NHERI Lehigh Real-time Cyber-Physical Structural Systems Laboratory – Overview and Demonstration

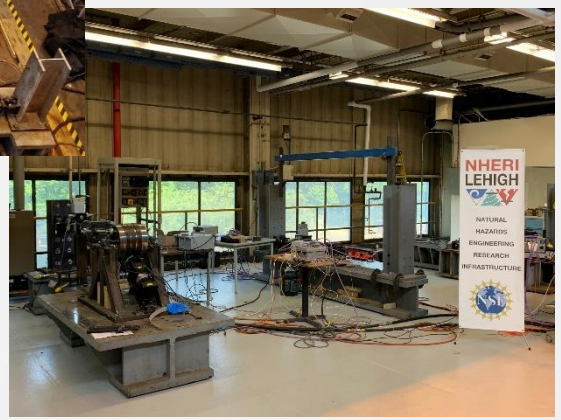
Liang Cao, Ph.D
NHERI Lehigh Research Scientist

LEHIGH UNIVERSITY

NSF

Real-time Cyber-Physical Structural Systems Laboratory (CPSSL) – Real-time Testbeds

- Purpose
  - Education & Training
  - Reduced-scale Testing
- Seven MTS Actuators:
  - 2 - Model 244.21G2
  - 1 - Model 244.20G2S
  - 2 - Model 244.20
  - 2 - Model 244.31
- Five Dampers:
  - Four Nonlinear Viscous Dampers
  - One Rotary Friction Damper

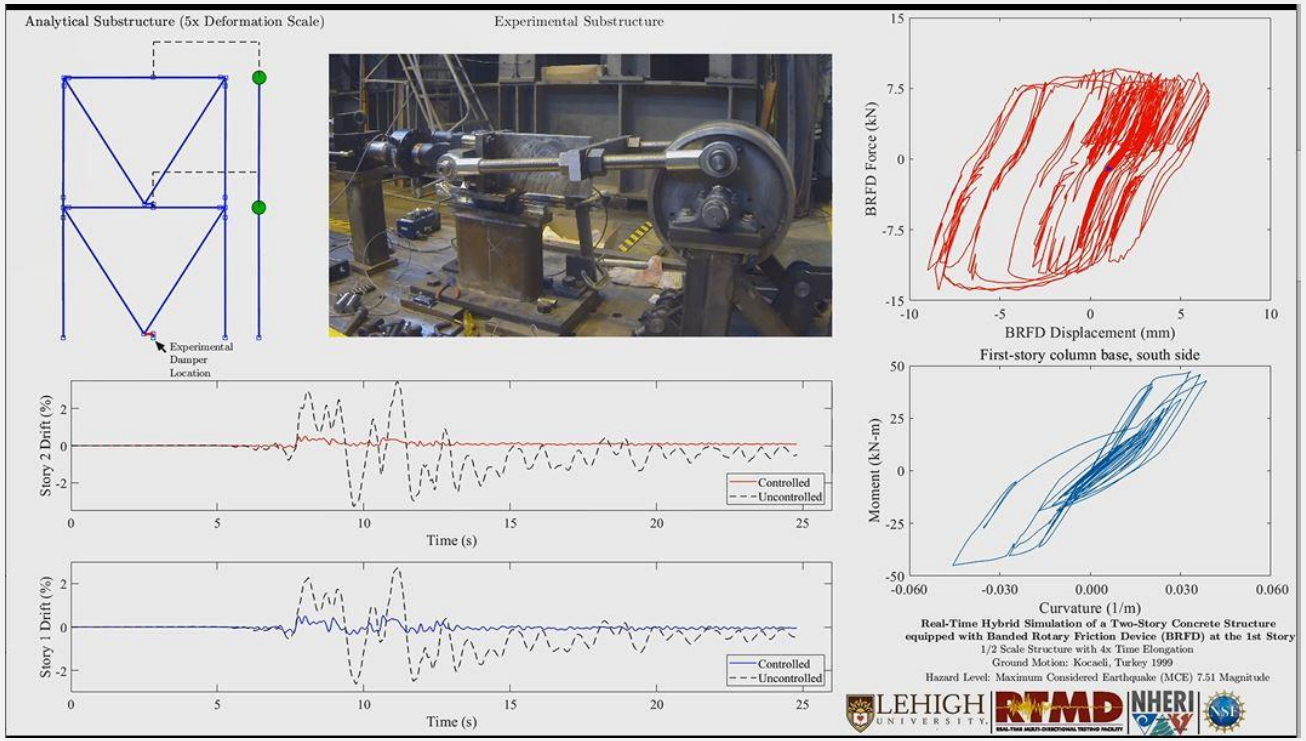


Actuator Specifications

	244.21G2	244.20G2s	244.20	244.31
Max Force	50 kN (11 kips)	82 kN (18.5 kips)	100 kN (22 kips)	250 kN (55 kips)
Max disp.	±254 mm (±10 in)	±177 mm (±7 in)	±76 mm (±3 in)	±127 mm (±5 in)
Max velocity	0.74 m/s (29 in/s)	1.29 m/s (51 in/s)	0.38 m/s (15 in/s)	0.47 m/s (18 in/s)
Servo Valve	30 gpm	90 gpm	30 gpm	90 gpm

Real-time Cyber-Physical Structural Systems Laboratory (CPSSL) – Real-time Testbeds

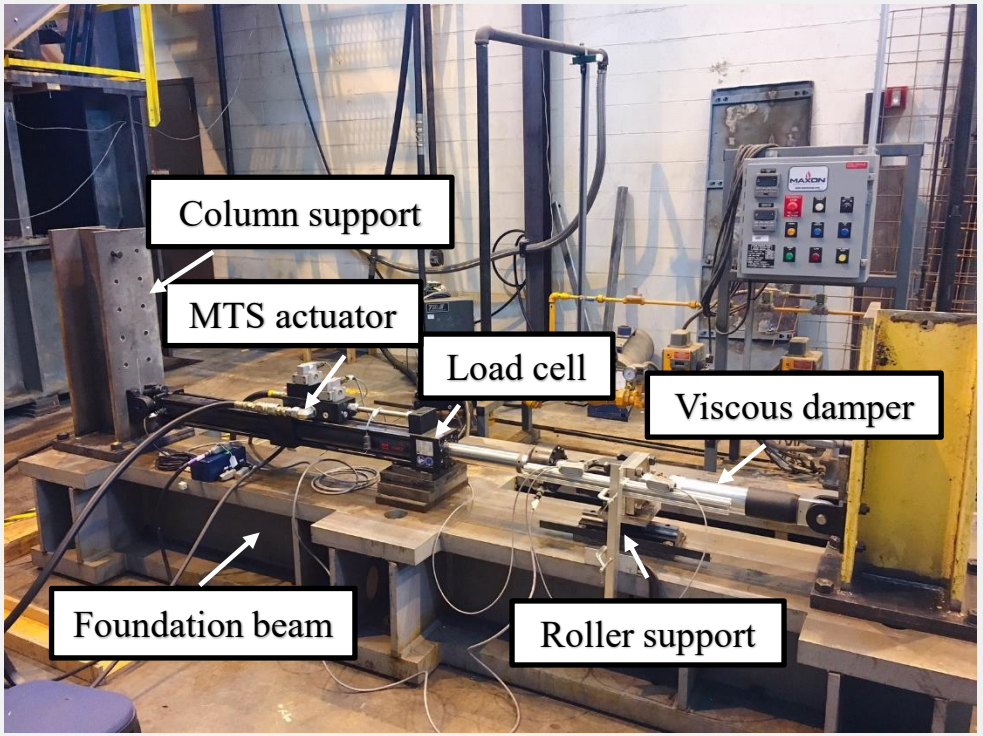
- Reduced-Scale Real-time Hybrid Simulation



Real-time hybrid simulation of a reduced-scale semi-active friction damper

Real-time Cyber-Physical Structural Systems Laboratory (CPSSL) – Real-time Testbeds

- Small-Scale Real-time Hybrid Simulation
- Predefined load or displacements (Quasi-static testing or characterization testing)

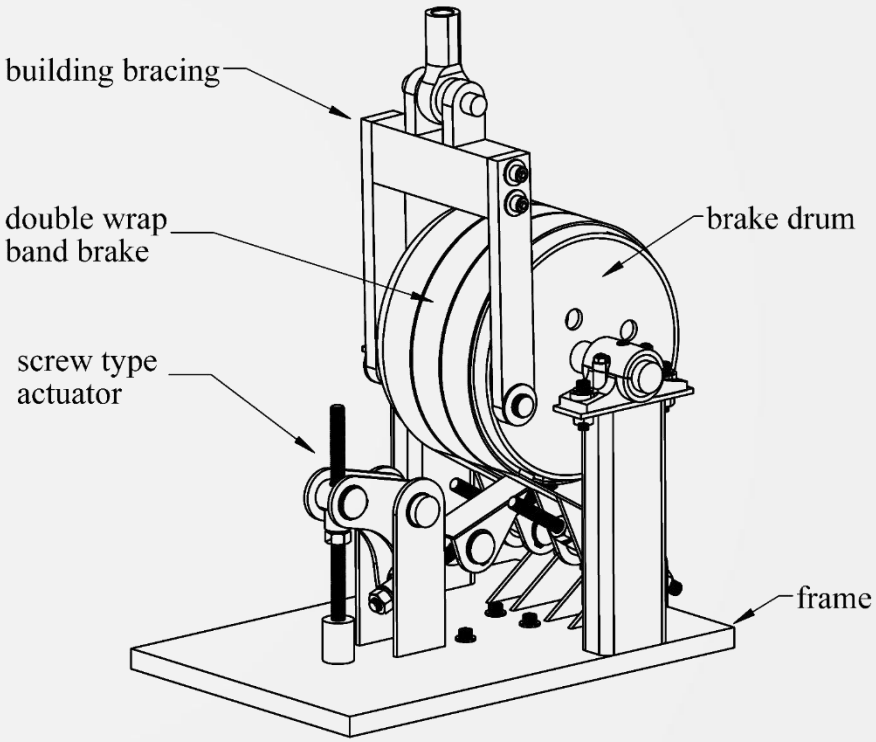


Characterization test of a Small-scale Passive Viscous Damper

Banded Rotatory Friction Damper (BRFD)

Damper Specifications

- 45 kN (10 kips) force capacity
- 305 mm (12 in) diameter drum
- Mechanically reliable & robust
- US Patent: # 9,896,836

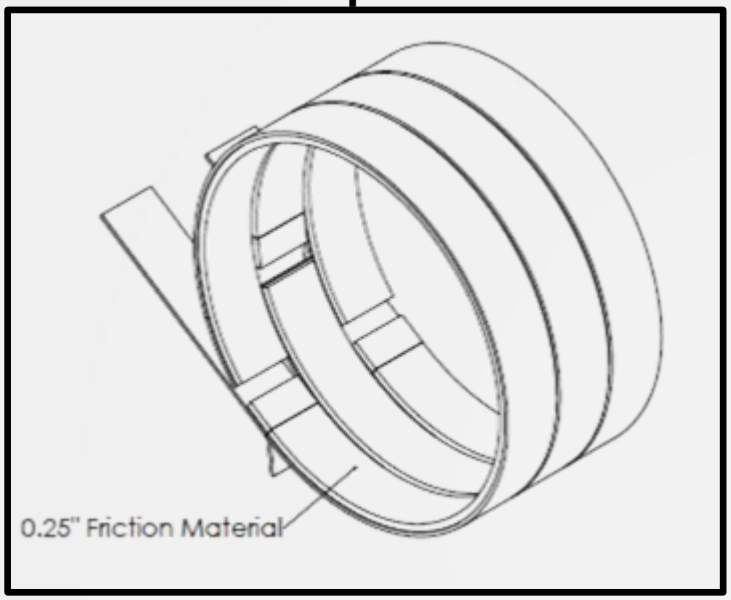


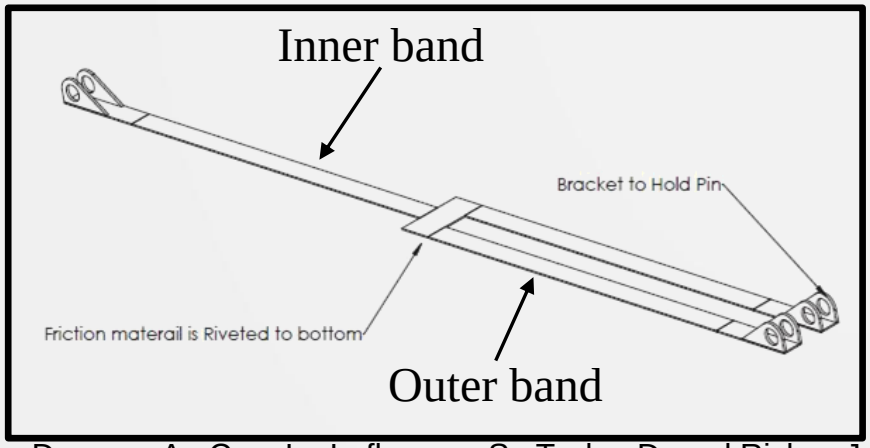
Banded Rotary Friction Damper (BRFD)

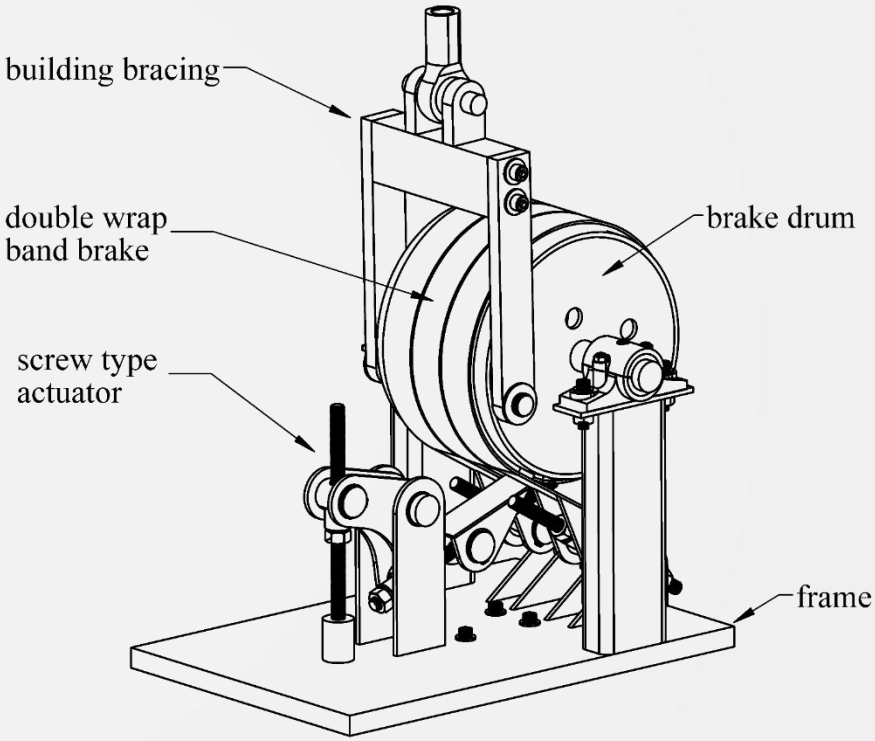
Downey, A., Cao, L., Laflamme, S., Taylor, D. and Ricles, J., (2016). High capacity variable friction damper based on band brake technology. Engineering Structures, 113, pp.287-298. doi:10.1016/j.engstruct.2016.01.035

Banded Rotatory Friction Damper (BRFD)

Double wrap band brake

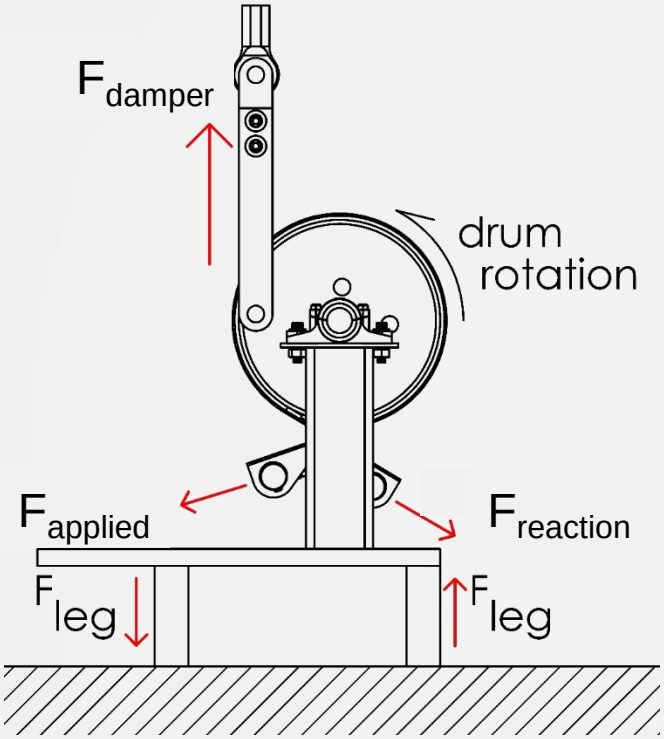




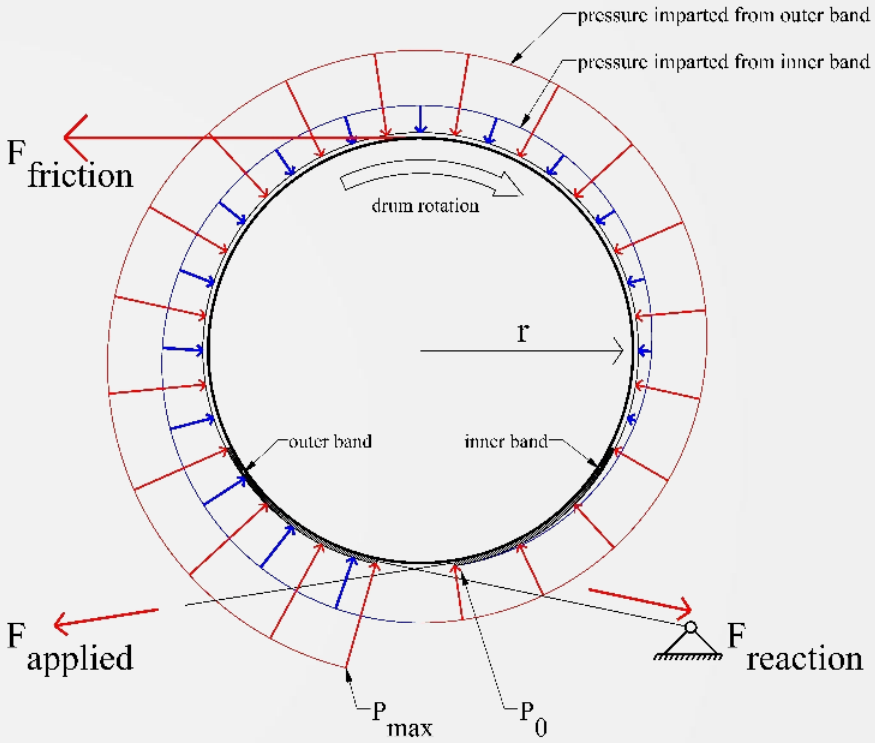


Downey, A., Cao, L., Laflamme, S., Taylor, D. and Ricles, J., (2016). High capacity variable friction damper based on band brake technology. Engineering Structures, 113, pp.287-298. doi:10.1016/j.engstruct.2016.01.035

Banded Rotary Friction Damper (BRFD)



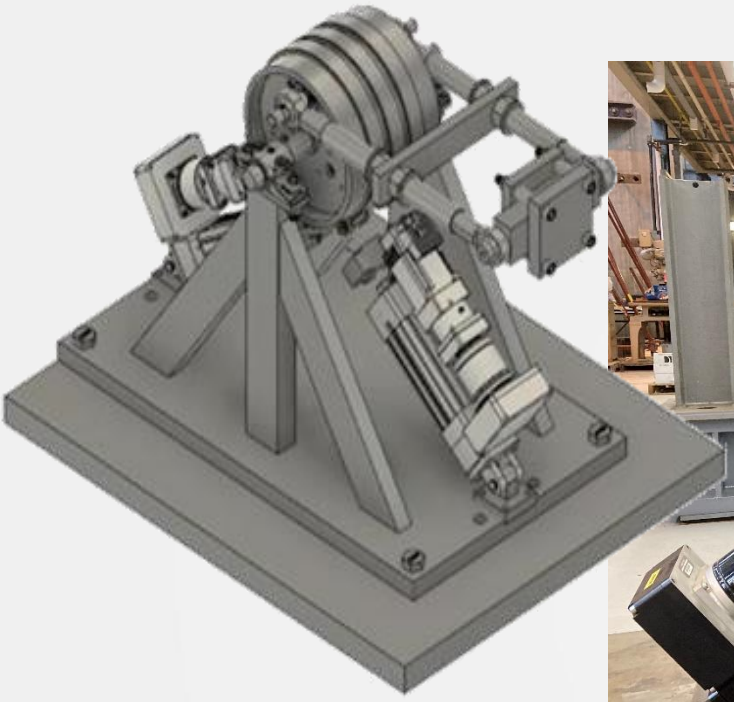
(a) Schematic of side view

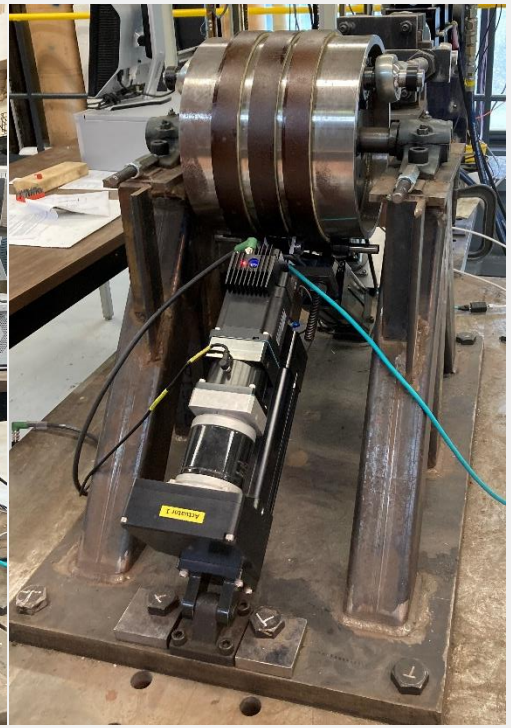


(b) Friction mechanism

Downey, A., Cao, L., Laflamme, S., Taylor, D. and Ricles, J., (2016). High capacity variable friction damper based on band brake technology. Engineering Structures, 113, pp.287-298. doi:10.1016/j.engstruct.2016.01.035

Banded Rotatory Friction Damper (Second Generation)

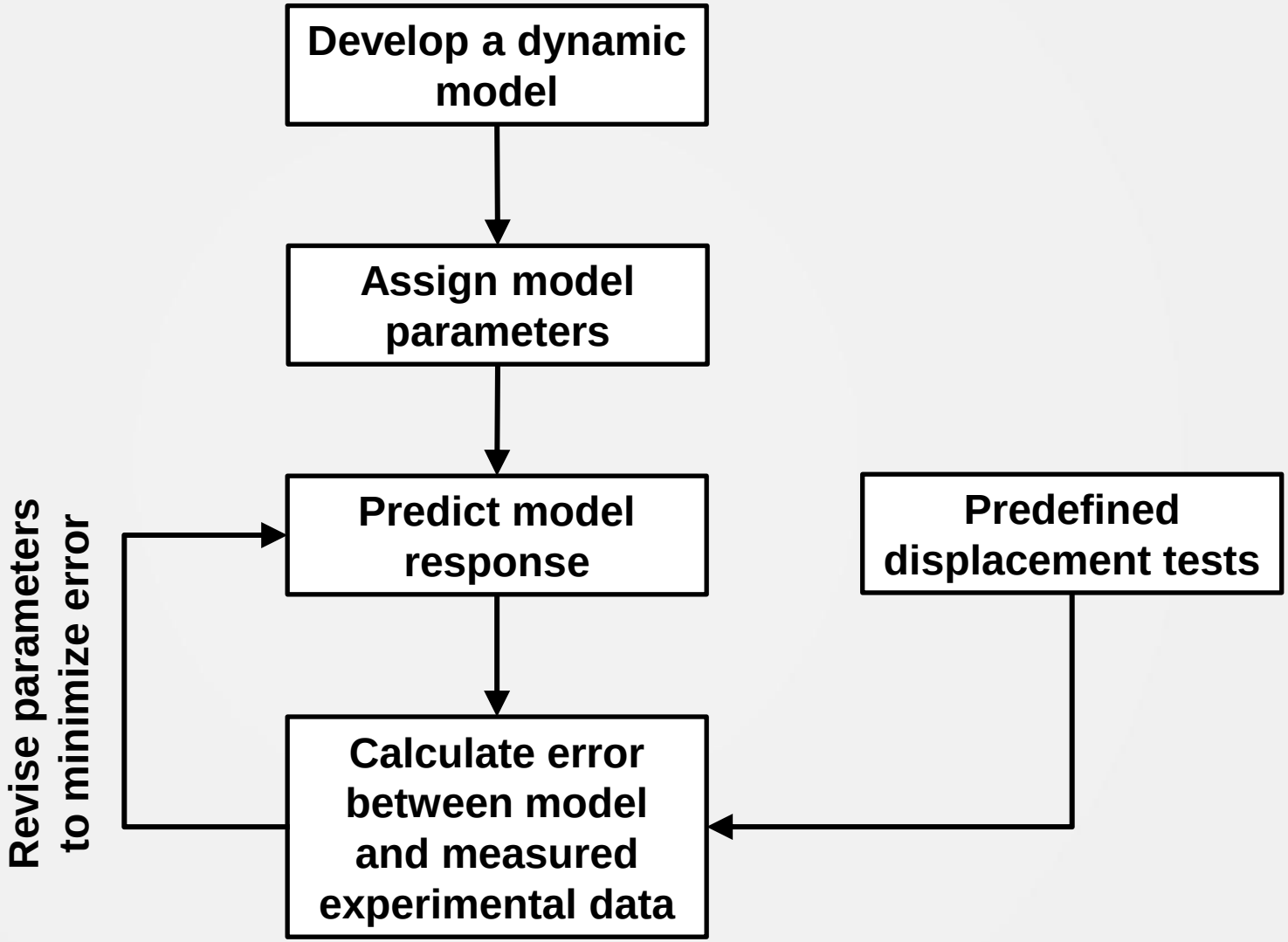




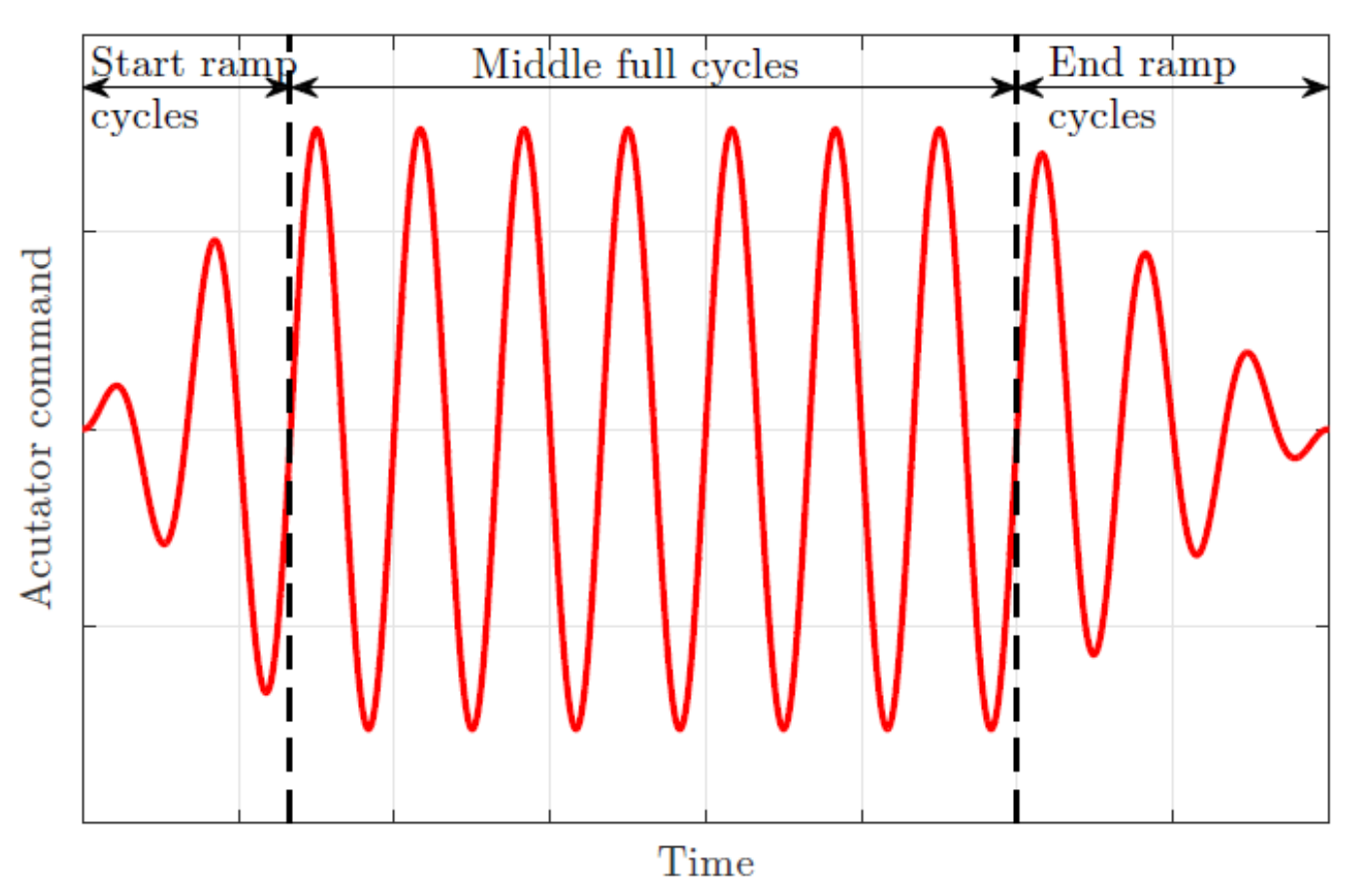
New Design Features

- Semi-active mechanism is achieved using two Tolomatic electric actuators
- Three individual frictional bands are manufactured.
- Two load cells are installed on connections between electric actuators and frictional bands

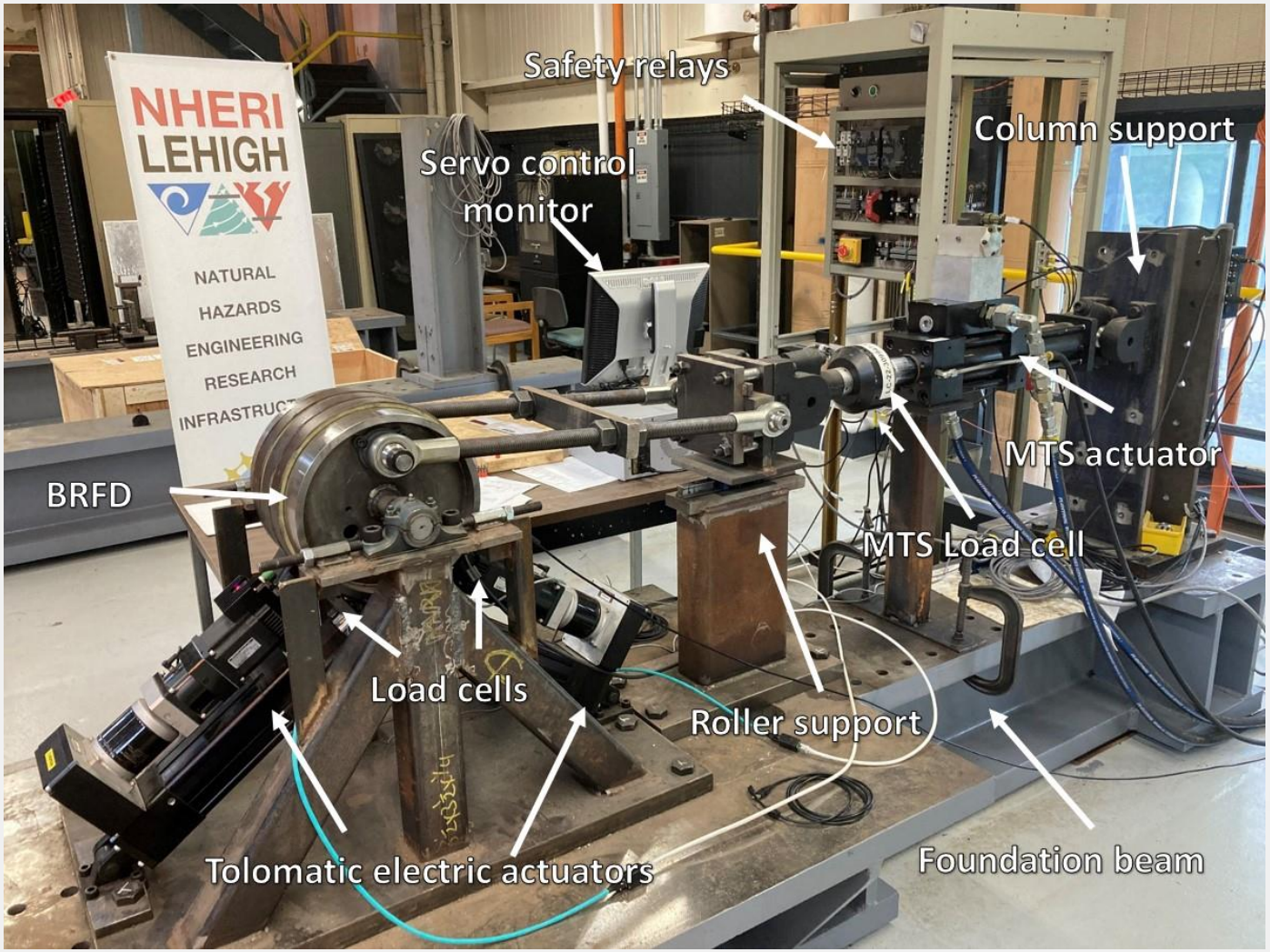
Procedure for Damper Characterization



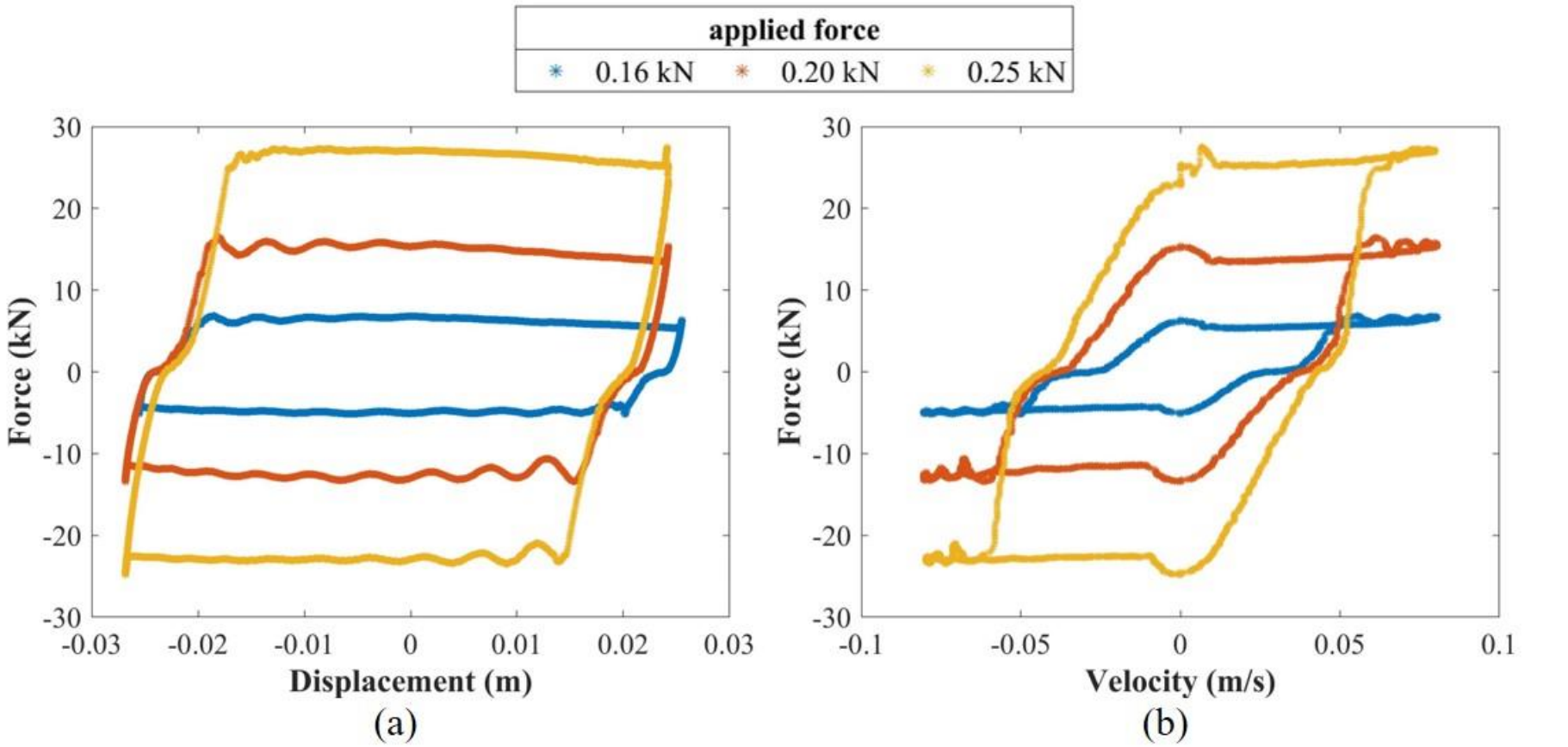
Characterization Test Input Displacement



Characterization Test of BRFD– Test Setup



BRFD Characterization Test Results



Harmonic displacement input:

- Amplitude : 1 inch
- Frequency : 0.5 Hz
- Applied force, $F_{applied}$: 0.16, 0.2 and 0.25 kN

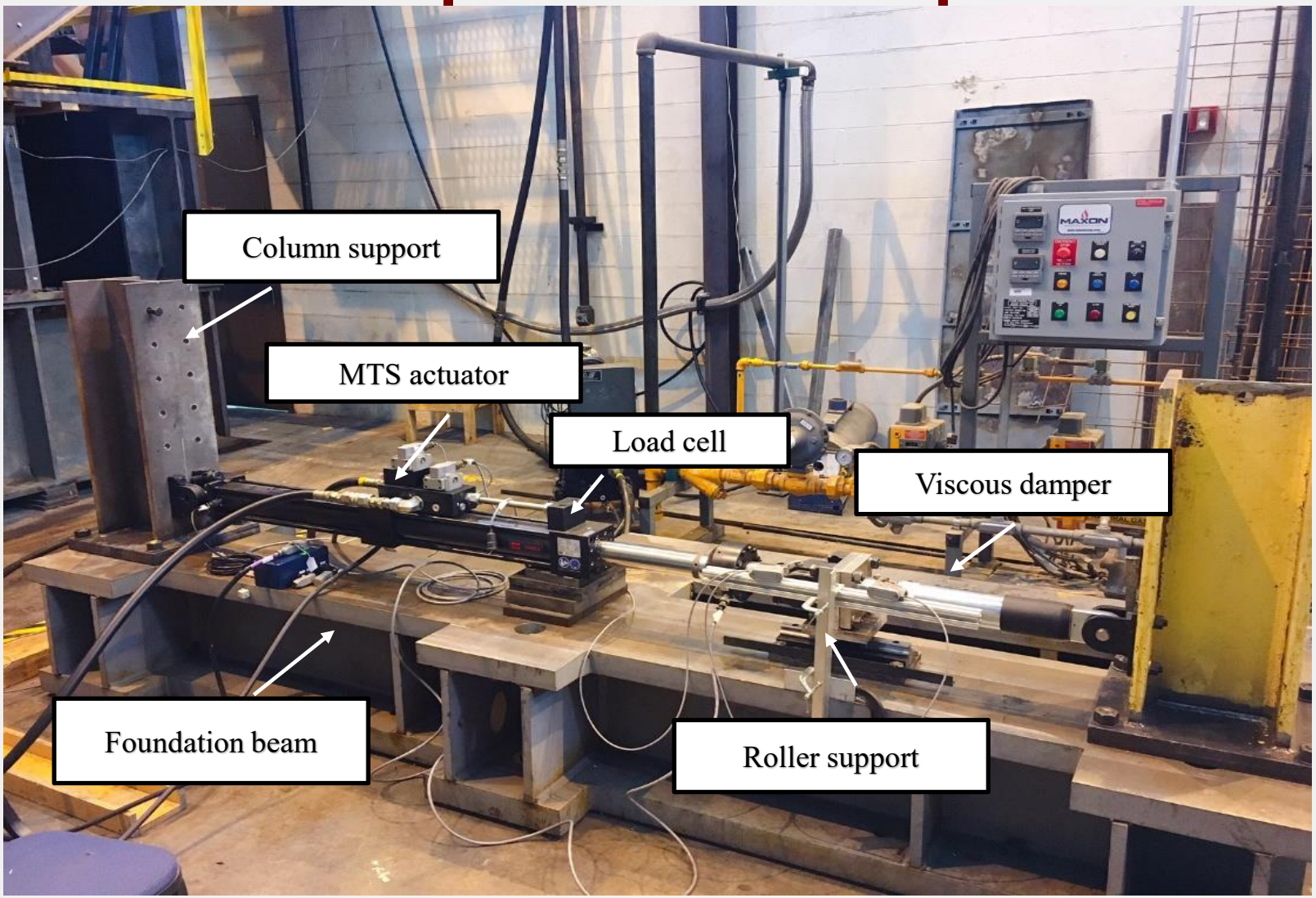
→ Force amplification ($F_{damper}/F_{applied}$) = 112

Characterization Test of Nonlinear Viscous Dampers

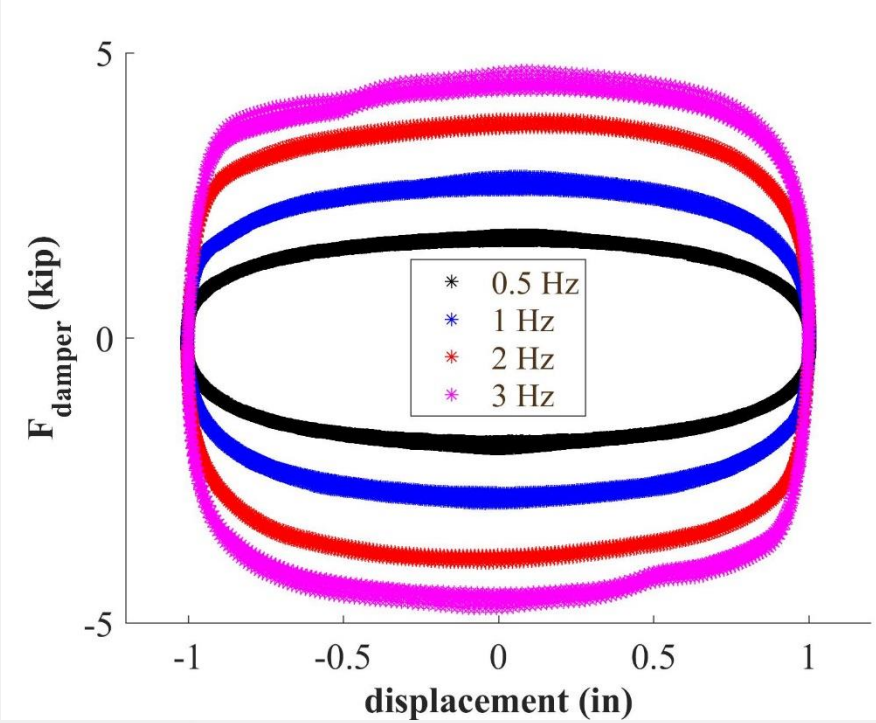
Nonlinear viscous damper property:

- Capacity : 6.6 kips (29 kN)
- Stroke length : ±2 inch (±50 mm)
- Nominal output force: F=1.7$V^{0.4}$ (kip)

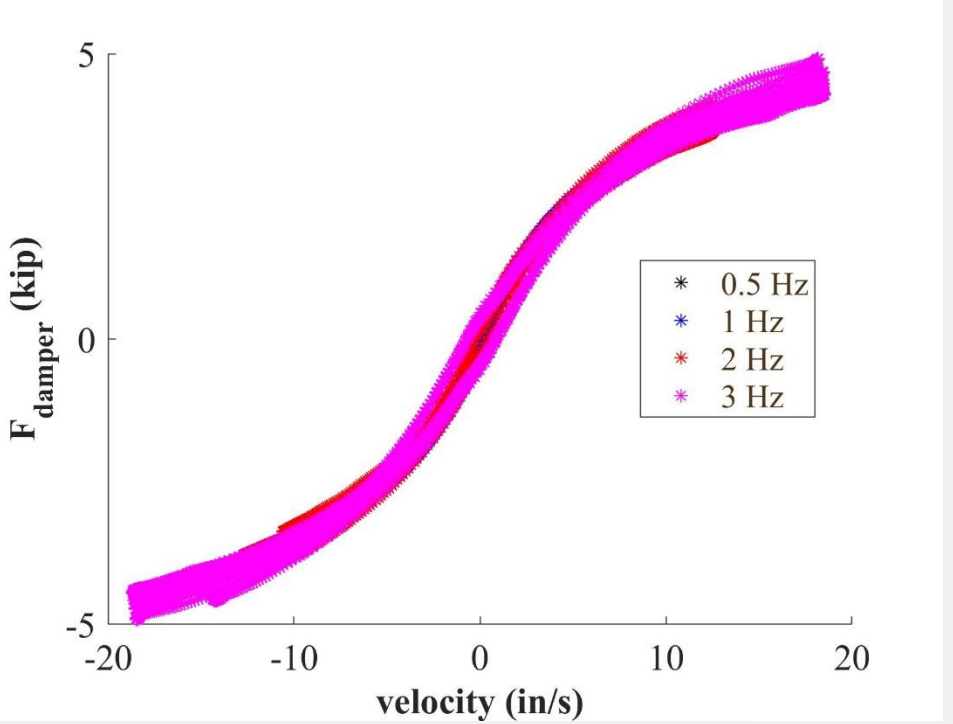
Characterization Test of Nonlinear Viscous Damper – Test Setup



Nonlinear Viscous Damper Characterization Test Results



(a) force-displacement



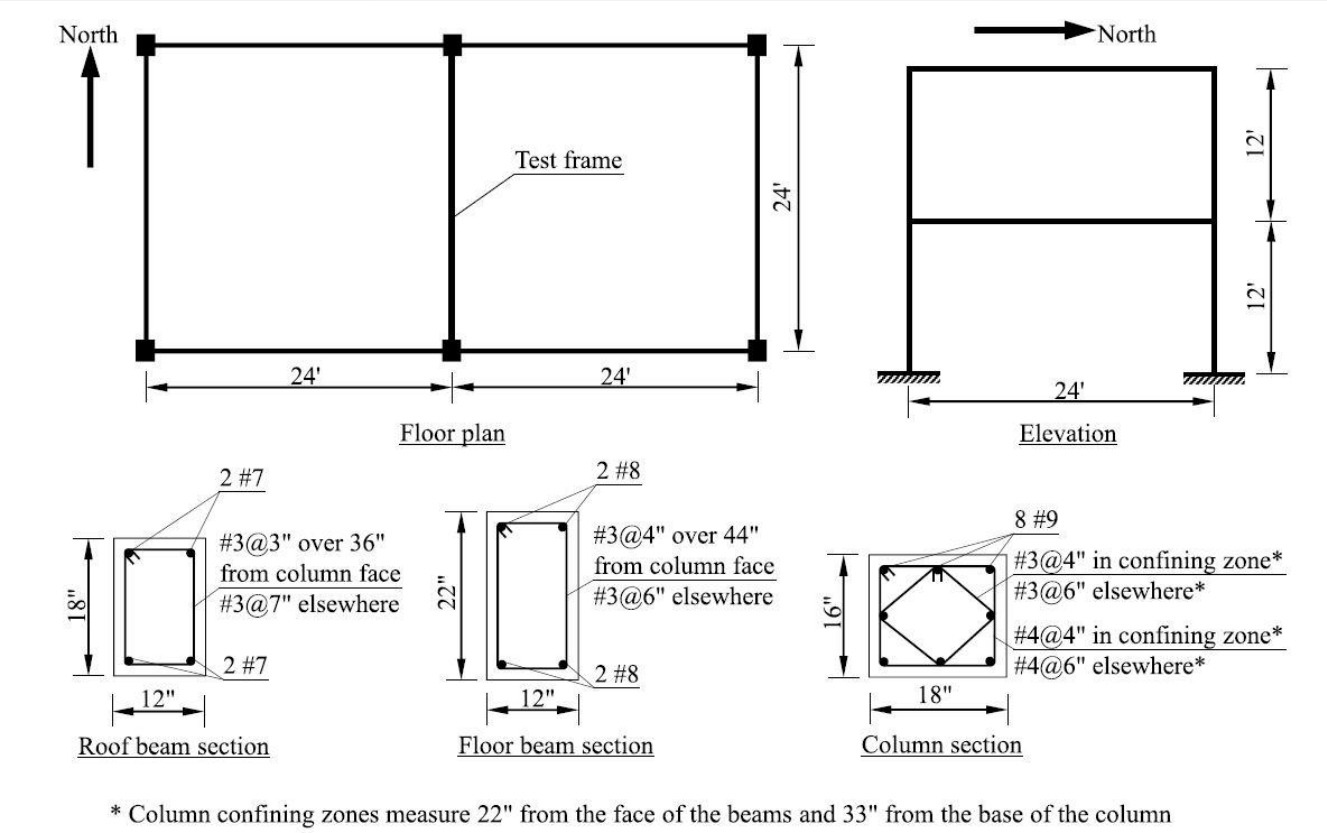
(b) force-velocity

Harmonic displacement input:

- Amplitude : 1 inch
- Frequency : 0.5, 1, 2 and 3 Hz

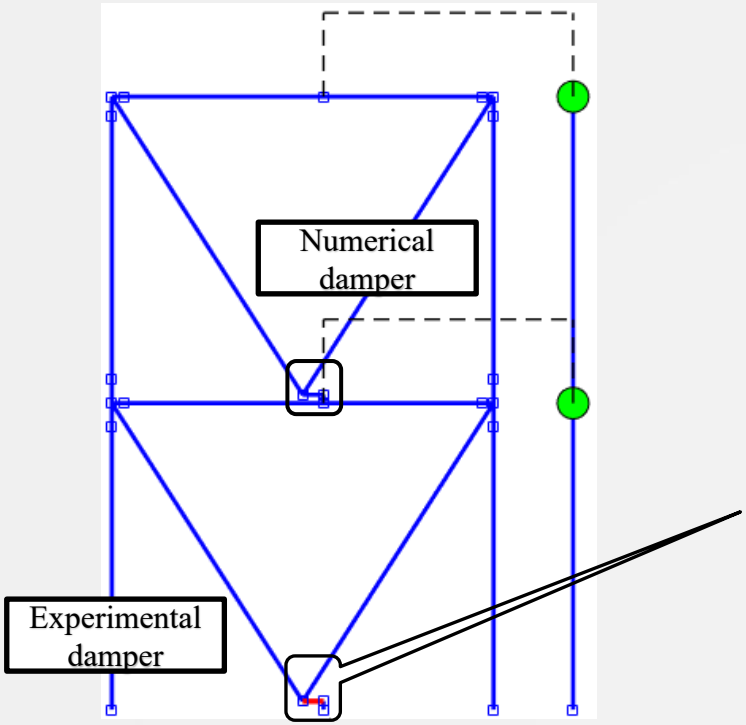
RTHS of a 2-story Reinforced Concrete Building

- 2-story RC special moment resisting frame (SMRF) building in Los Angeles area on a stiff soil site
- Objectives of study
  - Improve seismic performance using BRFD/nonlinear fluid viscous dampers
  - Assess performance using RTHS
- Utilize MKR-α integration algorithm and ATS actuator control

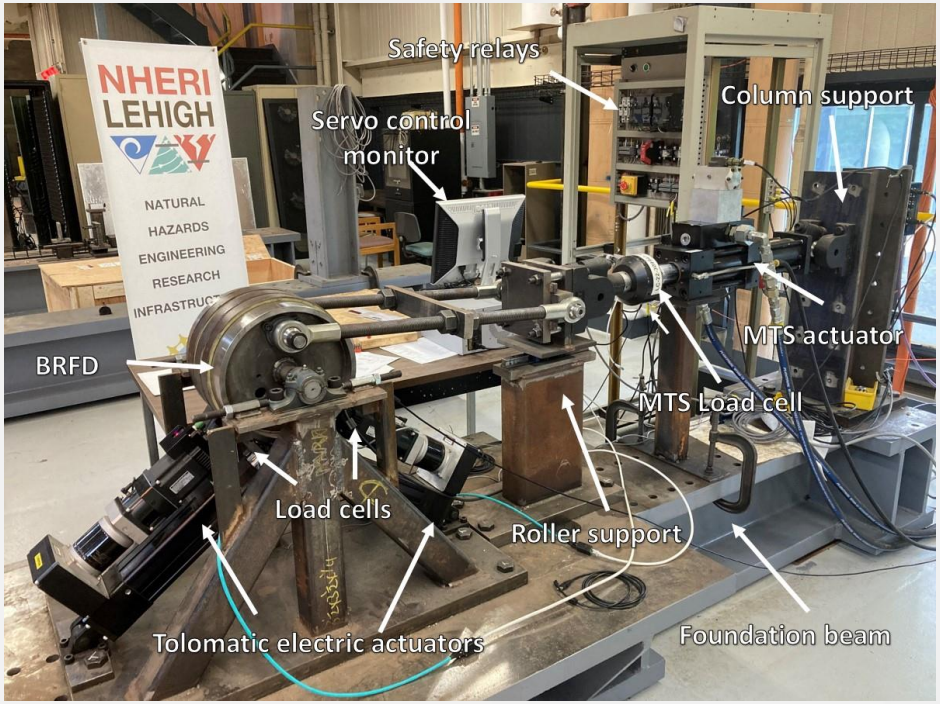


2D RTHS Substructures

Analytical Substructure



Experimental Substructures



Analytical Substructure Key Features:

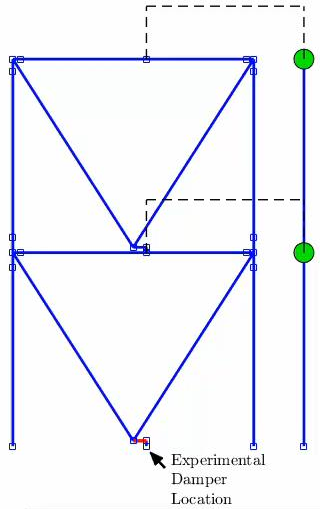
- P-Δ effects included
- 32 Nodes
- 30 Nonlinear Force-based Fiber Elements
- 71 DOFs
- Time step for RTHS, Δt=3/1024 sec.

Excitation Input:

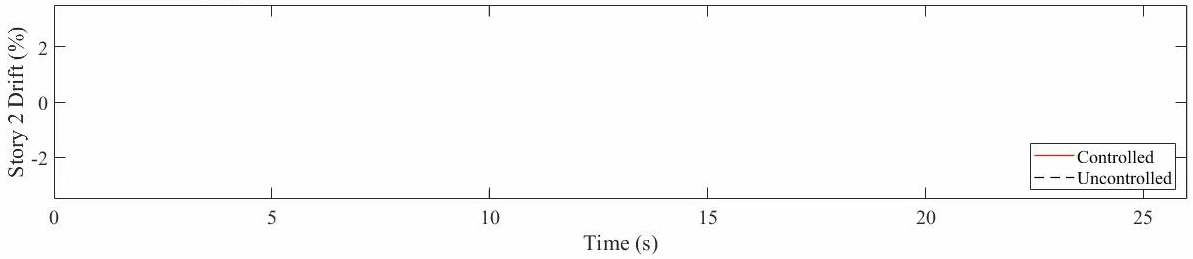
- Ground Motion: Kocaeli, Turkey 1999
- Hazard Level: Maximum Considered Earthquake (MCE) 7.51 Magnitude

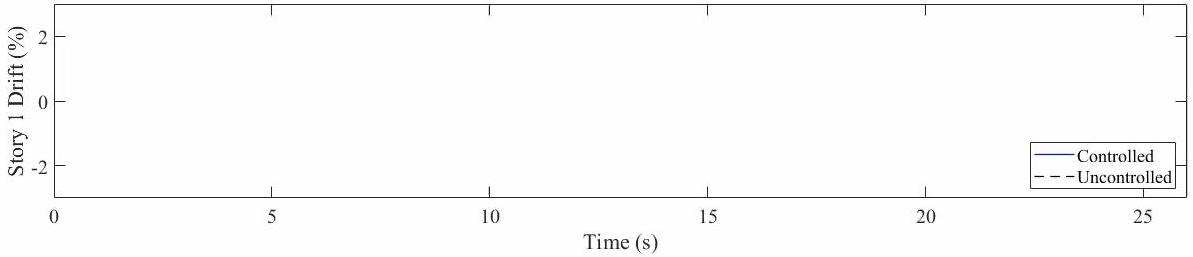
RTHS of a 2-story Reinforced Concrete Building Equipped with BRFD

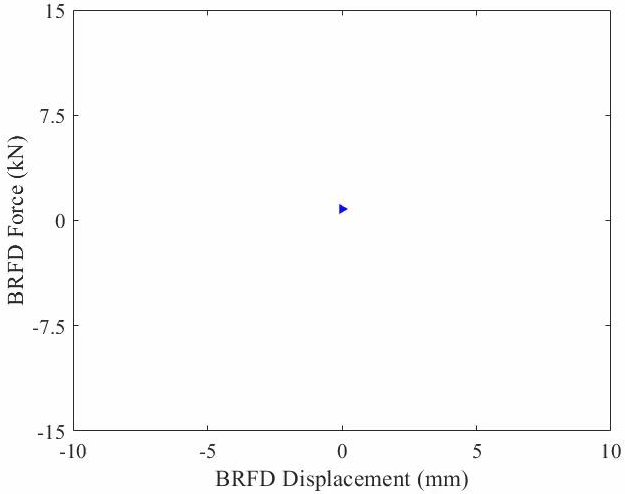
Analytical Substructure (5x Deformation Scale)



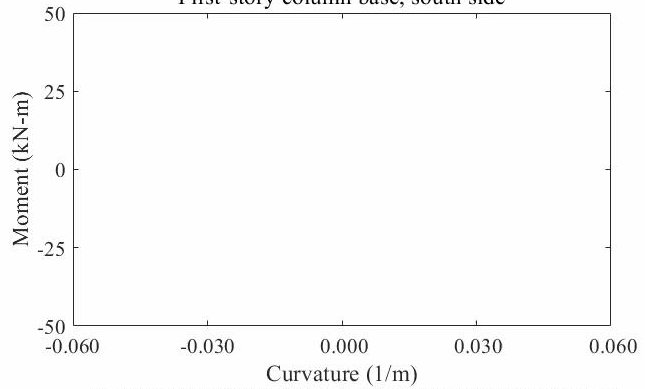
Experimental Substructure







First-story column base, south side



Real-Time Hybrid Simulation of a Two-Story Concrete Structure equipped with Banded Rotary Friction Device (BRFD) at the 1st Story

1/2 Scale Structure with 4x Time Elongation

Ground Motion: Kocaeli, Turkey 1999

Hazard Level: Maximum Considered Earthquake (MCE) 7.51 Magnitude

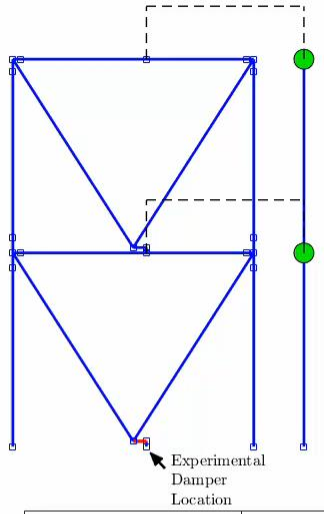
LEHIGH UNIVERSITY | RTMD REAL-TIME MULTI-DIRECTIONAL TESTING FACILITY | NHERI | NSF

LEHIGH UNIVERSITY | ATLSS

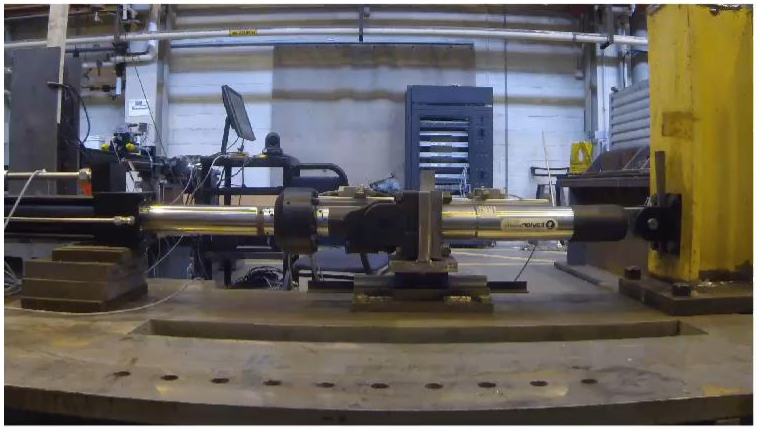
NSF | RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

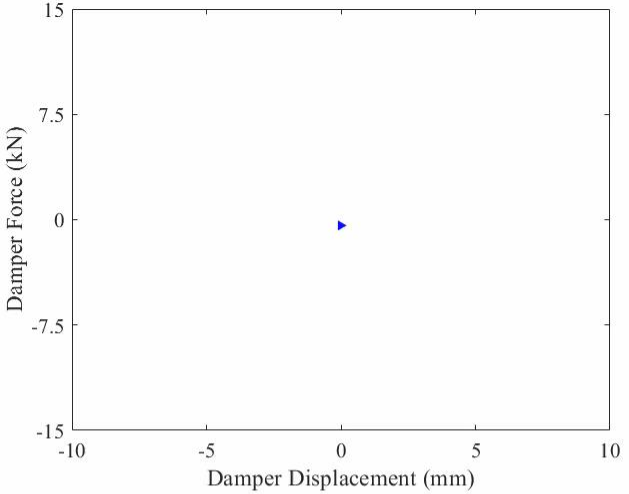
RTHS of a 2-story Reinforced Concrete Building Equipped with Nonlinear Viscous Damper

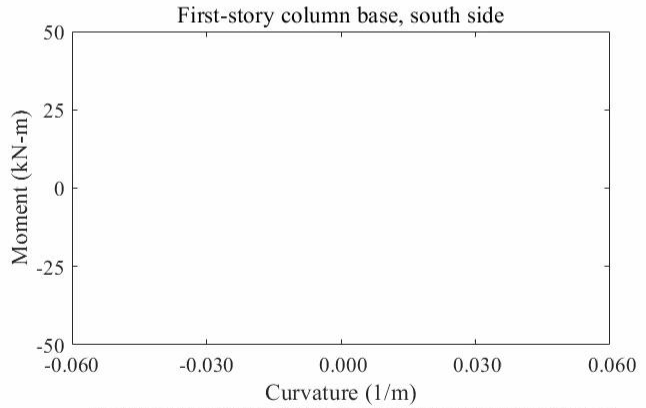
Analytical Substructure (5x Deformation Scale)

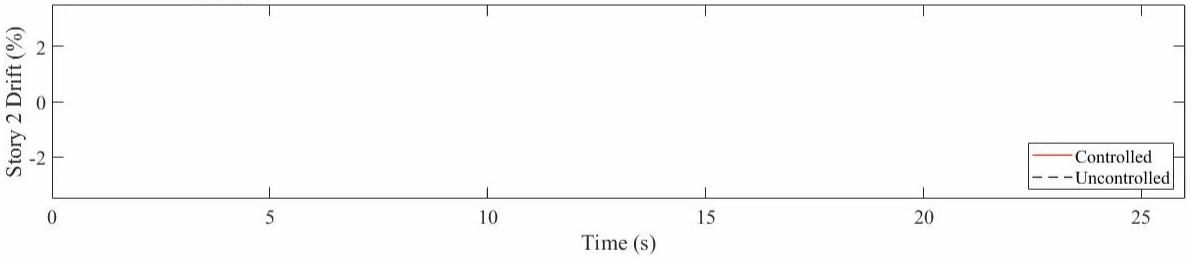


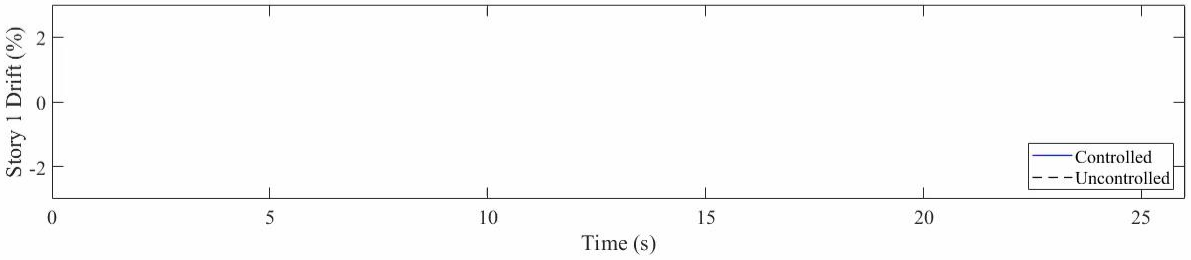
Experimental Substructure











Real-Time Hybrid Simulation of a Two-Story Concrete Structure equipped with Non-Linear Viscous Damper (NLVD) at the 1st Story

1/2 Scale Structure at Real-Time Execution

Ground Motion: Kocaeli, Turkey 1999

Hazard Level: Maximum Considered Earthquake (MCE) 7.51 Magnitude

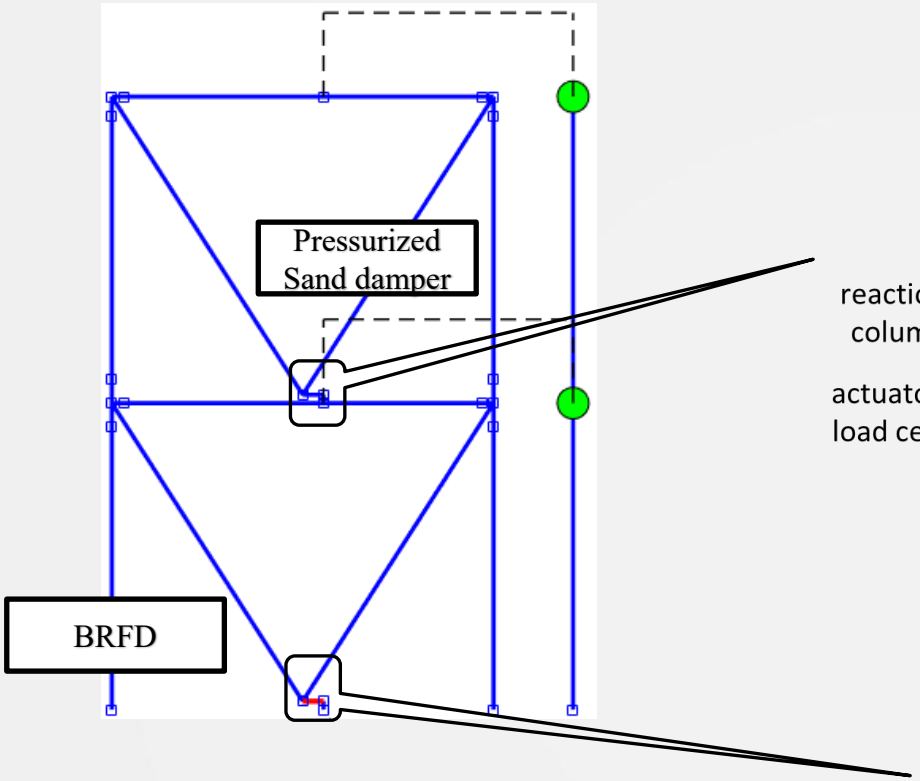
LEHIGH UNIVERSITY | RTMD REAL-TIME MULTI-DIRECTIONAL TESTING FACILITY | NHERI | NSF

LEHIGH UNIVERSITY | ATLSS

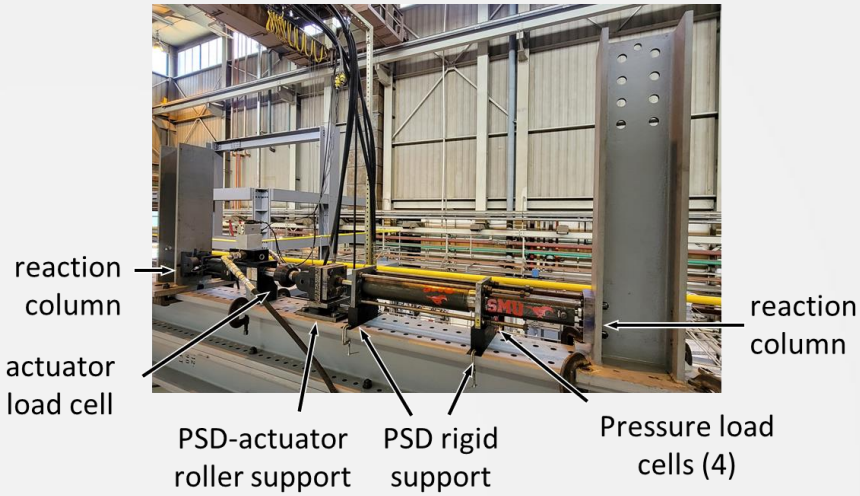
NSF | RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION | NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

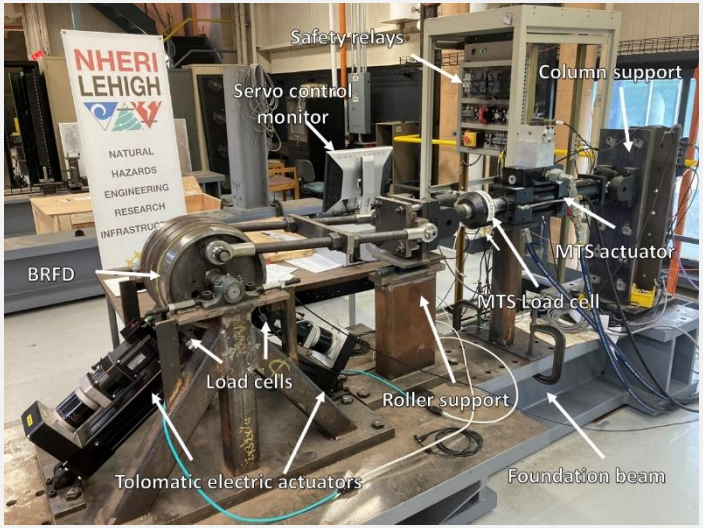
RTHS Test Demonstration

Analytical Substructure



Experimental Substructures





<u>Excitation Input</u>:

- Ground Motion: Kocaeli, Turkey 1999
- Hazard Level: Maximum Considered Earthquake (MCE) 7.51 Magnitude