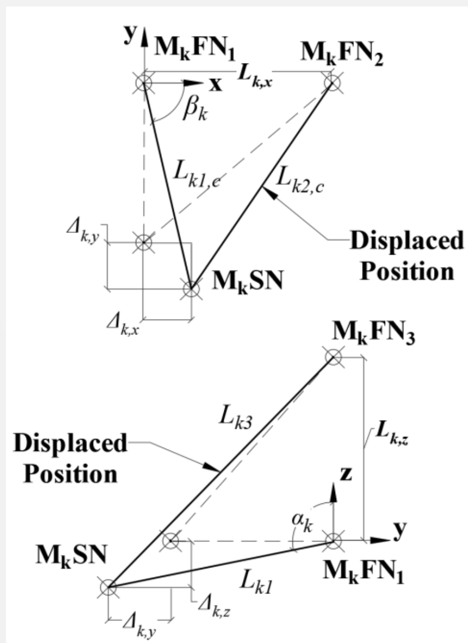
Collaborative Research: Development and Validation of Resilience-Based Seismic Design Methodology for Tall Wood Buildings

(CMMI 1636164) Colorado School Mines (Shiling Pei), (CMMI 1635156) Washington State (James Dolan), (CMMI 1635227) Lehigh University (James Ricles)

- Multidirectional Displacement Control Scheme
  - ➢ In-plane and out-of-plane story-drifts and vertical motion of the test sub-assembly
  - ➢ Control algorithm for 3-D large-scale lateral-load testing with flexible diaphragms
  - ➢ Kinematic relationship between the control node, feedback displacement sensors, and actuator command displacements



Instrumentation layout for 3-D displacement feedback



3-D motion of test sub-assembly

Amer, A. (2023) "Multidirectional Experimental Performance of a Seismically Resilient Self-Centering Cross-Laminated Timber Shear Wall System." PhD Dissertation, Lehigh University, Bethlehem, PA.

Research Projects

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

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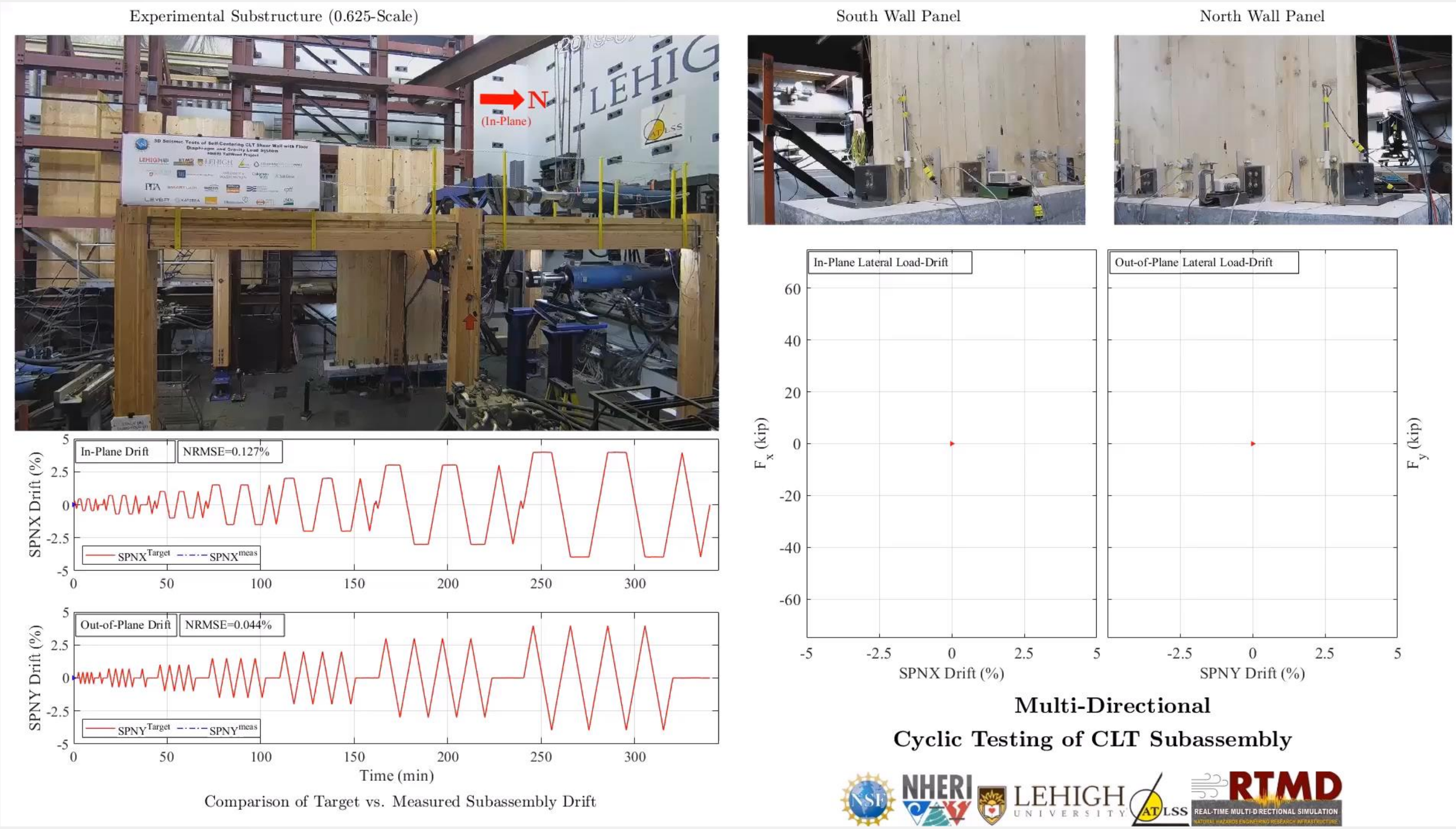
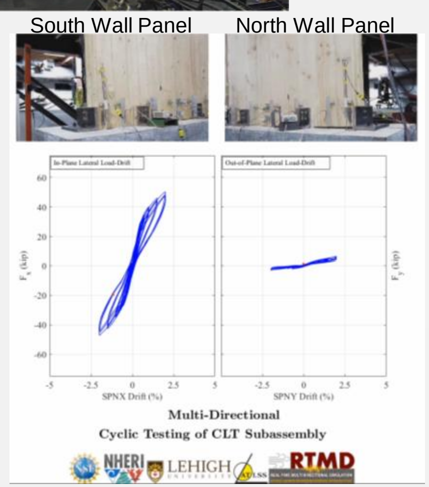


Illustration of the Important Aspects of Multi-directional Testing

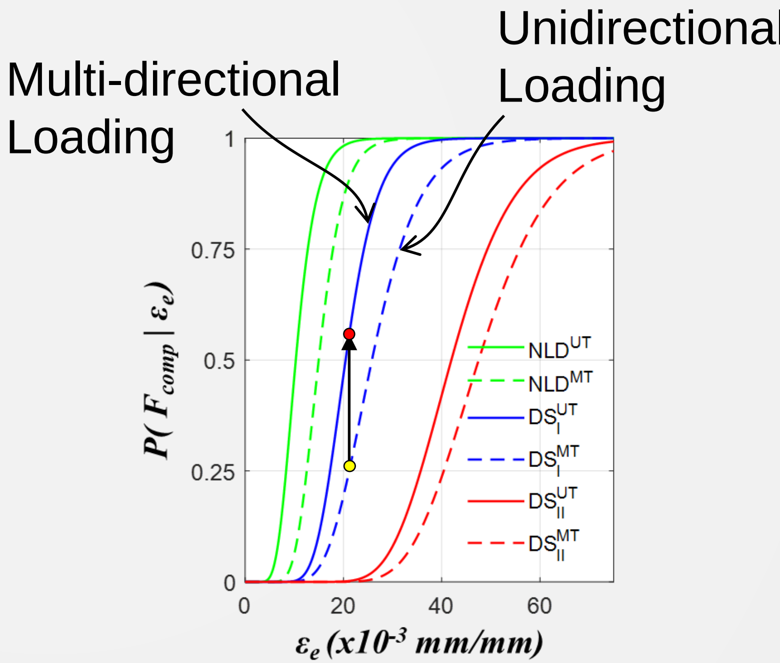
Seismic Performance of Self-Centering Cross-Laminated Timber Shear Walls Systems

Multi-directional Loading – Resulted in Significant diminishing of the resiliency of CLT Shear Walls (probability of exceeding damaging limit states increases by a factor of 2)

Experimental Substructure



Amer, A. (2023) "Multidirectional Experimental Performance of a Seismically Resilient Self-Centering Cross-Laminated Timber Shear Wall System." PhD Dissertation, Lehigh University, Bethlehem, PA.



Wall Toe Damage Fragility Curve

Current Projects at NHERI Lehigh EF

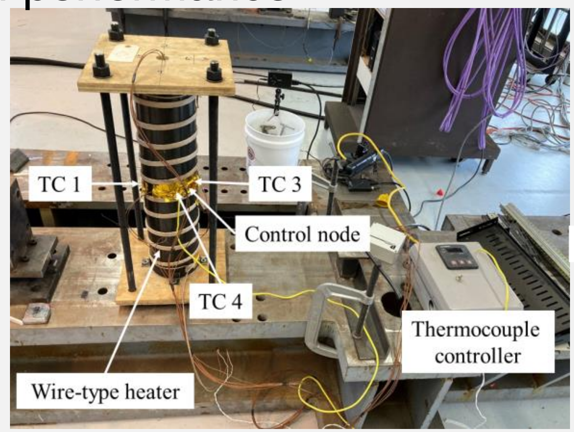
Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures: (CMMI 1662816) **University of Arizona (Robert**

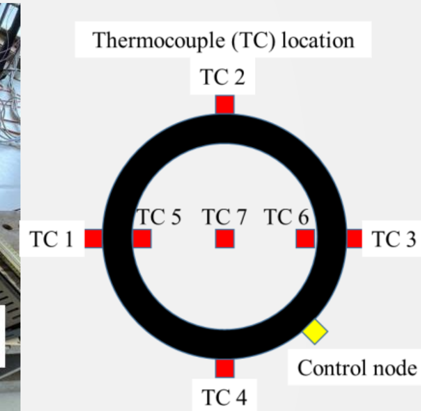
Research Projects

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

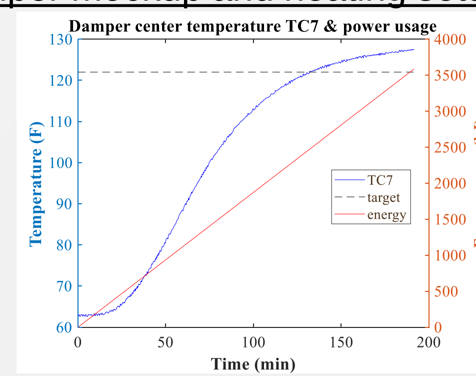
- ➢ Characterize dynamic behavior under various temperatures
- ➢ Perform RTHS to validate mitigation performance





Pressurized Sand-Damper [1]

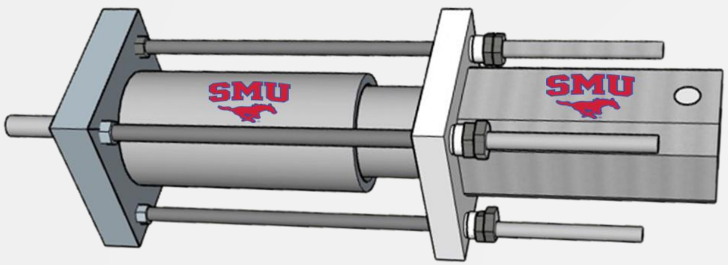
Damper mockup and heating setup



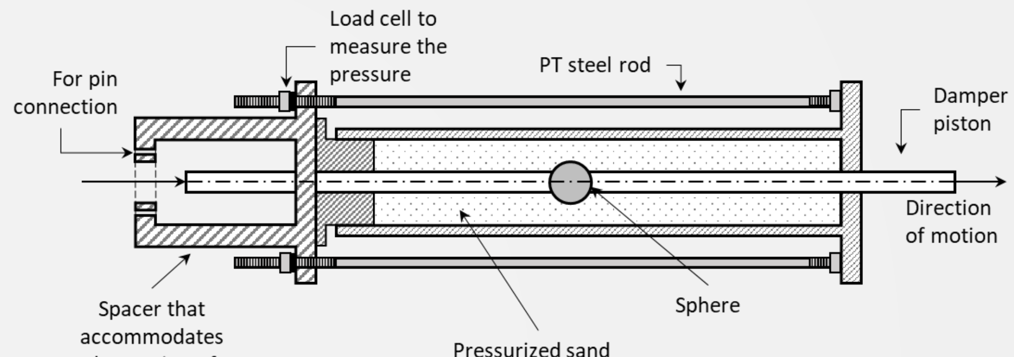
[1] Makris, N., Palios, X., Moghimi, R. and Bousias, S. Pressurized sand damper for earthquake and wind engineering: Design, testing and characterization. Journal of Engineering Mechanics, ASCE, 2021, 147(4): 04021014

Characterization test of Pressurized Sand Damper

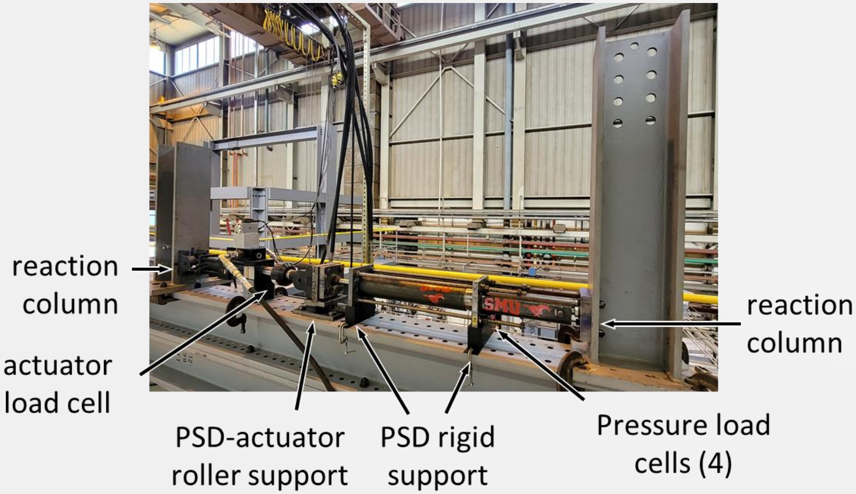
Investigation of a Novel Pressurized Sand Damper for Sustainable Seismic and Wind Protection of Buildings: (CMMI 2036131) **Southern Methodist University (Nicos Makris(PI))**



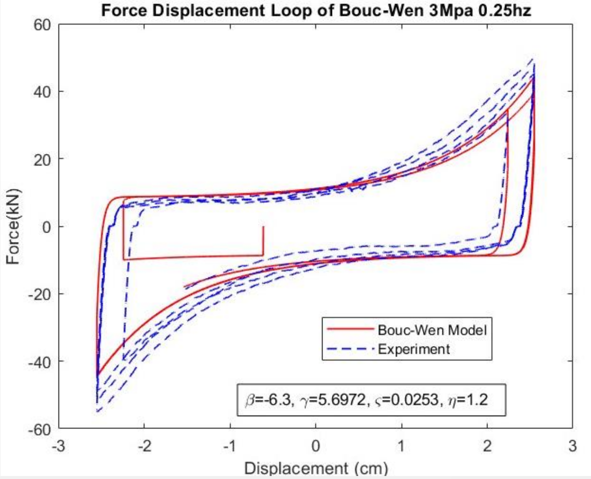
Pressurized Sand Damper (PSD)



Schematic of the PSD



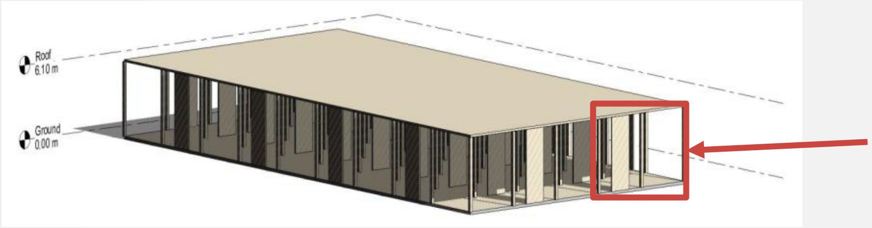
Characterization test setup



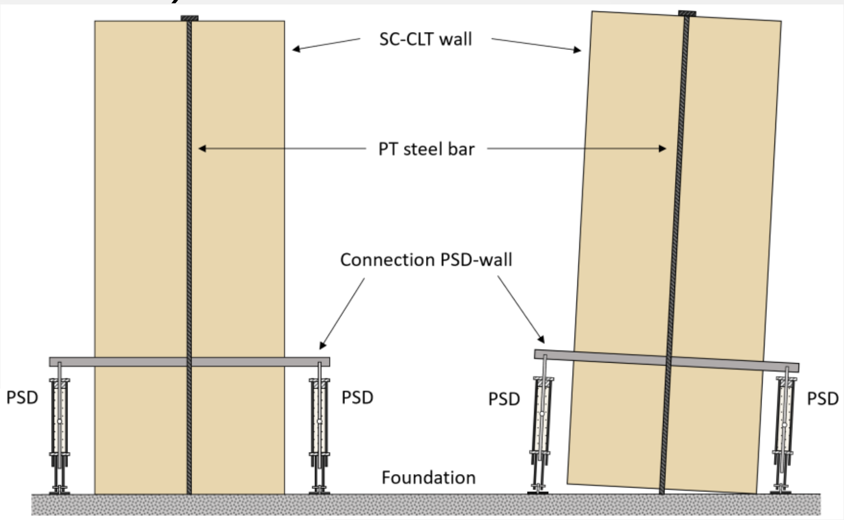
Model fitting result (Bouc-Wen Model)

RTHS of a Rocking Cross Laminated Timber (CLT) Structure Equipped with Pressurized Sand Damper

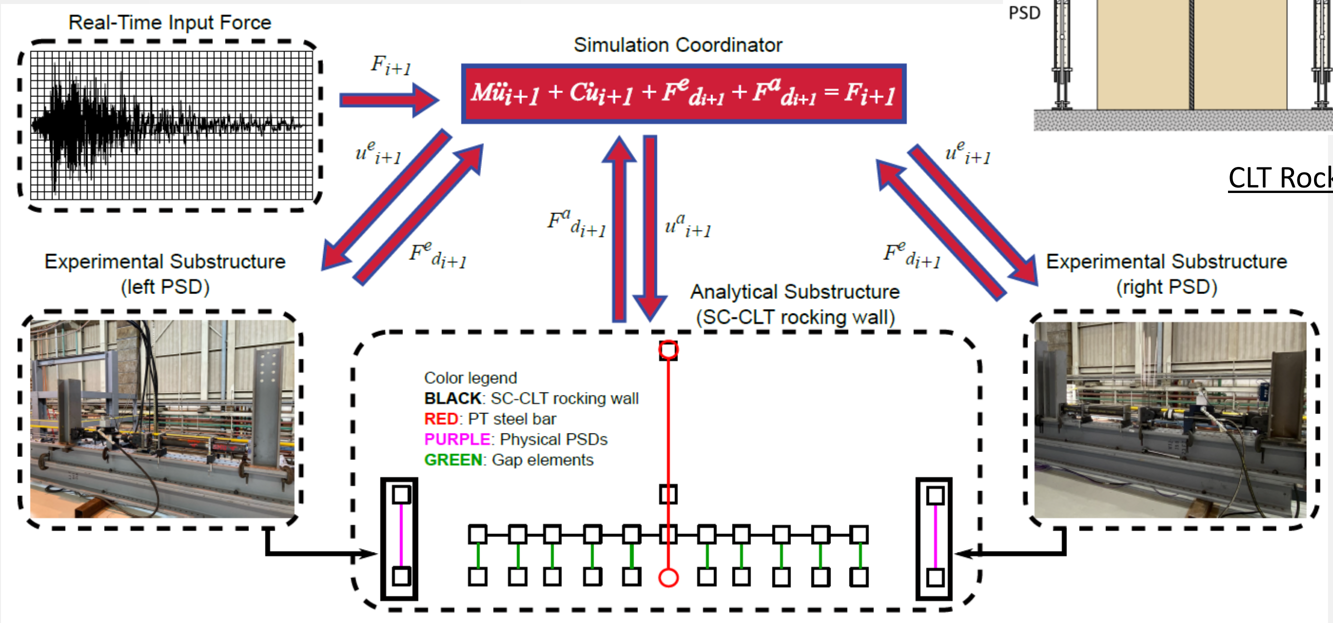
Investigation of a Novel Pressurized Sand Damper for Sustainable Seismic and Wind Protection of Buildings: (CMMI 2036131) **Southern Methodist University (Nicos Makris(PI))**



Selected CLT Structure

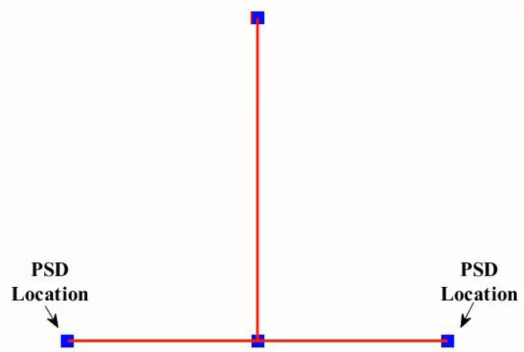


CLT Rocking Wall equipped with PSDs

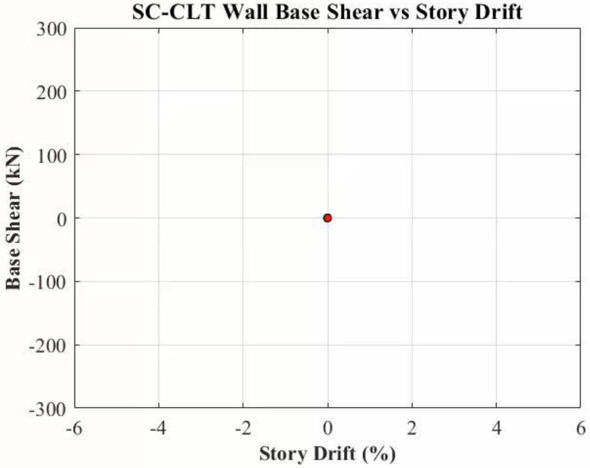


Real-time Hybrid Simulation of a CLT Rocking Wall System equipped with Pressurized Sand Dampers (PSD) subject to DBE Level Kocaeli Earthquake

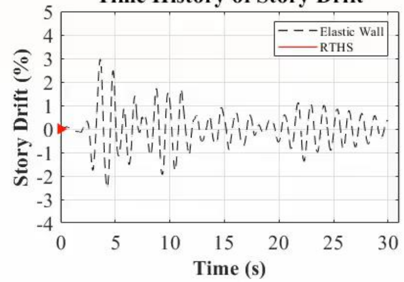
Analytical Substructure



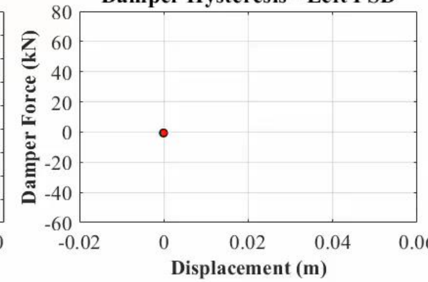
SC-CLT Wall Base Shear vs Story Drift



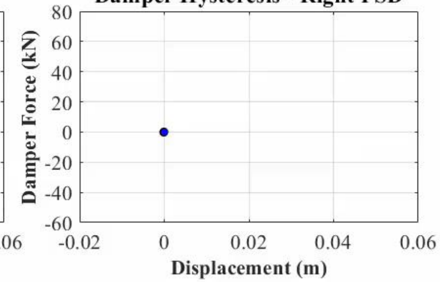
Time History of Story Drift



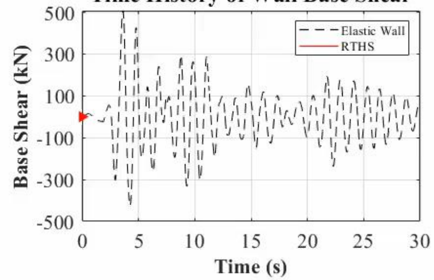
Damper Hysteresis - Left PSD



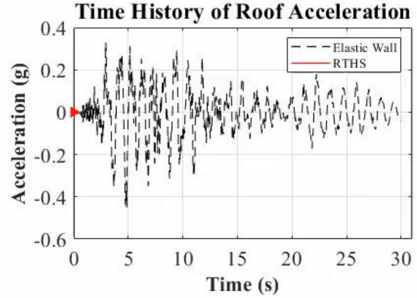
Damper Hysteresis - Right PSD



Time History of Wall Base Shear



Time History of Roof Acceleration



Experimental Substructure

Left PSD

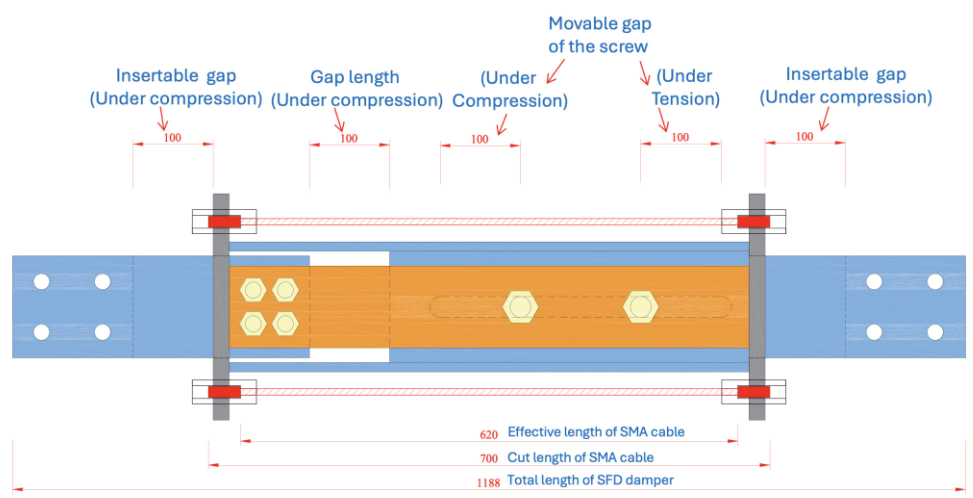
Right PSD

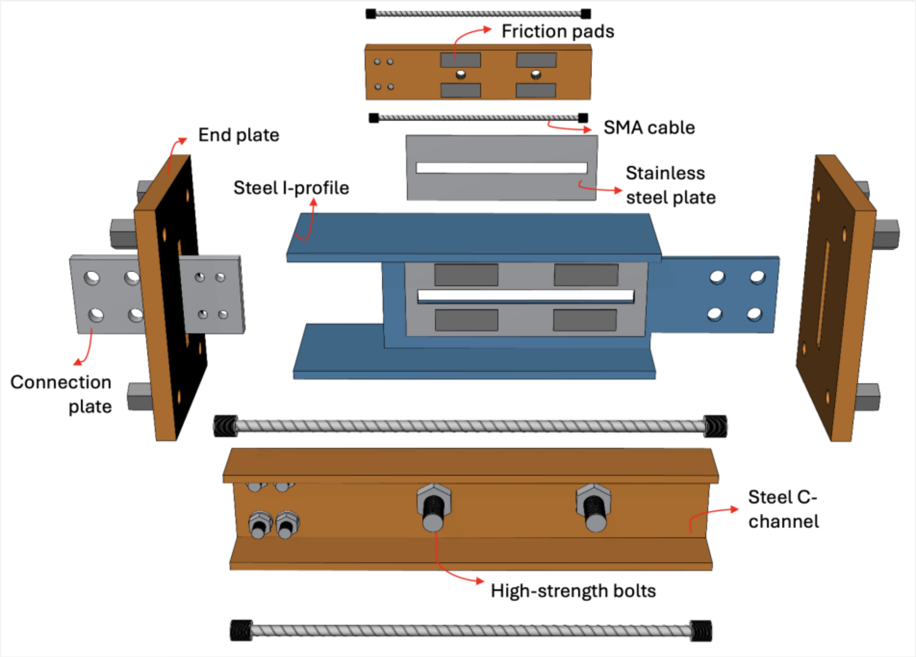
Research Projects

PFI-TT: Self-Centering Seismic Dampers for Resilience-Based Earthquake Design of Buildings: (CMMI 2141073) **University of Virginia (Osman Ozbulut (PI))**

- Characterize dynamic behavior under various displacement amplitudes and loading frequencies
- Perform RTHS to validate mitigation performance

Features Using NHERI Lehigh Underlined



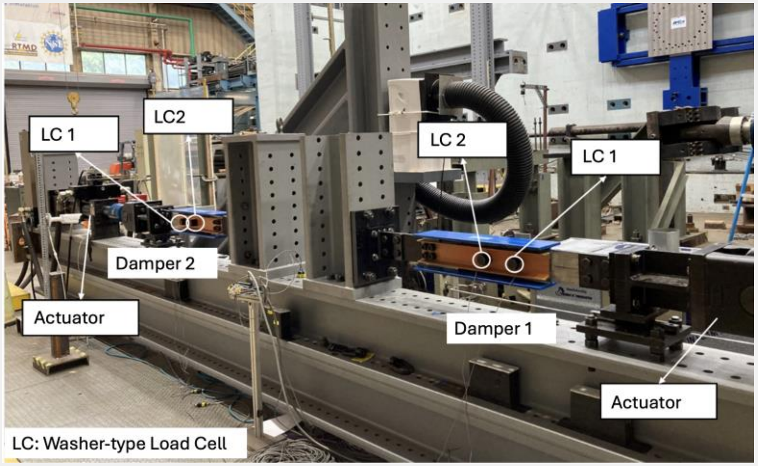


Shape Memory Alloys (SMA) based Friction Damper [1]

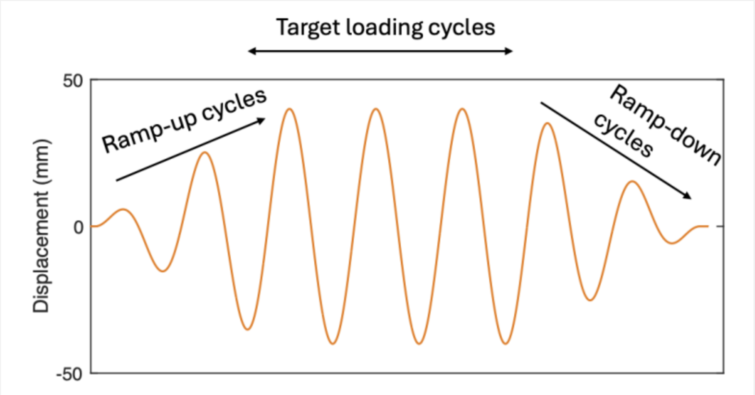
[1] Asfaw, Amedebrhan M. and Cao, Liang and Ozbulut, Osman E. and Ricles, James "Development of a shape memory alloy-based friction damper and its experimental characterization considering rate and temperature effects" Engineering Structures , v.273 , 2022

Research Projects

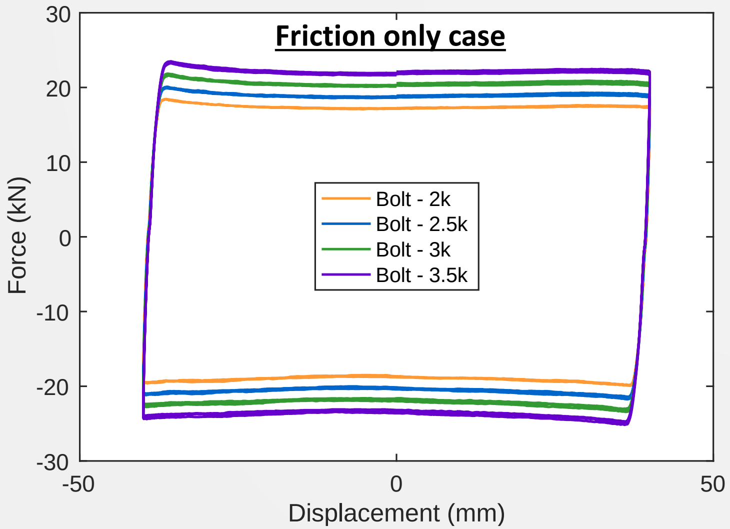
PFI-TT: Self-Centering Seismic Dampers for Resilience-Based Earthquake Design of Buildings: (CMMI 2141073) **University of Virginia (Osman Ozbulut (PI))**

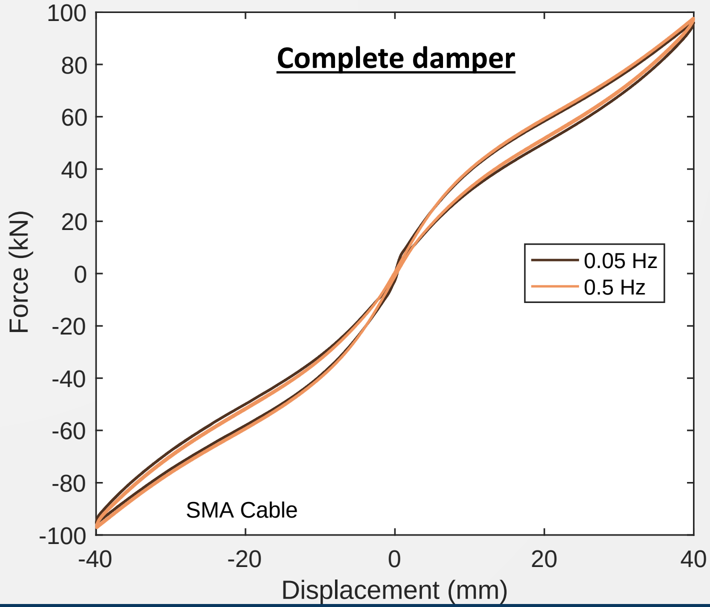


Characterization test setup



Characterization test loading protocol





Thank you