# NHERI Lehigh Real-Time Multi-Directional (RTMD) Experimental Facility Users' Workshop

Virtual

Lehigh University

September 25, 2020

# NHERI Lehigh Real-Time Multi-Directional (RTMD) Experimental Facility Users' Workshop

## Welcome

# September 25 - NHERI Lehigh RTMD Experimental Facility Researcher Workshop Draft Agenda

| Start Time | End Time | Description | Presenter | Title |
|---|---|---|---|---|
| 11:00 am | 11:10 am | Welcome, Objectives, and Science Plan | James Ricles | RTMD Facility PI |
| 11:10 am | 11:30 am | NHERI Lehigh: Facility Description, Capabilities, and Protocols | James Ricles | RTMD Facility PI |
| 11:30 am | 11:50 am | NHERI Lehigh Example Projects | James Ricles | RTMD Facility PI |
| 11:50 am | 12:00 pm | Q&A | ----- | ----- |
| 12:00 am | 12:15 pm | Hybrid Simulation: Framework, Hardware & Software Capabilities | Liang Cao | RTMD Research Scientist |
| 12:15 pm | 12:25 pm | Q&A | ----- | ----- |
| 12:25 pm | 12:45 pm | IT Infrastructure, Data Modeling, and Curation | Thomas Marullo | RTMD IT Systems Manager |
| 12:45 pm | 12:55 pm | Q&A | ----- | ----- |
| 12:55 pm | 1:10 pm | Site Support Operations and Payload Opportunities | Chad Kusko | RTMD Operations Manager |
| 1:10 pm | 1:20 pm | Q&A | ----- | ----- |
| 1:20 pm | 1:30 pm | Wrap-Up | All | ------ |

# Workshop Objectives

(1) Provide researchers with information on the capabilities of the NHERI Lehigh RTMD EF for advanced natural hazard engineering research

(2) Describe new capabilities and resources available for conducting research at the NHERI Lehigh RTMD EF

(3) Describe the procedures to perform large-scale experiments using the NHERI Lehigh RTMD EF

(4) Discuss the NHERI Science Plan and how the NHERI Lehigh RTMD EF enables key research in emerging areas in natural hazard engineering

(5) Explore opportunities to use the NHERI Lehigh RTMD EF for unsolicited, CAREER, and other types of NSF proposals

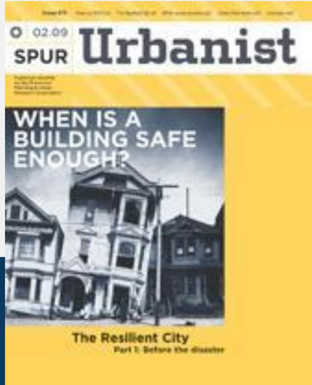
# NHERI Lehigh EF Science Plan

## James Ricles

# NHERI Lehigh EF Science Plan

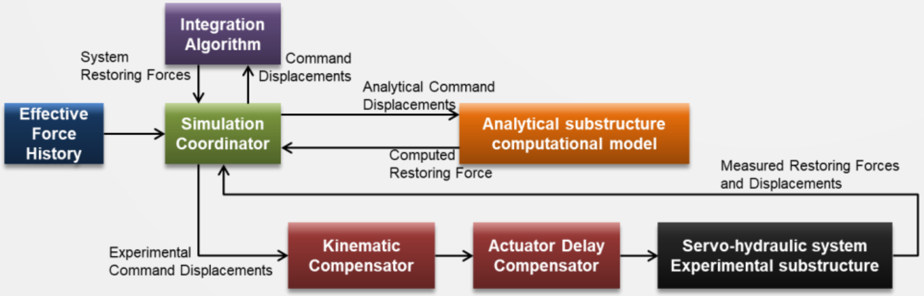
Provide a next generation multi-user facility to perform transformative research by closely integrating numerical simulations and experiments to advance natural hazards engineering research and education, enabling the challenge of community resilience to natural hazards to be met:

- Improved concepts for renewal and retrofit of the built environment
- Exploitation of new emerging materials
- Development of innovative, resilient structural concepts
- Economical design approaches toward natural hazard mitigation
- Development and validation of more accurate physics-based computational simulation models



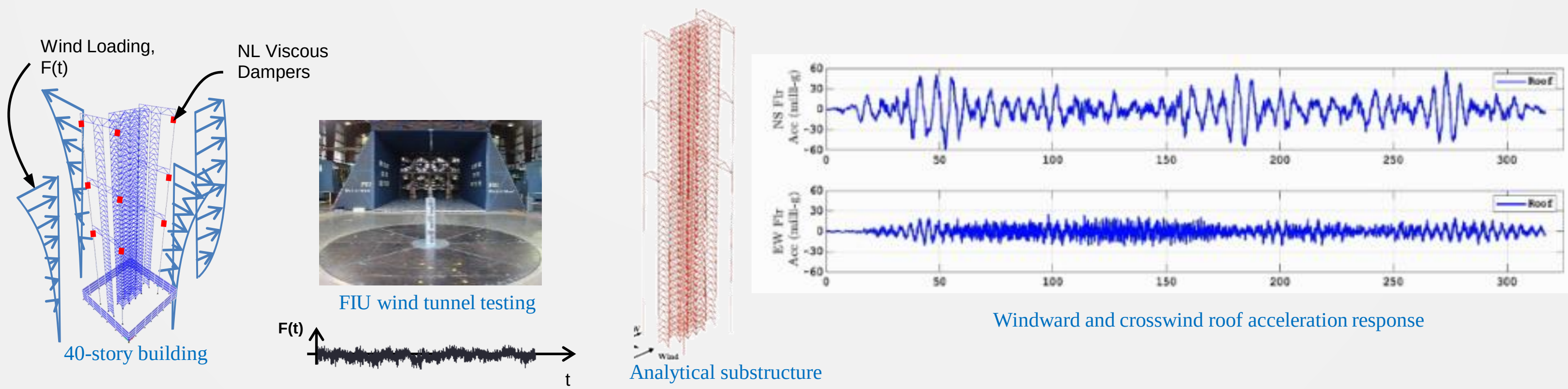
# NHERI Lehigh EF Science Plan

- The NEHRI Lehigh EF focus is on large-scale, multi-direction, real-time hybrid simulations that combine physical experiments with computer-based simulations for evaluating performance of large-scale components and systems.
- The NEHRI Lehigh EF provides user-friendly tools that enables researchers to readily utilize the advanced testing technology and algorithms to perform complex experiments.




# NHERI Lehigh EF

- Facility Enables Researchers to Readily Perform:
  - 3-D RTHS of large, complex nonlinear systems subjected to multi-natural hazards, (e.g., wind and earthquake) using analytical substructures created with robust computational models;
  - 3-D multi-natural hazard RTHS of systems with numerous response modification devices, where models of numerically modeled devices are updated in real-time using data from physically modeled devices;
  - Accurate large-scale 3-D multi-directional experiments (e.g., quasi-static, HS, RTHS) that involve nonlinear kinematics of actuator and specimen motions;
  - Accurate 3-D multi-natural hazard RTHS of systems with precise hydraulic actuator control.




**RTHS Wind Simulation Results, 40-story Building With Supplemental Damper Outriggers**

# NHERI Lehigh EF Broader Impacts

- Key questions in natural hazards mitigation can be addressed through research performed at NHERI Lehigh EF that will lead to:
  - Development and implementation into practice new natural hazard mitigation strategies and innovative resilient structural systems
  - Enhanced understanding of response to multi-natural hazards by accounting for SSI and potentially FSI effects
  - Comprehension of system-level effects on structural and non-structural components through large-scale 3-D system experiments.
- Acquire high quality experimental data, leading to improved computational models for predicting community infrastructure system response to natural hazards.
- Training the next-generation workforce in natural-hazards engineering through research and ECO activities.

# NHERI Lehigh EF Science Plan

- Examples of Potential Research Projects at NHERI Lehigh EF:
  - *Autonomous Semi-active Control Devices for Achieving Resilient Performance of Structural Systems Subject to Multi-hazards* (approach: real-time hybrid simulation)
  - *Advanced Bracing Systems with Shape Memory Alloys for Achieving Multi-hazard Resiliency of Buildings* (approach: quasi-static; hybrid simulation)
  - *Multi-agent Replicator Control Methodologies for Sustainable Vibration Control of Smart Building Structures* (approach: real-time hybrid simulation)
  - *Advancing Computational Modeling of Structural Damage in Reinforced Concrete Subject to Complex Loading Histories* (approach: quasi-static; multi-directional mixed mode control hybrid simulation)
  - *Quantifying Seismic Resilience of Multi-functional Floor Isolation Systems Through Cyber-physical Testing* (approach: real-time hybrid simulation)
  - *Performance of Nonstructural Components of Systems and Minimizing Multi-Hazard Losses* (approach: hybrid simulation, real-time hybrid simulation)
  - *Effects of Soil-Foundation-Structure Interaction on Multi-hazard Performance of Tall Buildings With Supplemental Damper Outrigger Systems* (approach: hybrid simulation, real-time hybrid simulation)
  - *Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings* (approach: hybrid simulation, real-time hybrid simulation)

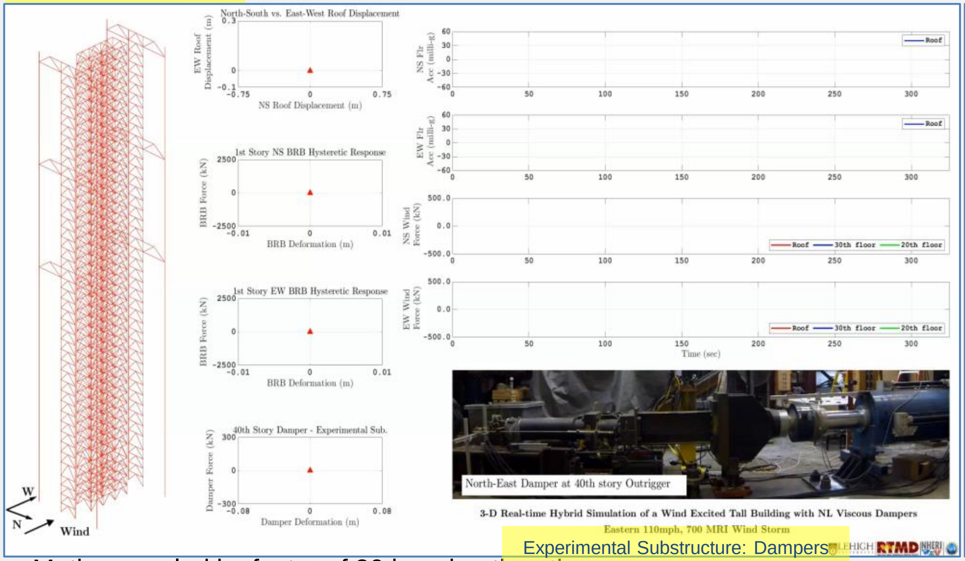
# Example of Research Vision at NHERI Lehigh

## Real-time Hybrid Simulations (RTHS) to Improve Resilience of Tall Buildings to Multi-Natural Hazards

[3D RTHS of 40-story Building with Supplemental Nonlinear Viscous Dampers in Outriggers]


Rate Dependent Nonlinear Viscous Damper

Analytical Substructure: Building



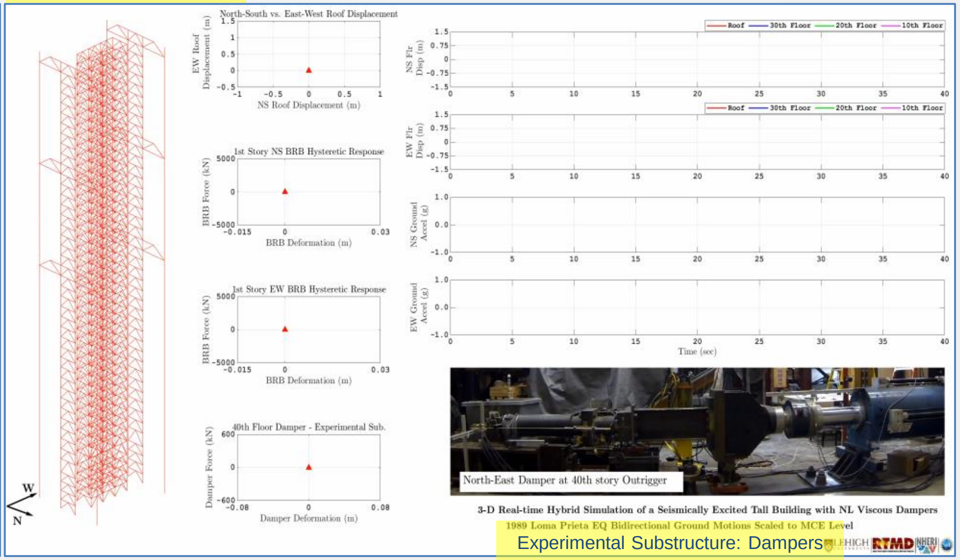

Experimental Substructure: Dampers

Motions scaled by factor of 20 in animation; time-lapse

RTHS: 700 year MRI (110 mph Wind Speed)

[Wind]

Analytical Substructure: Building




Experimental Substructure: Dampers

Motions scaled by factor of 5 in animation

RTHS: 2474 year EQ (MCE)

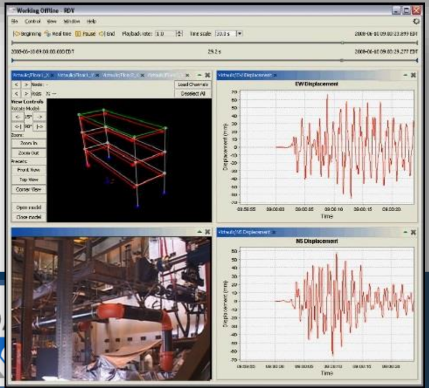
[Earthquake]

# NHERI Lehigh EF Description

## James Ricles

# What is the NHERI Lehigh EF?

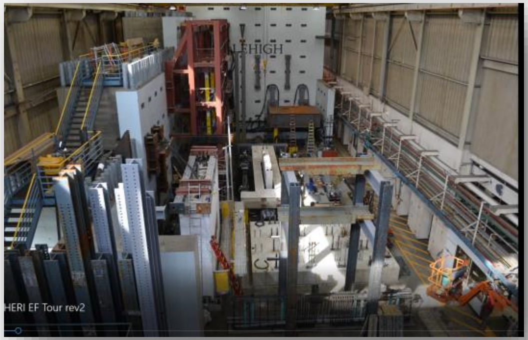
- Former NEES Site: Real-time Multi-directional (RTMD) Earthquake Simulation Facility
- Unique facility
  - ➢ Portfolio of equipment, instrumentation, infrastructure, testbeds, and experimental simulation control protocols for large-scale multi-directional testing

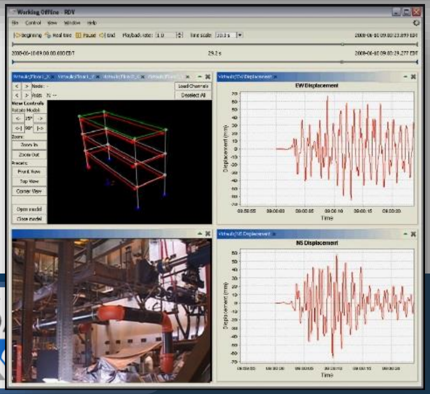



LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE NSF DESIGNS A NATURAL HAZARDS ENGINEERING COMMUNITY

# What is the NHERI Lehigh EF?

- Former NEES Site: Real-time Multi-directional (RTMD) Earthquake Simulation Facility
- Unique facility
  - Portfolio of equipment, instrumentation, infrastructure, testbeds, and experimental simulation control protocols for large-scale multi-directional testing
  - Concurrent multiple large-scale experiments
  - Operated by experienced staff
- Facility exists within ATLSS Center to provide access to additional resources and ATLSS infrastructure





# ATLSS Center

# NHERI Lehigh EF Strengths - Facility

- Large-scale, multi-directional testing
- Real-time loading
  - Actuators, hydraulic equipment and power
  - Actuator control with adaptive compensation
- Hybrid simulation
  - Integration algorithms
  - Analytical modeling
  - Multi-grid real-time simulations
  - Actuator multidirectional kinematic compensation
  - Real-time actuator control
  - Real-time on-line model updating
  - Data model for large-scale test data
- Instrumentation, DAQ, advanced instrumentation (Digital Image Correlation, laser transducers)
- Large inventory of ATLSS testing and ancillary equipment

# NHERI Lehigh EF Strengths - People

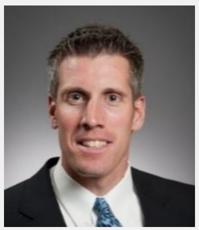
Lehigh Team includes

- Expertise in
  - Structural Engineering
  - EQ Engineering
  - Geotechnical Engineering
  - Aeroelasticity and Wind Engineering
  - Hydrodynamics and fluid-structure interaction
  - Probabilistic-based modeling
  - Structural monitoring and damage assessment
- Pioneers in real-time hybrid simulation (RTHS)
- Know-how in large-scale experimentation, RTHS
- Relationship with industry, practicing engineers, familiarity with codes and standards
- Experienced laboratory staff

# NHERI Lehigh EF Team

**James Ricles**, PI

**Richard Sause**, Co-PI



**Chad Kusko**
Operations Mgr

**Liang Cao**
Research Eng

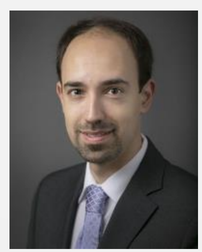
**Thomas Marullo**
IT Systems Mgr

**Darrick Fritchman**
ATLSS Lab Mgr

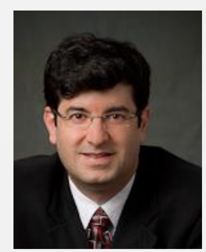
## Capacity Building Partners

**Justin Jaworski**
Aeroelasticity and
Fluid-Structure Interaction

**Muhannad Suleiman**
Soil-Structure Interaction



**Paolo Bocchini**
Probabilistic Modeling and
Infrastructure Resilience



**Shamim Pakzad**
Adv. Sensors,
Structural Monitoring

**Arindam Banerjee**
Hydrodynamics and
Fluid-Structure Interaction

# Experimental Protocols and Facility Resources

James Ricles

# What is Hybrid Simulation?

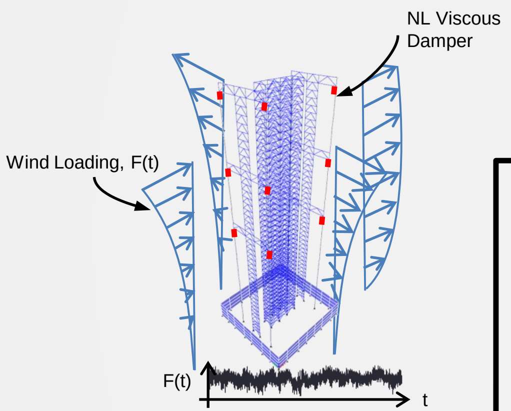
# Overall Concept of Real-time Hybrid Simulation (RTHS): Structural System Subject to Predefined Wind Loading

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

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

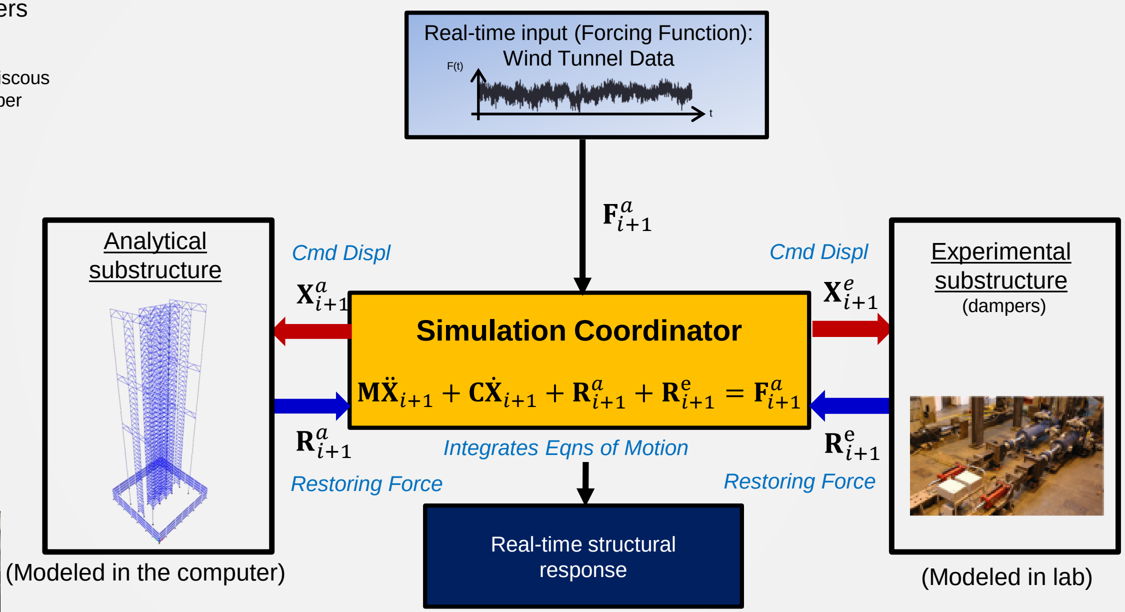
## Structural System

40-Story Building with Outriggers and Supplemental Dampers




Wind Tunnel Tests NHERI@FIU
Wind Load Determination

## Hybrid Wind Simulation Experiments



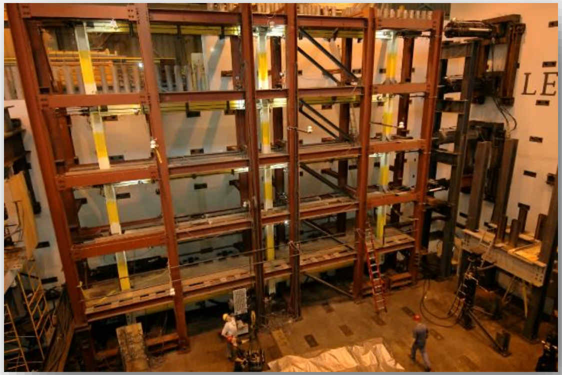
# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation - RTHS

RTHS EQ Simulation of Buildings with Dampers

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation - HS



HS EQ Simulation of Buildings with SC-MRF

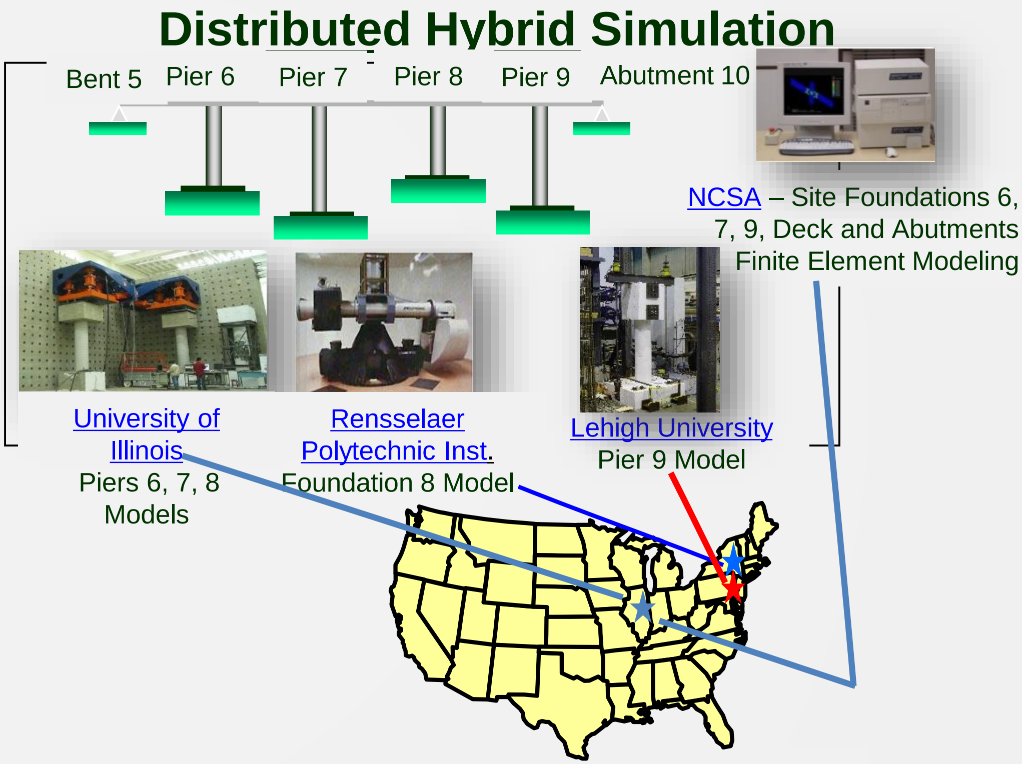
# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures

RTHS EQ Simulation of Building with Multiple Dampers

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation

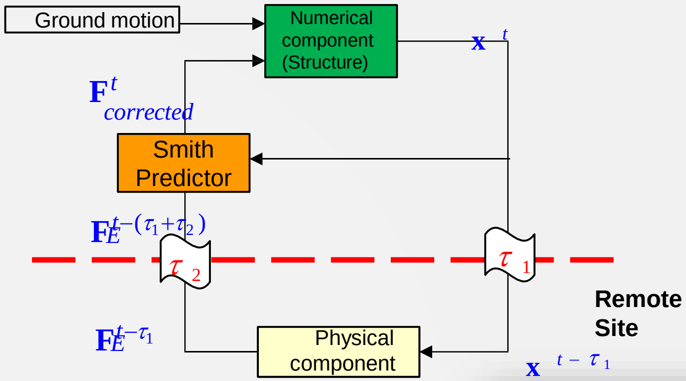



Equipment Site Locations

Distributed RTHS EQ Simulation of I-10 Collector Bridge

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation




Lehigh

UIUC

RTHS EQ Simulation of Building with MR Dampers (Kim, Christenson)

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing) - QS


Temperature Control Chamber

Characterization of Full-scale Semi-active and Passive Dampers for Wind and EQ

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
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Characterization of Large-scale RC Coupled Shear Wall System Subject to Lateral and Gravity Loading

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
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- Dynamic testing - DT

Multi-directional Dynamic Testing of Pipe Couplers

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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- Predefined load or displacements (Quasi-static testing or characterization testing)
- Dynamic testing
- Tsunami/storm surge debris impact

Tsunami Debris Impact Test

# NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Real-time Hybrid Simulation
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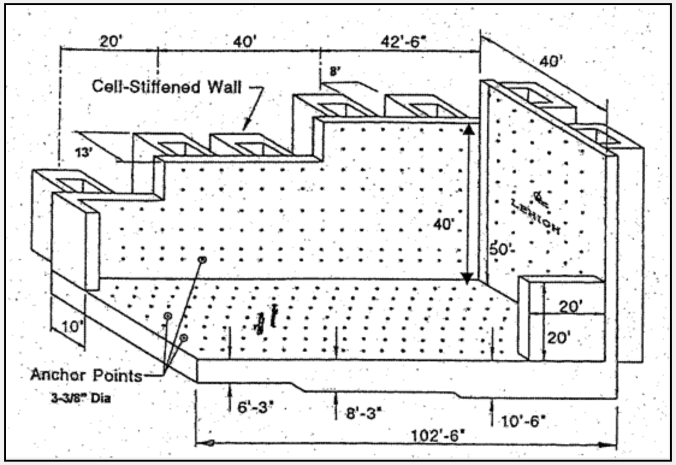
- Predefined load or displacements (Quasi-static testing or characterization testing)
- Dynamic testing
- Tsunami/storm surge debris impact
- Soil-pile interaction

Pile Lateral Load Test

# ATLSS Lab Infrastructure

- **3-D Multi-directional reaction wall facility**
  - 3-dimensional
  - Up to 50 ft height
  - 5 ft anchor point grid
- **Strong floor**
  - 40 ft by 100 ft
  - 5 ft anchor point grid
- **Hydraulic Supply System**
- **Over 30 Hydraulic Actuators**
- **Digital servo-hydraulic controllers**
- **Data Acquisition Systems**
- **Large array of conventional sensors**
- **Advanced sensors: Digital Image Correlation Systems**
- **Ancillary equipment: 40 kips crane, etc.**

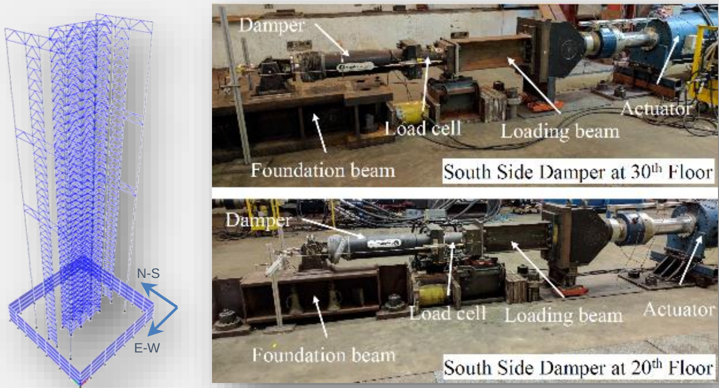



# NHERI Lehigh EF Hydraulic Equipment and Power

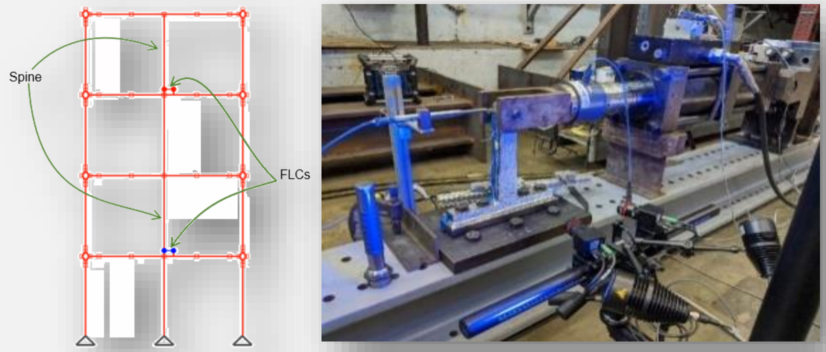
- **Enables real-time EQ large scale demand to be imposed for up to $30^{+}$ seconds**
- **Hydraulic supply system (ATLSS)**
  - 5-120 gal/min pumps
- **Accumulator System (NHERI)**
  - 16 piston accumulators
    - 50 gal each
- **5 dynamic hydraulic actuators (NHERI)**
  - Maximum load capacity
    - 2 actuators: 517 kips
    - 3 actuators: 382 kips
  - Stroke
    - **+/- 20 in**
  - Maximum velocity
    - **45 in/s for 382 kip** actuators
    - **33 in/s for 517 kip** actuators
- **10 - 550 gal/min servovalves and HSMs**

# ATLSS Lab Infrastructure and NHERI Lehigh EF Equipment

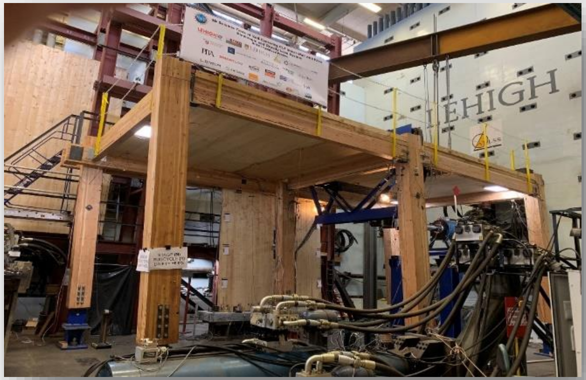
- Combined resources enables multiple concurrent large-scale experimental projects to be conducted




RTHS – Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings




HS – Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings

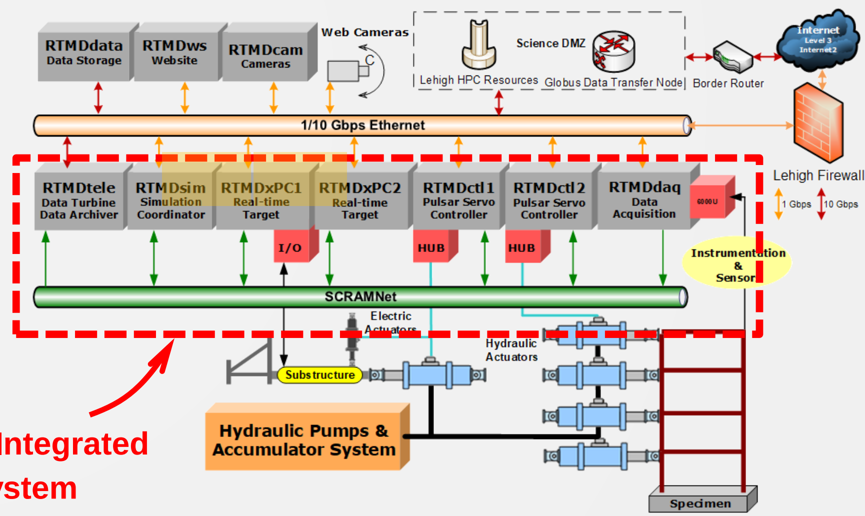



QS & HS – A Resilience-based Seismic Design Methodology for Tall Wood Buildings

QS – Advancing Knowledge on the Performance of Seismic Collectors in Steel Building Structures

# Real-time Integrated Control System

- **Configured with experimental protocol required by user to perform test**
  - Large-Scale Hybrid Simulation
  - Large-Scale Real-time Hybrid Simulation
  - Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
  - Geographically Distributed Hybrid Simulation
  - Geographically Distributed Real-time Hybrid Simulation
  - Predefined load or displacements (Quasi-static testing or characterization testing)
  - Dynamic testing
- **Testing algorithms reside on an RTMDxPC and run in real time**
  - <u>Experiments can be run in true real-time </u>(real-time hybrid simulation, real-time distributed hybrid simulation, dynamic testing, characterization testing).
  - <u>Or, experiments can be run at an expanded time scale</u> (hybrid simulation, distributed hybrid simulation, quasi-static testing).
- **Distributed hybrid simulation via:**
  - OpenFresco
  - Custom software
- **Flexible-designed system**
  - Software and middleware packages developed by users or NHERI CI can be plugged in and utilized for testing




Real-time Integrated Control System

# NHERI Lehigh EF: ATLSS Space, Resources, Accommodations

- **Specimen Prep Areas**
  - Staging Areas
  - Machine Shop
- **Laboratories**
  - Intelligent Structures
  - Mechanical Testing
  - Welding and Joining
  - Materials
  - Microscopy
- **Offices**: Faculty; Staff; Visiting Researchers
- **Meeting Rooms**: Auditorium; Conference Room
- **Storage Areas**
- **Secure Facility**

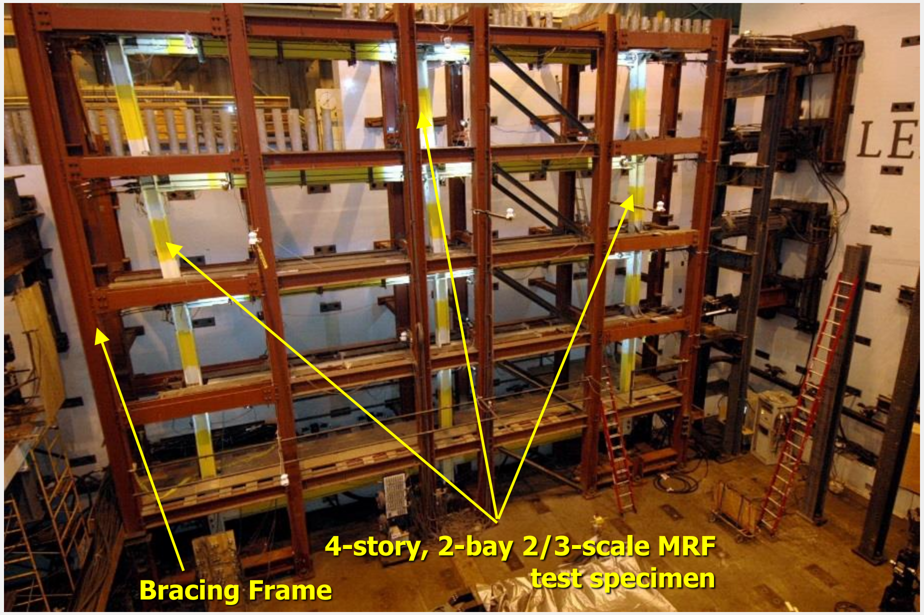
Specimen preparation staging area

Mechanical testing

Auditorium – ECO Activities

# NHERI Lehigh EF Testbeds

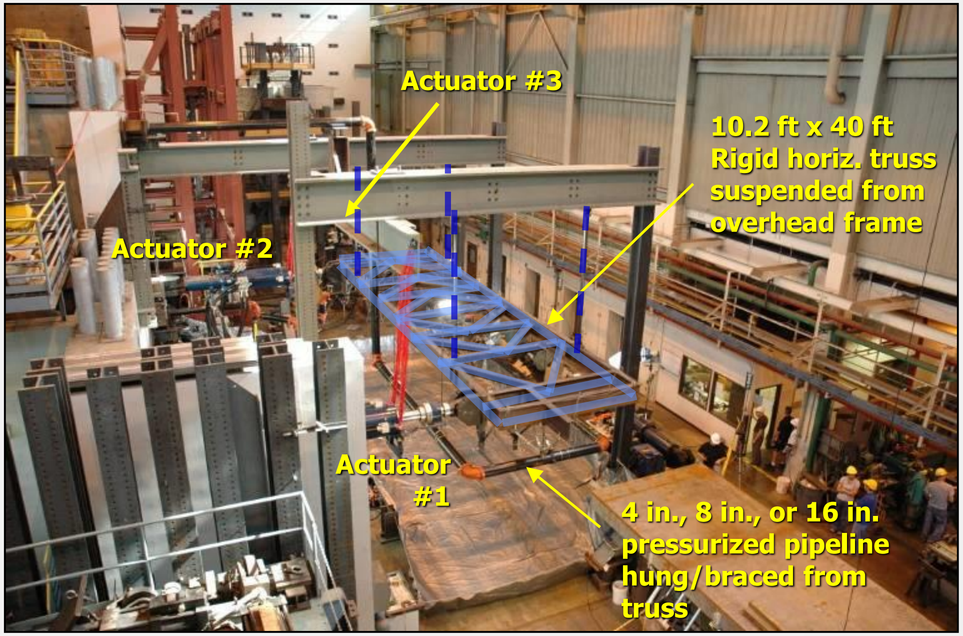
- **Lateral Load Resisting System Testbed**
  - Perform experiments on test frame specimens:
    - ➢ Up to 45 ft height
    - ➢ Up to 36 ft width
  - Large-scale lateral load system characterization tests
  - Real-time hybrid simulations




Hybrid simulation of building with self-centering resilient moment resisting frames

# NHERI Lehigh EF Testbeds

- **Non-Structural Component Multi-Directional Seismic Simulator**
  - Non-structural components and systems:
    - ➢ Up to 40 ft length
    - ➢ Up to 10 ft width
  - Multi-directional real-time characterization testing
  - Multi-directional real-time hybrid simulations




Multi-directonal Real-time hybrid simulation of building piping system

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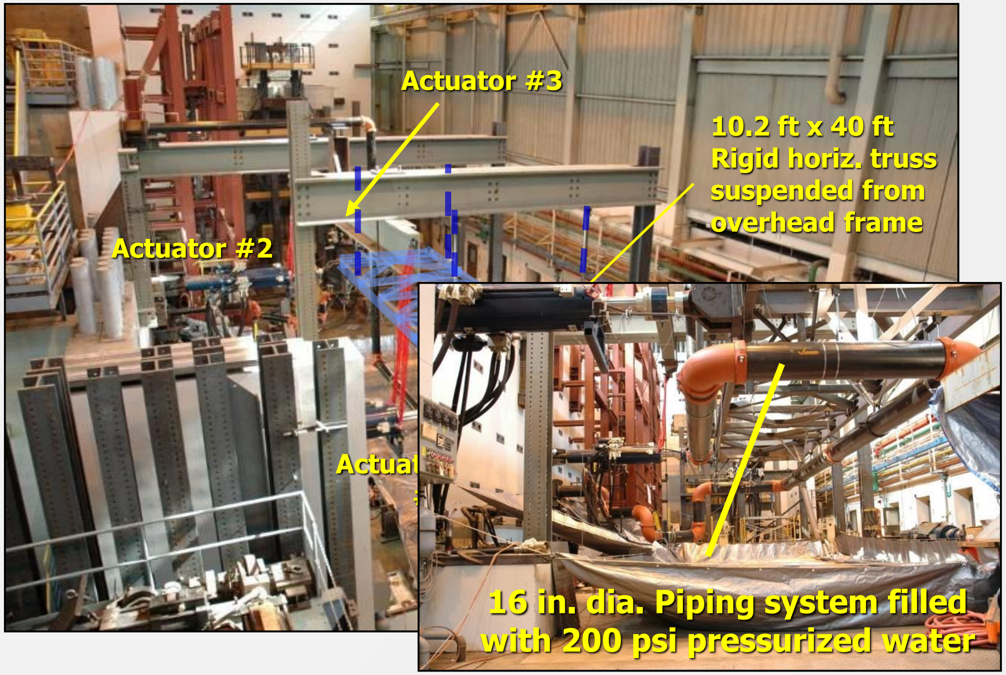
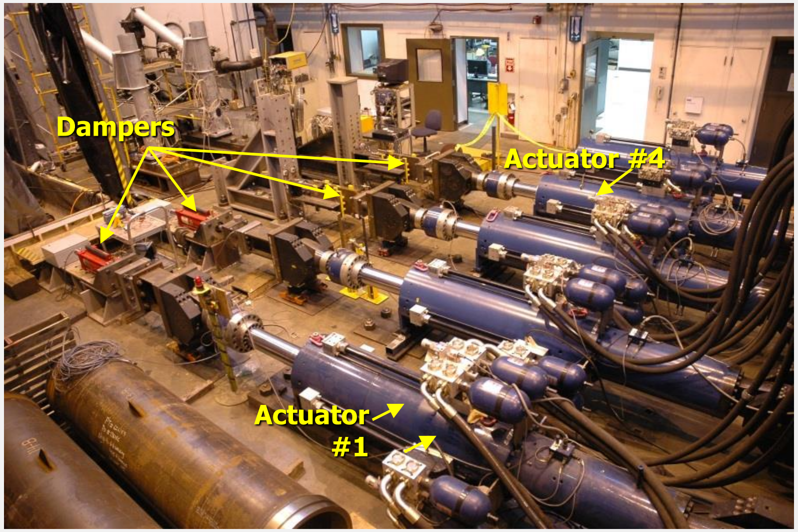



Multi-directonal Real-time hybrid simulation of building piping system

# NHERI Lehigh EF Testbeds

- **Full-scale Damper Testbeds**
  - Enables full-scale damper tests:
    - ➢ Damper characterization tests
    - ➢ Real-time hybrid simulations
  - Stoke, velocity, and force capacity:
    - ➢ +/- 20 in. stroke
    - ➢ 45 in/s for 382 kip actuators
    - ➢ 33 in/s for 517 kip actuators

<u>Real-time hybrid simulation of building with four passive dampers</u>



# NHERI Lehigh EF Testbeds

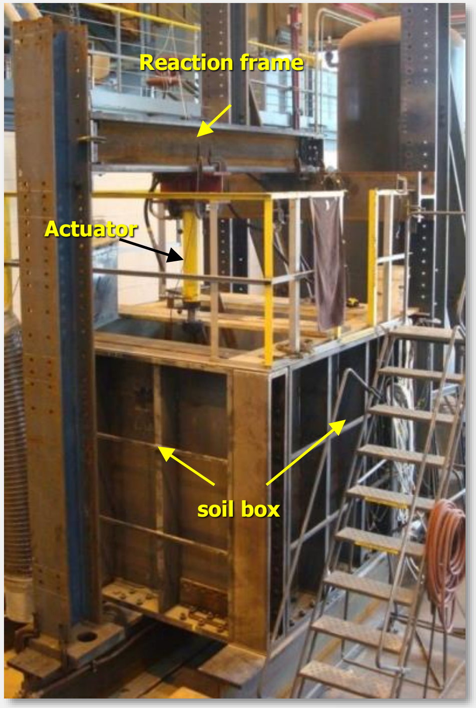
- **Tsunami & Storm Surge Debris Impact Force Testbed**
  - Enables full-scale debris impact tests:
    - ➢ High speed DAQ; high speed 5000 fps cameras
    - ➢ High bandwidth, resolution load cells
    - ➢ Accelerometers, laser-displacement transducers

<u>Real-time simulation of impact forces from tsunami shipping container debris</u>

# NHERI Lehigh EF Testbeds

- **Reduced-scale Soil Box**
  - Enables soil-structure interaction research
    - ➢ Flexible designs (6 x 6 x 6 ft and 6 x 6 x 3 ft in size )
    - ➢ Actuators with load cells; data acquisition system
    - ➢ Sensors for soil and foundation response measurements
    - ➢ Advanced sensors - Digital Imaging Correlation System

Soil-foundation structure interaction testbed



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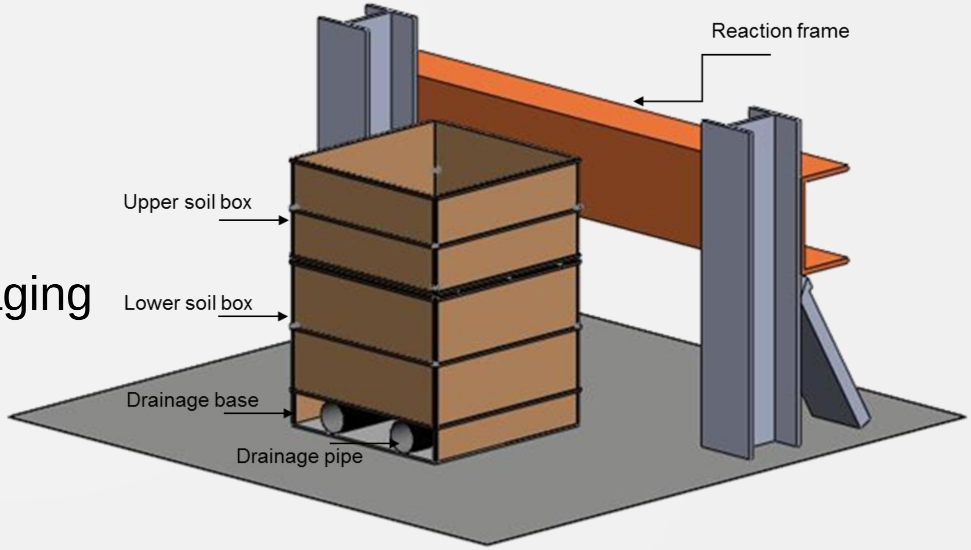
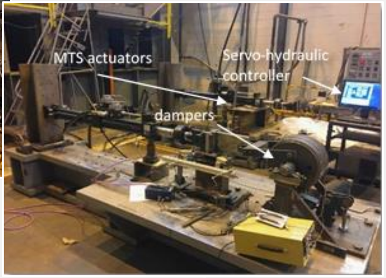
<u>Soil-foundation structure interaction testbed</u>



# NHERI Lehigh EF Testbeds

- **Real-time Cyber-Physical Structural Systems Laboratory (CPSSL)**
  - New resource created to enhance the research, ECO, and researcher training participant experience in cyber-physical systems (hybrid-simulation) with the goal of broadening the user base
  - Small-scale, lower costs with test beds, creating more hands-on opportunities in cyber-physical systems testing.
  - Efficient resource for capacity building pilot studies
    - Five Actuators:
      - 2 - Model 244.21G2
      - 1 - Model 244.20G2S
      - 2 - Model 244.20
    - Independent Real-time Integrated Control and DAQ Systems




**Actuator Specifications**

| | 244.21G2 | 244.20G2s | 244.20 |
|---|---|---|---|
| Max Force | 50 kN (11 kips) | 82 kN (18.5 kips) | 100 kN (22 kips) |
| Max disp. | ±254 mm (±10 in) | ±177 mm (±7 in) | ±76 mm (±3 in) |
| Max velocity | 0.74 m/s (29 in/s) | 1.29 m/s (51 in/s) | 0.38 m/s (15 in/s) |
| Servo Valve | 30 gpm | 90 gpm | 30 gpm |

# Lehigh NHERI EF Website

https://lehigh.designsafe-ci.org/

LEHIGH UNIVERSITY
EXPERIMENTAL FACILITY

DESIGNSAFE-CI
A NATURAL HAZARDS ENGINEERING COMMUNITY

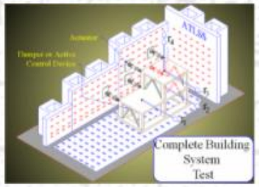
Facility ▾ | Protocols ▾ | Projects ▾ | Resources | Outreach ▾ | Contact

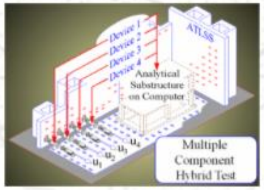
- Overview
- Equipment Portfolio
- Test Beds
- Personnel

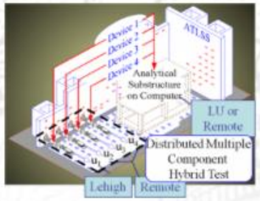
community resilience to natural hazards, the Natural
astructure (NHERI) Lehigh Experimental Facility (EF)
Foundation (NSF) to be a world-class, open-access facility that enables researchers to address key research questions associated with the challenge of community resilience. The NHERI Lehigh EF has a unique portfolio of equipment, instrumentation, infrastructure, testbeds, experimental simulation control protocols, large-scale simulation and testing experience along with know-how that does not exist elsewhere in the United States. The unique strength of the NHERI Lehigh EF is accurate, large-scale, multi-degree-of-freedom and multi-directional simulations of the effects of natural hazard events on civil infrastructure systems (i.e., buildings, bridges, industrial facilities, etc.) with potential soil-foundation effects..

The types of laboratory simulations and tests enabled by the NHERI Lehigh EF include:

1. Hybrid simulation (HS) which combines large-scale physical models with computer-based numerical simulation models.
2. Geographically distributed hybrid simulation (DHS) which is a HS with physical models and/or numerical simulation models located at different sites.
3. Real-time hybrid earthquake simulation (RTHS) which is a HS conducted at the actual time scale of the physical models.
4. Geographically distributed real-time hybrid earthquake simulation which combines DHS and RTHS.
5. Dynamic testing (DT) which loads large-scale physical models at real-time scales through predefined load histories.
6. Quasi-static testing (QS) which loads large-scale physical models at slow rates through predefined load histories.


## ESTABLISHING A PAYLOAD PROJECT AT THE NHERI LEHIGH EF

Researchers are encouraged to take advantage of the existing research projects that provide potential payload project testbeds. All ongoing and newly funded projects at the NHERI Lehigh Experimental Facility are posted on the site's website to enable researchers to identify potential payload project opportunities (see the list of project links under Projects tab). Interested payload researchers should review the posted information for the ongoing/new project scope, schedule, and additional relevant information to determine feasibility of proposing a payload project. If additional project detail is required, payload researchers are encouraged to contact the project's PI directly to foster collaboration towards the project. The PI for each project is included in their descriptions on the site's website. The staff of the NHERI Lehigh Experimental facility can also provide assistance with contacting a project PI.

To establish a payload project, interested payload project researchers will need to follow the payload project protocol that is posted on the site's website (see Payload Project Protocol under Protocols section). Payload projects funded by the NSF are classified as an NSF-sponsored project. Usage Rates for NSF sponsored projects can be found at NSF Sponsored Projects User Fees. Usage Rates for non-NSF sponsored payload projects can be found at non-NSF Sponsored Projects User Fees.

The Lehigh NHERI Experimental Facility is supported by a grant from the National Science Foundation (#1520765).

# Facility User Research Projects

James Ricles

# NHERI Lehigh EF Use

## Research Projects using the Lehigh EF During Current 5-year Award Period

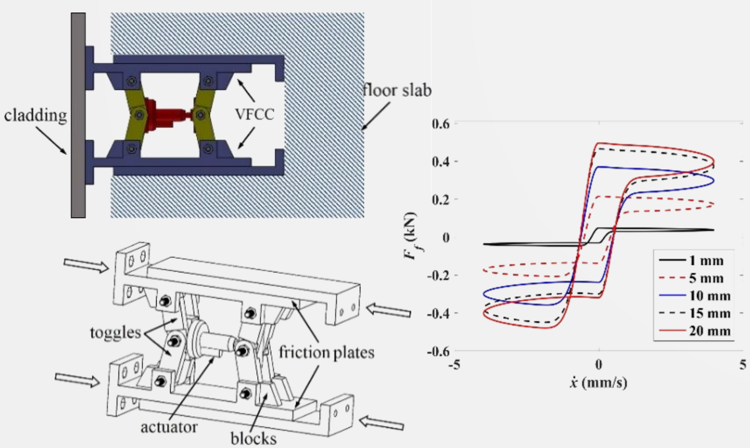
| NSF Award Number | PI Name | PI Institution | *Project Title* / (Major Resources Used; Experimental Protocol) |
|---|---|---|---|
| **CMMI 1351537** | Shamim Pakzad | Lehigh Univ | *CAREER: Toward a Mobile Sensing Platform for Bridge Condition Monitoring*. / (high bay lab; characterization testing) |
| **CMMI 1233566** | Muhannad Suleiman | Lehigh Univ | *Collaborative Research: Enhancement of Vertical Elements for Foundation Support by Ureolytic Carbonate Precipitation*. / (soil box, DIC; quasi-static cyclic testing) |
| **CMMI 1463497** | James Ricles | Lehigh Univ | *Collaborative Research: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings*. / (damper test beds, CPSSL; characterization testing, RTHS) |
| **CMMI 1463252** | Simon Laflamme | Iowa St. Univ | *Collaborative Research: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings*. / (damper test beds, CPSSL; characterization testing, RTHS) |
| **CMMI 1635227, 1636164, & 1635156** | James Ricles, Shiling Pei, James Dolan | Lehigh, CO School Mines, Univ WA | *Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings*. / (high bay lab, DIC; multi-directional quasi-static cyclic testing, hybrid simulation) |
| **CMMI 1635363, 1634204, & 1634628** | Keri Ryan, Jeff Berman, John van de Lindt | Univ NV, Univ WA, CO St. | *Collaborative Research: A Resilience-based Seismic Design Methodology for Tall Wood Buildings*. / (high bay lab; multi-directional quasi-static cyclic testing, hybrid simulation) |
| **CMMI 1662886, 1662964** | Maria Garlock, Spencer Quiel | Princeton, Lehigh Univ | *Collaborative Research: Shear-Buckling Mechanics for Enhanced Performance of Thin Plates*. / (high bay lab, DIC; quasi-static testing) |
| **CMMI 1662816** | Robert Fleischman | Univ Arizona | *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) |
| **CMMI 1928906, 1926365, & 1926326** | Larry Fahnestock, Barbara Simpson, Richard Sause | Univ Illinois, Oregon State, Lehigh Univ | *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) |
| **OIA 1929151** | Scott Harvey | Univ Oklahoma | *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) |

# Research Projects

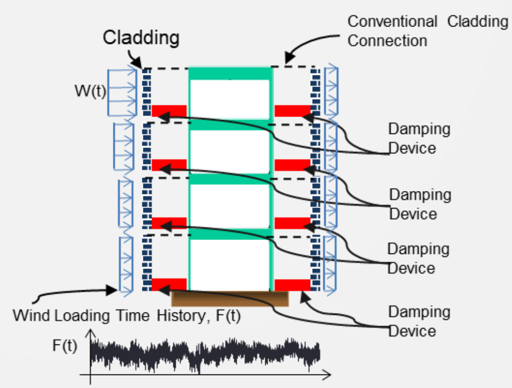
## *Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards*

**(CMMI 1463252) Iowa State University (Simon Laflamme)**

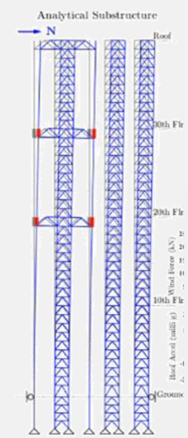
- Overview
  - ➢ Improve performance of buildings for multiple hazards <u>using controlled variable friction cladding panel connectors</u>
  - ➢ Hazards: Earthquake, Wind (NHERI UF and NHERI FIU)
- Scope
  - ➢ Design cladding connectors and control laws
  - ➢ Construct prototype connector, perform characterization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



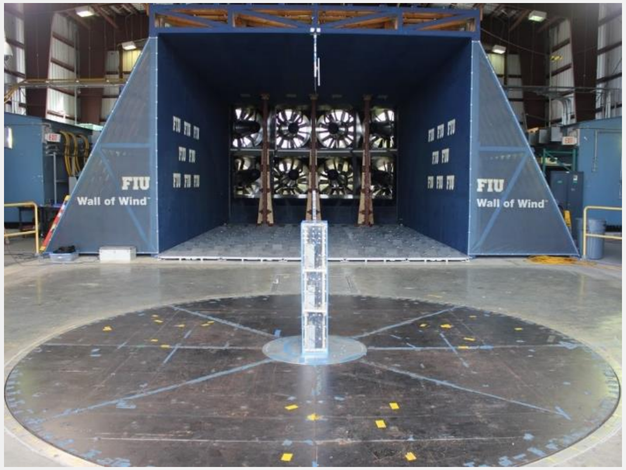

<u>40-story building with friction connectors</u>

# Research Projects

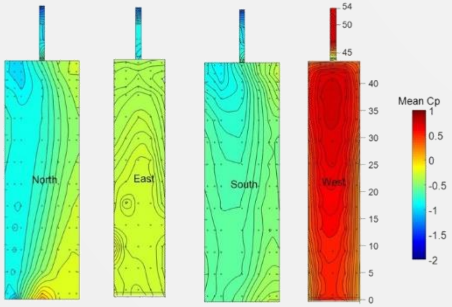
## *Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards*

**(CMMI 1463252) Iowa State University (Simon Laflamme)**

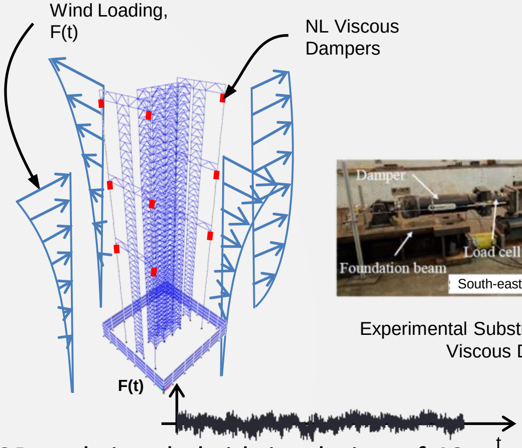
- Multiple NHERI facilities: NHERI EF at Florida; NHERI WOW EF at FIU; and NHERI EF at Lehigh

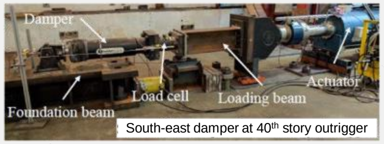



FIU wind tunnel aerodynamic model



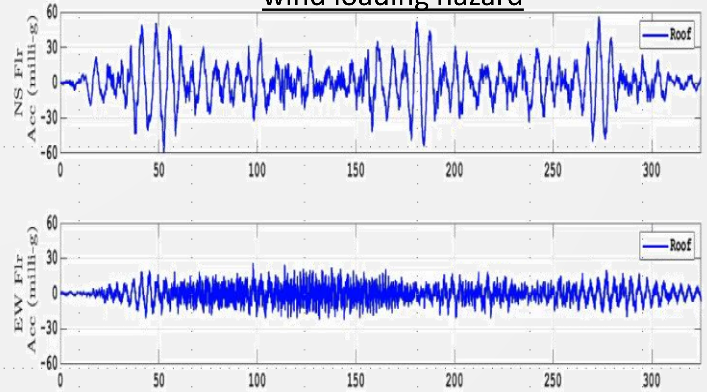

Measured mean wind pressure coefficients for 0° winds




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

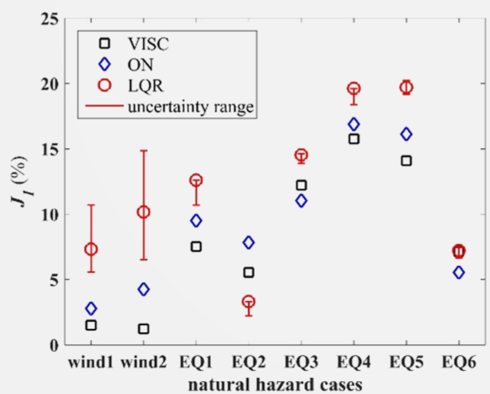
## *Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards*

**(CMMI 1463252) Iowa State University (Simon Laflamme)**

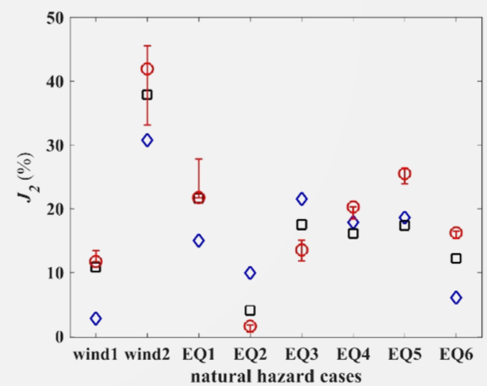
- Major Findings
  - Semi-active controlled cladding connections improve multi-hazard performance of cladding and building systems

| Response Quantity | Reduction using LQR semi-active controller | |
|---|---|---|
| | **Wind** | **EQ** |
| Maximum story drift | 7 to 10% | 5 to 20% |
| Maximum absolute acceleration | 12 to 42% | 12 to 25% |

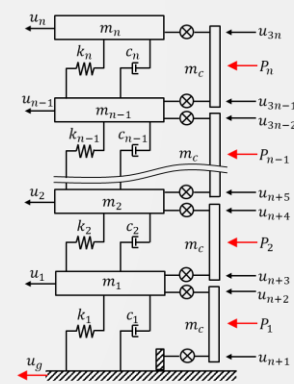
Prototype building




Reduction in maximum story drift




Reduction in maximum absolute accelerations




Numerical simulation model

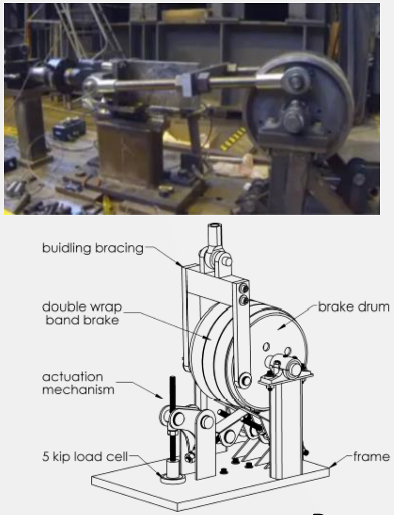

Yongqiang Gong, Liang Cao, Laura Micheli, Simon Laflamme, Spencer Quiel, and James Ricles, (2018) "Performance evaluation of a semi-active cladding connection for multi-hazard mitigation," *Active and Passive Smart Structures and Integrated Systems XII*, vol. 10595, p. 105950B. International Society for Optics and Photonics.

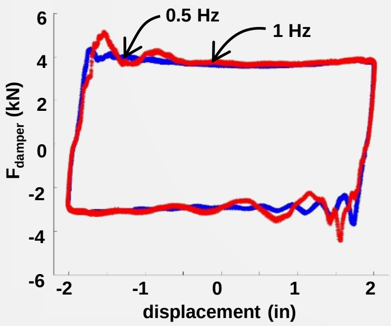
# Research Projects

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

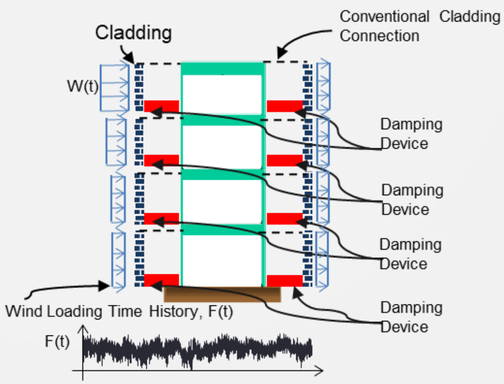
**(CMMI 1463497) Lehigh University (James Ricles)**

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

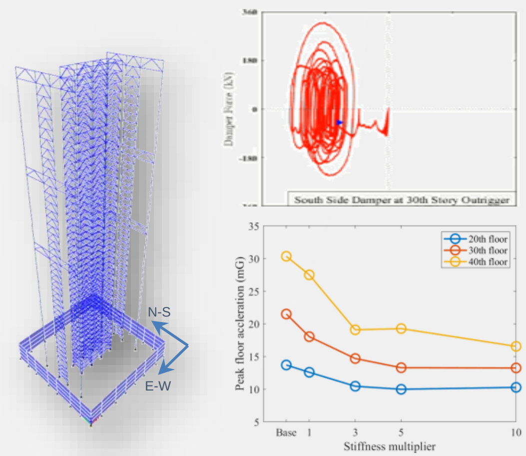



<u>Rotary friction damper</u>




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



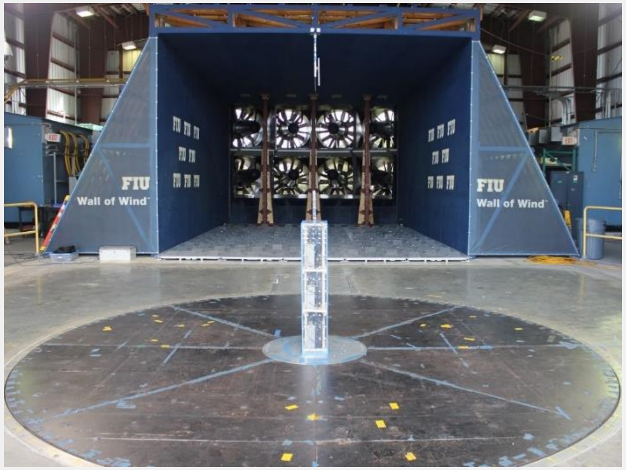

<u>40-story building with nonlinear viscous dampers</u>

# Research Projects

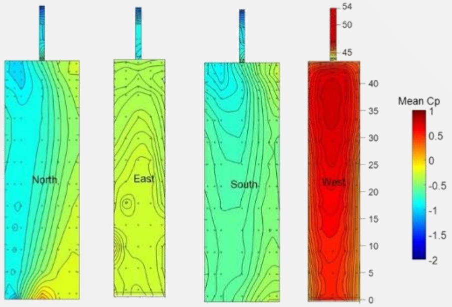
## *Collaborative Research: Semi-Active Controlled Panel Cladding to Improve the Performance of Buildings under Multiple Hazards*

### (CMMI 1463497) Lehigh University (James Ricles)

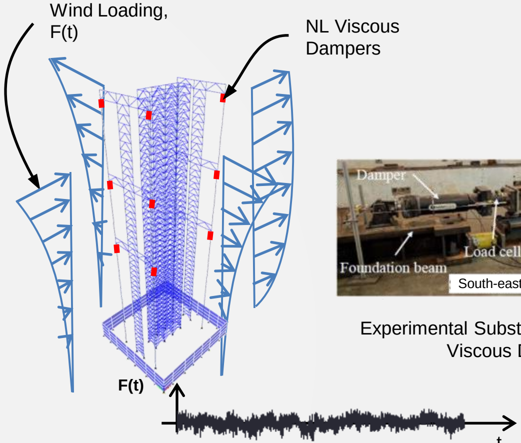
- Multiple NHERI facilities: NHERI EF at Florida; NHERI WOW EF at FIU; and NHERI EF at Lehigh

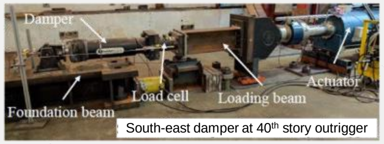



FIU wind tunnel aerodynamic model



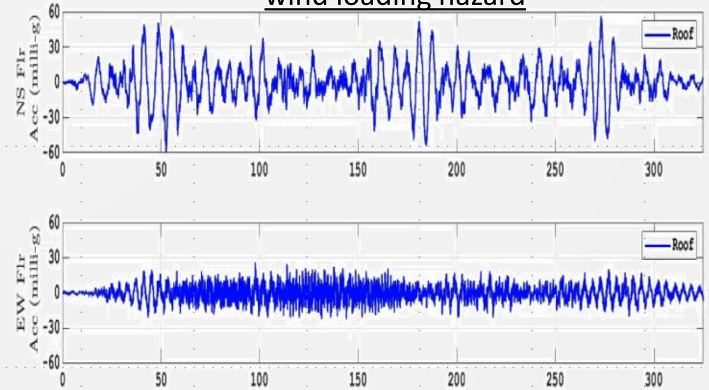

Measured mean wind pressure coefficients for 0° winds




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*

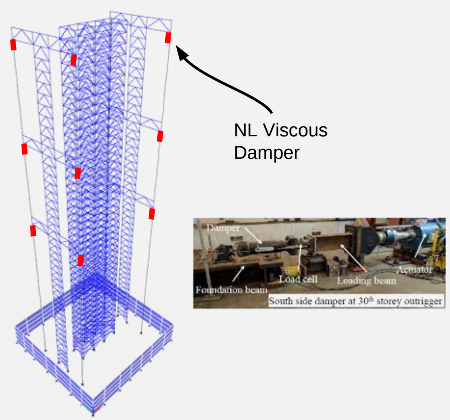
**(CMMI 1463497) Lehigh University (James Ricles)**

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

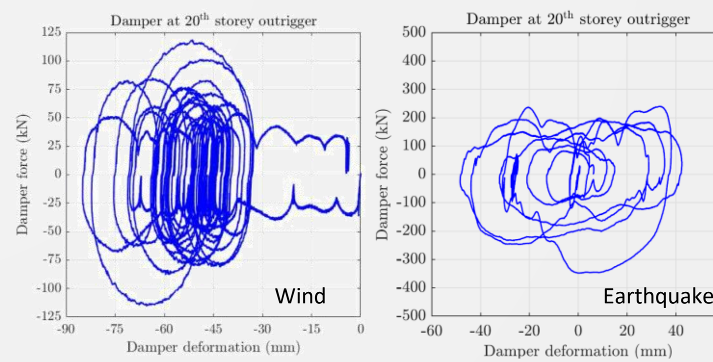
- Major Findings
  - ➢ Nonlinear viscous dampers in outrigger systems can be effective in improving multi-hazard performance of tall buildings.

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

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




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




<u>Damper force-deformation response</u>

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

# Research Projects

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

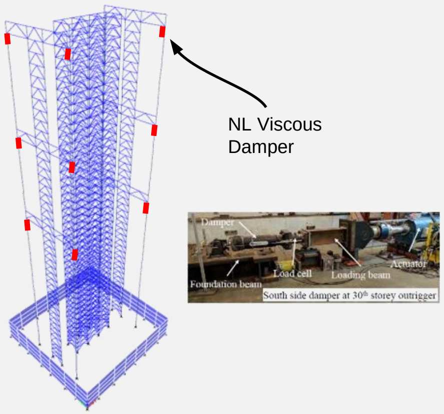
**(CMMI 1463497) Lehigh University (James Ricles)**

## 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.
  - 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% |


Prototype 40-story building

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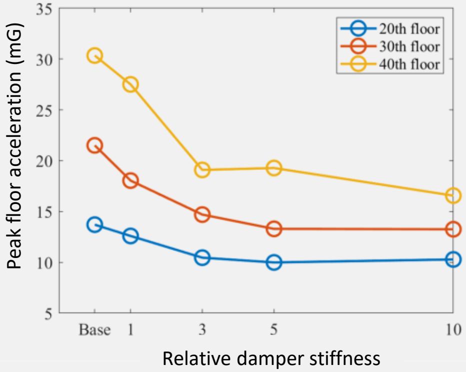


Al-Subaihawi, S., Kolay, C., Thomas Marullo, Ricles, J. M. and S. E. Quiel. (2020) "Assessment of Wind-Induced Vibration Mitigation in a Tall Building with Damped Outriggers Using Real-time Hybrid Simulations," *Engineering Structures*, 205, https://doi.org/10.1016/j.engstruct.2019.110044.

# Research Projects

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

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With Supplemental Dampers in Outrigger Systems for Tall Buildings

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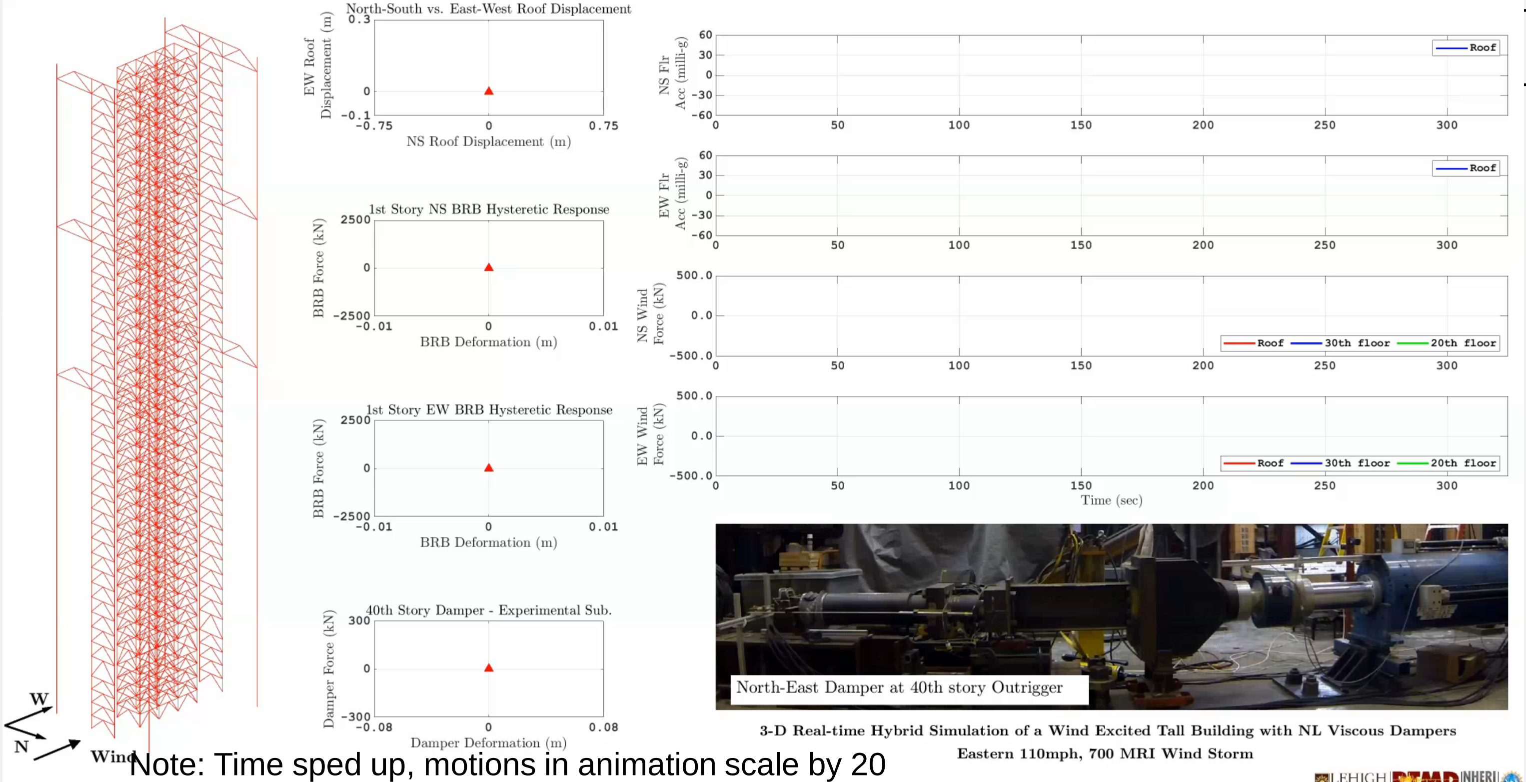
| | | 25% |




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

Note: Time sped up, motions in animation scale by 20

3-D RTHS : 40-story Building with Nonlinear Viscous Dampers in Outriggers, 700 year MRI (110 mph Wind Speed)

# 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 1635227) Lehigh University (James Ricles), (CMMI 1635156) Washington State (James Dolan)**

- 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 and interaction with floor diaphragm and gravity load system under bi-directional loading
- Scope
  - ➢ Conduct large-scale tests of structural subassemblies under in-plane & out-of-plane (bi-directional) loading (with associated vertical motion)
  - ➢ Calibrate high fidelity computational models of SC-CLT walls subjected to multi-directional loading using test data
  - ➢ Project is part of a larger collaborative research program led by Pei (CSM)
  - ➢ Project is supporting work to model tall CLT buildings and to conduct shake table tests (2-story and 10-story) led by Pei (CSM) at NHERI UCSD EF

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

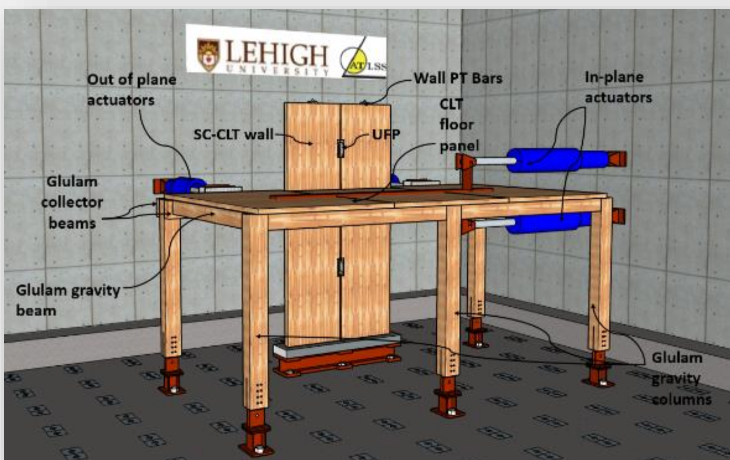
# Research Projects

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

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

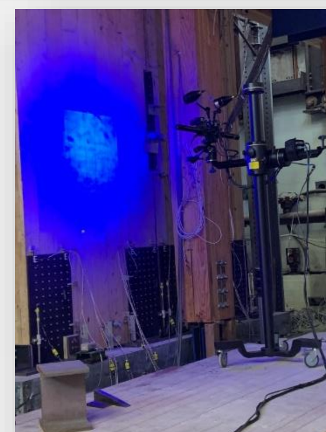
- Overview
  - ➢ Develop seismic design methodology for tall wood buildings with high-performance <u>structural</u> and non-structural systems
  - ➢ Study self-centering rocking cross-laminated timber (SC-CLT) wall and interaction with floor diaphragm and gravity load system under bi-directional loading
- Scope

<u>Multi-directional loading test setup</u>




<u>Test setup: CLT shear wall-floor diaphragm-gravity load system subassembly</u>

<u>Digital Imaging System to measure shear wall deformations</u>



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

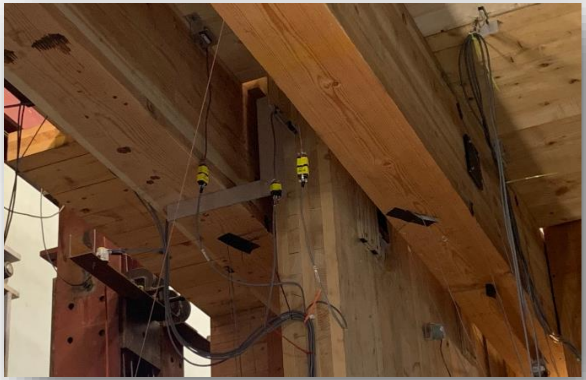
# Research Projects

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

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

- Specimen Design
  - ➢ Develop innovative design details for SC-CLT walls, floor diaphragm, gravity load system and connections to remain damage-free up to 3% bi-directional story drift


SC-CLT shear wall, floor diaphragm, and gravity system subassembly test specimen



Collector beam- to-shear wall force connection detail

Gravity system column-to-floor beam connection detail

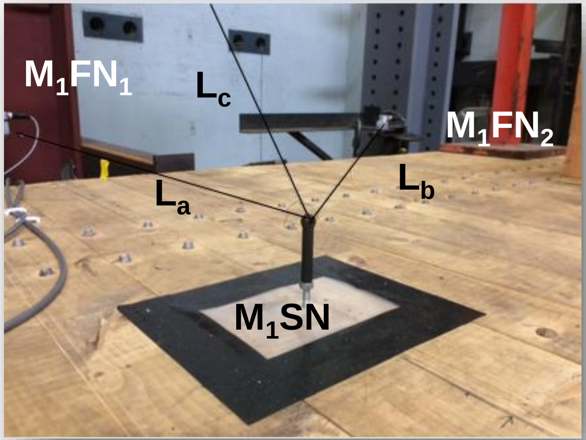
Amer, A., Sause, R., Ricles, J, and T. Marullo, (2020) “Multi-Directional Cyclic Testing of Cross-Laminated Timber Rocking Wall-Floor Diaphragm Sub-Assemblies,” *Proceedings of the 17th World Conference on Earthquake Engineering*, September 13-18, Sendai, Japan

# Research Projects

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

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

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




Instrumentation for measuring 3D motion

3D motions of test specimen

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

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

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

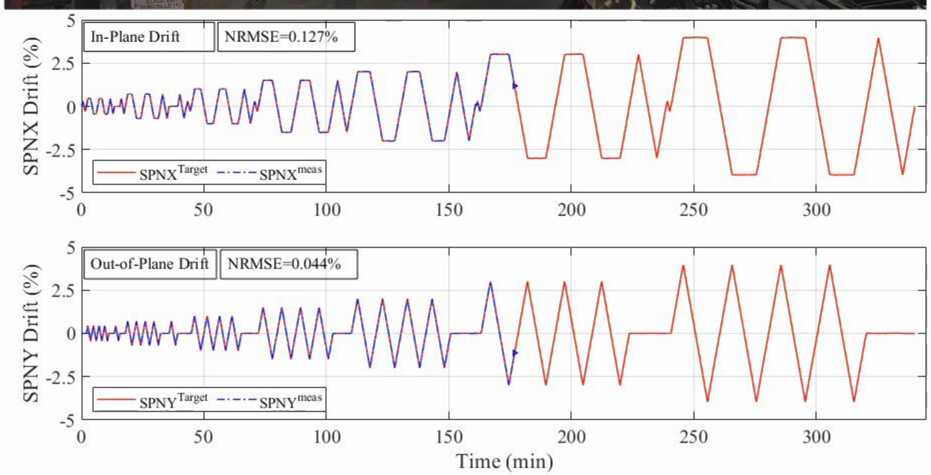
$$(SPN^m x_{new}, SPN^m y_{new}) = (M_1SN^m x_{new} - \left|\overrightarrow{VM_1}\right|\cos(\Theta M_{1,0} + d^m SPN\Theta), M_1SN^m y_{new} - \left|\overrightarrow{VM_1}\right|\sin(\Theta M_{1,0} + d^m SPN\Theta))$$

# Research Projects

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

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

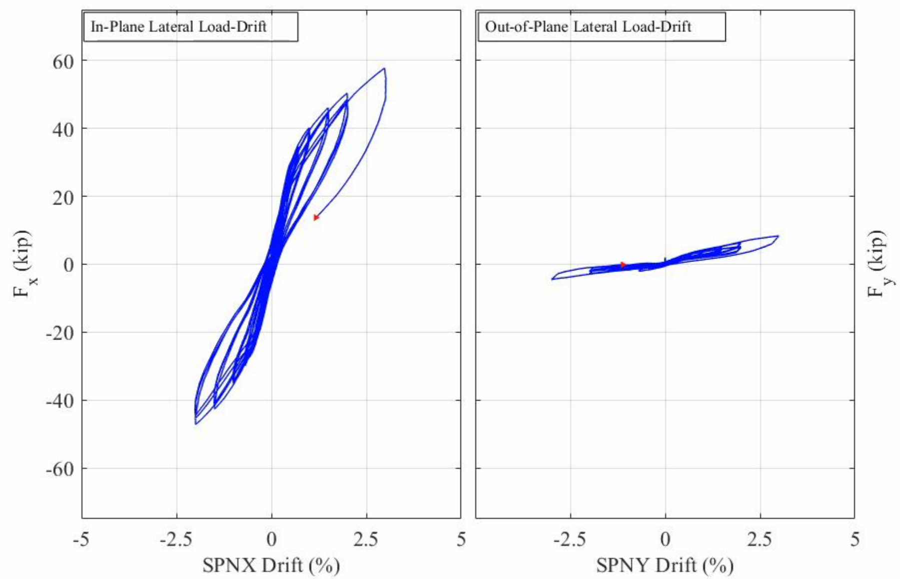
Experimental Substructure (0.625-Scale)


Comparison of Target vs. Measured Subassembly Drift

South Wall Panel

North Wall Panel




Multi-Directional Cyclic Testing of CLT Subassembly

NHERI LEHIGH UNIVERSITY ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION

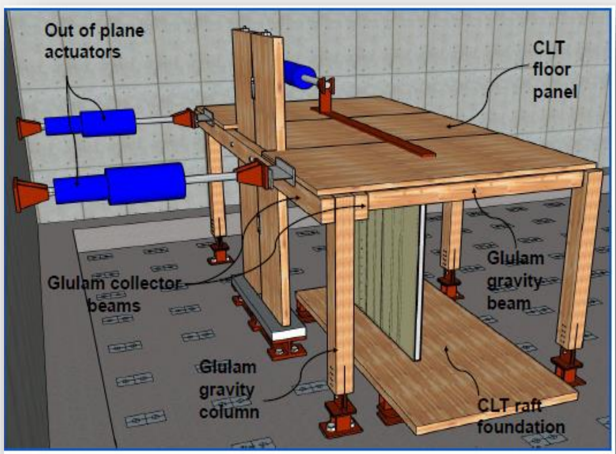
# Research Projects

## *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

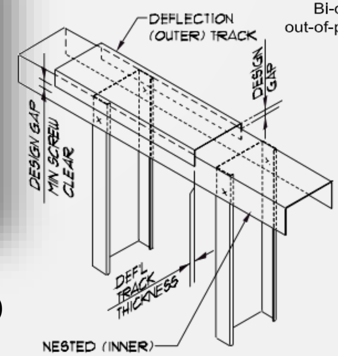
Multi-directional loading test setup

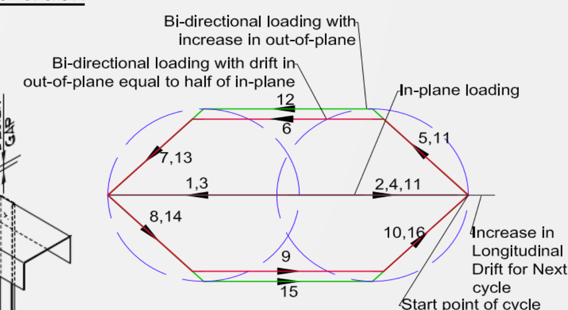



Drywall framing photo

Credit: Hasani and Ryan (2020)

Drywall framing slip-track details




Multi-directional loading protocol

Hasani, H and K. Ryan. (2020) “Experimental Cyclic Test of Reduced Damage Detailed Drywall Partition Walls Integrated with a Timber Rocking Wall”, Submitted to *Journal of Earthquake Engineering*.

# Research Projects

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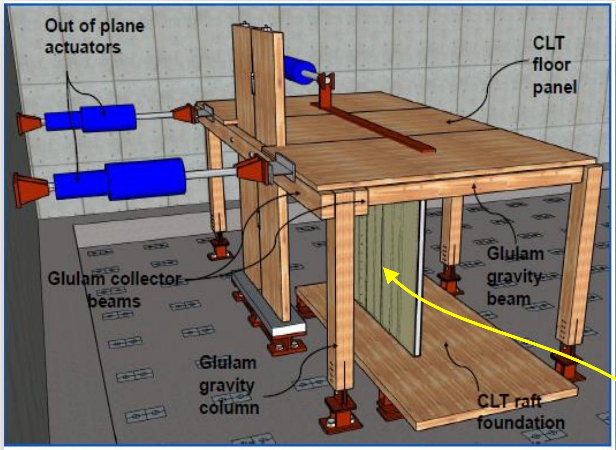
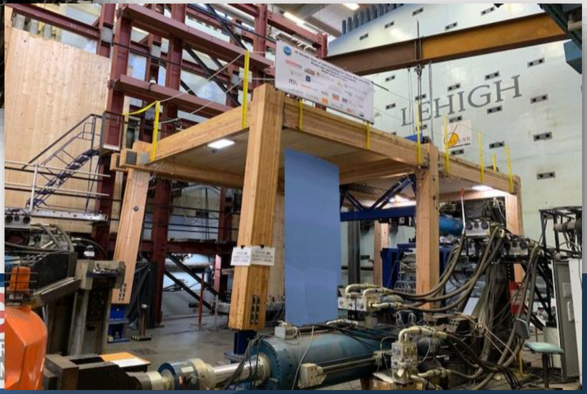



Partition wall

<u>Multi-directional loading test setup</u>


<u>3D motions of subassembly</u>



# Research Projects

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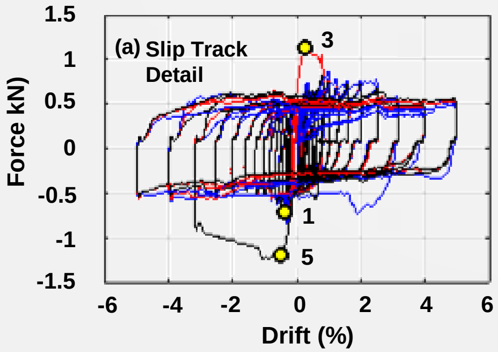
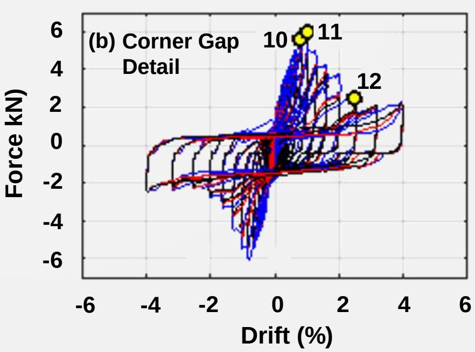
<u>Wall Base Shear- Drift Response</u>




**Ref: Hasani and Ryan (2020)**

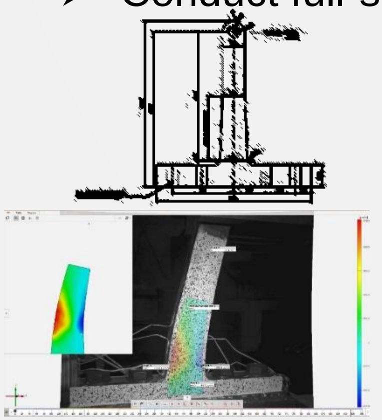
# Research Projects

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

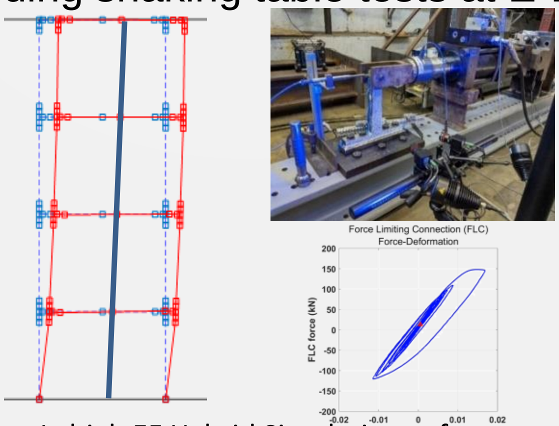
**(CMMI 1928906) Univ Illinois (Larry Fahnestock), (1926365) Oregon State (Barbara Simpson), (1926326) Lehigh University (Richard Sause)**

- 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

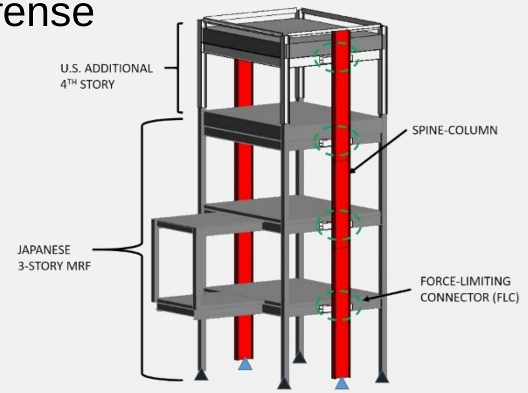
US-Japan research meetings



Lehigh EF testing of force-limiting connector




Lehigh EF Hybrid Simulations of system



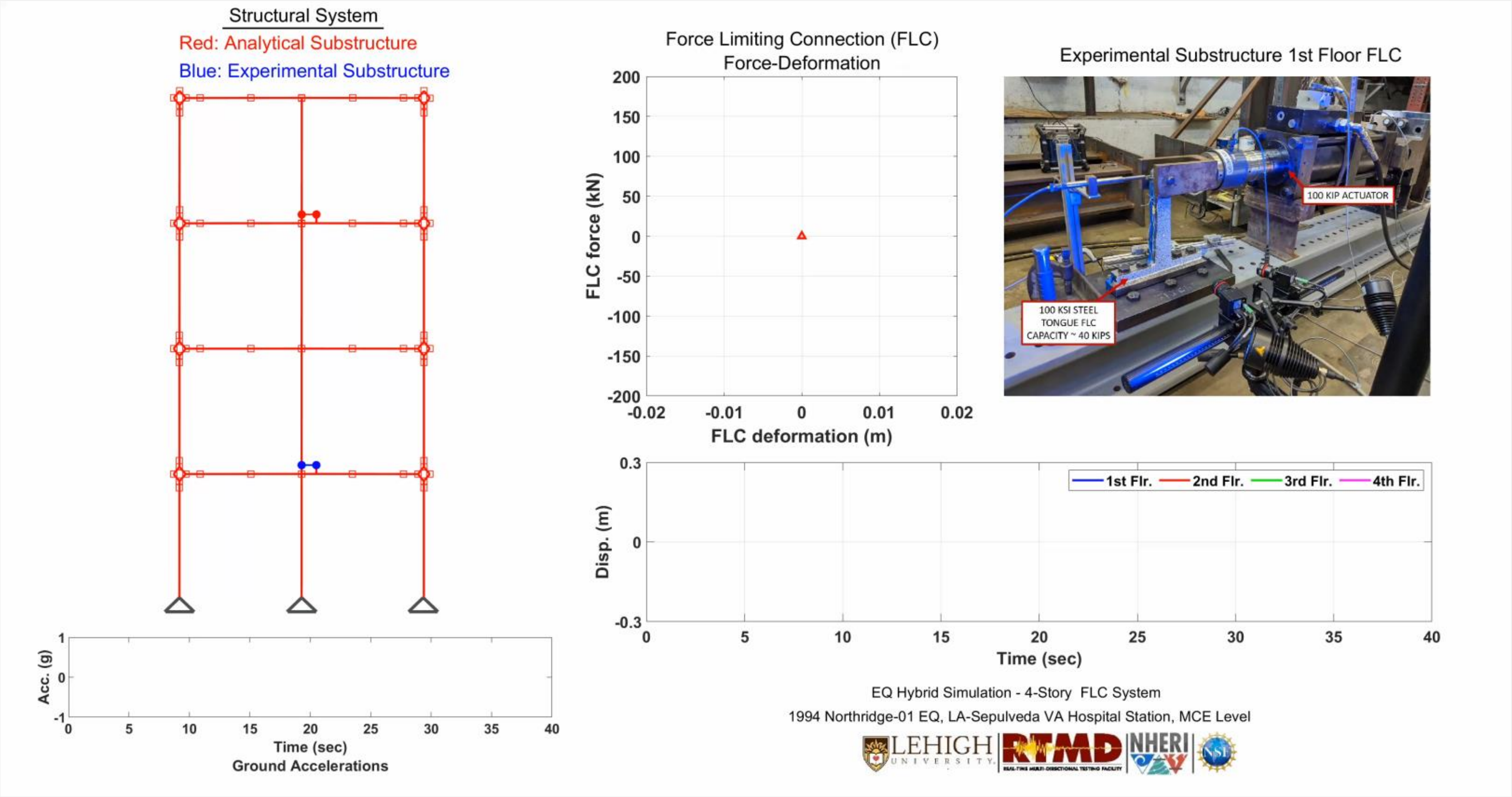

E-Defense Shake table testing of system

# 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

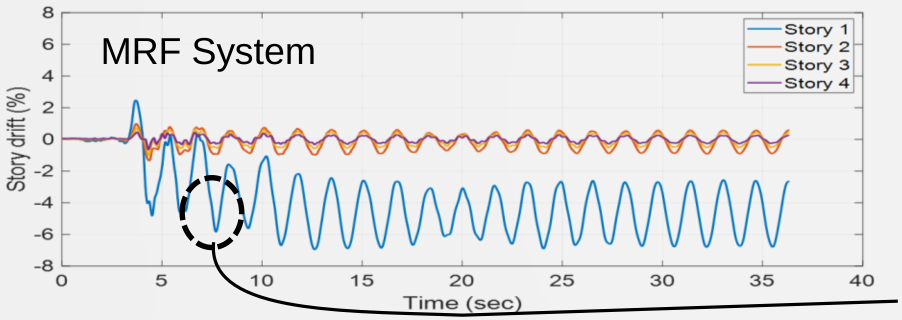


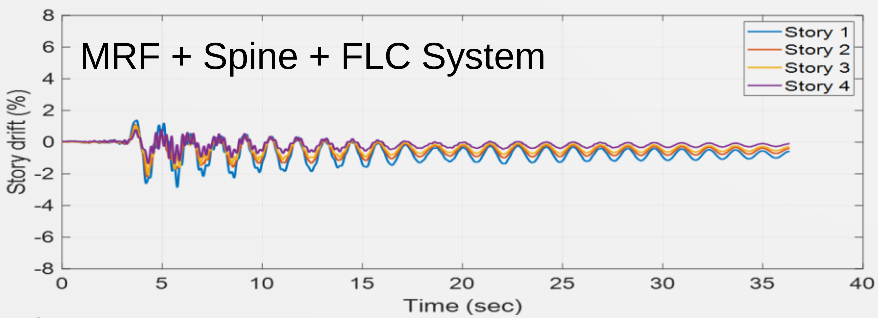
# Research Projects

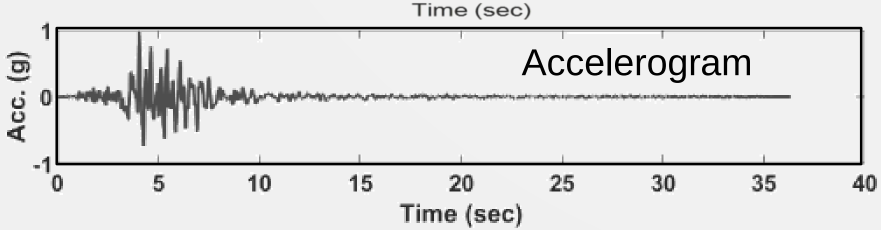
## *Collaborative Research: Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic Resilient Buildings*

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

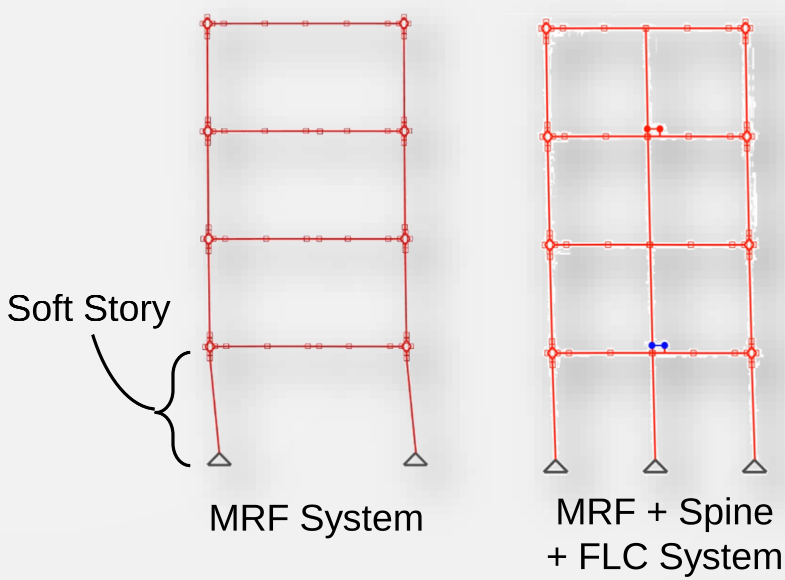
- Major Findings
  - Adding spine with FLCs to MRF:
    a. Eliminates the formation of a soft story, reducing drift and damage.
    b. Reduces lateral accelerations from higher modes.




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 |

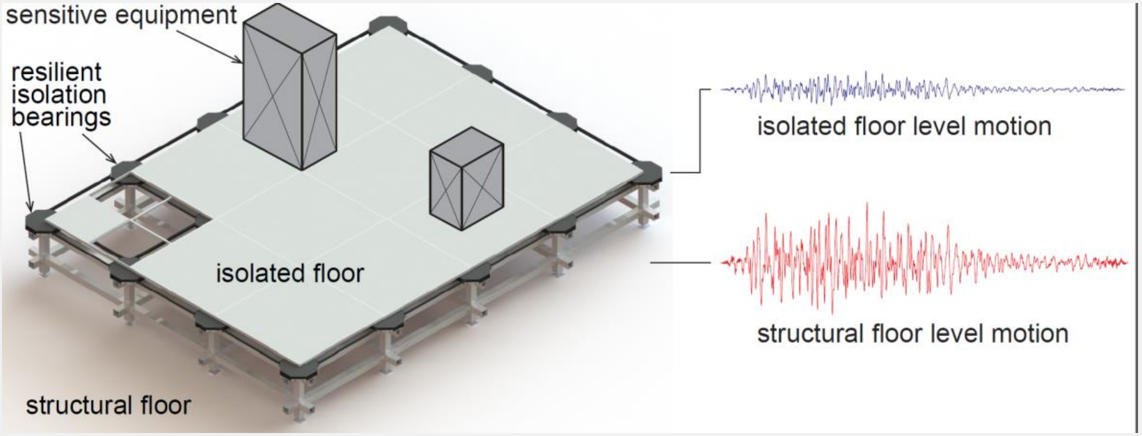
# Research Projects

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

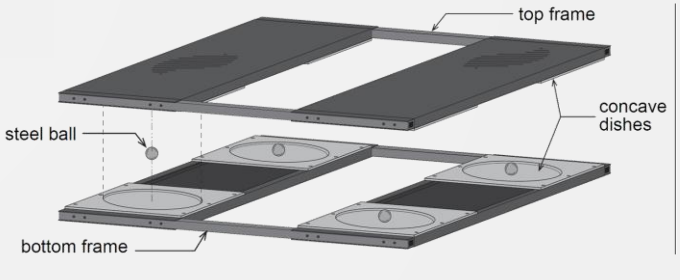
**(OIA 1929151) University of Oklahoma (Scott Harvey)**

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

# Research Projects

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

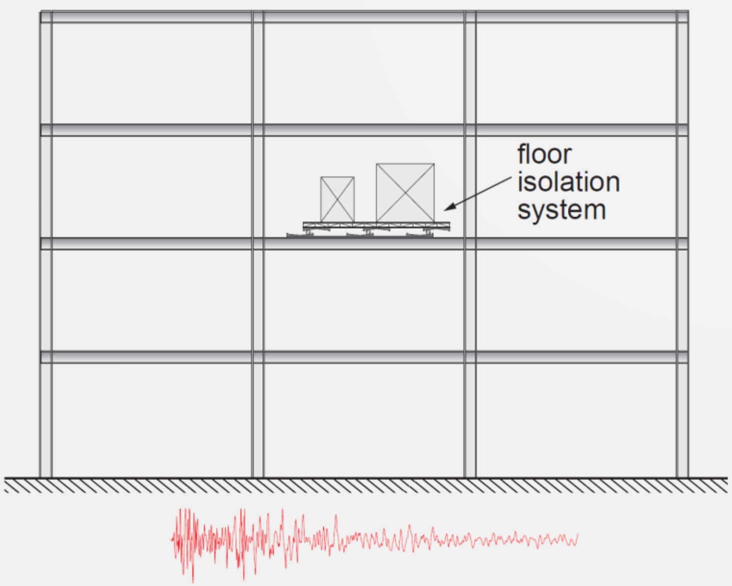
**(OIA 1929151) University of Oklahoma (Scott Harvey)**

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.

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 the Real-time Cyber-Physical Structural Systems Laboratory (CPSSL)

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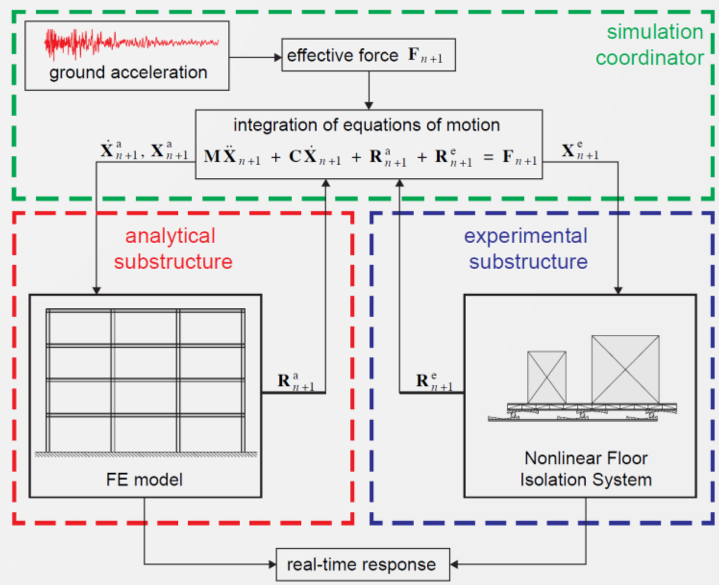



RTHS Process

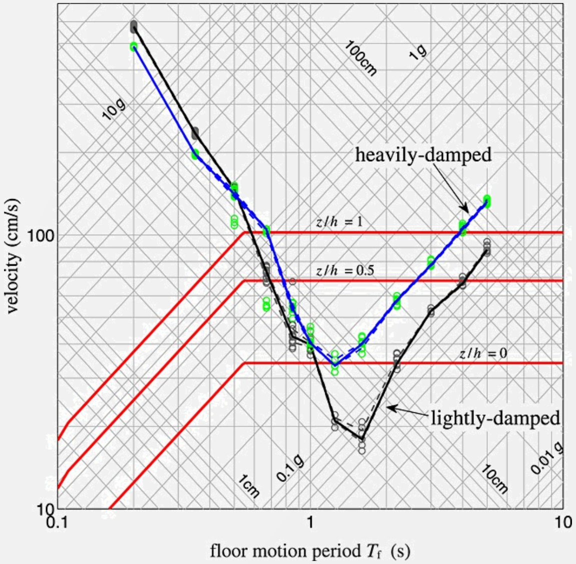
# Research Projects

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

**(OIA 1929151) University of Oklahoma (Scott Harvey)**

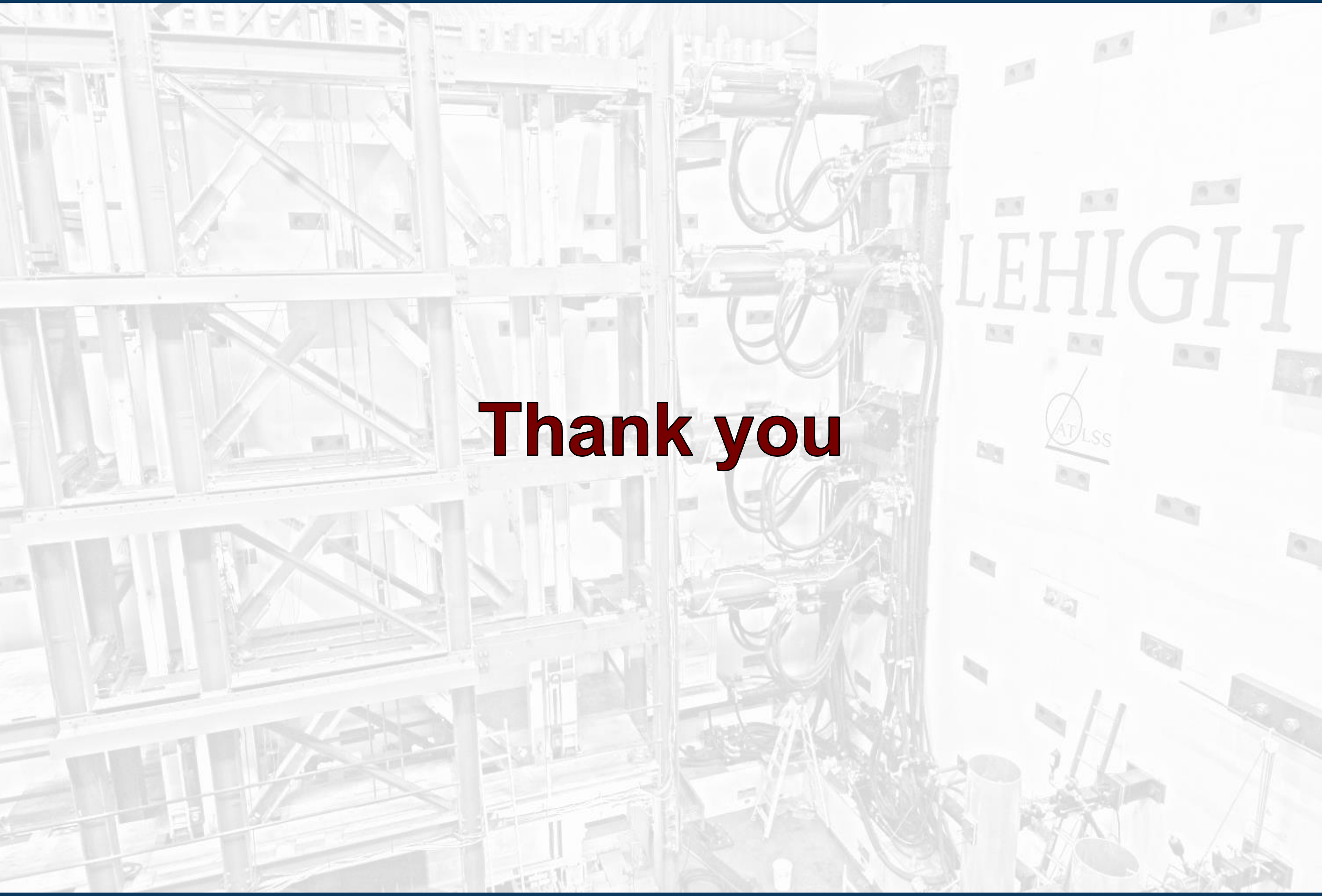
- Impact of Research
  - Validated physics-based mathematical models will enable accurate numerical simulations of FISs in building systems to be performed; valuable asset for assessing performance and validating performance-based design procedures.
  - Potentially lower the repair and demolition costs of post-earthquake recovery, including damage to non-structural elements/contents, save lives, and provide immediate operation for critical facilities.

Isolation bearing characterization testing and RTHS




Bearing characterization results

Tehrani, M. H., and P. S. Harvey Jr. (2020) "Dynamic Coupling of Nonlinear Equipment Isolation Systems and the Supporting Structure." in: *Proceedings of the 38th International Modal Analysis Conference*, Houston, TX,.




# Thank you

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

NSF

DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY