NHERI Lehigh EF Overview

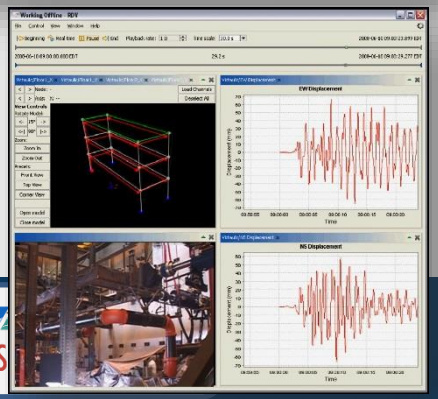
James Ricles, PhD, PE

NHERI Lehigh EF Director

NHERI Lehigh EF Description

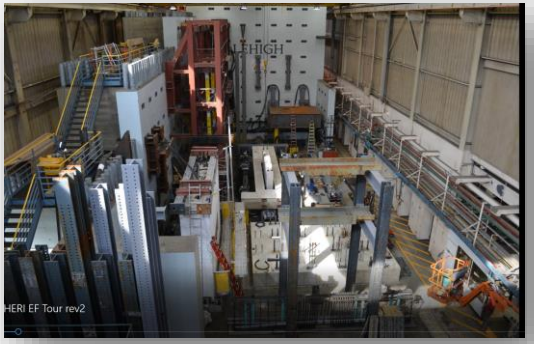
What is the NHERI Lehigh EF?

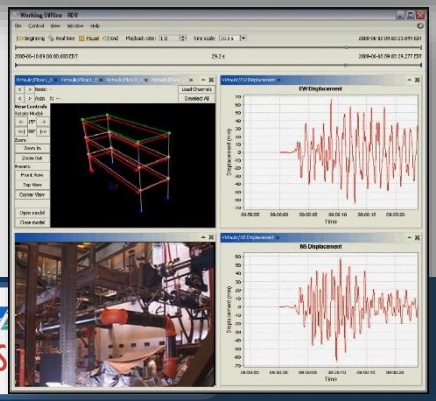
- Former NEES Site: Real-time Multi-directional (RTMD) Earthquake Simulation Facility
- Unique facility
  - Portfolio of equipment, instrumentation, infrastructure, testbeds, and experimental simulation control protocols for large-scale multi-directional testing



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 capabilities
- Real-time loading
  - Dynamic actuators, hydraulic equipment and power
  - Actuator control with kinematic and adaptive compensation
- Hybrid simulation
  - Large-scale, real-time, multi-directional
  - Soil-structure interaction
  - Fluid-structure interaction
  - Integration algorithms
  - Analytical substructures with geometric and material nonlinearities
  - Multi-grid real-time simulations
  - Machine learning neural network modeling
  - Actuator multidirectional kinematic compensation
  - Real-time adaptive 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
  - Structural Control
  - Structural Dynamics
  - EQ Engineering
  - Geotechnical Engineering
  - Aeroelasticity and Wind Engineering
  - Hydrodynamic and Fluid-structure Interaction Engineering
  - Probabilistic-based and Catastrophe Modeling Engineering
  - 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

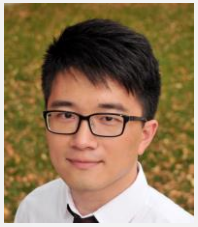
NHERI Lehigh EF Team

James Ricles, PI
NHERI EF Director
ATLSS Director

Richard Sause
Co-PI

Claudia Reis
Co-PI

Joseph Saunders
Operations Mgr
ATLSS Assoc Dir Ops



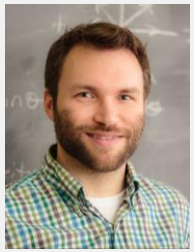
Liang Cao
Research Eng

Thomas Marullo
IT Systems Mgr

Darrick Fritchman
ATLSS Lab Mgr

Sandra Nemeth
ATLSS Finance Mgr

Lehigh Faculty Capacity Building Partners



Keith Moored
Aero- and Hydrodynamics,
Fluid-Structure Interaction

Muhannad Suleiman
Soil-Structure Interaction

Paolo Bocchini
Probabilistic Modeling and
Infrastructure Resilience

Shamim Pakzad
Adv. Sensors,
Structural Monitoring

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

Advisory Council

- ***Advisory Council:*** *provide advice on marketing to broaden user base and ECO; advise on recent developments in natural-hazards engineering*
  - ***Expertise****: Community Resilience, Geotechnical Engineering, Performance-Based Engineering, Isolation Systems, Structural Control, Structural Surveillance and Health Monitoring, Advanced Damping and Structural Response Modification Devices.*

Elaina Sutley
Univ Kansas

Brady Cox
Utah State

Dawn Lehman
Univ Washington

John van de Lindt
Colorado State

Scott Harvey
Univ Oklahoma

Patricia Clayton
Wake Forest Univ

Claudia Marin
Howard Univ

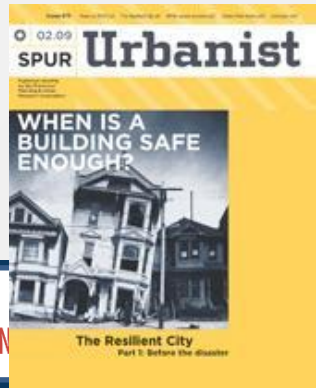
Erik Johnson
Univ Southern Cal

NHERI Lehigh EF Science Plan

NHERI Lehigh EF Science Plan

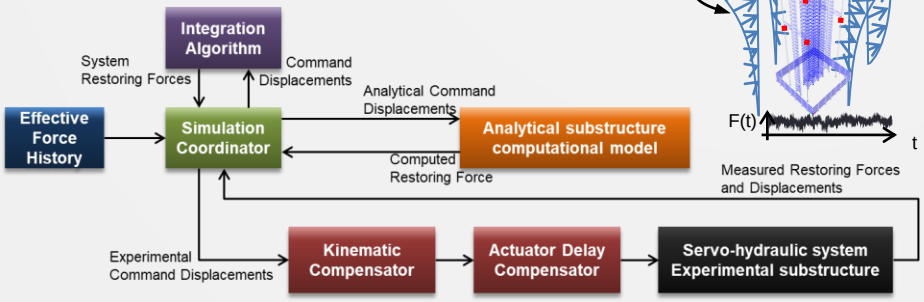
Provide a next generation multi-user facility to perform transformative research by closely integrating numerical simulations and experiments to advance natural hazards engineering research and education, enabling the challenge of community resilience to natural hazards to be met:

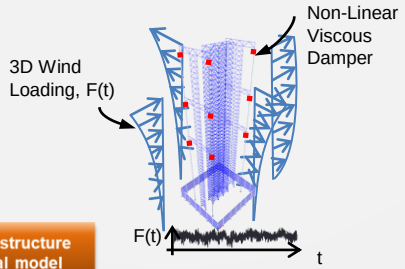
- Improved concepts for renewal and retrofit of the built environment
- Exploitation of new emerging materials
- Development of innovative, resilient structural concepts
- Economical design approaches toward natural hazard mitigation
- Development and validation of more accurate physics-based computational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



NHERI Lehigh EF Science Plan

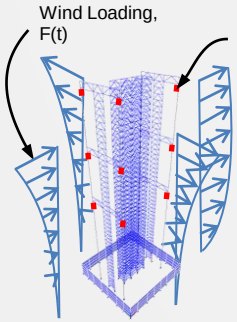
- The NEHRI Lehigh EF focus is on large-scale, multi-direction, real-time hybrid simulations that combine physical experiments with computer-based simulations for evaluating performance of large-scale components and systems.
- The NEHRI Lehigh EF provides user-friendly tools that enables researchers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





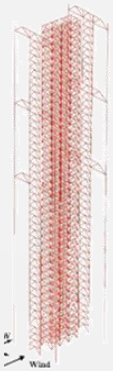
NHERI Lehigh EF

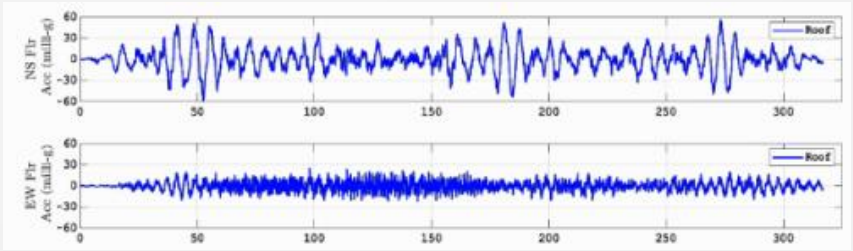
- Facility Enables Researchers to Readily Perform:
  - 3-D RTHS of large, complex nonlinear systems subjected to multi-natural hazards, (e.g., wind, water, and earthquake) using analytical substructures created with robust computational models that include machine learning-trained neural network models;
  - 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 experiments of systems with precise hydraulic actuator control.



40-story building


FIU wind tunnel testing


Analytical substructure



Windward and crosswind roof acceleration response

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 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)
  - *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)
  - *Resilience of Civil Infrastructure Transportation Systems to Multi-Natural Hazards* (approach: real-time hybrid simulation)
  - *Performance-based Engineering of Civil Infrastructure to Fire Hazards* (approach: hybrid simulation with furnace)
  - *Efficacy of Response Modification Devices in Structural Systems Accounting for the Effects of Soil-Structure and Fluid-Structure Interactions* (approach: real-time hybrid simulation)
  - *Resiliency of Coastal Infrastructure to Inundation from Storm Surge and Tsunamis* (approach: real-time hybrid simulation)

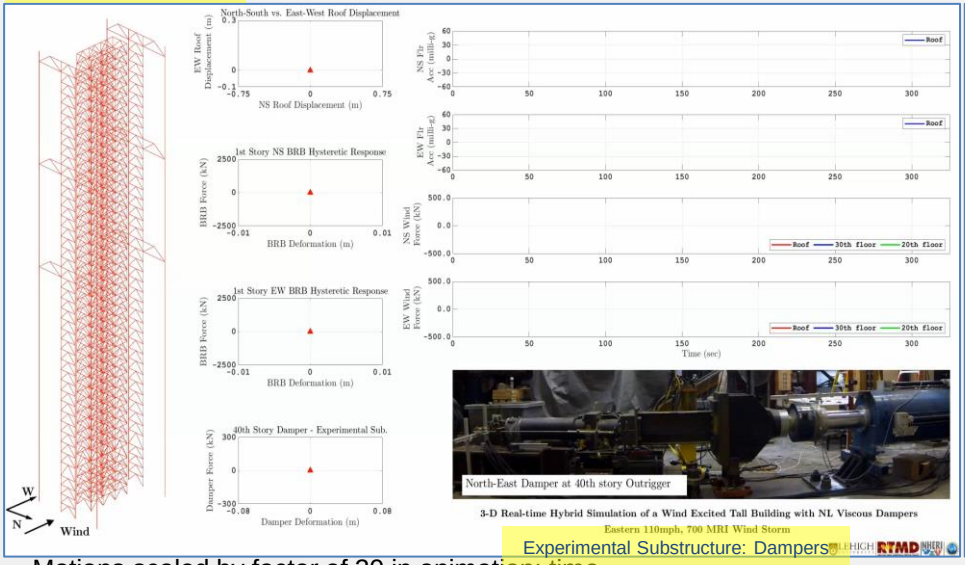
Examples of Research Vision at NHERI Lehigh

Multi-directional Nonlinear Real-time Hybrid Simulations (RTHS) to Improve Multi-Natural Hazards Resiliency of Tall Buildings

Rate Dependent Nonlinear Viscous Damper

3D Multi-hazards RTHS of 40-story Building with Supplemental Nonlinear Viscous Dampers in Outriggers

Analytical Substructure: Building



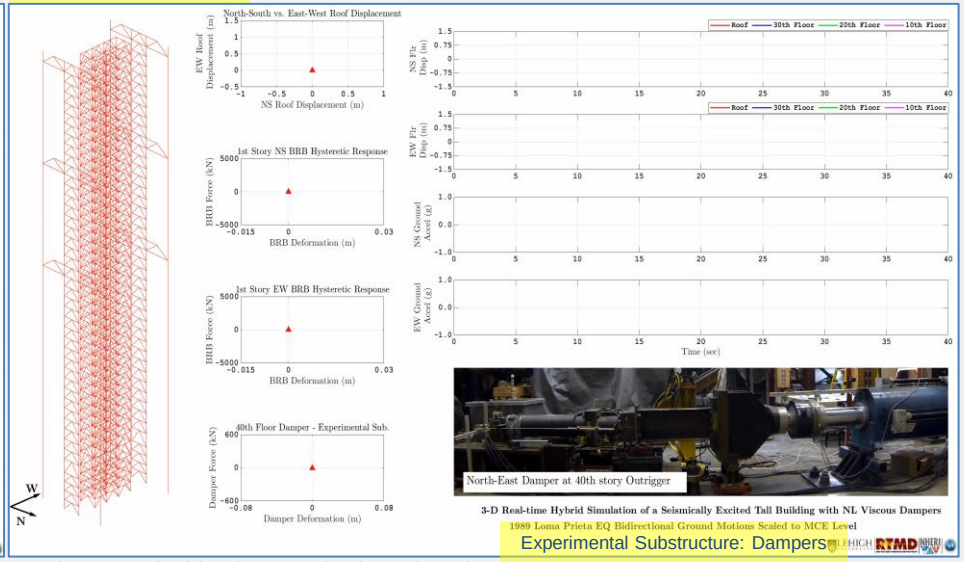
Experimental Substructure: Dampers

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

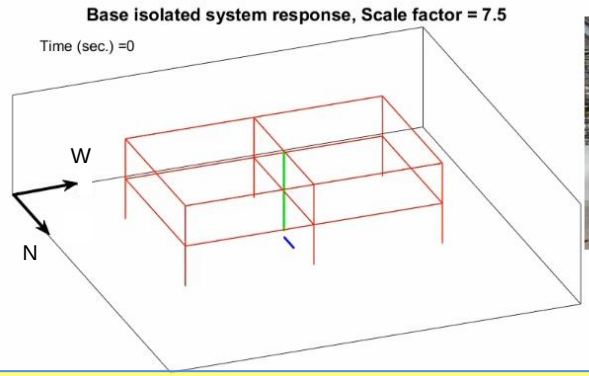
ATLSS | RTMD Real-Time Multi-Directional Simulation, Natural Hazards Engineering Research Infrastructure | Lehigh University | NSF NHERI Cyber-Physical Simulation

Examples of Research Vision at NHERI Lehigh

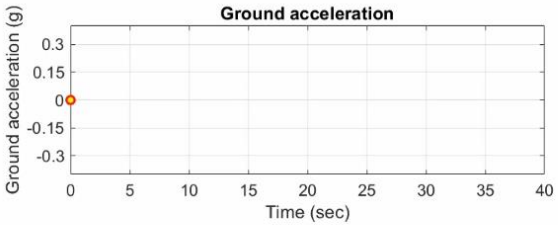
Multi-directional Nonlinear Real-time Hybrid Simulations (RTHS) to Improve Seismic Resiliency of RC Buildings

Banded Rotatory Friction Damper

RTHS of 2-story RC Building Outfitted with a Next-generation Rotary Banded Friction Base Isolation System



Experimental + Analytical Substructures = Base-Isolated Building



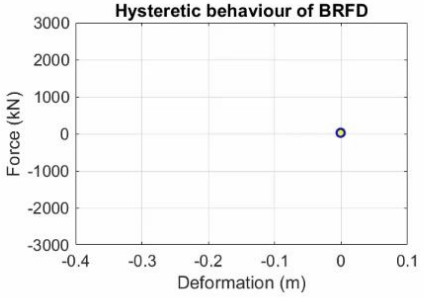
RTHS of 2-Story RC Building with BRFD Base Isolation System

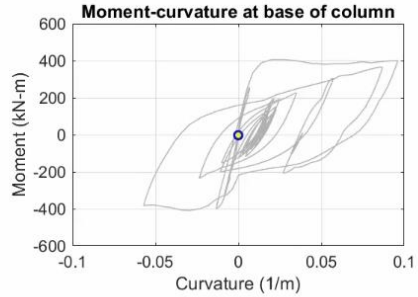
000 Component 1989 Loma Prieta EQ, Saratoga-Aloha Ave Recording Station. Scaled to MCE Hazard Level

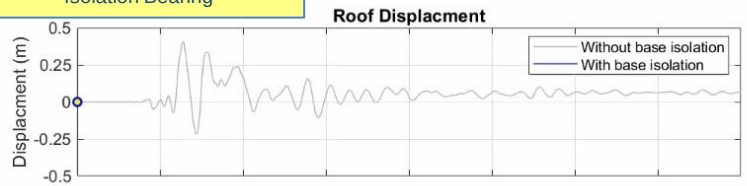
Liang Cao, Faisal Malik, James Ricles, Austin Downey, Simon Laflamme

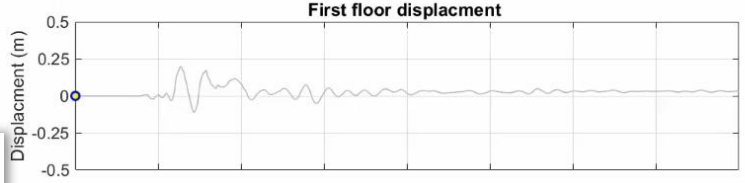
Experimental substructure

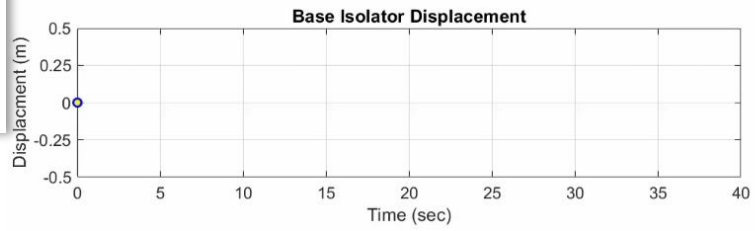
Experimental Substructure: Banded Rotary Friction Damper Isolation Bearing

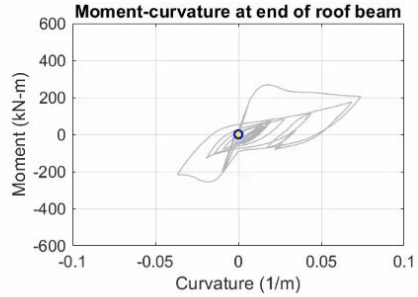


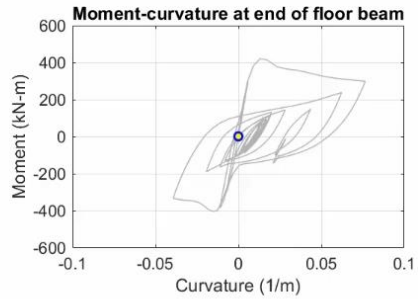










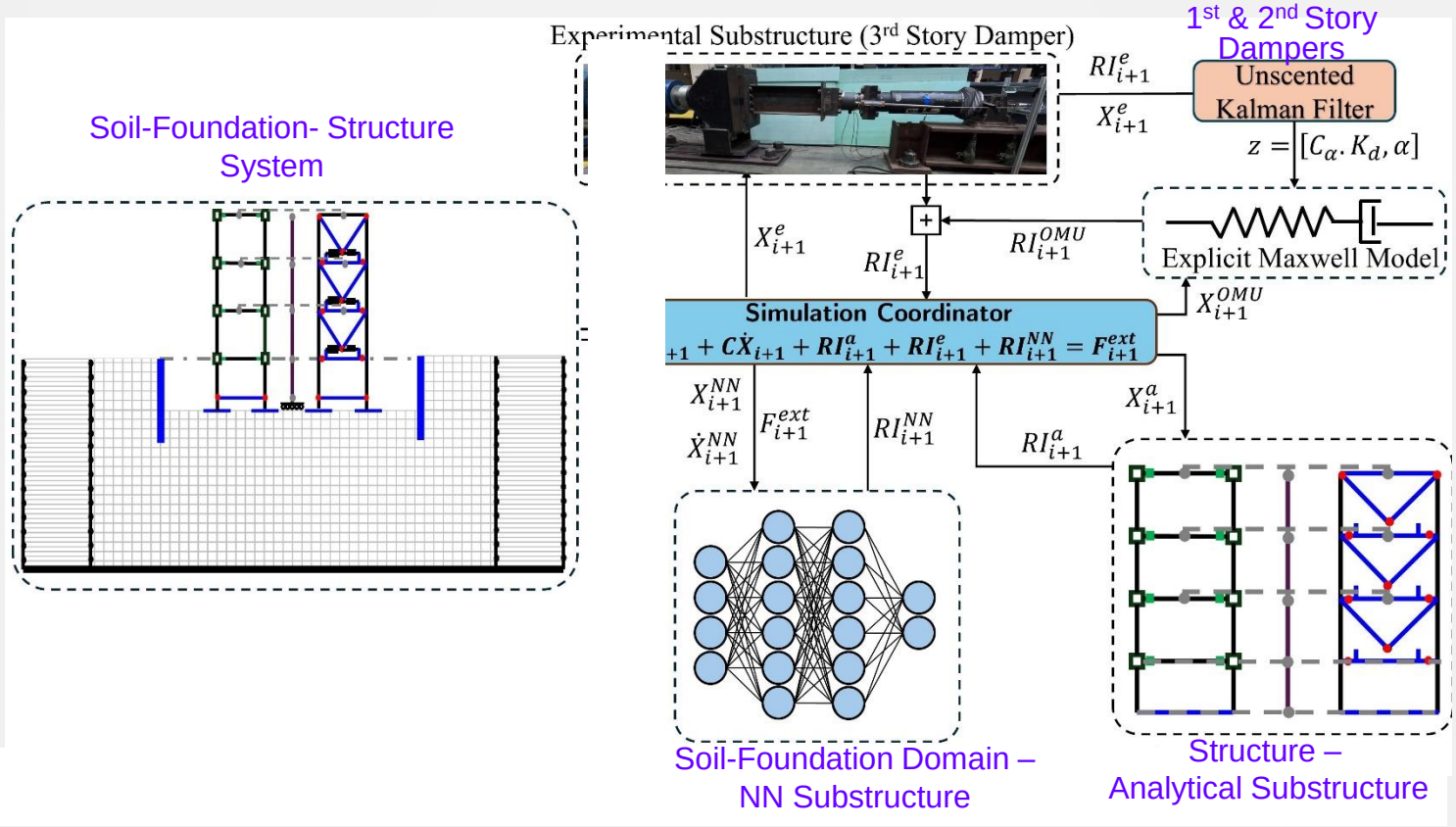


Examples of Research Vision at NHERI Lehigh

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

NL Viscous Damper

[RTHS of 3-story Steel Frame Building Outfitted with Nonlinear Viscous Dampers]

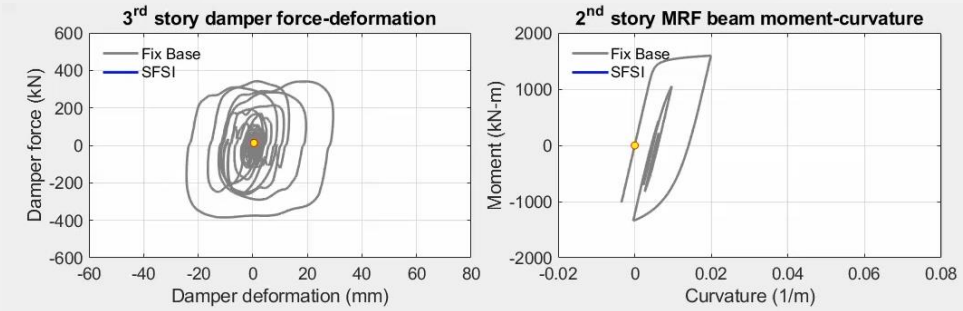


Malik, F. "Multi-Physics Real-Time Cyber-Physical Simulation of Complex Nonlinear Structural Systems with Soil-Foundation-Structure Interaction," PhD Dissertation, Lehigh Univ., in progress

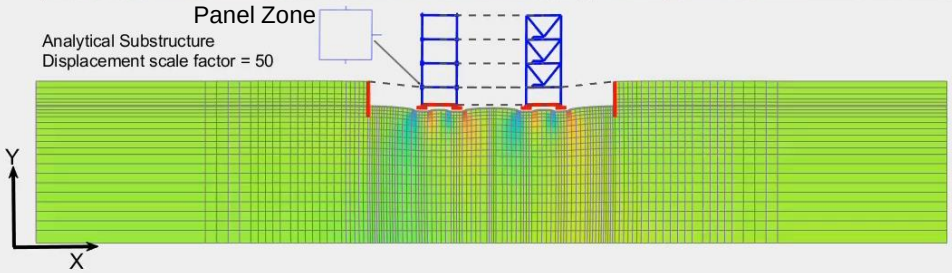
Malik, F. Gorini, D,N, Ricles, J., and M. Rahnesmoonfar, (2024). "Multi-Physics Framework for Seismic Real-time Hybrid Simulations with Soil-Foundation-Structure Interaction," *Engineering Structures*, in preparation

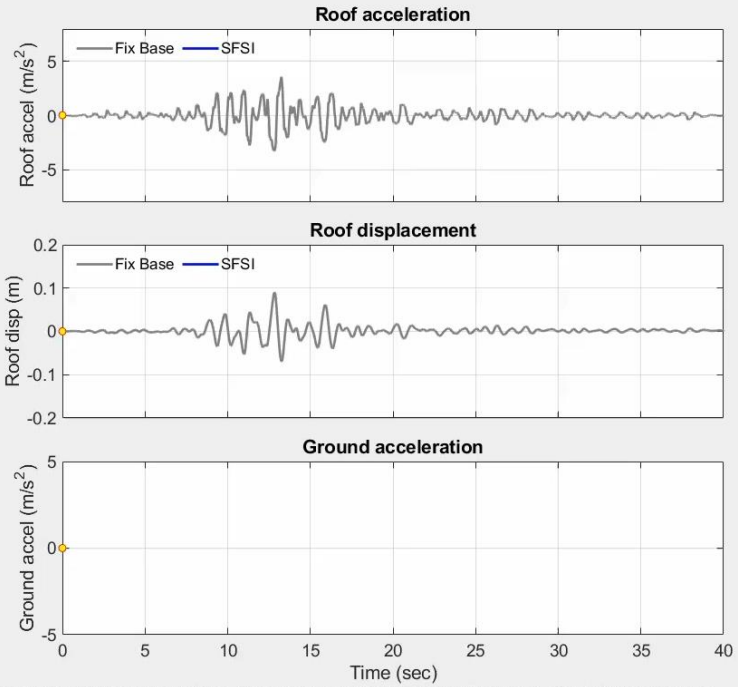
Multi-physics RTHS: Seismic Real-time Hybrid Simulation with Soil-Foundation-Structure Interaction Using Neural Networks

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



Experimental Substructure - 3rd story damper





Real-time Cyber Physical Simulation of a 3-story Moment Resisiting Frame and Damped Brace Building with Soil-Foundation-Structure Interaction

Faisal Nissar Malik, Davide Noe Gorini, James Ricles, Maryam Rahnemoonfar

000 Component of Loma Prieta Earthquake recorded at SF - Cliff House and scaled to Uniform Hazard Spectrum for Design Basis Earthquake

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

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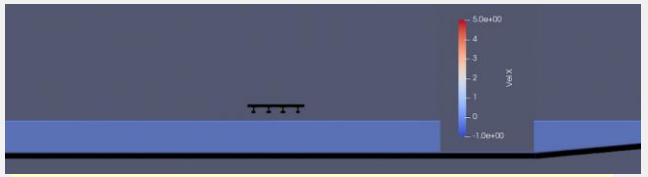
Resiliency: Understanding the Effects of Natural Hazards on the Built Environment

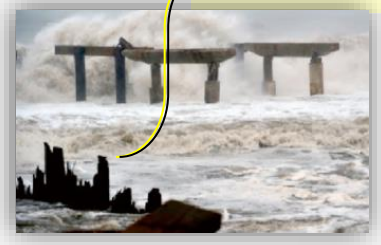
What needs to be considered?

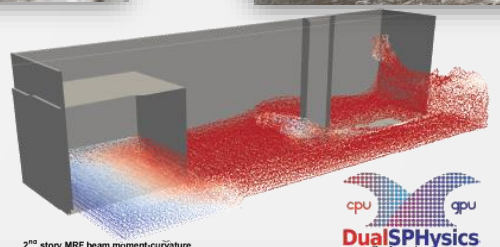
Simulations that include:

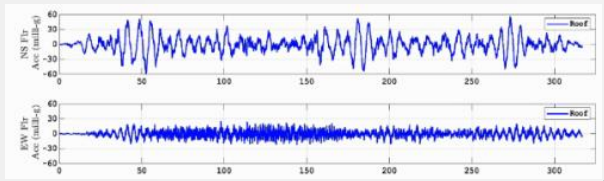
- **Spatial and Temporal Discretization & Multi-directionality Effects**
- **Real-time**
- **Multi-physics**



NHERI Lehigh EF







$\tilde{x}_{i+1} = \{Kd_{i+1}, Cd_{i+1}, \alpha_{i+1}\}^T$

Southside damper at 40th floor

Explicit damper model

Southside damper at 30th floor

Loading beam

Clevis Damper Load cell Actuator

$\mathbf{X}^e_{i+1}$

$\mathbf{R}^e_{i+1}$

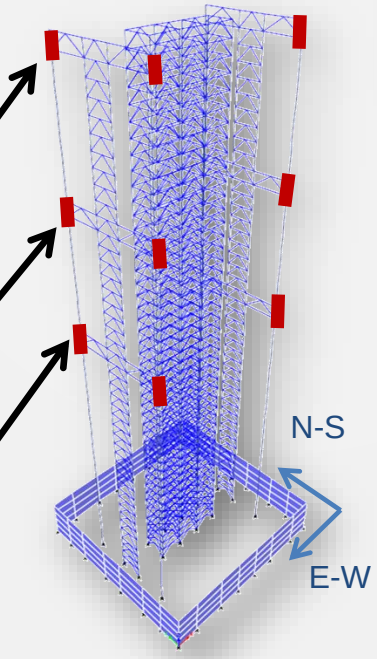
UKF

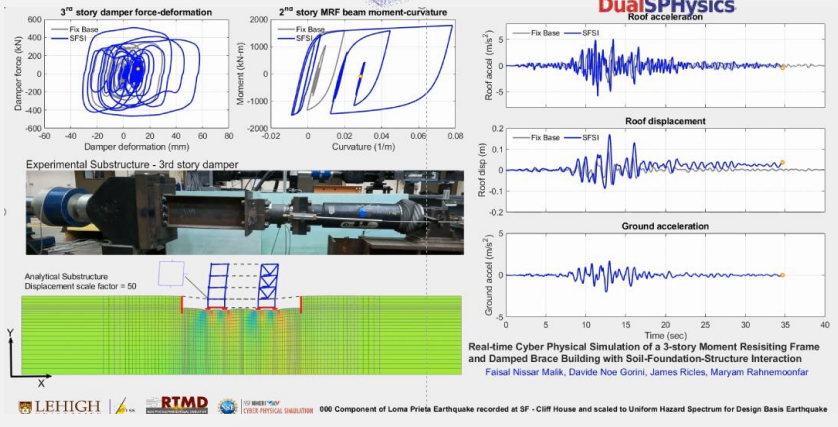
Real-time system identification

Southside damper at 20th floor

Loading beam

Actuator Load cell Damper Clevis





Thank you