NHERI Lehigh Experimental Facility
Description, Experimental Capabilities and Protocols

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NHERI Lehigh EF
Outline

• Experimental Capabilities
• Real-time Hybrid Simulation: Overview, NHERI Lehigh Developments
• Test Beds
• Equipment
• Experimental Protocols
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation

HS EQ Simulation of Buildings with SC-MRF
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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

RTHS EQ Simulation of Buildings with Dampers
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

- Large-Scale Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)

\[ \hat{x}_{t+1} = \{Kd_{t+1}, C_d_{t+1}, u_{t+1}\}^T \]

RTHS Wind and EQ Simulation of Tall Buildings with Dampers
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

• Large-Scale Hybrid Simulation
• Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)
• 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 Hybrid Simulation
- Large-Scale Real-time Hybrid Simulation (with Real-time Online Model Updating)
- Large-Scale Real-time Hybrid Simulation with Multiple Experimental Substructures
- Geographically Distributed Hybrid Simulation

Distributed Hybrid Simulation

Distributed RTHS EQ Simulation of I-10 Collector Bridge
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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

RTHS EQ Simulation of Building with MR Dampers (Kim, Christenson)
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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- 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)

Characterization of Full-scale Semi-active and Passive Dampers

Temperature Control Chamber
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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• Geographically Distributed Real-time Hybrid Simulation
• Predefined load or displacements (Quasi-static testing or characterization testing)

Characterization of Large-scale RC Coupled Shear Wall System
NHERI Lehigh EF Testing Capabilities for Natural Hazards Engineering Research

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- Geographically Distributed Hybrid Simulation
- Geographically Distributed Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)
- Dynamic testing

Multi-directional Dynamic Testing of Pipe Couplers
Overall Concept of Real-time Hybrid Simulation: Structural System Subject to Multi-Natural Hazards

**Structural System**
- 40-Story Building with Outriggers and Supplemental Dampers
- EQ Ground Accelerations
  - N-S
  - E-W

**Hybrid Earthquake Simulation Experiments**
- Real-time input EQ ground acceleration $F(t)$
- Simulation Coordinator
  - $M\ddot{X}_{i+1} + C\dot{X}_{i+1} + R^a_{i+1} + R^e_{i+1} = F^a_{i+1}$
  - $\text{Cmd Displ}$
  - $X^a_{i+1}$ (Restoring Force)
  - $X^e_{i+1}$ (Experimental substructure (dampers))
  - Integrates Eqns of Motion
- Wind Tunnel Tests NHERI@FIU
  - Wind Load Determination

*Image of ATLSS substructure*
*Image of simulation experiments*
*Image of real-time structural response*
RTHS: Implementation issues and challenges

Simulation coordinator

- Numerical integration algorithm
  - Accurate
    - Explicit
    - Unconditionally stable
    - Dissipative
  Preferred
- Fast communication

Experimental substructure

- Large capacity hydraulic system and dynamic actuators required
- Actuator kinematic compensation
- Robust control of dynamic actuators for large-scale structures

Analytical substructure

- Fast and accurate state determination procedure for complex, nonlinear structures
RTHS: Implementation solutions

Simulation coordinator

- Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative

- Fast communication

NHERI Lehigh Solutions

Explicit model-based integration algorithms
Numerical Integration Algorithms

Explicit Modified KR-α (MKR-α) Method

- Explicit Integration of Equations of Motion, Model-based
- Unconditionally Stable
- Controlled Numerical Damping – eliminate spurious high frequency noise

Velocity update:
\[ \dot{X}_{n+1} = \dot{X}_n + \Delta t \alpha_1 \ddot{X}_n \]

Displacement update:
\[ X_{n+1} = X_n + \Delta t \ddot{X}_n + \Delta t^2 \alpha_2 \dddot{X}_n \]

MKR-α: One parameter (\( \rho_{\infty} \)) family of algorithms

- \( \rho_{\infty} \), Parameter controlling numerical energy dissipation
  - \( \rho_{\infty} = \) spectral radius when \( \Omega = \omega \Delta t \to \infty \)
  - varies in the range \( 0 \leq \rho_{\infty} \leq 1 \)
  - \( \rho_{\infty} = 1 \): No numerical energy dissipation
  - \( \rho_{\infty} = 0 \): Asymptotic annihilation


Steel Structure with Nonlinear Viscous Dampers Studied using Large-scale RTHS

- **Prototype building**
  - 3-story, 6-bay by 6-bay office building located in Southern California
  - Moment resisting frame (MRF) with RBS beam-to-column connections, damped brace frame (DBF), gravity load system, inherent damping of building


Nonlinear Viscous Dampers

Characterization testing

Damper testbed

Loading Protocol

Damper force - deformation

Damper force - velocity
Large-scale RTHS on Structure with Nonlinear Viscous Dampers: Substructures

Substructures for RTHS Phase-1

Analytical substructure (MRF, mass, gravity system, inherent damping)

- Real-time state determination
  - Analytical substructure has 296 DOFs and 91 elements;
  - Nonlinear fiber elements for beams, columns, and RBS;
  - Nonlinear panel zone elements for panel zone of beam-column connection;
  - Elastic beam-column element for the lean-on column;
  - P-delta effects included in the analytical substructure.

Experimental substructure (0.6-scale DBF)
MCE level RTHS using $\rho_\infty = 1.0$

- Under nonlinear structural behavior, pulses are introduced in the acceleration at the Nyquist frequency $\left(= \frac{1}{2\Delta t}\right)$ when the state of the structure changes within the time step.
- Pulses excite spurious higher modes present in the system which primarily contribute to the member forces.
- Problem becomes worst by the noise introduced through the measured restoring forces and the actuator delay compensation which can amplify high frequency noise.

### 3-story Steel Frame Building with NL Viscous Dampers

MCE level RTHS using $\rho_\infty = 0.75$

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**Introduction**

RTHS: Implementation solutions

Analytical substructure

- Fast and accurate state determination procedure

NHERI Lehigh Solutions

Explicit force-based fiber elements
Fiber Element State Determination

Displacement-based fiber elements

- Curvature varies linearly
  - Requires numerous elements per structural member to model nonlinear response
  - Increases number of DOFs
- State determination is straightforward

Force-based fiber elements

- Equilibrium is strictly enforced
  - Material nonlinearity can be modeled using a single element per structural member
  - Reduces number of DOFs
- Requires iterations at the element level

Jeopardizes explicit integration

\[
\begin{align*}
\mathbf{Q} &= [Q_1 \ Q_2 \ Q_3 \ Q_4 \ Q_5 \ Q_6]^T = \text{Element forces} \\
\mathbf{D} &= [D_1 \ D_2 \ D_3]^T = \text{Section forces} \\
\mathbf{d} &= [d_1 \ d_2 \ d_3]^T = \text{Section deformation} \\
\mathbf{q} &= [q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6]^T = \text{Element deformations} \\
\mathbf{s} &= [s_6]^T = T \\
\end{align*}
\]
Explicit-formulated Force-Based Fiber Element

- Used with explicit integration algorithm
- Material nonlinearity
- Equilibrium is strictly enforced along element
- Reduced DOFs in system modeling
- Fixed number of iterations during state determination with carry-over and correction of unbalanced section forces in next time step

\[
\mathbf{d} = [d_1 \ d_2 \ d_3]^T = \text{Section deformation}
\]
\[
\mathbf{D} = [D_1 \ D_2 \ D_3]^T = \text{Section forces}
\]
\[
\mathbf{q} = [q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6]^T = \text{Element deformations}
\]
\[
\mathbf{Q} = [Q_1 \ Q_2 \ Q_3 \ Q_4 \ Q_5 \ Q_6]^T = \text{Element forces}
\]

3-D Fiber element – Deformation Modes


Column develops inelastic behavior with cyclic strength and stiffness deterioration, and hysteretic pinching in force-deformation response.
RTHS: Implementation solutions

**Experimental substructure**

- Large capacity hydraulic system and dynamic actuators required
- Actuator kinematic compensation
- Robust control of dynamic actuators for large-scale structures

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**NHERI Lehigh Solutions**

- Large hydraulic power supply system
- Large capacity dynamic actuators
- Servo hydraulic actuator control: Adaptive Time Series Compensator (ATS)
- Development of actuator kinematic compensation
Servo Hydraulic Actuator Control

- Nonlinear servo-valve dynamics
- Nonlinear actuator fluid dynamics
- Test specimen material and geometric nonlinearities
- Slop, misalignment, deformations in test setup

- Variable amplitude error and time delay in measured specimen displacement

- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause instability

It is important to compensate
Adaptive Time Series (ATS) compensator

\[ u_k^c = a_0 x_k^t + a_{jk} x_k^t + a_{2k} x_k^t \]

- \( u_k^c \): compensated input displacement into actuator
- \( x_k^t \): target specimen displacement
- \( a_{jk} \): adaptive coefficients

Adaptive coefficients are optimally updated to minimize the error between the specimen target and measured displacements using the least squares method

\[ A = \left( X_m^T X_m \right)^{-1} X_m^T U_c \]

- \( A = \begin{bmatrix} a_{0k} & a_{1k} & \cdots & a_{nk} \end{bmatrix}^T \)
- \( X_m = x^m \; \dot{x}^m \; \cdots \; \frac{d^n}{dt^n} \left( x^m \right) \) (Output (measured) specimen displacement history)
- \( U_c = u_k^c \; u_k^c \; \cdots \; u_k^c \) (Input actuator displacement command history)

Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator

• No user-defined adaptive gains ➞ applicable for large-scale structures susceptible to damage (i.e., concrete structures)

• Negates both variable time delay and variable amplitude error response

• Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients

• Use specimen feedback

\[
A_k = \frac{1}{a_{0k}}
\]

\[
k = \frac{a_{1k}}{a_{0k}}
\]
MCE level RTHS using $\rho_\infty = 0.75$

Actuator control: Typical MCE level RTHS & $\rho_\infty = 0.75$

$x^t$: targeted specimen displacement

$x^m$: measured specimen displacement

Synchronized Subspace Plots: $x^t$ vs. $x^m$

NRMSE = 0.29%

NRMSE = 0.14%

NRMSE = 0.13%

Time History of Adaptive Coefficients

Amplitude Correction

$A_k^{(j)} \approx \frac{1}{a_0^{(j)}} = 0.83 \sim 1.25$

Delay Compensation

$\tau_k^{(j)} \approx \frac{a_1^{(j)}}{a_0^{(j)}} = 18 \sim 75$ msec
Actuator Kinematic Compensation

• Kinematic compensation scheme and implementation for RTHS (Mercan et al. 2009)
  - Kinematic correction of command displacements for multi-directional actuator motions
  - Robust, avoiding accumulation of error over multiple time steps; suited for RTHS
  - Exact solution

\[
(M_1 SN_x l_{new}, M_1 SN_y l_{new}) = (-LM_{a_{new}} \sin(\Theta_2 + \phi_1), LM_{a_{new}} \cos(\Theta_2 + \phi_1))
\]

\[
\Theta_2 = \arcsin \left[ \frac{LM_{a_{new}}}{y_F / \cos \phi_1} \sin \Theta_3 \right]
\]

\[
\Theta_3 = \arccos \left( \frac{LM_{a_{new}}^2 + LMB_{b_{new}}^2 - (y_F / \cos \phi_1)^2}{2LM_{a_{new}} LMB_{b_{new}}} \right)
\]

\[
(SPN_x^{new}, SPN_y^{new}) = (M_1 SN_x^{new} - \sqrt{VM \| \cos(\Theta M_{1,0} + d^m SPN \Theta)}, M_1 SN_y^{new} - \sqrt{VM \| \sin(\Theta M_{1,0} + d^m SPN \Theta)})
\]

NHERI Lehigh EF/ATLSS Testbeds

• Bracing Frame
  • Perform experiments on test frame specimens of:
    ➢ Up to 13.7 m (45 ft) in height
    ➢ Up to 11 m (36 ft) in width
NHERI Lehigh EF/ATLSS Testbeds

• **Non-Structural Component Seismic Simulator**
  - Enables multi-directional real-time hybrid simulation of non-structural components and systems:
    - Up to 12.2 m (40 ft) in length
    - Up to 3.1 m (10 ft) in width

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

- 3.1 m x 12.2 m Rigid horiz. truss suspended from overhead frame
- Actuator #1
- Actuator #2
- Actuator #3
- 406 mm dia. Piping system filled with 1.38 MPa pressurized water
NHERI Lehigh EF/ATLSS Testbeds

• Full-scale Damper Testbeds
  • Enables full-scale damper tests:
    ➢ Damper characterization tests
    ➢ Real-time hybrid simulations
  • Stoke, velocity, and force capacity:
    ➢ +/- 500 mm (20 in.) stroke
    ➢ 1140 mm/s (45 in/s) for 1700 kN actuators
    ➢ 840 mm/s (33 in/s) for 2300 kN actuators

Real-time hybrid simulation of building with four passive dampers
NHERI Lehigh EF/ATLSS Testbeds

• Tsunami 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

Real-time simulation of impact forces from tsunami shipping container debris
NHERI Lehigh EF/ATLSS 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
Soil-Structure Interaction Testbed

- Pile Driver
- Guiding system
- Cone tip
- Mandrel
- Vibrator
- Guiding system
- Soil-Structure Interaction Testbed
Lehigh Real-time Cyber-Physical Structural Systems Laboratory

- **Purpose**
  - Education & Training
  - Small-scale Testing
- **Three MTS Actuators:**
  - 2 - Model 244.21G2
  - 1 - Model 244.20G2S

**Actuator Specifications**

<table>
<thead>
<tr>
<th></th>
<th>244.21G2</th>
<th>244.20G2s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Force</td>
<td>50 kN (11 kips)</td>
<td>82 kN (18.5 kips)</td>
</tr>
<tr>
<td>Max displacement</td>
<td>±254 mm (±10 in)</td>
<td>±177 mm (±7 in)</td>
</tr>
<tr>
<td>Max velocity</td>
<td>0.74 m/s (29 in/s)</td>
<td>0.43 m/s (51 in/s)</td>
</tr>
<tr>
<td>Servo Valve</td>
<td>30 gpm</td>
<td>90 gpm</td>
</tr>
</tbody>
</table>
**Existing ATLSS Infrastructure**

- **3-D Multi-directional reaction wall facility**
  - 3-dimensional
  - Up to 15.2 m (50 ft) height
  - 1.5 m (5 ft) anchor point grid

- **Strong floor**
  - 12.2 m by 30.5 m (40 ft by 100 ft)
  - Anchor assembly capacity
    - 2,224 kN (500 kips) shear
    - 1,334 kN (300 kips) tension

- **Hydraulic Supply System**
- Over 30 Hydraulic Actuators
- Large array of Conventional Sensors
- Crane
- Skilled staff
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 variable axial piston pumps
- Accumulator System (NHERI)
  - 16 piston accumulators
    - 50.2 gal each
- 5 dynamic hydraulic actuators (NHERI)
  - Maximum load capacity
    - 2 actuators: 517 kips at 3000 psi
    - 3 actuators: 382 kips at 3000 psi
  - Stroke
    - +/- 19.7 in
  - Maximum velocity
    - 45 in/s for 382 kip actuators
    - 33 in/s for 517 kip actuators
- 10 3-stage 550 gal/min Servovalves and HSMs (NHERI)
Other NHERI Lehigh EF Equipment

• High Speed 300+ Channel Data Acquisition System
• 3 Real-Time Targets for simulation coordination, including additional DAQ
• Three real-time servo-hydraulic controllers
• Sensors (displacement, accelerometers, inclinometers)
• Telepresence webcams
• Specs for all equipment found in User’s Guide
Instrumentation

- Displacement transducers
  - Strokes ranging from ±6.4mm (LVDTs) to 1524mm (linear potentiometers).
  - Temposonnic position sensors with a ±760 mm stroke, to a ±1100 mm stroke.
  - All transducers are calibrated to within ±1% accuracy, with the LVDTs calibrated to within ±0.1%.
- Inclinometers ranging up to ±20 degrees with 1% accuracy.
- Each hydraulic actuator is equipped with a load cell.
  - All load cells are calibrated to within ±0.1% accuracy.
Other Major NHERI Lehigh EF Equipment

• Real-time Integrated Control System
  • Multiple Real-Time targets for simulation coordination with additional DAQ
  • Three real-time servo-hydraulic controllers
  • High Speed 300+ Channel Data Acquisition System
  • Web and Data telepresence system
  • Local data repository
Control Center

- Houses Real-time Integrated Control System
- Camera Control
- Data Acquisition System and Server
- Data Streaming System
  - Video
  - Sensors
- Video Displays
- Local Repository
NHERI Lehigh EF non-NHERI Equipment

• Site leverages Non-NHERI equipment to provide capability, improve capacity and maintain throughput.
  – 30 Actuators
  – ATLSS Wineman Controller
  – 2 MTS 458 Controllers
  – MTS FlexTest 100 Controller
  – DAQ systems
  – Trilion System for Digital Image Correlation - full field displacement and strain
  – Transducers - over 96 LVDTs, 62 load cells, Temposonics (12 ATLSS)
  – SSI instrumentation

• Users Guide - Available ATLSS Equipment
  [https://lehigh.designsafe-ci.org/resources](https://lehigh.designsafe-ci.org/resources)
Instrumentation

- Digital imaging correlation (DIC) systems.
  - Utilize the 3D image correlation method.
  - Works on both random and regular pattern, thus simplifying sample preparation.
  - The same sensor uses white light to measure small and large objects (1mm up to 100m) and strains in the range of 0.05% up to several 100%.

Figure F.4 DIC System: reinforced concrete coupled-shear wall test specimen measured pier vertical displacements (courtesy M. McGinnis)
Soil-Structure Interaction Instrumentation

- Advanced instrumentation to understand SSI of foundation systems under different loading conditions
- Combine with hybrid simulation to improve analytical substructure models, or
- Hybrid simulation with soil included in experimental substructure

Test Setup and instrumentation:

- Pressure sensors
- Shear wave sensors
- Soil-pile interaction
- Pressure sheets
- In-soil null pressure sensors
- Shape acceleration arrays

Advanced instrumentation to understand SSI of foundation systems under different loading conditions. Combine with hybrid simulation to improve analytical substructure models, or hybrid simulation with soil included in experimental substructure.
NHERI Lehigh EF - ATLSS Space and Resources

- **Specimen Prep**
  - 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 Experimental Protocols

• **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
    - Experiments can be run in true real-time (real-time hybrid simulation, real-time distributed hybrid simulation, dynamic testing, characterization testing).
    - Experiments can be run at an expanded time scale (hybrid simulation, distributed hybrid simulation, quasi-static testing).
  - Distributed hybrid simulation via:
    - OpenFresco
    - Simcor
    - Custom software
  - Flexible-designed system
    - Software and middleware packages developed by users or NHERI CI can be plugged in and utilized for testing

[https://lehigh.designsafe-ci.org/protocols/experimental-protocol/]
**NHERI Lehigh EF Experimental Protocols**

- **Real-time Integrated Control System**
  - Hydraulics-off mode
    - Used for validation of testing methods/algorithms, training, education
    - Both servo-hydraulic system, test structure and any analytical substructure modeled analytically
  - Safety
    - Software limits are enabled on the System.
    - Hardware actuator position stroke and test specimen displacement limit switches placed.
    - Emergency stop system activated throughout laboratory
NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hybrid simulation:
    - Robust integration algorithms: **Explicit MKR-\( \alpha \) Integration Algorithm** - Explicit unconditionally stable integration algorithm with controlled numerical energy dissipation and controlled overshoot (*Kolay and Ricles, 2014, 2017*).
    - Multi-directional actuator control: **Multi-directional Kinematic Compensation** (*Mercan et al. 2009*)

NHERI Lehigh EF Experimental Protocols

- **Real-time Integrated Control System**
  - Hybrid simulation analytical substructure created by either
    - HybridFEM
    - OpenSees with OpenFresco interface

\[
M \ddot{X}_{i+1} + C \dot{X}_{i+1} + (R^a_{i+1} + R^e_{i+1}) = F_{i+1}
\]

Schematic of hybrid simulation
HybridFEM

- MATLAB and Simulink based computational modeling and simulation coordinator software for dynamic time history analysis of inelastic-framed structures and performing real-time hybrid simulation
- Simulink architecture facilitates real-time testing through multi-rate processing
- Run Modes
  - MATLAB script for numerical simulation
  - Simulink modeling for Real-Time Hybrid simulation with experimental elements via Real-Time Targets, and hydraulics-off for training and validation of user algorithms.
- User’s Manual for training
HybridFEM

Configuration Options:
- Coordinate system of nodes
- Boundary, constraint and restraint conditions
- Explicit-formulated Elements
  - Elastic beam-column
  - Elastic spring
  - Inelastic beam-column stress resultant element
  - Non-linear spring
  - NL Displacement-based beam-column fiber element
  - NL Force-based beam column fiber element
  - Zero-length
  - NL planar panel zone
  - Elastic beam-column element with geometric stiffness
  - User-defined Reduced Order Modeling elements
- Geometric nonlinearities
- Steel wide flange sections (link to AISC shapes Database)
- Reinforced concrete sections
- Structural mass & inherent damping properties
- Adaptable integration methods
- Real-time online model updating

Materials:
- Elastic
- Bilinear elasto-plastic
- Hysteretic
- Bouc-Wen
- Trilinear
- Stiffness degrading
- Concrete
- Steel
- Fracture
- Initial stress
Users Guide

• Details of the Equipment Specifications, Experimental Protocols, and Equipment Inventory are given in the User’s Guide

https://lehigh.designsafe-ci.org/resources/
Thank you