Hybrid Simulations: Theory and Applications in Earthquake Engineering

Khalid M. Mosalam, Professor
Director of *nees@berkeley*

Structural Engineering, Mechanics, and Materials
Department of Civil and Environmental Engineering
University of California, Berkeley

Acknowledgements

Dr. Selim Günay, UCB
Dr. Shakhzod Takhirov, UCB
Mr. Mohamed Moustafa, UCB
Mr. Ahmed Bakhaty, UCB
Mr. Eric Fujisaki, PG&E

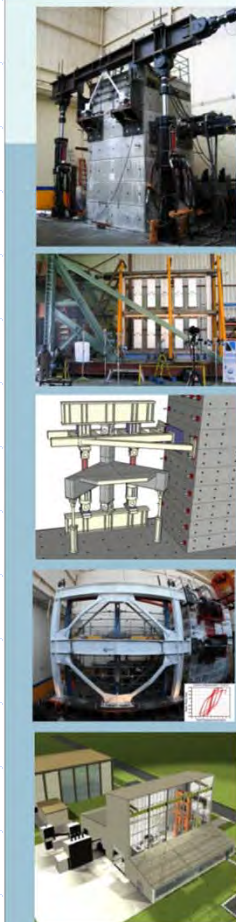
Sponsors:

- California Institute for Energy and Environment (CIEE)
- US-DoE
- PG&E
- National Science Foundation (NSF) [**PEER**; **NEES**]

Introduction

15 sites

http://nees.org



nees@berkeley

The George E. Brown, Jr. Network for Earthquake Engineering Simulation

Hybrid Simulation Workshop

with Emphasis on Real-Time Loading

June 28 and 29, 2012

UC Berkeley, Richmond Field Station

nees@berkeley Equipment Site

Workshop URL: http://nees.berkeley.edu/workshop/

10th

Hybrid simulation is a set of methods for examining the seismic response of structures using a hybrid model comprised of both physical and numerical sub-structures. This year's workshop emphasizes real-time loading, including demonstrations of our new "smart" dynamic platform. The workshop is aimed for NEES researchers, both current and future. Attendees will:

- Learn the basics of hybrid simulation methods.
- Learn about OpenSees and OpenFresco.
- Conduct a real-time hybrid simulation demonstrations at the *nees@berkeley* Lab.
- Be able to use hybrid simulation in their NEES and non-NEES projects.
- Prepare to develop new hybrid simulation tests and algorithms.
- Learn about modern non-conventional monitoring and measuring techniques (accuracy, limits, ease of use, field application in damage assessment): Krypton position monitoring system, high-definition laser scanners, and image correlation techniques.

We will review the basics of hybrid simulation, including similitude requirements for model design, model implementation including integration methods, and simulation result interpretation. Then, we will demonstrate how hybrid simulation is implemented at *nees@berkeley* using our hardware and OpenSees and OpenFresco software. The attendees will have a unique opportunity to develop a hybrid model and, with the help of our staff, implement and run a hybrid simulation at *nees@berkeley*. Throughout the workshop we will demonstrate how to use the *nees@berkeley* Equipment Site hardware and software portfolio and how to process and archive hybrid simulation data.

Application Procedure

Please apply at http://nees.berkeley.edu/workshop/ by June 15, 2012. This workshop session is offered at not cost. Limited travel support is available for graduate students, young post-doctoral researchers and tenure-track faculty at US schools.

Logistics

The workshop will be held at the *nees@berkeley* Equipment Site located at the UC Berkeley Richmond Field Station (http://nees.berkeley.edu). See the workshop webpages for more information.

nees@berkeley **URL:** http://nees.berkeley.edu

Workshop URL: http://nees.berkeley.edu/workshop/

Technical
Khalid Mosalam
mosalam@ce.berkeley.edu
510-643-4805

Administration
Veronica Rodriquez
vrodriquez@berkeley.edu
510-665-3594

http://nees.berkeley.edu

All our presentation from Oct. 1-4, 2012 will be made available in this site

http://nees.berkeley.edu

Introduction

NEES@Berkeley

Large-scale Structural Engineering Lab with Reconfigurable Reaction Wall & Hybrid Simulation Capability

The NEES equipment site at the University of California Berkeley (nees@berkeley) specializes in earthquake response simulation using both next-generation, dynamic hybrid simulation and conventional testing capabilities to examine the behavior of large-scale structural systems under earthquake excitation through real-time integration of computer models and physical testing of sub-structures.

The facility supports NEES researchers by providing training for conventional and hybrid testing, simulation and the development of test algorithms. The facility also assists researchers with the design of test setups, pre-test modeling and model simulation. The facility provides telepresence and real time data viewing for the users and collaborators. The experimental site also provides connection to the NEES cyber infrastructure.

A variety of outreach efforts take place at the nees@berkeley site. The largest activity is the K-12 outreach program that teaches local school students about earthquake engineering then sponsors an exploratory field trip to the laboratory.

nees@berkeley
The George E. Brown, Jr. Network for Earthquake Engineering Simulation

Laboratory Features

- Servo controller and computer hardware capable to control up to 8 actuators simultaneously in hybrid modeling or conventional testing
- Servo controller and computer hardware capable to control up to 4 actuators simultaneously in hybrid modeling or conventional testing
- Strong floor
- Reconfigurable reaction walls
- 4 million pound capacity compression-tension test machine
- 4 high performance hydraulic actuators
- 3 static hydraulic actuators
- 192-channel digital data acquisition system
- REPEAT reconfigurable testing frame
- Laser scanners for surface monitoring controlled from a data acquisition system
- Many transducers to monitor load, position, velocity, acceleration, inclinations of specimens during a test
- Video cameras and high resolution still imaging cameras controlled from a data acquisition system

NEES
This site is supported by the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation Under Award Number CMS-0927178.

nees@berkeley Laboratory, UC Berkeley
Richmond Field Station
1301 South 46th Street, Building 484
Richmond, CA 94804
http://nees.berkeley.edu/
Tel: 510 - 665 - 3594
Fax: 510 - 665 - 3544

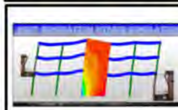
nehrp NSF

NEES@Berkeley in FY12

Performance-Based Design of Squat Reinforced Concrete Shear Walls
PIs: Andrew Whittaker (University at Buffalo), Bozidar Stojadinovic (UC Berkeley), Laura Lowes (University of Washington), Abraham Lynn (California Polytechnic State University)
Sponsor: National Science Foundation (NEESR)
Abstract: Squat structural walls with aspect ratio (wall height/wall length) of approximately 0.5 are often the primary seismic lateral-force-resisting components in nuclear and industrial facilities. This combination of a thick and squat wall results in a high wall stiffness. The goals of this project are to develop hybrid testing methods suited to this problem of a very stiff specimen (large-scale squat wall) and to better understand their earthquake response behavior.

Pathways Project: Experimental Determination of Performance of Drift-Sensitive Nonstructural Systems under Seismic Loading
PI: Kurt McMullin (San Jose State University)
Sponsor: National Science Foundation (NEESR)
Abstract: The project explores seismic damage to three different nonstructural systems: precast concrete cladding, inset windows, and vertical plumbing risers. A series of six full-scale experiments are conducted. The primary experimental test objectives include defining component and system force-deformation relationships, quantifying damage events with applied drift, evaluation of a robotic plumbing inspection system, and qualitative understanding of the behavior of façade systems.

TIPS: Tools to Facilitate Widespread Use of Isolation and Protective Systems
PIs: Stephen Mahin (UC Berkeley), Keri Ryan (University of Nevada, Reno)
Sponsor: National Science Foundation (NEESR)
Abstract: The R-values of seismically isolated buildings may lead to yielding under the DBE, and will certainly result in yielding during the MCE. Using the NEES Reconfigurable Platform for Earthquake Testing (REPEAT) frame, the project investigates multiple superstructure configurations to determine, in the event of superstructure yielding, what is the best design approach to achieve acceptable post-yield performance. The experimental setup consists of a 1/3-scale two-story, two-bay by one-bay frame supported on six triple friction pendulum bearings.



Next Generation Hybrid Simulation - Evaluation and Theory
PIs: Khalid M. Mosalam (UC Berkeley), Sanjay Govindjee (UC Berkeley)
Sponsor: National Science Foundation (EAGER)
Abstract: This exploratory project brings together the two fields of hybrid testing and computational mechanics, in a synergistic fashion, aiming at the interdisciplinary advancement of the field. This work represents a major conceptual shift from the present hybrid simulation techniques and will establish a thorough basis for hybrid simulations rooted on sound experimentation coupled with theoretical and applied multi-scale mechanics.

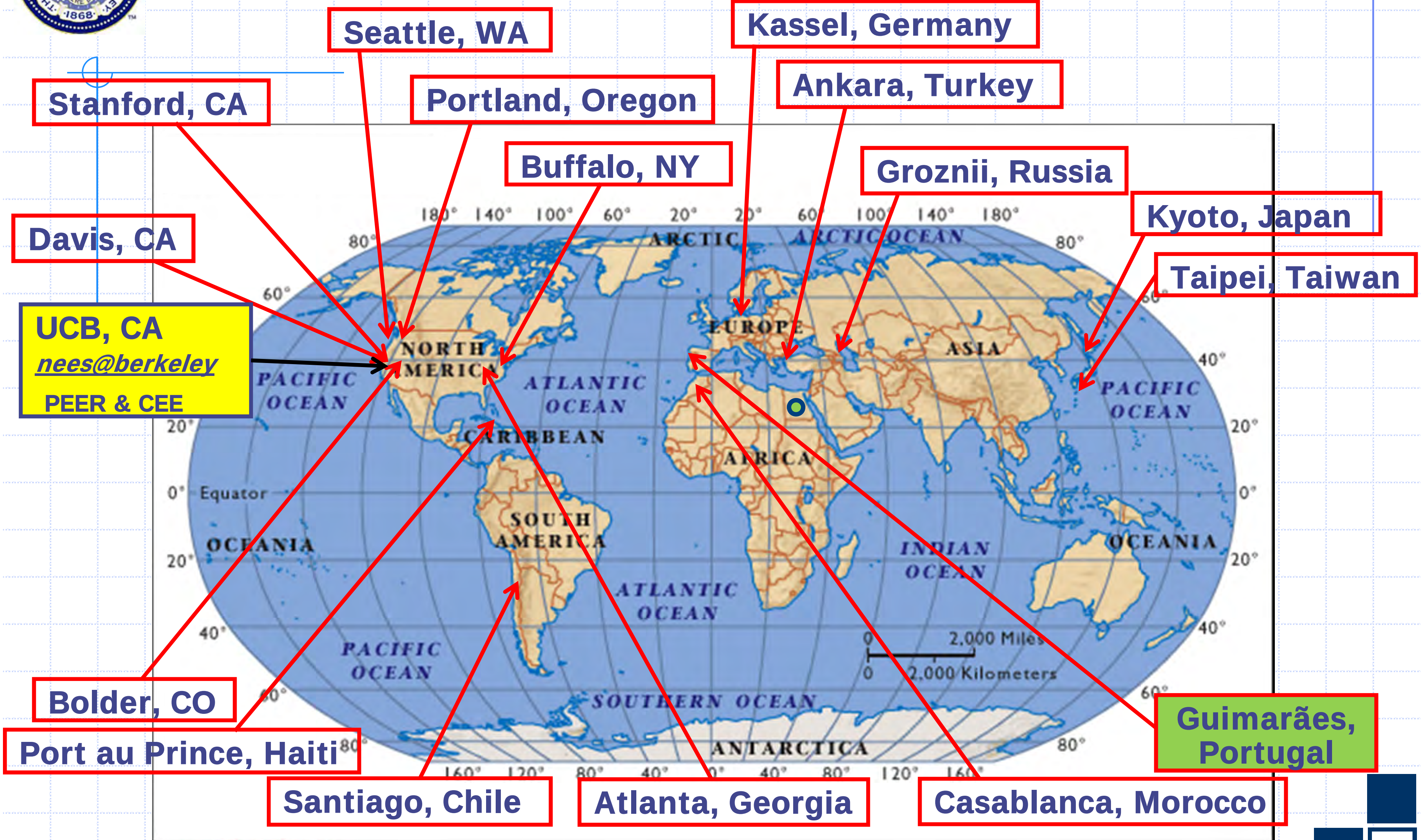
Toward Rapid Return to Occupancy in Unbraced Steel Frames
PIs: Peter Dusicka (Portland State Univ.), Jeffrey Berman (Univ. of Washington), Rupa Purasinghe (Cal State LA)
Sponsor: National Science Foundation (NEESR)
Abstract: The project focuses on validating the system response of the linked column frame system, developed as a braced free structural steel lateral system capable of returning rapidly to functionality via replacement of key components. Hybrid tests will be conducted on 2 different frames, each with different structural characteristics as governed by the replaceable components and the contributions of the remainder of the system.

Seismic Performance of Column Splices
PI: Amit Kanvinde (UC Davis)
Sponsor: Shared
Abstract: Research suggested that partial joint penetration (PJP) welds in column splices in pre-Northridge design were prone to brittle failure. Since the Northridge quakes, weld quality has improved measurably and the objective of the project is to determine the feasibility of using PJP welds in modern steel SMRF's.

Hybrid Simulation of Multi Story Structural Systems through Collapse
PI: Eduardo Miranda (Stanford University)
Sponsor: National Science Foundation (NEESR)
Abstract: Estimation and mitigation of the collapse risk of a structure is one of the main goals of this research. In this project, a series of 1:2 scale beam-column specimens with Enhanced Gravity Connections will be tested using hybrid simulation through collapse. The tests will help further understanding and prediction of collapse and hybrid simulation methods, as well as evaluate the performance of the proposed gravity connections, whose aim is to significantly increase the capacity of a building to resist collapse.

NEES
This site is supported by the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation Under Award Number CMS-0927178.
nees@berkeley Laboratory, UC Berkeley
Richmond Field Station
1301 South 46th Street, Building 484
Richmond, CA 94804
http://nees.berkeley.edu/
Tel: 510 - 665 - 3594
Fax: 510 - 665 - 3544

Introduction

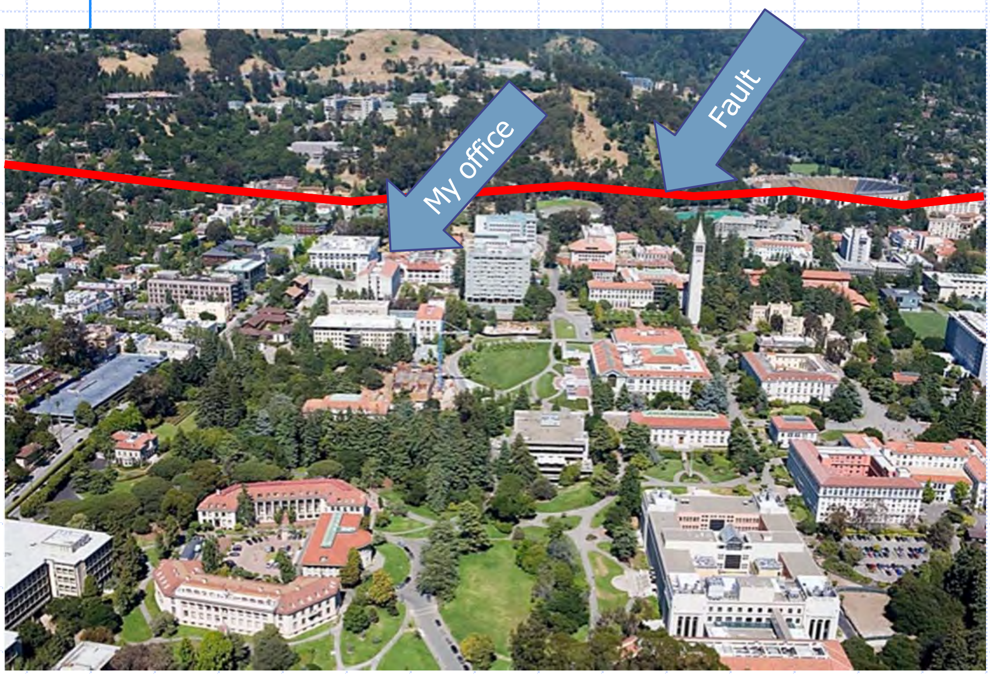


Mini-Symposium on Hybrid Simulation: Theory and Applications [Tomorrow]

1. Hybrid simulation fundamentals [**3.0 hours**]
   1. Substructuring
   2. Integration methods
   3. Simulation errors
2. Hybrid simulation applications [**2.5 hours**]
   1. Introduction to OpenSees
   2. Introduction to OpenFresco
   3. **Application I**: Hybrid simulation of structural insulated panels
   4. **Application II**: Real-time hybrid simulation of high voltage electric disconnect switches
3. Seismic testing of lifelines related to the electric grid [**1.5 hours**]
   1. Shaking table and static tests and finite element simulations of high voltage electric disconnect switches
   2. Fragility tests of concrete duct-banks for high voltage distribution lines
4. Use of advanced monitoring (**e.g. Laser scanning in Haiti**) and measurement systems in structural testing [**1.0 hour**]

We would like your ***feedback*** via the electronic form set especially for this workshop on the link below:
https://peercenter.wufoo.com/forms/hybrid-simulation-workshop-evaluation-portugal/

Short Course on Probabilistic Performance-based Earthquake Engineering (PBEE) [Oct. 3-4]



Courtesy of Prof. S. Mahin

Pacific Earthquake Engineering Research (PEER) Center Mission

- Advance and apply PBEE tools to meet the needs of various stakeholders
- Problem-focused, multi-disciplinary research built upon foundation of engineering and scientific fundamentals
- Close partnerships with government, industry and engineering professionals
- Strong national and global research collaborations
- Commitment to education at all levels

Short Course on Probabilistic Performance-based Earthquake Engineering (PBEE) [Oct. 3-4]

1. PBEE assessment methods [**2.0 hours**]
    1. Conditional probability approaches such as PEER and SAC/FEMA formulations
    2. Unconditional probabilistic approach
2. PBEE design methods [**2.0 hours**]
    1. Optimization-based methods
    2. Non-optimization-based methods
3. PEER PBEE formulation [**4.0 hours**]
    1. Hazard analysis
    2. Structural analysis
    3. Damage analysis
    4. Loss analysis
    5. Combination of analyses
4. **Application 1**: Evaluation of the effect of unreinforced masonry infill wall on reinforced concrete frames with probabilistic PBEE [**1.0 hour**]
5. **Application 2**: Evaluation of the seismic response of structural insulated panels with probabilistic PBEE [**1.0 hours**]
6. **Application 3**: PEER PBEE assessment of a shear-wall building located on the University of California, Berkeley campus [**1.0 hours**]
7. Future extension to multi-objective performance-based sustainable design [**0.5 hour**]
8. Recapitulation [**0.5 hour**]

Hybrid Simulations: Theory and Applications in Earthquake Engineering

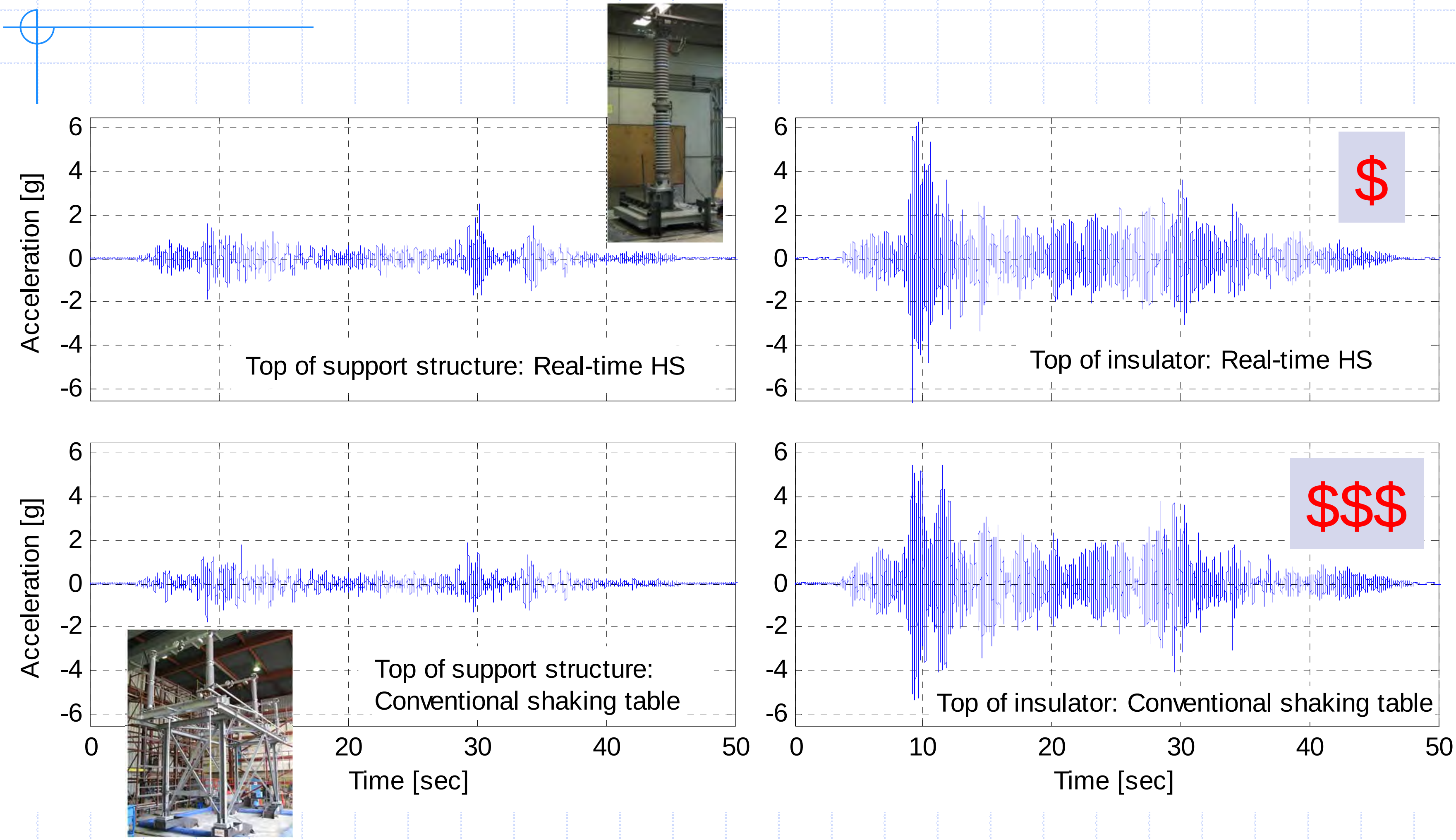
Khalid M. Mosalam, Professor
Director of *nees@berkeley*

Structural Engineering, Mechanics, and Materials
Department of Civil and Environmental Engineering
University of California, Berkeley

Outline

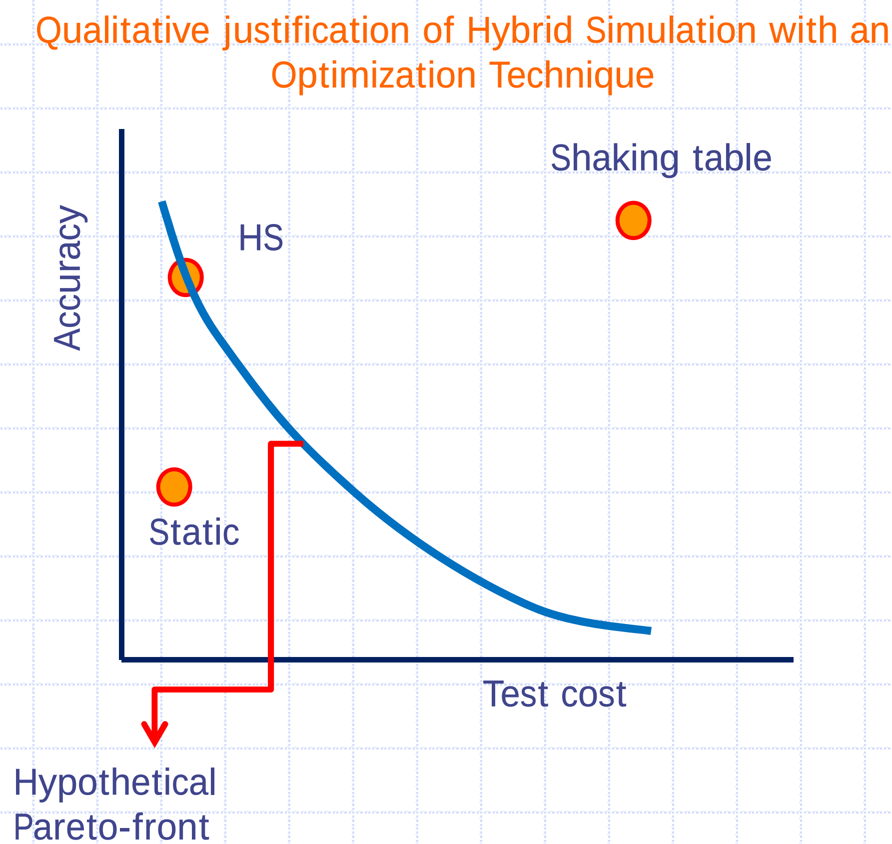
1. Motivation
2. Theory
   a) Background
   b) Substructuring
   c) Integration Methods
   d) Simulation Errors
   e) Geographically Distributed HS
   f) Real-time HS
3. Application I: HS of Structural Insulated Panels (SIPs)
4. Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table
5. Future Directions

Motivation



We will see this again today and in tomorrow's HS workshop!

Motivation



We will discuss this further during the PBEE course on 3-4 October!

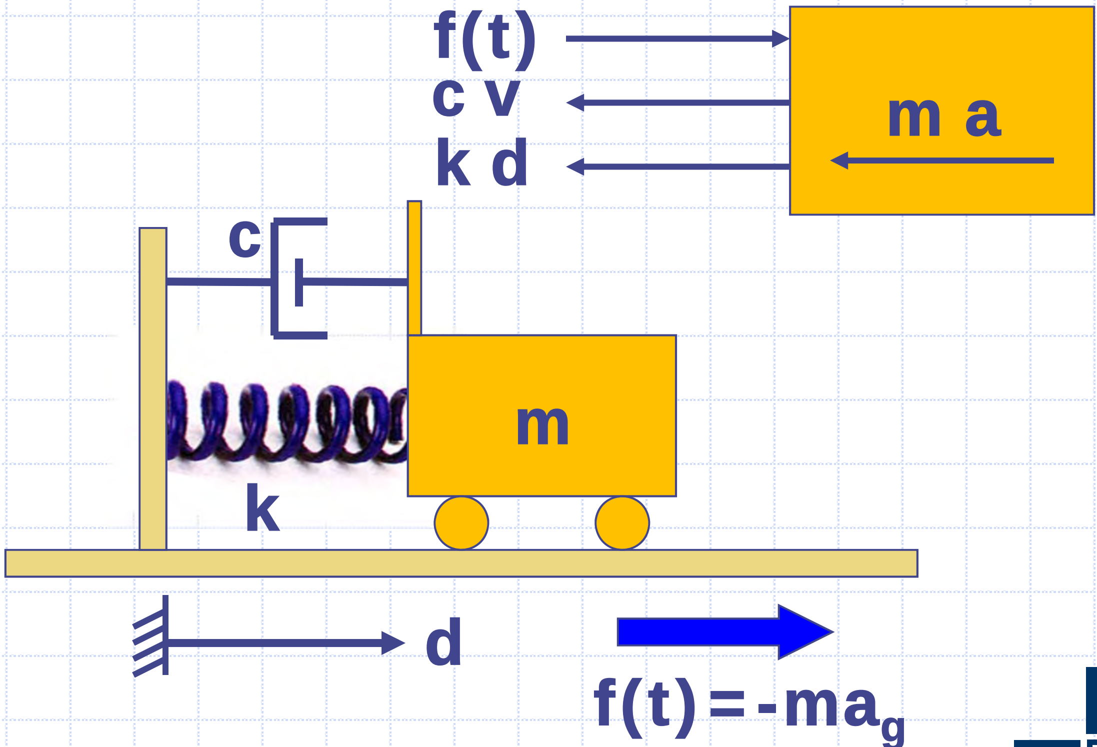
Theory: Background

- **Physical models** of structural resistance
- **Computer models** of structural damping and inertia

$m\,a + c\,v + k\,d = -m\,a_g$

$m\,a + c\,v + R = -m\,a_g$

$m\,a + m\,a_g + c\,v = -R$

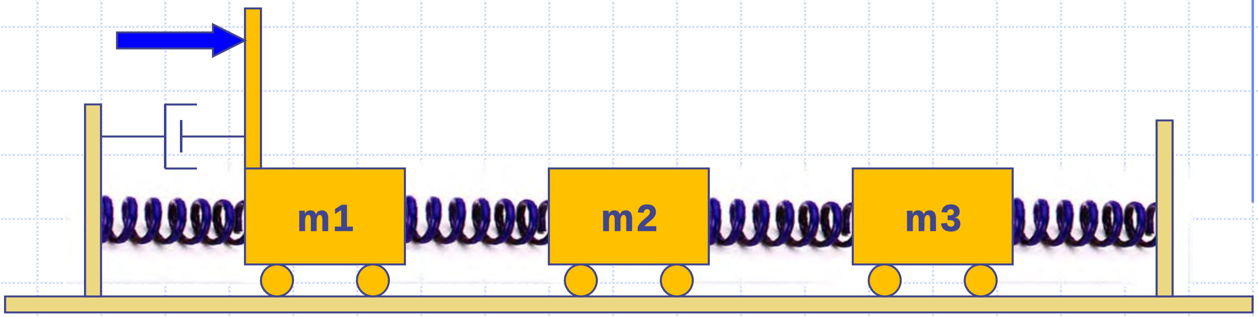


m: mass

k: spring constant

c: damping coefficient

Theory: Background

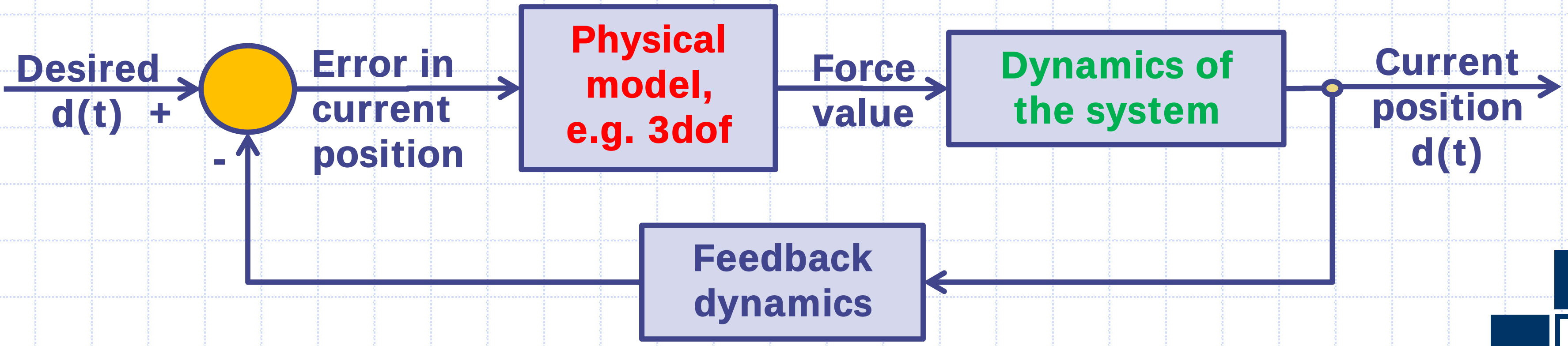


Need to assemble:

a) Restoring forces (Geometric stiffness may be considered, $\overline{R} = R - K_G d$)

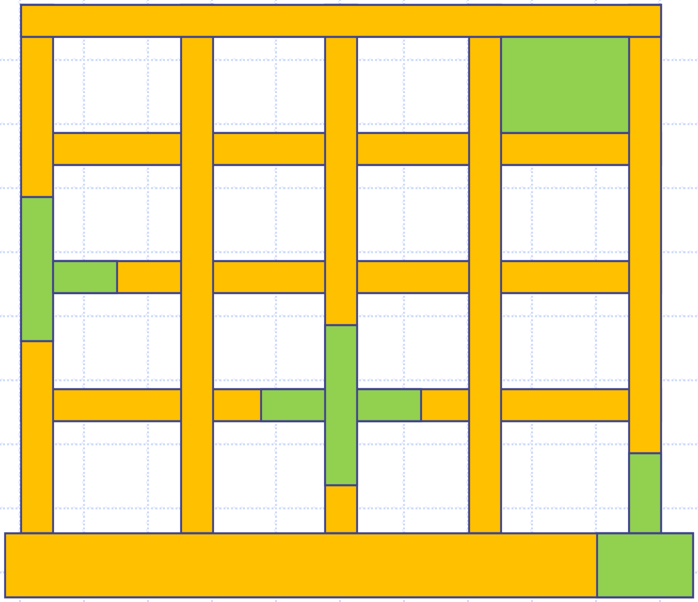
b) Damping forces from physical dampers

c) Inertia forces from the mass of the physical specimens



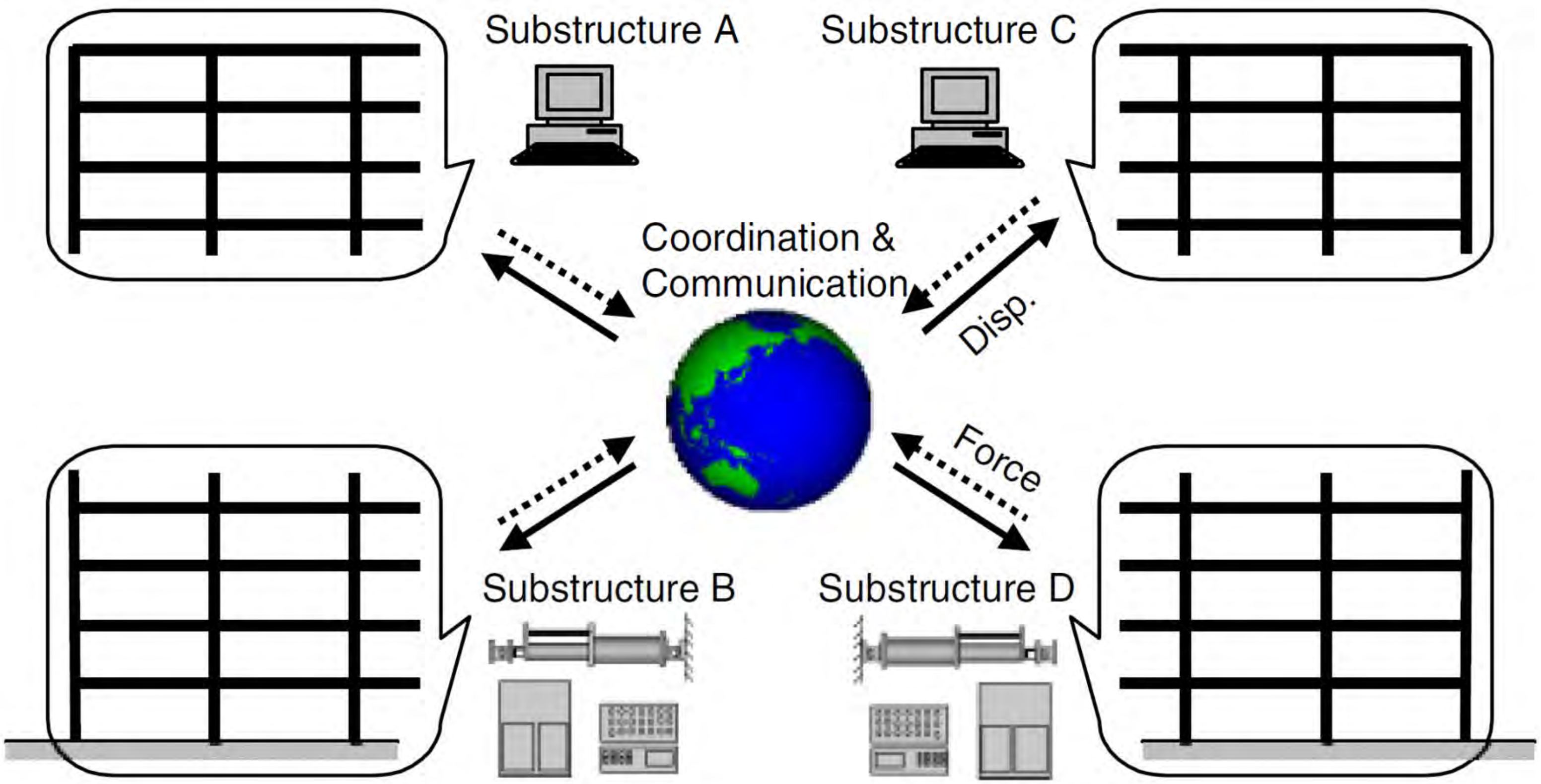
Theory: Background

- By definition, a hybrid model is sub-structured
- Multiple sub-structures can be used
- Many analytical sub-structures (Soft models)
- Many physical sub-structures (Hard model)



Theory: Background

- Testing infrastructure must enable:
  1. Simulation of individual sub-structures
  2. Integration of equations of motion



Theory: Background

- Advantages:
  1. Physical model resistance of sub-structures whose computer models are not good enough.
  2. Model the inertia forces (and damping, and second-order effects) in the computer.

- Disadvantages:
  1. Substructures are connected and interact at their boundaries.
  2. Specimens have inertia and damping, too.

Theory: Background

$$\begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} a_p \\ a_c \end{Bmatrix} + \begin{bmatrix} c_{pp} & c_{pc} \\ c_{cp} & c_{cc} \end{bmatrix} \begin{Bmatrix} v_p \\ v_c \end{Bmatrix} + \begin{Bmatrix} R_p \\ R_c \end{Bmatrix} = -\begin{bmatrix} m_{pp} & m_{pc} \\ m_{cp} & m_{cc} \end{bmatrix} \begin{Bmatrix} a_{pg} \\ a_{cg} \end{Bmatrix}$$

Subscript *c* → computed sub-structure

Subscript *p* → physical sub-structure

- Restoring forces can be assembled
- Also the following can be assembled:
  1. Damping forces from physical dampers
  2. Inertia forces from the mass of the physical specimens

Theory: Background

- Damping and inertia:
  1. Explicit consideration of physical dampers and physical masses, based on measured velocities and accelerations.
  2. DOF condensation must be performed carefully.
  3. Coordinate transformations must be propagated to velocities and accelerations.

- Second-order effects:

  Geometric stiffness may be assembled into the resistance:

$$\overline{R} = R - K_G d$$

Theory: Background

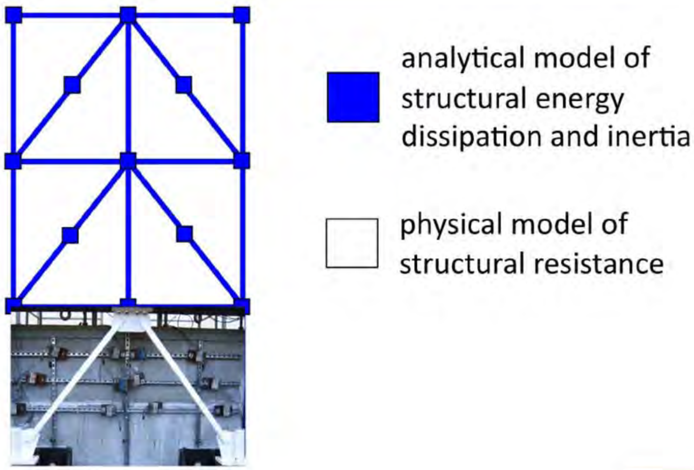
Interface between Sub-Structures

- Equilibrium and compatibility must be satisfied
- Deformations and forces
  1. Displacement (**relatively easy**)
  2. Rotation (**very difficult**)
- Opportunity to do:

  DOF condensation
- Coordinate transformations

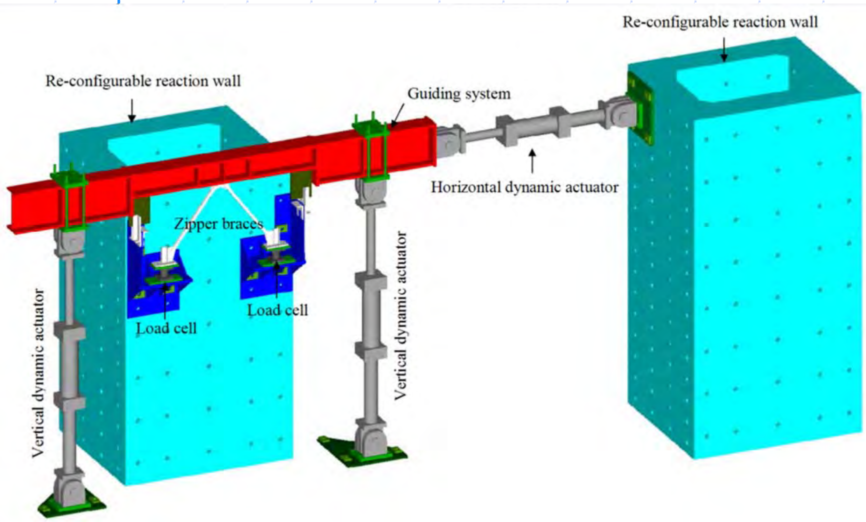
  Physical to computational DOF's: $d_p=Td_c$
- Geometry corrections

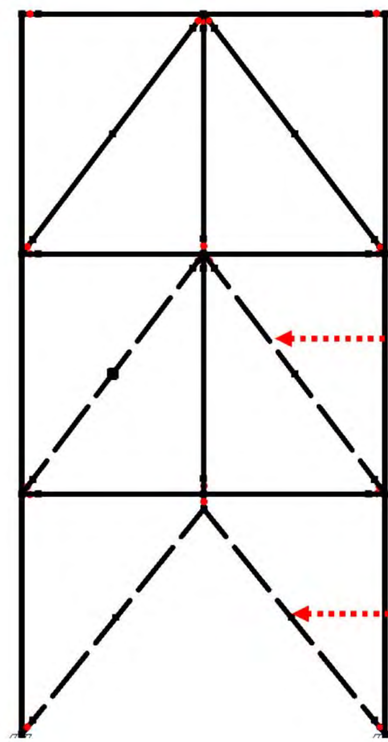
  Actuator movements

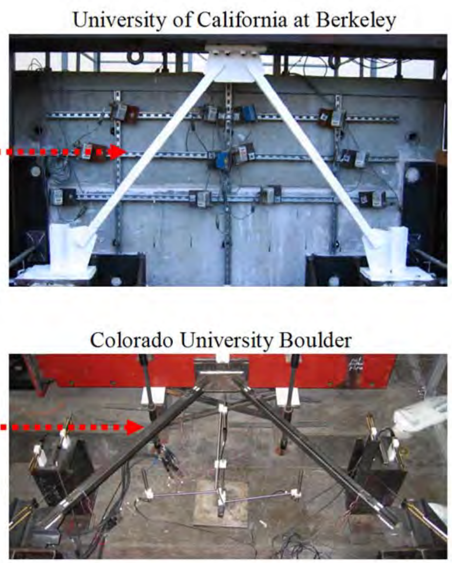


Theory: Background

Distributed Hybrid Simulation

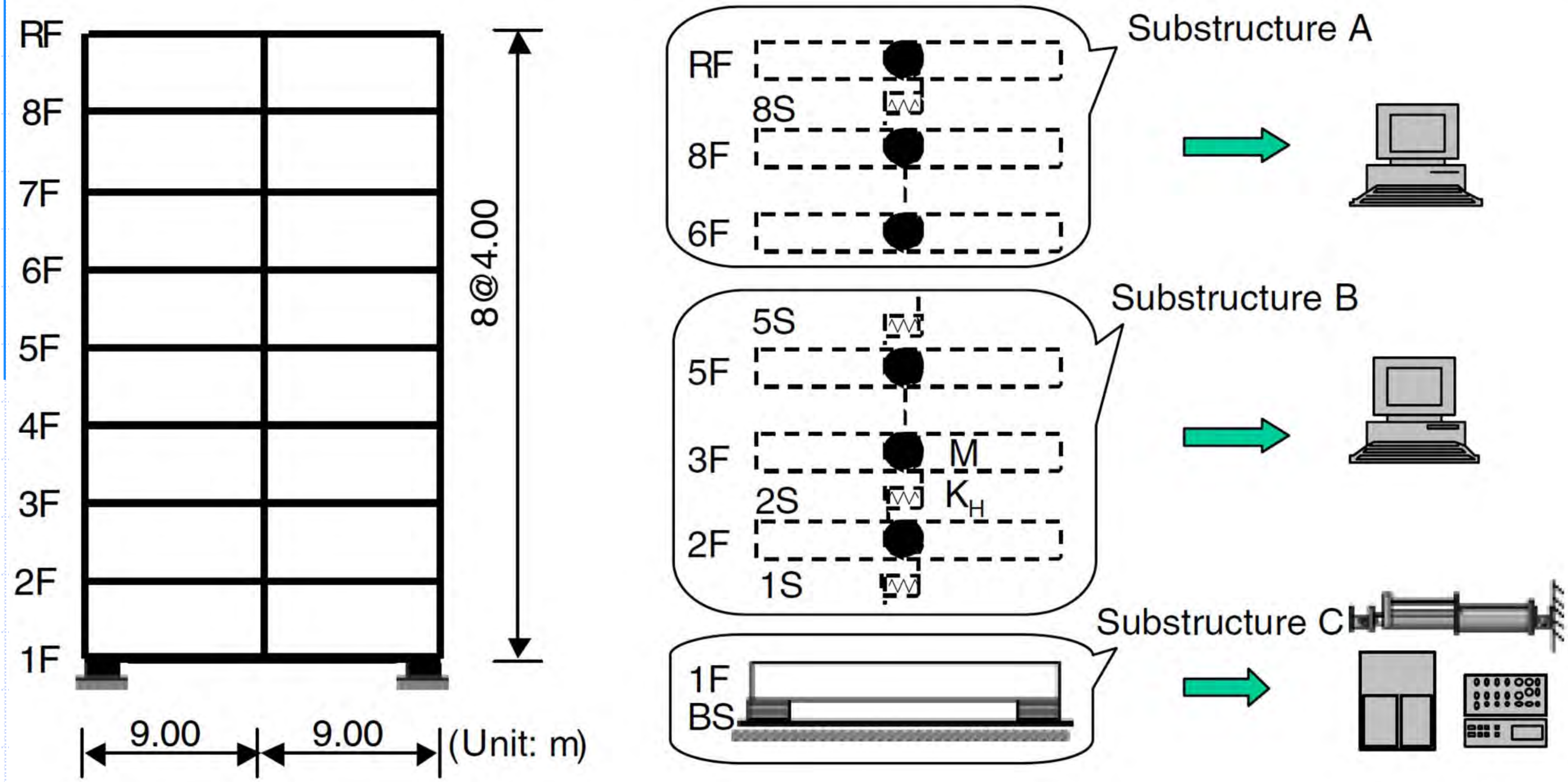






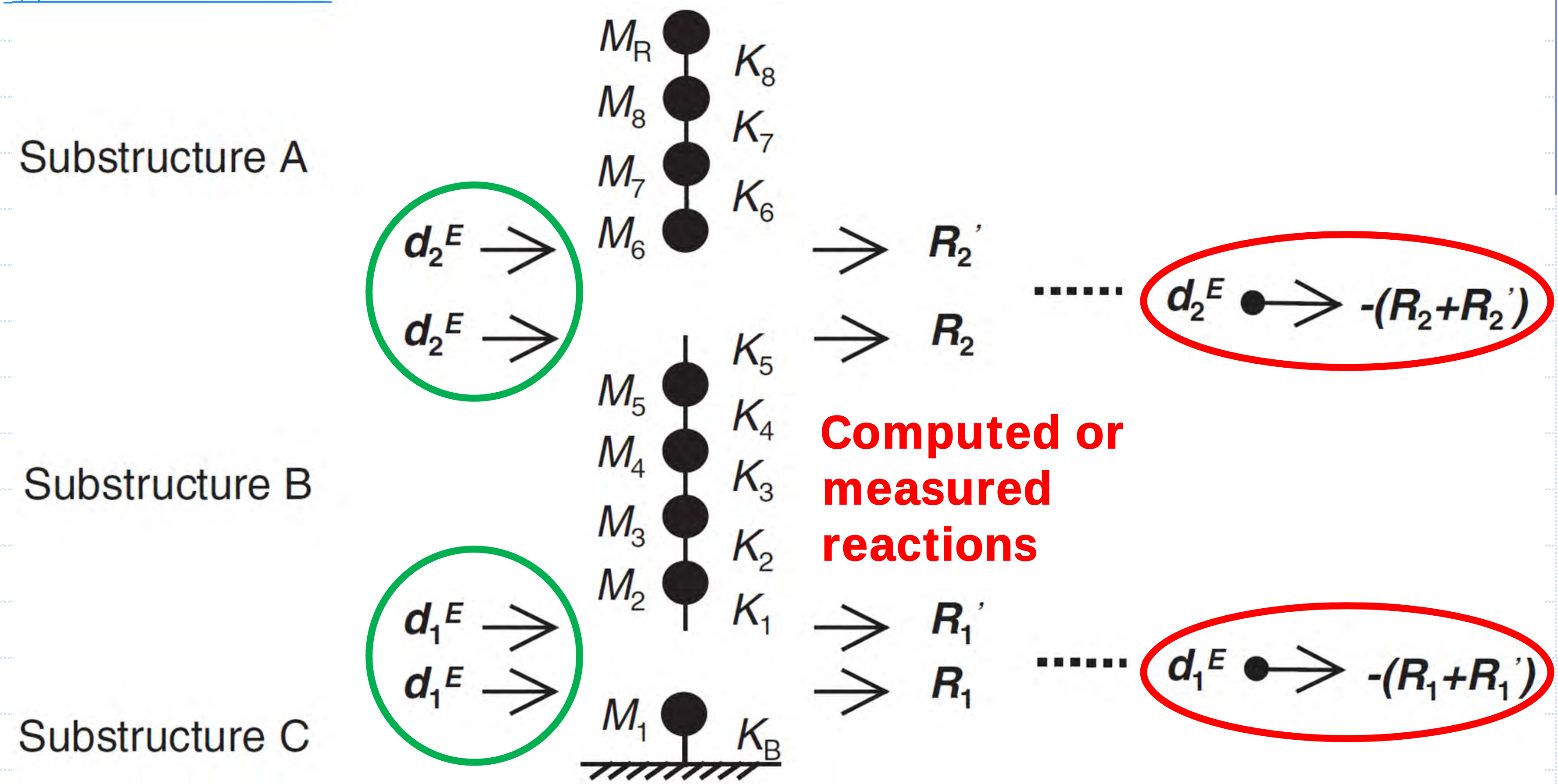
T. Yang, B. Stojadinovic, & J. Moehle

Theory: Background



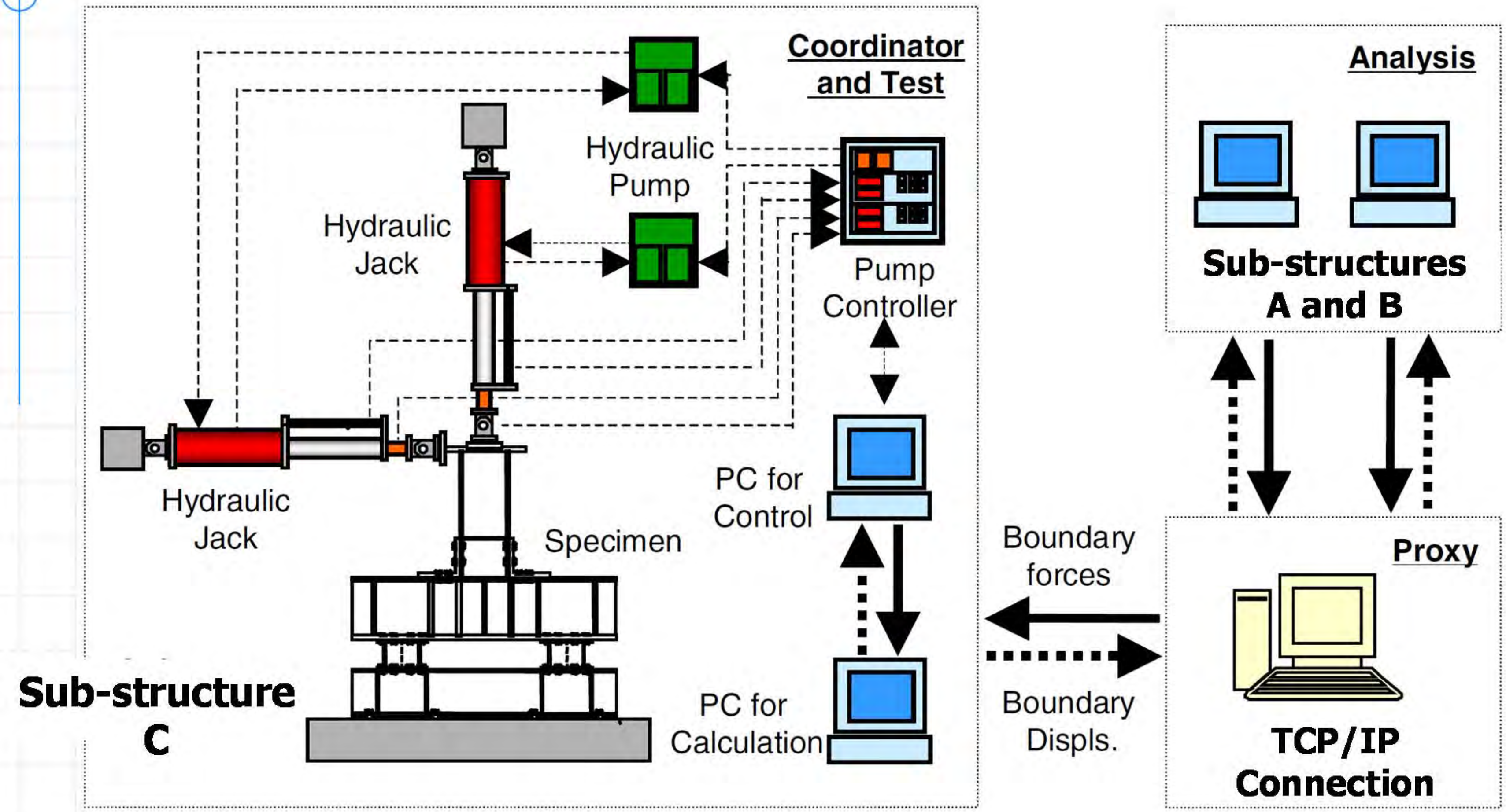
Pan, P., Tomofuji, H., Wang, T., Nakashima, M., Ohsaki, M., & Mosalam, K.M., "Development of Peer-to-Peer (P2P) Internet Online Hybrid Test System," *EESD*, 35: 867-890, 2006.

Theory: Background



Pan, P., Tomofuji, H., Wang, T., Nakashima, M., Ohsaki, M., & Mosalam, K.M., "Development of Peer-to-Peer (P2P) Internet Online Hybrid Test System," *EESD*, 35: 867-890, 2006.

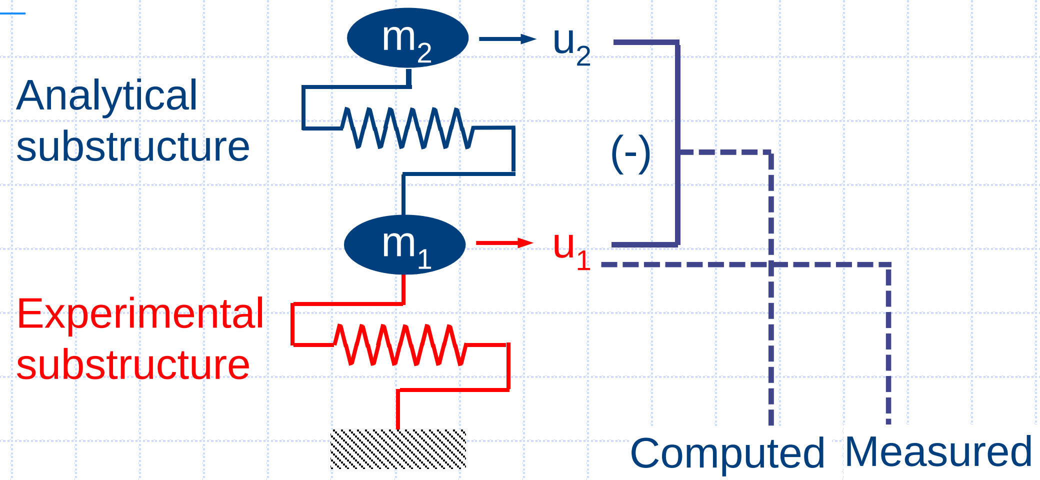
Theory: Background



Pan, P., Tomofuji, H., Wang, T., Nakashima, M., Ohsaki, M., & Mosalam, K.M., "Development of Peer-to-Peer (P2P) Internet Online Hybrid Test System," *EESD*, 35: 867-890, 2006.

Proxy Server: a computer system acts as an intermediary for requests from clients seeking resources from other servers.
TCP/IP: Transmission Control Protocol and Internet Protocol, networking communications protocols for the Internet.

Theory: Substructuring



$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{bmatrix} + \begin{bmatrix} -f_a + f_e \\ f_a \end{bmatrix} = -\begin{bmatrix} m_1 \\ m_2 \end{bmatrix}\ddot{u}_g$$

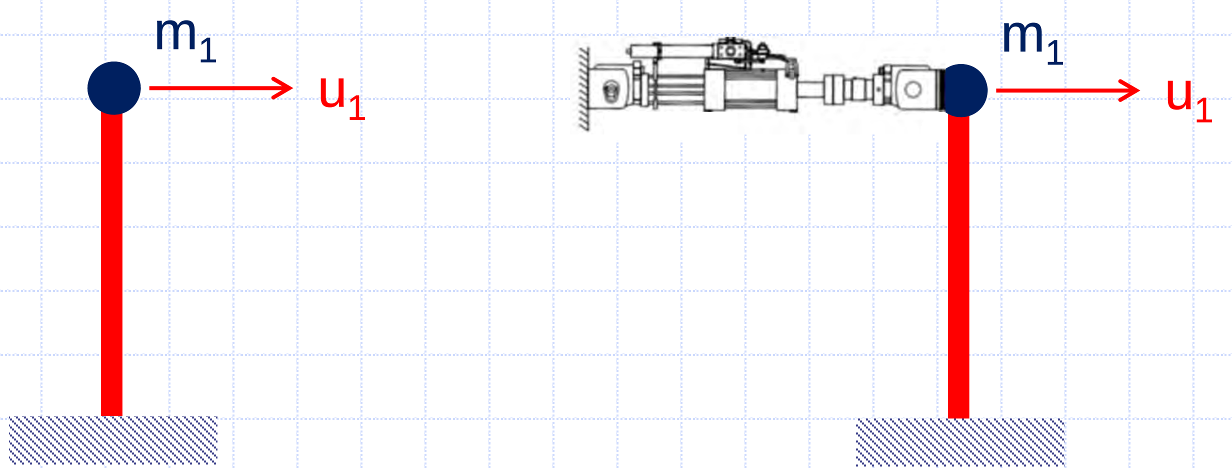
- **Nature of the problem requires substructuring**
- **Presence of experimental substructures requires the use of special integration methods**
- **Presence of a transfer system introduces simulation errors**
- **Rate dependent materials require real-time hybrid simulation (RTHS)**
- **Making use of multiple labs extends the method to geographically distributed testing**

Theory: Substructuring

- Dermitzakis and Mahin (**1985**)
- Nakashima, Kaminosono, Ishida, and Ando (1990)
- Schneider and Roeder (1994)
- Nakashima and Masaoka (1999)
- Mosqueda, Cortes-Delgado, Wang, and Nakashima (**2010**)

Theory: Substructuring

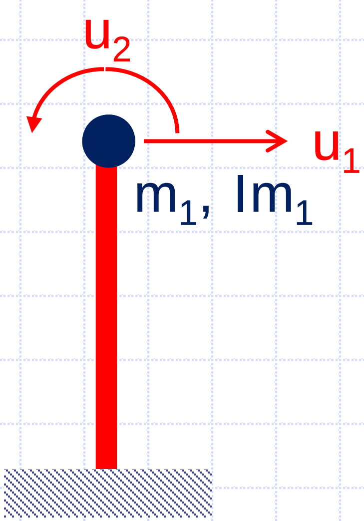
CASE 1: CANTILEVER COLUMN with MASS [No MASS MOMENT of INERTIA or ANALYTICAL SUBSTRUCTURE]

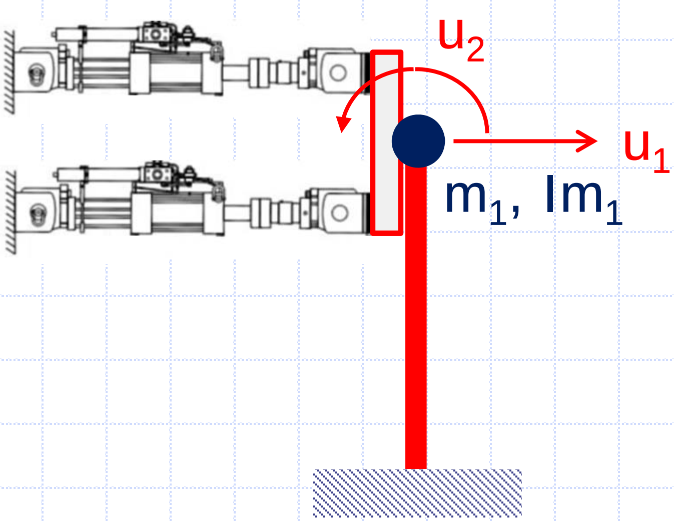


Red : Experimental
Blue: Analytical

Theory: Substructuring

CASE 2: CANTILEVER COLUMN with MASS and MASS MOMENT of INERTIA [No ANALYTICAL SUBSTRUCTURE]

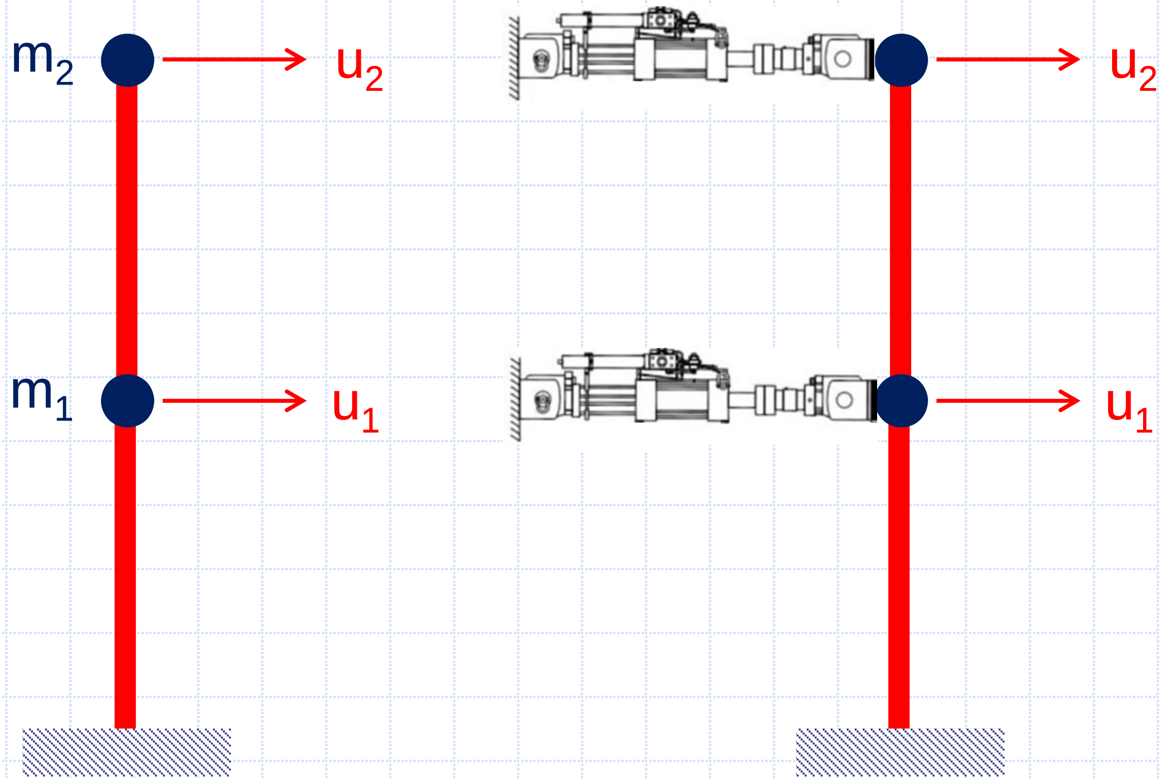




Red : Experimental
Blue: Analytical

Theory: Substructuring

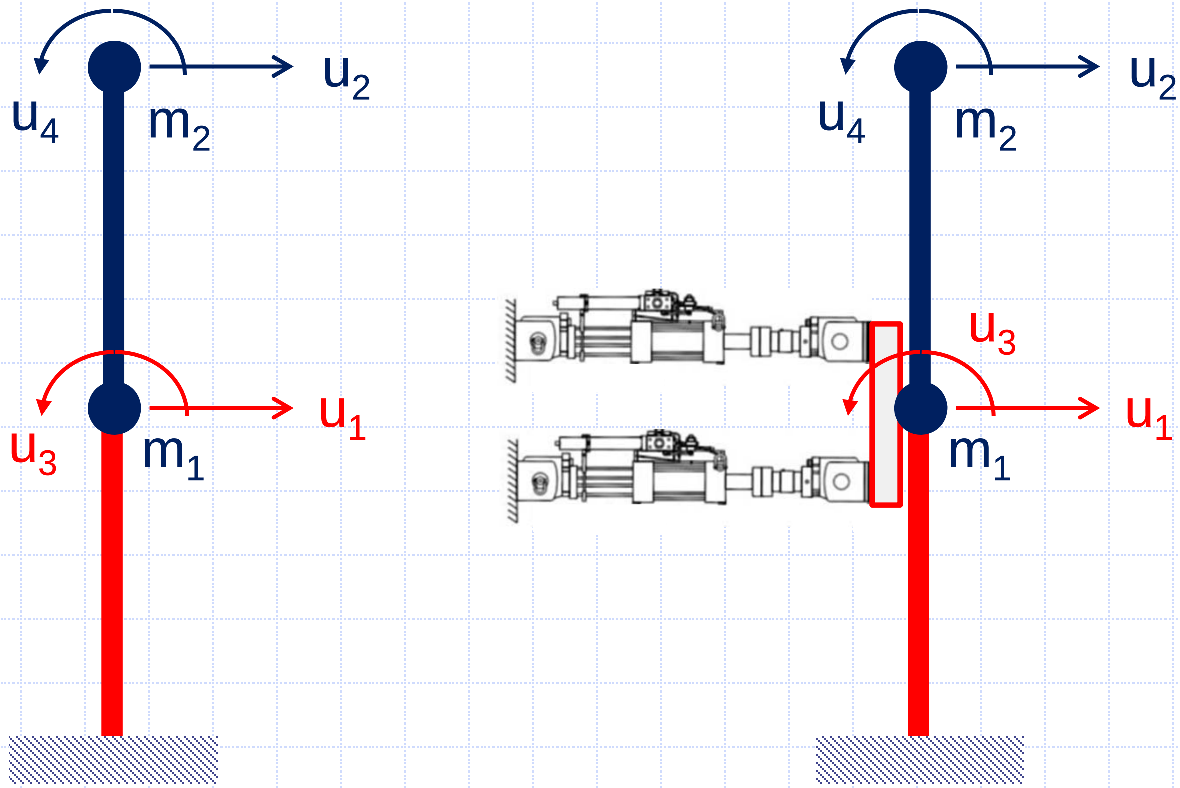
CASE 3: TWO COLUMNS without ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Theory: Substructuring

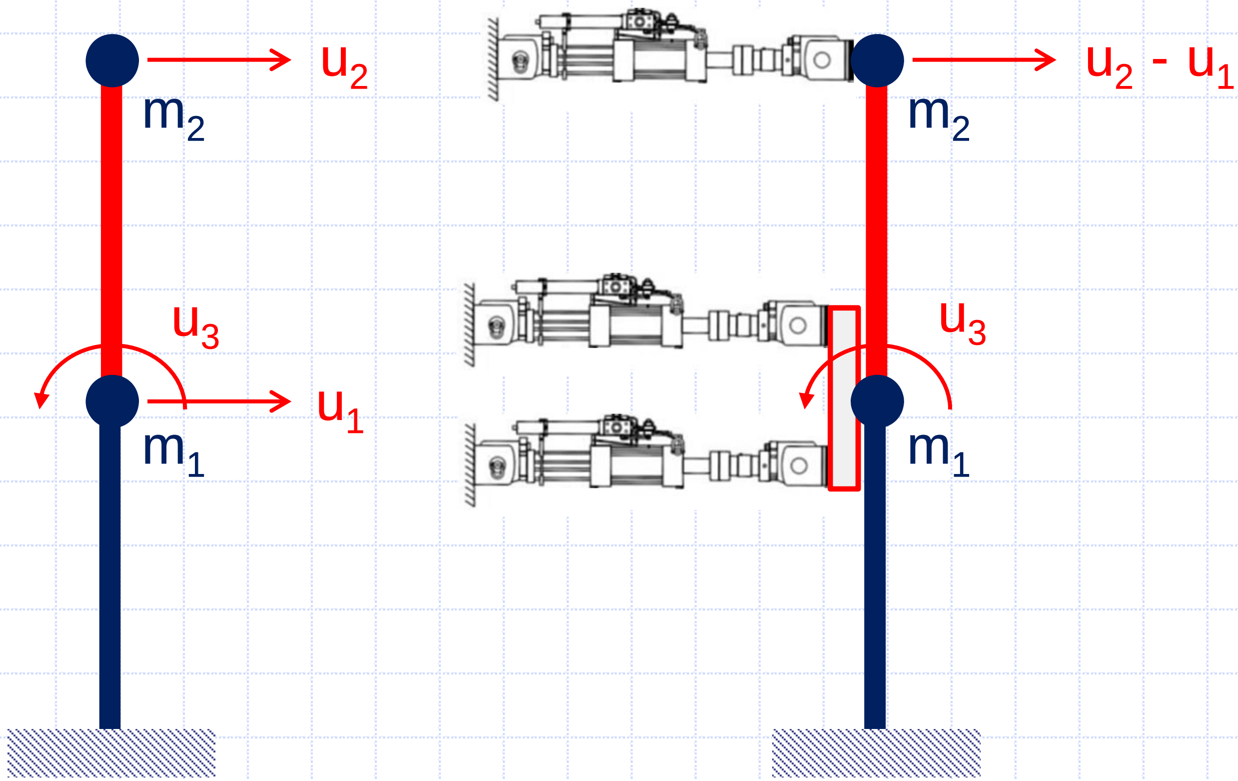
CASE 4: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Theory: Substructuring

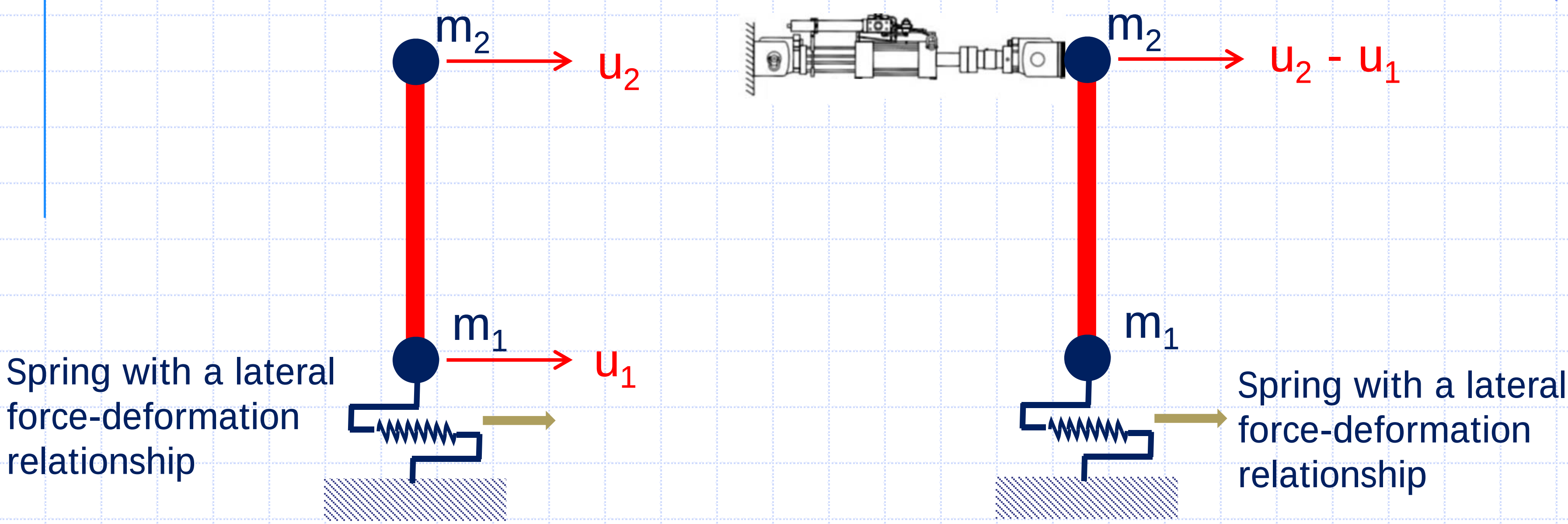
CASE 4-1: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Theory: Substructuring

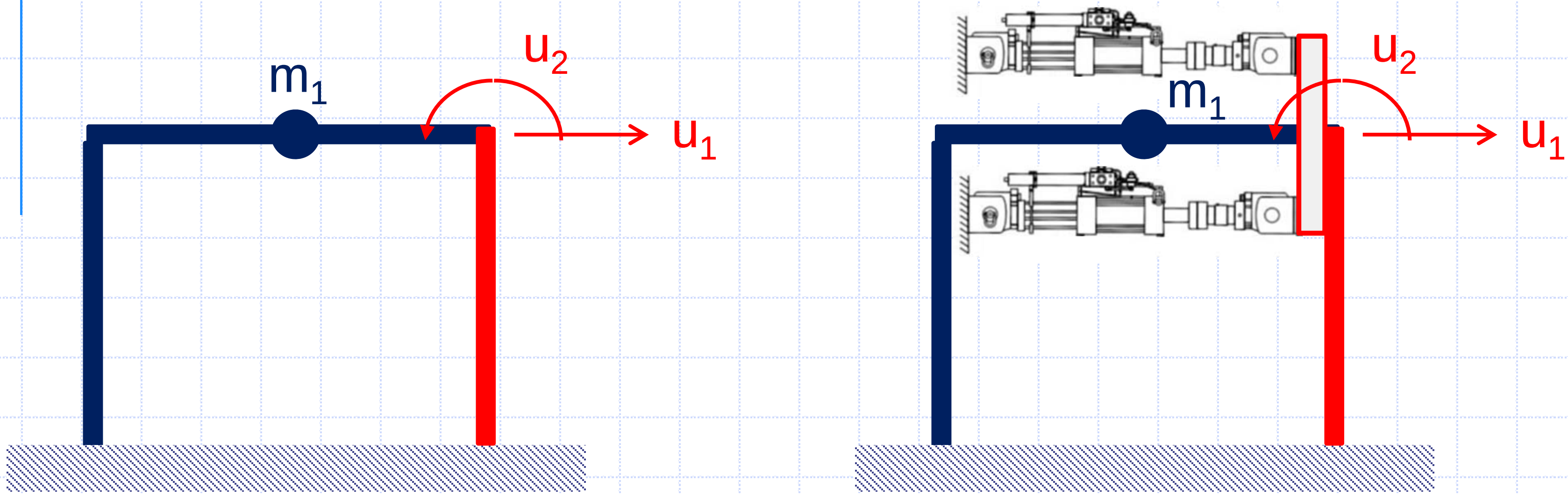
CASE 4-2: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Theory: Substructuring

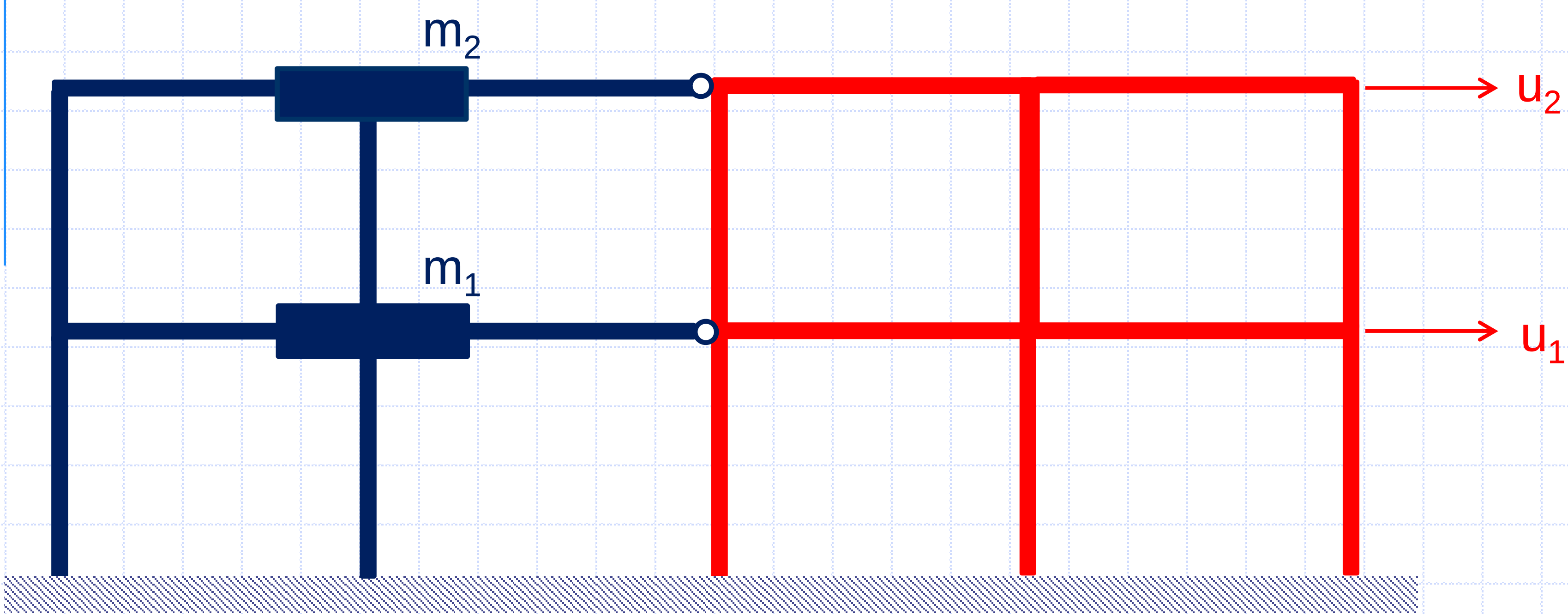
CASE 5: PORTAL FRAME with one of the COLUMNS and BEAM as ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Theory: Substructuring

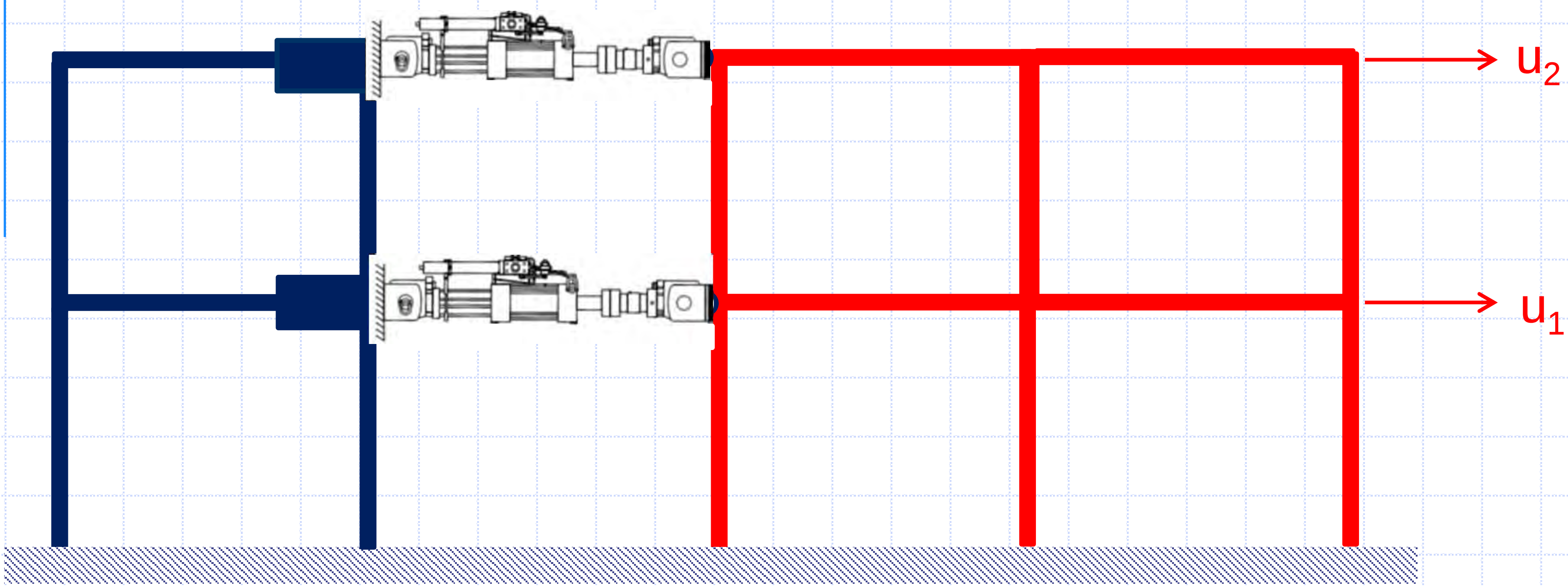
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Theory: Substructuring

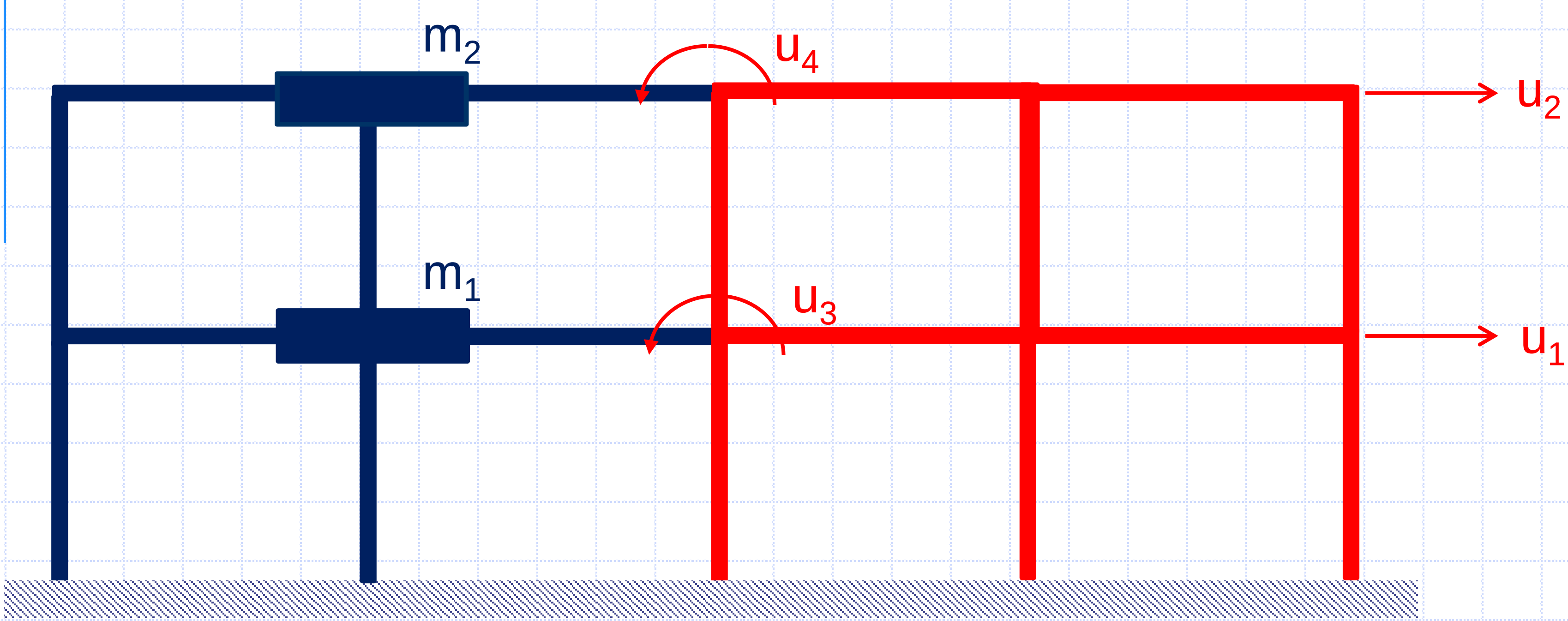
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Theory: Substructuring

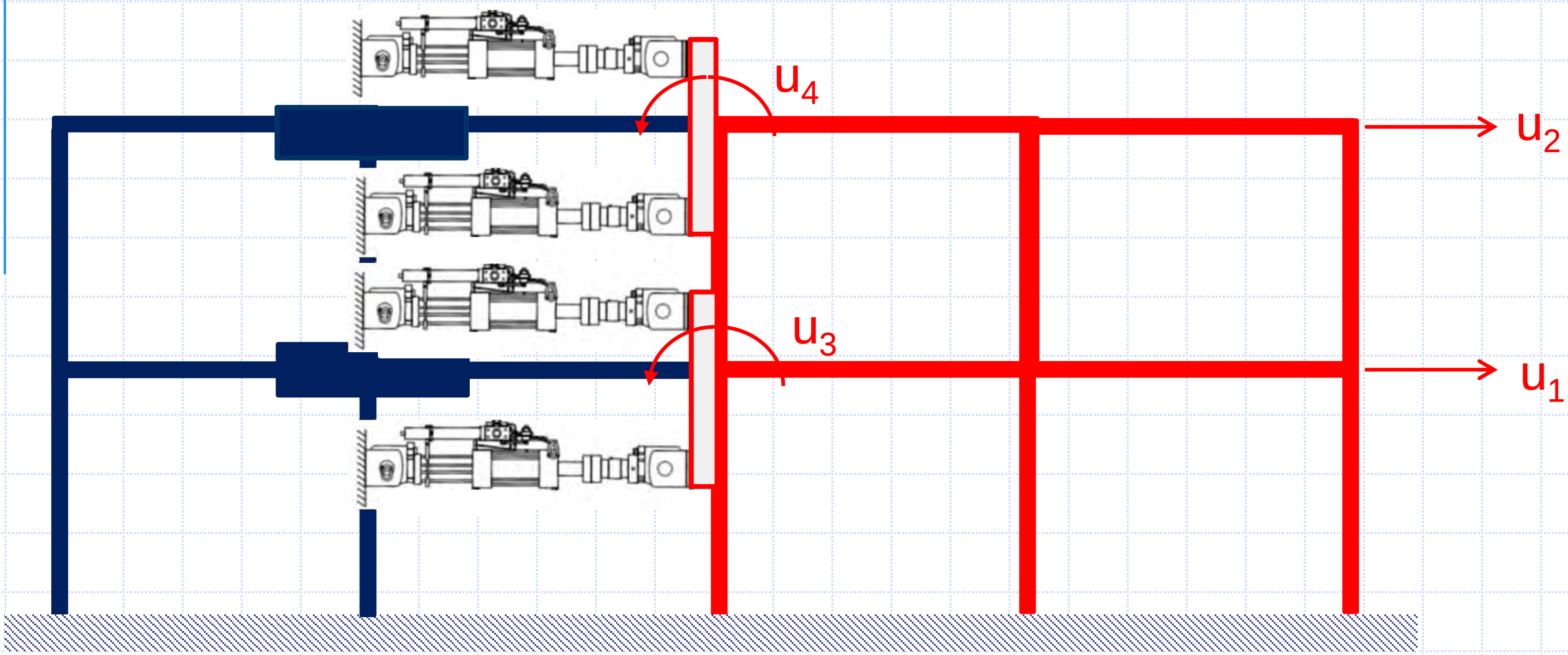
CASE 6-1: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Theory: Substructuring

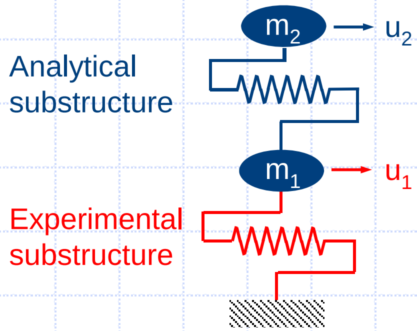
CASE 6-1: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Theory: Integration Methods

A straightforward integration application: Explicit Newmark Integration



$$\underbrace{\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}}_{\mathbf{m}} \underbrace{\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix}}_{\ddot{\mathbf{u}}} + \underbrace{\begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}}_{\mathbf{c}} \underbrace{\begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{bmatrix}}_{\dot{\mathbf{u}}} + \underbrace{\begin{bmatrix} -f_a + f_e \\ f_a \end{bmatrix}}_{\mathbf{f}} = \underbrace{-\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \ddot{u}_g}_{\mathbf{p}}$$

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{f} = \mathbf{p}$$

1. Determine the initial values of response variables: $\mathbf{u}_0, \dot{\mathbf{u}}_0, \ddot{\mathbf{u}}_0$
2. Calculate the effective mass: $\mathbf{m}_{eff} = \mathbf{m} + \Delta t\,\gamma\,\mathbf{c}$

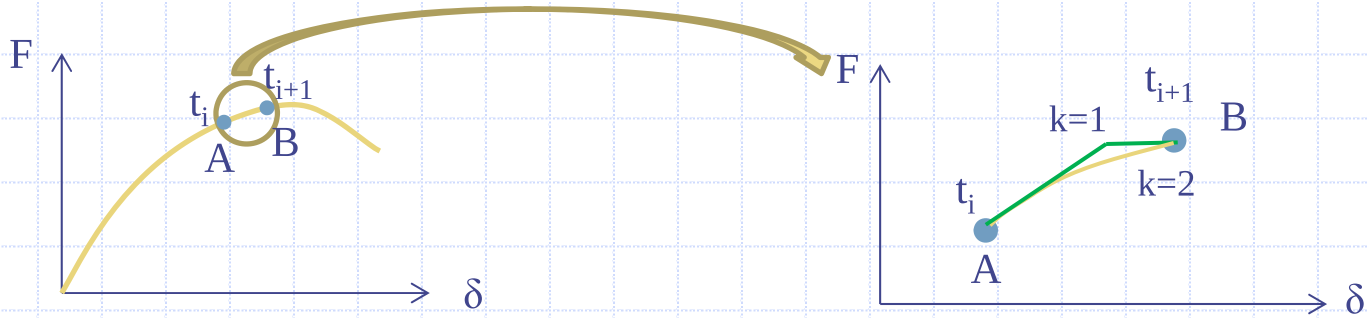
   Δt: integration time step, γ: integration parameter
3. For each time step i; $1 \le i \le N$, N: total number of steps
   - a. Compute the displacement: $\mathbf{u}_i = \mathbf{u}_{i-1} + \Delta t \times \dot{\mathbf{u}}_{i-1} + \left(\Delta t^2/2\right) \times \ddot{\mathbf{u}}_{i-1}$
   - b1. Compute the force $f_{a,i}$ corresponding to the displacement $u_{2,i} - u_{1,i}$ from the constitutive relationship of the analytical spring
   - b2. Apply the displacement $u_{1,i}$ to the experimental spring and measure the corresponding force $f_{e,i}$
   - b3. Determine $\mathbf{f}_i$ from $f_{e,i}$ and $f_{a,i}$
   - c. Compute the predicted velocity: $\tilde{\dot{\mathbf{u}}}_i = \dot{\mathbf{u}}_{i-1} + \Delta t (1-\gamma) \ddot{\mathbf{u}}_{i-1}$
   - d. Compute the effective force: $\mathbf{p}_{eff} = \mathbf{p}_i - \mathbf{f}_i - \mathbf{c}\tilde{\dot{\mathbf{u}}}_i$
   - e. Compute the acceleration by solving the linear system of equations: $\mathbf{m}_{eff}\ddot{\mathbf{u}}_i = \mathbf{p}_{eff}$
   - f. Compute the velocity: $\dot{\mathbf{u}}_i = \tilde{\dot{\mathbf{u}}}_i + \Delta t\,\gamma\,\ddot{\mathbf{u}}_i$
   - g. Increment i and go to step a

Theory: Integration Methods

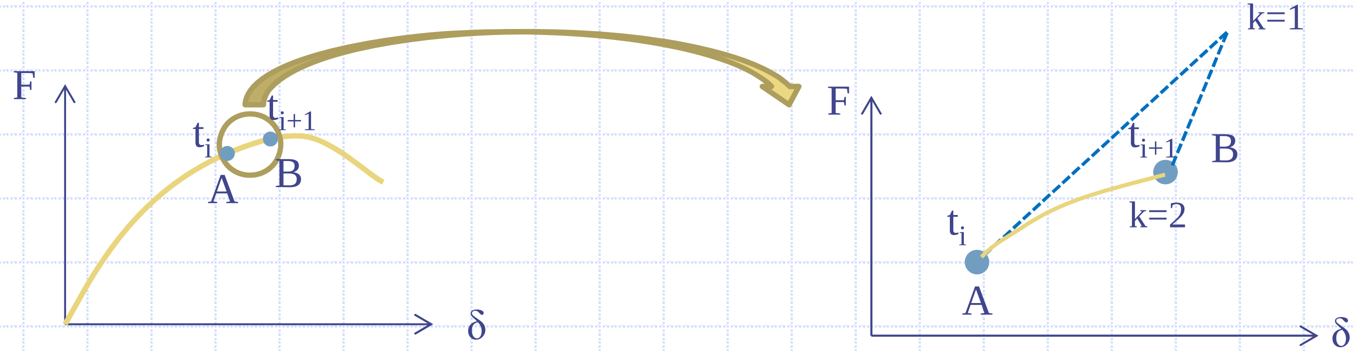
The most common integration for pure numerical case: Implicit Newmark

Not suitable for hybrid simulation

- Nonuniform displacement increments: velocity and acceleration oscillations within the step



- Displacement overshoot: artificial unloading



- Iterations may not converge !

Theory: Integration Methods

The most common integration for pure numerical case: Implicit Newmark

HS compatible alternatives:

- Implicit Newmark Integration with Fixed Number of Iterations
  - Uniform displacement increments
  - Number of iterations constant → No convergence problems
  - Number of iterations should be determined with prior analyses
  - Very suitable for slow hybrid simulation with restricted use in real-time hybrid simulation
- Alpha-Operator Splitting (OS) Method
  - Tangential stiffness matrix not required
  - Iterations are not required (one predictor & one corrector) → No convergence problems
  - Computationally efficient
  - Numerical damping present
  - Very suitable for slow and real-time hybrid simulation for softening systems
- Explicit Newmark Integration
  - Initial and tangential stiffness matrices not required
  - Iterations are not required → No convergence problems
  - Computationally very efficient
  - No numerical damping
  - Conditionally stable
  - Very suitable for slow and real-time hybrid simulation when stability criterion is met

Theory: Simulation Errors

ERROR SOURCES

- **Errors due to Structural Modeling**
- **Errors due to Numerical Methods**

Errors due to numerical solution nature of HS

- **Experimental Errors: 1) Random or 2) Systematic**

Theory: Simulation Errors

Random errors:

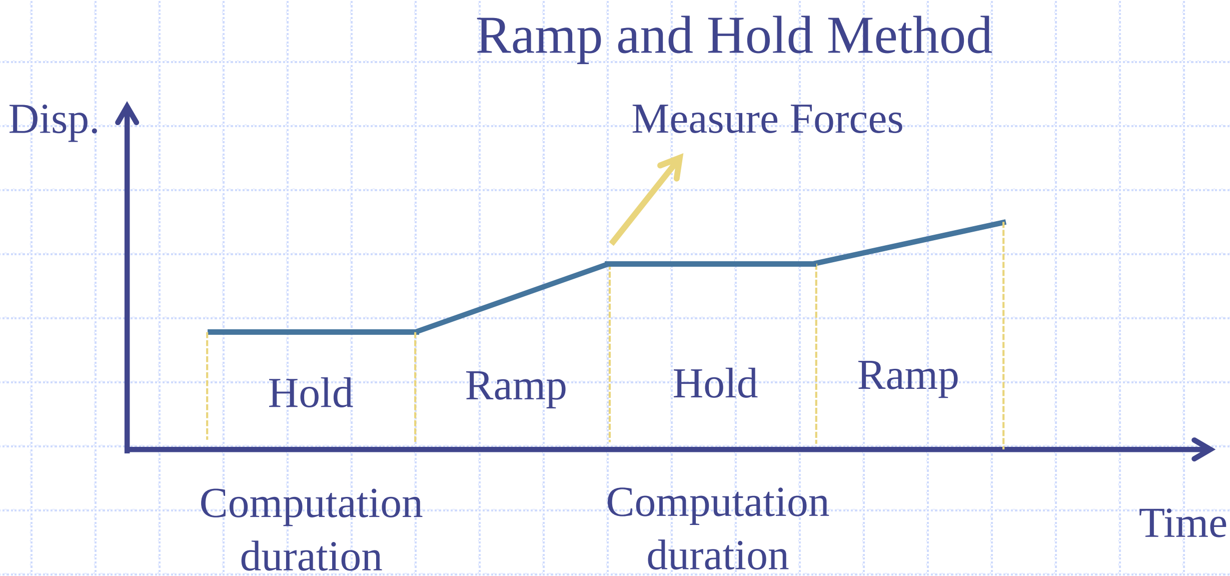
- No distinguishable pattern & generally no specific physical effects are anticipated
- Random electrical noise in wires and electronic systems
- Random rounding-off or truncation in the A/D conversion of electrical signals
- Random noise in measured forces is problematic → excites spurious response in higher modes

Systematic errors:

- Measurement errors (Errors in load cells & displacement transducers of actuators)
    - Calibration
    - Friction or slippage (gaps) in the attachments
    - A/D and D/A conversion (Digital controllers & digital transducers for improved accuracy)
- Hybrid simulation technique (ramp and hold, continuous, real-time)
- Servo-hydraulic closed control loop

Theory: Simulation Errors

Errors due to HS technique (Systematic)

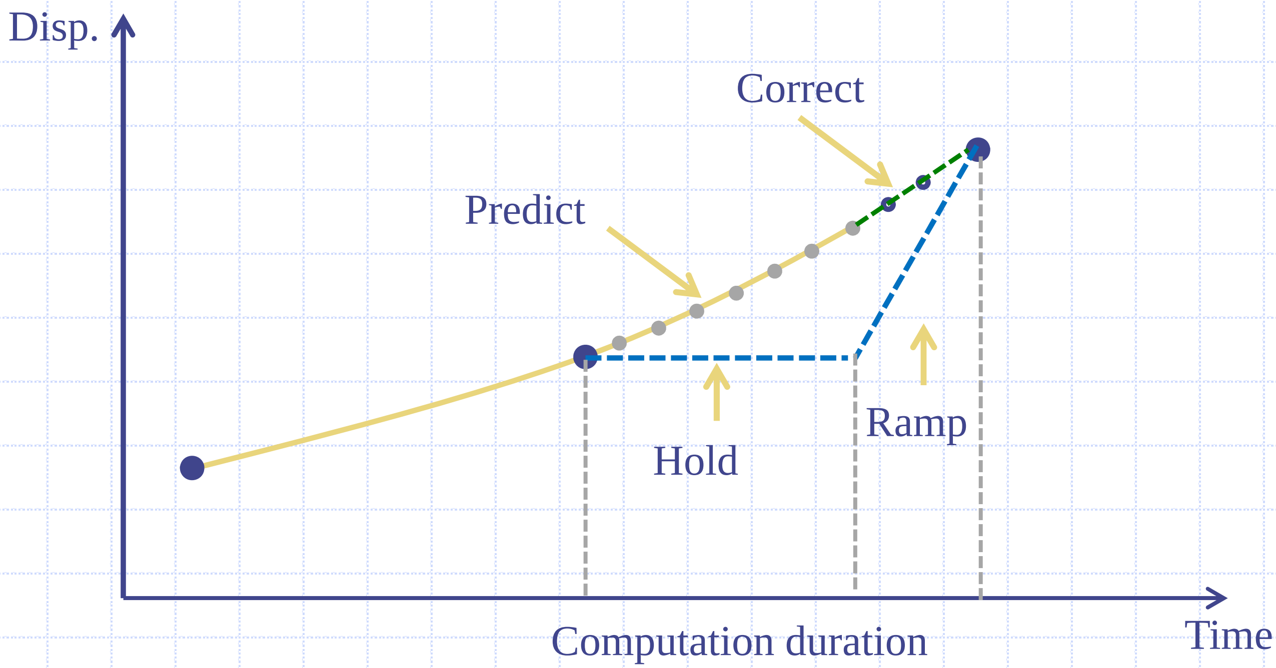


- Force relaxation during hold phase
- Discontinuity in velocity
- Not applicable in real-time HS

Theory: Simulation Errors

Errors due to HS technique (Systematic)

Continuous Testing (Predictor-Corrector Algorithms)



- Continuous movement of actuators
- Preferred HS technique
- Indispensable for real-time HS and geographically distributed HS

Theory: Simulation Errors

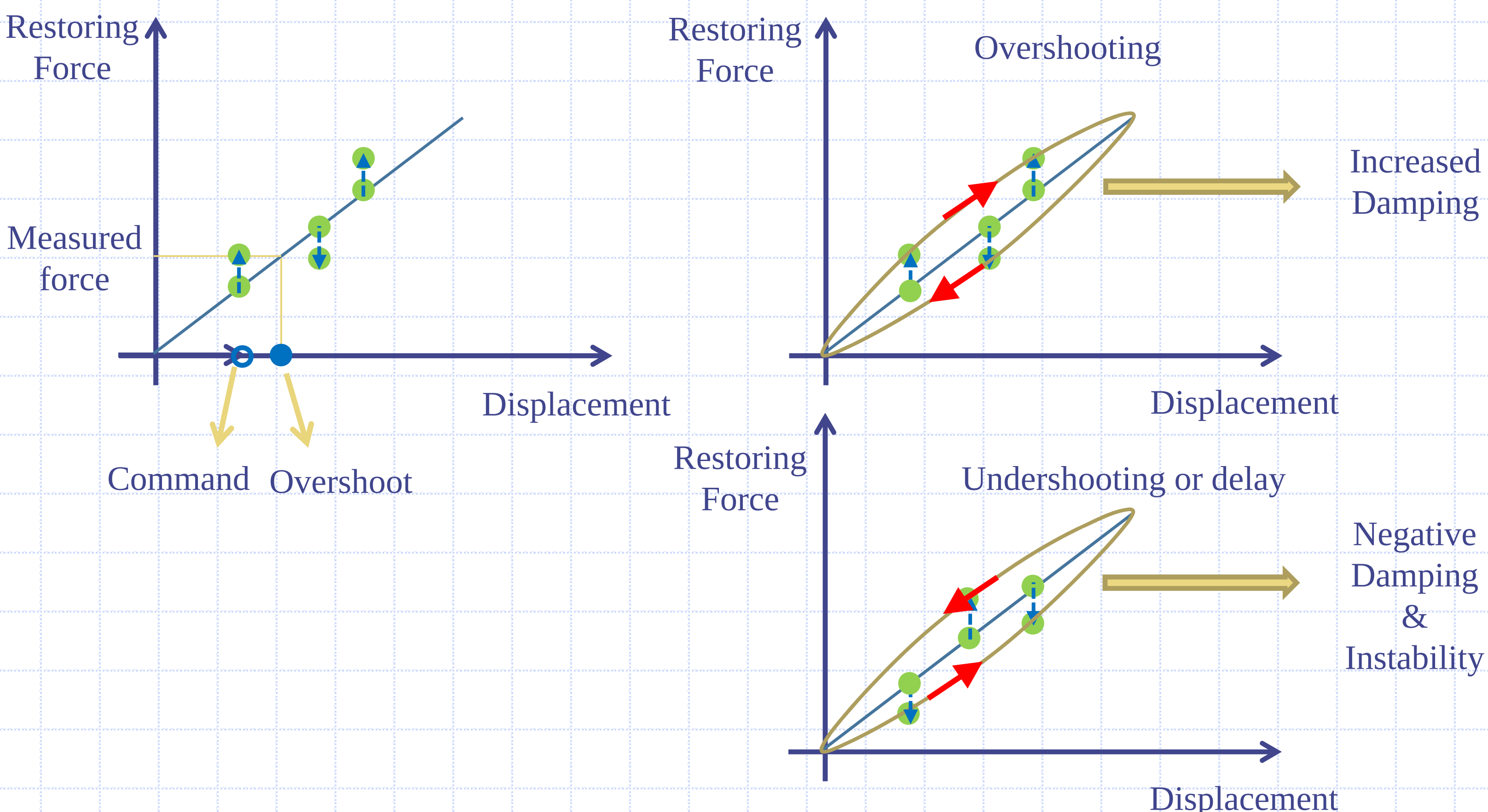
Control loop errors (Systematic)

- ❑ Actuator dynamics
  - Servo-valve
  - Hydraulic power-supply
- ❑ Control-loop dynamics
  - Inherent lag in the displacement response
  - PIDF gains

Theory: Simulation Errors

Control loop errors (Systematic)

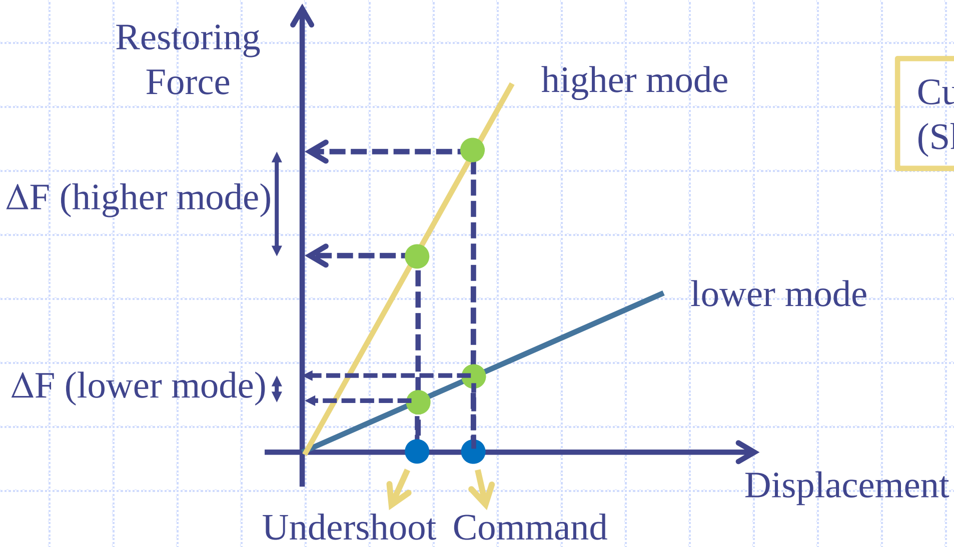
- Integration: Command displacement & measured force
- True behavior: Measured displacement & measured force



Theory: Simulation Errors

Control loop errors (Systematic)

- Integration: Command displacement & measured force
- True behavior: Measured displacement & measured force



Cumulative errors increase with ωΔt (Shing and Mahin, 1983)

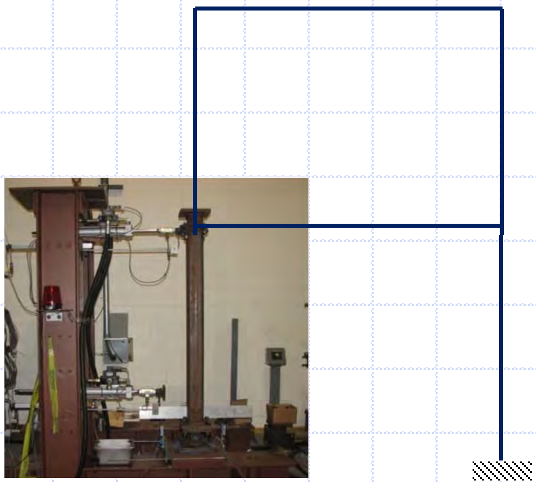
- Integration methods which introduce numerical damping to suppress the excitation of higher modes can be used to overcome the effects of these errors
- Adaptive minimal control synthesis (**MCS**) algorithm which provides **adaptive gain settings** as the test specimen properties change can be used instead of **PID** control algorithm

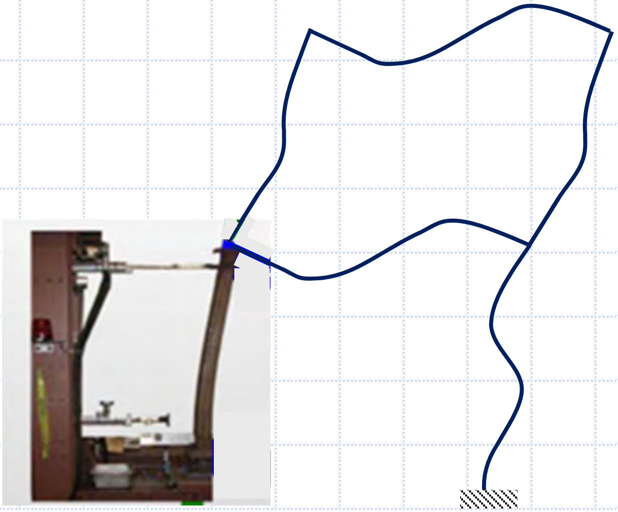
Theory: Simulation Errors

Control loop errors (Systematic)

Error Identification: Free vibration

Stage 1: Push the hybrid structure, generally in the first mode, to a displacement within the linear range



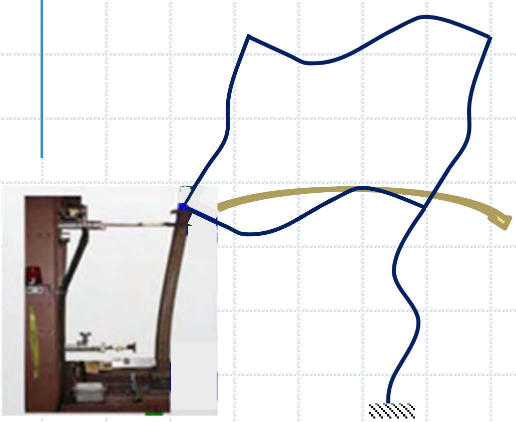


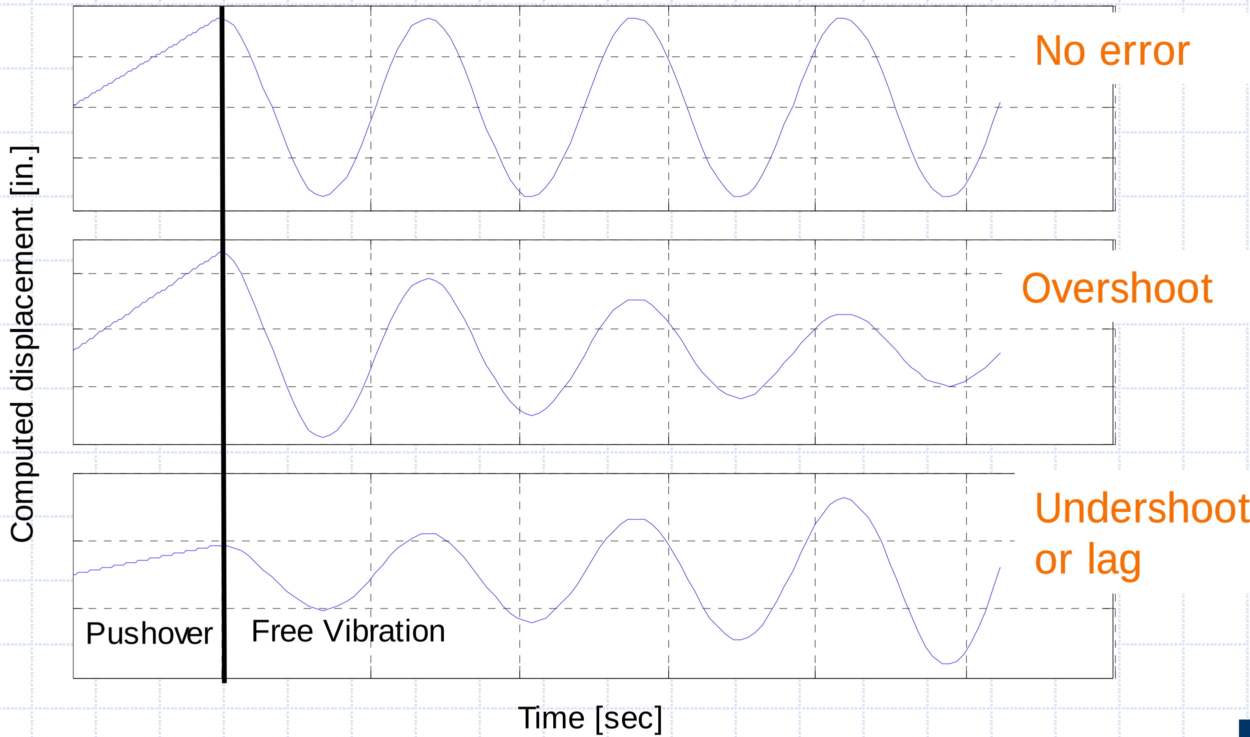
Stage 2: Run the free vibration hybrid simulation test from the displaced configuration

Theory: Simulation Errors

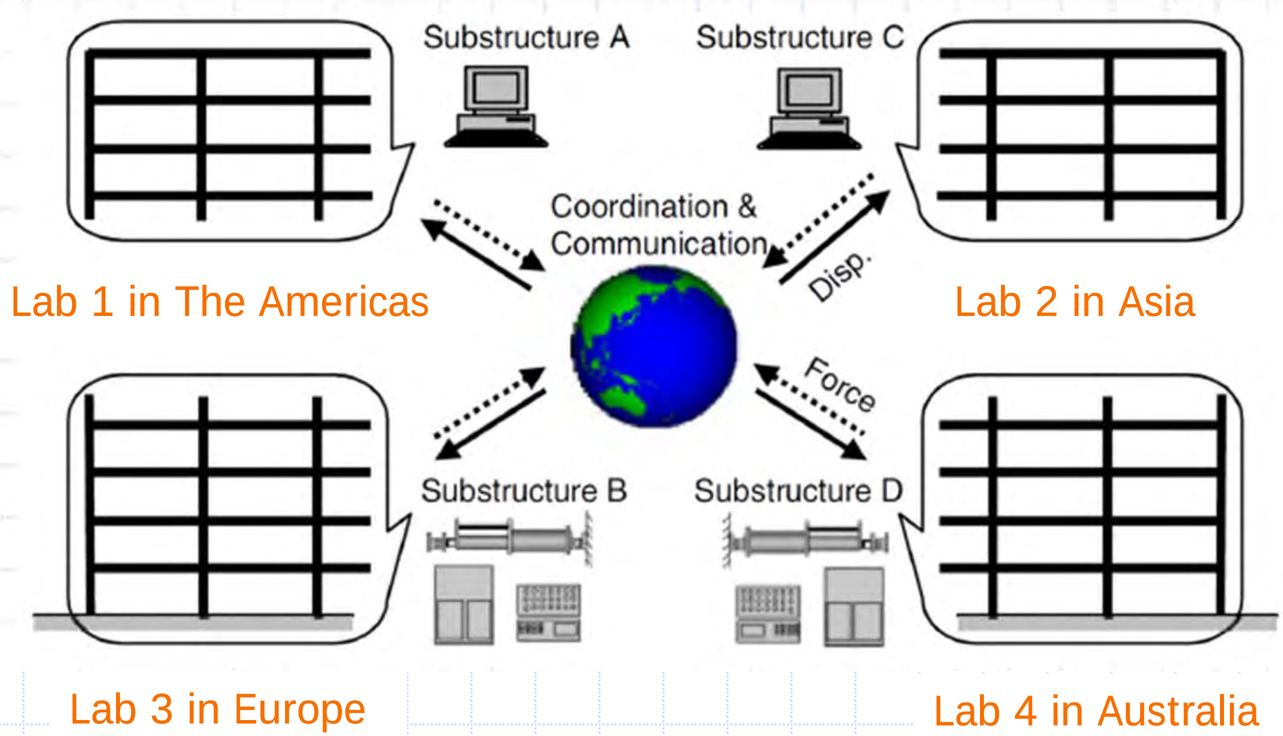
Control loop errors (Systematic)

Error Identification: Free vibration





Theory: Geographically Distributed HS



Pan, P., Tomofuji, H., Wang, T., Nakashima, M., Ohsaki, M., & Mosalam, K.M., "Development of Peer-to-Peer (P2P) Internet Online Hybrid Test System," *EESD*, 35: 867-890, 2006.

Theory: Real-time HS

- **Requirement for real time**: Loading rate = computed velocity
- Slow HS sufficient for most cases when rate effects are not important
- Real-time HS essential for rate-dependent materials and devices, e.g. viscous dampers or triple friction pendulum isolators
- RTHS classified into two groups:
  - RTHS conducted in a discrete actuator configuration
  - RTHS conducted in a shaking table configuration (**Application II**)

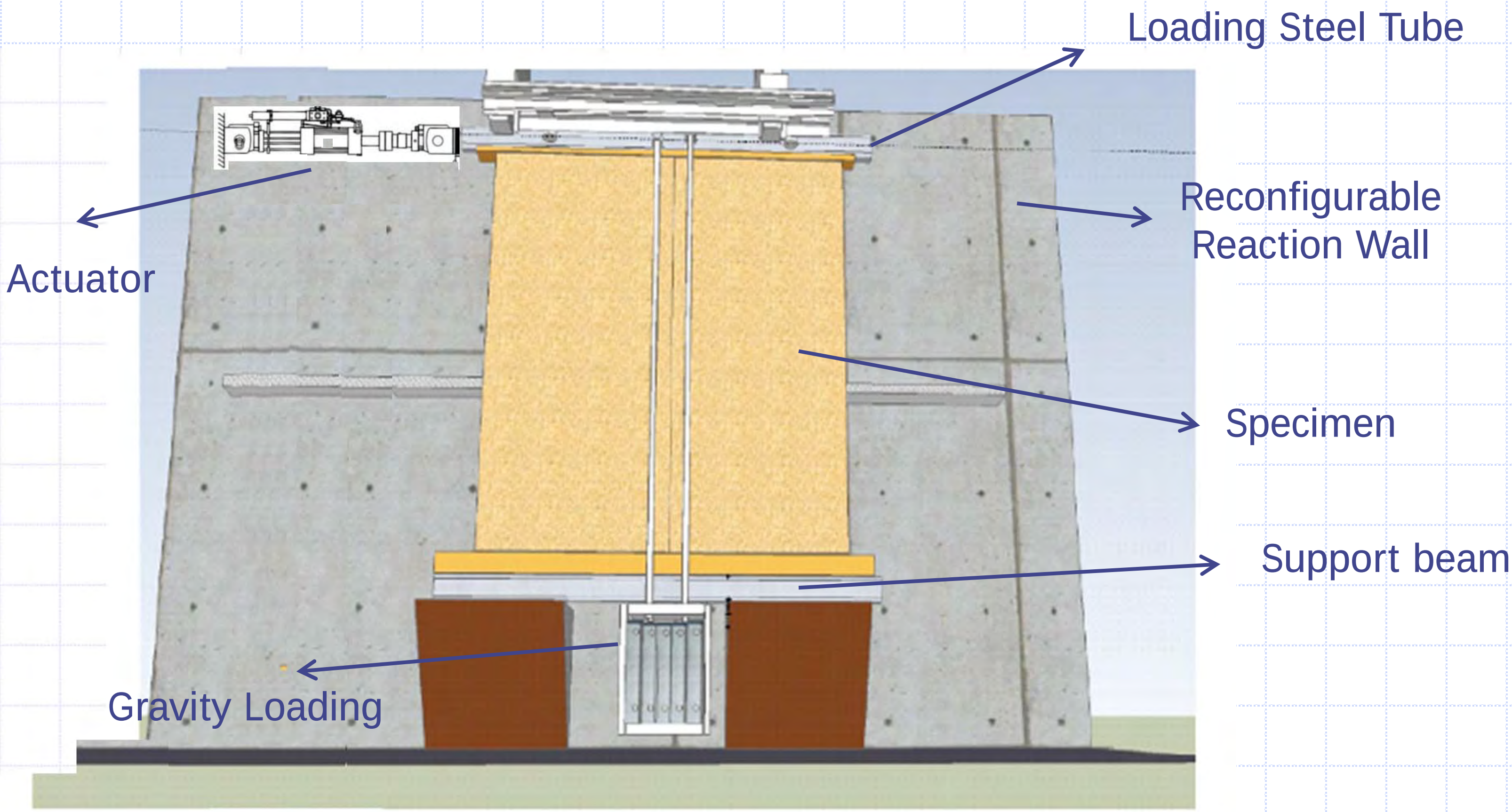
Application I: HS of Structural Insulated Panels (SIPs)

Motivation for Hybrid Simulation

- Structural Insulated Panels (SIPs) are composite panels for energy efficient construction
- Composed of an energy-efficient core placed in between facing materials
- Their application in seismically hazardous regions is limited due to somewhat unacceptable performance as demonstrated by cyclic testing
- Limited number of tests with more realistic dynamic loading regimes
- Hybrid simulation is ideal to test SIPs with a variety of structural configurations and ground motion excitations

Application I: HS of Structural Insulated Panels (SIPs)

Test Setup



Application I: HS of Structural Insulated Panels (SIPs)

Test Setup

Application I: HS of Structural Insulated Panels (SIPs)

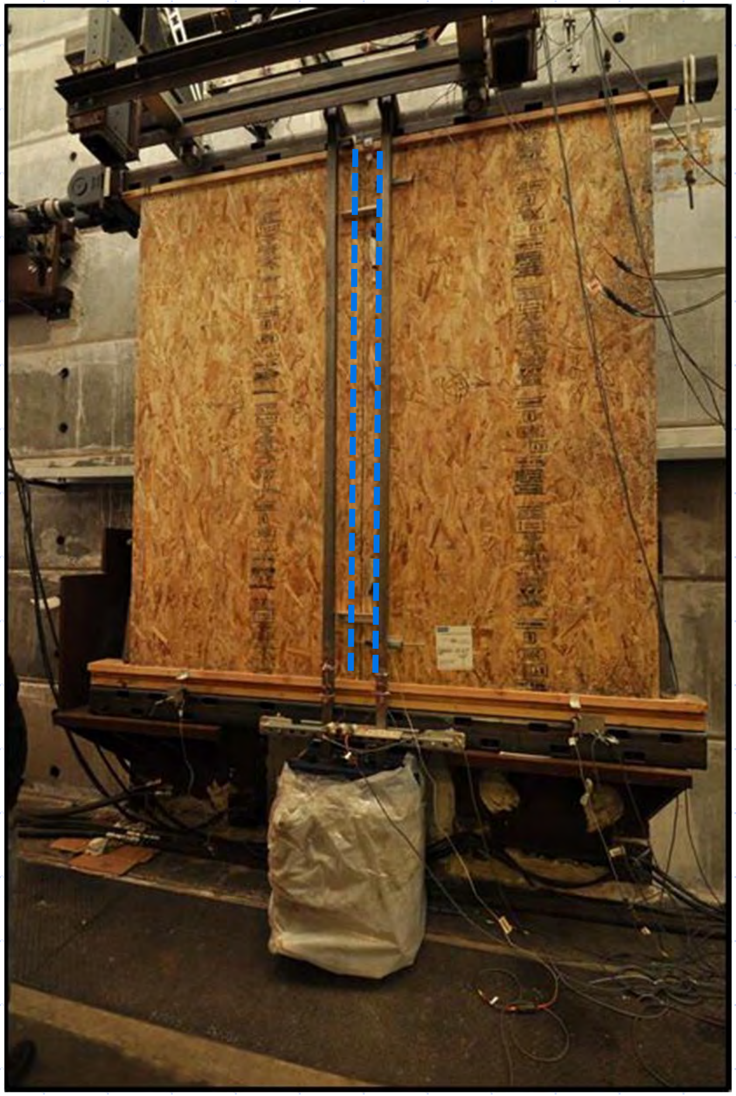
Test Specimen

7/16" OSB Skins (~11 mm)

3-5/8" EPS Insulating Foam (~92 mm)

Application I: HS of Structural Insulated Panels (SIPs)

Test Setup and Specimen



Application I: HS of Structural Insulated Panels (SIPs)

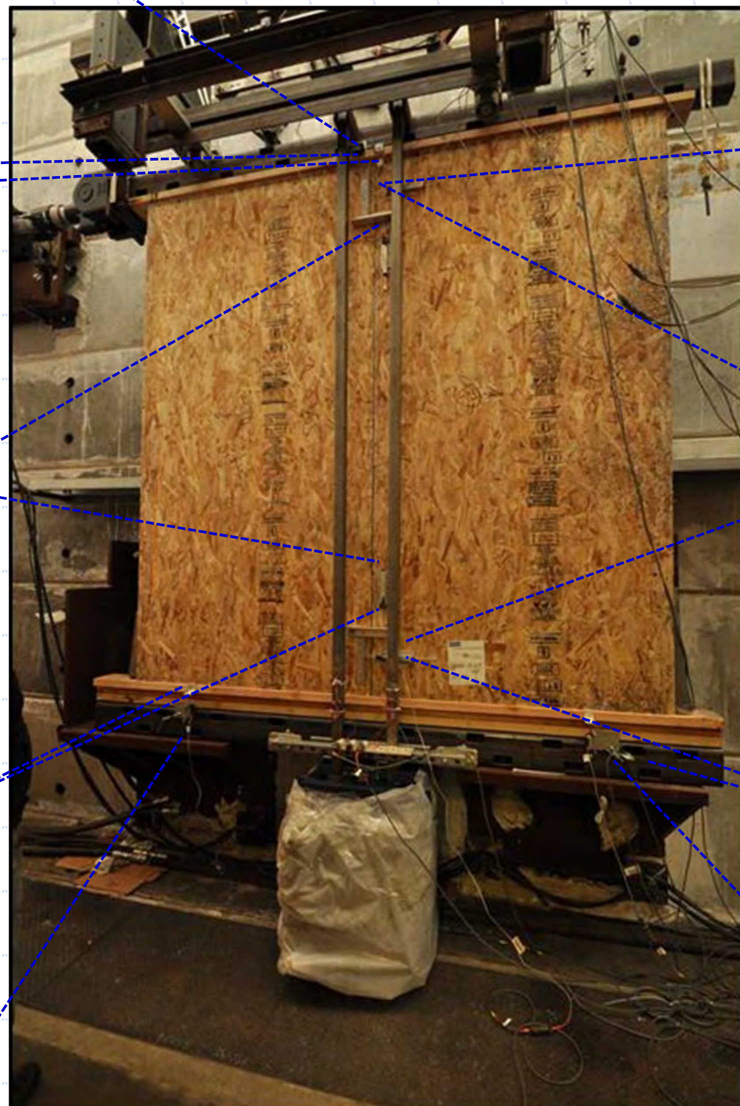
Instrumentation

Tube sliding

Top vertical sliding

Bottom vertical sliding

Left Uplift



Top gap opening

Bottom gap opening

Right Uplift

Application I: HS of Structural Insulated Panels (SIPs)

Test Matrix

Specimen	Protocol	Gravity	Nail spacing [in]	Remarks
S1	CUREE	No	6	Conventional wood panel
S2	CUREE	No	6	-
S3	CUREE	Yes	6	-
S4	HS	Yes	6	Near-fault pulse-type GM
S5	HS	Yes	3	Near-fault pulse-type GM
S6	CUREE	Yes	3	-
S7	HS	Yes	3	Long duration, harmonic GM
S8	HS	Yes	3	Near-fault GM; 3 stories computational substructure

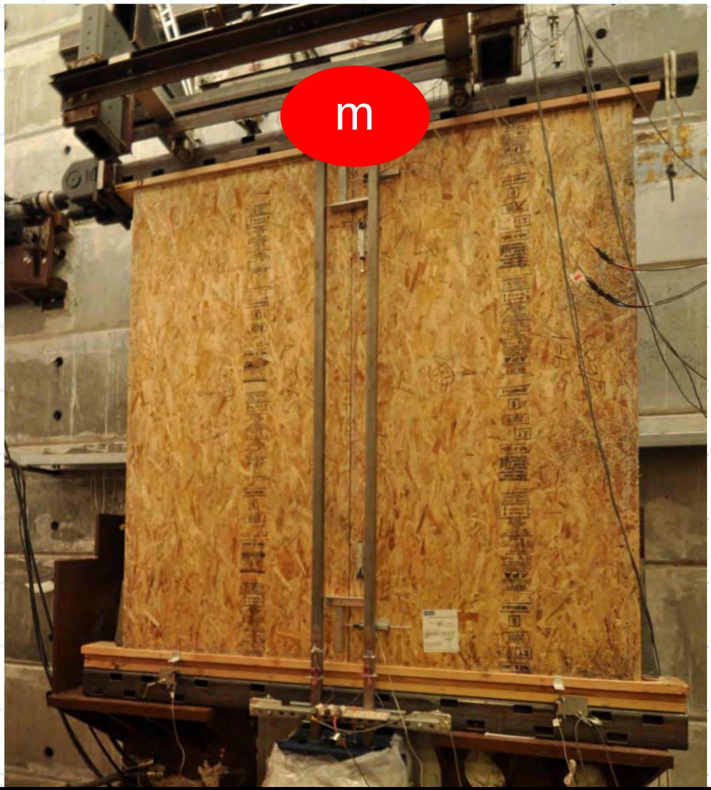
Investigate the effects of:

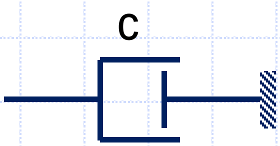
- ✓ Lateral loading: CUREE protocol vs HS
- ✓ Type of ground motion (Pulse type vs Long duration, harmonic)
- ✓ Presence of an analytical substructure

Application I: HS of Structural Insulated Panels (SIPs)

Hybrid Simulation

Specimens S4, S5, S7



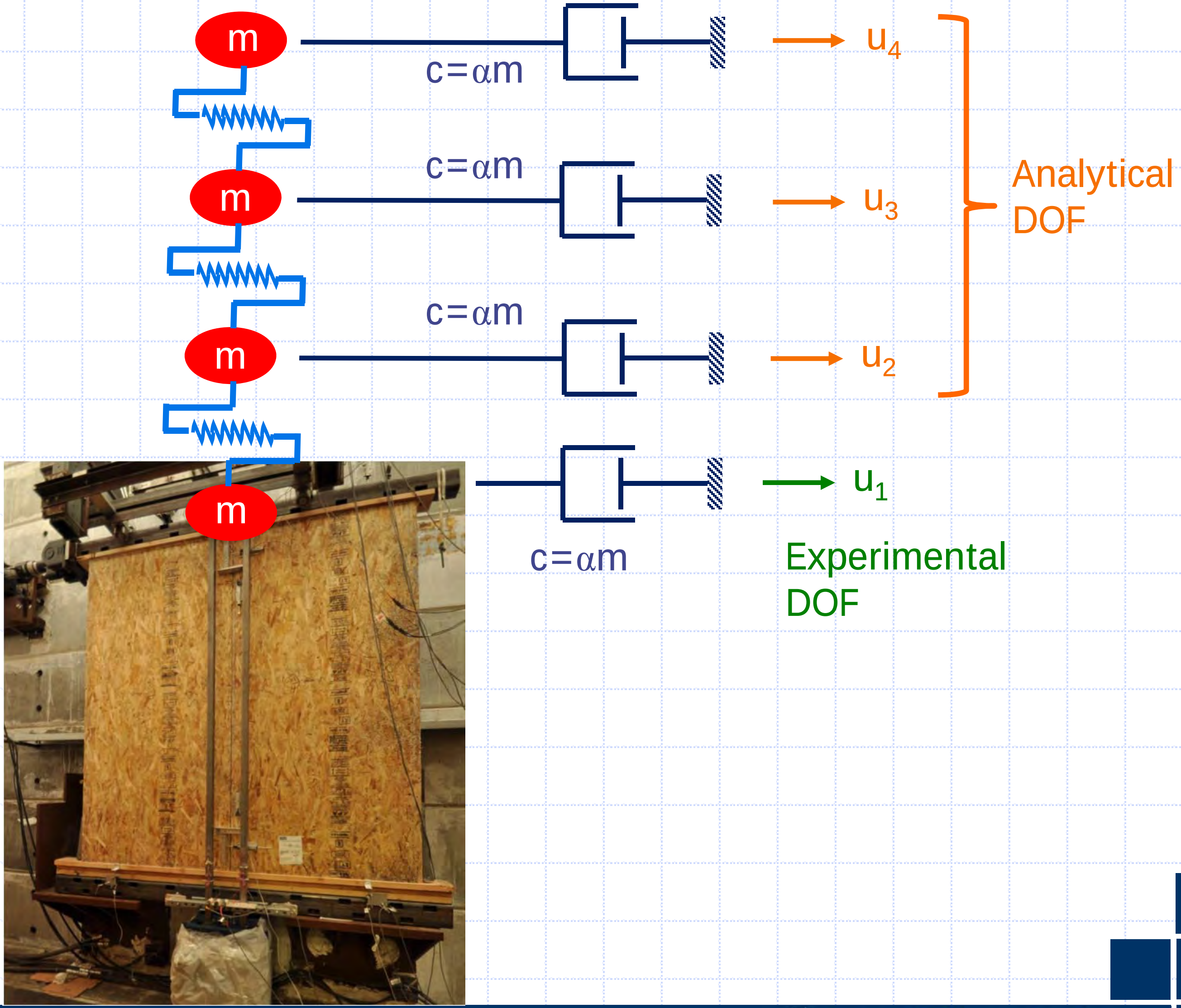


Specimen	m (kip-sec²/in)	ξ	k (kip/in)	c (kip-sec/in)	T (sec)
S4	0.0325	0.05	18	0.0076	0.27
S5	0.0325	0.05	32	0.0102	0.20
S7	0.0325	0.05	32	0.0102	0.20

Application I: HS of Structural Insulated Panels (SIPs)

Hybrid Simulation

Specimen S8



Application I: HS of Structural Insulated Panels (SIPs)

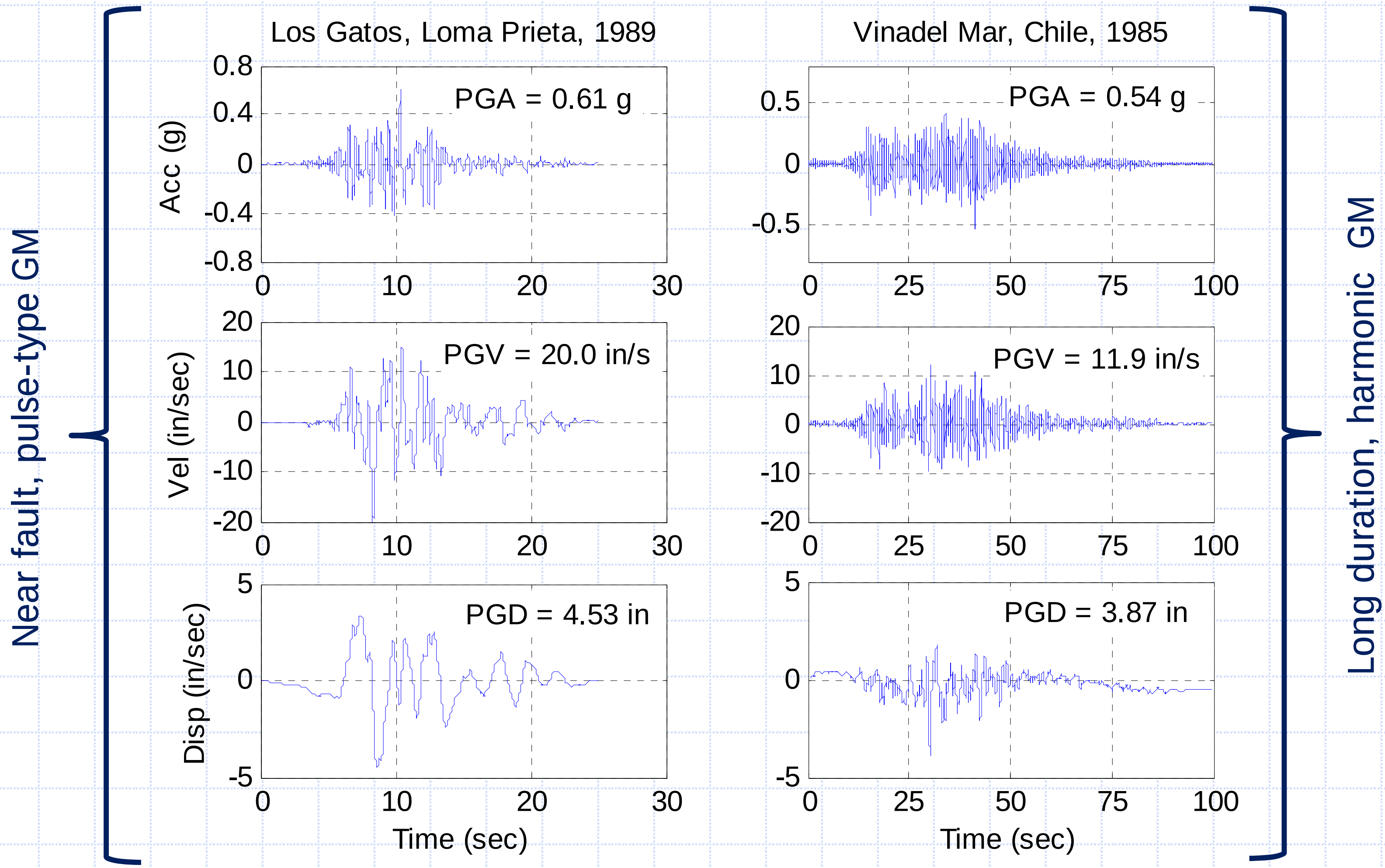
Hybrid Simulation: Numerical Integration

- Explicit Newmark Integration with $\gamma=0.5$
- Does not require iterations
- Does not require knowledge of initial experimental stiffness

Specimen	m	k	T (sec)	dt (sec)	dt / T
S4	0.0325	18	0.27	0.0050	$0.0180 \leq 1/\pi$
S5	0.0325	32	0.20	0.0050	$0.0250 \leq 1/\pi$
S7	0.0325	32	0.20	0.0125	$0.0625 \leq 1/\pi$
S8	-	-	$T_4=0.10$	0.0050	$0.0500 \leq 1/\pi$

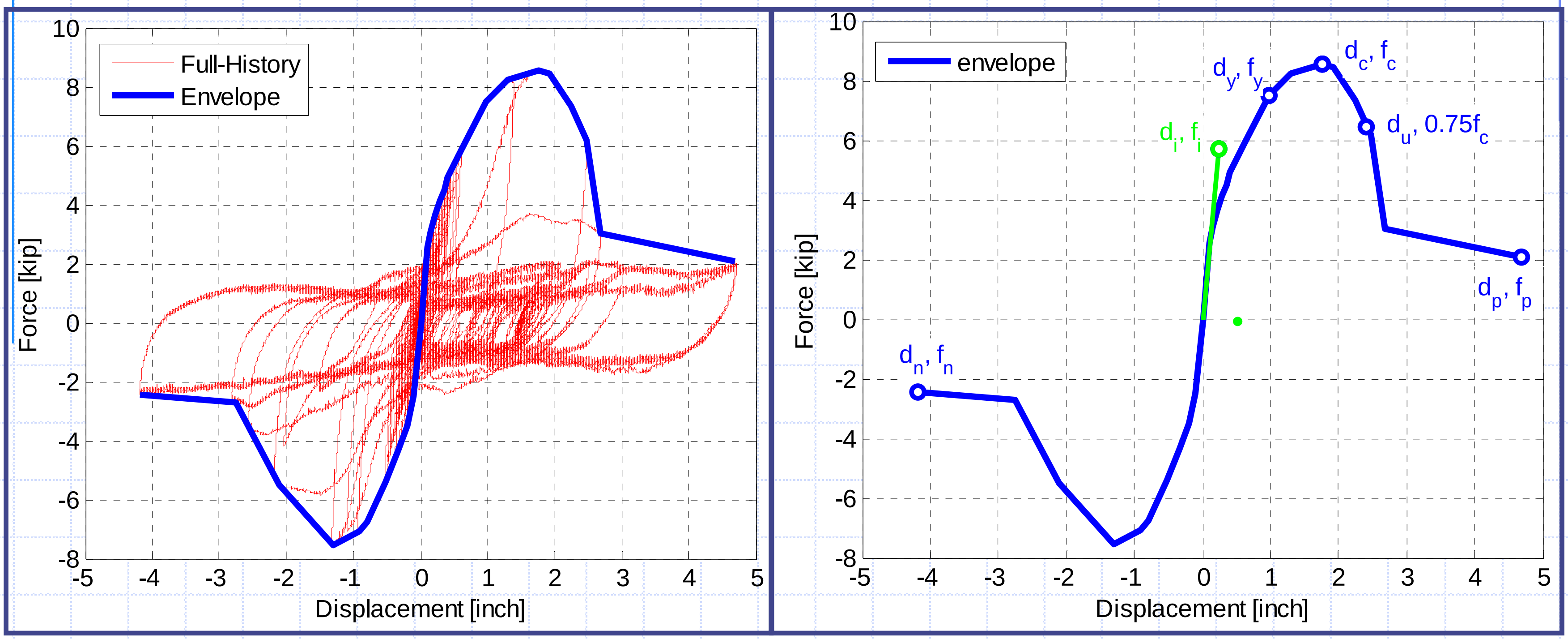
Application I: HS of Structural Insulated Panels (SIPs)

Hybrid Simulation: Ground Motions



Application I: HS of Structural Insulated Panels (SIPs)

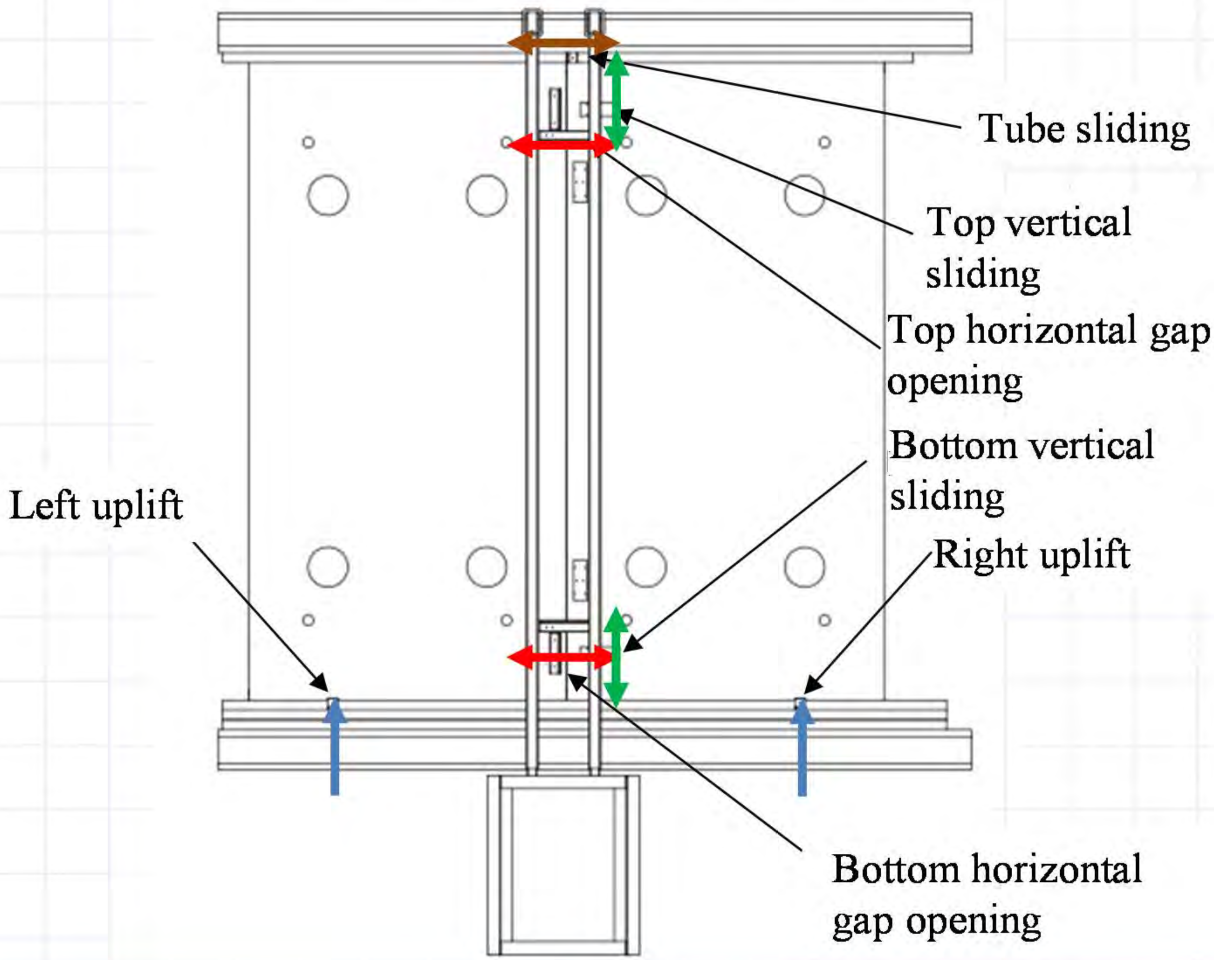
Test Results: Global Parameters



- ✓ Initial stiffness $= f_i / d_i$
- ✓ Force capacity $= f_c$
- ✓ Ductility $= d_u / d_y$
- ✓ Hysteretic energy $= \int f dx$
- ✓ Positive peak displacement $= d_p$
- ✓ Negative peak displacement $= d_n$
- ✓ Residual displacement

Application I: HS of Structural Insulated Panels (SIPs)

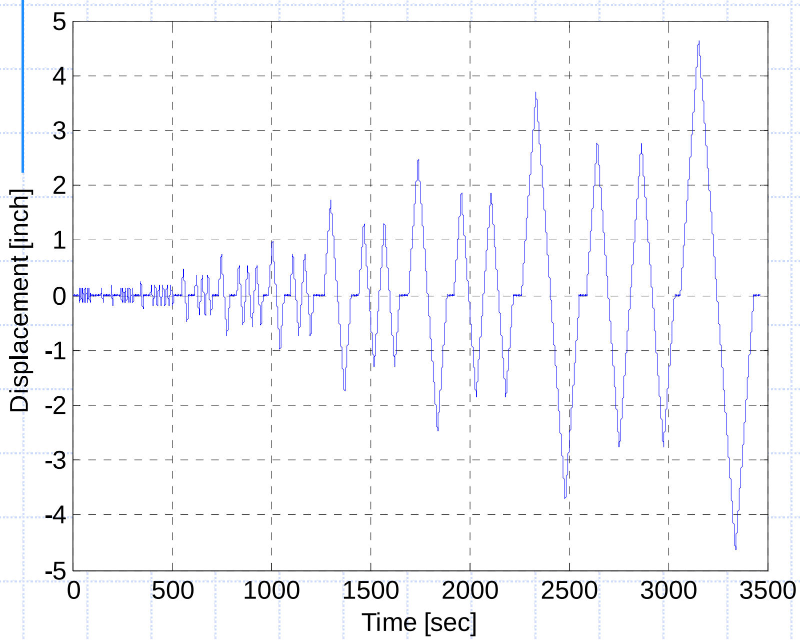
Test Results: Peaks of local responses



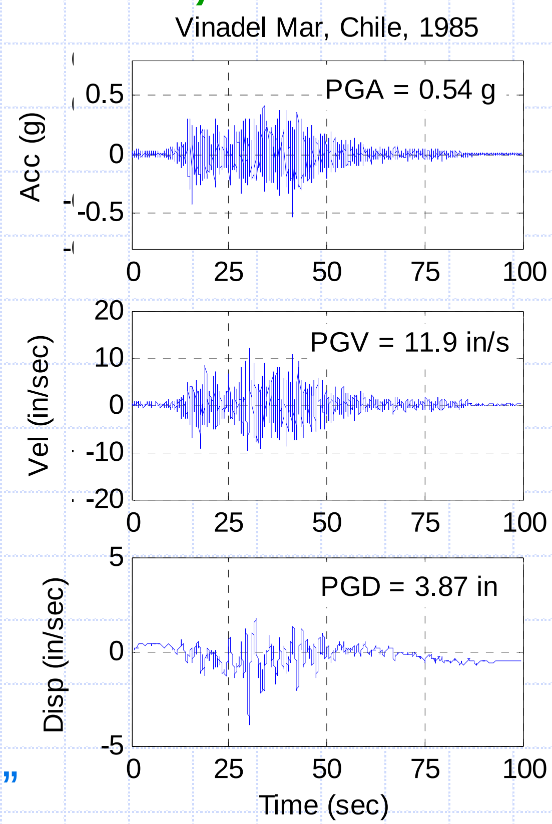
Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Lateral Loading (S6 vs S7)

Cyclic Testing with CUREE Protocol for Ordinary GM (S6)



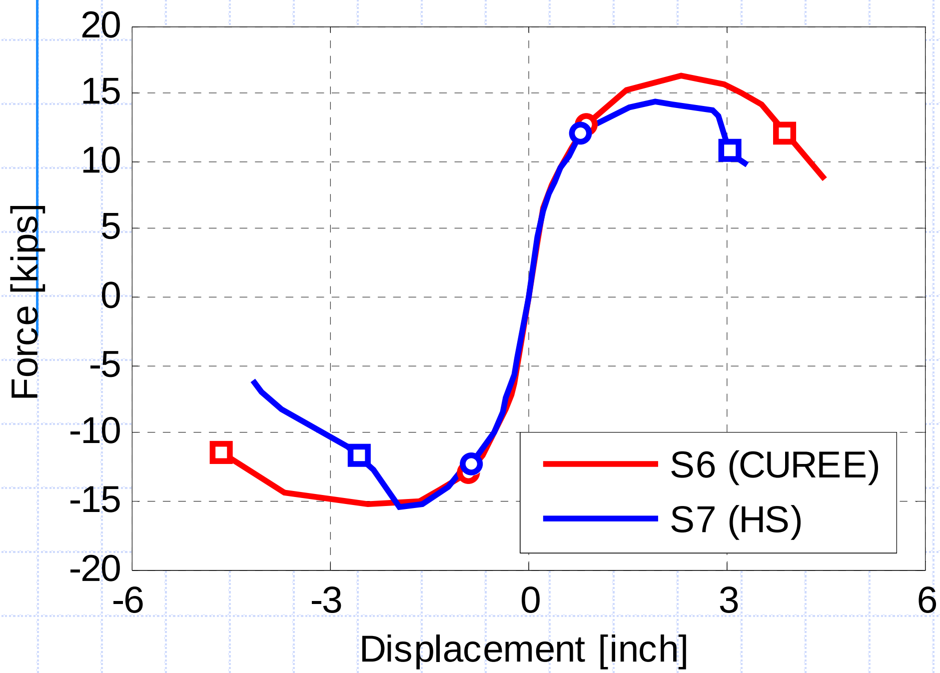
Hybrid Simulation with Long Duration, Harmonic GM (S7)



Nail spacing: 3”

Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Lateral Loading (S6 vs S7)



Specimen	S6	S7
Initial Stiffness [kip/in]	32.7	33.2
Force Capacity [kip]	16.2	15.5
Ductility	4.8	3.4
Hysteretic Energy [kip-in]	309.9	1077.8

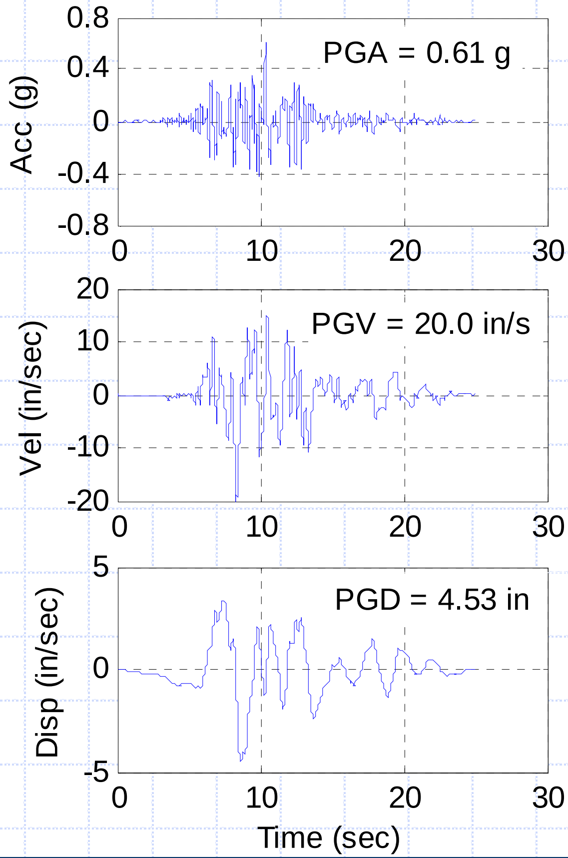
Specimen	S6	S7
Peak Disp. (+)	4.7	3.3
Peak Disp. (-)	-4.7	-4.2
Residual Disp.	0.0	0.3

Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Ground Motion Type (S5 vs S7)

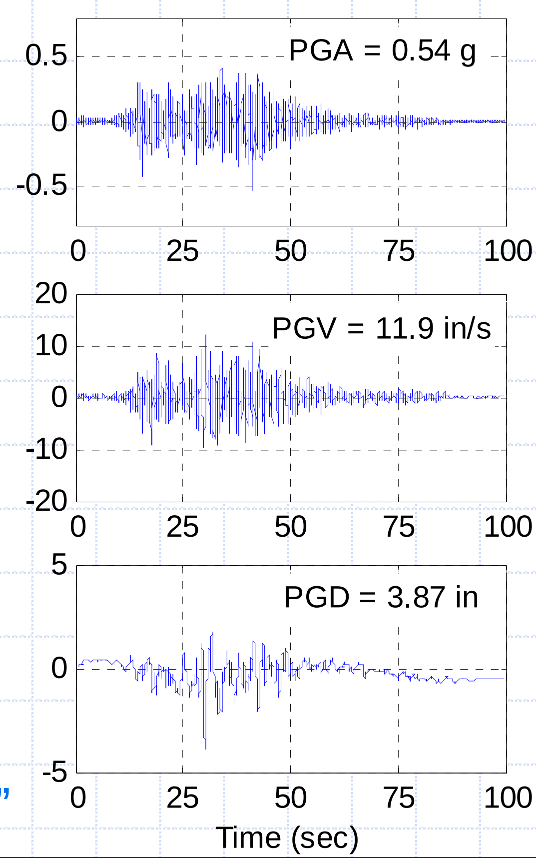
Hybrid Simulation with Pulse-Type GM (S5)

Los Gatos, Loma Prieta, 1989



Hybrid Simulation with Long Duration, Harmonic GM (S7)

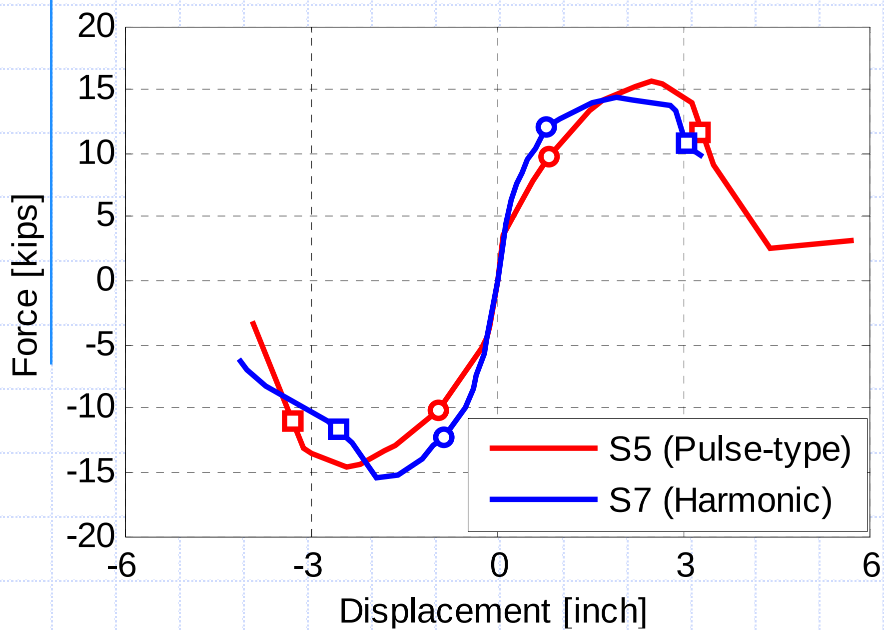
Vinadel Mar, Chile, 1985



Nail spacing: 3”

Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Ground Motion Type (S5 vs S7)

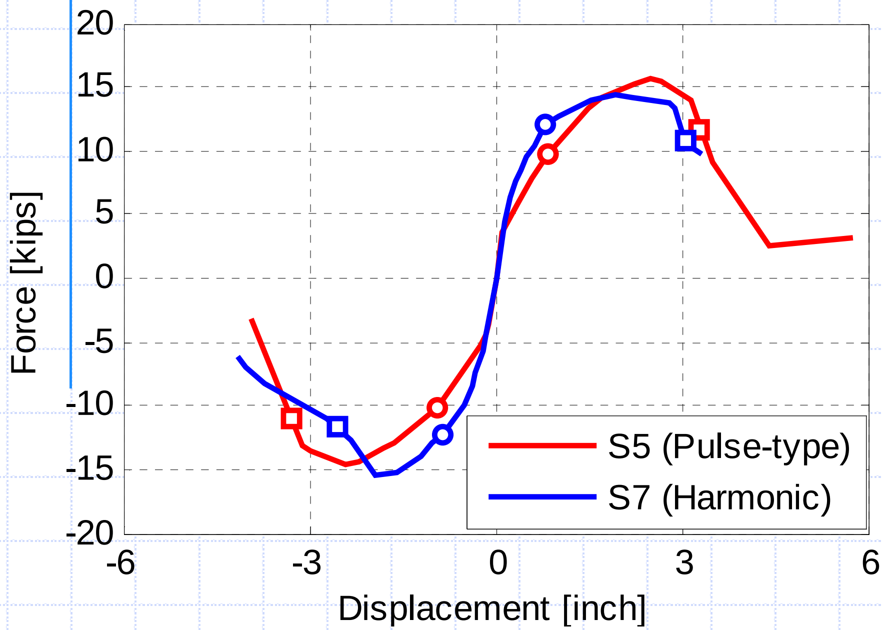


Specimen	S5	S7
Initial Stiffness [kip/in]	35.5	33.2
Force Capacity [kip]	15.6	15.5
Ductility	3.7	3.4
Hysteretic Energy [kip-in]	363.1	1077.8

Specimen	DE		MCE		1.5MCE	
	S5	S7	S5	S7	S5	S7
Peak Disp. (+)	1.3	1.1	3.5	2.2	5.8	3.3
Peak Disp. (-)	-1.0	-1.0	-3.2	-2.0	-	-4.2
Residual Disp.	0.1	0.0	0.8	0.0	-	0.3

Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Ground Motion Type (S5 vs S7)

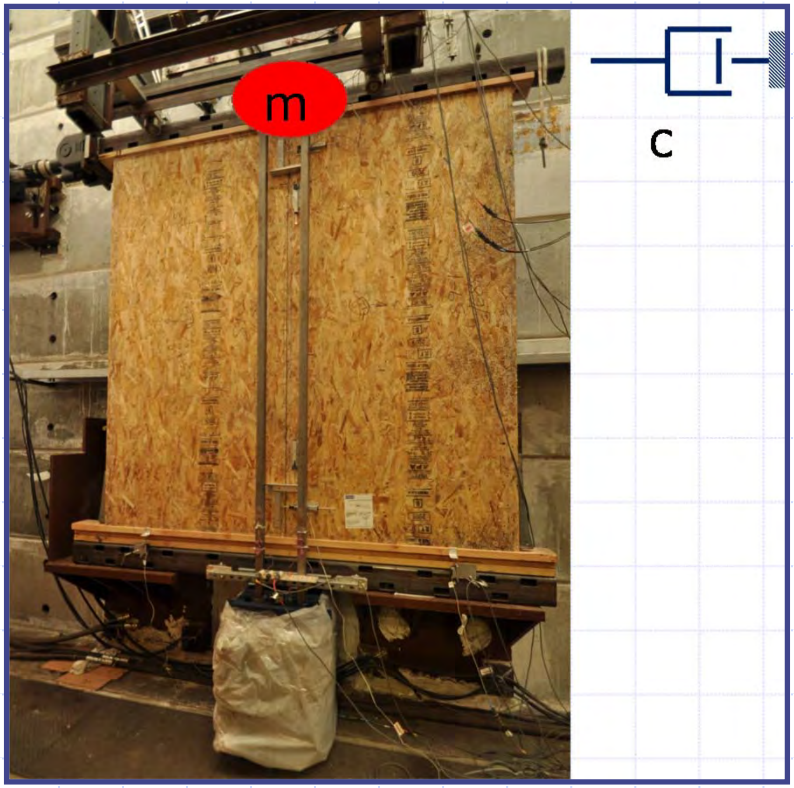


Specimen	DE		MCE		1.5MCE	
	S5	S7	S5	S7	S5	S7
Peak Disp. (+)	1.3	1.1	3.5	2.2	5.8	3.3
Peak Disp. (-)	-1.0	-1.0	-3.2	-2.0	-	-4.2
Residual Disp.	0.1	0.0	0.8	0.0	-	0.3

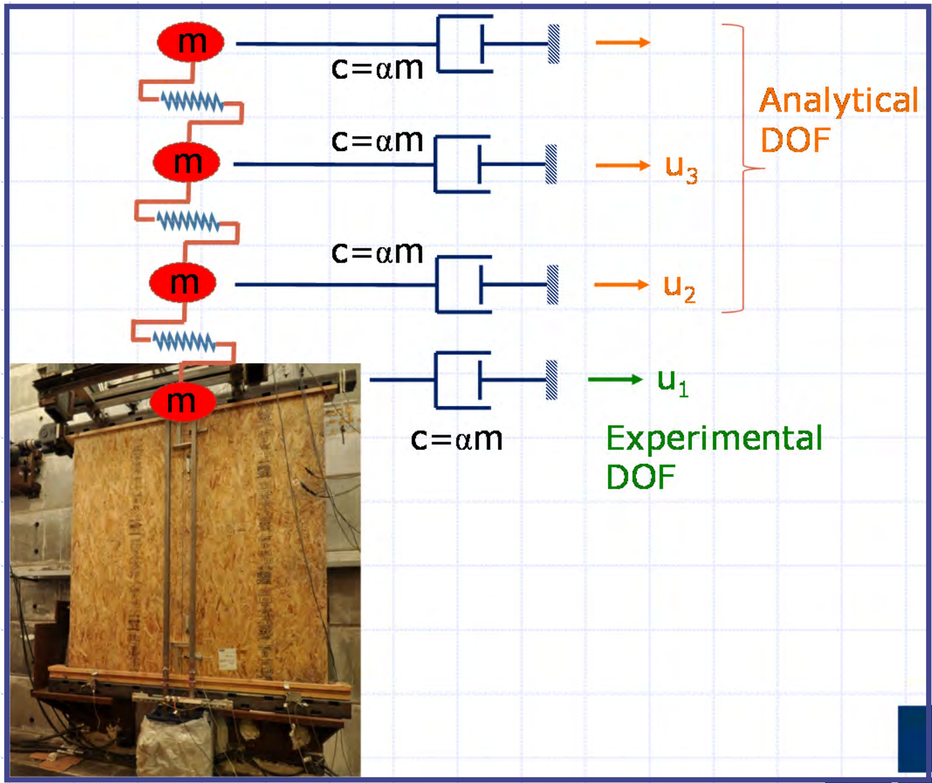
Specimen		Bottom ver. sliding	Bottom gap opening	Top ver. sliding	Top gap opening	Uplift right	Uplift left	Tube sliding
DE	S5	0.26	0.02	0.27	0.03	0.08	0.07	0.18
	S7	0.23	0.02	0.21	0.02	0.15	0.04	0.02
MCE	S5	0.63	0.05	0.64	0.09	0.14	0.12	0.19
	S7	0.45	0.03	0.43	0.04	0.53	0.09	0.06

HS Results: Effect of Analytical Substructuring (S5 vs S8)

Hybrid Simulation with no Analytical Substructure (S5)



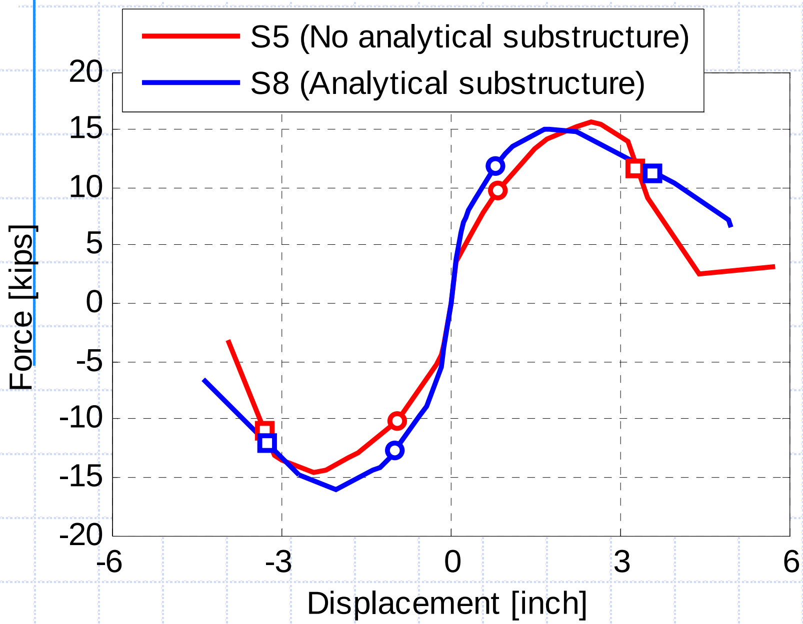
Hybrid Simulation with Analytical Substructure (S8)



Pulse-Type GM

Application I: HS of Structural Insulated Panels (SIPs)

HS Results: Effect of Analytical Substructuring (S5 vs S8)



Specimen	S5	S8
Initial Stiffness [kip/in]	35.5	38.3
Force Capacity [kip]	15.6	16.0
Ductility	3.7	4.0

Specimen	DE		MCE	
	S5	S8	S5	S8
Peak Disp. (+)	1.3	1.2	3.5	2.4
Peak Disp. (-)	-1.0	-1.7	-3.2	-3.1
Residual Disp.	0.1	0.0	0.8	0.4

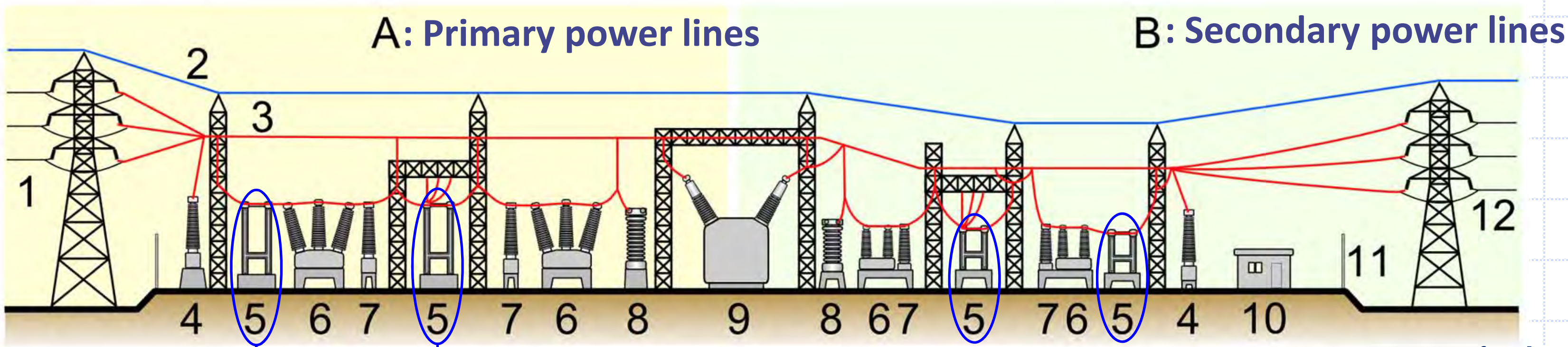
Specimen		Bottom ver. sliding	Bottom gap opening	Top ver. sliding	Top gap opening	Uplift right	Uplift left	Tube sliding
DE	S5	0.26	0.02	0.27	0.03	0.08	0.07	0.18
	S8	0.37	0.03	0.37	0.04	0.09	0.11	0.13
MCE	S5	0.63	0.05	0.64	0.09	0.14	0.12	0.19
	S8	0.65	0.03	0.55	0.05	0.16	0.27	0.14

Application I: HS of Structural Insulated Panels (SIPs)

Concluding Remarks

- HS provides the force-deformation envelope that can also be obtained from a cyclic test. But it also provides response values, where the cyclic test would require complimentary analytical simulations for these values.
- HS with harmonic ground motion provides a slightly more degraded post-yield response than the CUREE protocol due to the large number of cycles demanded by the harmonic ground motion.
- Based on global and local displacements, near-fault pulse-type GM is more critical & damaging for SIPs compared to long duration GM with many cycles.
- Although the global and local responses of SIPs with and without analytical substructuring are not dramatically different, there is a need for analytical substructuring for a more realistic dynamic representation.

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table



* Courtesy of Wikipedia

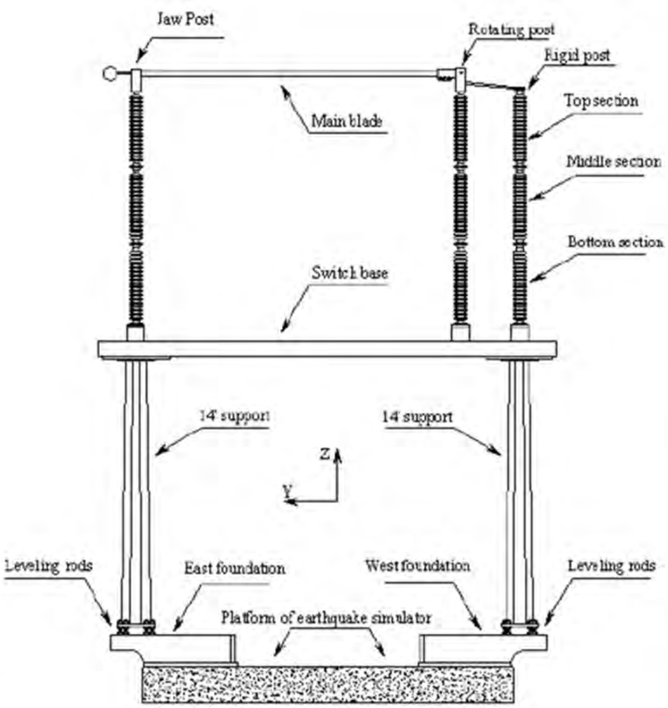
1. Primary power lines
2. Ground wire
3. Overhead lines
4. Transformer
5. Disconnect switch
6. Circuit breaker
7. Current transformer
8. Lightning arrester
9. Main transformer
10. Control building
11. Security fence
12. Secondary power lines

Disconnect switches are key components of power transmission and distribution systems.

Major elements of an electrical substation (distribution substation shown)

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

1. Disconnect switches: Key components of power transmission & distribution systems to control flow of electricity between substation equipment & to isolate them for maintenance.
2. Seismic qualification tests in typical field installation according to IEEE 693 (Recommended Practices for Seismic Design of Substations) requirements.

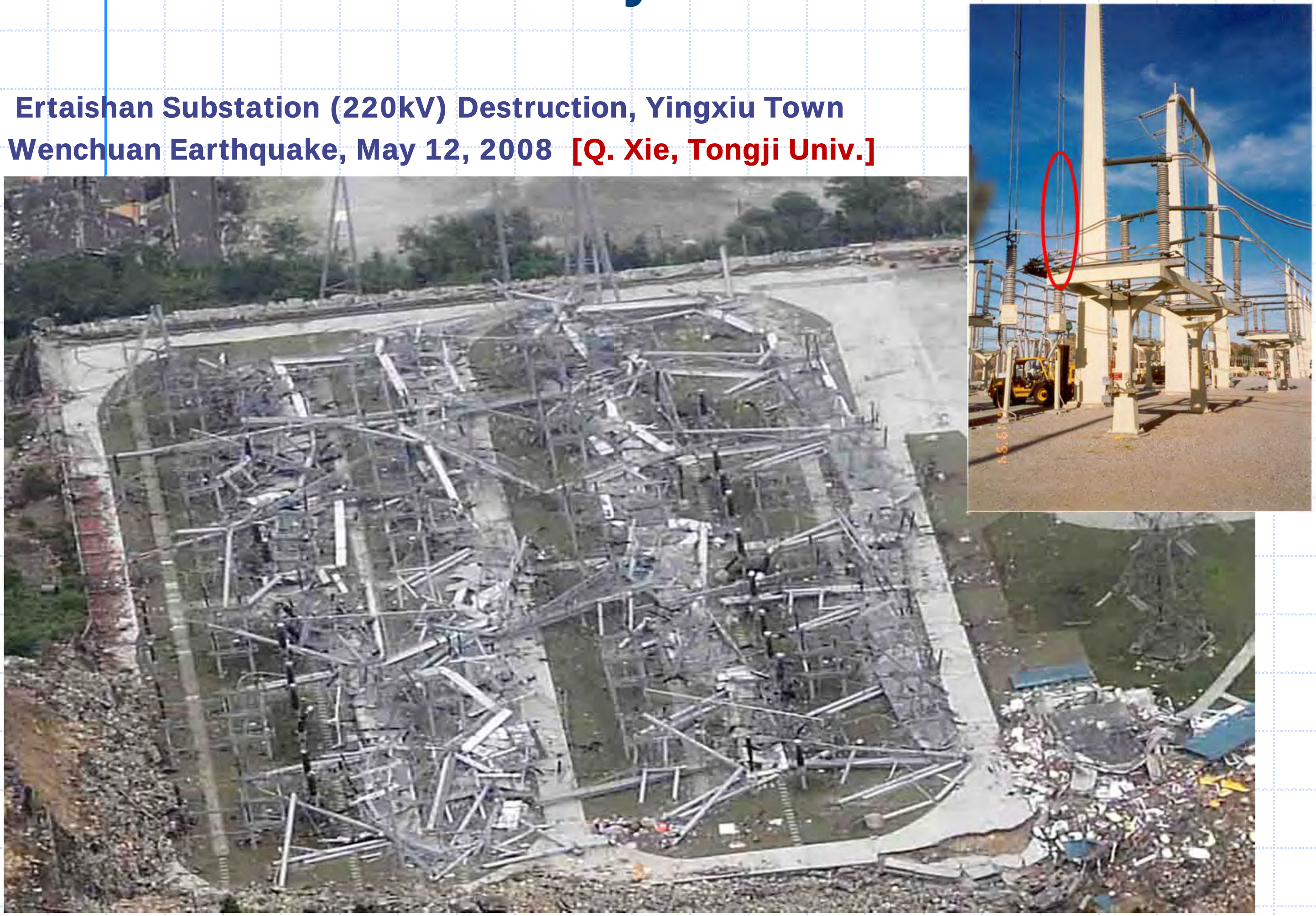


Typical field installation of vertical-break 500-kV disconnect 3-phase switch

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Motivation for Hybrid Simulation

Ertaishan Substation (220kV) Destruction, Yingxiu Town
Wenchuan Earthquake, May 12, 2008 [Q. Xie, Tongji Univ.]



EQ damage to 500 kV vertical disconnect switch [E. Fujisaki, PG&E]

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Motivation for Hybrid Simulation

500 kV switch

230 kV switch

IEEE693 requires seismic qualification of disconnect switches by shaking table tests →
A disconnect switch & its support structure should be mounted to a shaking table & tested

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Several tested configurations

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

500-kV switch testing

Support structure identification tests (stiffness & frequency) with two typical installation:

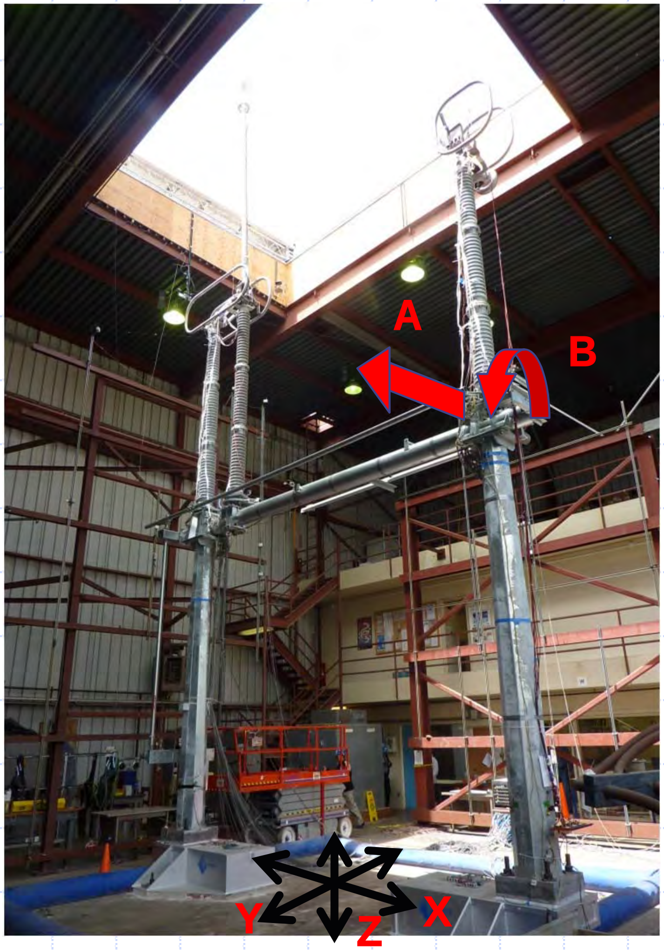
- **a) Leveling bolts, no grout**
- **b) Leveling bolts with space packed with grout**

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

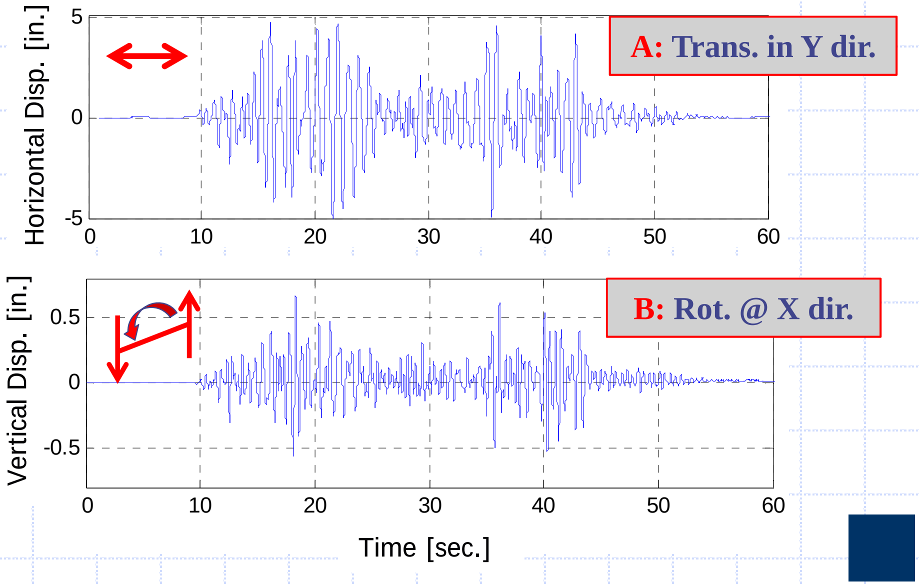
Sub-structuring tests w/o support structure in different configurations

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

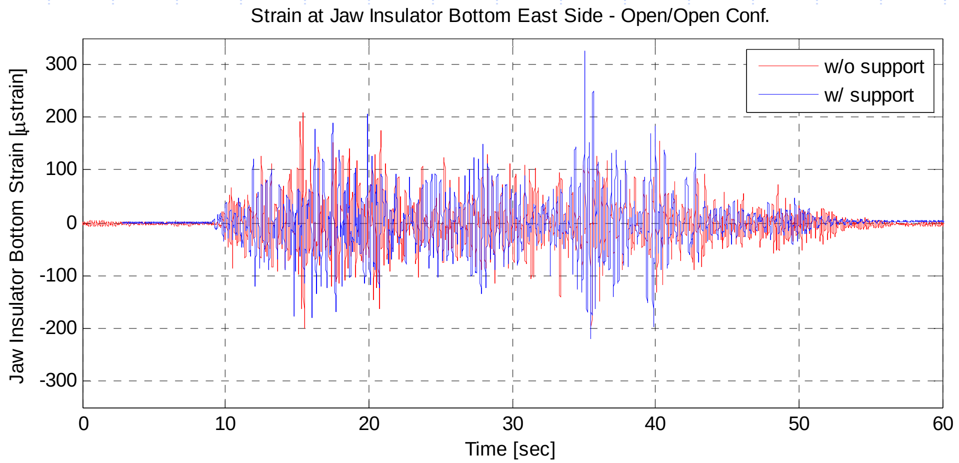
Test w/ support structure

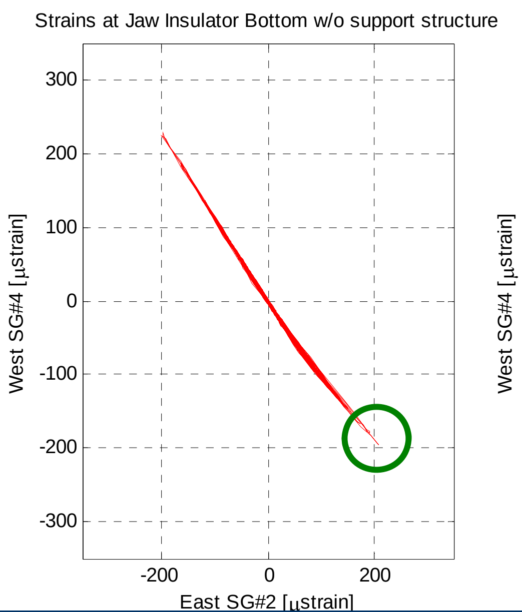


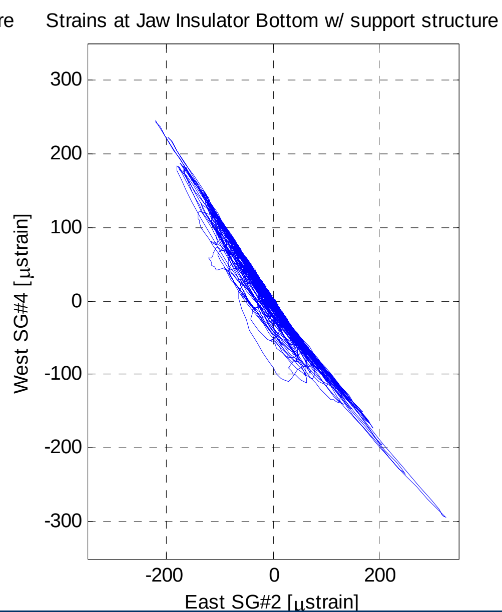
Test w/o support structure



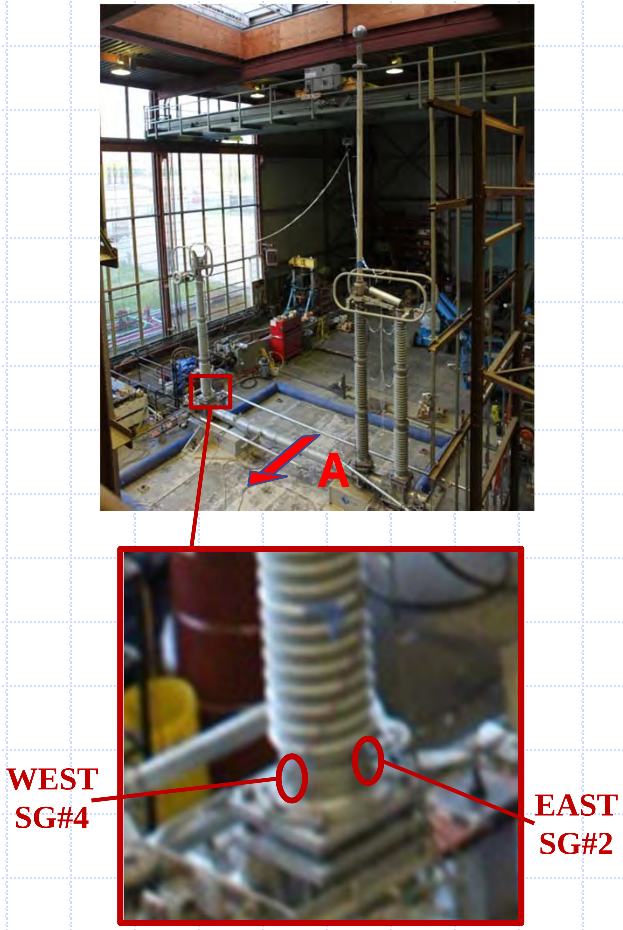
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table



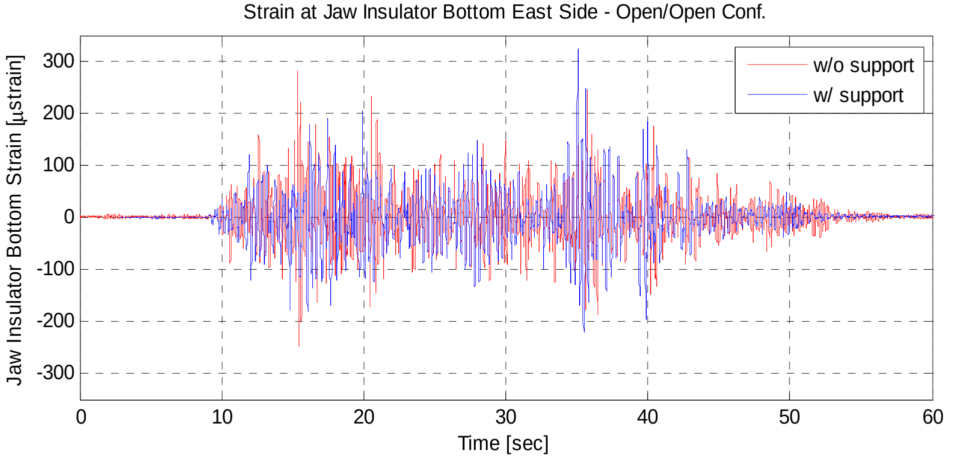


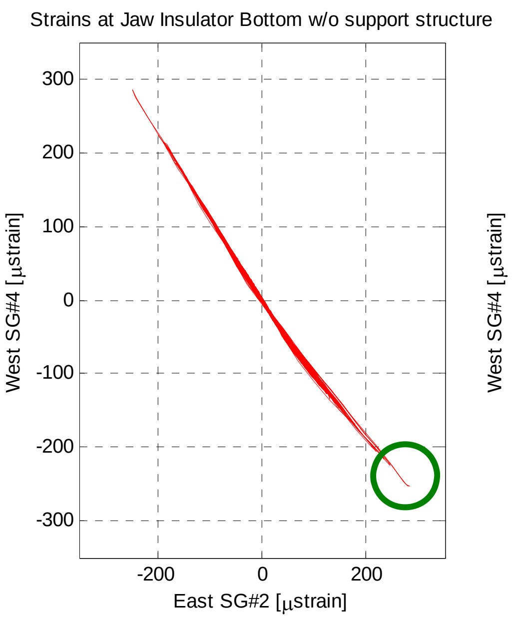


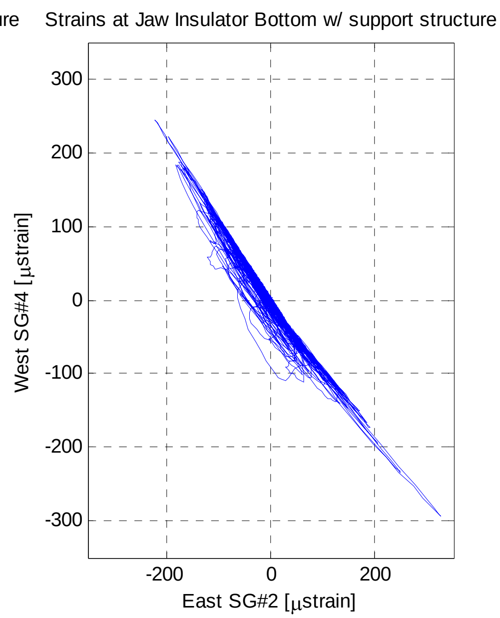
Y-direction Input
(**Signal A only**)



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

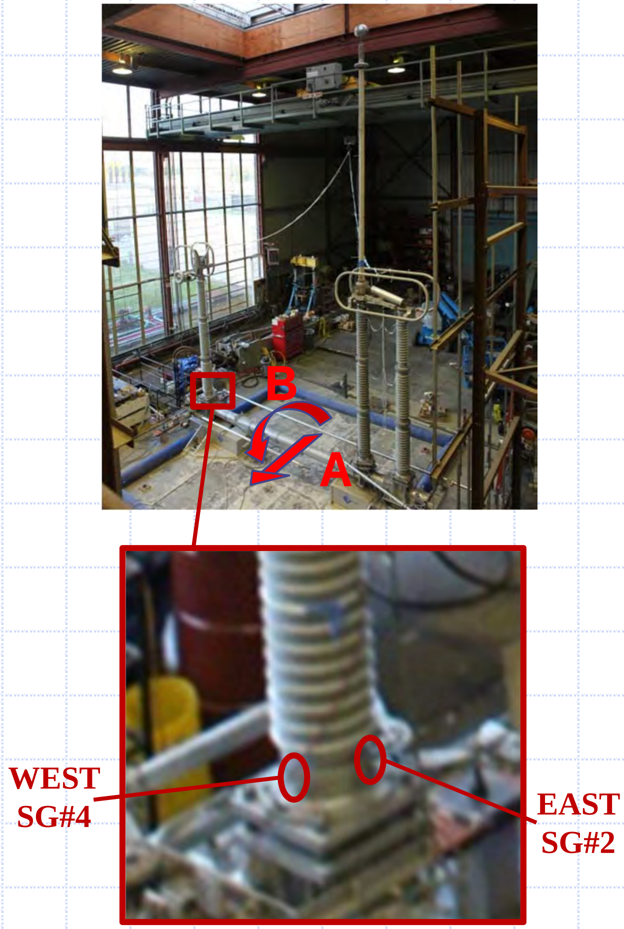






Y-direction + Rotation Input

(**Signals A + B**)



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

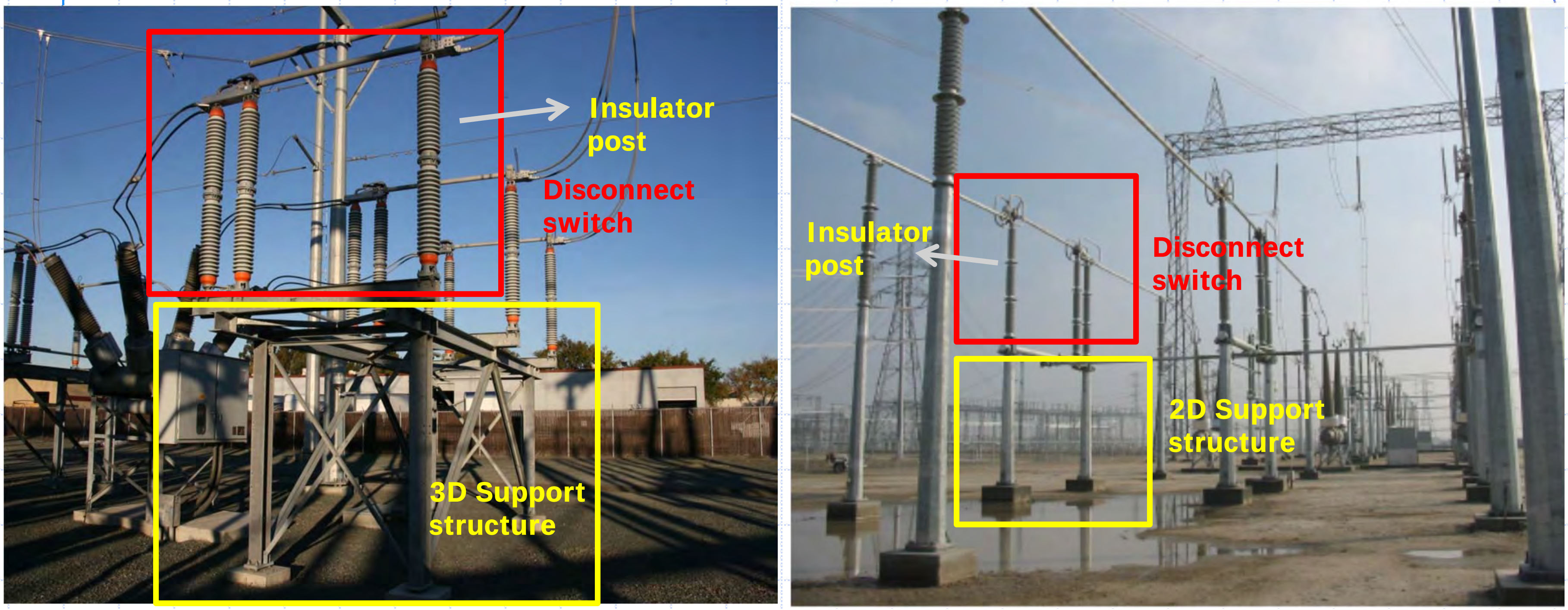
Motivation for Hybrid Simulation

- Hybrid simulation: a cost effective and efficient alternative to the conventional shaking table testing of the disconnect switches
- Requirement for real-time: Rate-dependency of some types of insulator posts, e.g. polymer composite insulators, mandates use of RTHS
- Requirement for a shaking table configuration: Distributed mass of insulator posts prevents practical use of actuators at discrete locations along the height & requires RTHS conducted on shaking table configurations.

→ **A RTHS system is developed for testing insulator posts of high voltage disconnect switches on a "smart" shaking table**

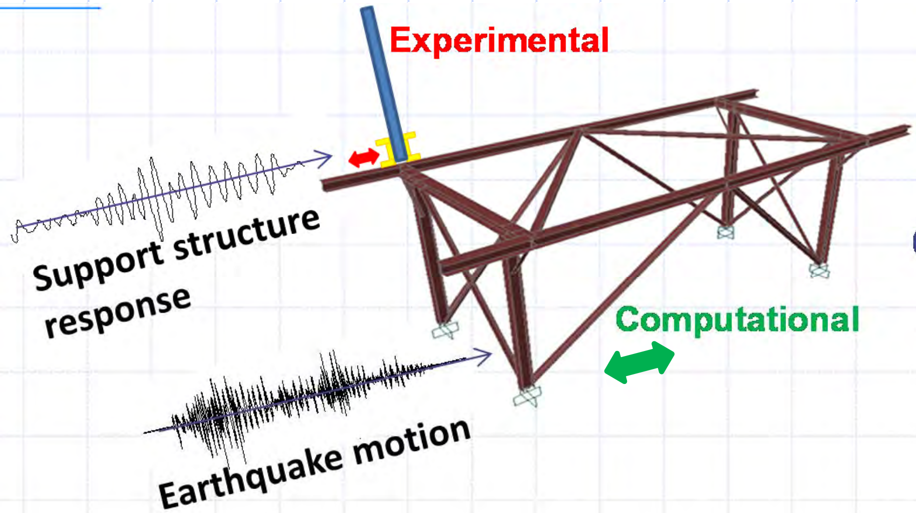
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

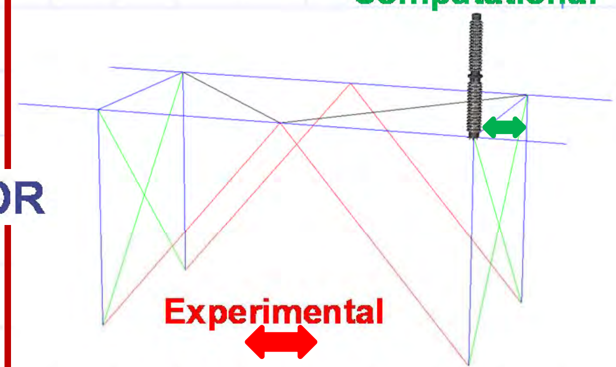


For benefits of HS: Support structures → computational substructures & insulator posts → physical substructures

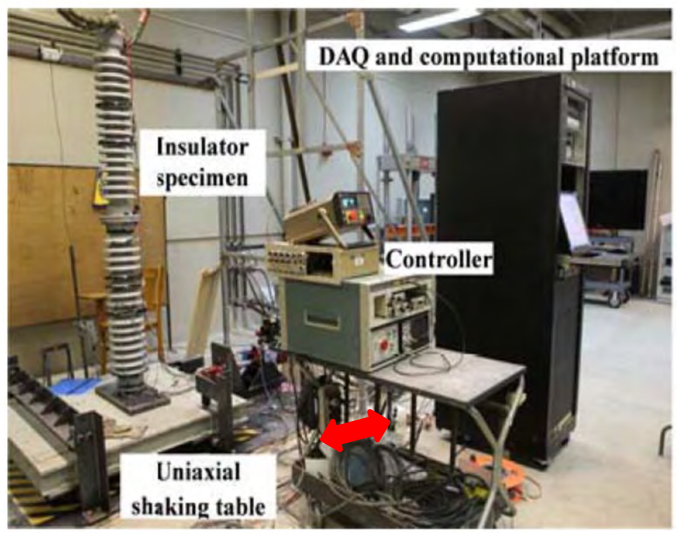
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

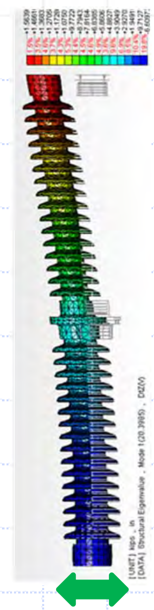


OR



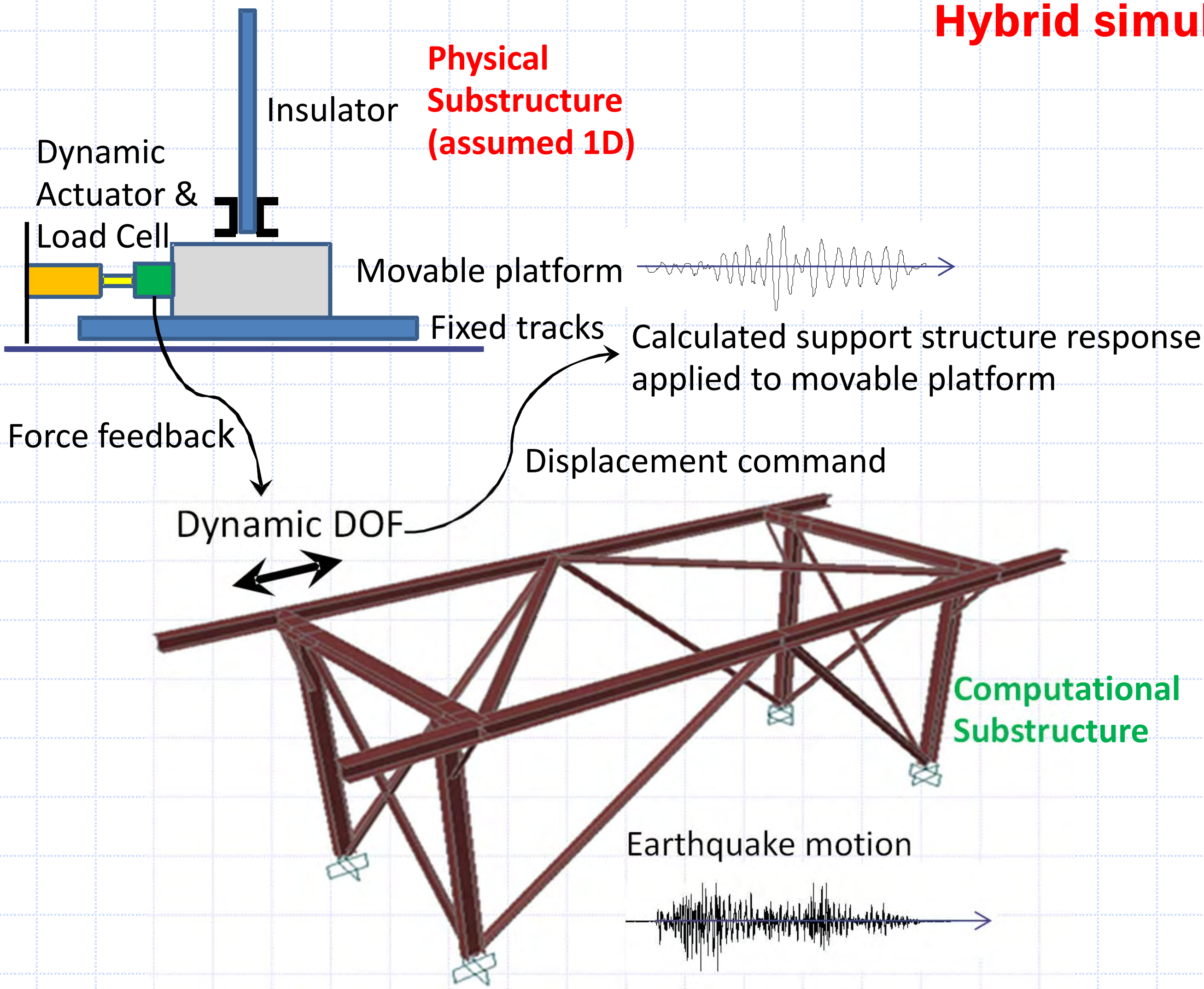
A method of analysis where a structure is split into physical and numerical substructures





Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

RTHS: Real Time Hybrid simulation



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Comparison RTHS vs. Shaking Table tests

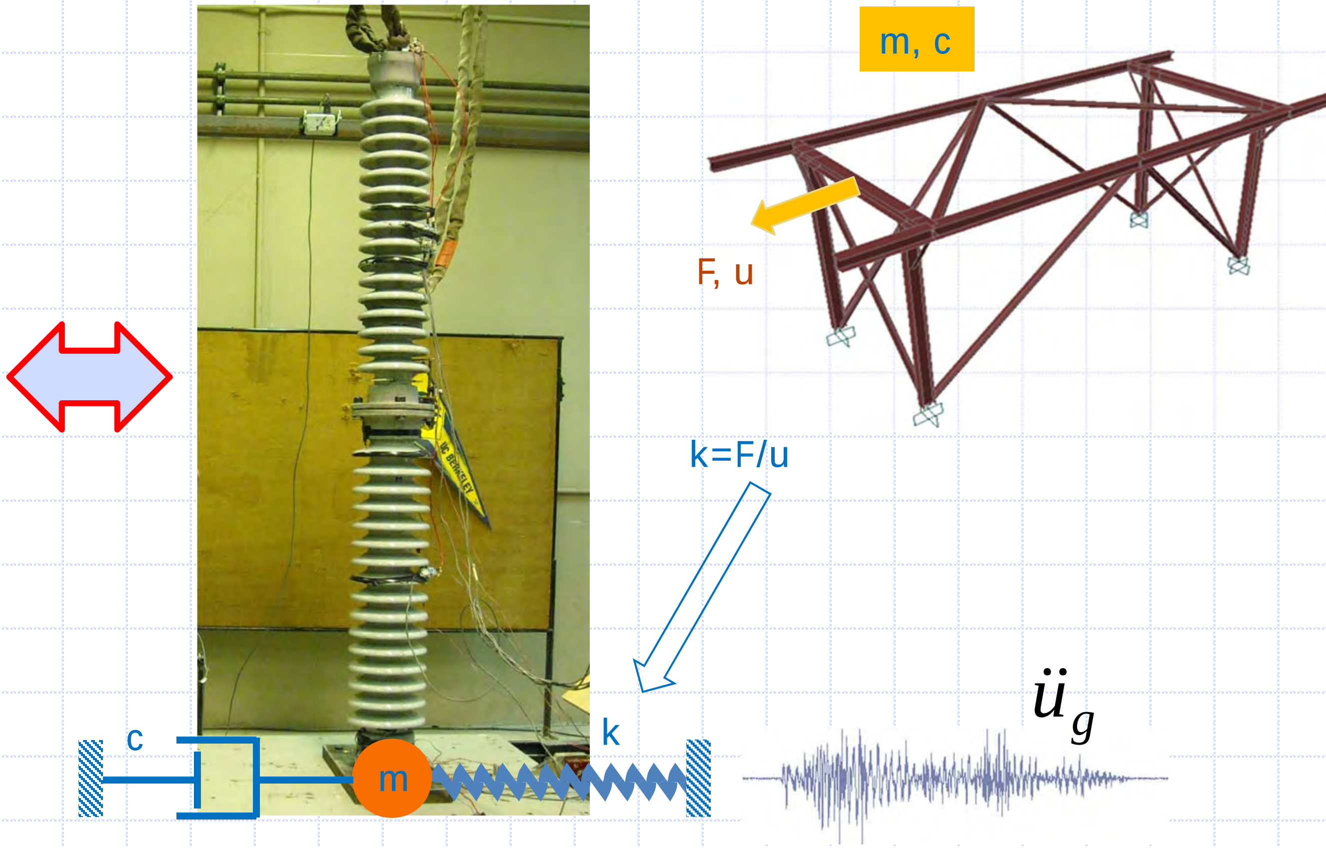
vs.

RTHS test (UC Berkeley, 2011)

Full switch shaking table test (PEER, 2008)

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

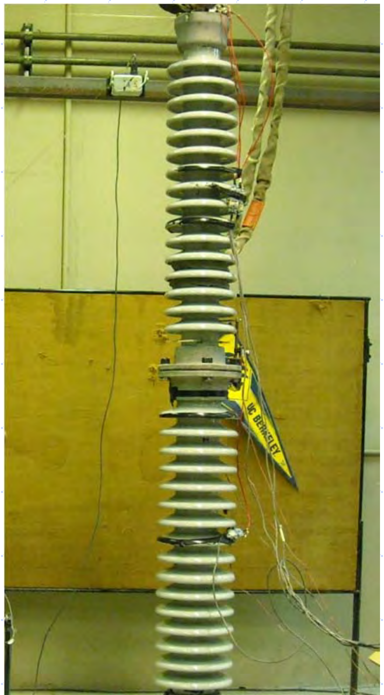
Real-time Hybrid Simulation System



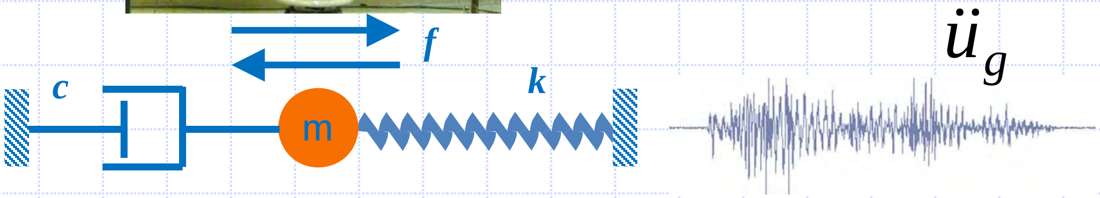
m, k, & c: mass, spring, & damping constant for SDOF system representing support frame

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System



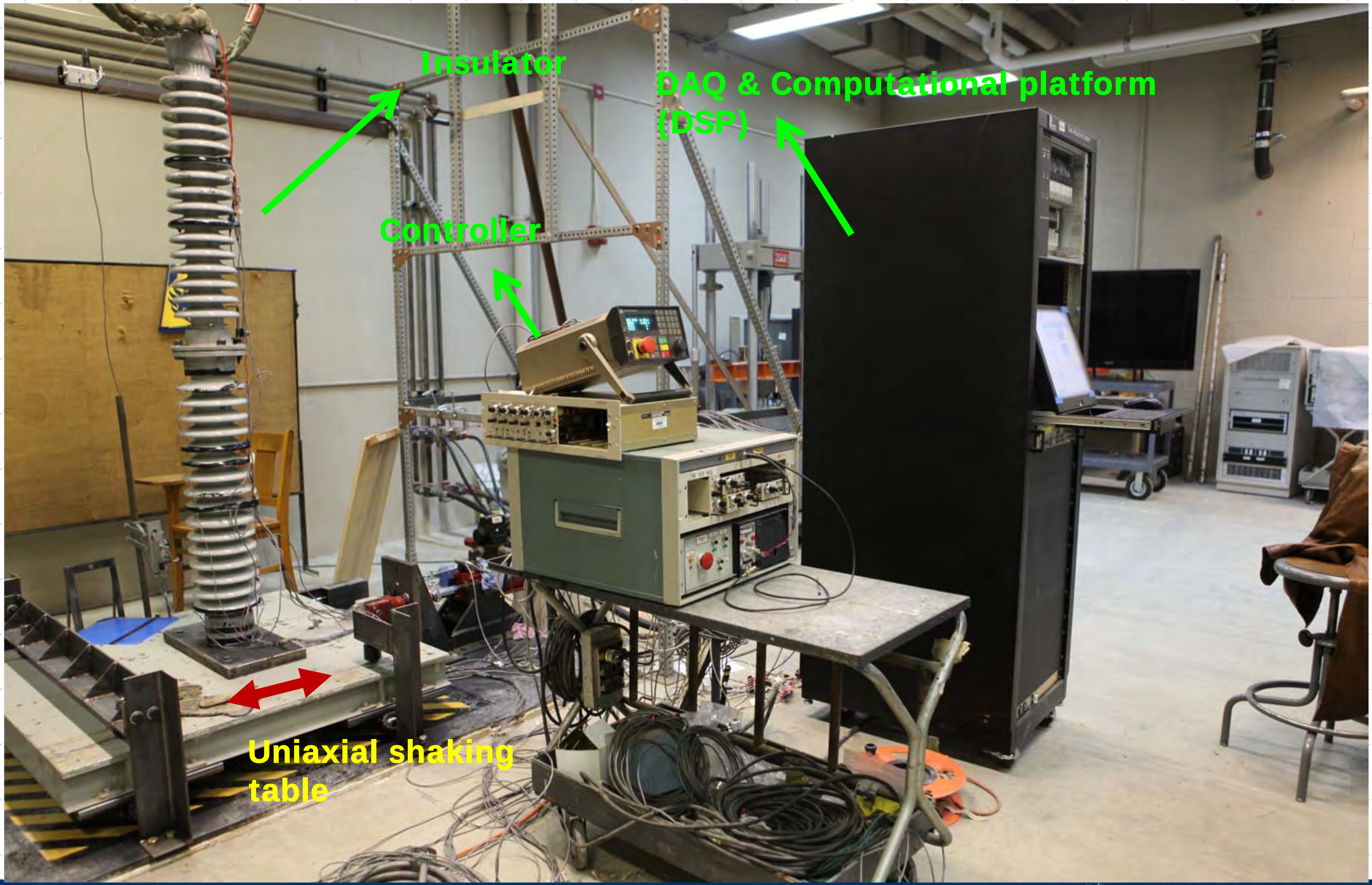
$$ma + cv + ku - f = -m\ddot{u}_g$$



Force f includes inertia & damping forces acting on the insulator since HS is conducted in real time

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Computational Algorithm: Explicit Newmark Integration

$$\text{Initialize}\, u_0, \dot{u}_0, \ddot{u}_0, m_{eff} = m + \Delta t \times \gamma \times c, i = 1$$

1) $\tilde{\dot{u}}_i = \dot{u}_{i-1} + \Delta t \times (1-\gamma) \times \ddot{u}_{i-1}$

2) $u_i = u_{i-1} + \Delta t \times \dot{u}_{i-1} + \left(\Delta t^2 / 2\right) \times \ddot{u}_{i-1}$

3) Apply u_i & Measure f_i

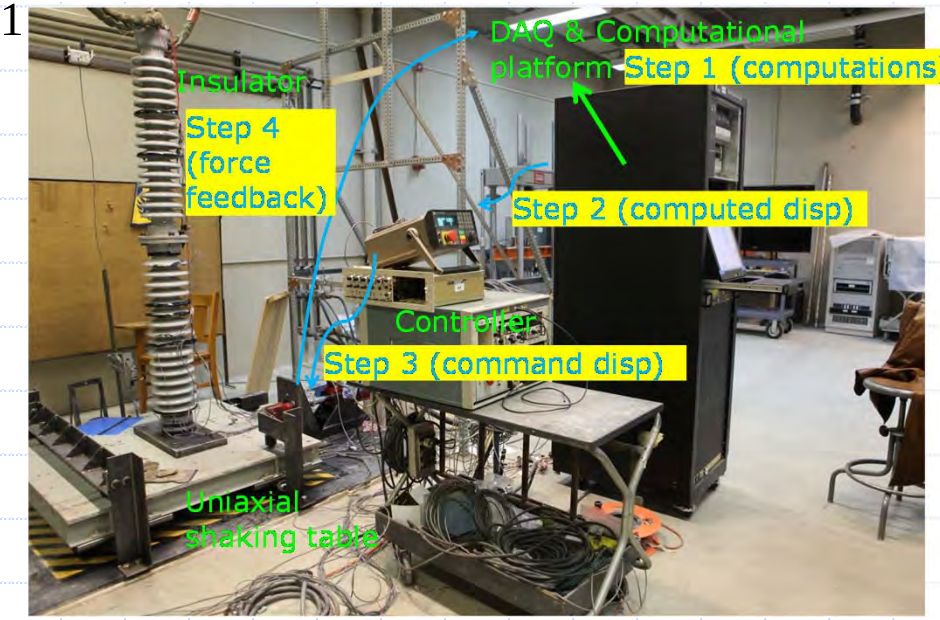
4) $p_{eff} = -m\,\ddot{u}_{g_i} - k\,u_i + f - c\,\tilde{\dot{u}}_i$

5) $\ddot{u}_i = p_{eff} / \left(m_{eff} + m_{table}\right)$

6) $\dot{u}_i = \tilde{\dot{u}}_i + \Delta t \times \gamma \times \ddot{u}_i$

7) Set $i = i + 1$

8) Go to Step 1

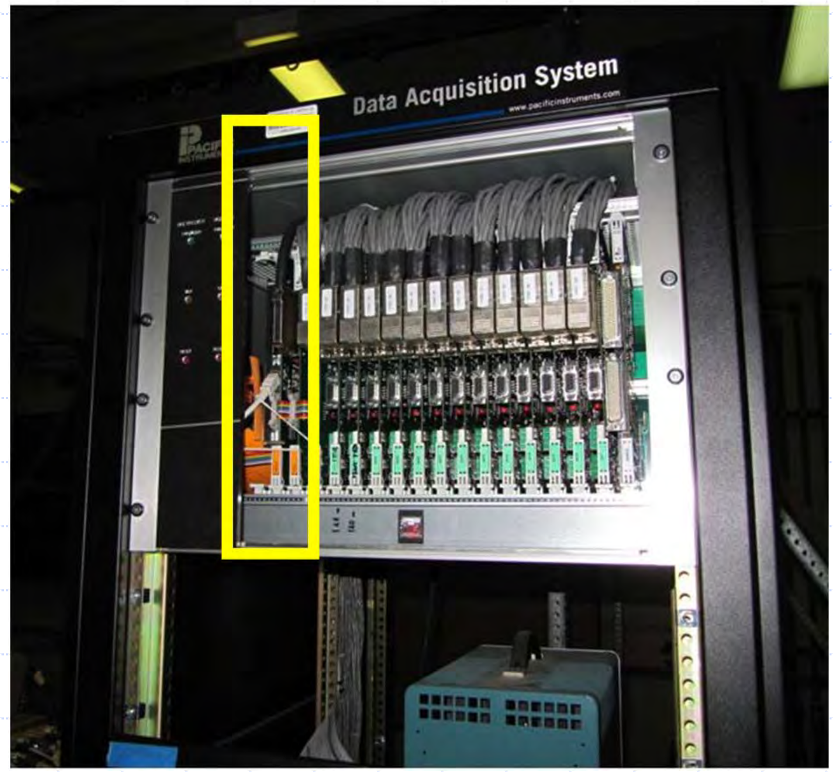


One simulation step completed in **one milisecond**!

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Implementation of Computational Algorithm



Digital signal processor (DSP) I/O module of Pacific Instruments (PI) DAQ system

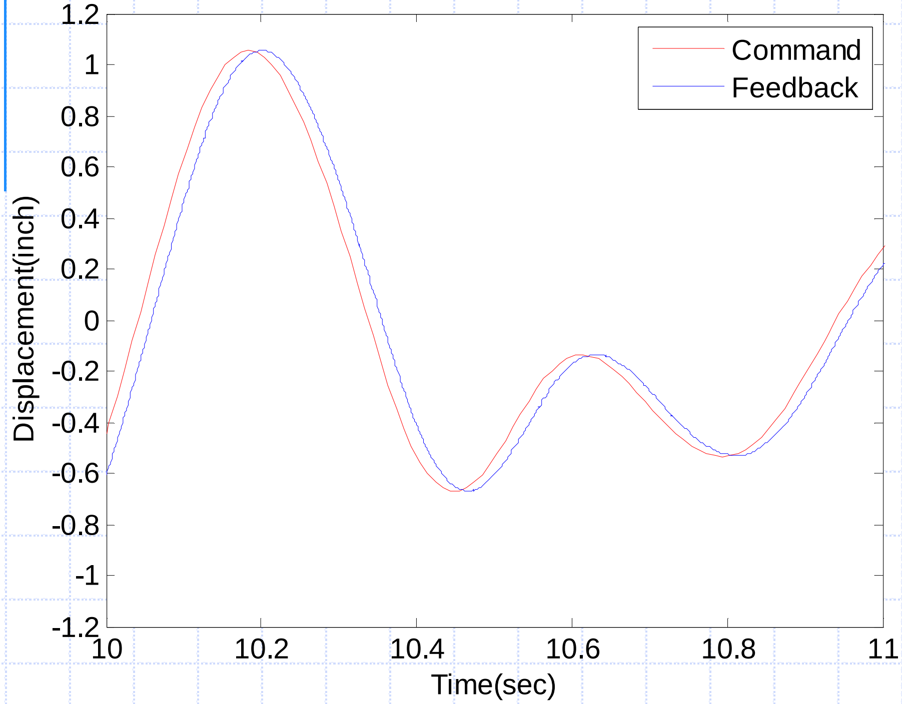
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

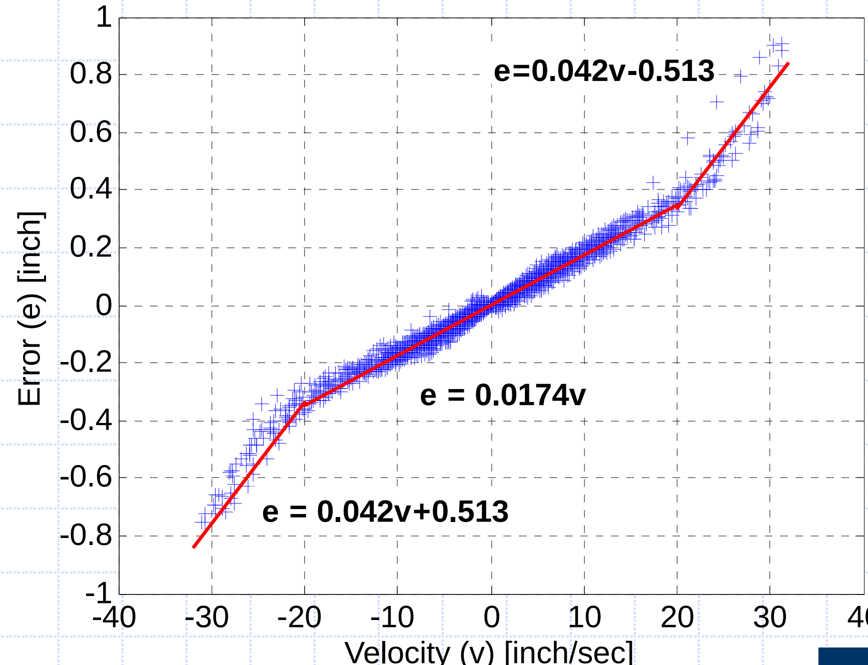
Real-time Hybrid Simulation System

Feed-forward error compensation

PIDF

Add the error to the command

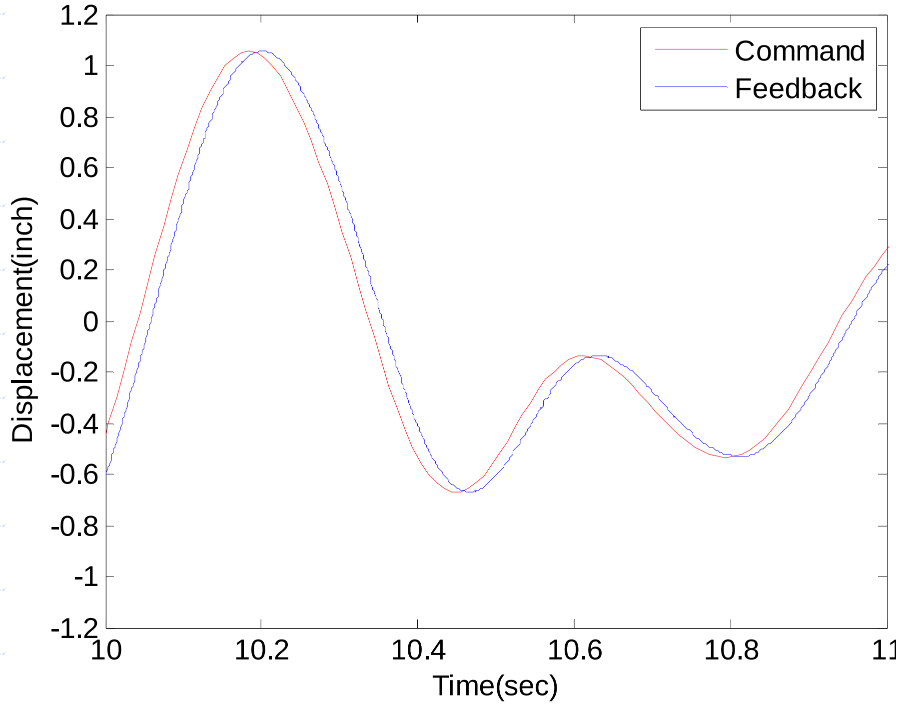




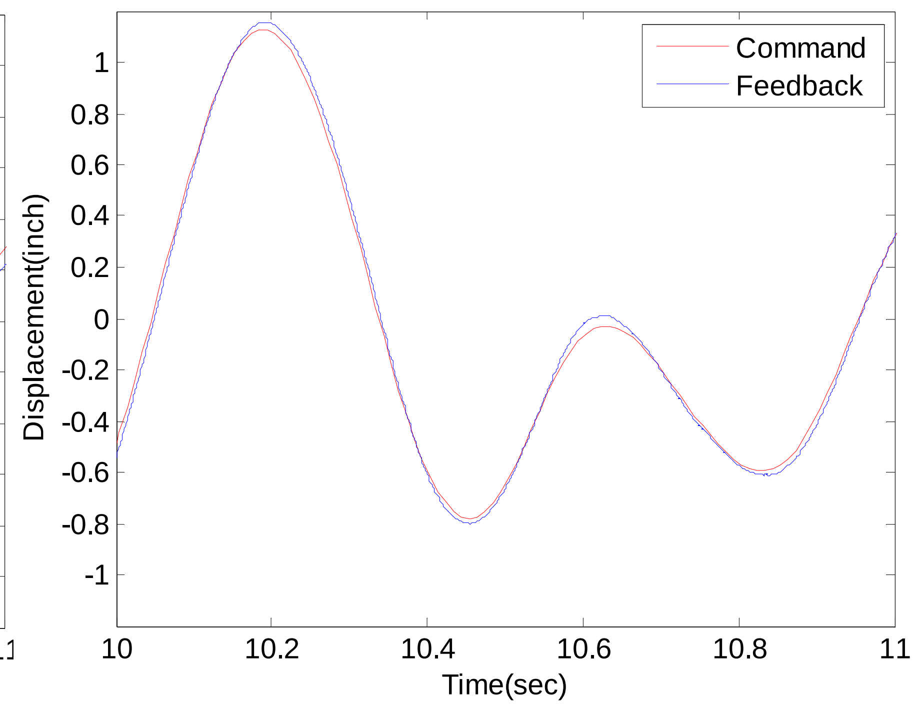
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Feed-forward error compensation



No correction



Feed-forward error correction

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation Framework

Verification of algorithm implementation and measurements

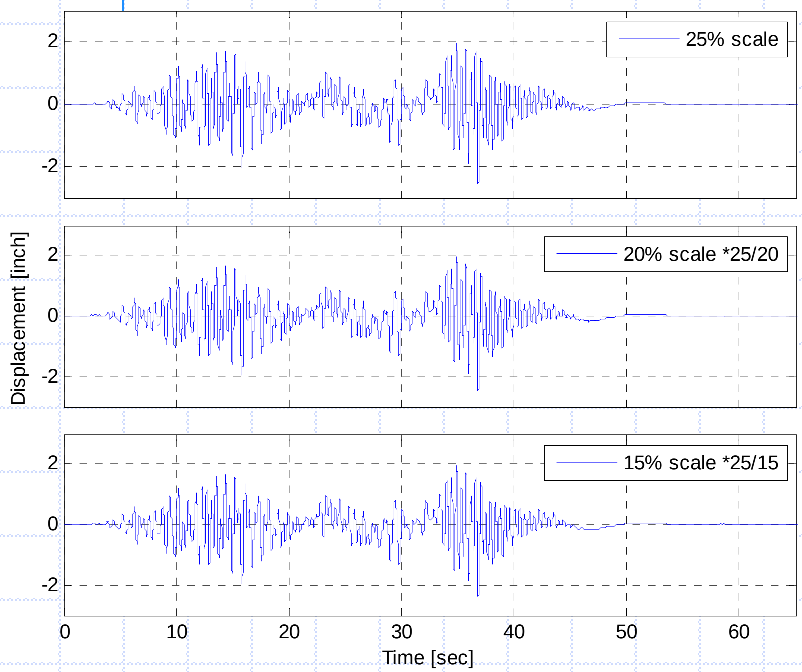
Test #	Analytical Substructure				Excitation Scale
	Stiffness, k, [kip/in]	Mass, m, slug	Period, $T=2\pi(m/k)^{0.5}$, sec	Damping ratio	
1	4.4	150	0.37	1%	15%
2	4.4	150	0.37	1%	20%
3	4.4	150	0.37	1%	25%

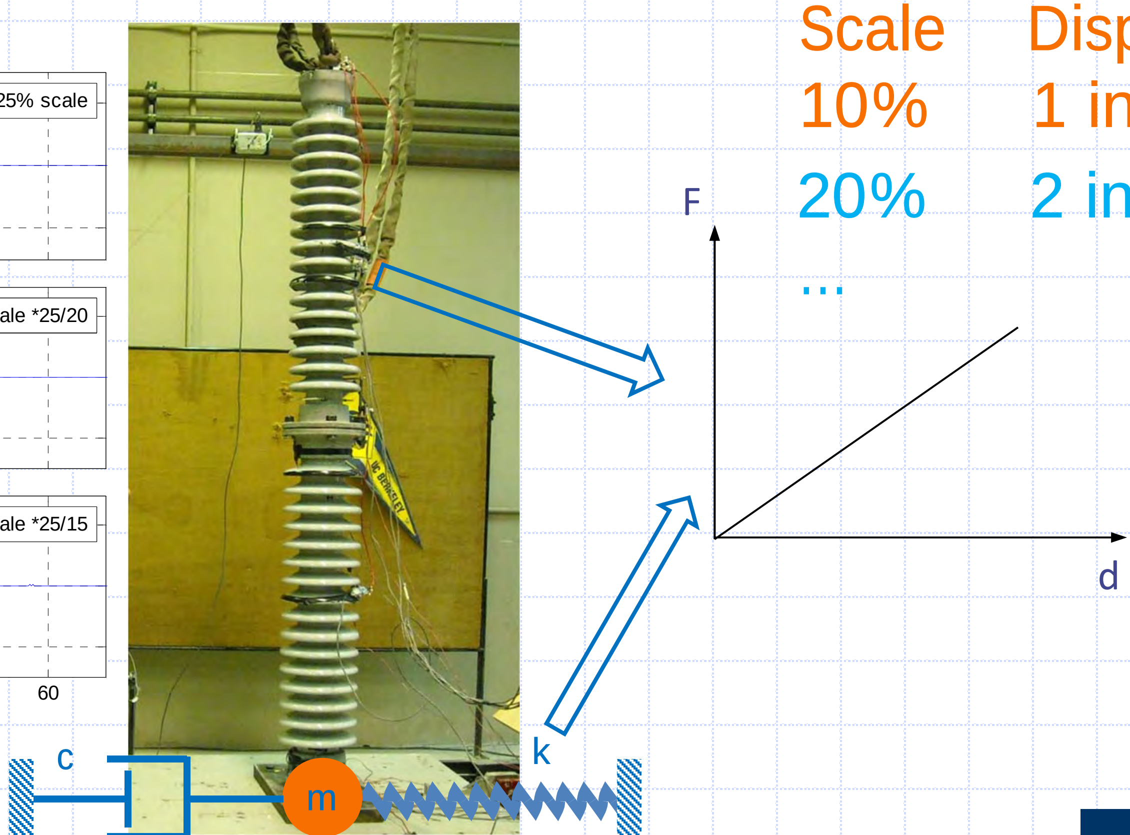
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Verification of algorithm implementation and measurements

Scale	Disp.
10%	1 in.
20%	2 in.
...	

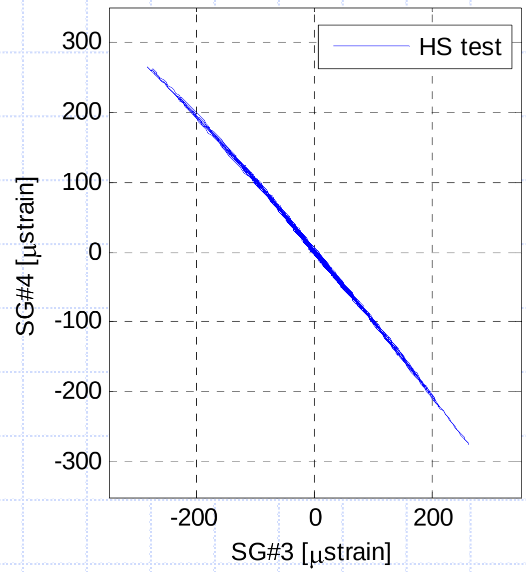


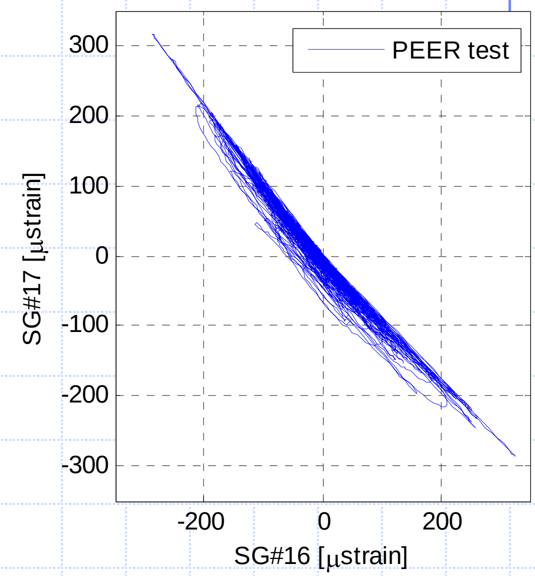


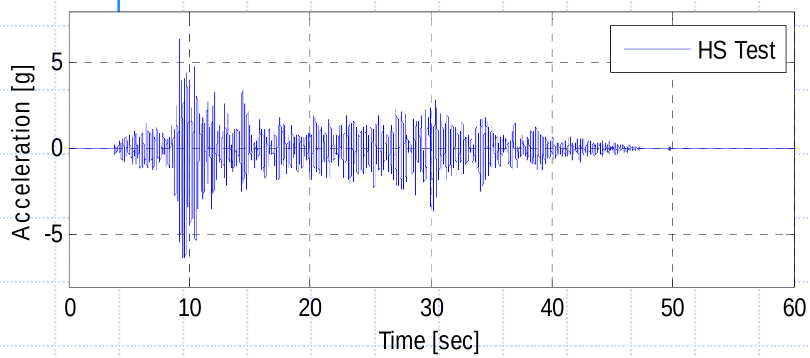
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Comparison RTHS vs. Shaking Table tests

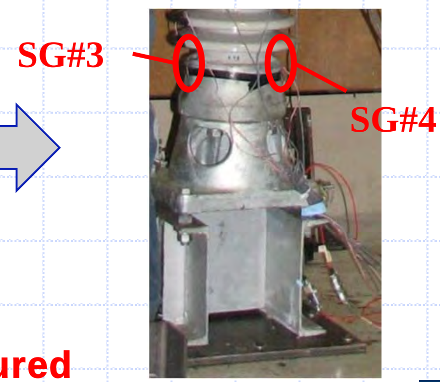
Accelerations at top
Strains at bottom

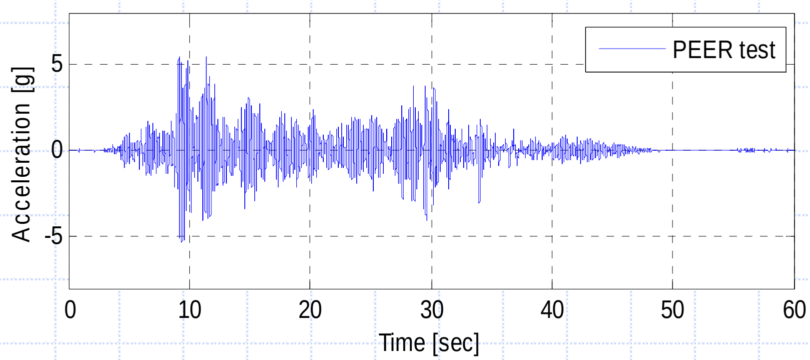






Strains measured at insulator bottom



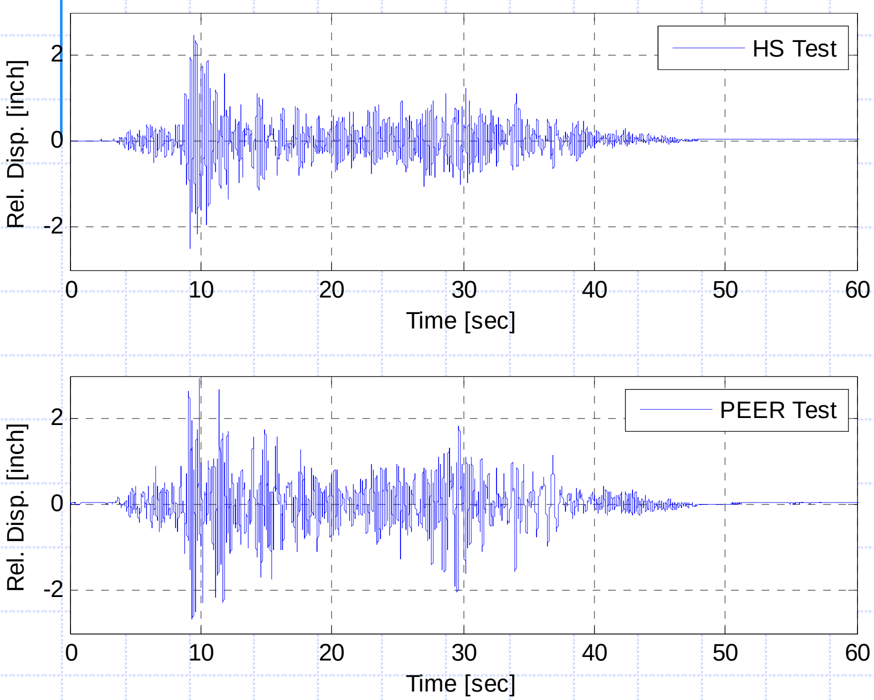


Acceleration measured at insulator top

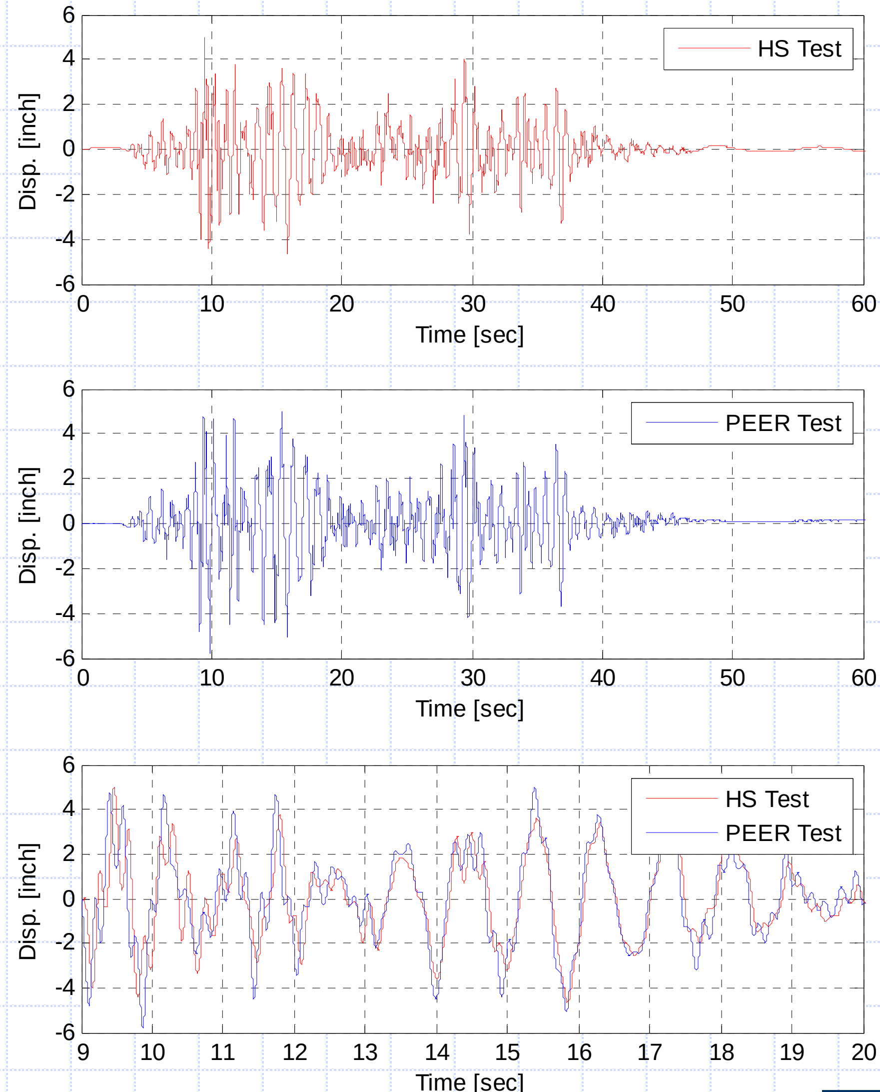
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Comparison RTHS vs. Shaking Table tests

Total and Relative Displacements at top



Relative Displacements



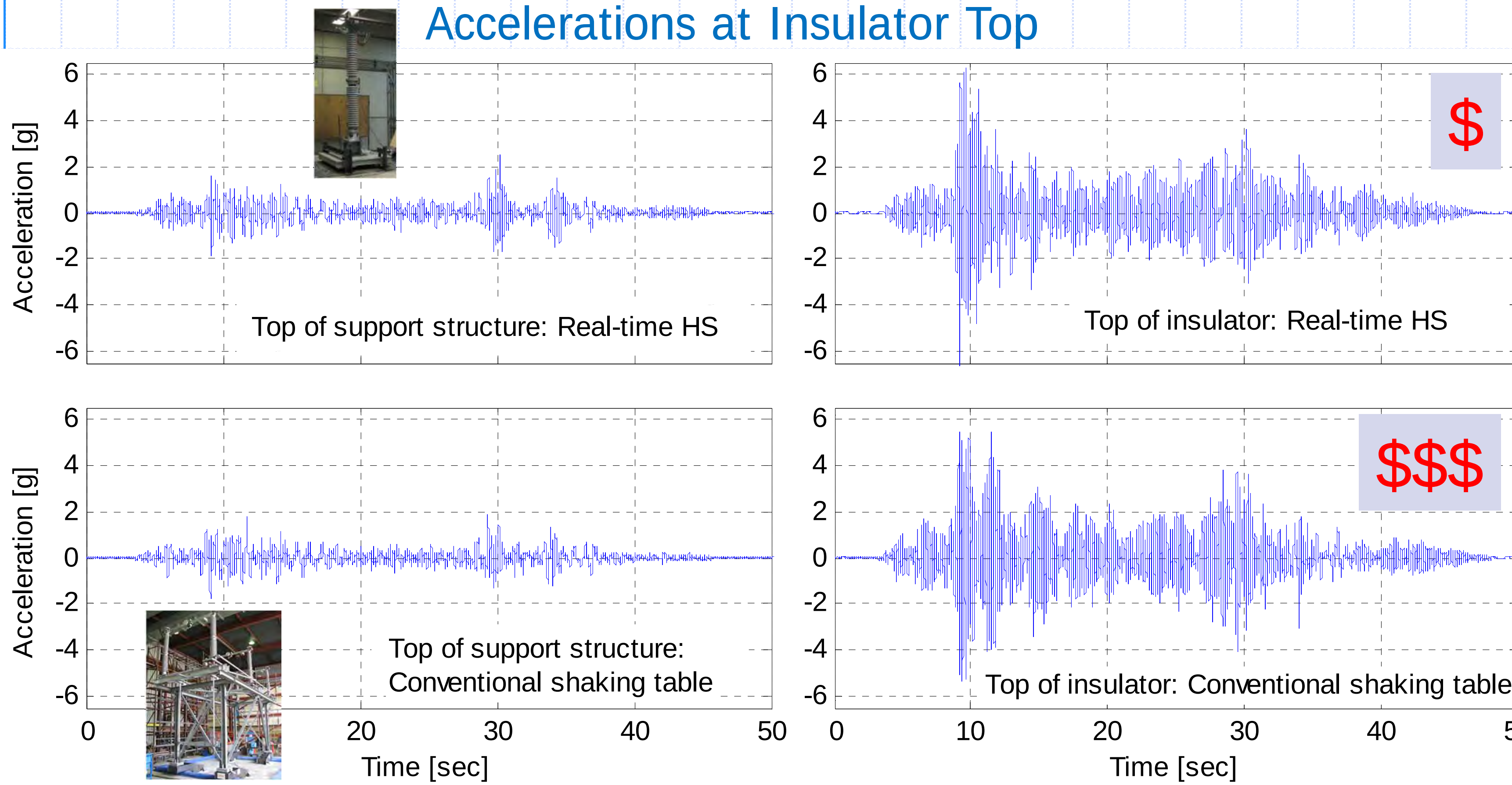
Total Displacements

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Comparison with conventional shaking table tests

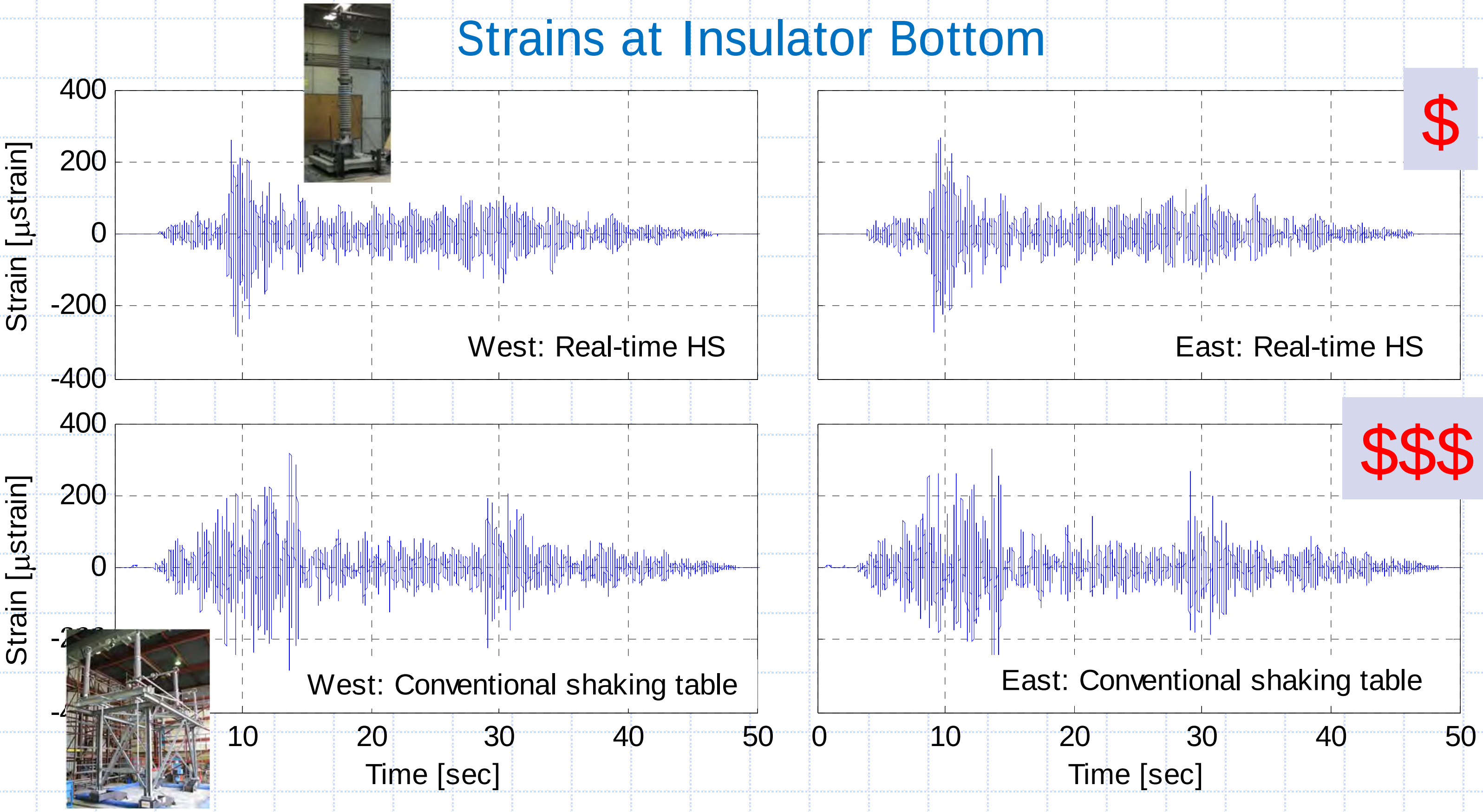
Accelerations at Insulator Top



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Comparison with conventional shaking table tests

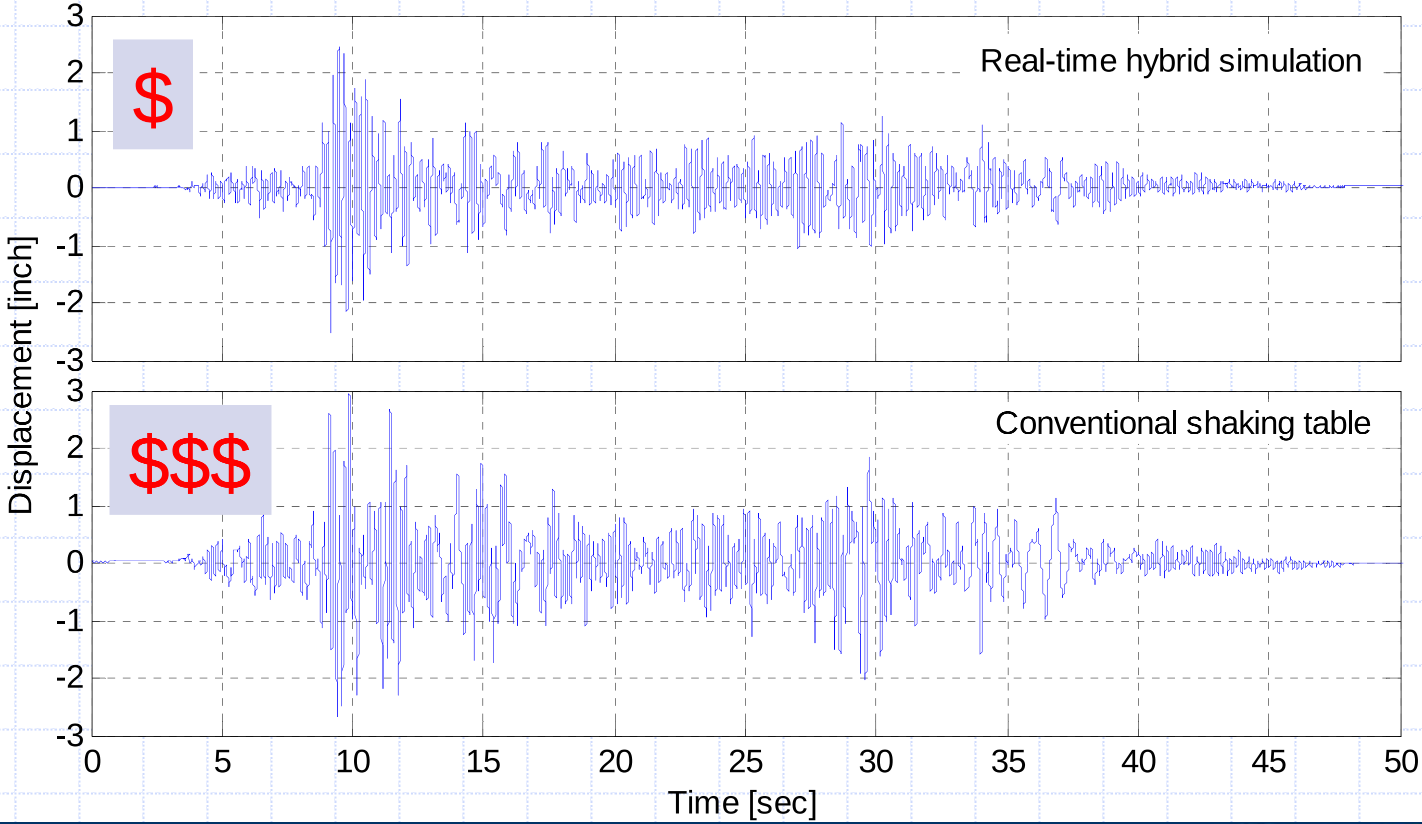


Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Real-time Hybrid Simulation System

Comparison with conventional shaking table tests

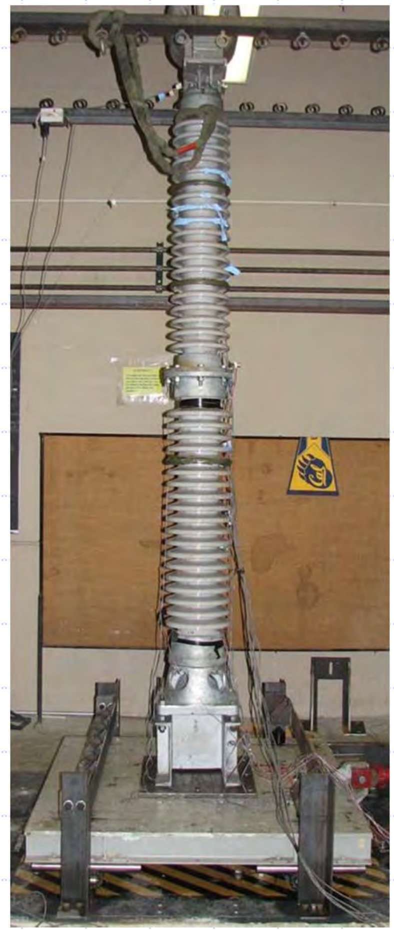
Relative displacement of insulator top w.r.t. top of support structure



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study

Polymer

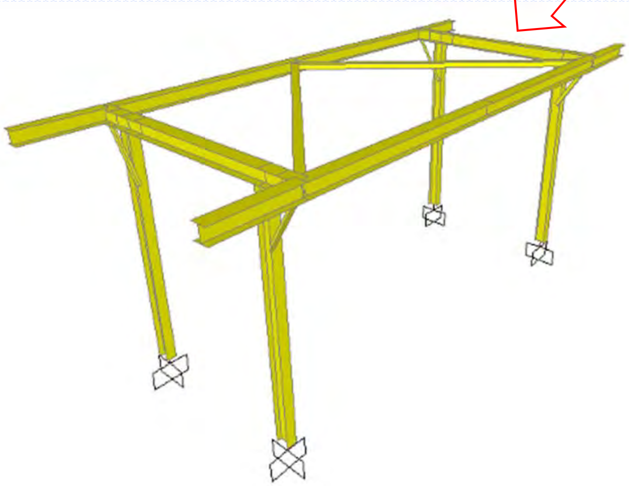


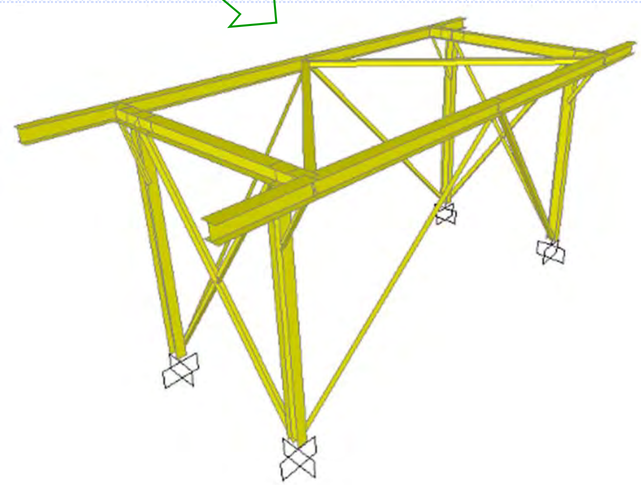
Porcelain

Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study

- 13 support structure stiffness, k, values between 2.2 kips/in and 60 kips/in





- 3 damping ratios for support structure: ξ= 1%, 3% , 5%
- Tests with 10%-scale IEEE motion to ensure linear insulator behavior

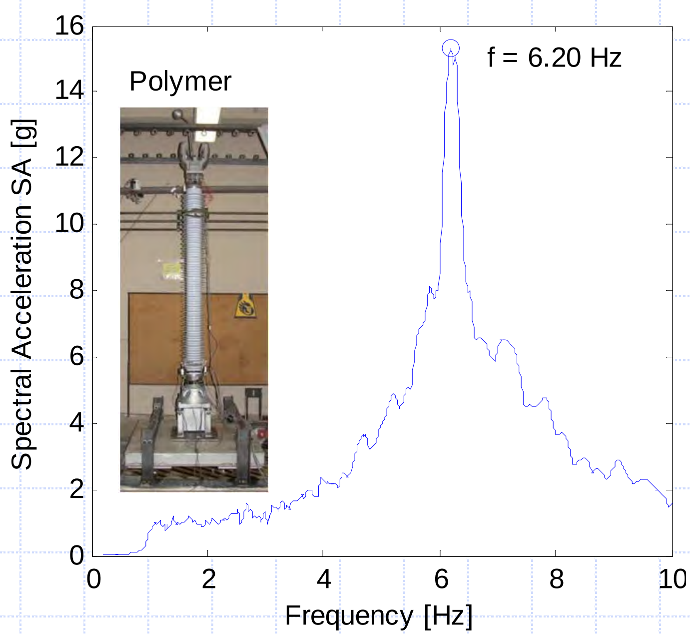
Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

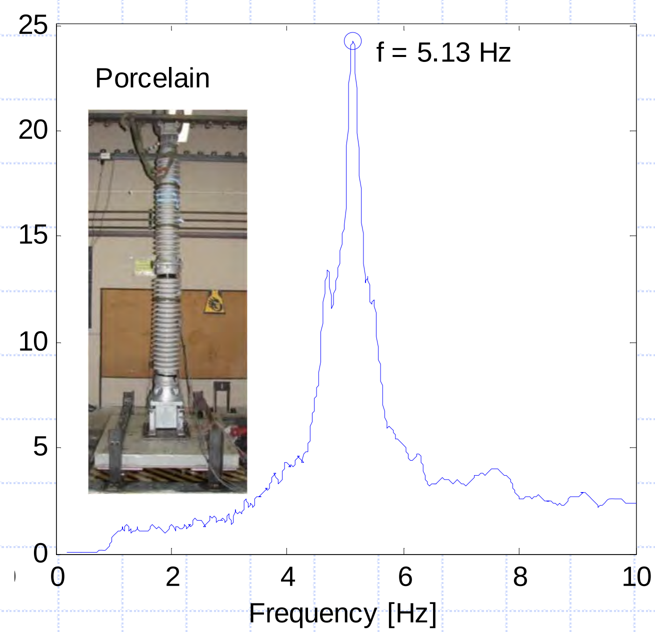
Parametric Study: Natural Frequencies

k [kip/in]	60.0	55.0	50.0	44.0	40.0	35.0	30.0	22.0	16.0	11.0	7.0	4.4	2.2
f_{ss} [Hz]	10.0	9.6	9.2	8.6	8.2	7.7	7.1	6.1	5.2	4.3	3.4	2.7	1.9
f_{ss} / f_{ins} (polymer)	1.6	1.6	1.5	1.4	1.3	1.2	1.1	1.0	0.8	0.7	0.6	0.4	0.3
f_{ss} / f_{ins} (porcelain)	2.0	1.9	1.8	1.7	1.6	1.5	1.4	1.2	1.0	0.8	0.7	0.5	0.4

$$f_{ss} = (1/2\pi)\sqrt{k/m}$$

m = 150 slug

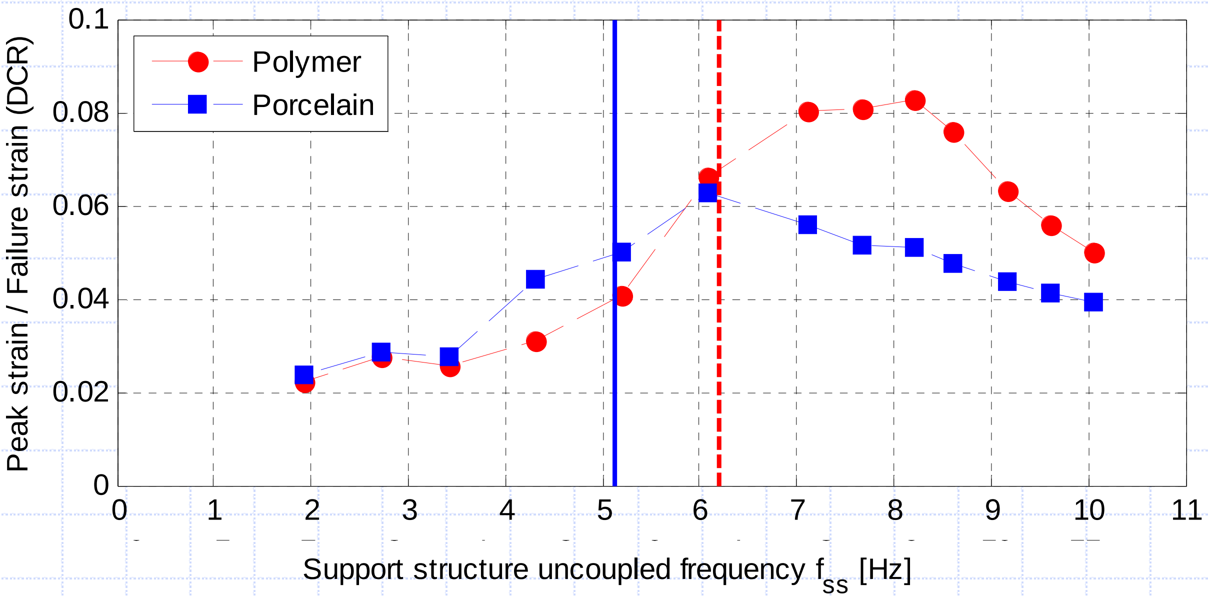




Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study: Effect of Insulator Type

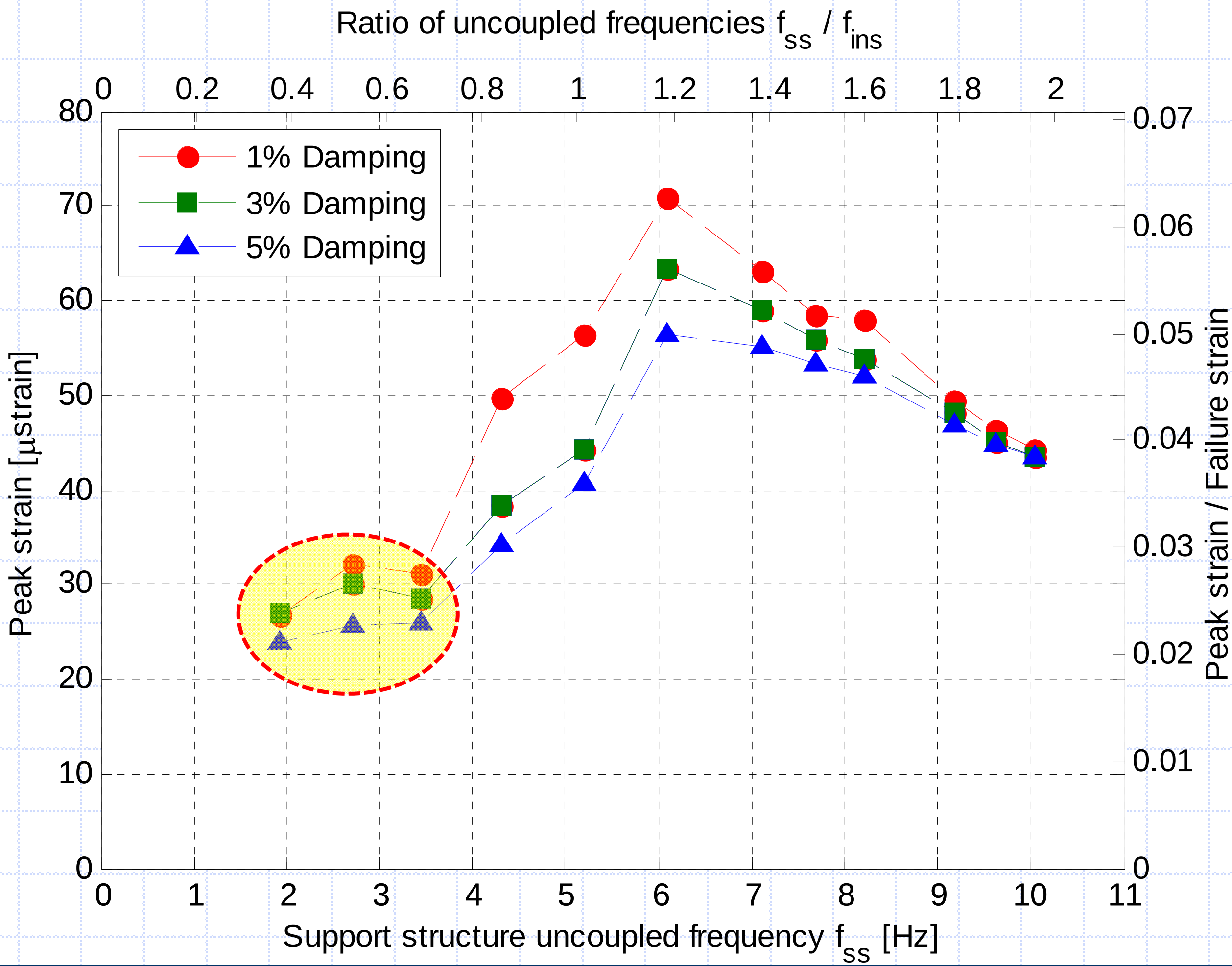
Failure strains from fragility tests:
Polymer → 4800 μstrain
Porcelain → 1130 μstrain



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study: Effect of Support Structure

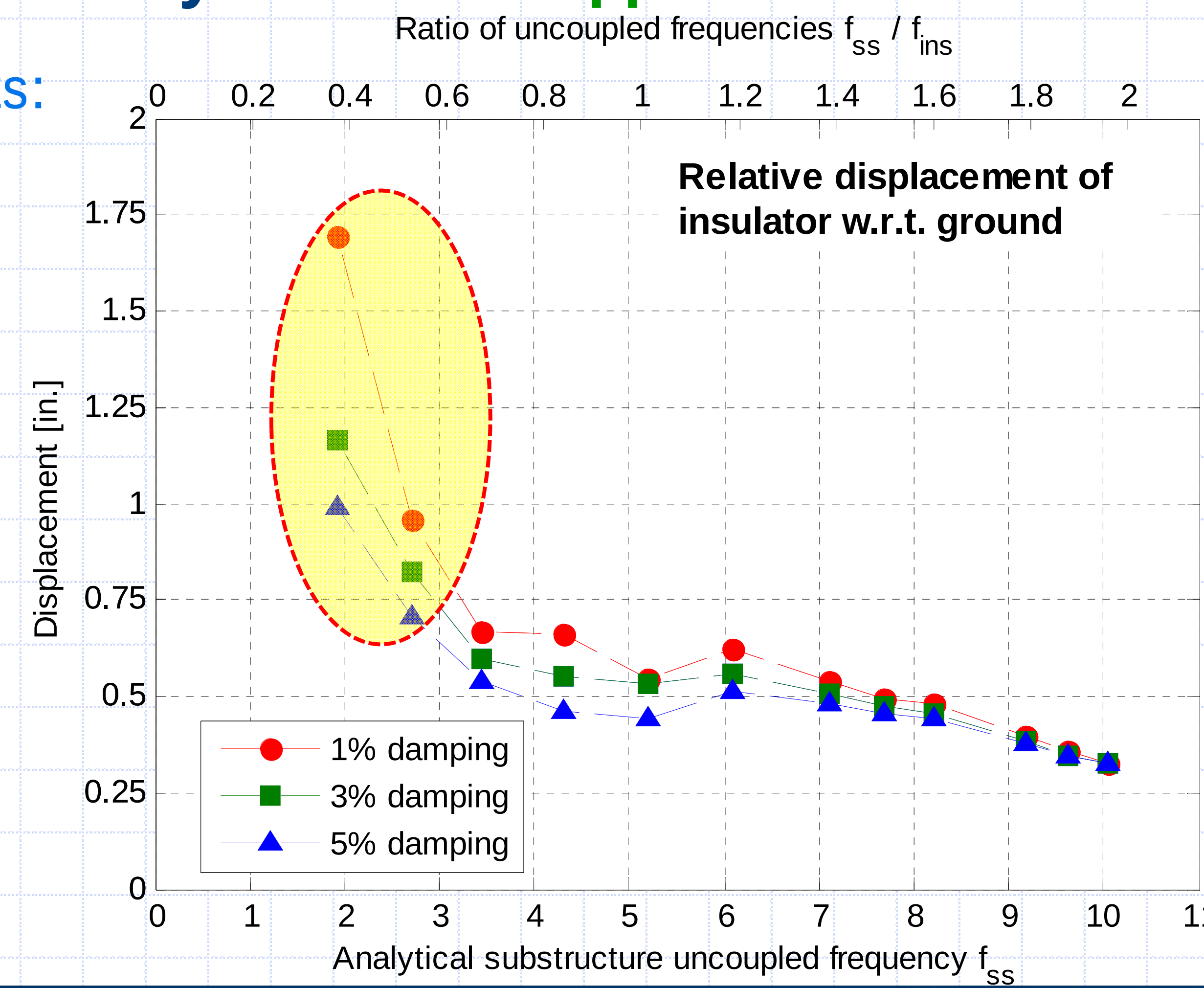
Strains: Porcelain Insulator



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study: Effect of Support Structure

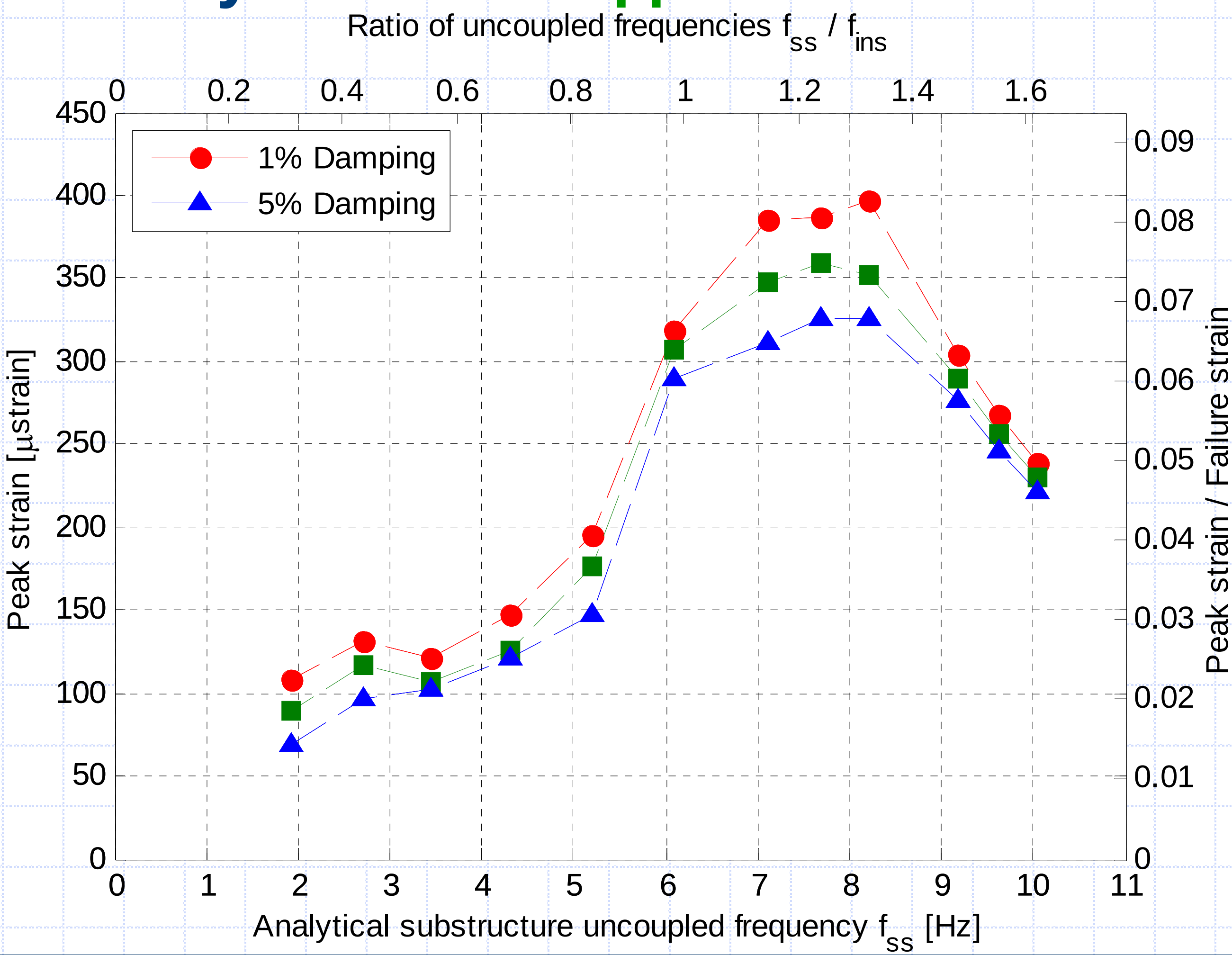
Displacements:
Porcelain Insulator



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study: Effect of Support Structure

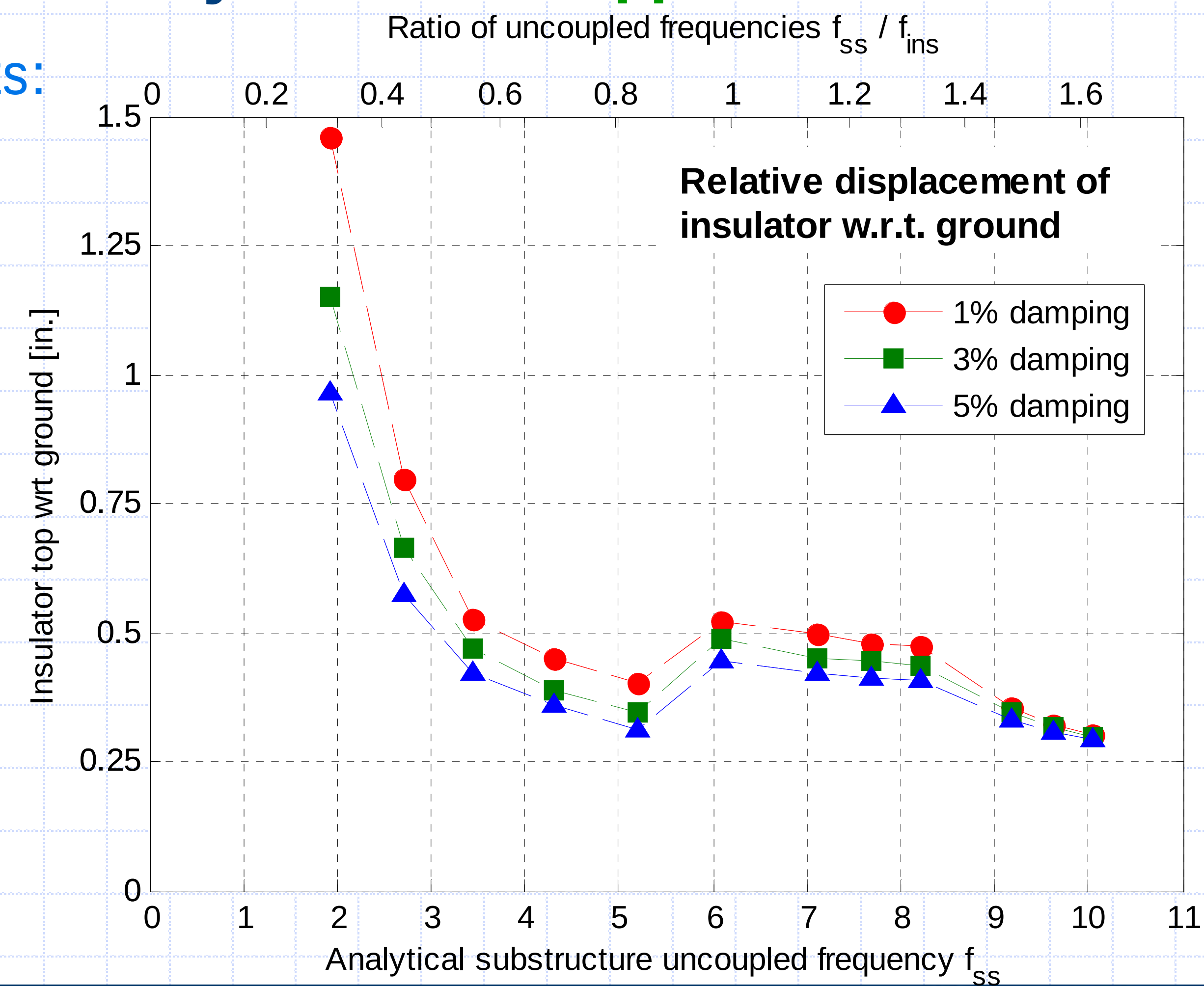
Strains: Polymer Insulator



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Parametric Study: **Effect of Support Structure**

Displacements:
Polymer
Insulator



Application II: RTHS of Electrical Insulator Posts on a Smart Shaking Table

Concluding Remarks

- ❖ Good match of the results with a benchmark shaking table test is a strong verification of HS

- ❖ Economically and time efficiently conducted **78** RTHS tests and results regarding the design of disconnect switches related to the selection of both the insulators and support structures are a proof of the usefulness of HS

Future Directions

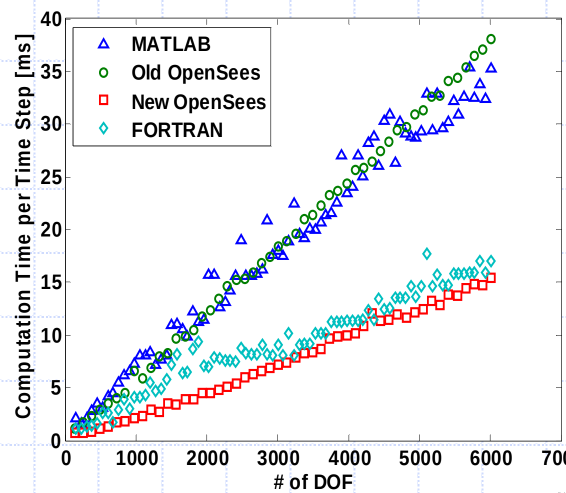
❖ Direct consideration of transfer system and analytical-experimental boundary in the HS solution

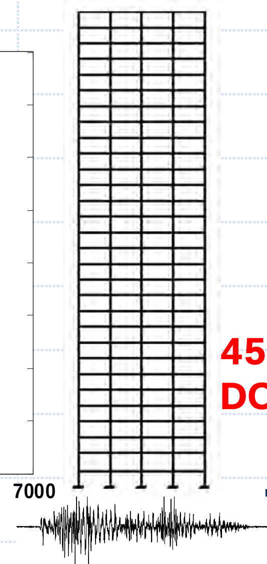
$$\left.\begin{aligned}&\text{Governing PDE}: \mathbf{M}\ddot{\mathbf{u}} + \mathbf{R}(\mathbf{u},\dot{\mathbf{u}}) = \underbrace{\mathbf{F}_a(t)}_{\text{applied}} + \underbrace{\mathbf{F}_c(t)}_{\text{control}}\\ &\text{Boundary Conditions}: G(\mathbf{u},\dot{\mathbf{u}}) = \mathbf{0}\\ &\text{PID Control}: H\left(\mathbf{F}_c, \mathbf{u}, \dot{\mathbf{u}}, \int \mathbf{u}\,dt\right) = 0\end{aligned}\right\}$$

Set of Differential-Algebraic Equations (DAE)

❖ HS of analytical substructures with large # of DOF:

- ➢ Solution affected more from the errors as # of DOF increases
- ➢ Need to reduce the computation duration (parallel computing) [OpenSees-SP, OpenSees-MP]

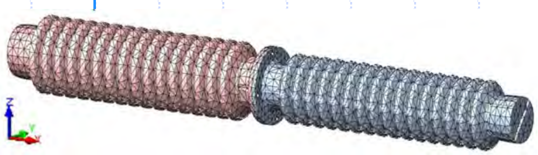


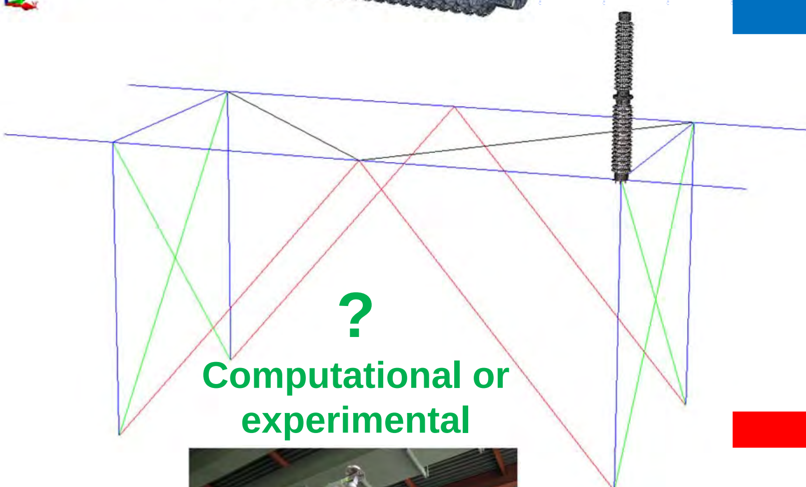


450 DOF

Future Directions

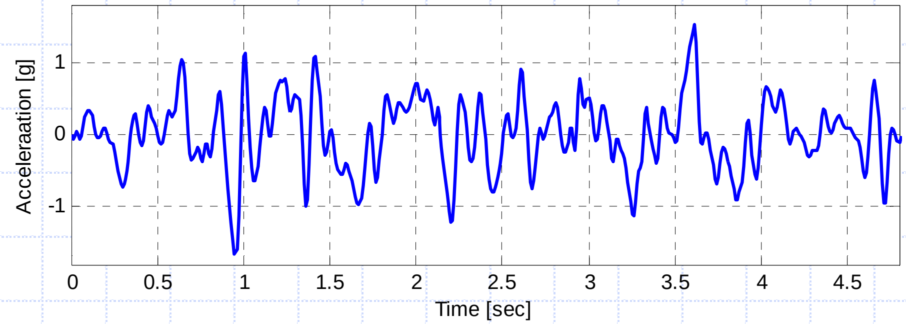
Optimize design of support structure to improve the switch seismic response



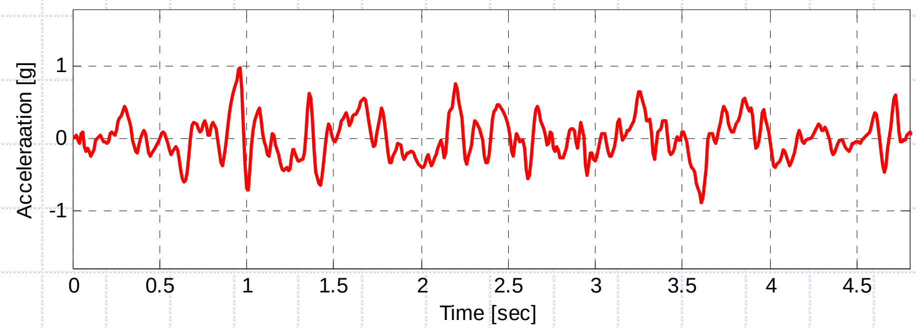


?

Computational or experimental



Accelerations at Insulator Top



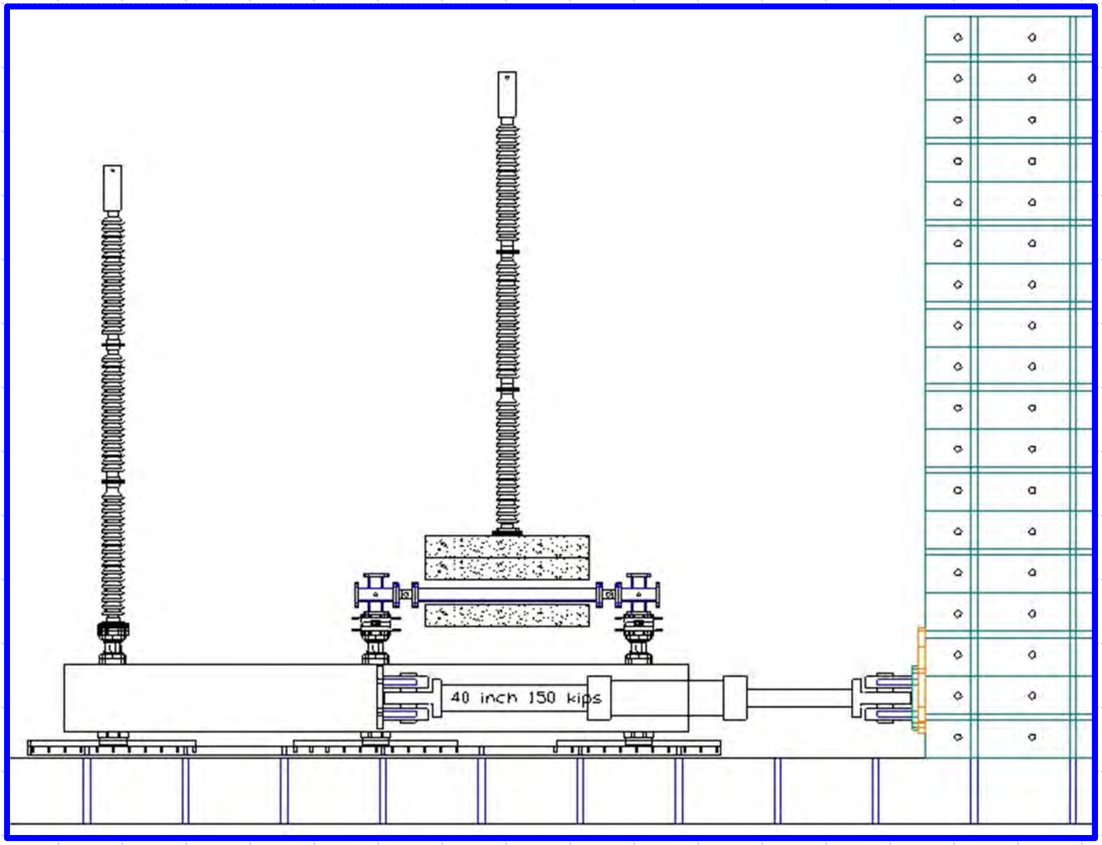
Accelerations at Switch Base (Ground Motion)

Future Directions

- Need for a mixed control as a combination of acceleration control for higher frequencies and displacement control for lower frequencies in RTHS on smart shaking table configurations

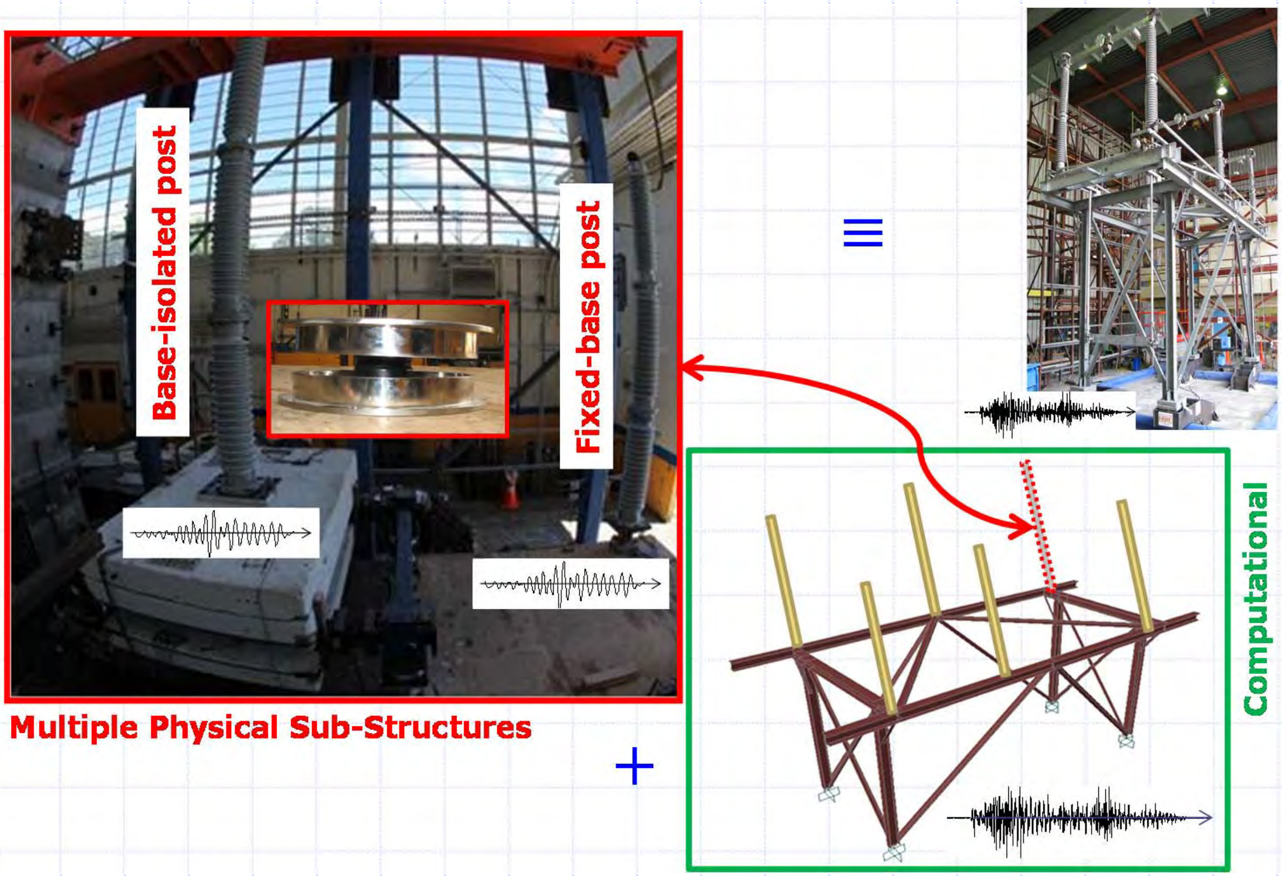
Future Directions

- Need for a mixed control as a combination of acceleration control for higher frequencies and displacement control for lower frequencies in RTHS on smart shaking table configurations



Future Directions

❖ Need for a mixed control as a combination of acceleration control for higher frequencies and displacement control for lower frequencies in RTHS on smart shaking table configurations



Thank You!

Questions? Comments?