Nonlinear Multi-directional Real-time Hybrid Simulation of Rolling Pendulum Isolation Systems

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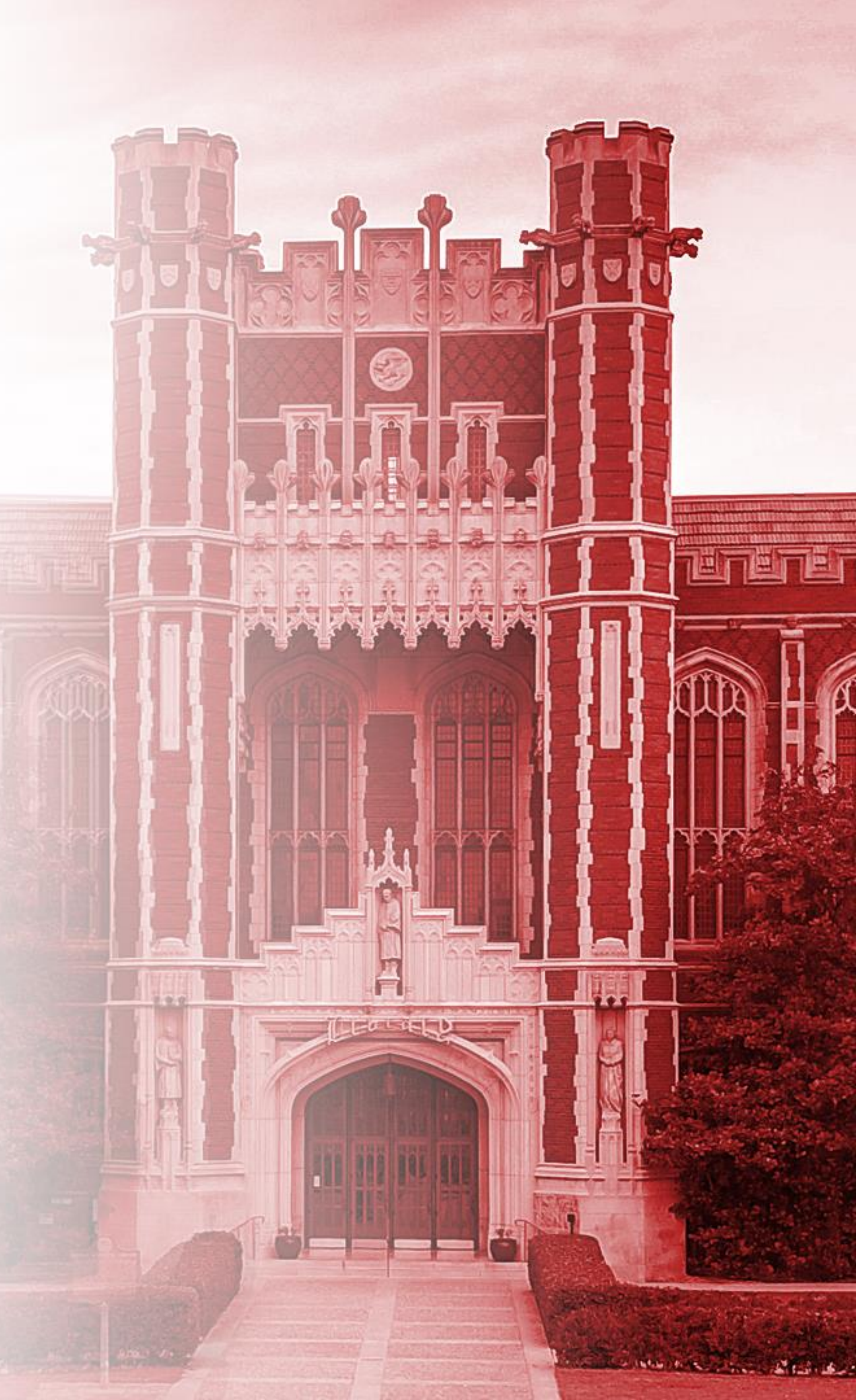
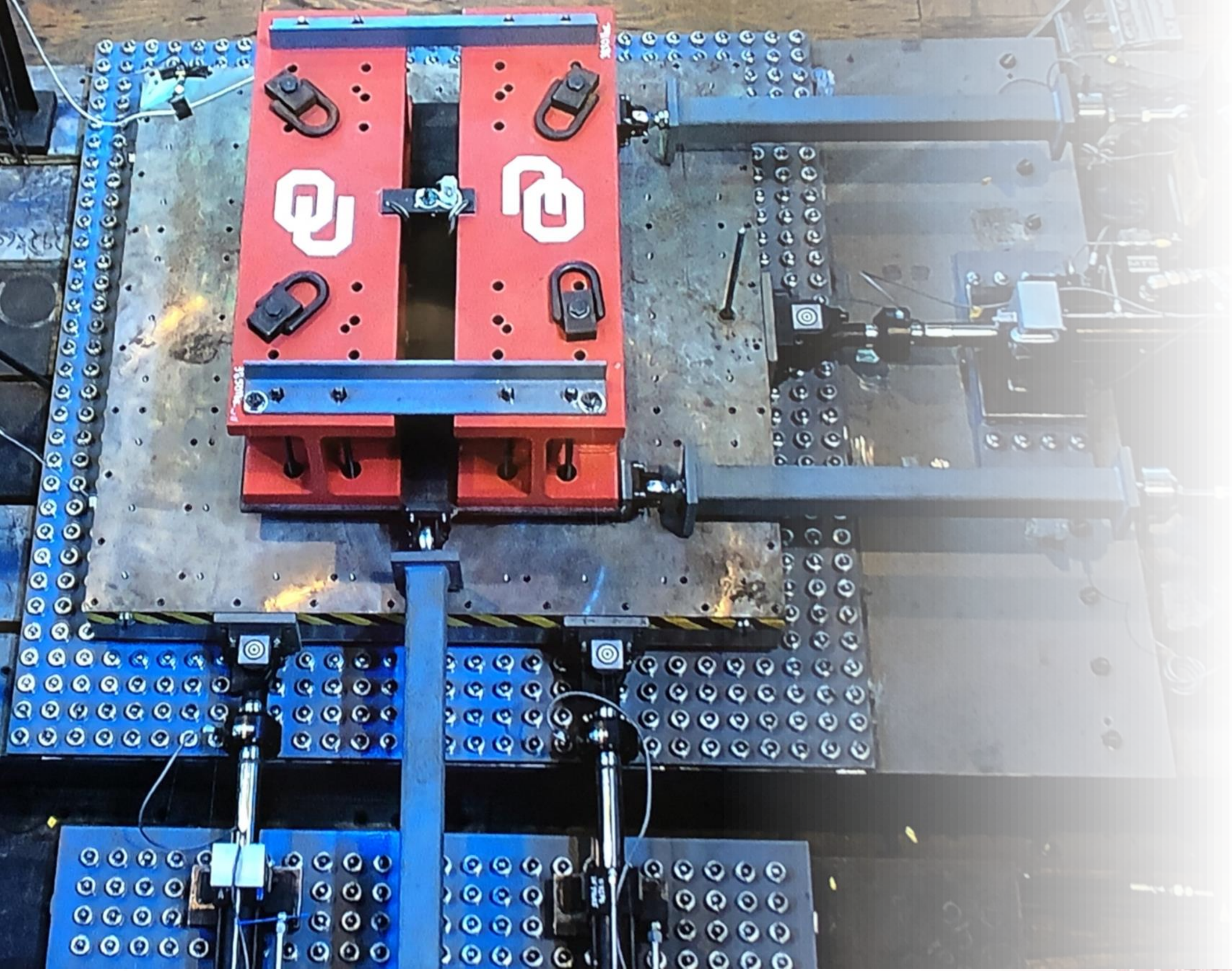
GALLOGLY COLLEGE OF ENGINEERING
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE
The UNIVERSITY of OKLAHOMA





Introduction

Damage to structures due to earthquakes

Vulnerable non-structural building contents[1]

Hospital equipment

(a)
https://dir.indiamart.com/impcat/crash-cart.html

(b)
https://www.shelving.com/Teardrop-Pallet-Rack-Starter-Units-p/ir3su36144-p.htm

Warehouse shelving

Valuable artwork

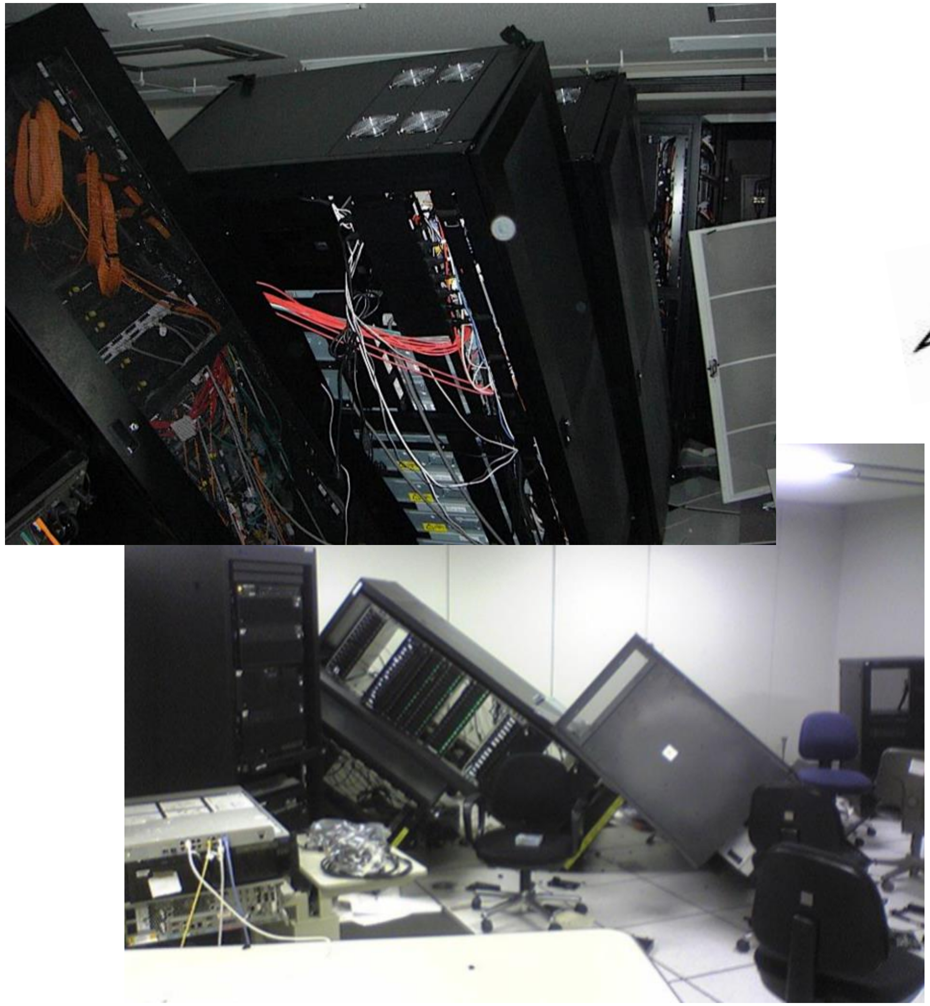
(c)
https://quatr.us/greeks/classical-sculpture-ancient-greece.htm

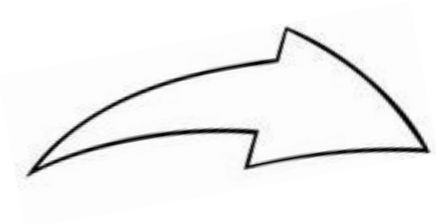
(d)
https://www.cdw.com/shop/products/PANDUIT-NET-ACCESS-N-TYPE-CABINETS/2898087.aspx

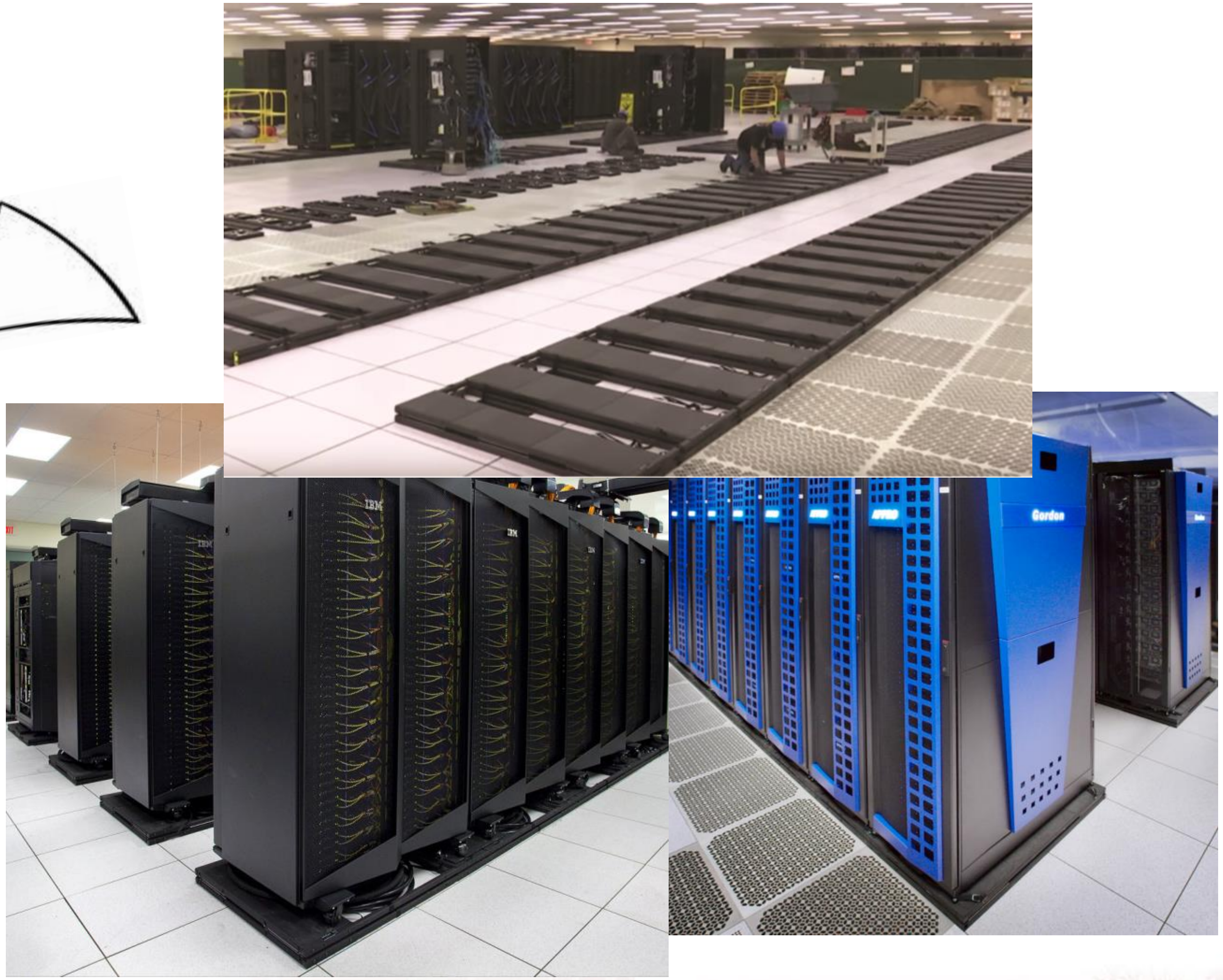
Network cabinet

[1]Casey, Corey D., *Rolling-Type Isolation: An Experimental Characterization and Numerical Parametric Study*, Masters Thesis, University of Oklahoma, 2017.

Damage to non-structural components[2,3]



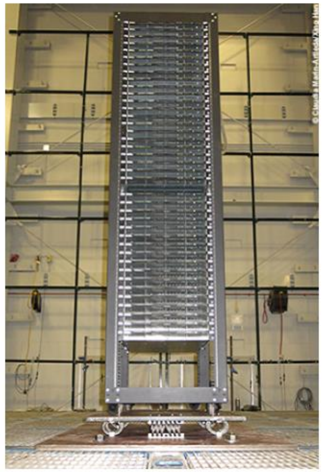




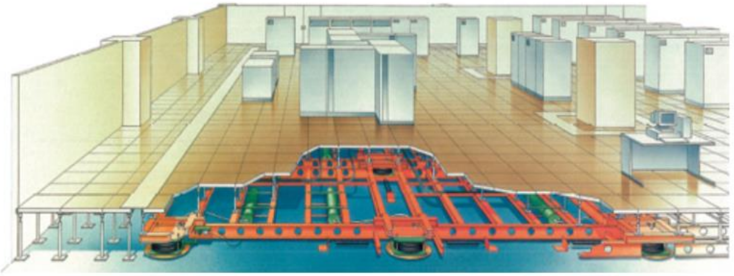
[2]WorkSafe Technologies, Inc., RISK VS ROI, Online, URL https://worksafetech.com/risk-vs-roi/, 2021.

[3]WorkSafe Technologies, Inc., PROJECT GALLERY, Online, URL https://worksafetech.com/resources/product-gallery/, 2021.

Seismic Isolation



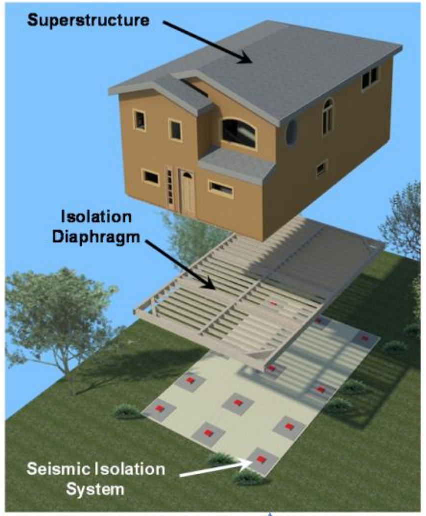
Marin-Artieda *et al.*



IHI (https://www.ihi.co.jp/iis/english/products/damper_floor.html)

Buckle *et al.*

Harvey & Song

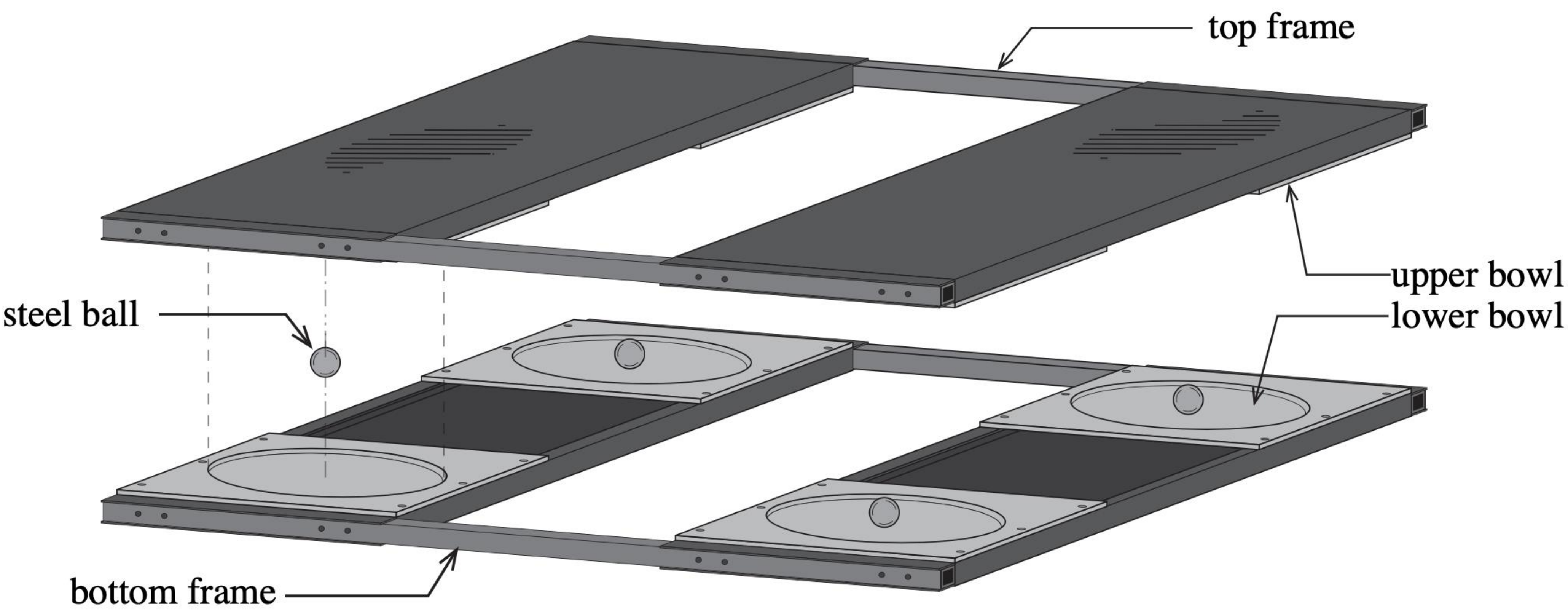


Deierlein *et al.*

Ryan *et al.*

Light (~10^1 kN) → Moderate (~10^2 kN) → Heavy (~10^3 kN)

Rolling Pendulum (RP) bearing[4]

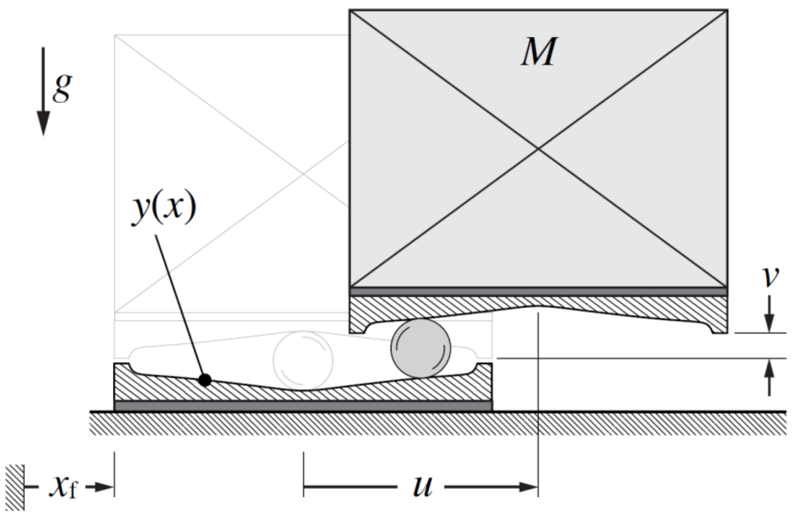


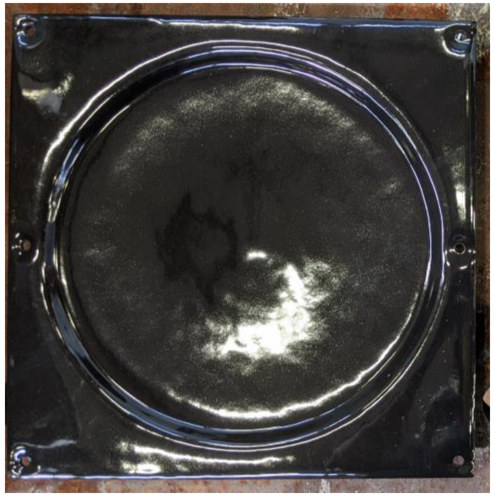
Single cabinet configuration

[4]Casey, C.D., Harvey Jr., P.S. & Song, Journal of Earthquake Engineering. doi: 10.1016/j.engstruct.2018.06.118

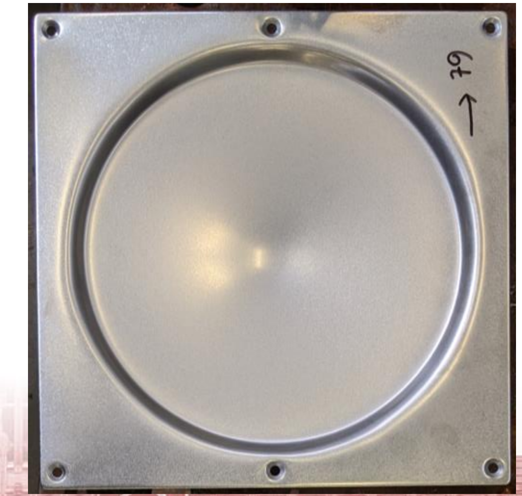
Rolling Pendulum (RP) bearing (cont.)

Individual RP bearing

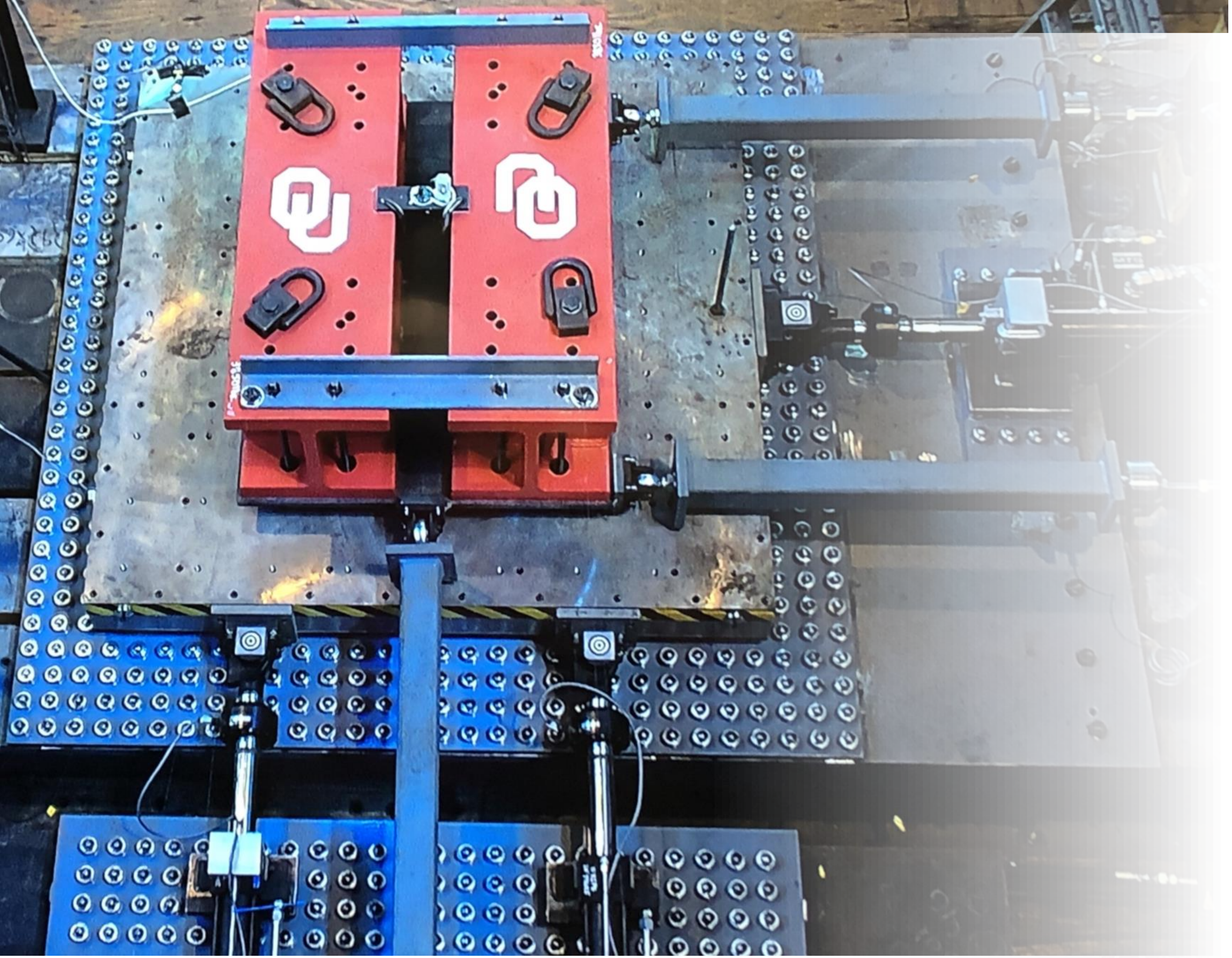




Coated (QuakeCoat™)



Uncoated

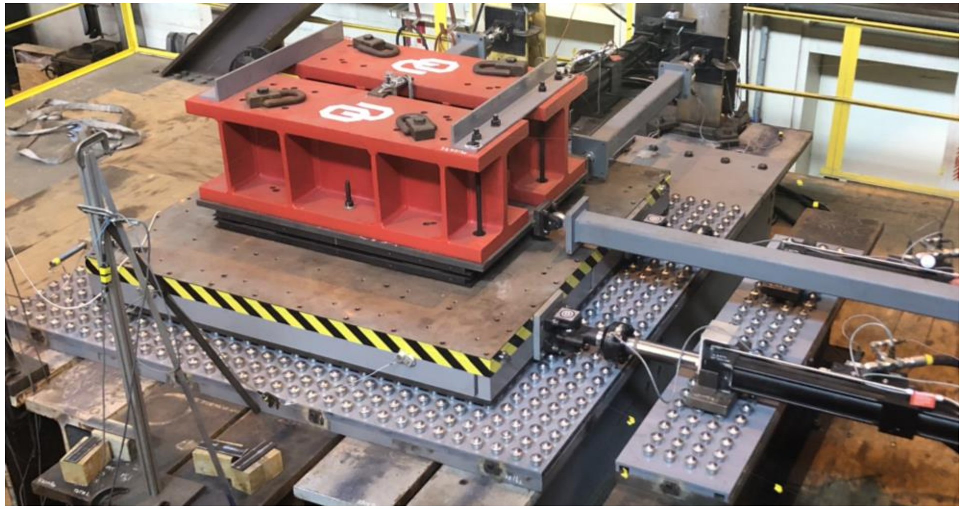


Test set-up

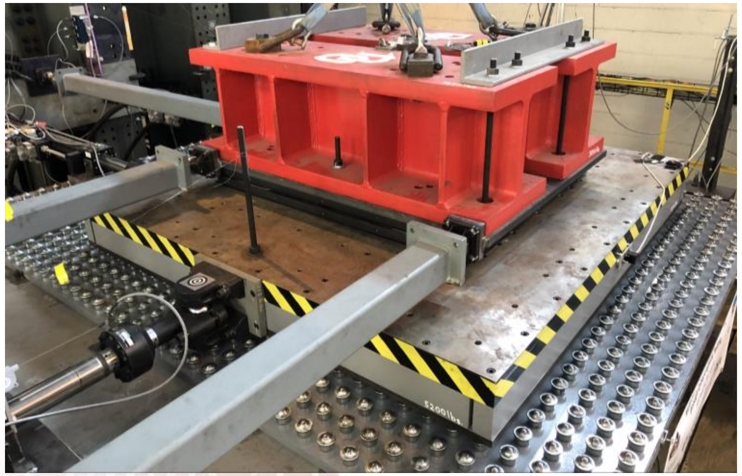
Test set-up

- Single full-scale OCTO-Base^{TM} isolation system (4 RP bearings) from WorkSafe^{TM} Technologies (coated and uncoated)

- Shake table NHERI Lehigh EF is mounted on top of a roller bearing bed and free to move and rotate in the plane (X, Y, θ) by means of 3 actuators



South-West top general view



North-East view

Test set-up

- Bottom component of the isolation system is attached to the shake table
- Attached atop: assembly composed of I-beams and a transfer plate, which represents the tributary weight of 17.9 kN (3,850 lb)

Top isolation system + Tributary weight

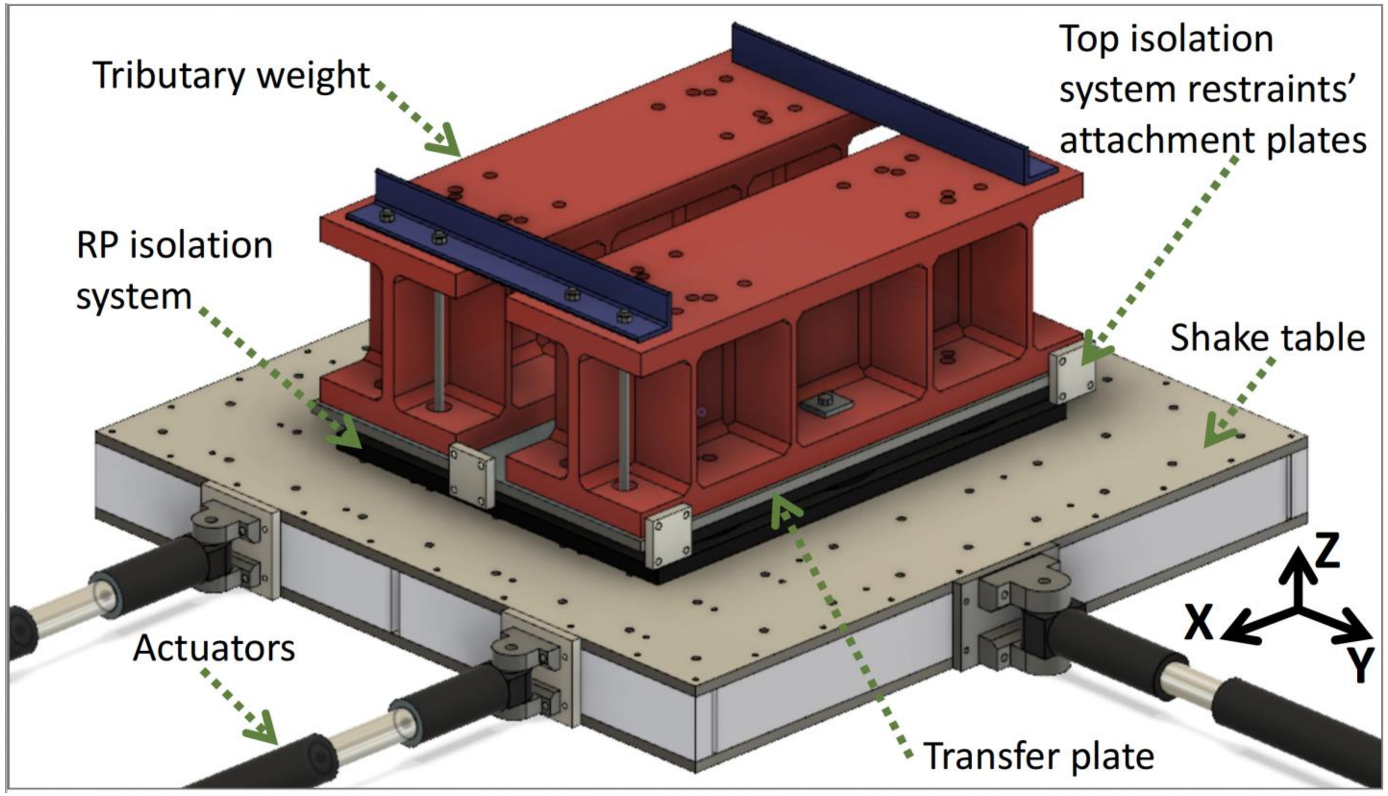
Top isolation system restraints

Bottom isolation system

North view
(handling top components)

Test set-up (cont.)

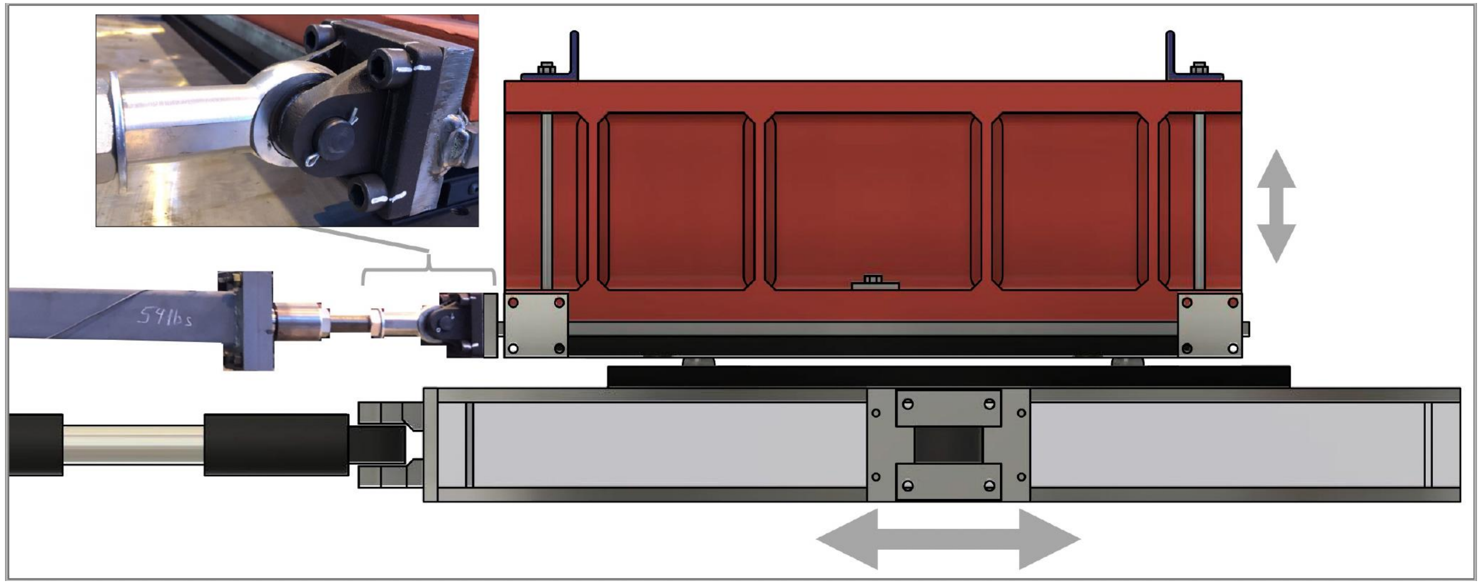
- Top component is restricted from any horizontal movement or rotation by means of 3 restraints attached to the transfer plate



South-East schematic view

Test set-up (cont.)

- Restraints pinned at both ends
- Uniaxial load cells located at the restraints to obtain directly the experimental restoring force

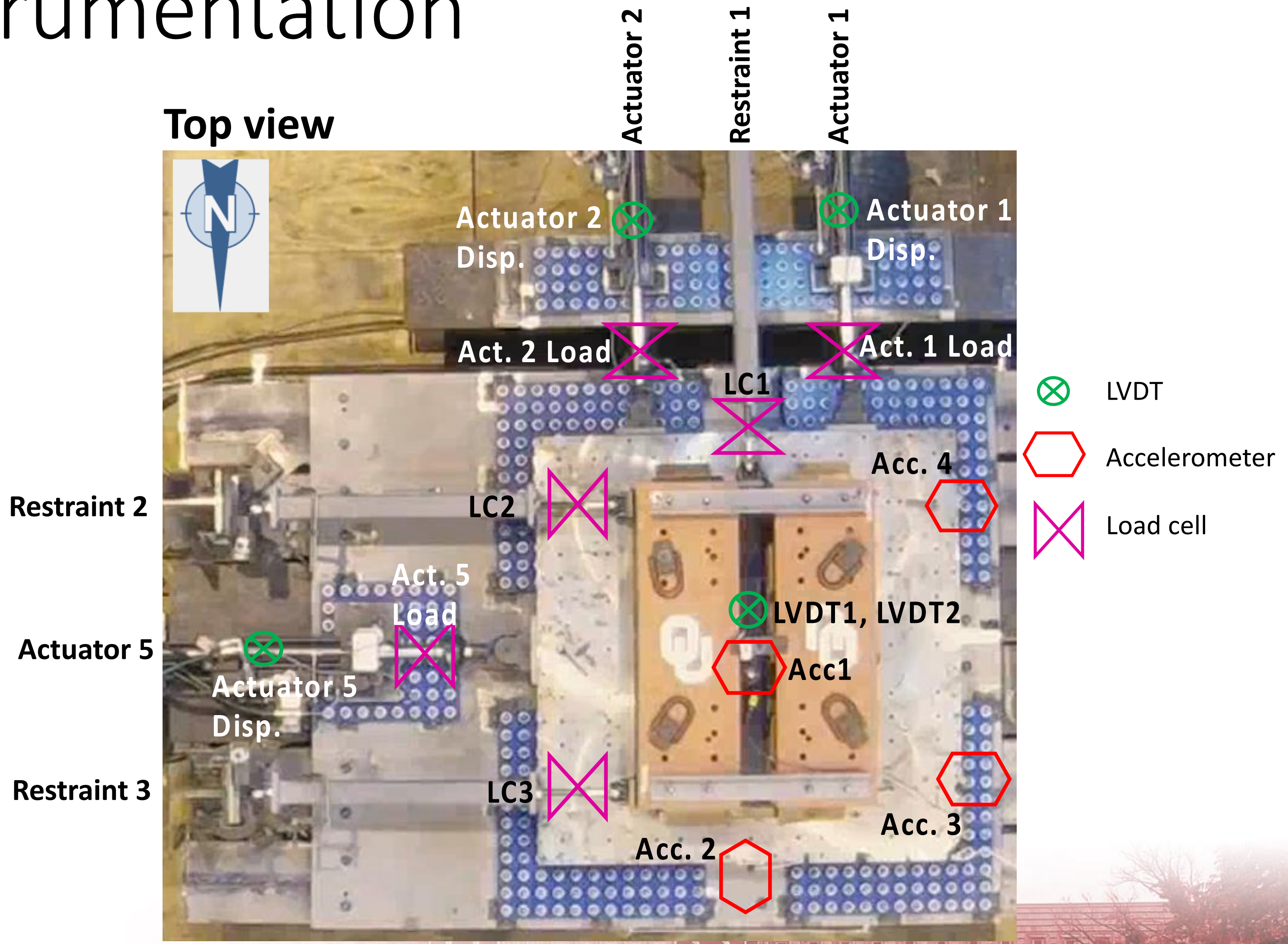


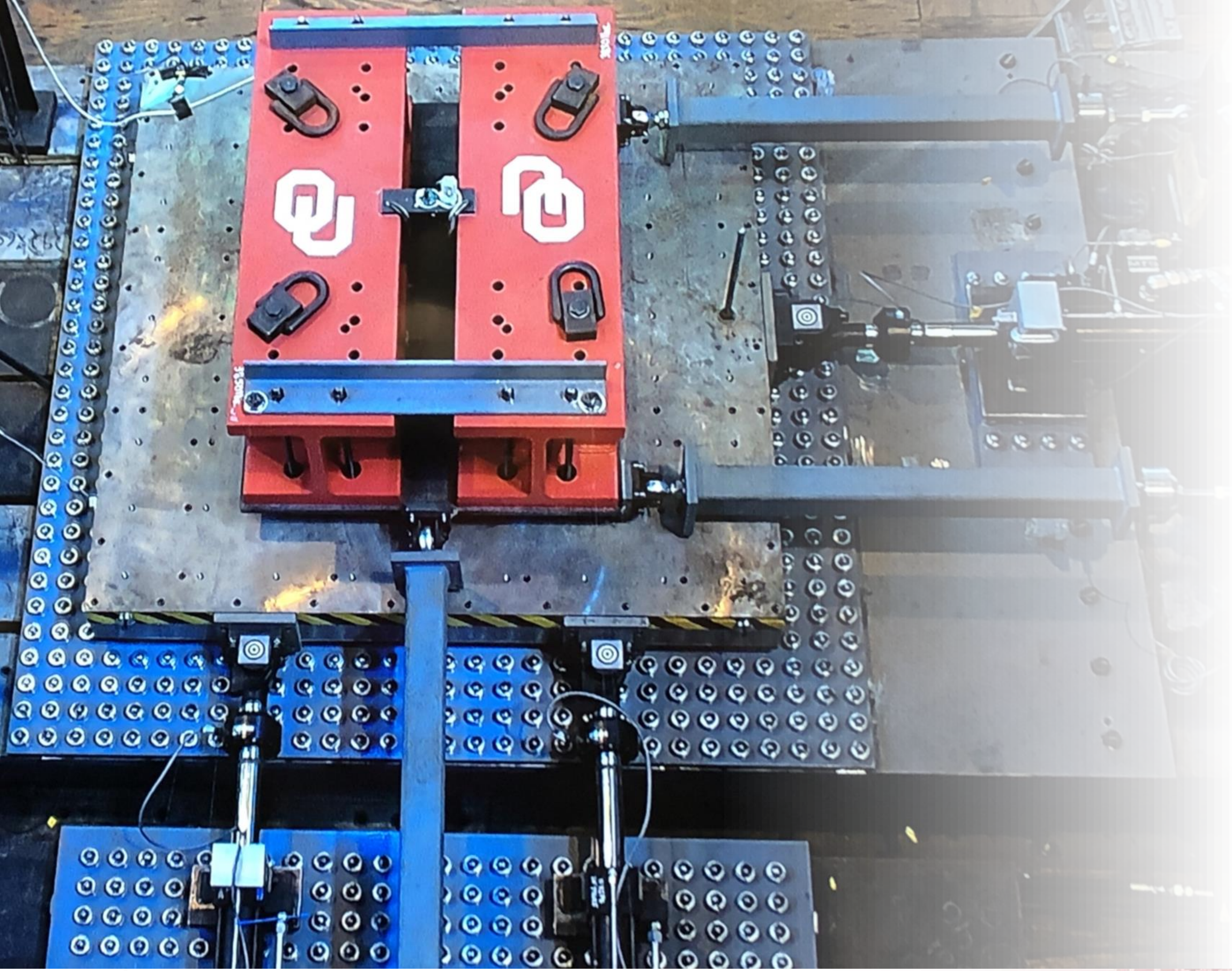
East schematic view of restraints

Test set-up: Instrumentation

- Load cells on each actuator and restraint
- Accelerometers on shake table
- LVDTs to measure the horizontal position of the shake table
- Accelerometer and LVDTs to measure the vertical motion on top of the isolation system

Top view

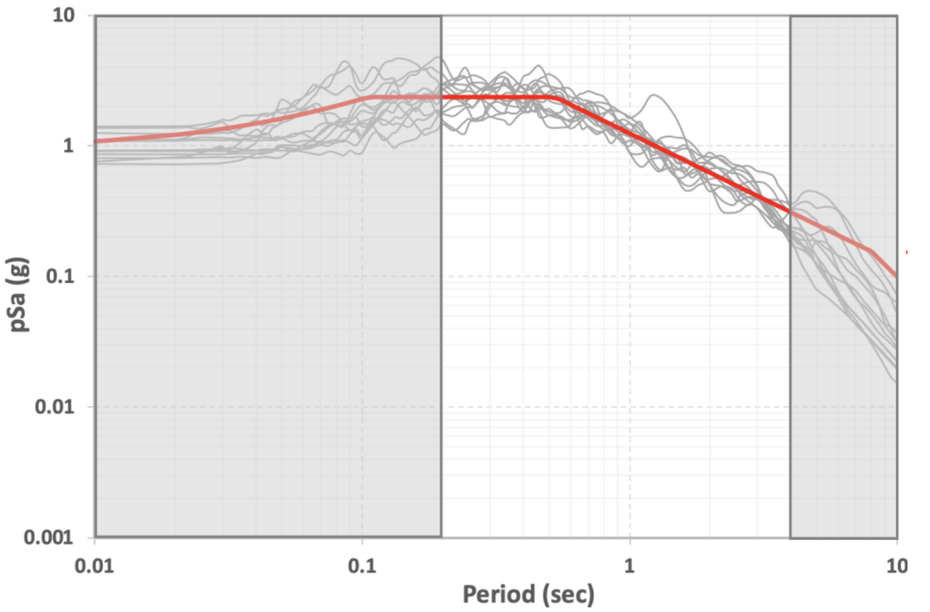




Real-time hybrid simulation

Set of earthquake records

- ASCE 7-22 Section 16.2 approach for nonlinear response history analysis:
  - Target, 5%-damped, MCE_R response spectrum was defined for the Los Angeles financial district[5]
  - Deaggregation analysis of the location showed that even though far-field controls FOE hazard, DBE and MCE are controlled by the near-fault events[6]
  - Use of the NGA-West2 database and online tool for amplitude scaling[7]



MCE_R target response spectrum (near-field without pulse)

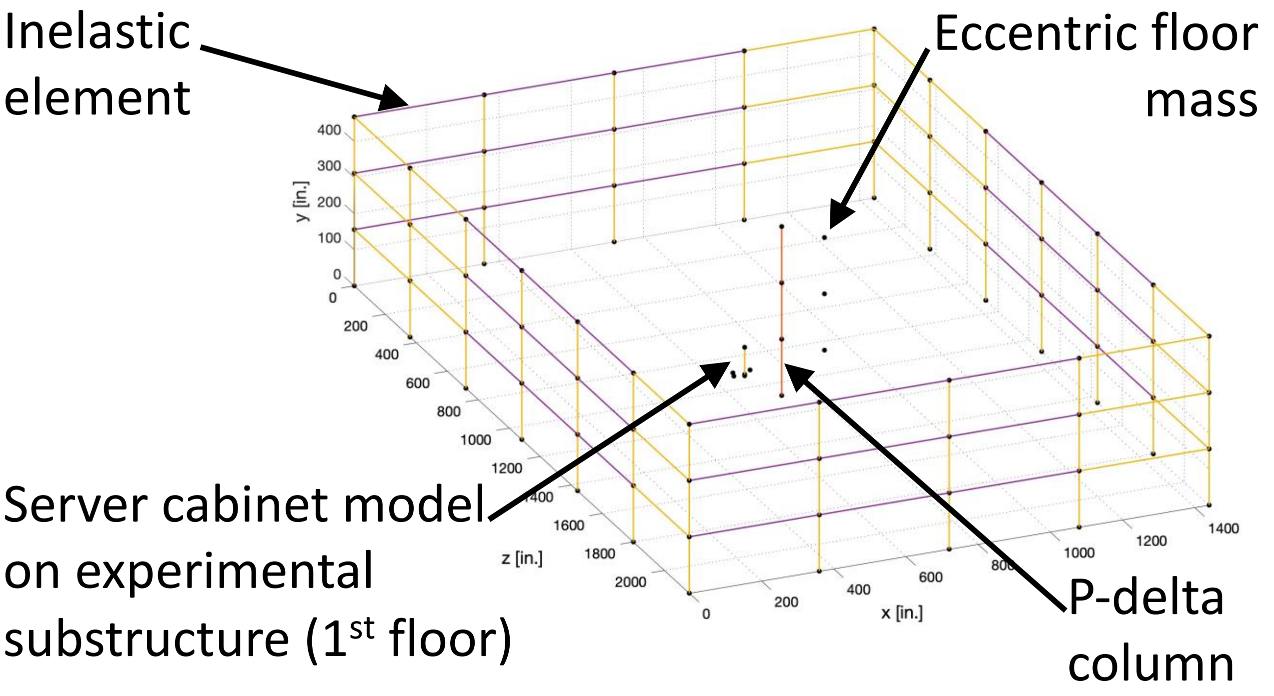
[5]ASCE, ASCE 7 Hazard Tool, Online, URL https://asce7hazardtool.online/, 2022.

[6]USGS, Unified Hazard Tool, Online, URL https://earthquake.usgs.gov/hazards/interactive/, 2022.

[7]PEER, NGA-West2–Shallow Crustal Earthquakes in Active Tectonic Regimes, Online, URL https://peer.berkeley.edu/research/nga-west-2, 2021.

Analytical substructure: SMRF model

- Steel 3-story (LA3) special moment resisting frame (SMRF)[8]
- Inelastic force-based fiber beam-column elements for SMRF's girders
- Elastic elements for remaining structural components
- Modeled in 3D, including P-Δ effects, using HyCOM-3D[9]



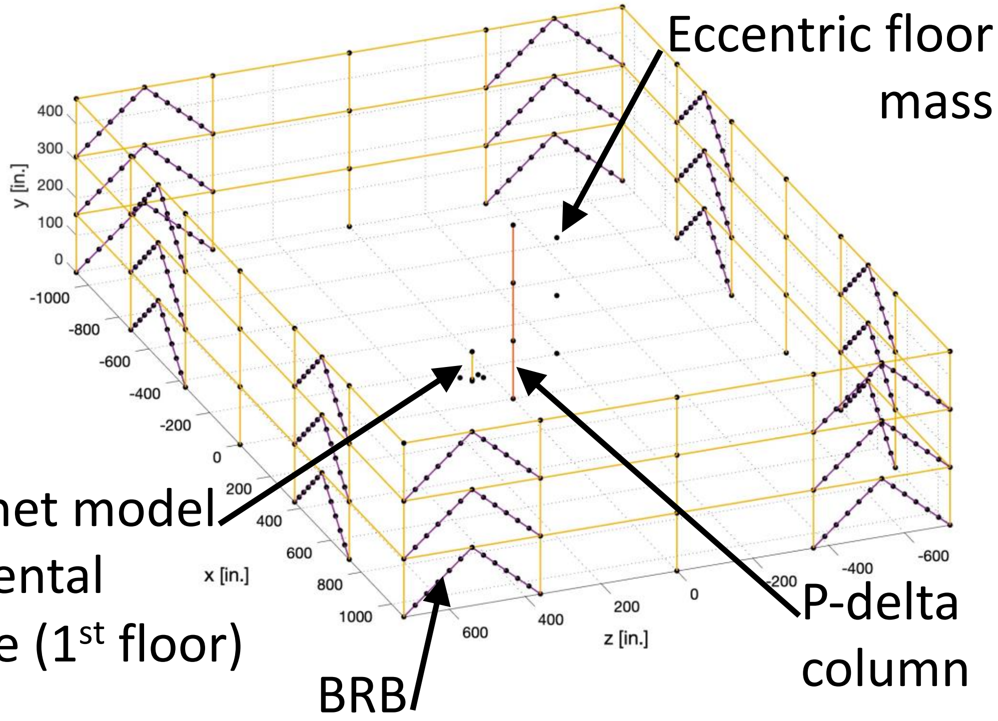
LA3 SMRF model

[8]SAC Joint Venture (2000), *State of the Art Report on Systems Performance of Steel Moment Frames Subject to Earthquake Ground Shaking*, Tech. Rep. FEMA-355C, Washington, DC.

[9]Ricles, J., Kolay, C., Marullo, T. M. (2021), *HyCoM-3D: A Program for 3D Nonlinear Dynamic Analysis and Real-Time Hybrid Simulation of 3-D Civil Infrastructure Systems*, Tech. Rep., Hybrid Computational Modeling (HyCoM) Program–3D Version 3.8 User's Manual, Lehigh University.

Analytical substructure: BRBF model

- Steel 3-story (3vb) buckling-restrained brace frame (BRBF)[10]
- 3D inelastic truss elements for the BRBs[7]
- Elastic elements for remaining structural components
- Modeled in 3D, including P-Δ effects, using HyCOM-3D[11]



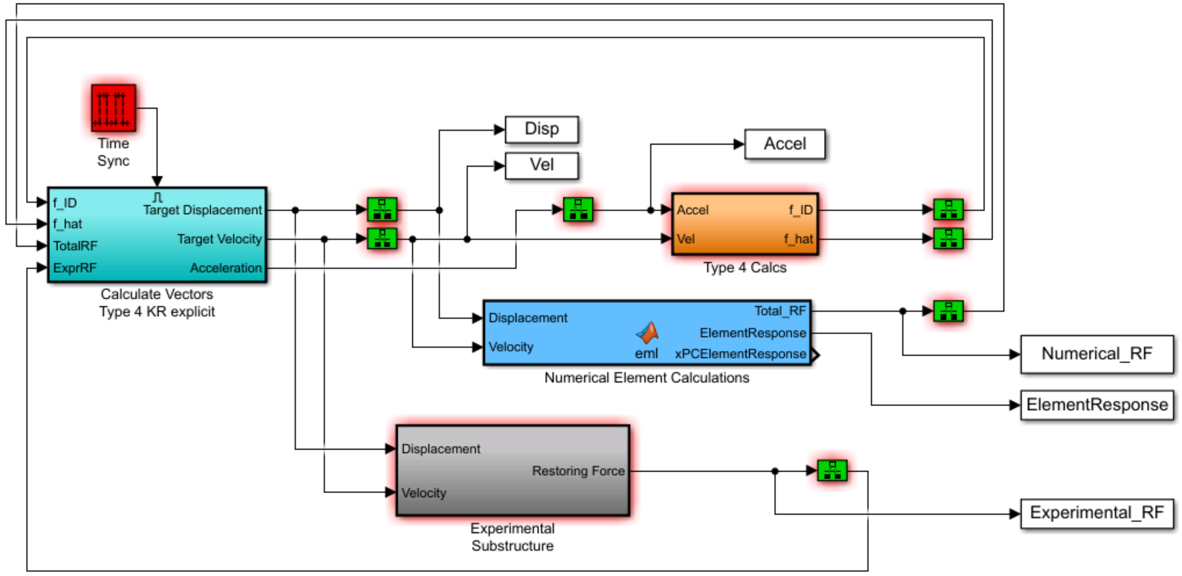
3vb BRBF model

[10]Sabelli, R. (2001), *Research on Improving the Design and Analysis of Earthquake Resistant Steel Braced Frames*, Tech. Rep. PF2000-9, Earthquake Engineering Research Institute, Oakland, CA.

[11]Kersting, R. et.al. (2015), *Seismic Design of Steel Buckling-Restrained Braced Frames: A guide for practicing engineers*, NEHRP Seismic Design Technical Brief No. 11, NIST GCR 15-917-34.

RTHS implementation

- MATLAB/Simulink[12] simulation coordinator interface
- Analytical substructure component modeled in customized RTHS software HyCOM-3D[5], using explicit-formulated computational elements[13]
- MKR-α used as the integration algorithm (model-based, second-order accuracy, explicit unconditionally stable)[14, 15]



Simulation coordinator of synchronized control & data acquisition in MATLAB/Simulink[8]

[12]MATLAB and Optimization Toolbox Release R2022a, The MathWorks, Inc., Natick, Massachusetts, United States

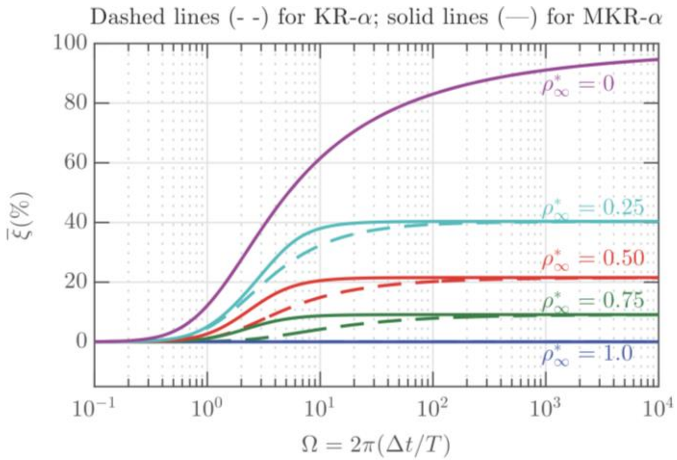
[13]Kolay, C. & Ricles, J.M. (2018), *Journal of Structural Engineering*. doi: 10.1061/(ASCE)ST.1943-541X.0001944.

[14]Kolay, C. & Ricles, J.M. (2014), *Earthquake Engng Struct Dyn*. doi: 10.1002/eqe.2401.

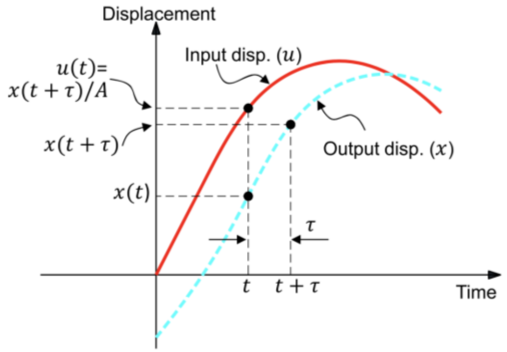
[15]Kolay, C. & Ricles, J.M. (2017), *Journal of Earthquake Engineering*. doi: 10.1080/13632469.2017.1326423.

RTHS implementation (cont.)

- To control numerical dissipation and overshoot, dissipative integration algorithm $\rho^*_\infty = 0.5$ [14, 15]
- The integration time step was established at 2/1024 s with 2-step interpolations
- Adaptive time series (ATS) compensator essential to actuator control[16]



Variation of equivalent damping ratio with $\boldsymbol{\Omega}$ for various values of ρ^*_∞[11]

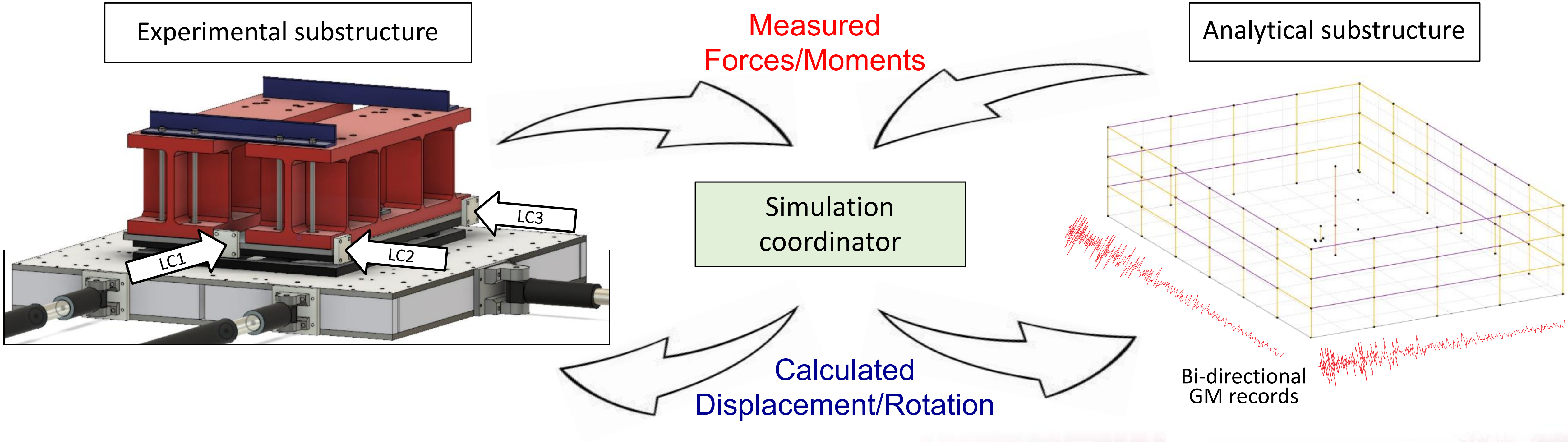


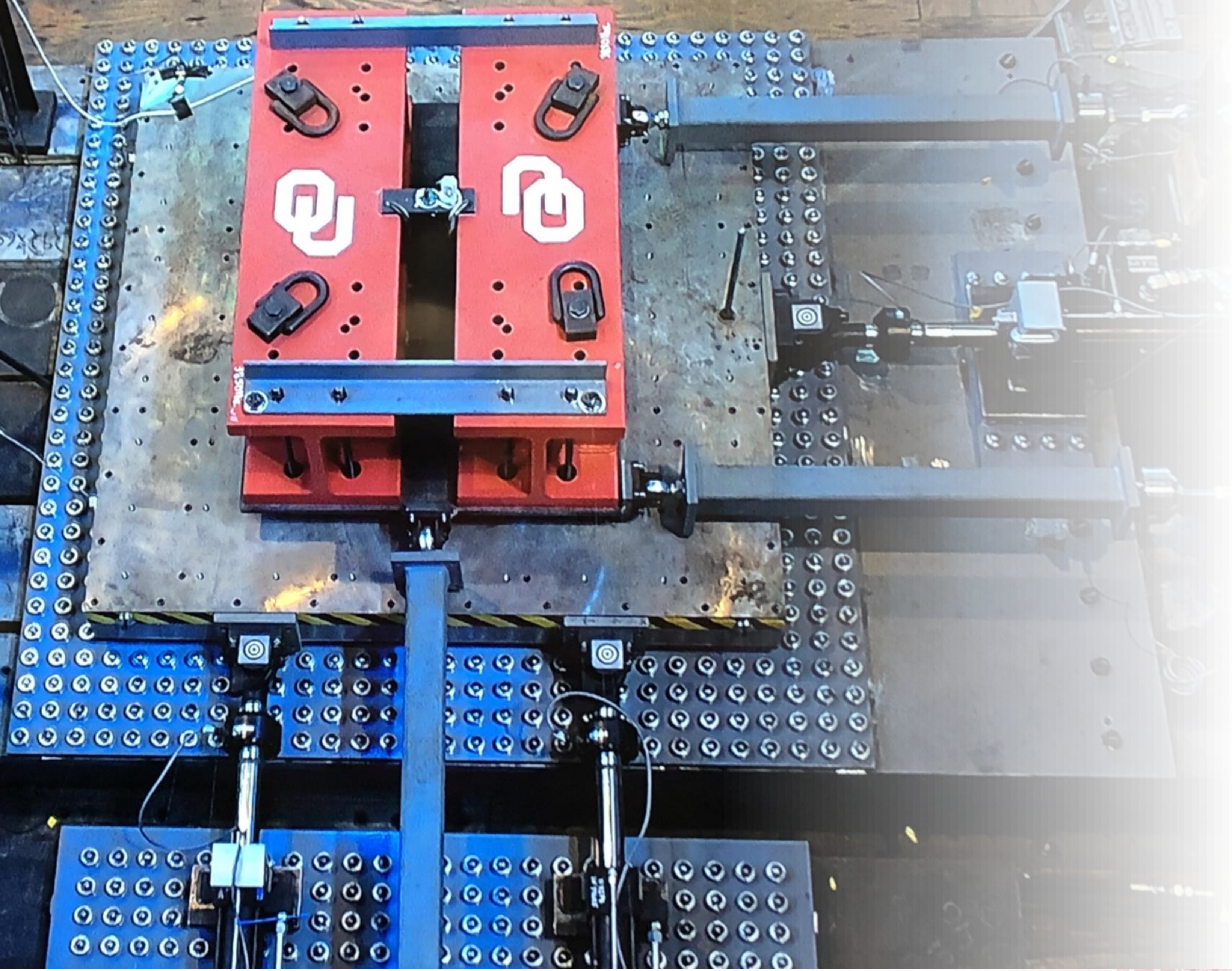
Input & output disp. servo-hyd. system with experimental substructure relationship[12]

[16]Chae, Y., Kazemibidokhti, K., & Ricles, J.M. (2013), *Earthquake Engng Struct Dyn.* doi: 10.1002/eqe.2294.

RTHS implementation (cont.)

- Restraints are equipped with uniaxial load cells to obtain directly and in real-time the experimental restoring forces



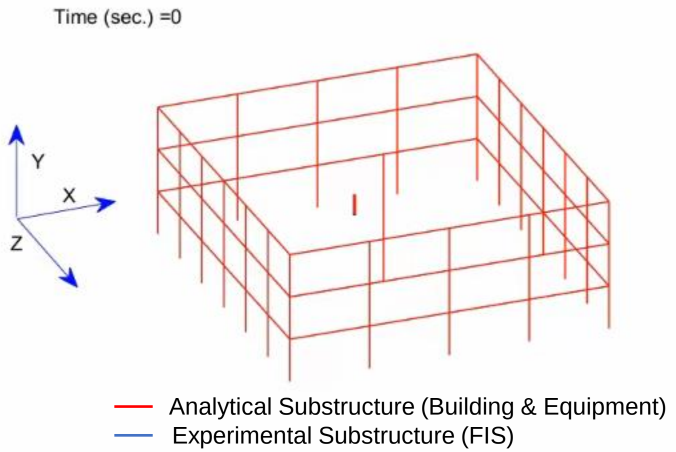


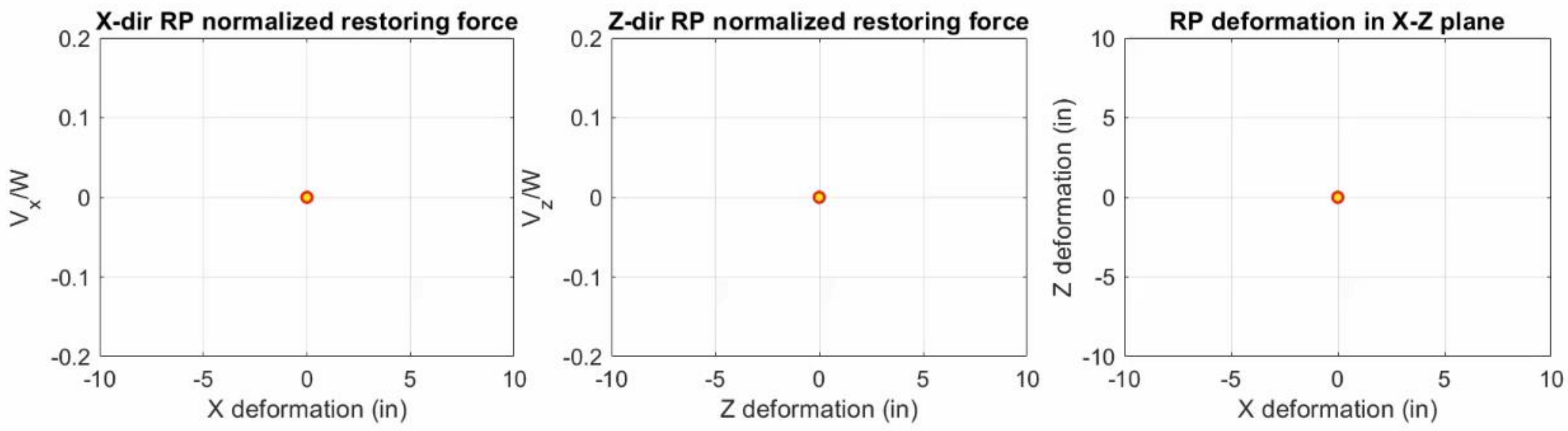
Selected results

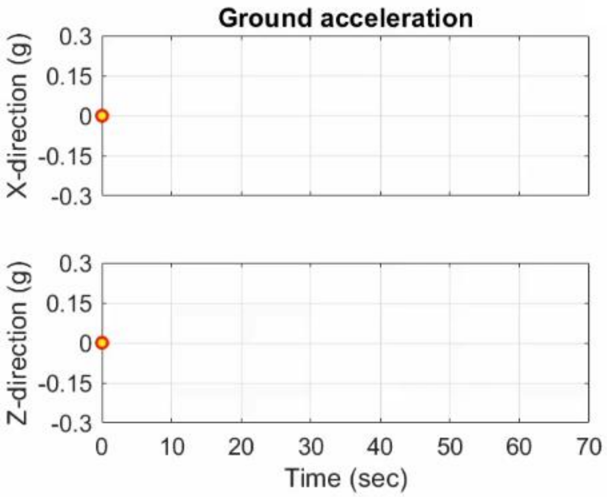
3-D Real-time Hybrid Simulation

SMRF with RP Isolation System (FIS) @ 2nd Floor, Coalinga EQ Scaled to SLE

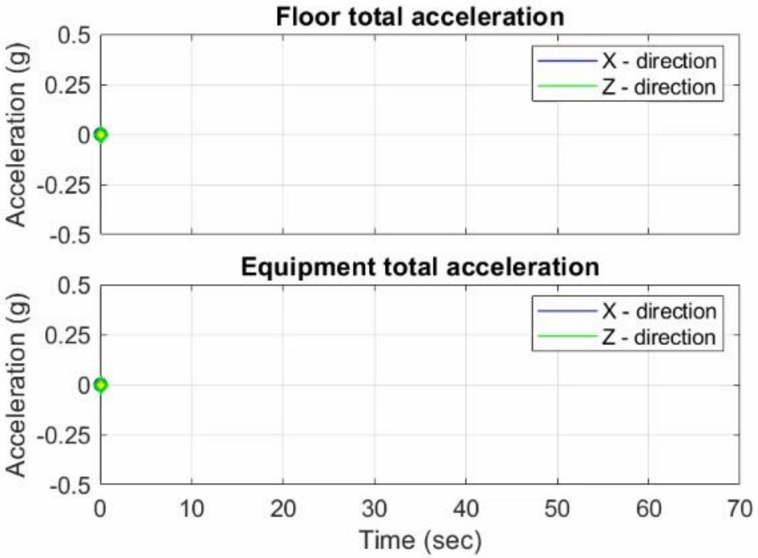
Analytical Substructure, Scale factor = 25

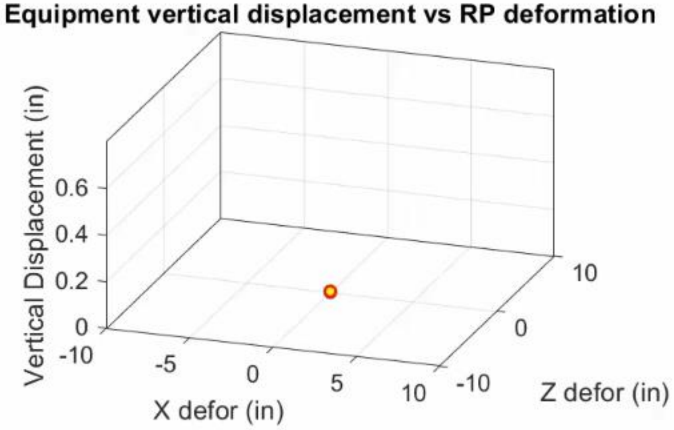






FIS - Experimental Substructure





X-direction = 270 component, Z-direction = 360 component

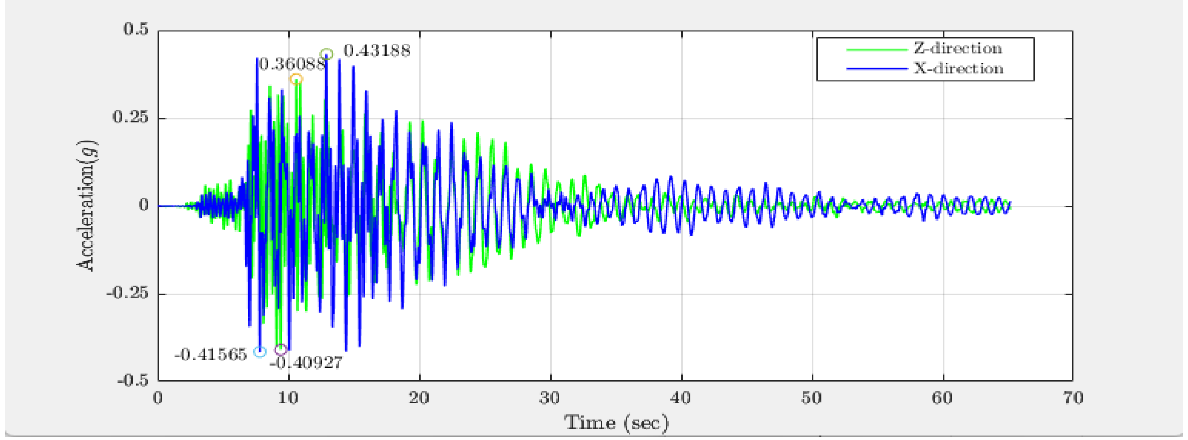
3-D Real-time Hybrid Simulation of a 3-Story SMRF with 2nd Floor Rolling Pendulum Equipment Isolation System:
1983 Coalinga EQ Bidirectional Ground Motions Recorded at Cantua Creek School and Scaled to SLE Hazard Level.

Equipment Acceleration

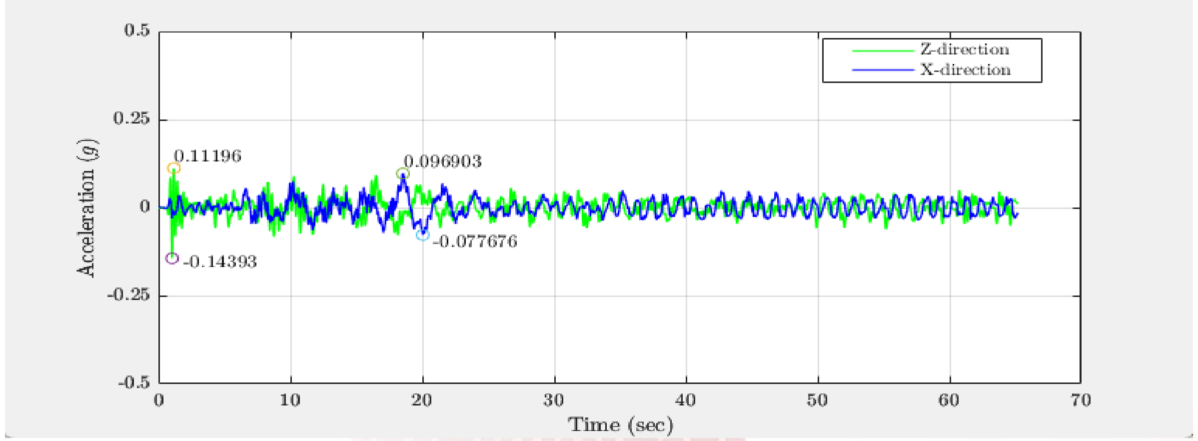
SMRF with RP Isolation System @ 2nd Floor

Reduction in Equipment Total Acceleration	
X-Direction	Z-Direction
81.3%	68.9%

SMRF 2nd Floor Total Acceleration



Equipment Total Acceleration



Acknowledgements

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The opinions expressed herein are those of the authors and do not necessarily reflect the views of the sponsors