Multidirectional Hybrid Simulation Tests at Polytechnique Montreal: System, Challenges and Applications

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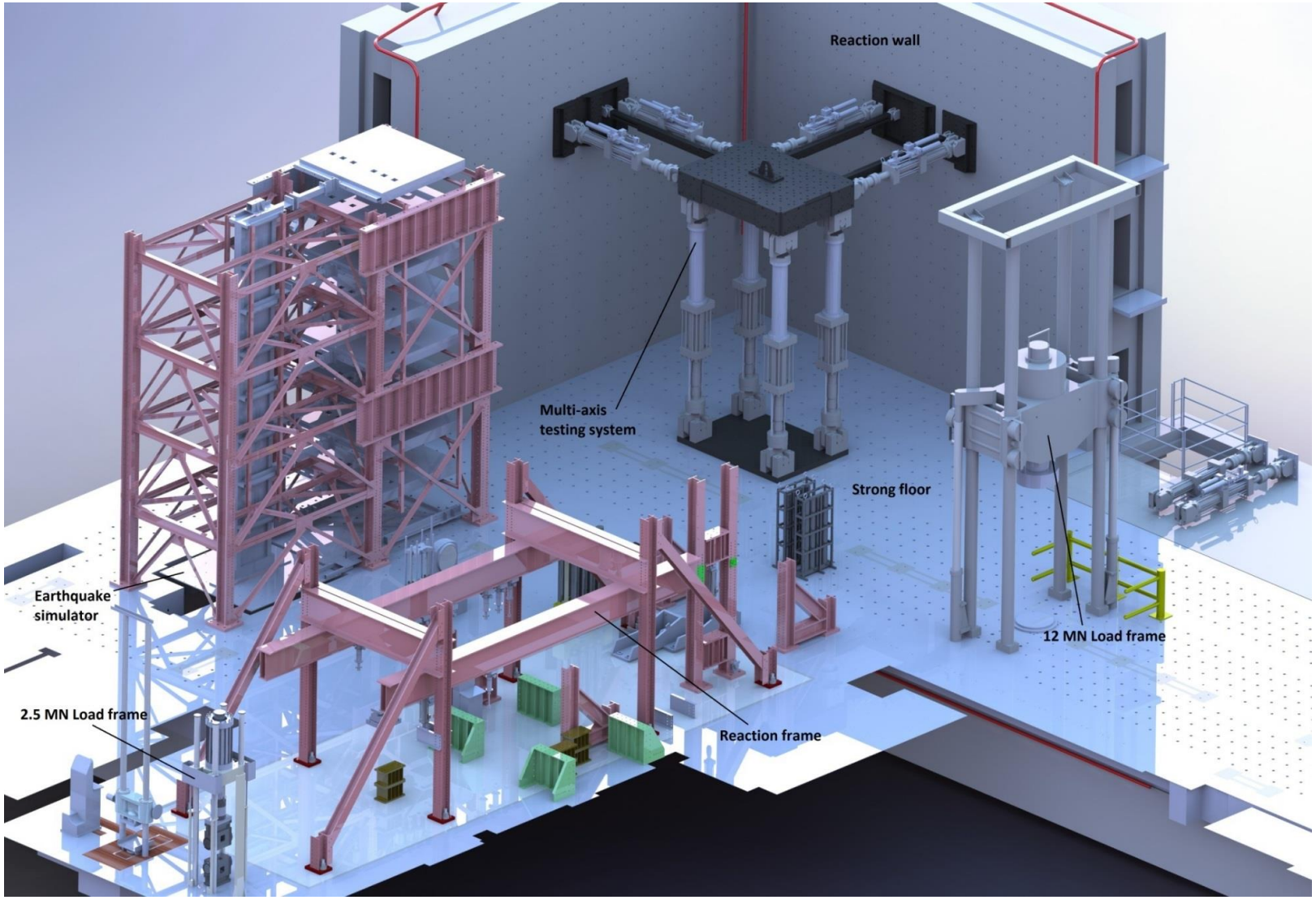
Group for Research in STRUCTURAL ENGINEERING

POLYTECHNIQUE MONTRÉAL

Plan

1. MDHTS System
2. Challenges:
    1. System stiffness
    2. Friction in actuator's swivels
    3. Measurements precision
3. Applications
4. Conclusions

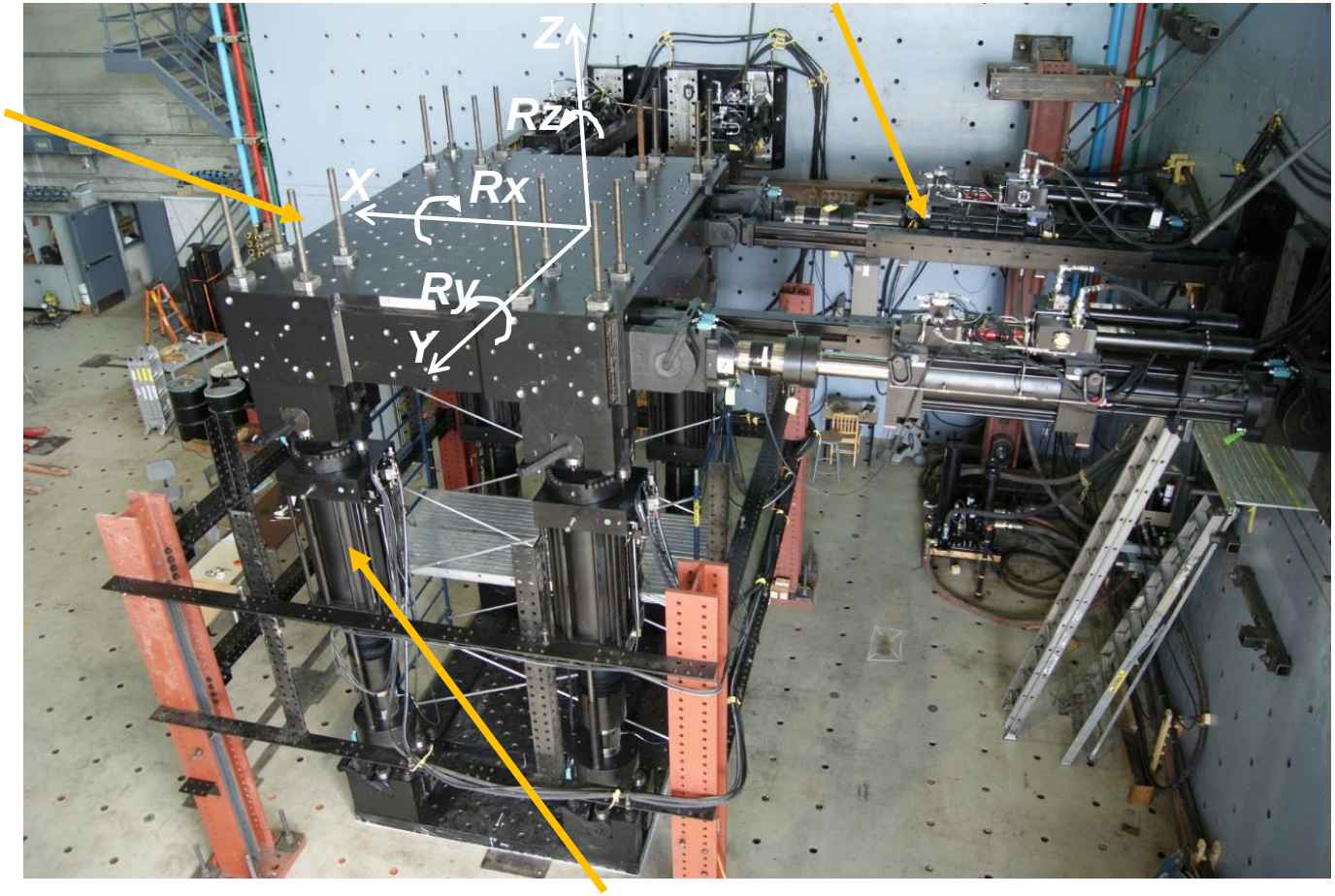
Laboratory at Polytechnique Montreal



MDHTS

4 – 1000 kN Actuators

Upper Platen



4 – 2000 kN Actuators

MDHTS

- Manufacturer: MTS Corporation
- Full 6 DOF control (X, Y, Z, θ_X, θ_Y, θ_Z)
  - Mixed mode of displacement/force control
- Multi-axis testing of substructures
  - quasi-static (cyclic)
  - Pseudo-dynamic testing
  - Hybrid Testing
- 2 Two displacement feedback signals:
  - Absolute referencing (from actuator displacement)
  - Relative referencing (from transducer's readings)
- 2 Hybrid configurations:
  - ScramNet (Matlab, Simulink & xPC Target)
  - CSI (MTS)

MDHTS

Total System Capacity	
Vertical Force, Fz	4 x ±1800 kN (±7200 kN)
Horizontal Force, Fx & Fy	2 x ±1000 kN (±2000 kN)
Vertical Displacement, Z	±300mm
Horizontal Displacement, X & Y	±375mm
Rotation in swivels (all)	±7 deg (±0.122 rad)
Maximum moment X-X	From vertical actuators • +/- 2 x 1800 kN x 3 m = ±10800 kN-m From Horizontal actuators • +/- 2 x 1000 kN x 4.73 m = ±9460 (Y-actuators at 4 m elevation) • +/- 2 x 1000 kN x 9.23 m = ±18460 kN-m (Y-actuators at 8 m elevation) Combined • ±20260 to ±29260 kN-m
Maximum Moment Y-Y	From vertical actuators • +/- 2 x 1800 kN x 2 m = ±7200 kN-m From Horizontal actuators • +/- 2 x 1000 kN x 4.73 m = ±9460 (X-actuators at 4 m elevation) • +/- 2 x 1000 kN x 9.23 m = ±18460 kN-m (X-actuators at 8 m elevation) Combined • ±16660 to ±25660 kN-m
Maximum Moment Z-Z	+/- (1000 kN x 2 m + 1000 kN * 3 m) = ±5000 kN-m

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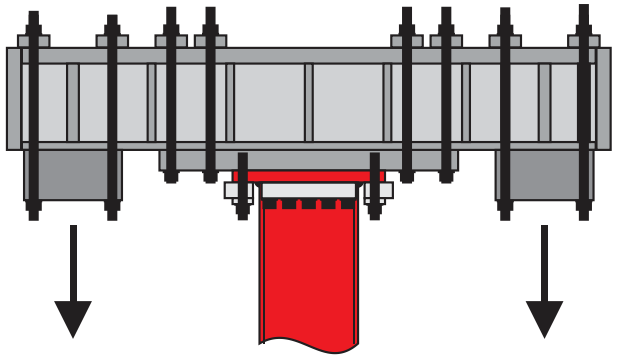
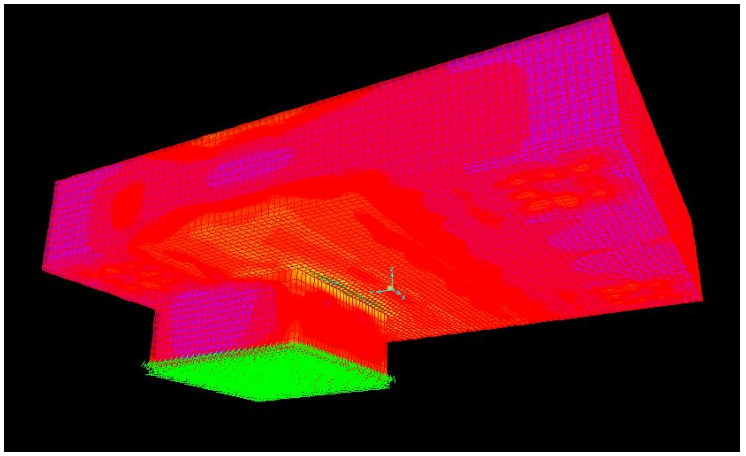
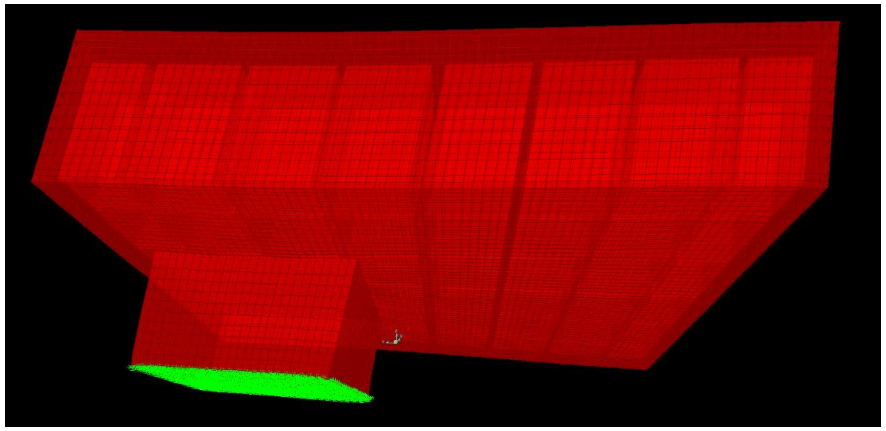
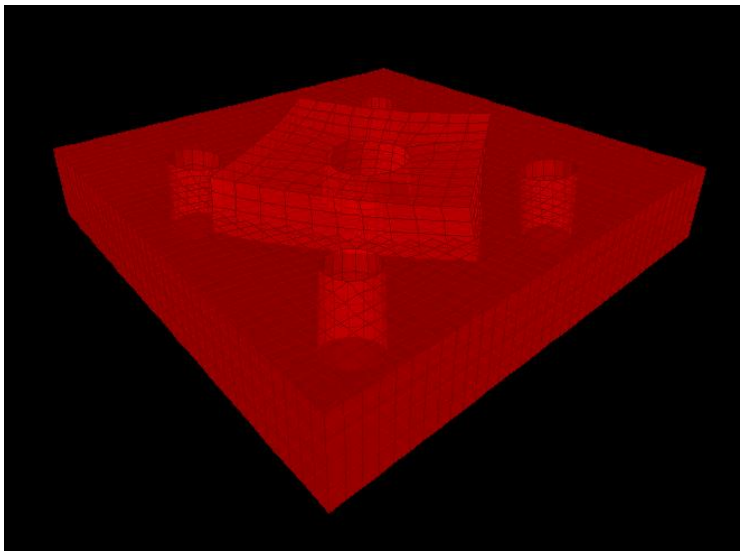
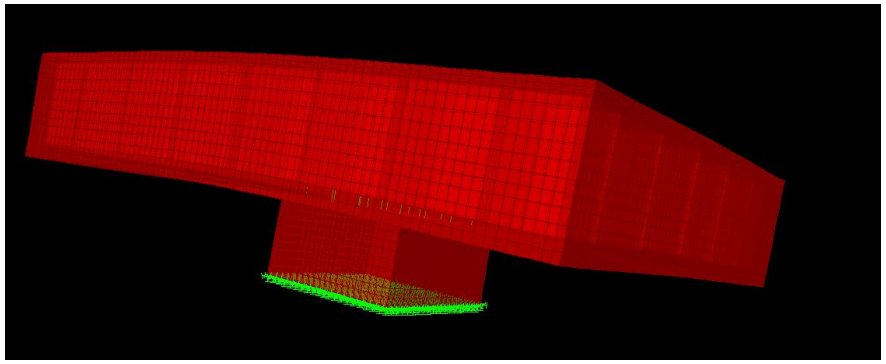
Challenges: System stiffness



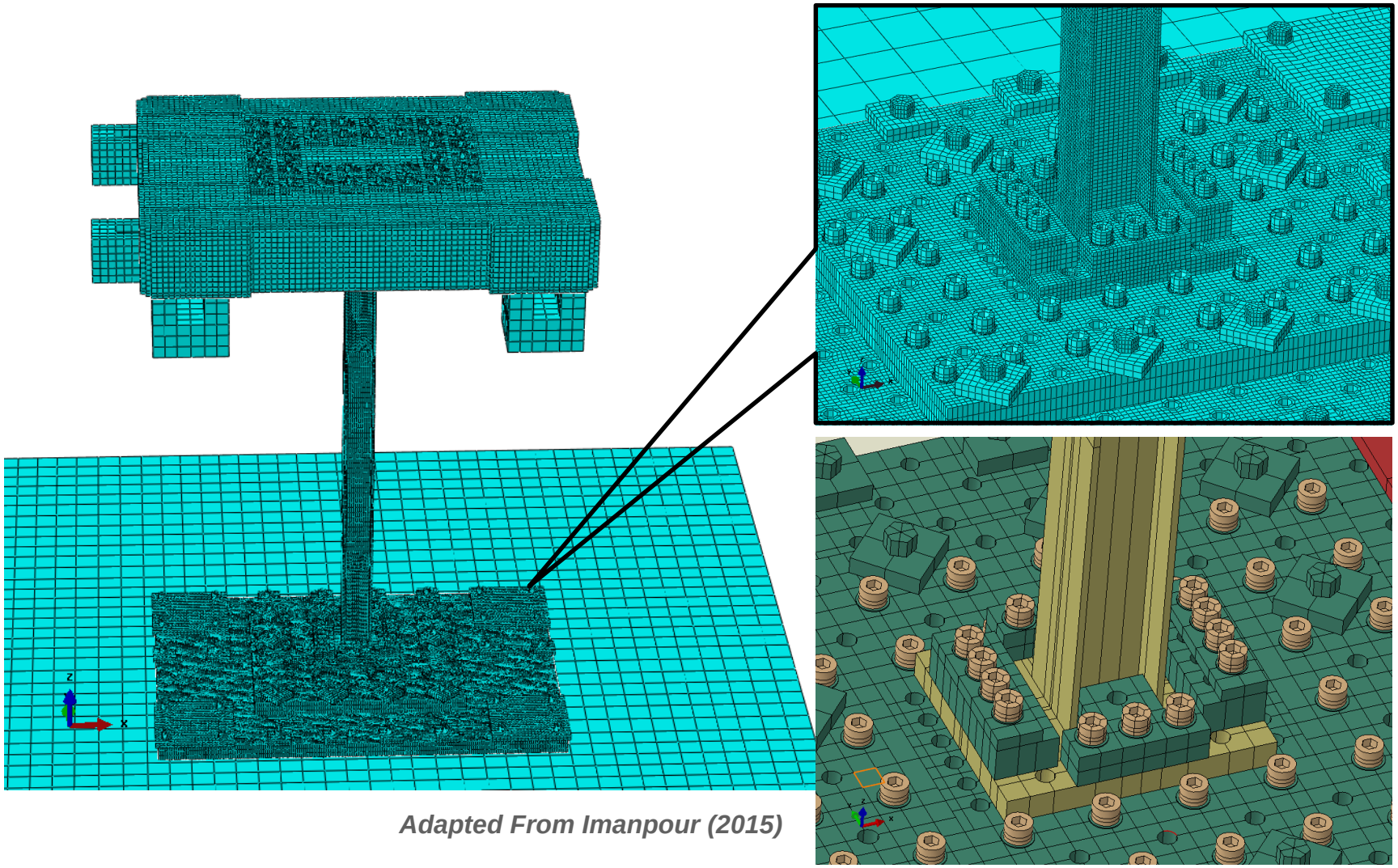








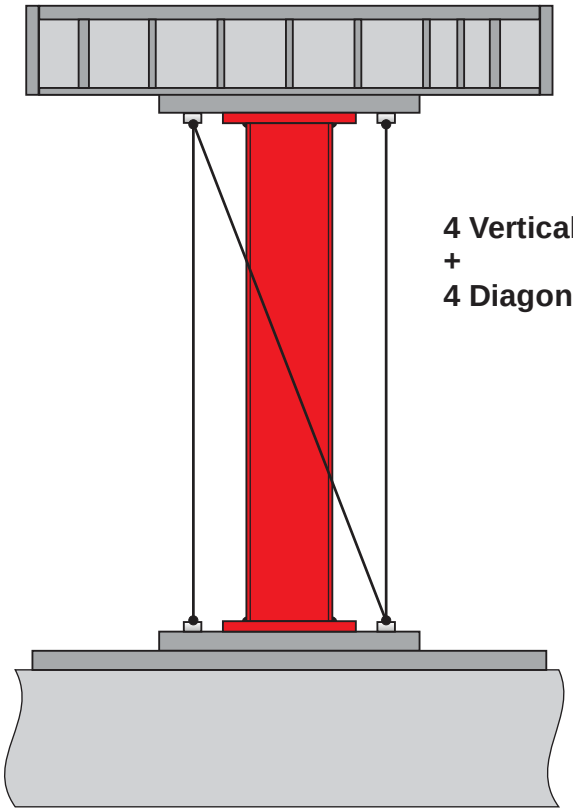
Challenges: System stiffness



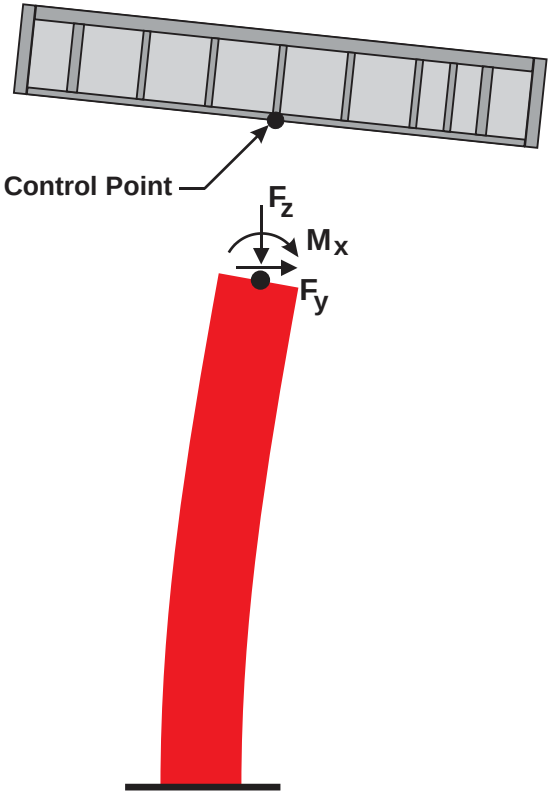
Adapted From Imanpour (2015)

Challenges: System stiffness

Control on specimen's displacements only (relative displacement)



4 Vertical Transducers
+
4 Diagonal Transducers

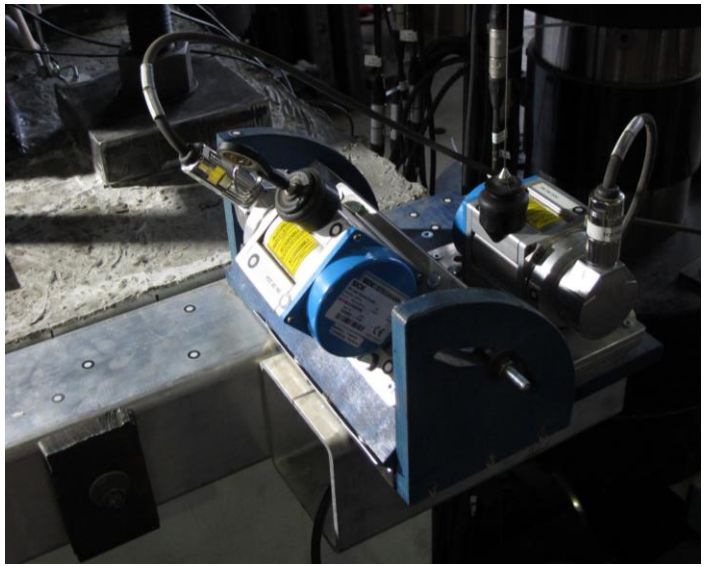


At Control Point: Forces: From Actuators Load Cells

Displacements: From Actuators LVDTs & 8 Local Transducers

Challenges: System stiffness

Metrology-grade scanners used to locate encoders in 3D space



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1. MDHTS System
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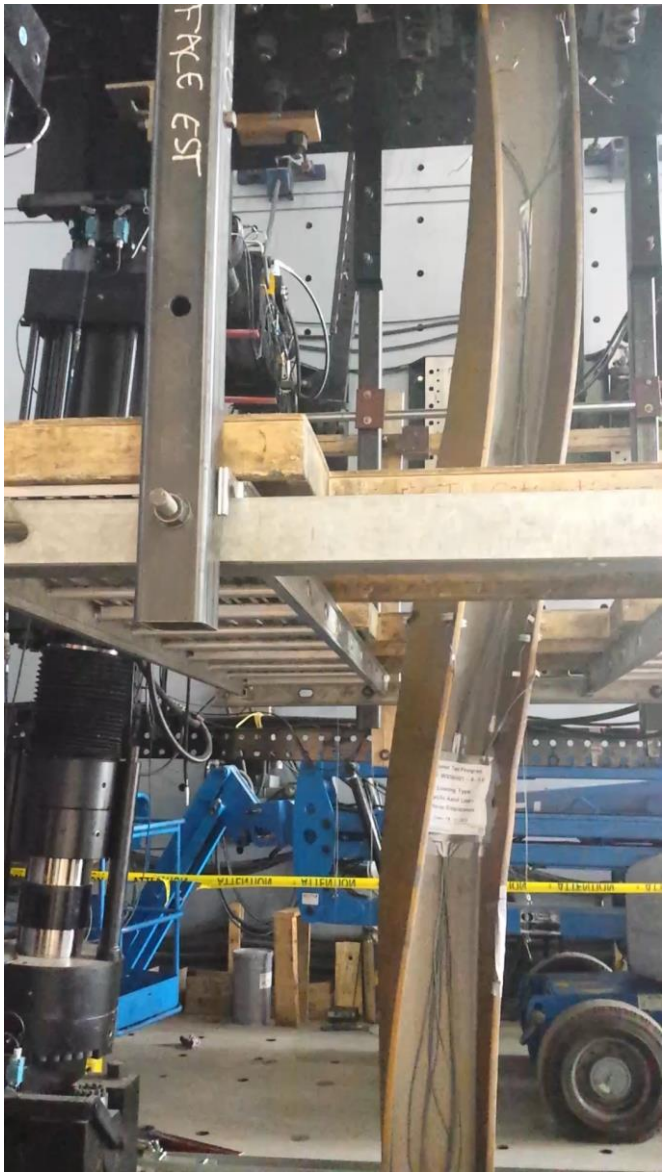
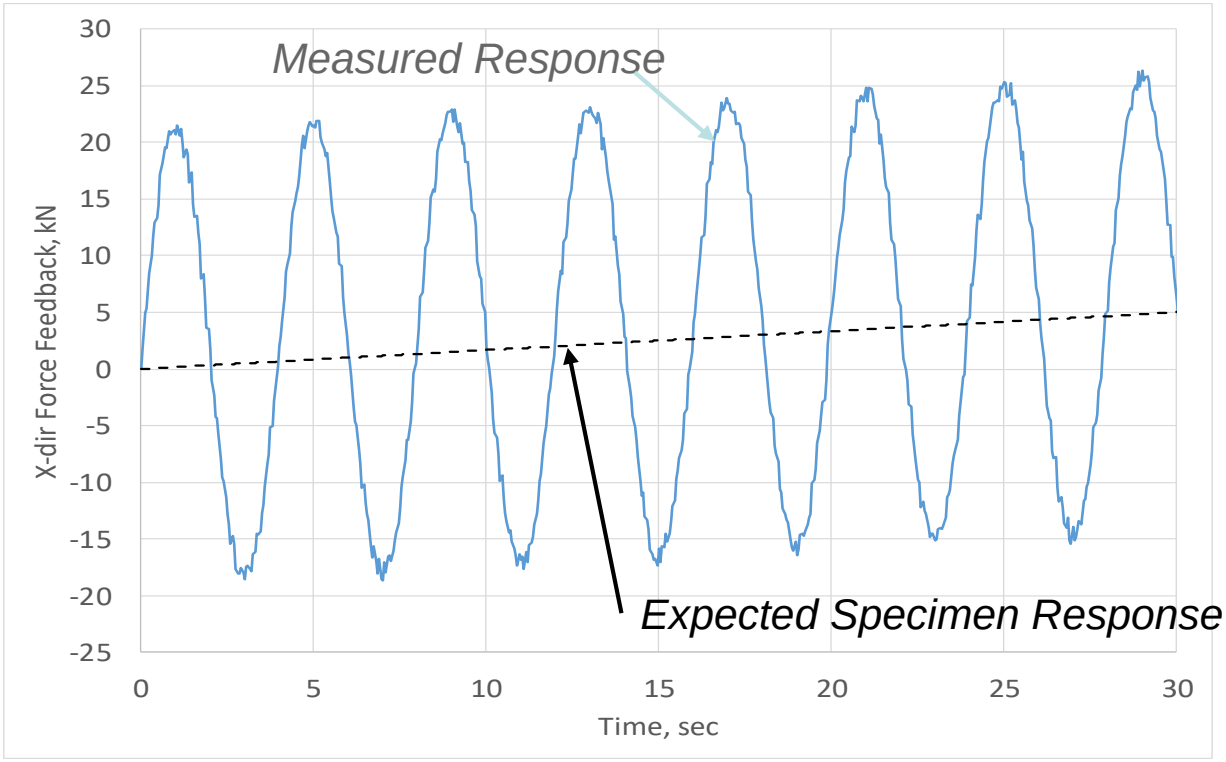
Challenges: Friction in actuator's swivels

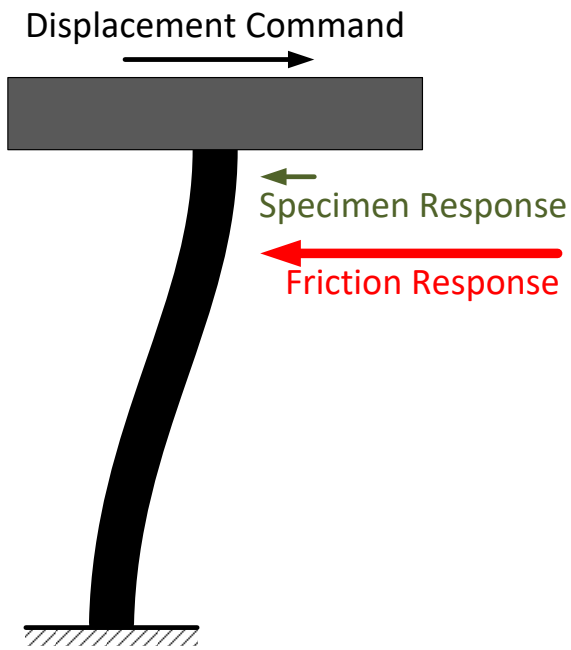
Preliminary Hybrid Simulation:

- ***Flexible specimen***
- ***3 DOF (X, Y & Rx)***
- ***Unstable control (large oscillations)***



Challenges: Friction in actuator's swivels

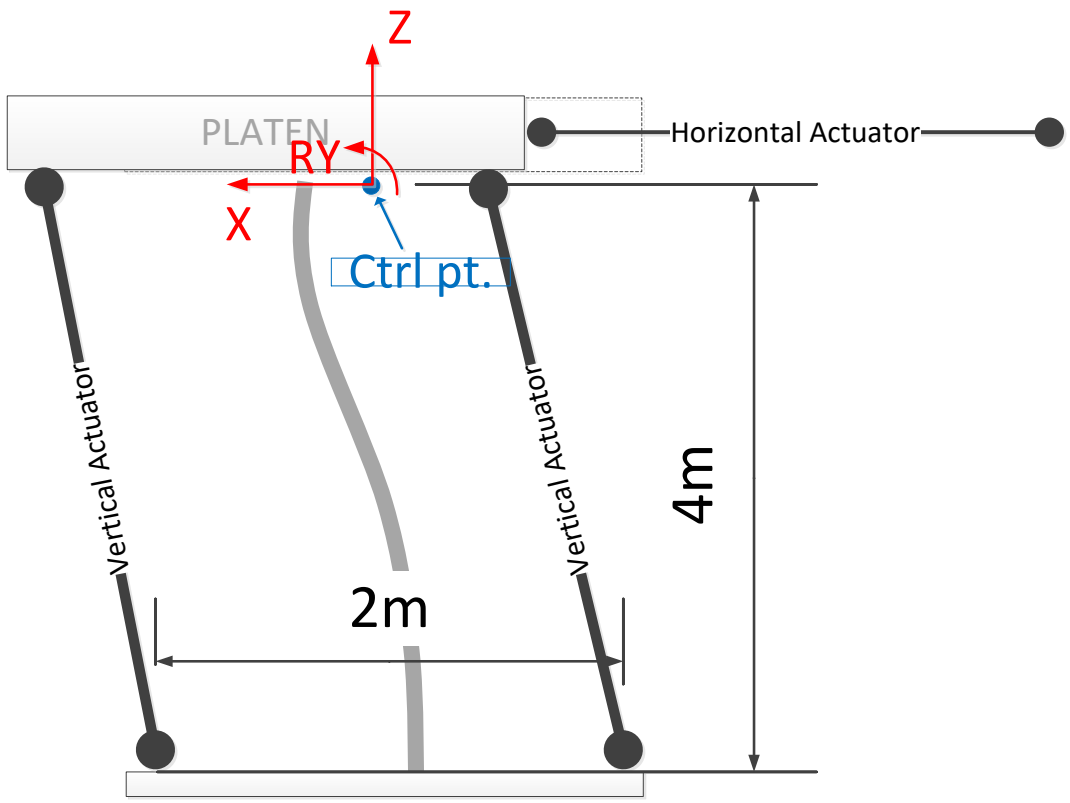




$$M\ddot{u} + C\dot{u} + [K_s u + Friction] = -m\ddot{g}$$

Challenges: Friction in actuator's swivels

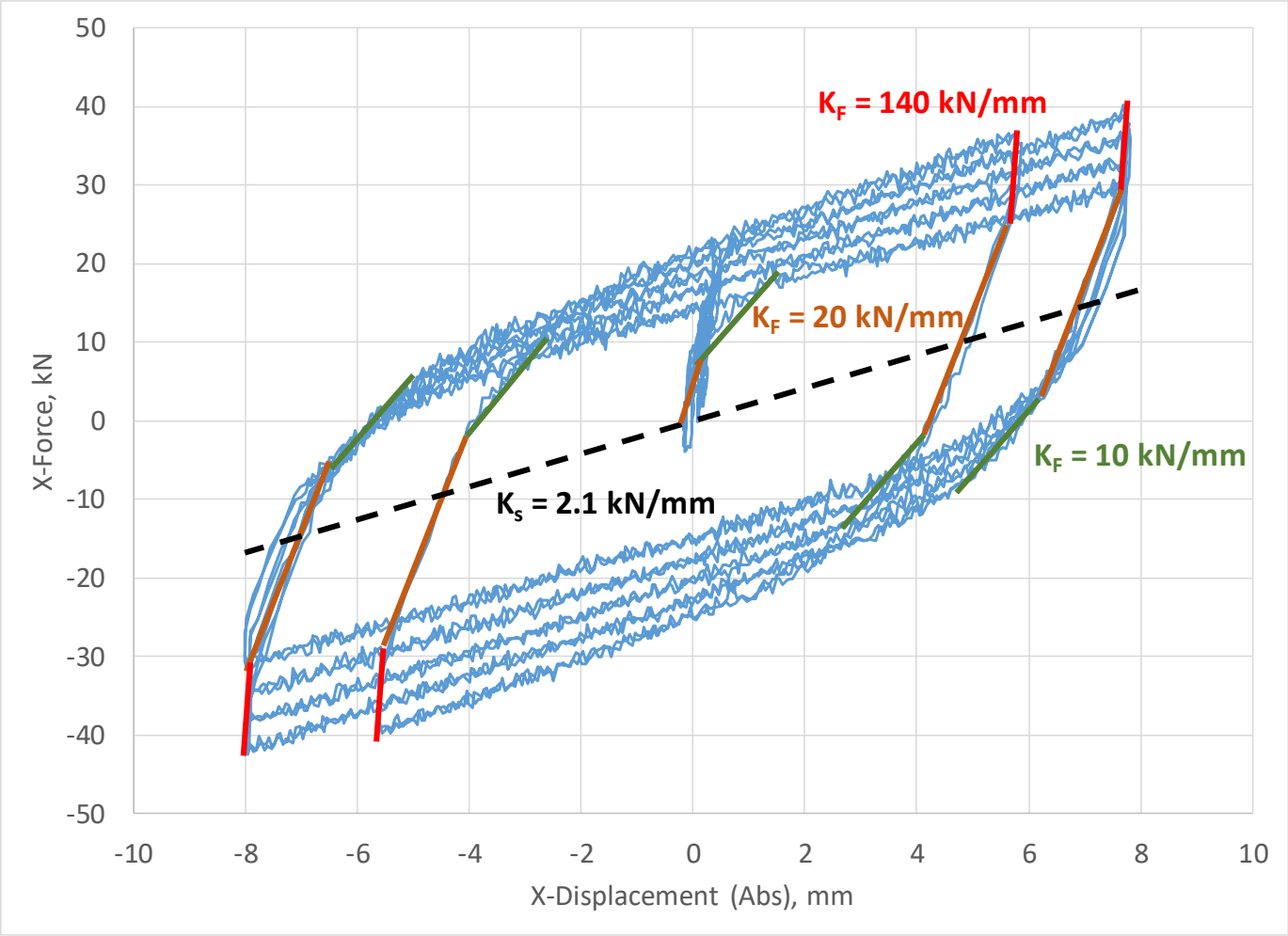
Friction characterization:



Direction	Control mode
X	Relative = cyclic
Y	Relative = 0
Z	stepwise incremented Load
Rx	Relative = 0
Ry	Relative = 0
Rz	Relative = 0

Challenges: Friction in actuator's swivels

X Force , Combined Specimen Response (linear) and Friction

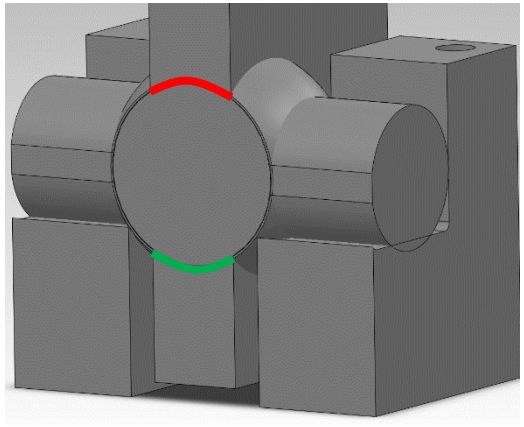


Challenges: Friction in actuator's swivels

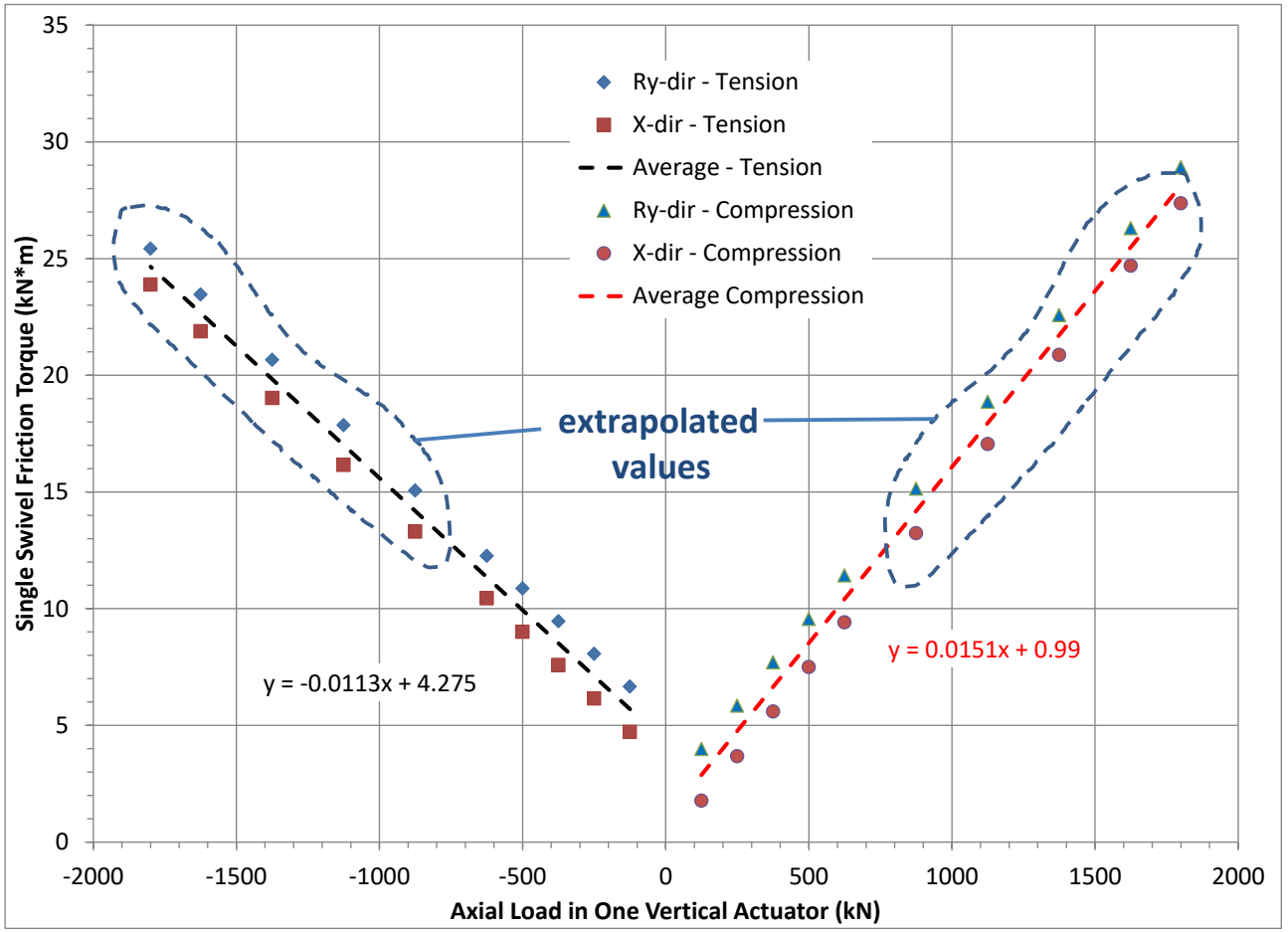
Friction in One Vertical Actuator Swivel vs Actuator Load

Contact Surface

Actuator in Compression



Actuator in Tension



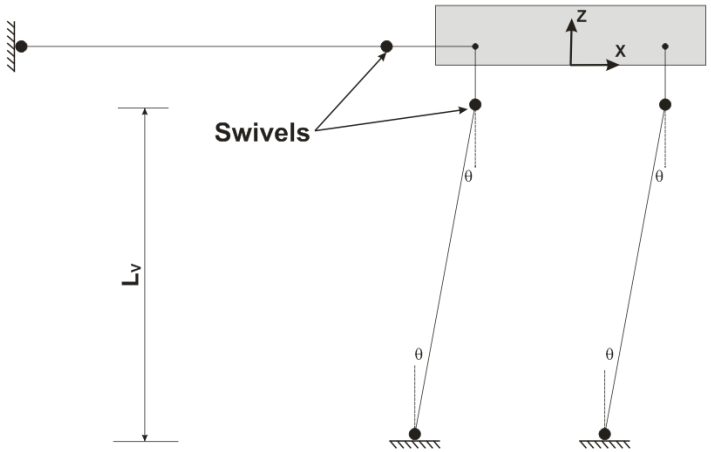
** When specimen is in tension, actuator is in compression and vice-versa*

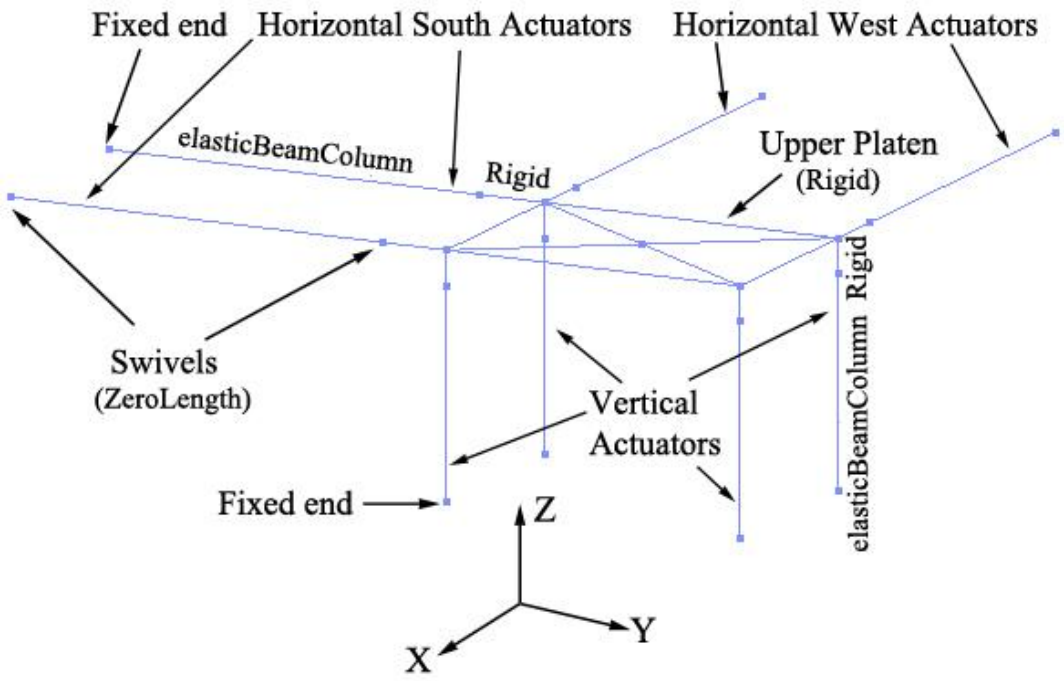
$$T_v(kN \cdot m) \approx 0.0132 * |Fz(in\ kN)| + 2.63$$

Challenges: Friction in actuator's swivels

Mitigation Techniques: Friction Compensator

- Negative friction model (add negative stiffness!!!)
  - OpenSEES model of MDHTS (Ali Imanpour)

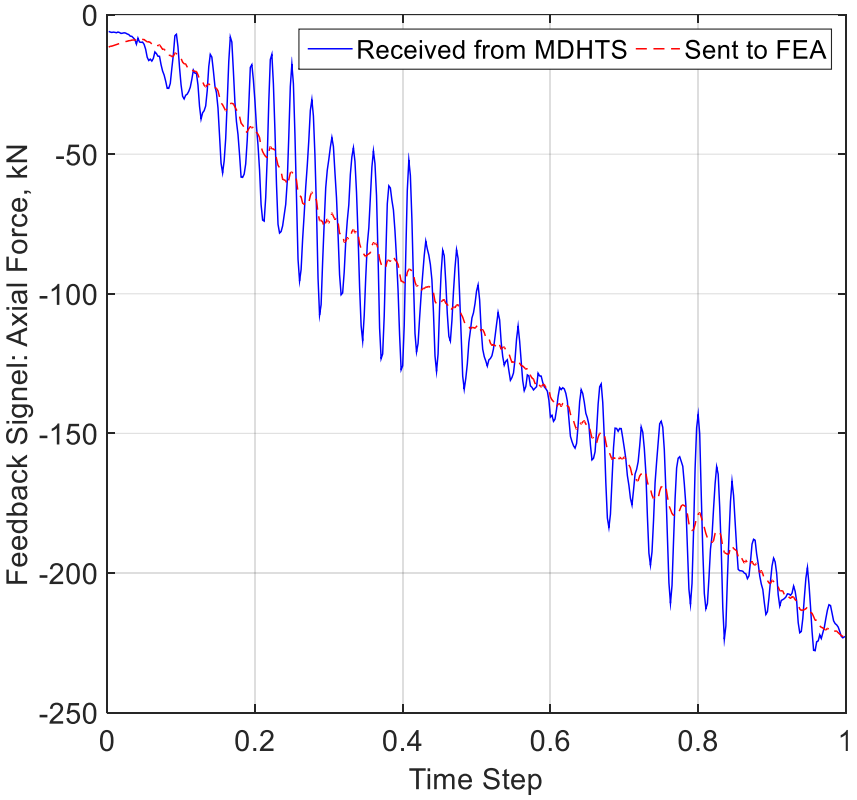


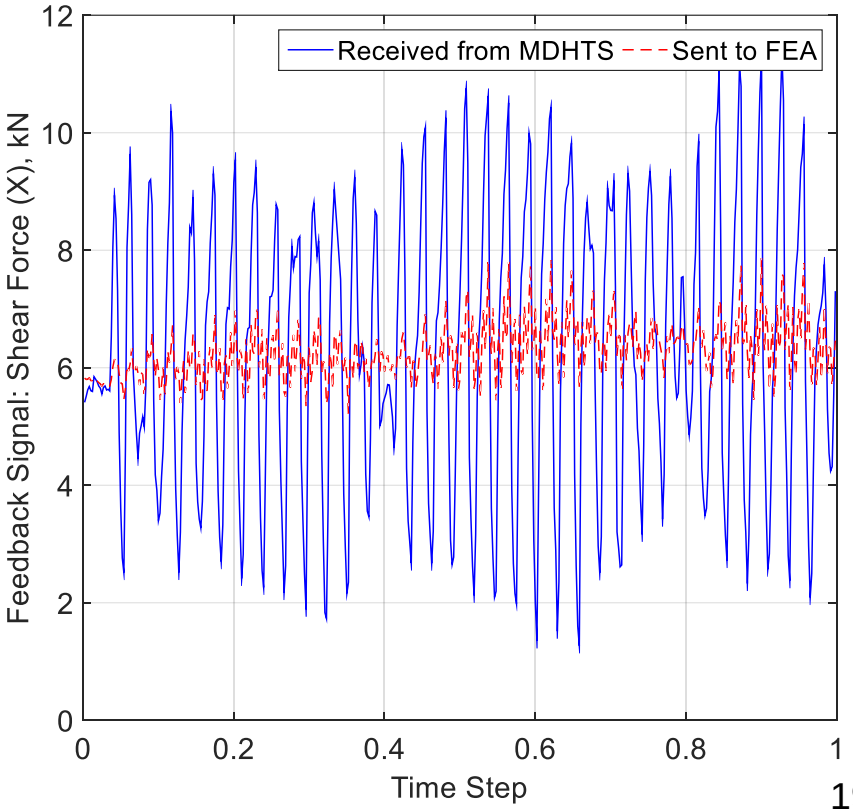


Challenges: Friction in actuator's swivels

Mitigation Techniques: Feefback Instabilities

- Polynomial smooting of feedback signals
  - Quadratic function in MTS controller

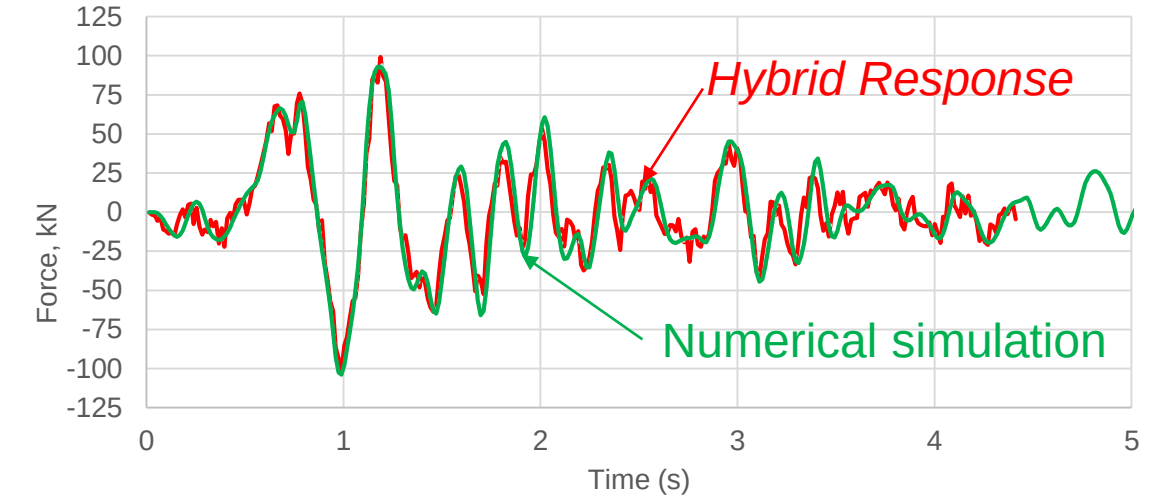


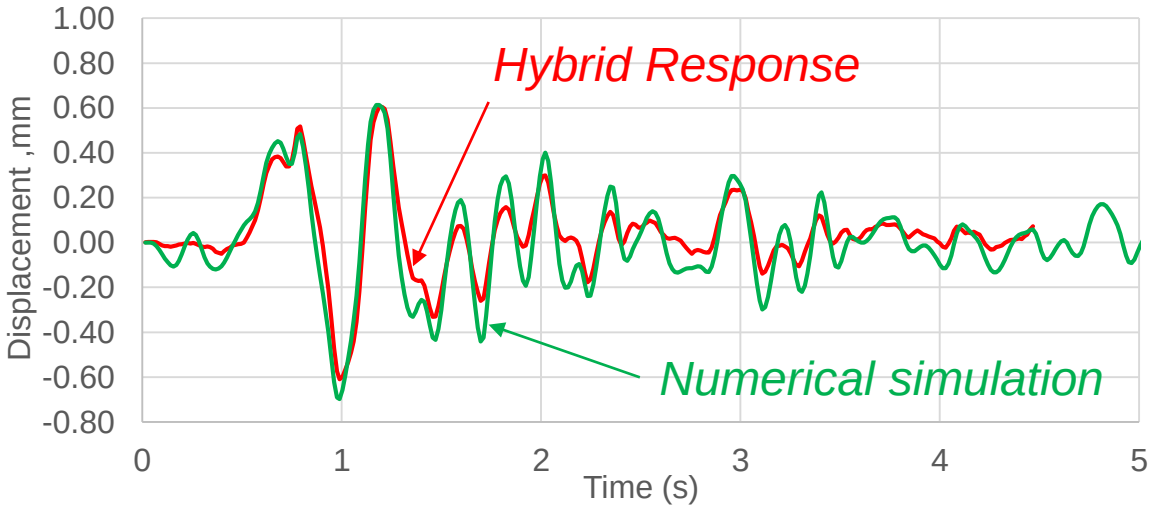


Challenges: Friction in actuator's swivels

Bridge Pier, H=2.75m

Youness Mechmachi (2016)



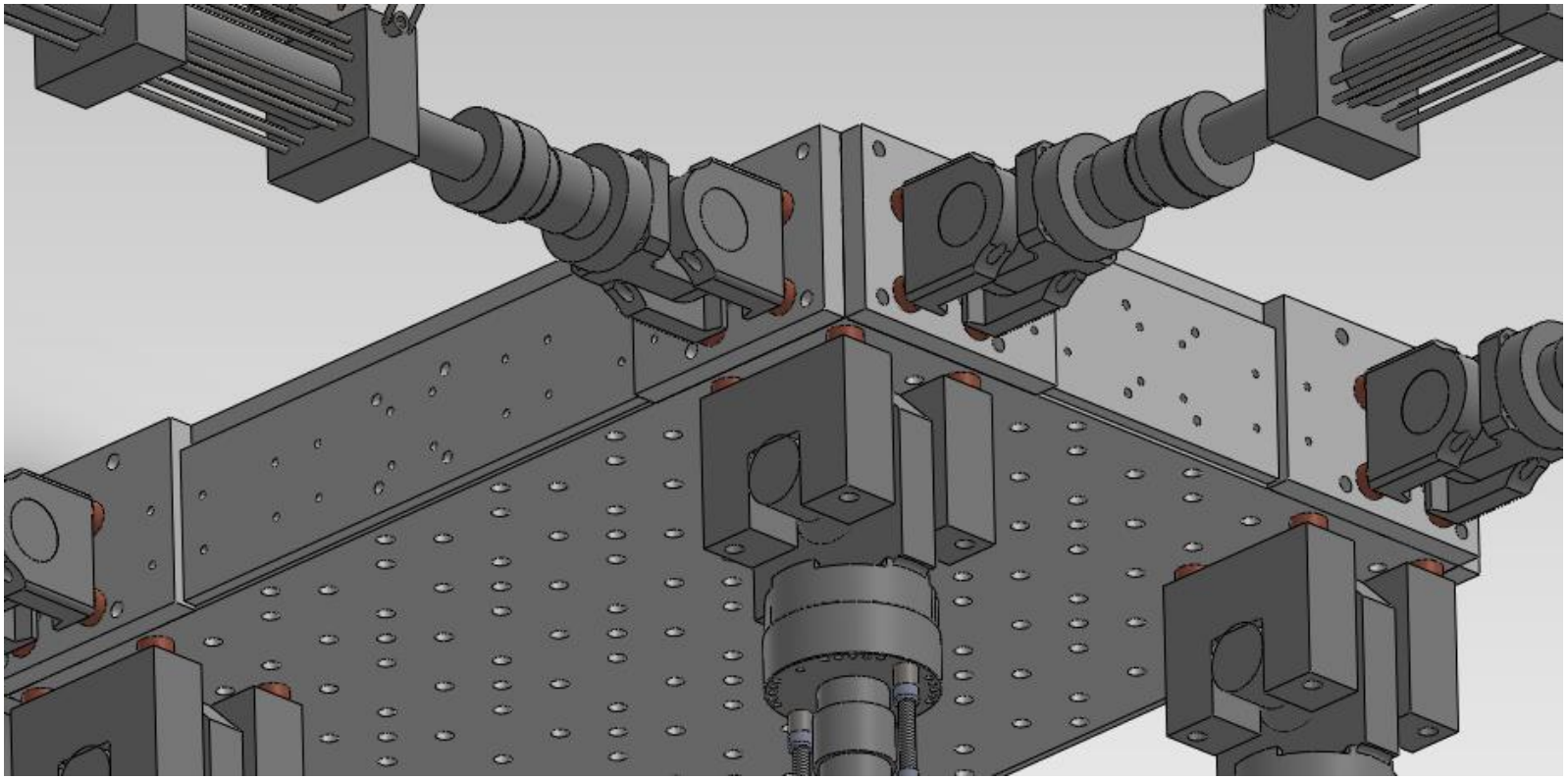


$$M\ddot{u} + C\dot{u} + [K_s u + Friction] = -m\ddot{g}$$

Challenges: Friction in actuator's swivels

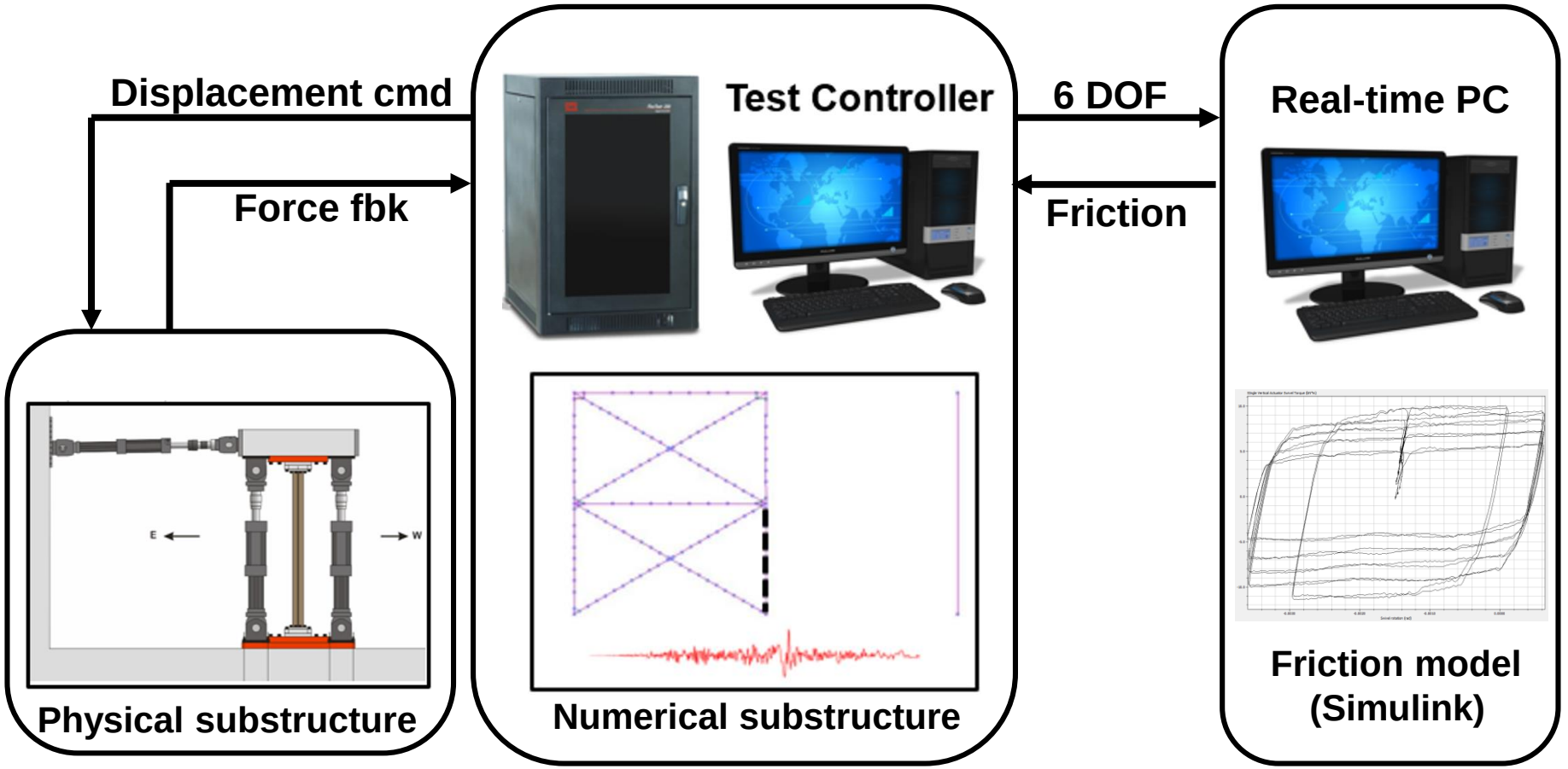
Mitigation Techniques: Load Cells

One approach was to add 64 load cells to measure friction at each end of actuator swivel and compensate in real time.



Challenges: Friction in actuator's swivels

Mitigation Techniques: Real-time friction computation



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Challenges: Measurements precision

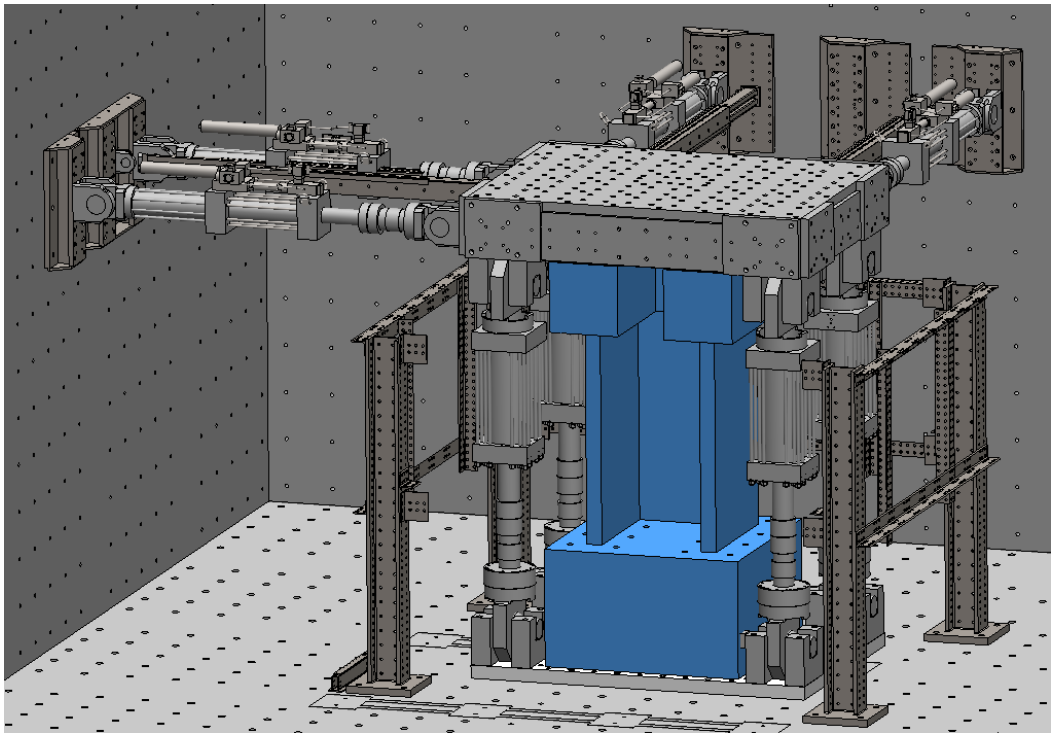
Stiff specimen vs. encoder's resolution

Original resolution : 0.02500 mm

→ Unstable control

Upgraded resolution: 0.00076 mm

→ Stable control



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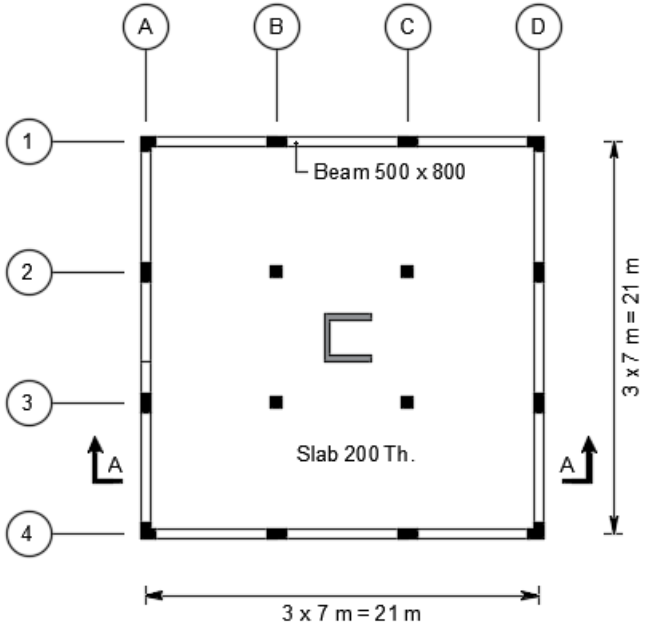
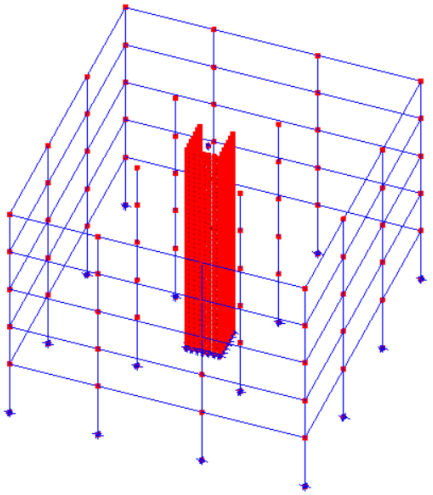
Applications:

Hybrid Simulation Testing:

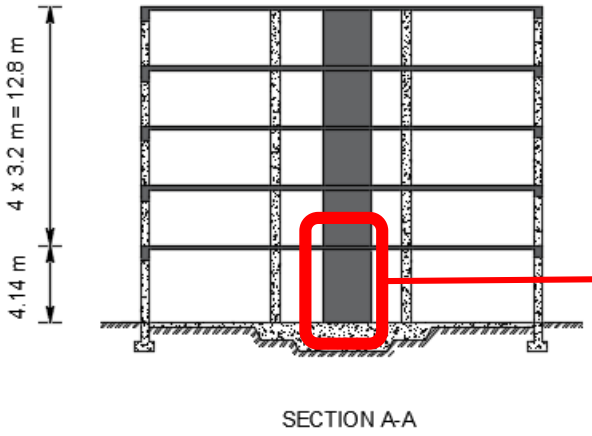
- ***Computational driver***
  - ***Finite element model (OpenSees)***
- ***Physical testing system***
  - ***MTS FlexTest 200 controller***
  - ***Experimental equipment: MDHTS***
- ***Middleware***
  - ***OpenFresco***
- ***Interfaces between OpenFresco & Flextest controller***
  - ***MTS Computer Simulation Interface (CSI)***
  - ***Mathworks Simulink Platform (xPC Target)***

Application: Concrete C-shape wall

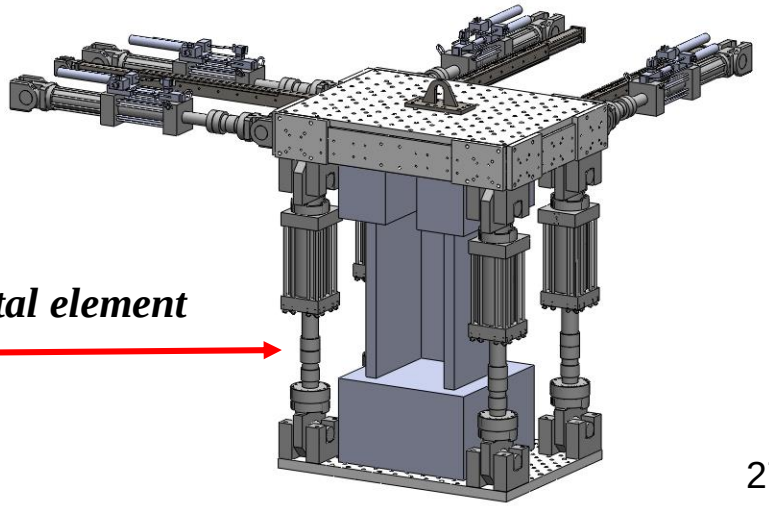




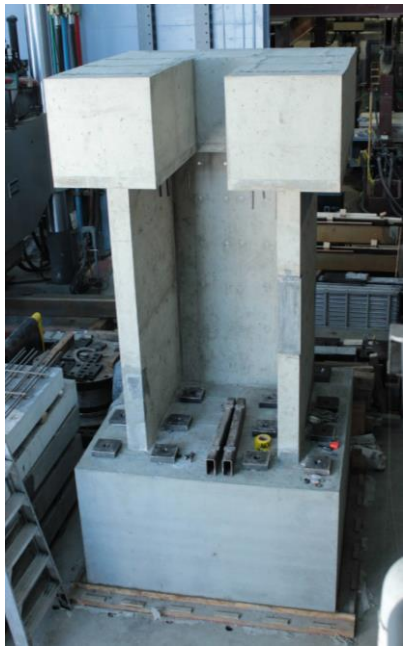
OpenSees/OpenFresco



Experimental element



Application: Concrete C-shape wall



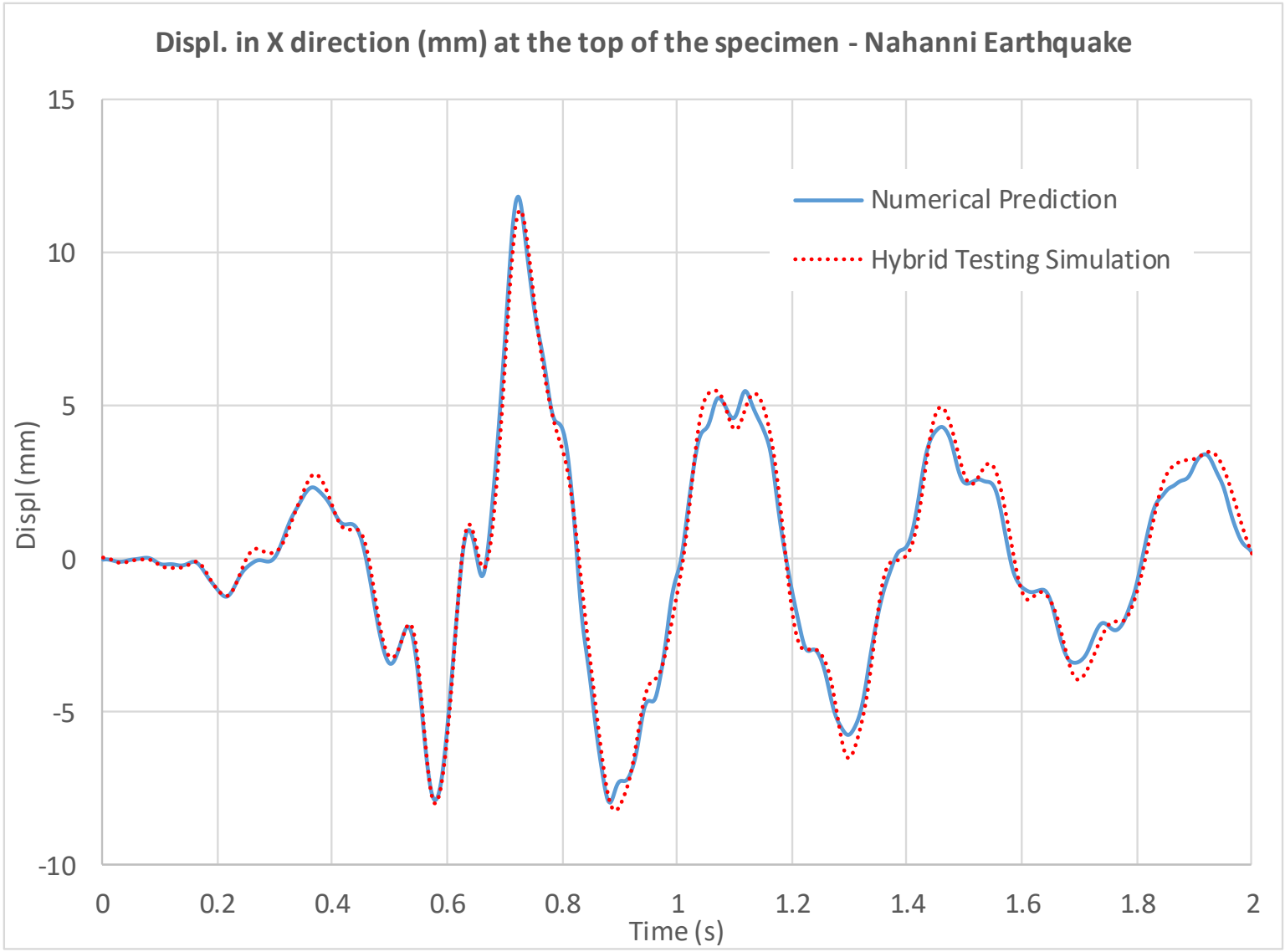
Sound specimen:
(Youness Mechmachi)

(November 2017: 89hrs test)

Carbon-fiber repaired specimen:
(Hamid Arabzadeh)

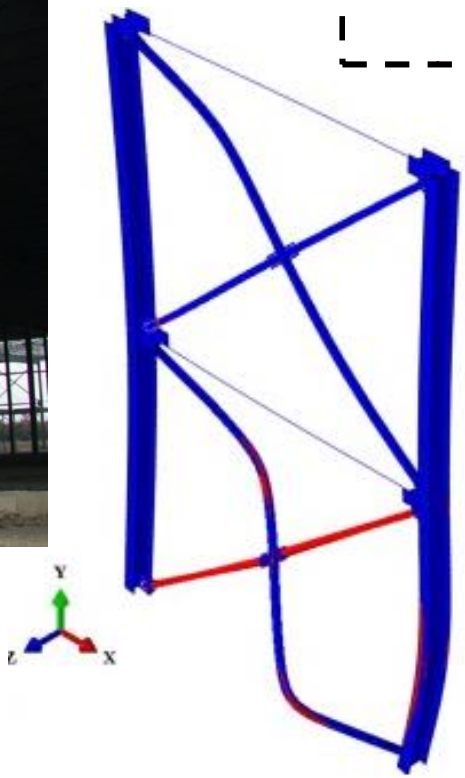
(March 2018: Tested yesterday!)

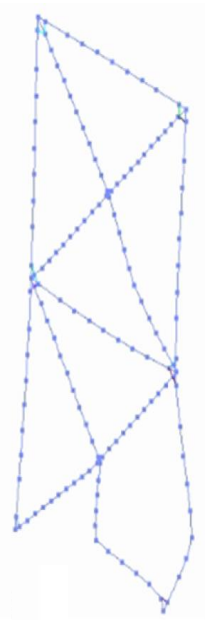
Application: Concrete C-shape wall



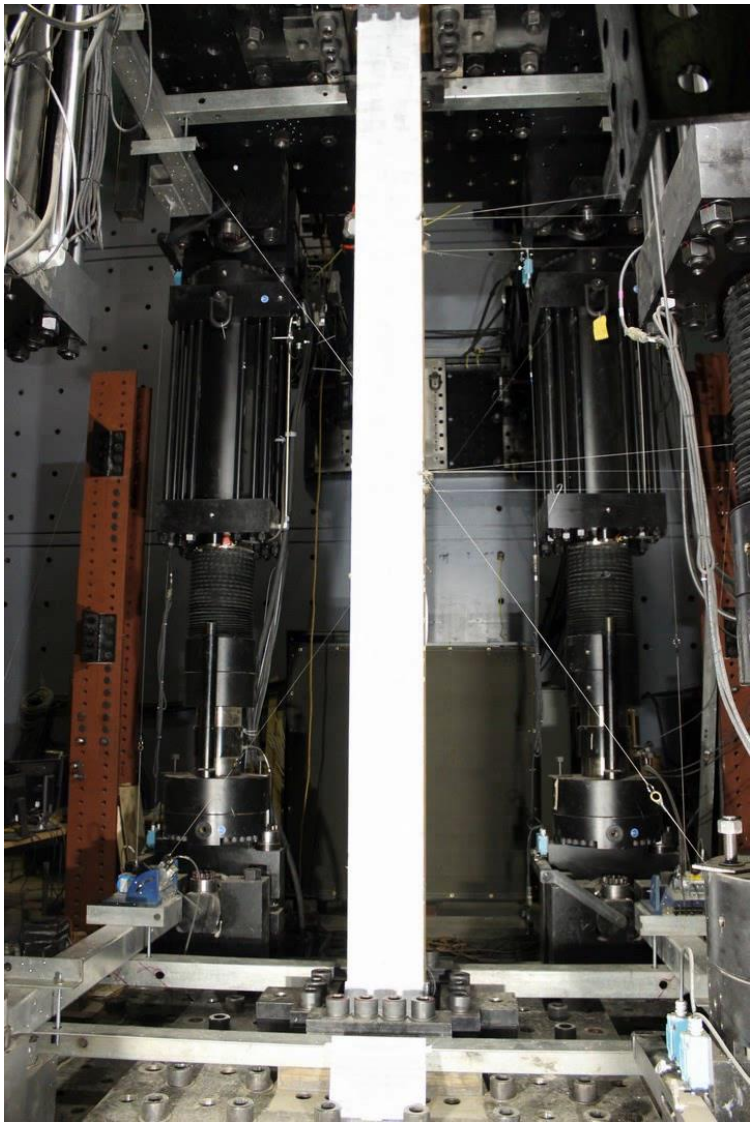
Application: Multi-Tiered Braced Frames

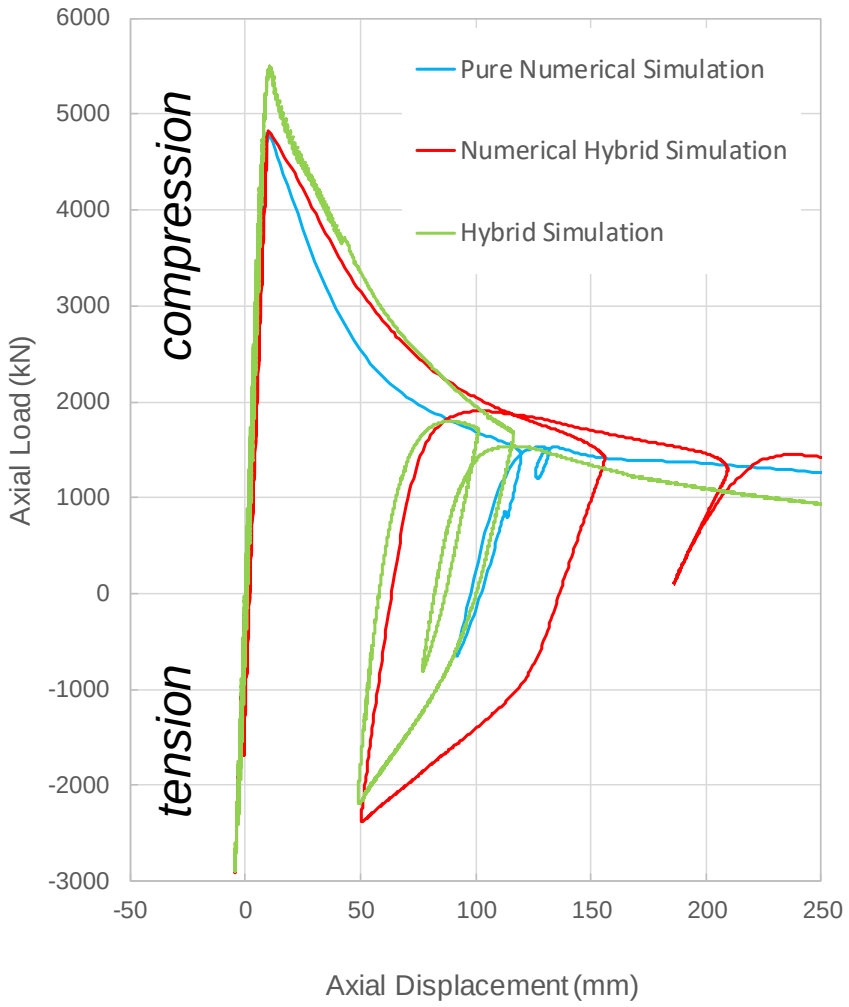
Column Biaxial Buckling





Application: Multi-Tiered Braced Frames





Conclusions

- ***Testing facility fully operational for multi-directional hybrid simulation testing (6 DOF) of large-scale structural components***
- ***Test programs successfully completed on steel columns and concrete structural members***
- ***Local displacement control must be used to obtain realistic deformations***
- ***Friction removal AND smoothing of force's feedbacks must to be combined***
- ***6 DOF Hybrid simulation testing on stiff specimens is highly sensitive to system accuracy (noise level) and precision (resolution) to achieve convergence***

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- **UC Berkeley PEER for OpenSees and OpenFresco**
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