Example Past Projects at NHERI Lehigh

Richard Sause, PhD, PE

ATLSS Director & NHERI Lehigh EF Co-PI
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-story building with piping system</td>
<td>Multi-directional real-time hybrid simulation</td>
</tr>
<tr>
<td>Self-centering moment-resisting frame (SC-MRF)</td>
<td>Large-scale hybrid simulation</td>
</tr>
<tr>
<td>Self-centering concentrically-braced frame (SC-CBF)</td>
<td>Large-scale hybrid simulation</td>
</tr>
<tr>
<td>Real-time testing of structures with dampers</td>
<td>Large-scale real-time hybrid simulation with multiple experimental substructures</td>
</tr>
<tr>
<td>Seismic hazard mitigation using passive damper systems</td>
<td>Predefined displacement dynamic testing (for characterization)</td>
</tr>
<tr>
<td></td>
<td>Large-scale real-time hybrid simulations</td>
</tr>
<tr>
<td>Tsunami-driven debris</td>
<td>Dynamic testing (impact loading)</td>
</tr>
<tr>
<td>Post-tensioned coupled shear wall system</td>
<td>Complex large-scale multi-directional predefined force and displacement quasi-static testing</td>
</tr>
<tr>
<td>Inertial force-limiting floor anchorage systems for buildings</td>
<td>Predefined displacement dynamic testing (for characterization)</td>
</tr>
<tr>
<td>Cross-Laminated Rocking Wall-Floor Diaphragm Systems</td>
<td>Multi-directional quasi-static and hybrid simulation</td>
</tr>
</tbody>
</table>
Multi-Directional Large-Scale Real-Time Hybrid Simulation of 3-story Building with Piping System

Multi-Directional Large-Scale Real-Time Hybrid Simulation

3-story MRF

Piping system

Analytical Substructure

Experimental Substructure

\[ \Delta = Td \]
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

SC-CBF

6-story : 6 bays @ 30 ft = 180 ft
Plan of Prototype Building

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

NEES
Large-Scale Hybrid Simulation (SC-CBF)
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](image)

**Damper force - deformation**

**Damper force - velocity**

Loading protocol:

- 2 ramp up cycles
- 7 stable full cycles
- 3 ramp down cycles

**Actuator stroke (inches)**

- 3 ramp down cycles
- 2 ramp up cycles
- 7 stable full cycles

**Time (s)**

- 0
- 2
- 4
- 6
- 8
- 10
- 12
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

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

Plan of Prototype Building

Steel MRF with Passive Dampers

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)
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
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

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

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

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)

![Experimental Substructure (0.625-Scale)](image)

![South Wall Panel](image)

![North Wall Panel](image)

![Graph of In-Plane Lateral Load-Drift](image)

![Graph of Out-of-Plane Lateral Load-Drift](image)

**Multi-Directional Cyclic Testing of CLT Subassembly**

Comparison of Target vs. Measured Subassembly Drift
Example Recent and Current Research Projects at NHERI Lehigh

Liang Cao, PhD

NHERI Lehigh EF Research Scientist
## Recent and Current Projects at NHERI Lehigh EF

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

(1) Capacity Building Projects
## Recent and Current Projects at NHERI Lehigh EF

<table>
<thead>
<tr>
<th>Project</th>
<th>Resource, Testing Method</th>
<th>PI</th>
<th>Institution of PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFI-TT: Self-Centering Seismic Dampers for Resilience-Based Earthquake</td>
<td>High-bay lab, damper test beds, CPSSL; characterization testing, RTHS</td>
<td>Osman Ozbulut, Robert Archer</td>
<td>University of Virginia</td>
</tr>
<tr>
<td>Design of Buildings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSF Convergence Accelerator Track D: Intelligent Surveillance Platform</td>
<td>High bay lab, DIC; quasi-static testing</td>
<td>Claudia Marin</td>
<td>Howard University</td>
</tr>
<tr>
<td>for Damage Detection and Localization of Civil Infrastructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMMI 2040665</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAREER: Mitigation of Seismic Risk to Critical Building Contents via</td>
<td>High-bay lab, damper test beds, CPSSL; characterization testing, RTHS</td>
<td>Scott Harvey</td>
<td>University of Oklahoma</td>
</tr>
<tr>
<td>Optimum Nonlinear 3D Isolation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMMI 1943917</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAREER: Data-Driven Control of High-Rate Dynamic Systems</td>
<td>High-bay lab, damper test beds, CPSSL; characterization testing, RTHS</td>
<td>Austin Downey</td>
<td>University of South Carolina</td>
</tr>
<tr>
<td>CMMI 2237696</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAREER: Accelerating Real-time Hybrid Physical-Numerical Simulations in</td>
<td>High-bay lab, damper test beds, CPSSL, RTHS</td>
<td>Barbara Simpson</td>
<td>Oregon State University</td>
</tr>
<tr>
<td>Natural Hazards Engineering with a GPU-driven Paradigm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMMI 2145665</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

13 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 using controlled variable friction cladding panel connectors
  - Hazards: Earthquake, Wind (NHERI UF and NHERI FIU)

- **Scope**
  - Design cladding connectors and control laws
  - Construct prototype connector, perform characterization testing
  - Perform large-scale RTHS to validate numerical models and results
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](image1.png)

- 4-story building with friction connectors
- 40-story building with nonlinear viscous dampers

---

![Graphs and diagrams](image2.png)
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 (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


Full-Scale Nonlinear Viscous Dampers

Characterization testing

Damper testbed

Loading Protocol

(b) Damper force - deformation

(b) 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=IaX0A1aRBo

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 Sub. Key features:

• 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 20\(^{th}\), 30\(^{th}\), & 40\(^{th}\) floors)
  ➢ 553 Nonlinear truss elements

• Geometric nonlinearities
• Mass
• Inherent damping of building

Experimental Substructure – Banded Rotary Friction Damper

Analytical Substructure

Experimental Substructure – Nonlinear Fluid Viscous Damper

Analytical Substructure – Nonlinear Viscous Damper

Experimental Substructure – South-east damper at 40\(^{th}\) story outrigger
3-D Real-time Hybrid Simulation
110 mph, 700 MRI Wind Storm (Northwestern Windward Direction)

Multiple Experimental Substructures; Multi-natural Hazards

Motions scaled by factor of 20 in animation
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 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.

<table>
<thead>
<tr>
<th>Response Quantity</th>
<th>Reduction using passive controlled damped outriggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum story drift</td>
<td>Wind: 10%  EQ: 22%</td>
</tr>
<tr>
<td>Maximum absolute acceleration</td>
<td>Wind: 35%  EQ: 25%</td>
</tr>
</tbody>
</table>

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

**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

336 total number of pressure taps
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
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

- NS Direction Wind Force
- EW Direction Wind Force
- NS Direction Structure Response
- EW Direction Structure Response
- NS Direction Roof Acceleration
- EW Direction Roof Acceleration
- EW Direction Roof Displacement
- EW Direction Roof Displacement

© 2023 Lehigh University - Thomas Marullo & Liang Cao
3D RTAHS Results: Aeroelastic Effect

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

(a) Aerodynamic Model

(b) RTAHS Model
RTHS of Soil-Structure-Foundation Systems Using Neural Networks – Lehigh University, MTS

(a) System

(b) RTHS

Real-time input EQ ground acceleration

Simulation Coordinator

MX_i + CX_i + R_i^e + R_i^e = F_i^e

Experimental Substructure
Dampers (Modeled in lab)

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**

- 2-D OpenSees Model
- 2-D RTHS with Neural Network Model
- Neural Network Model of Soil Training
- Comparison with OpenSees

Simulink Block – User Tool
RTHS of Soil-Structure-Foundation System
Roof Displacement Time History- Windward Direction
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.
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

Actuator

Restraint

Shake table multidirectional movement in the plane

South-West top general view

Tributary weight

Top isolation platform

Bottom isolation platform

Pinned end connection

reaction column (foundation)

load cells

Actuators

Shake table

Floor isolation of critical building contents
Characterization Tests

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

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

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

<table>
<thead>
<tr>
<th>X-Direction</th>
<th>Z-Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.3%</td>
<td>68.9%</td>
</tr>
</tbody>
</table>
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))**

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

---

**Pressurized Sand-Damper**

---

**Features Using NHERI Lehigh**

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

---

**Pressurized Sand Damper**

---

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) Characterization test setup

Model fitting result (Bouc-Wen Model)

Schematic of the PSD

- Load cell to measure the pressure
- PT steel rod
- Sphere
- Spacer that accommodates the motion of the rod
- Direction of motion
- Damper piston

Characterization test setup

- Reaction column
- Actuator load cell
- PSD-actuator roller support
- PSD rigid support
- Pressure load cells (4)
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

PSD Location

PSD Location

SC-CLT Wall Base Shear vs Story Drift

Time History of Story Drift

Damper Hysteresis - Left PSD

Time History of Wall Base Shear

Damper Hysteresis - Right PSD

Experimental Substructure

Left PSD

Right PSD

© 2023 Lehigh University - Thomas Marullo, Liang Cao, Kostas Kalfias, Nicos Markis
Thank you