Basics of Hybrid Simulation

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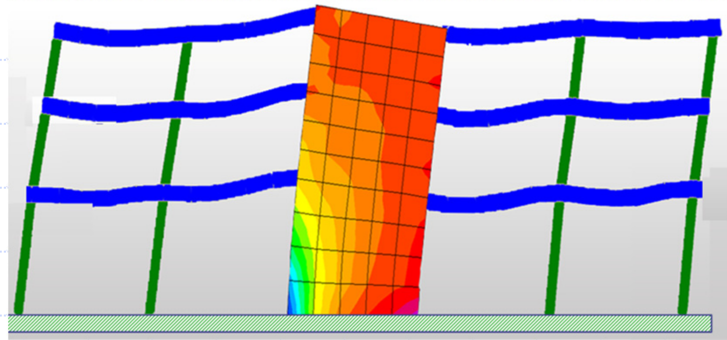
Outline

1. **Hybrid Simulation (HS) Background**
2. **HS Classification**
3. **Benefits of HS**
4. **Review of HS Related Research**

HS Background

Analytical Simulation



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Experimental Simulation

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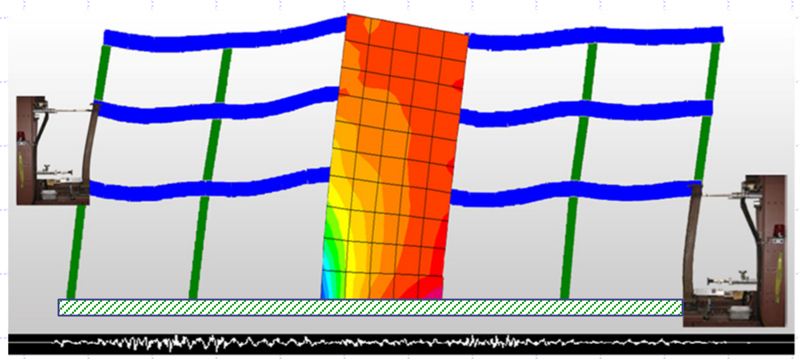
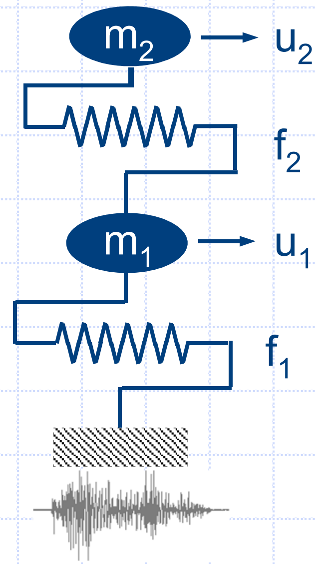
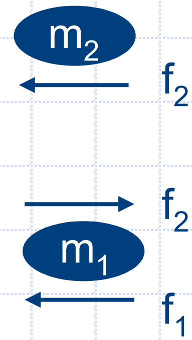
Hybrid Simulation



HS Background

Analytical Simulation:





$$-f_2 = m_2 \ddot{u}_2^t$$

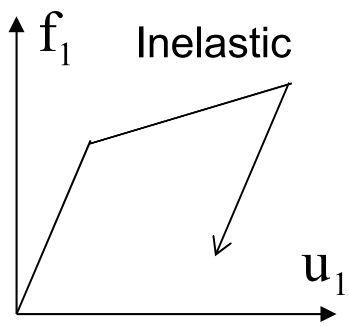
$$-f_1 + f_2 = m_1 \ddot{u}_1^t$$

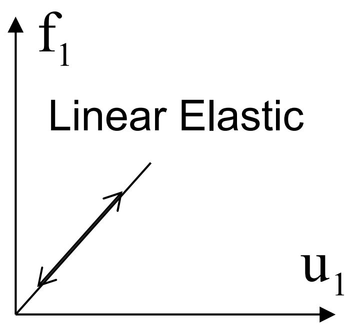
$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{u}_1^t \\ \ddot{u}_2^t \end{bmatrix} + \begin{bmatrix} -f_2 + f_1 \\ f_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

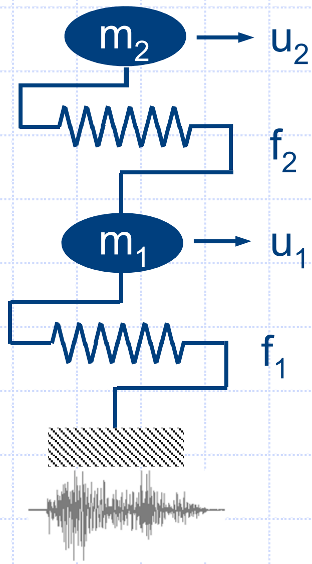
$$\ddot{u}_1^t = \ddot{u}_1 + \ddot{u}_g \qquad \ddot{u}_2^t = \ddot{u}_2 + \ddot{u}_g \quad \Rightarrow \quad \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} -f_2 + f_1 \\ f_2 \end{bmatrix} = -\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \ddot{u}_g$$

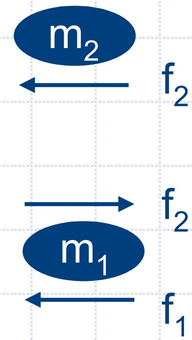
HS Background

Analytical Simulation:









$$-f_2 = m_2 \ddot{u}_2^t$$

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For the linear-elastic case

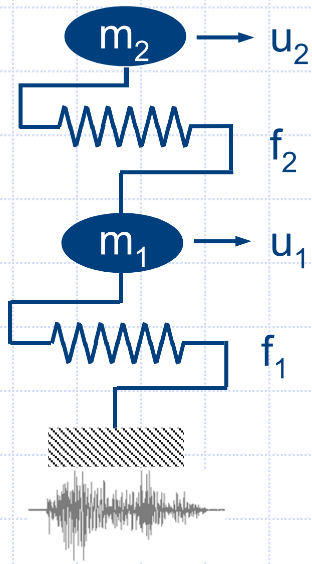
$$f_1 = k_1 u_1$$

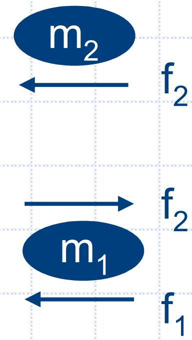
$$f_2 = k_2 (u_2 - u_1)$$

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_1 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \ddot{u}_g$$

HS Background

Analytical Simulation:





$$-f_2 = m_2\ddot{u}_2^t$$

$$-f_1 + f_2 = m_1\ddot{u}_1^t$$

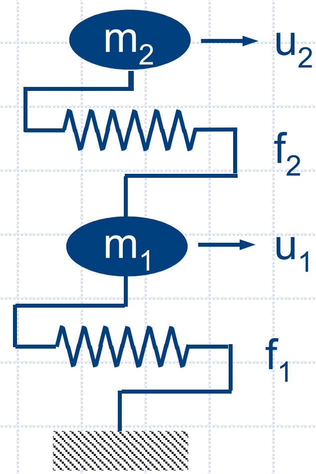
$$C = \alpha M + \beta K$$

Damping is commonly represented as a linear combination of mass and stiffness matrices

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_1 \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = -\begin{bmatrix} m_1 \\ m_2 \end{bmatrix}\ddot{u}_g$$

HS Background

Analytical Simulation:



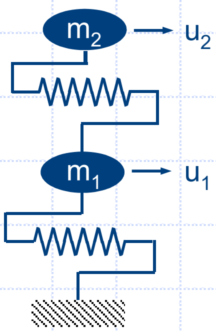
General case of inelastic response

$$\underbrace{\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}}_{\mathbf{m}} \underbrace{\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix}}_{\ddot{\mathbf{u}}} + \underbrace{\begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}}_{\mathbf{c}} \underbrace{\begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{bmatrix}}_{\dot{\mathbf{u}}} + \underbrace{\begin{bmatrix} -f_2 + f_1 \\ f_2 \end{bmatrix}}_{\mathbf{f}} = \underbrace{-\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \ddot{u}_g}_{\mathbf{p}}$$

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

Objective of Analytical Simulation: Solve the equation of motion using numerical integration methods

HS Background

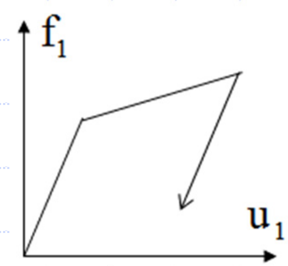


$$\underbrace{\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}}_{\mathbf{m}} \underbrace{\begin{bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{bmatrix}}_{\ddot{\mathbf{u}}} + \underbrace{\begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}}_{\mathbf{c}} \underbrace{\begin{bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{bmatrix}}_{\dot{\mathbf{u}}} + \underbrace{\begin{bmatrix} -f_2 + f_1 \\ f_2 \end{bmatrix}}_{\mathbf{f}} = \underbrace{-\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} \ddot{u}_g}_{\mathbf{p}}$$

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

A straightforward integration application: Explicit Newmark Integration

1) Compute the displacements $\mathbf{u}_{i+1} = \mathbf{u}_i + \Delta t\,\dot{\mathbf{u}}_i + \frac{(\Delta t)^2}{2}\ddot{\mathbf{u}}_i$



2) Compute the restoring forces $\mathbf{f}_{i+1}$ corresponding to $\mathbf{u}_{i+1}$

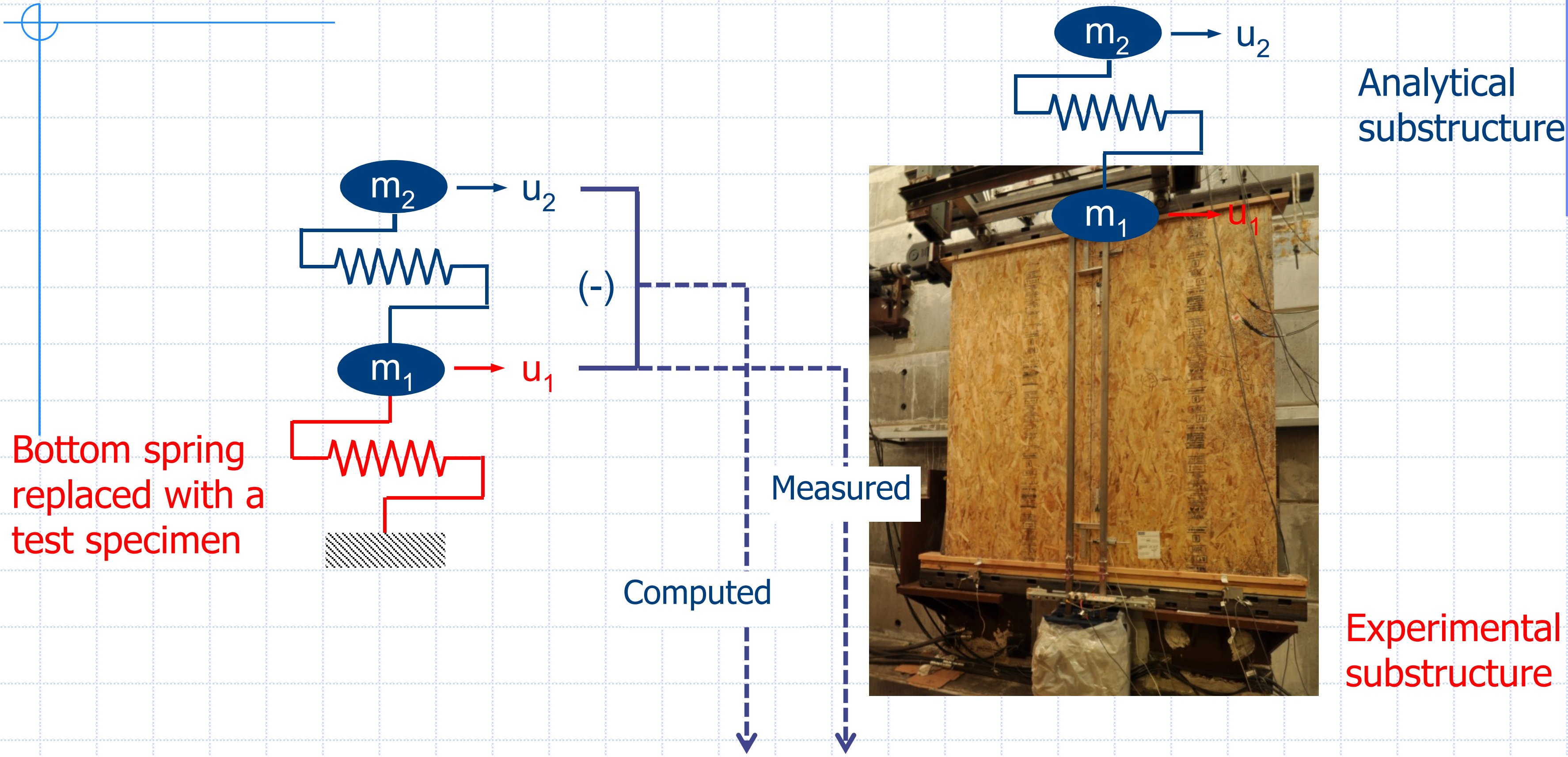
3) Compute the accelerations $[\mathbf{m} + \Delta t\,\gamma\,\mathbf{c}]\ddot{\mathbf{u}}_{i+1} = \mathbf{p}_{i+1} - \mathbf{f}_{i+1} - \mathbf{c}[\dot{\mathbf{u}}_i + \Delta t(1-\gamma)\ddot{\mathbf{u}}_i]$

$$\mathbf{m}_{\text{eff}}\,\ddot{\mathbf{u}}_{i+1} = \mathbf{p}_{\text{eff}}$$

4) Compute the velocities $\dot{\mathbf{u}}_{i+1} = \dot{\mathbf{u}}_i + \Delta t[(1-\gamma)\ddot{\mathbf{u}}_i + \gamma\,\ddot{\mathbf{u}}_{i+1}]$

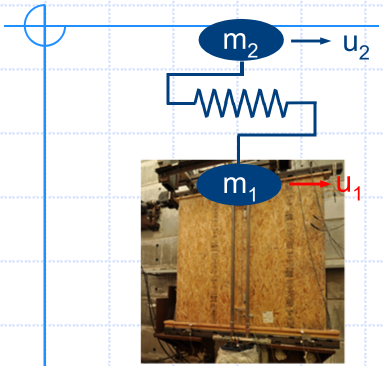
5) Increment i

HS Background



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

HS Background



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

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

A straightforward integration application: Explicit Newmark Integration

1) Compute the displacements $\mathbf{u}_{i+1} = \mathbf{u}_i + \Delta t\,\dot{\mathbf{u}}_i + \frac{(\Delta t)^2}{2}\ddot{\mathbf{u}}_i$

2a) Compute the restoring force $f_{a,i+1}$ corresponding to the displacement $u_{2,i+1} - u_{1,i+1}$

2b) Impose $u_{1,i+1}$ to the test specimen and measure the corresponding force $f_{e,i+1}$

3) Compute the accelerations $[\mathbf{m} + \Delta t\,\gamma\,\mathbf{c}]\ddot{\mathbf{u}}_{i+1} = \mathbf{p}_{i+1} - \mathbf{f}_{i+1} - \mathbf{c}[\dot{\mathbf{u}}_i + \Delta t(1-\gamma)\ddot{\mathbf{u}}_i]$

$$\mathbf{m}_{\mathbf{eff}}\ddot{\mathbf{u}}_{i+1} = \mathbf{p}_{\text{eff}}$$

4) Compute the velocities $\dot{\mathbf{u}}_{i+1} = \dot{\mathbf{u}}_i + \Delta t[(1-\gamma)\ddot{\mathbf{u}}_i + \gamma\,\ddot{\mathbf{u}}_{i+1}]$

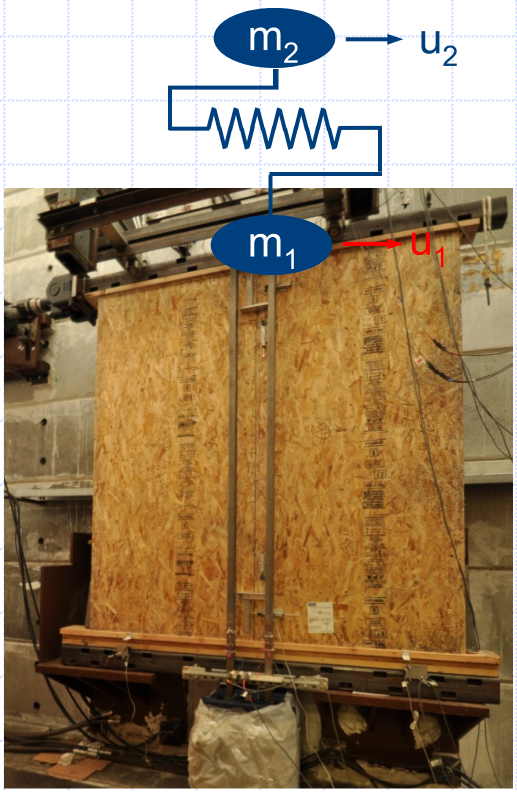
5) Increment i

HS Classification

- Slow Hybrid Simulation
- Real-time Hybrid Simulation
  - Actuator Configuration
  - Shaking Table Configuration
  - Actuator + Shaking Table Configuration

HS Classification

- Slow Hybrid Simulation

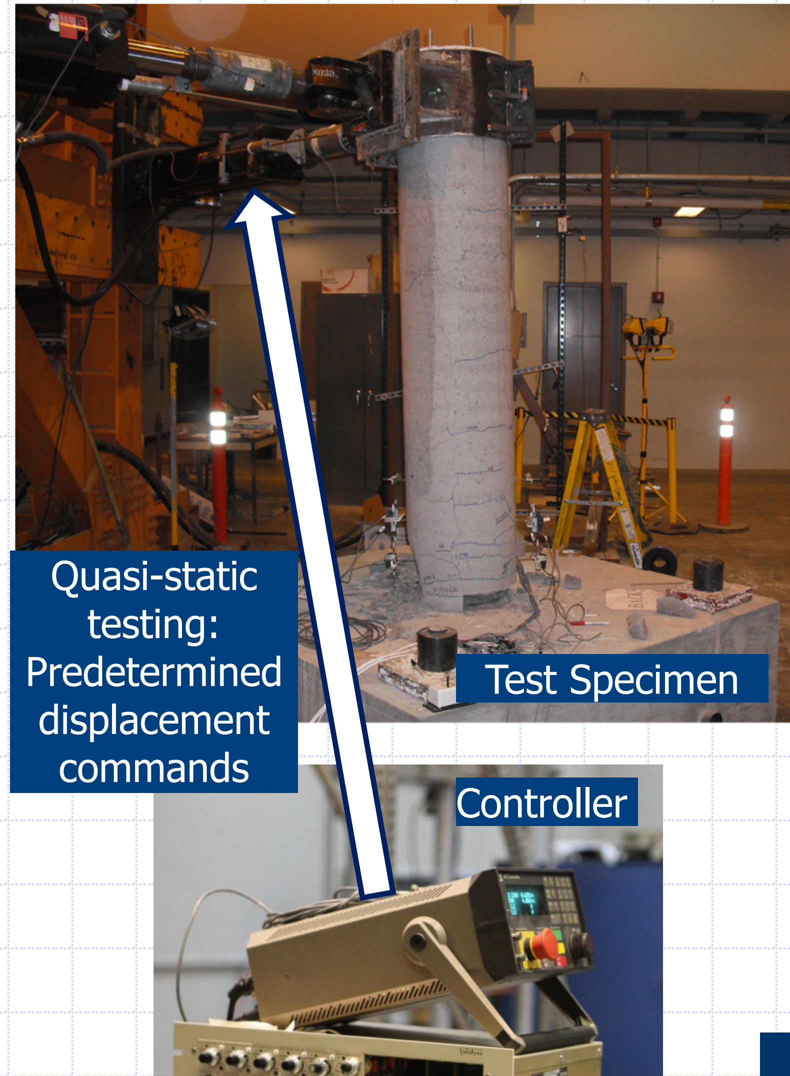


- ✓ Rate of loading **<** Computed velocity
- ✓ Duration of hybrid simulation **>** $N \times \Delta t$
  N: number of integration steps
  Δt: integration time step
- ✓ Applicable when rate effects are not important
- ✓ Experimental substructure is connected to actuator(s)
- ✓ Physical mass generally doesn't exist

HS Classification

- From the experimental perspective, slow hybrid simulation is equivalent to quasi-static testing

- Predetermined displacement commands are based on a load protocol



HS Classification

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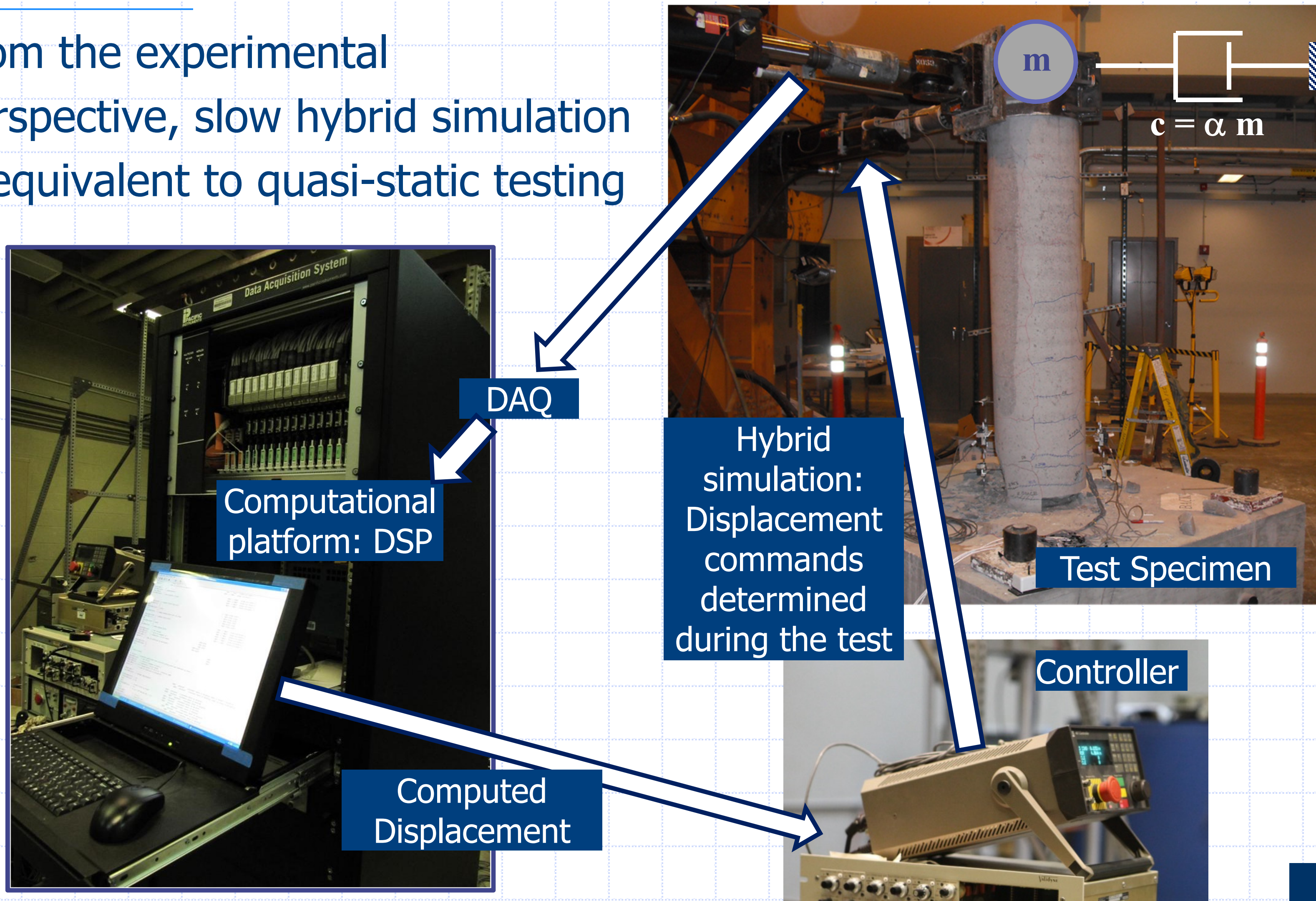
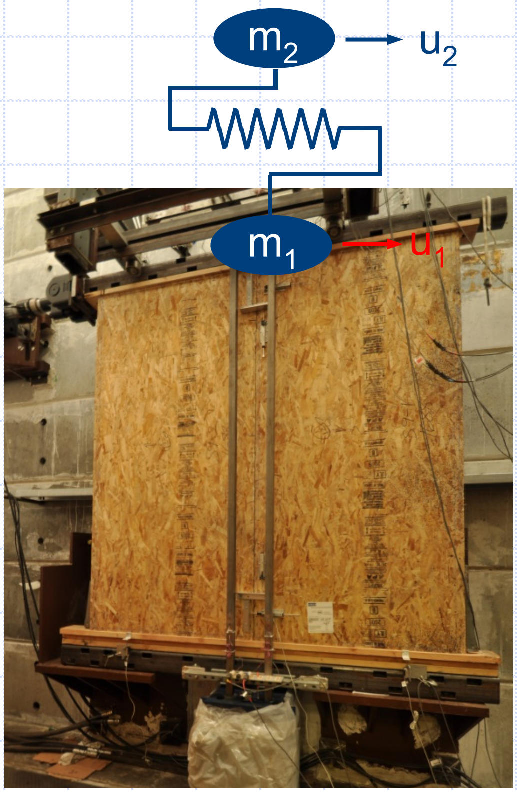


HS Classification

- Real-time Hybrid Simulation (Actuator Configuration)



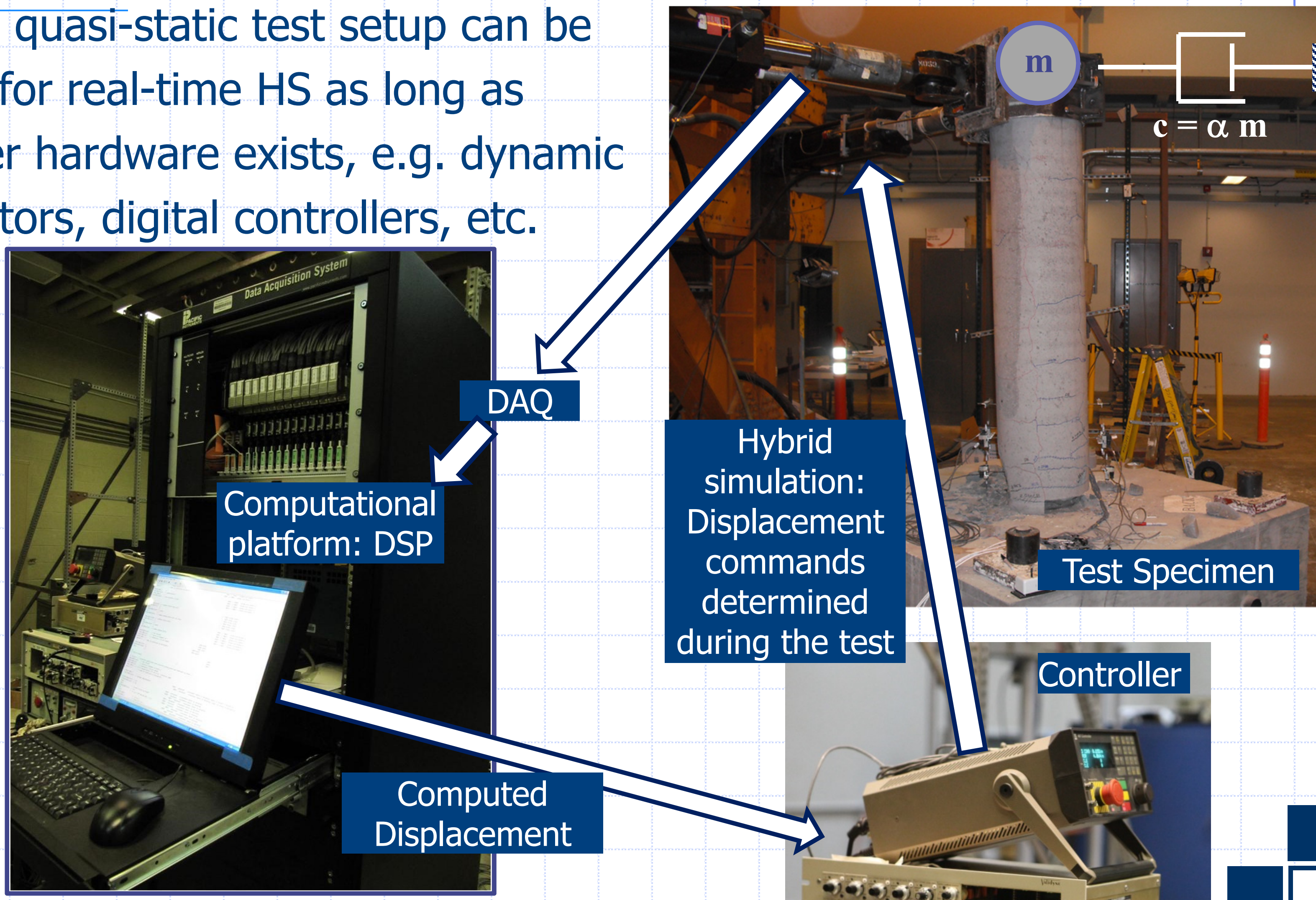
- ✓ Rate of loading = Computed velocity
- ✓ Duration of hybrid simulation = $N \times \Delta t$

  N: number of integration steps

  Δt: integration time step
- ✓ Crucial when rate effects are important
- ✓ Experimental substructure is connected to actuator(s)
- ✓ Physical mass generally doesn't exist

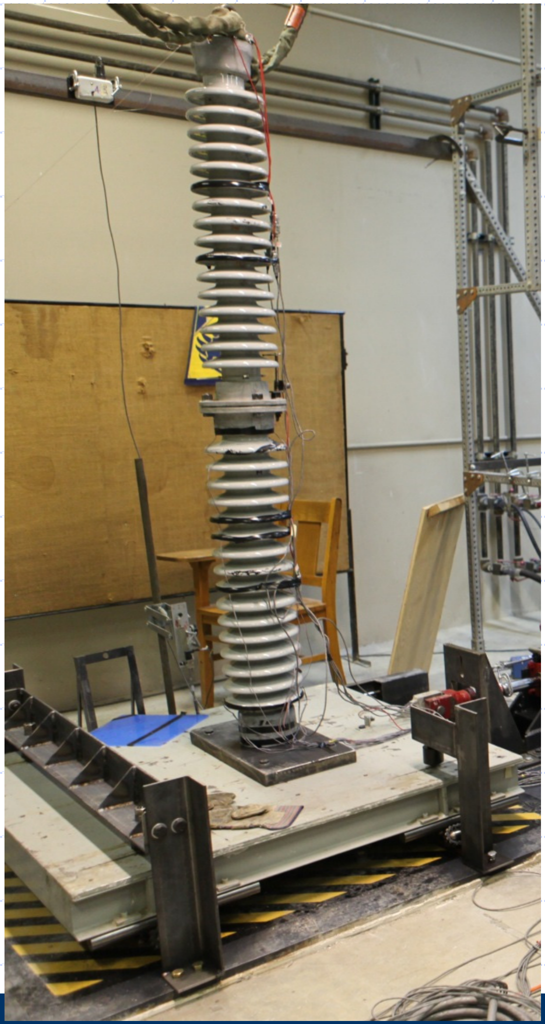
HS Classification

- Same quasi-static test setup can be used for real-time HS as long as proper hardware exists, e.g. dynamic actuators, digital controllers, etc.



HS Classification

- Real-time Hybrid Simulation (Shaking Table Configuration)

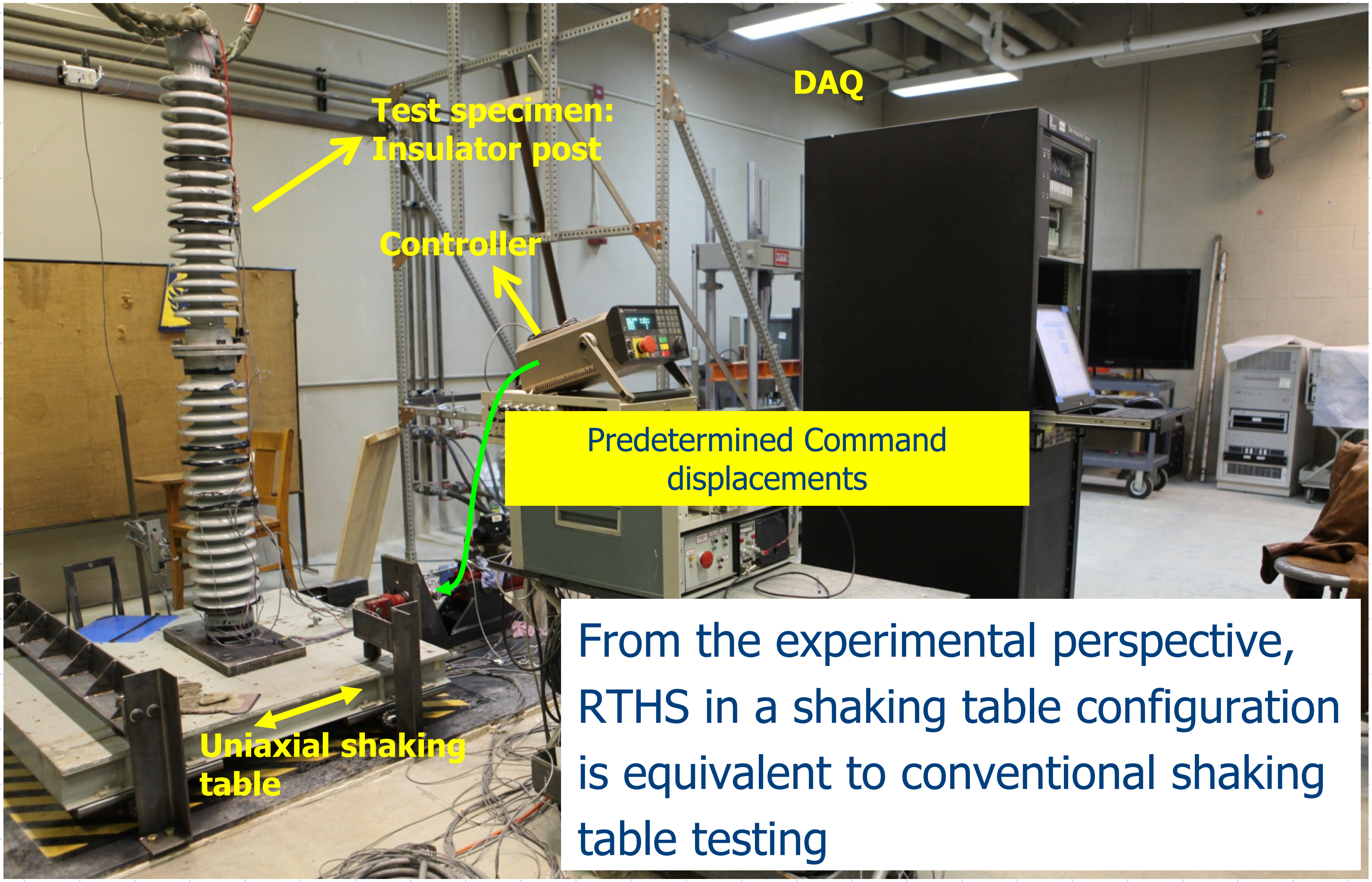


- ✓ Experimental substructure is located on a shaking table
- ✓ Physical mass generally exists
- ✓ Rate of loading = Computed velocity
- ✓ Duration of hybrid simulation = $N \times \Delta t$

  N: number of integration steps

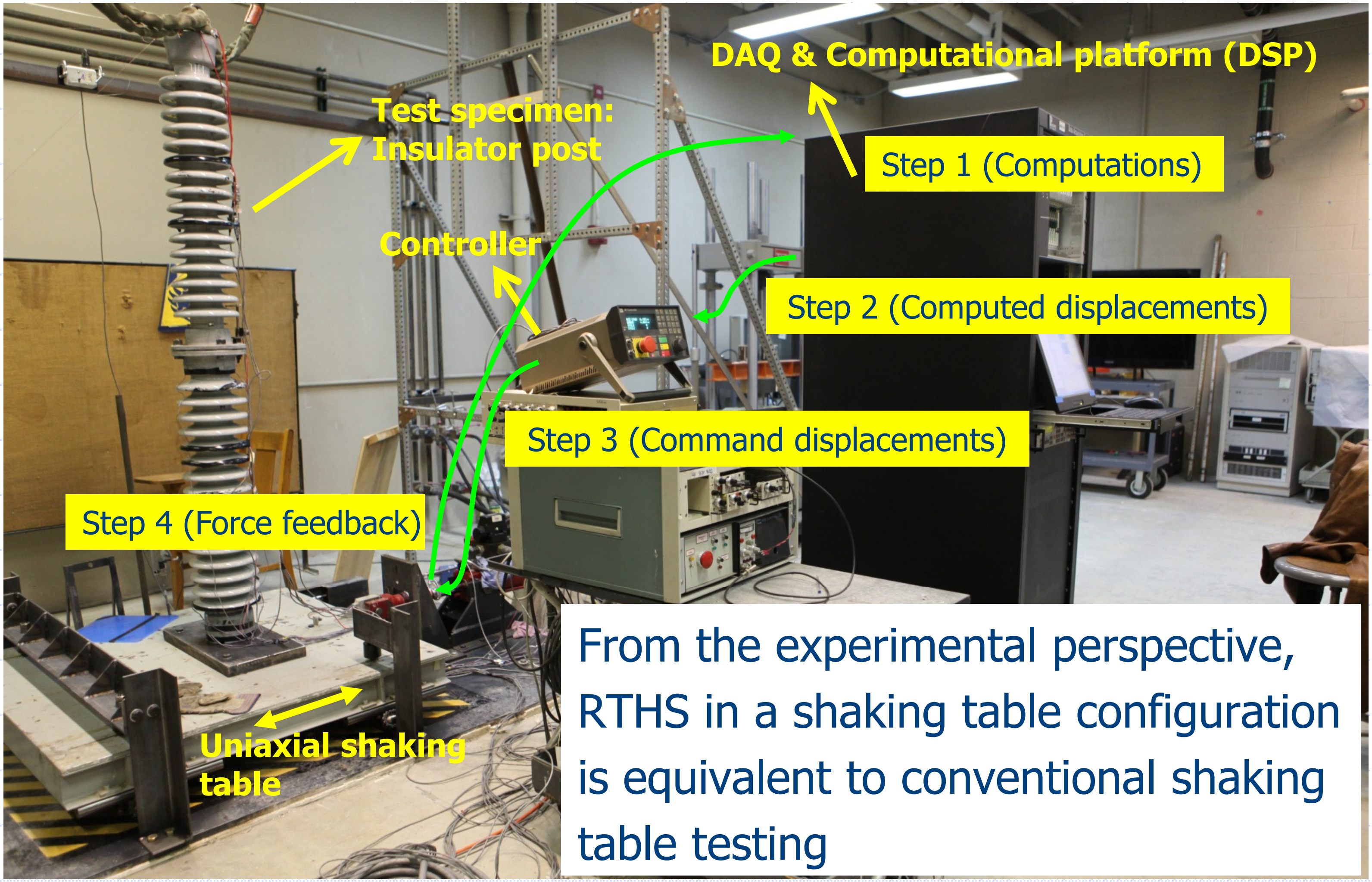
  Δt: integration time step
- ✓ Crucial when rate effects are important

HS Classification



From the experimental perspective, RTHS in a shaking table configuration is equivalent to conventional shaking table testing

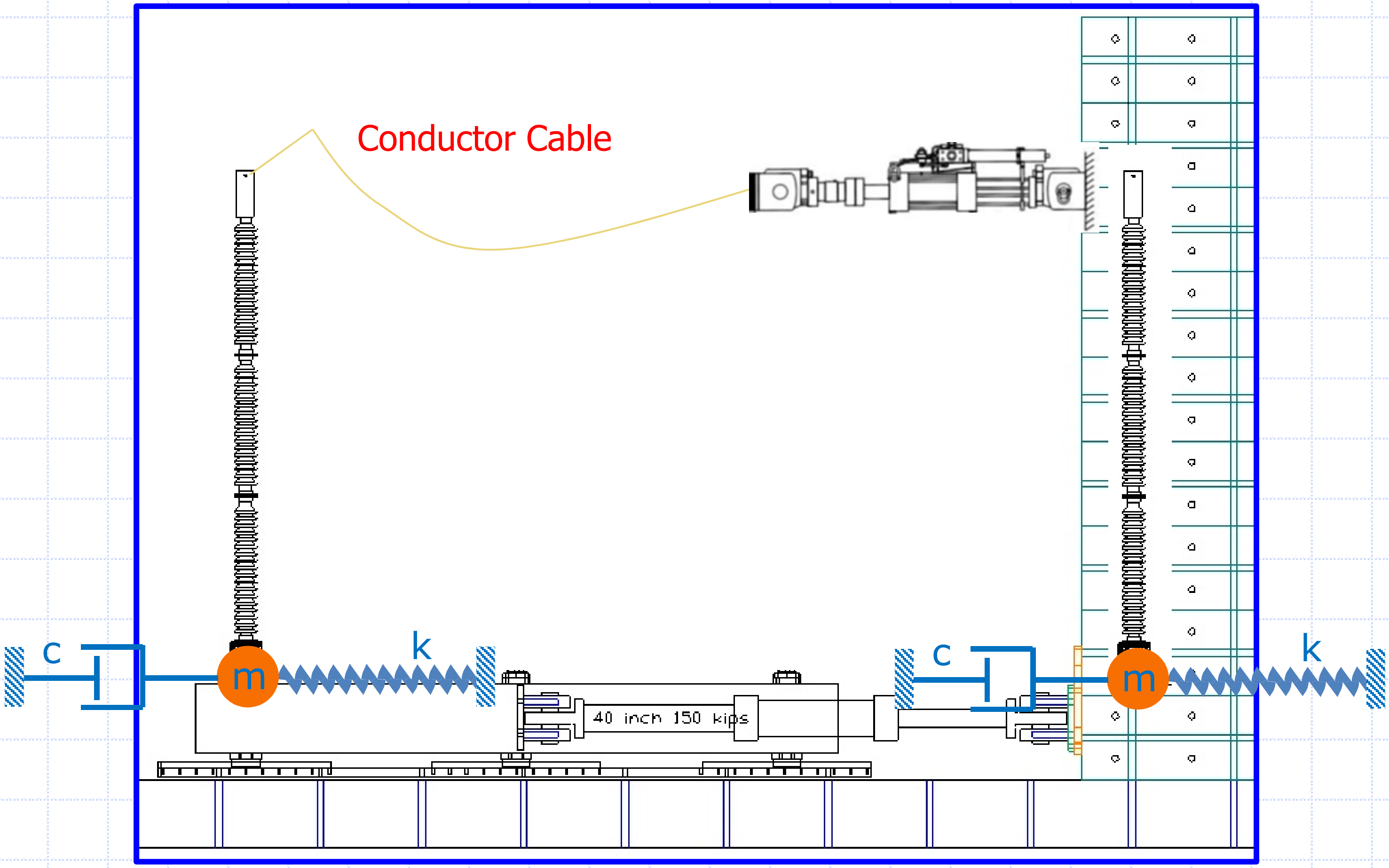
HS Classification



From the experimental perspective, RTHS in a shaking table configuration is equivalent to conventional shaking table testing

HS Classification

- Real-time Hybrid Simulation (Actuator + Shaking Table Configuration)

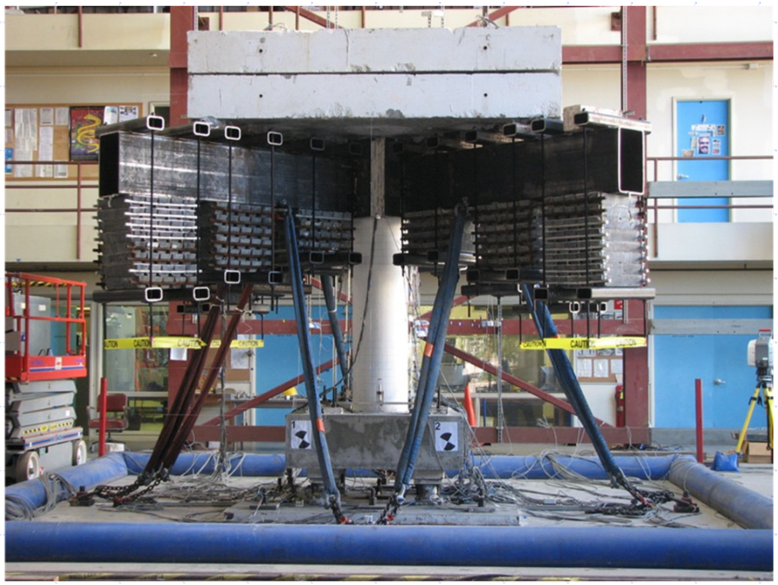


✓ Experimental substructure is located on a shaking table and connected to an actuator

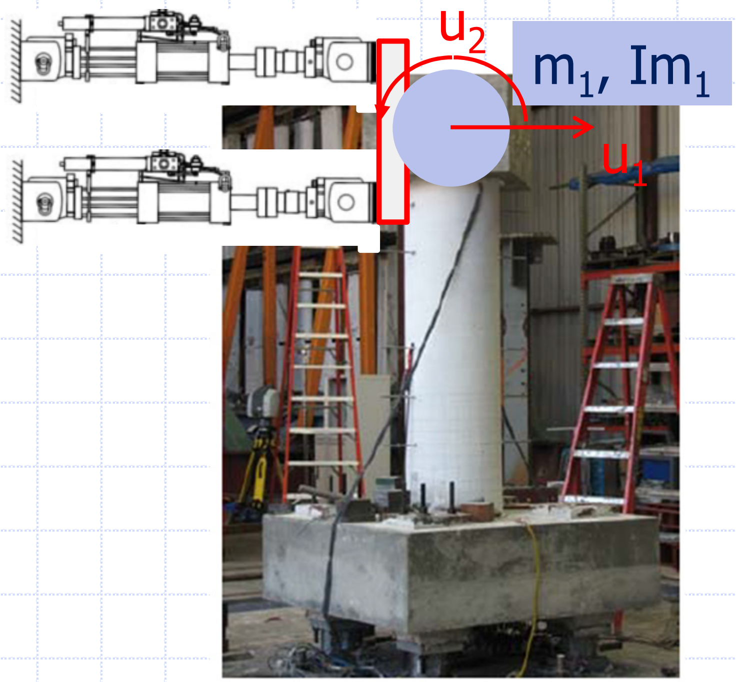
Benefits of HS

Convenience in mass modeling

Shaking Table

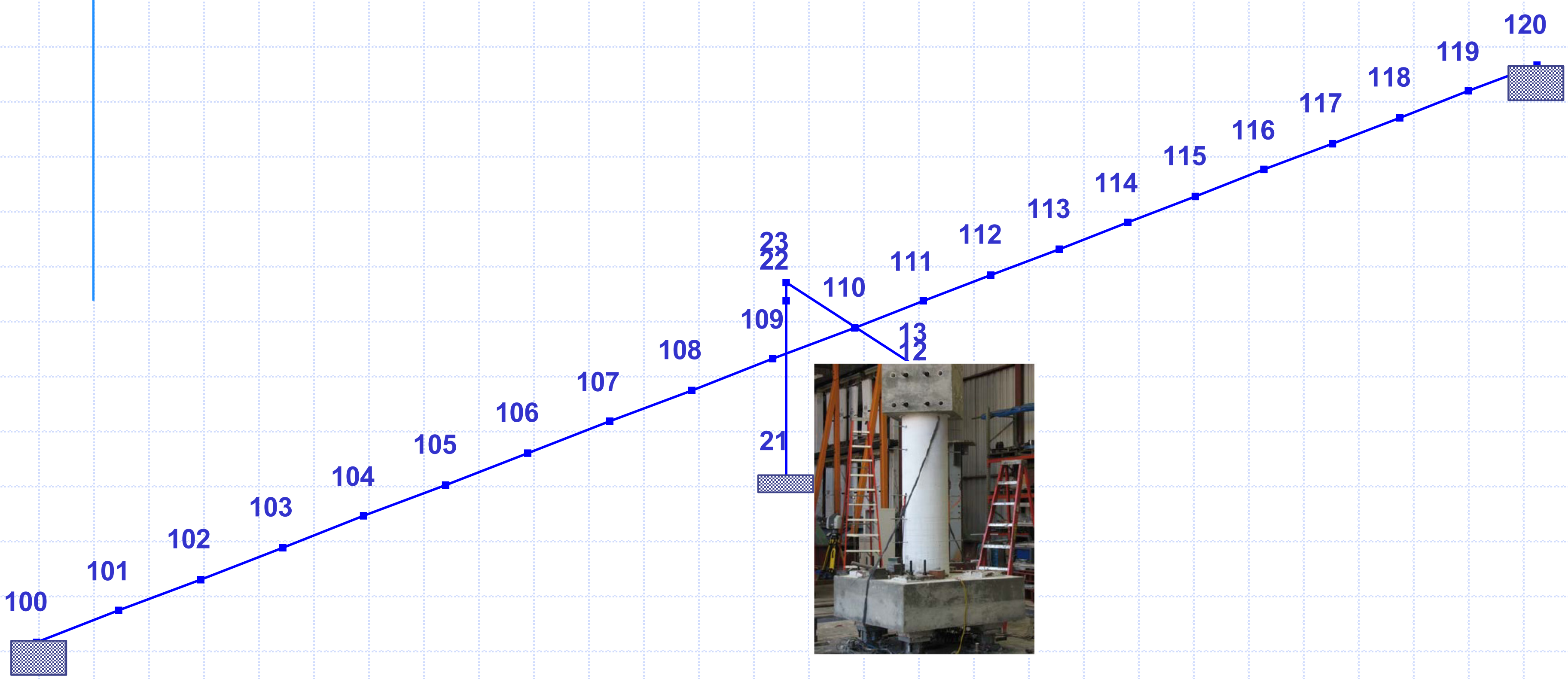


Hybrid Simulation



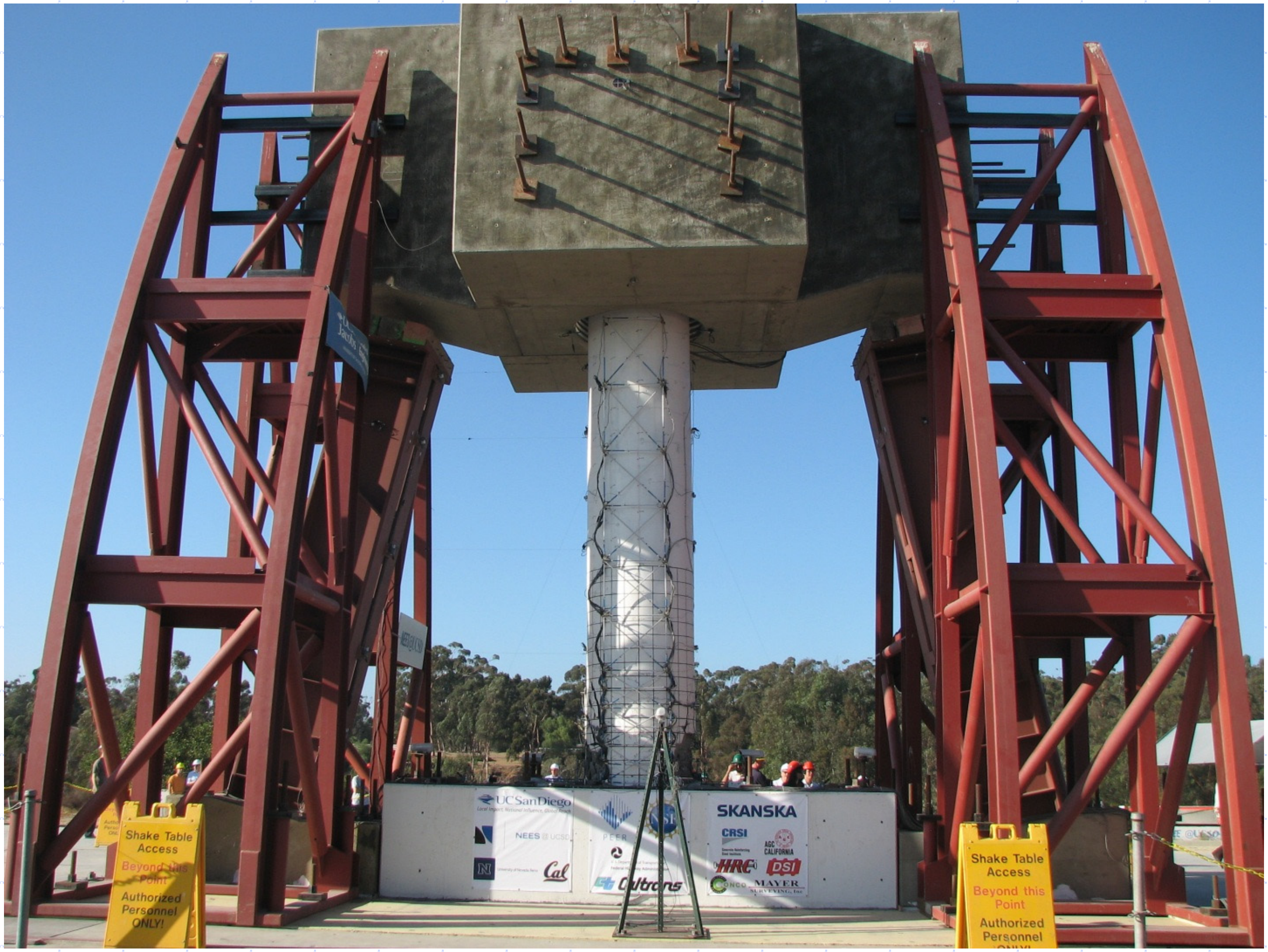
Benefits of HS

Convenience in system level testing



Benefits of HS

Convenience in mass modeling



Benefits of HS

Convenience in full scale testing

Benefits of HS

Time efficiency due to elimination of physical construction

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Experimental substructure

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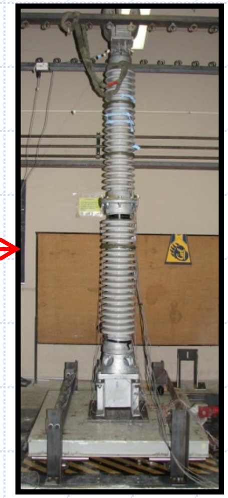
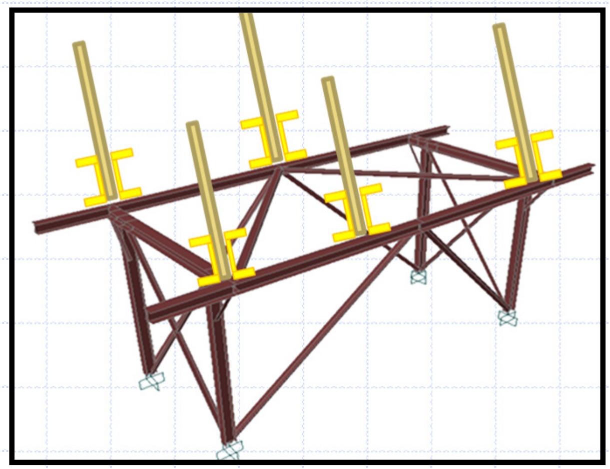


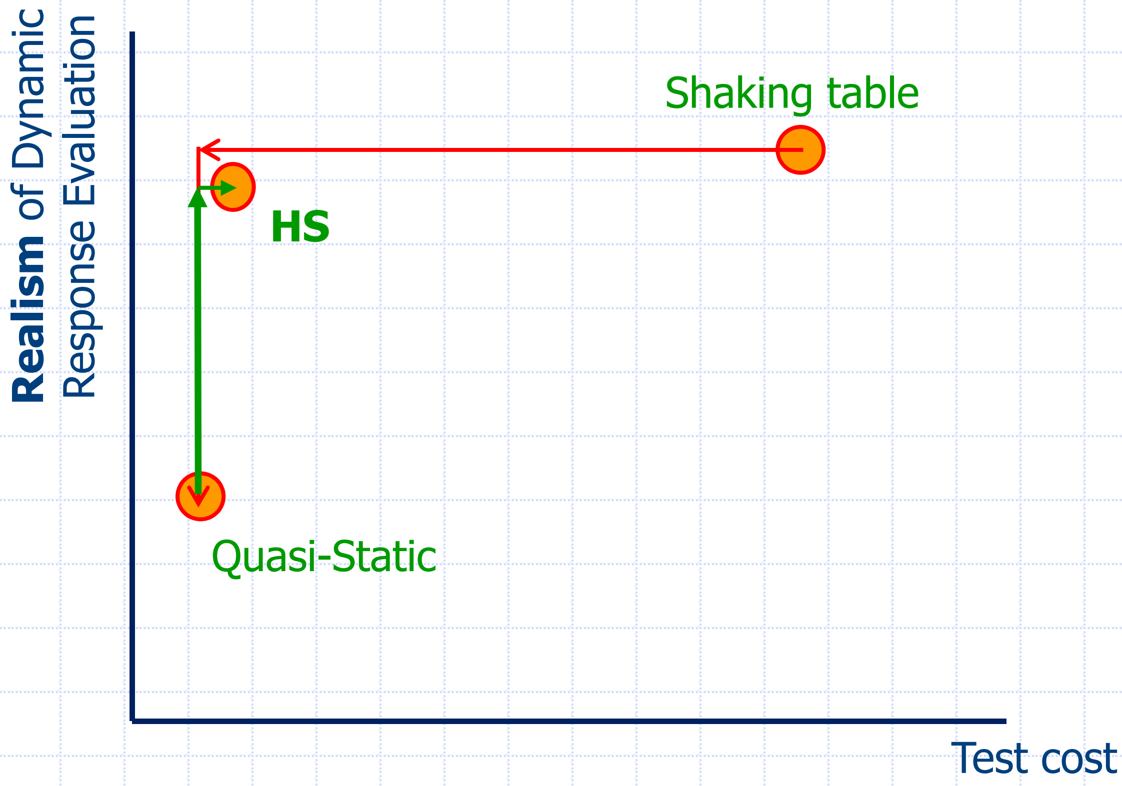
Details in the HS application lecture

Analytical substructure

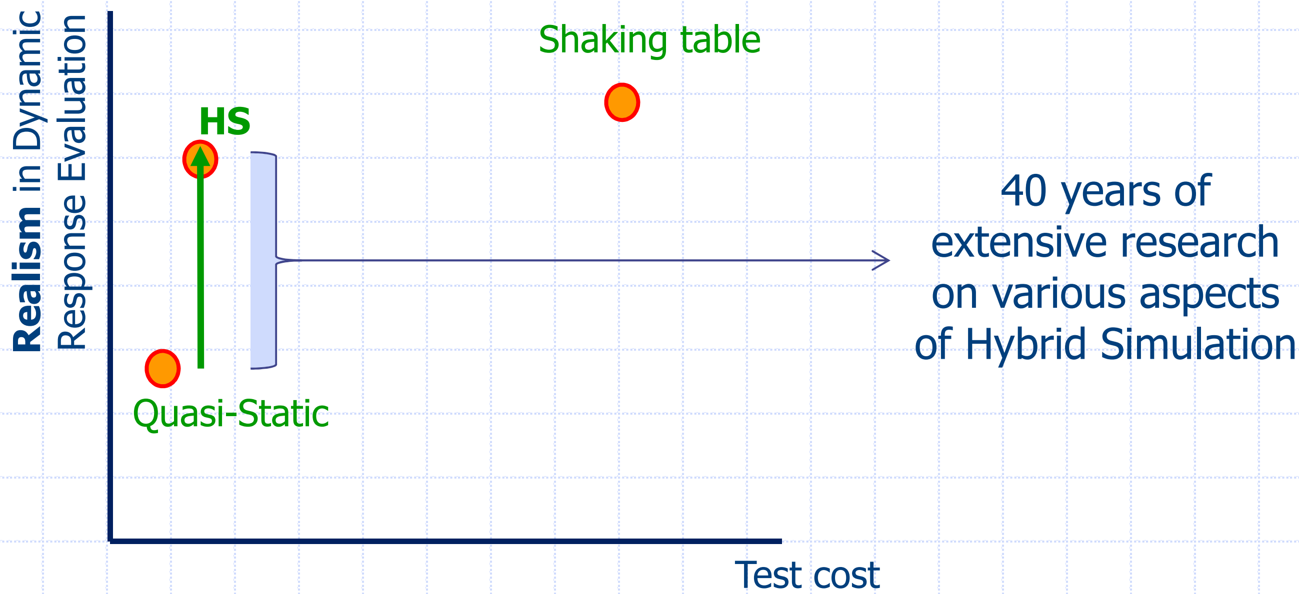


Benefits of HS

Economical Convenience



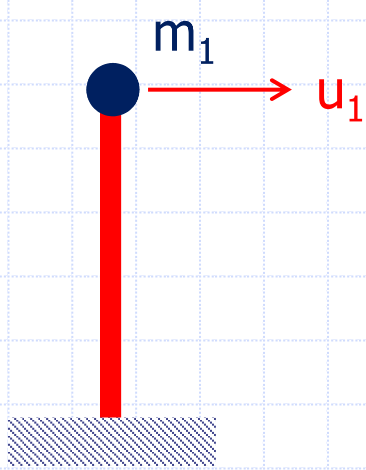
Benefits of HS



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

Substructuring Cases

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



Red : Experimental
Blue: Analytical

Substructuring Cases

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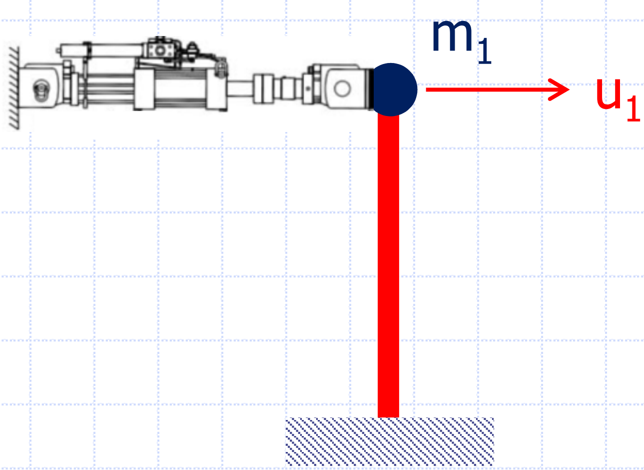

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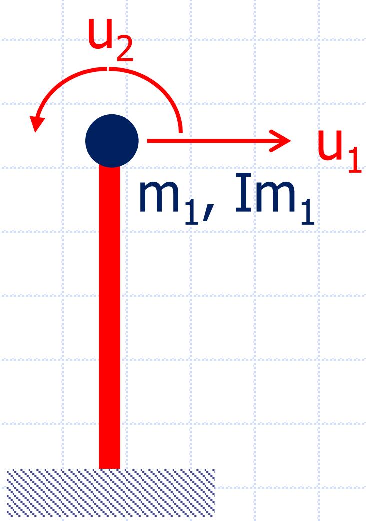
Substructuring Cases

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



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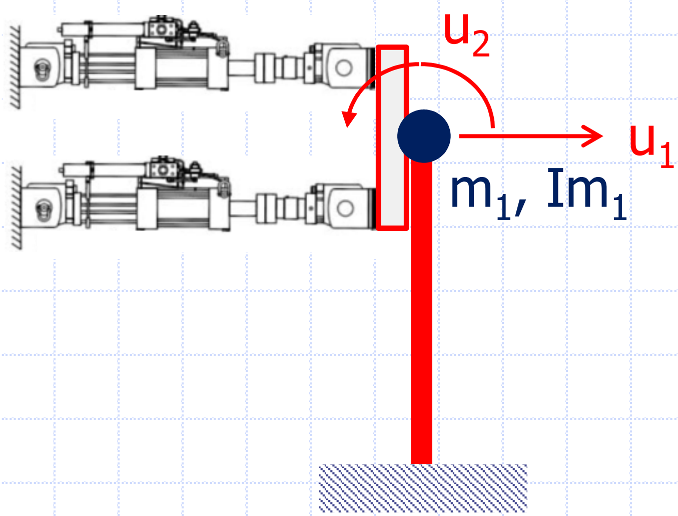
Substructuring Cases

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



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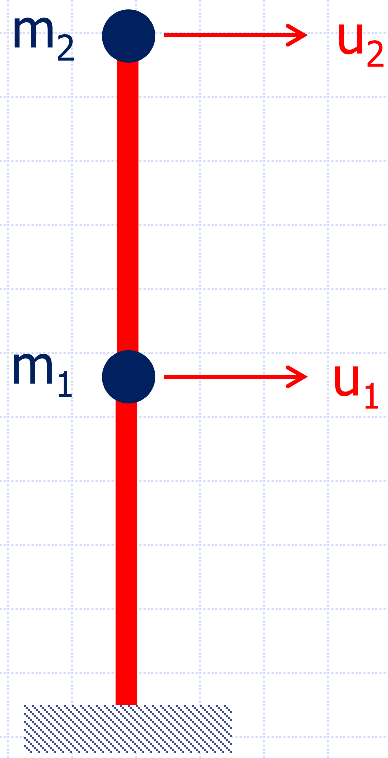
Substructuring Cases

CASE 3: TWO COLUMNS without ANALYTICAL SUBSTRUCTURE



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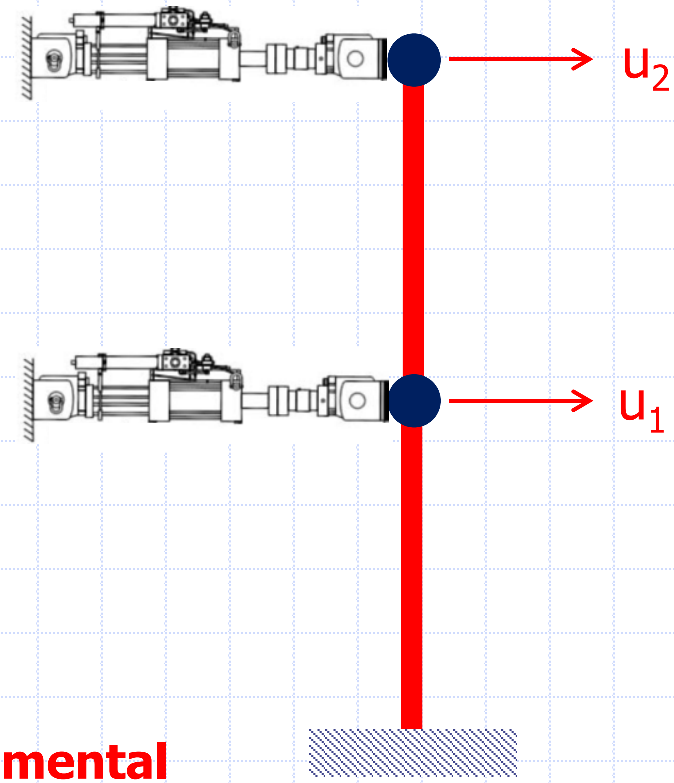
Substructuring Cases

CASE 3: TWO COLUMNS without ANALYTICAL SUBSTRUCTURE



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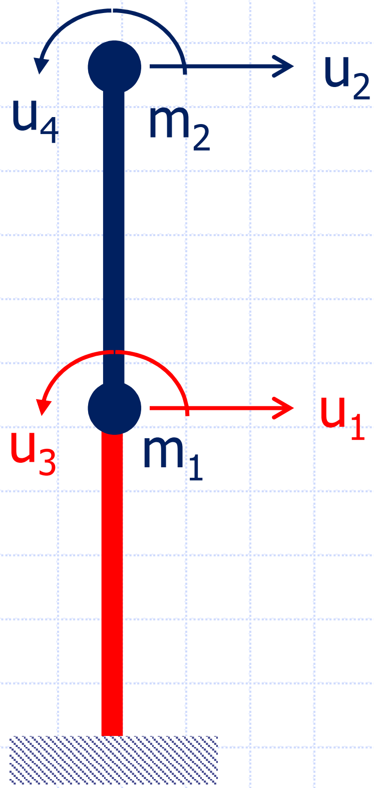
Substructuring Cases

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



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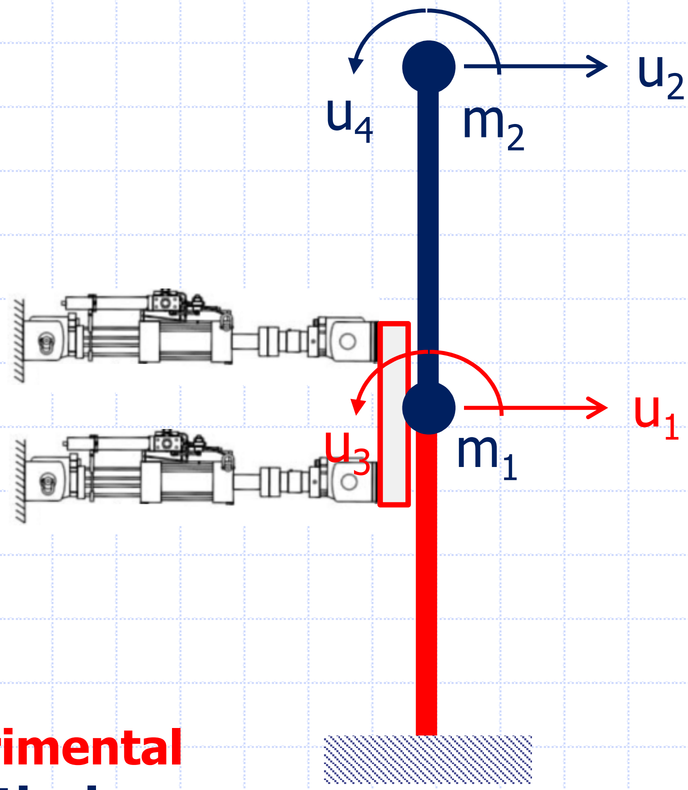
Substructuring Cases

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



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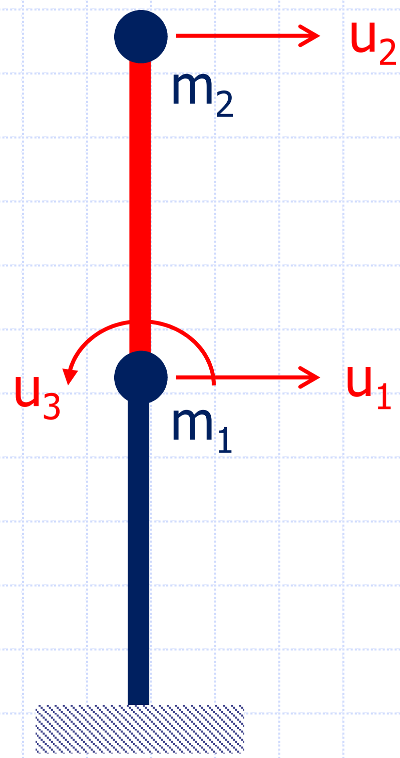
Substructuring Cases

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



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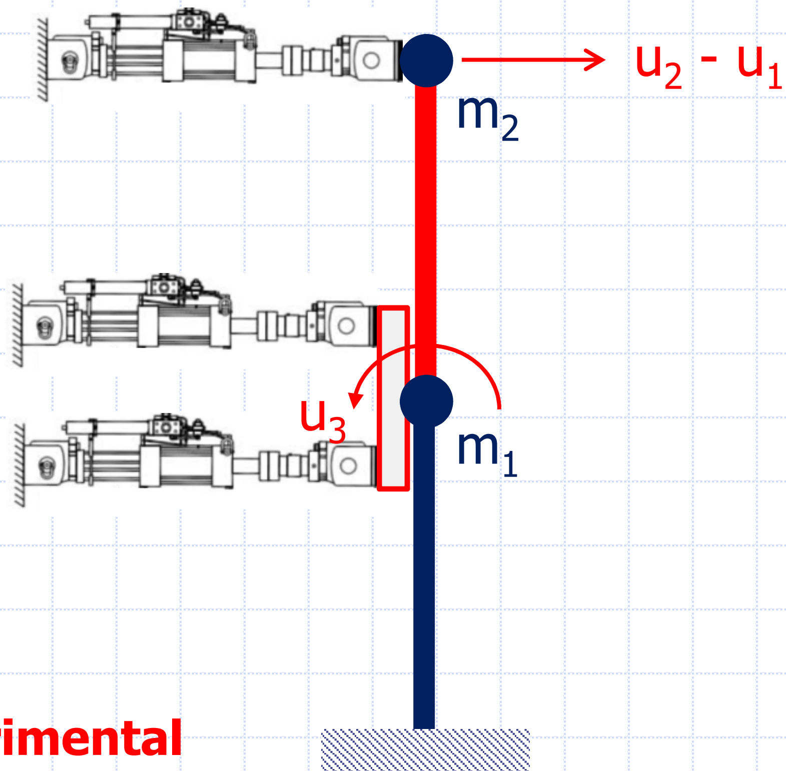
Substructuring Cases

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



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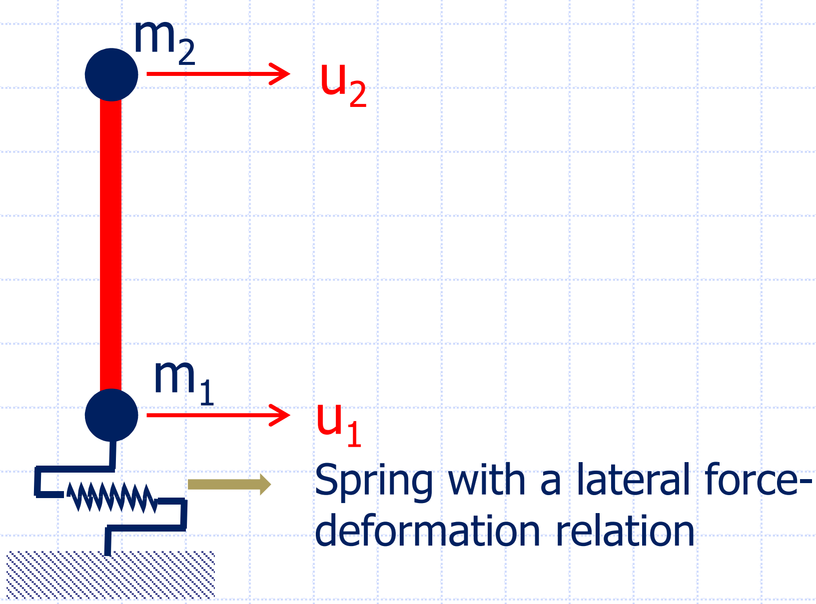
Substructuring Cases

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



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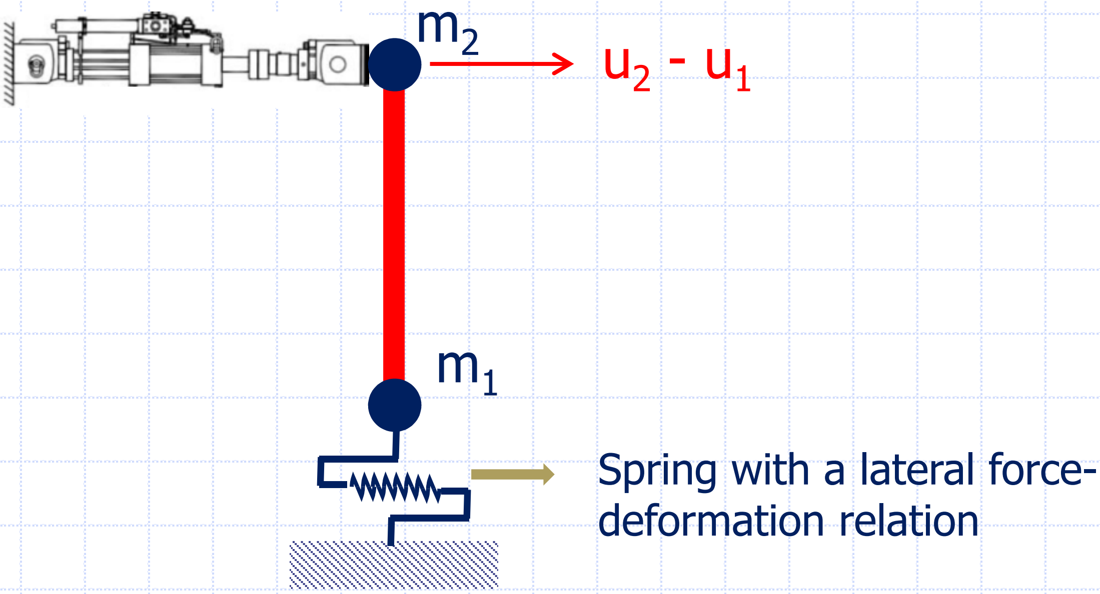
Blue: Analytical

Substructuring Cases

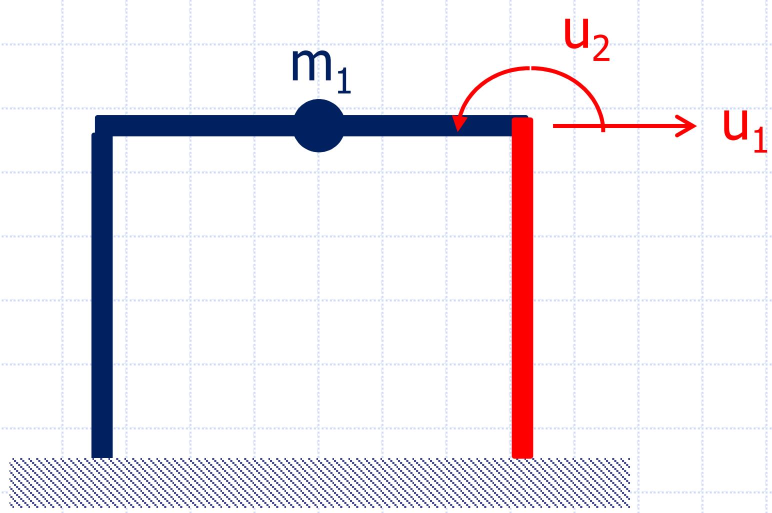
CASE 4-2: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

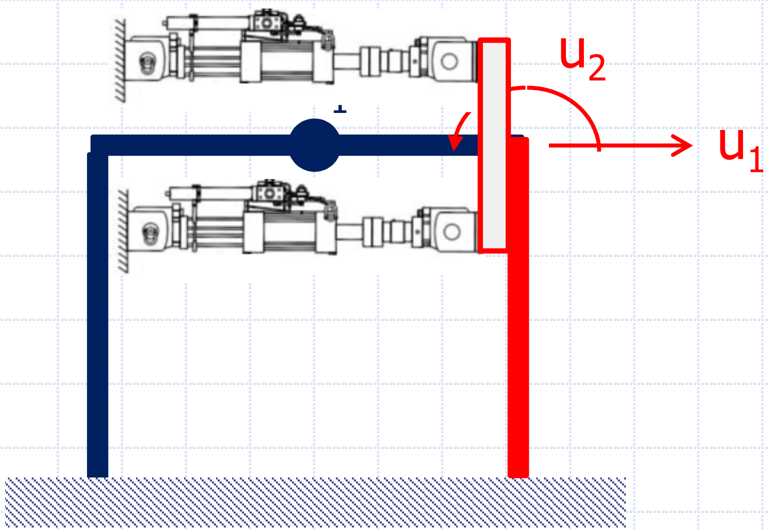
CASE 5: PORTAL FRAME with ONE OF THE COLUMNS AND BEAM AS ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

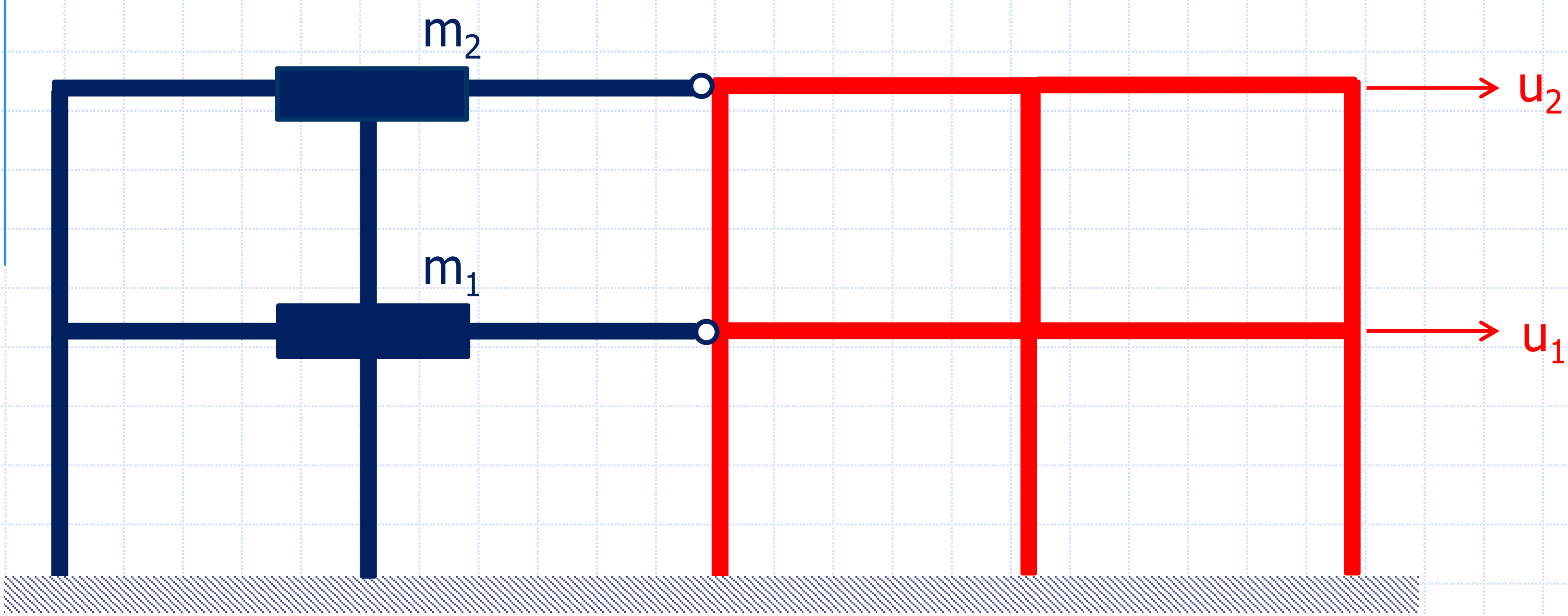
CASE 5: PORTAL FRAME with ONE OF THE COLUMNS AND BEAM AS ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

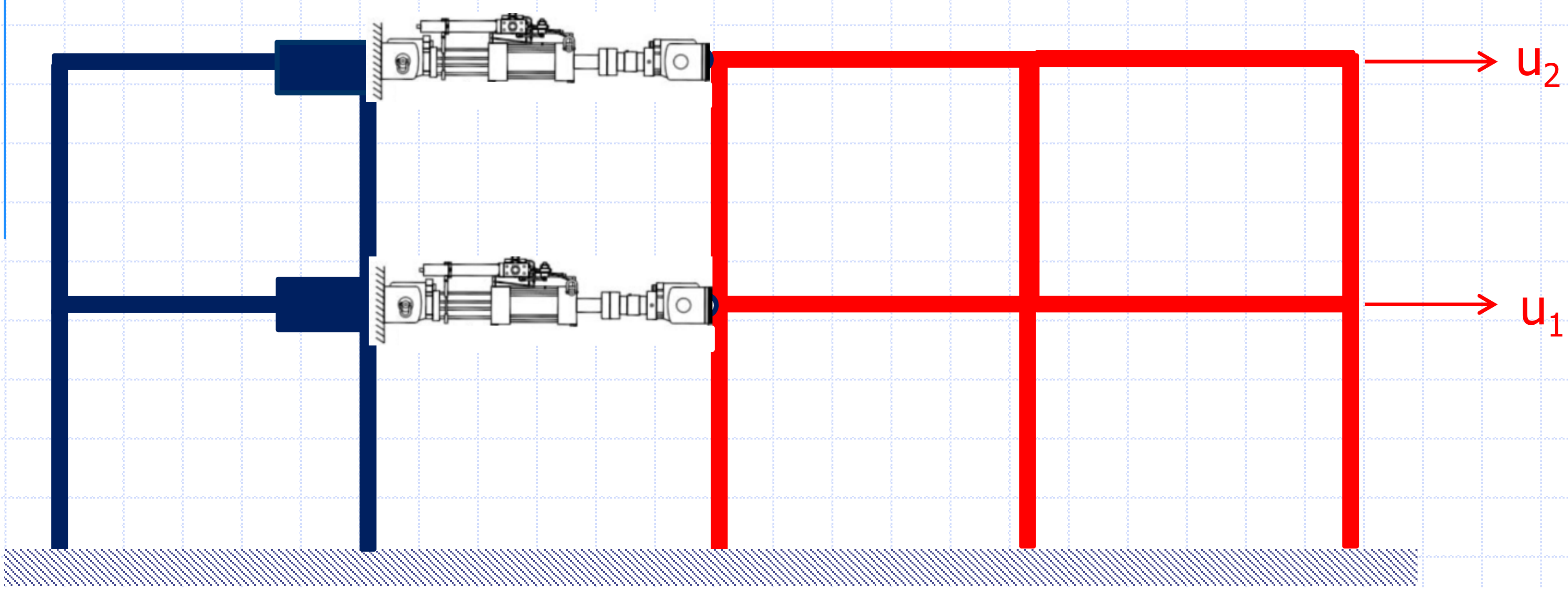
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Substructuring Cases

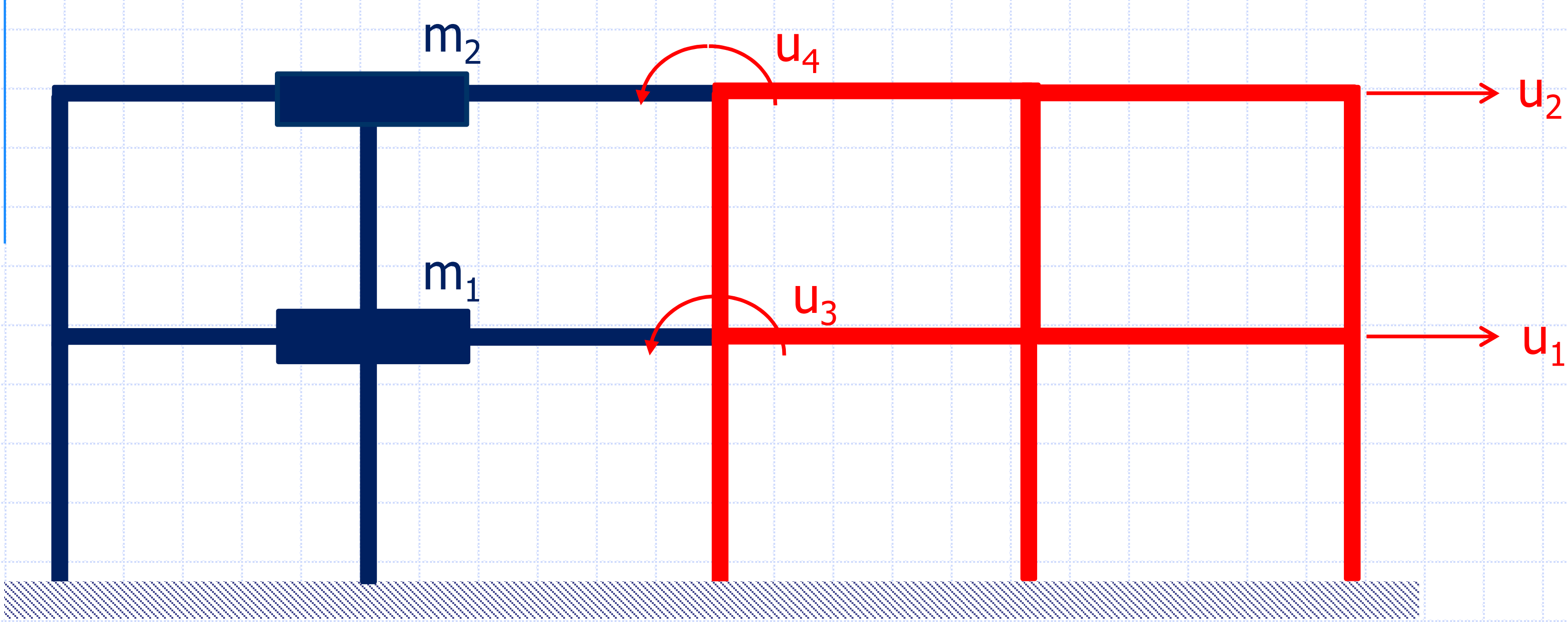
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Substructuring Cases

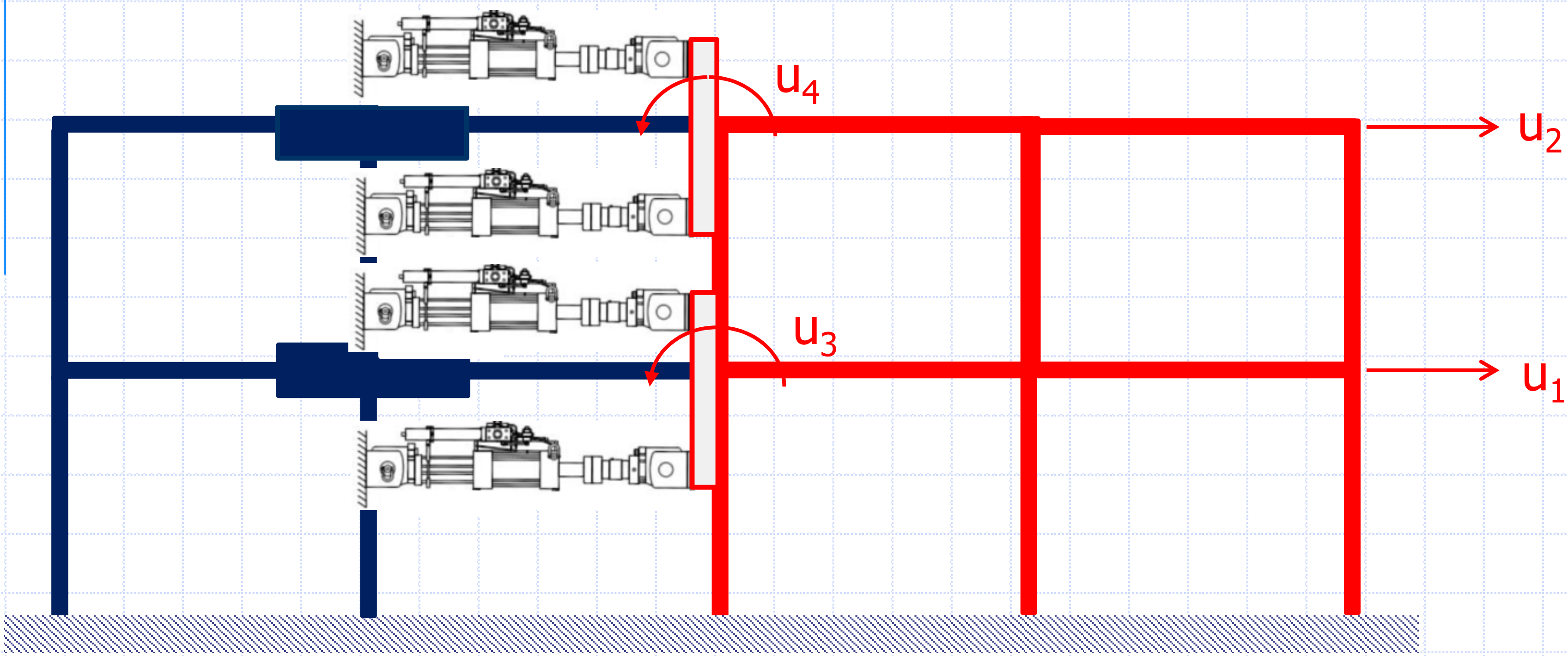
CASE 6-1: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Substructuring Cases

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



Red : Experimental
Blue: Analytical

Integration Methods

Analytical Simulation + Experimental Simulation = Hybrid Simulation

All the integration methods developed for analytical simulations are not suitable for hybrid simulation

Example: The most common and standard integration method for analytical simulation, Implicit Newmark Integration

Integration Methods

Implicit Newmark Integration

$$\mathbf{p}_{i+1} - \mathbf{m}\ddot{\mathbf{u}}_{i+1} - \mathbf{c}\dot{\mathbf{u}}_{i+1} - \mathbf{p}_{\mathbf{r}}(\mathbf{u}_{i+1}) = \mathbf{0}$$

Equilibrium equation

$$\ddot{\mathbf{u}}_{i+1} = \frac{1}{(\Delta t)^2 \beta}(\mathbf{u}_{i+1} - \mathbf{u}_i) - \frac{1}{\Delta t \beta}\dot{\mathbf{u}}_i - \left(\frac{1}{2\beta} - 1\right)\ddot{\mathbf{u}}_i$$

$$\dot{\mathbf{u}}_{i+1} = \frac{\gamma}{\Delta t \beta}(\mathbf{u}_{i+1} - \mathbf{u}_i) - \left(\frac{\gamma}{\beta} - 1\right)\dot{\mathbf{u}}_i - \Delta t\left(\frac{\gamma}{2\beta} - 1\right)\ddot{\mathbf{u}}_i$$

Difference equations

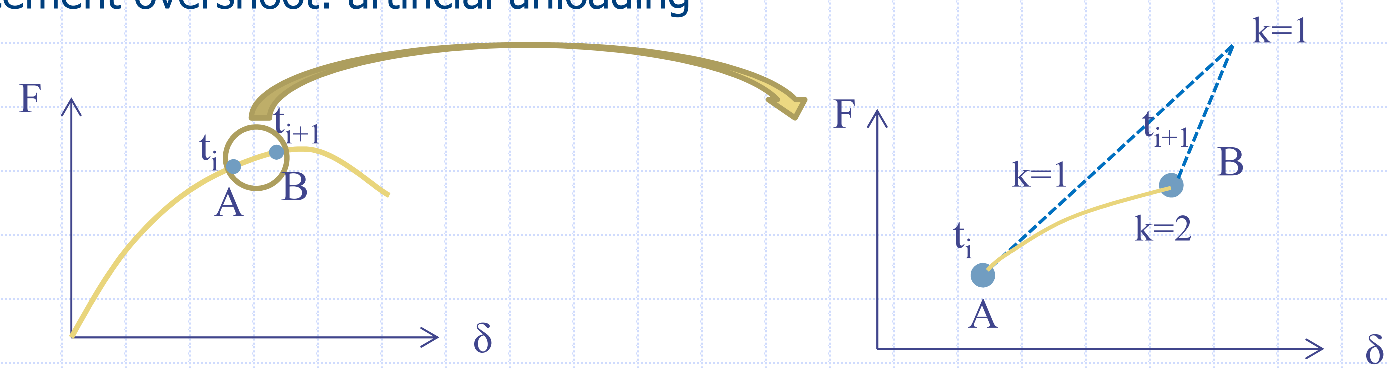
Equilibrium and difference equations represent a nonlinear system of equations, $f(\mathbf{u}_{i+1}) = \mathbf{p}_{i+1} - \mathbf{m}\ddot{\mathbf{u}}_{i+1} - \mathbf{c}\dot{\mathbf{u}}_{i+1} - \mathbf{p}_{\mathbf{r}}(\mathbf{u}_{i+1}) = \mathbf{0}$

which can be solved using iterative methods such as Newton-Raphson method $f'(\mathbf{u}_{i+1}^k)\Delta\mathbf{u}_{i+1}^k = -f(\mathbf{u}_{i+1}^k)$

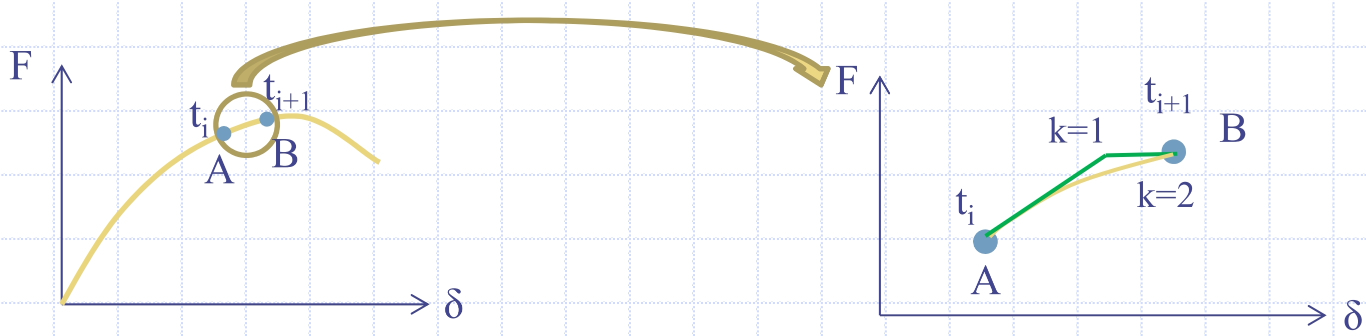
Integration Methods

Iterations of Implicit Newmark are not suitable for hybrid simulation:

- Iterations may not converge
- Displacement overshoot: artificial unloading



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



Integration Methods

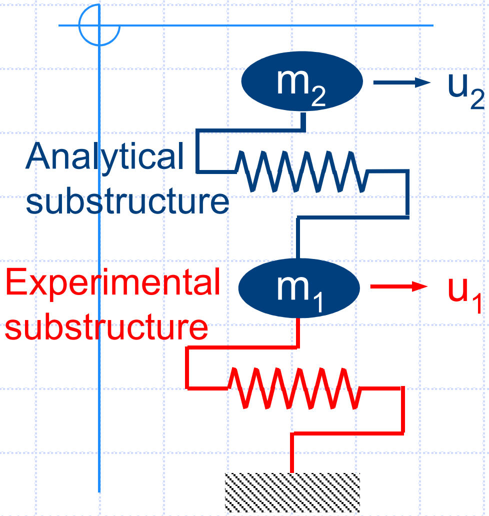
HS compatible alternative integrators

- Explicit Newmark Integration
- Operator Splitting Method

} Do not require iterations

- Implicit Newmark Integration with Fixed Number of Iterations

Simulation Errors



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

1. Apply $u_{1,i+1}$ to the test specimen
2. Measure the corresponding force $f_{e,i+1}$

- Reliability of a hybrid simulation depends on the accuracy of f_e
- All the errors that occur during stages 1 and 2 are experimental errors and affect hybrid simulation

Simulation Errors

Experimental errors → Random errors

Experimental errors → Systematic errors

Random errors:

- They have no distinguishable pattern and generally no specific physical effects can be anticipated.
- **Examples**:
  1. Random electrical noise in wires and electronic systems
  2. Random rounding-off or truncation in the A/D conversion of electrical signals
- They do not introduce significant errors to hybrid simulation.

Simulation Errors

Experimental systematic errors:

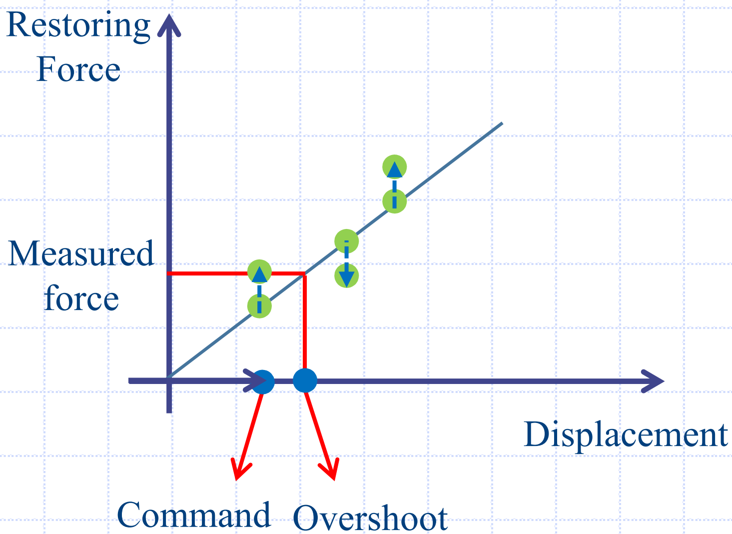
- They may lead to error propagation and numerical instability
- **Examples**:
  1. Measurement errors
  2. Hybrid simulation technique (ramp and hold, continuous, real-time)
  3. Servo-hydraulic closed control loop

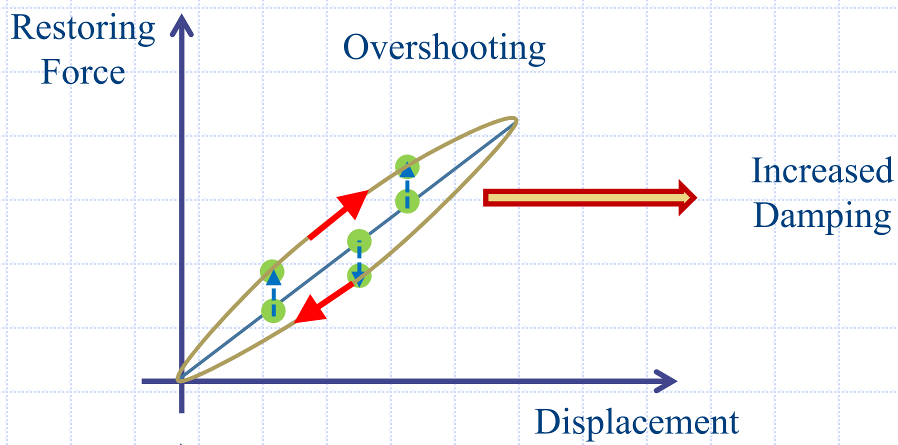
1. Measurement errors

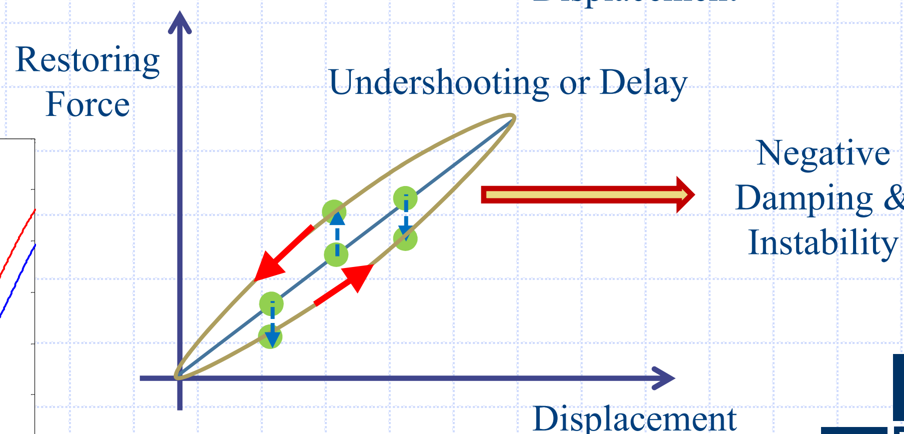
- Errors in load cells & displacement transducers of actuators due to:
  a. Calibration
  b. Friction or slop in the attachments
  c. A/D and D/A conversions

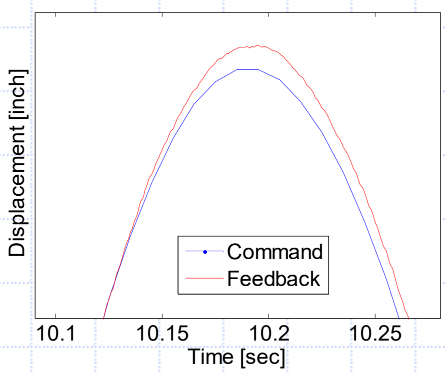
Simulation Errors

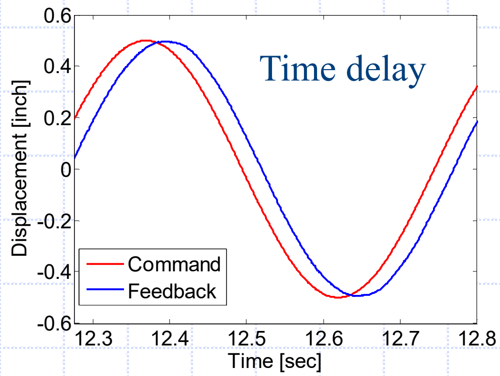
Control-loop errors (Errors in displacement tracking): Demonstration of the effect of control-loop errors





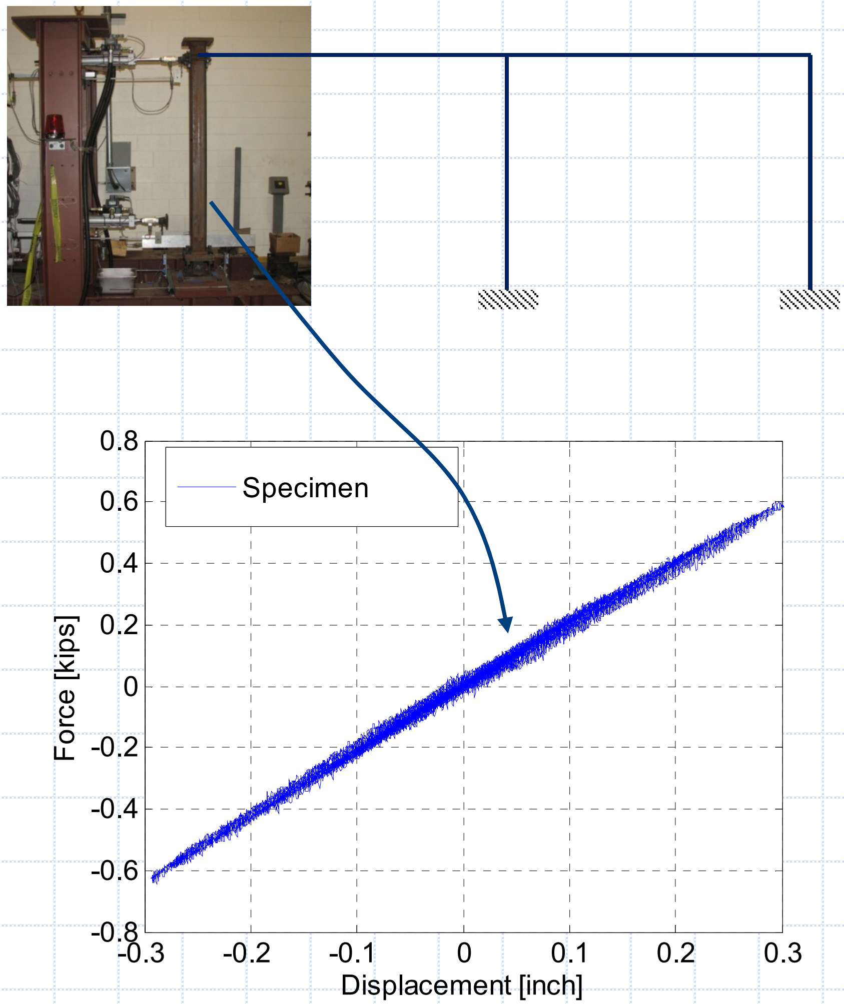






Simulation Errors

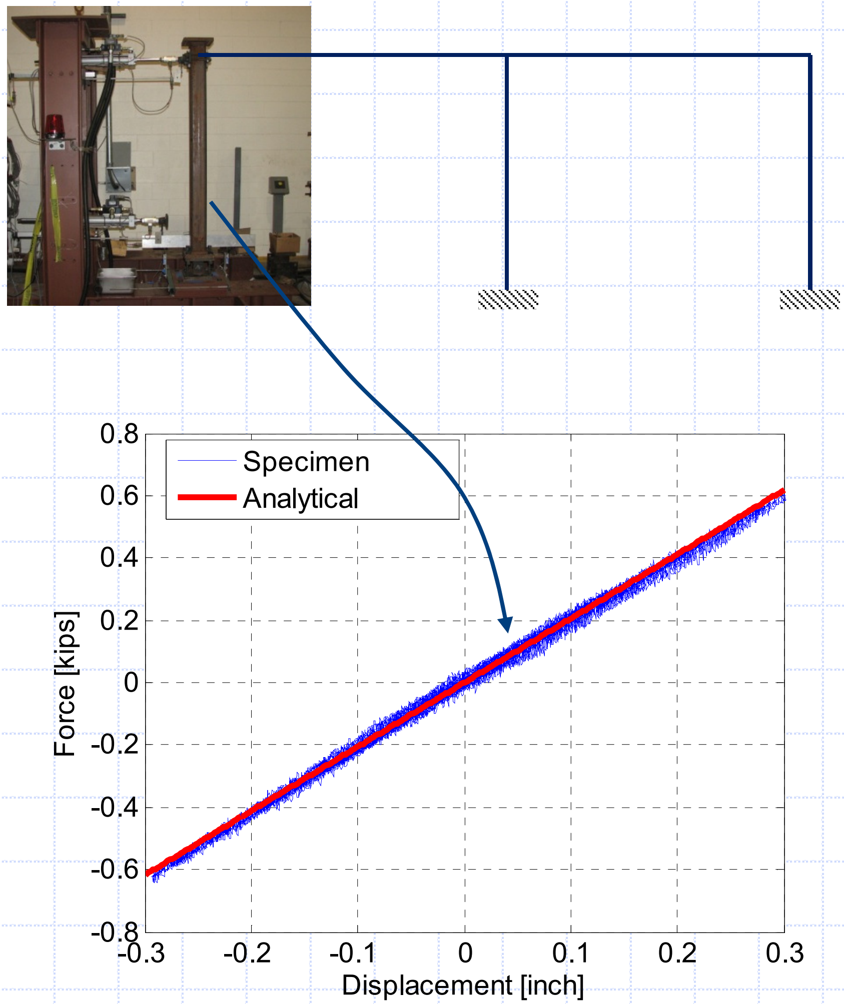
Control-loop errors: Demonstration tests



T = 0.5 sec
ζ = 5%

Simulation Errors

Control-loop errors: Demonstration tests

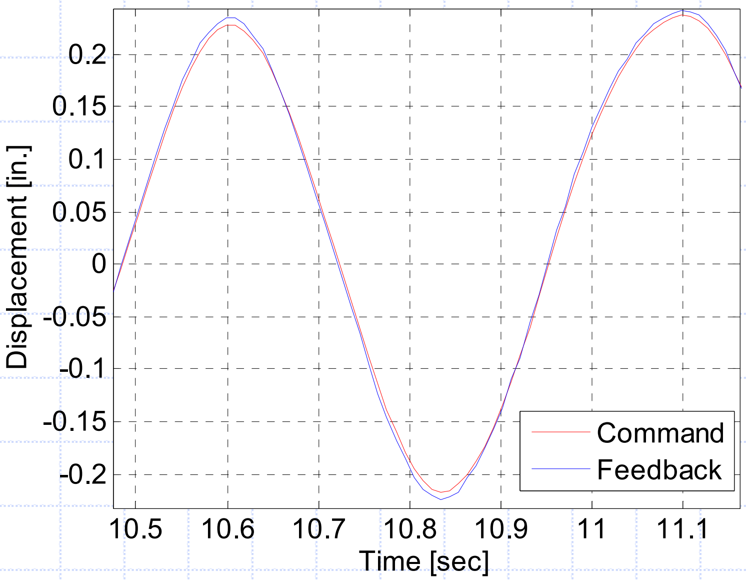


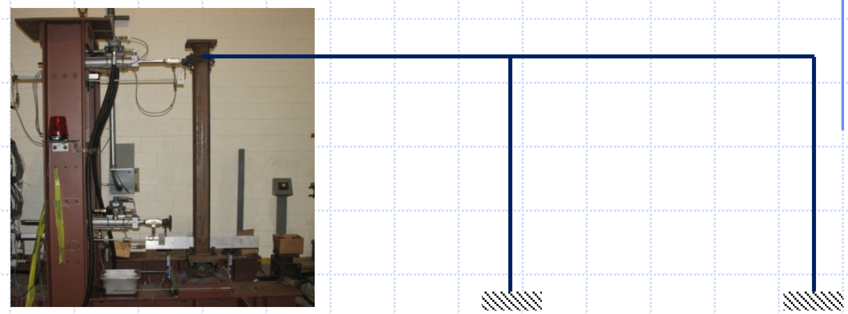
T = 0.5 sec
ζ = 5%

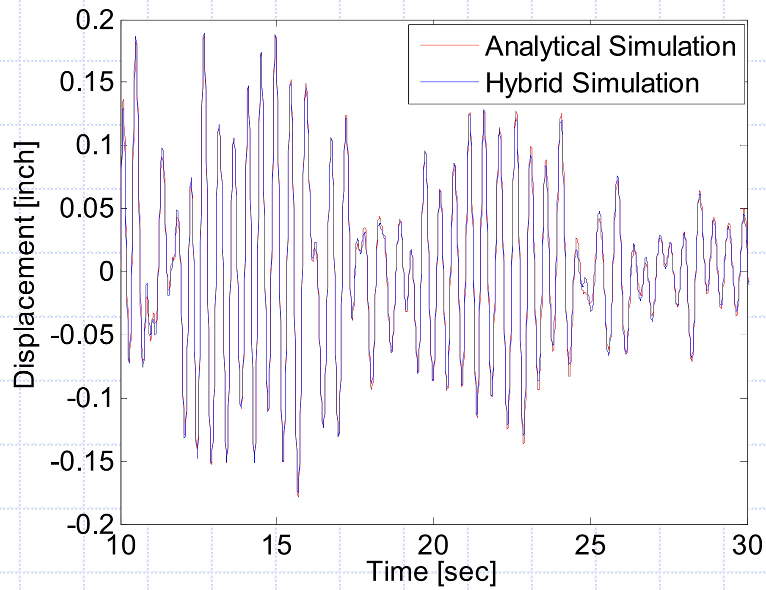
Simulation Errors

Control-loop errors: Demonstration tests

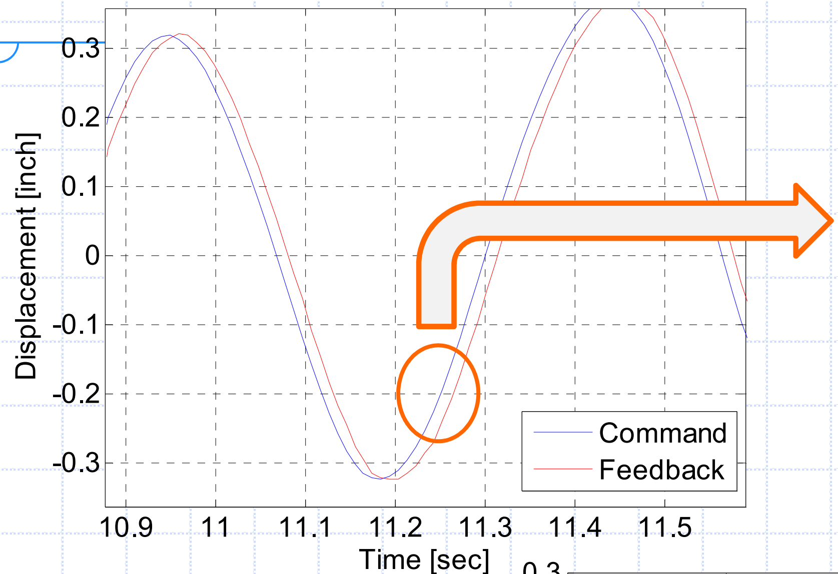
No time delay

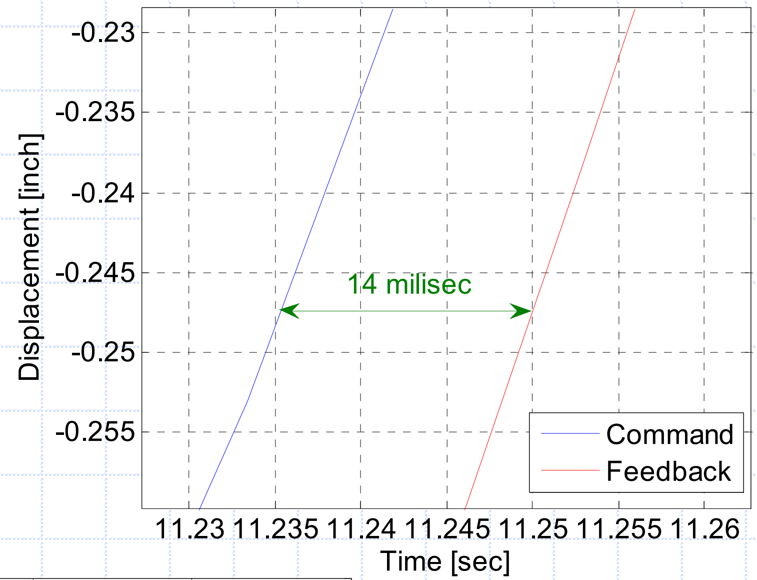




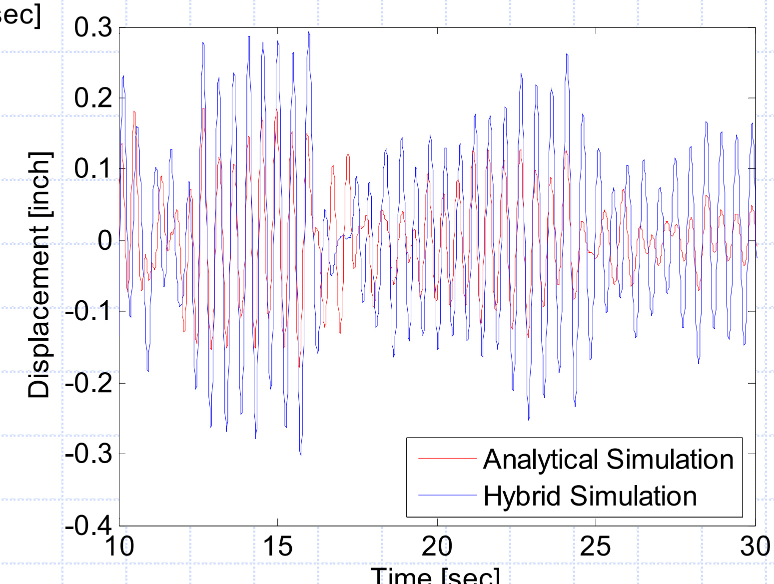


Simulation Errors





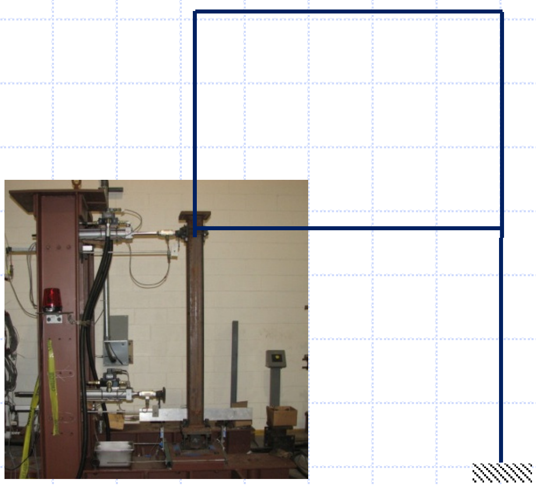
14 msec time delay introduced artificially by adjusting the feed-forward gain

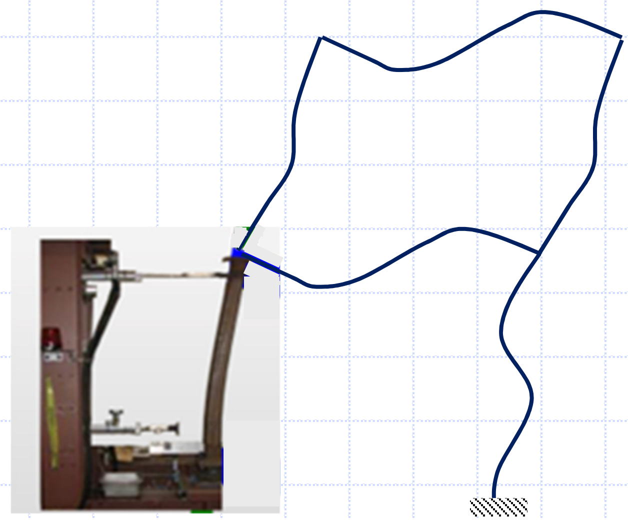


Simulation Errors

Control loop errors: Error identification using free vibration

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

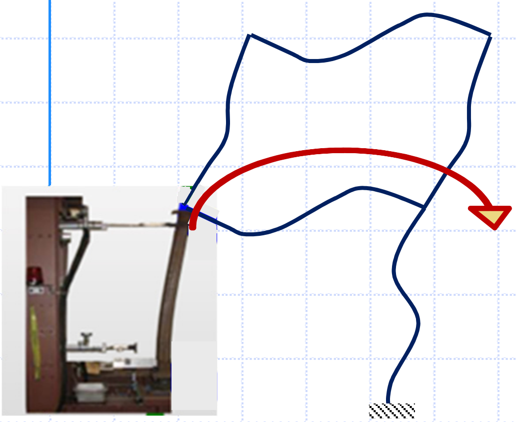


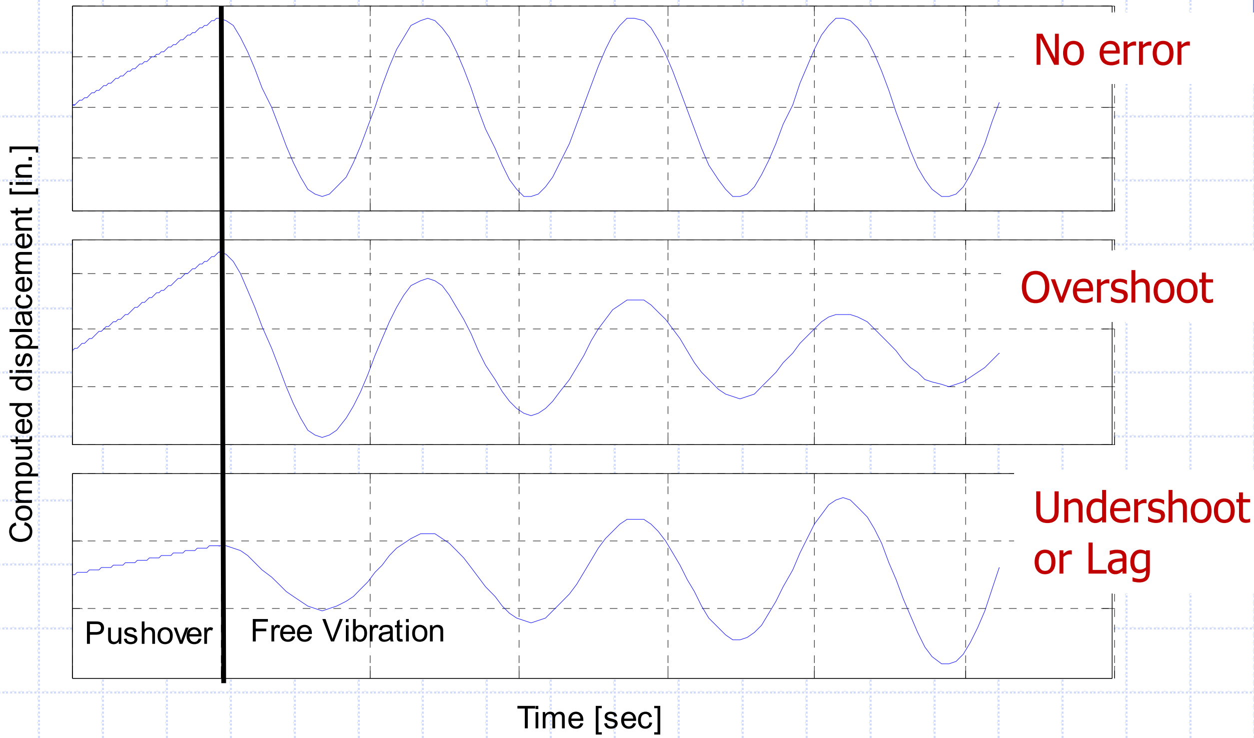


Step 2: Run the free vibration hybrid simulation test from this displaced configuration

Simulation Errors

Control loop errors: Error identification using free vibration





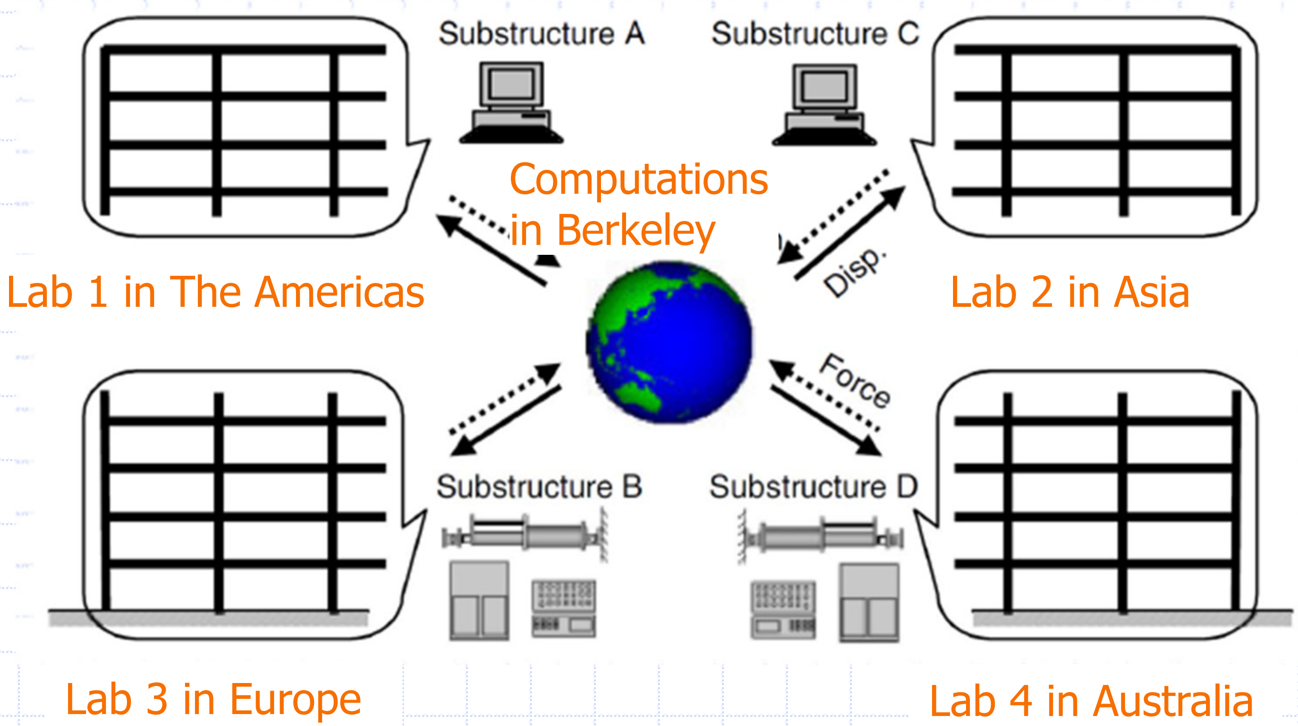
Simulation Errors

Methods to Reduce the Effects of Errors

- Error Compensation Methods
- Integration Methods with Numerical Damping
- Tuning
- Advanced Control Methods

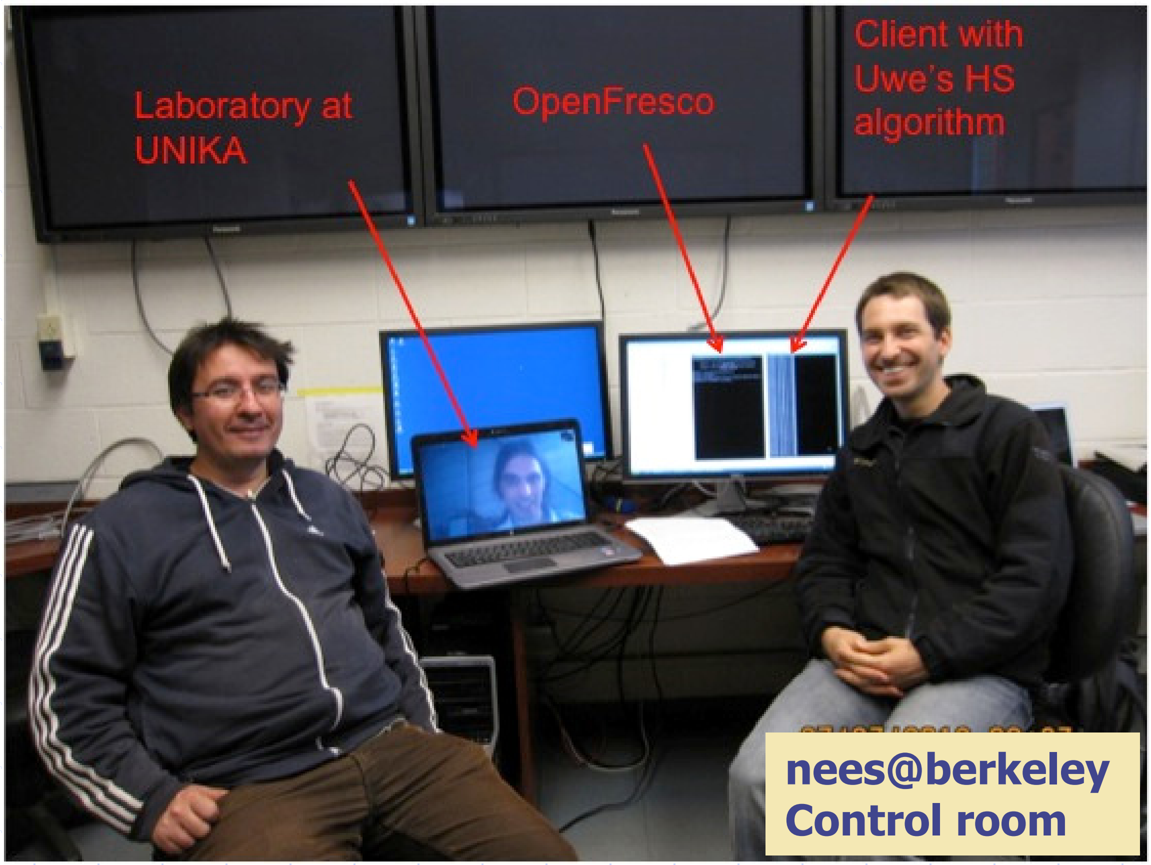
HS Related Research

Geographically Distributed HS



Geographically Distributed HS

Geographically distributed HS test between nees@berkeley and UNIKA, Germany



Experimental substructure: Friction device and a fixed tuned-mass-damper @UNIKA

Analytical substructure: SDOF mass with viscous damping @Berkeley

OpenFresco: The Open-source Framework for Experimental Setup and Control http://openfresco.berkeley.edu/

Real-time Hybrid Simulation (RTHS)

- **Requirement for real time**:

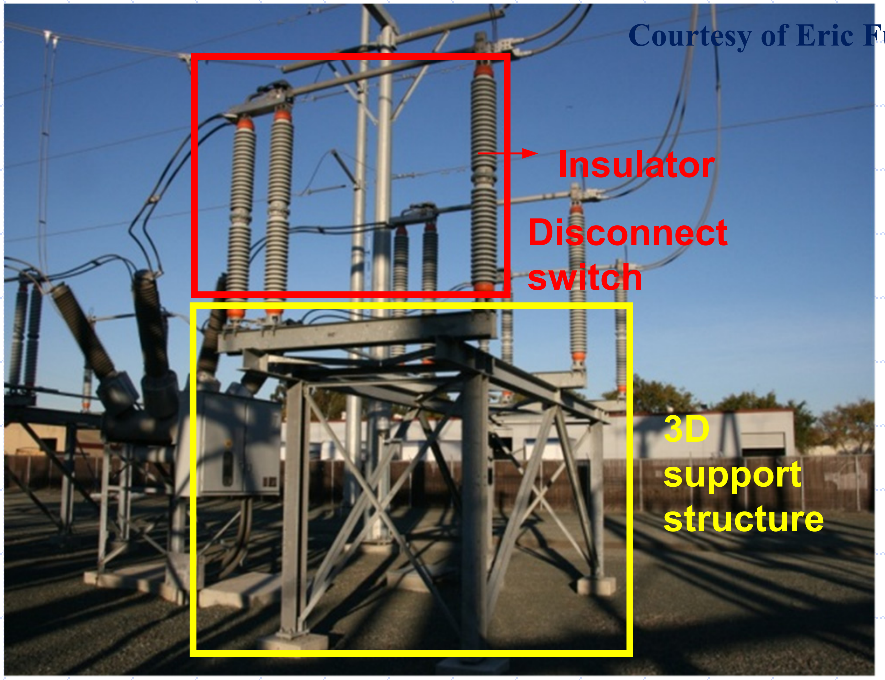
  Loading rate = Computed velocity

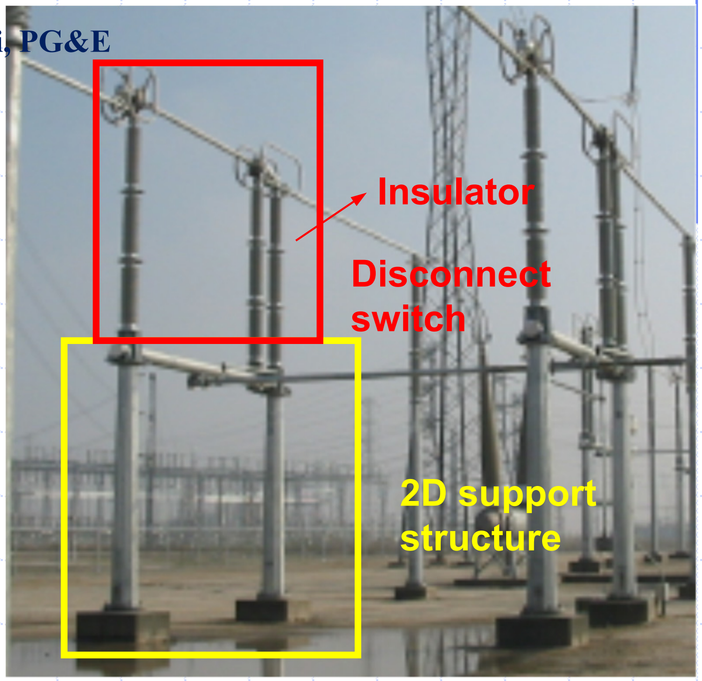
- Slow HS: Sufficient for most cases when rate effects are not important.

- RTHS: Essential for rate-dependent materials and devices, e.g. viscous dampers, friction pendulum isolators or polymer insulators.

Use of HS for Testing of Electrical Equipment

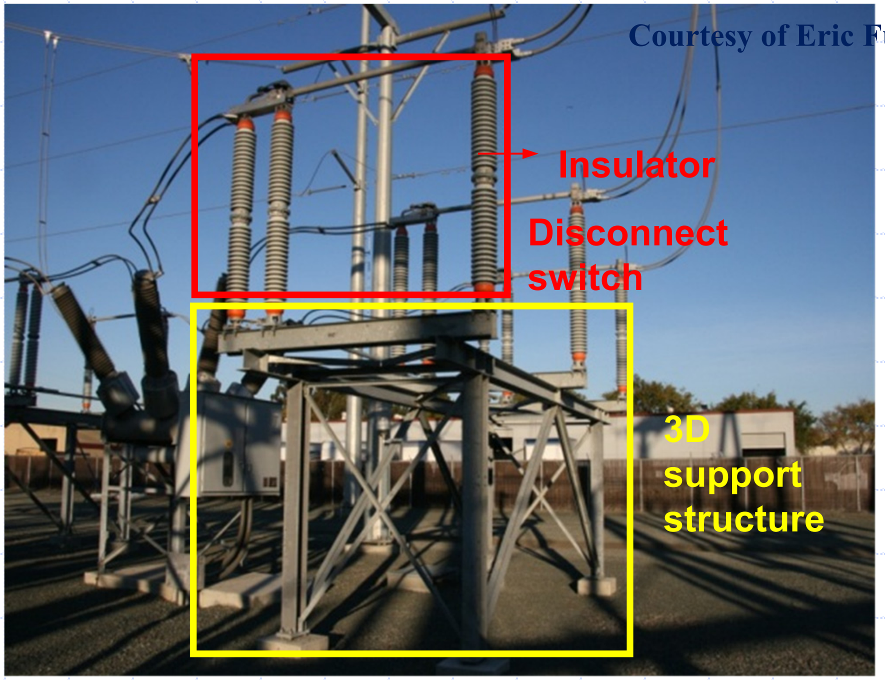
Courtesy of Eric Fujisaki, PG&E



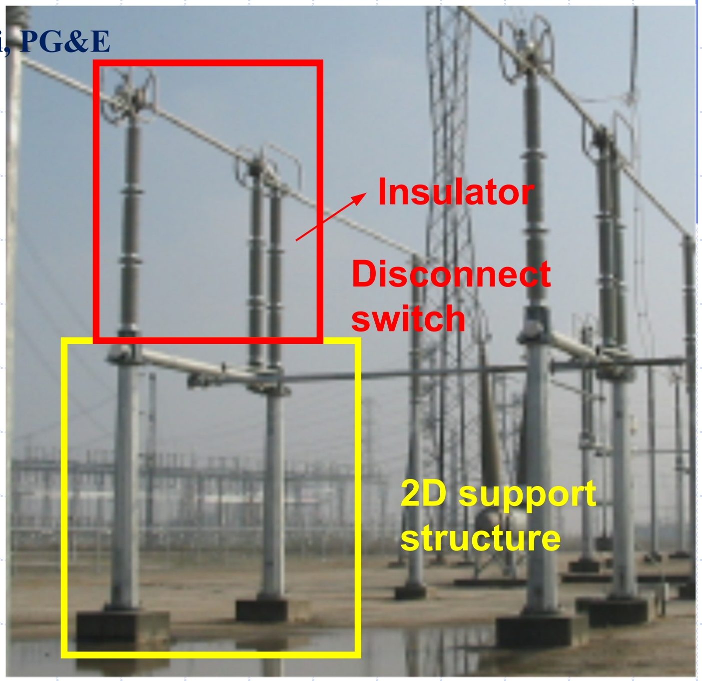


- Electrical equipment in substations are typically mounted on support structures to provide sufficient clearance of the ground, and to integrate them into the design of the substation.
- Support structures are generally **steel frames with well defined geometry and material properties**. Therefore they are suitable to be modeled in the computer as **analytical substructure**.
- Electrical equipment generally have **complex geometry and material properties with larger uncertainty**.
- HS provides an **effective, efficient and economic** testing opportunity by combining the electrical equipment testing with support structure modeling.

Use of HS for Testing of Electrical Equipment



Courtesy of Eric Fujisaki, PG&E



- HS provides an **effective, efficient and economic** testing opportunity by testing of the electrical equipment and modeling of the support structures.

1. Application I: Evaluation of the Effect of Support Structure Stiffness and Damping on Porcelain and Polymer Insulators
2. Application II: Full Disconnect Switch Tests in Open and Closed Configurations
3. Application III: Testing of Interconnected Equipment

Thank you!