PEER-MTS Workshop on Hybrid Simulation Technologies & Methods for Civil Engineering
Richmond Field Station, 03/20/2018

Substructuring, Integration Methods and Simulation Errors

Selim Günay,
Project Scientist, PEER
University of California, Berkeley

Outline

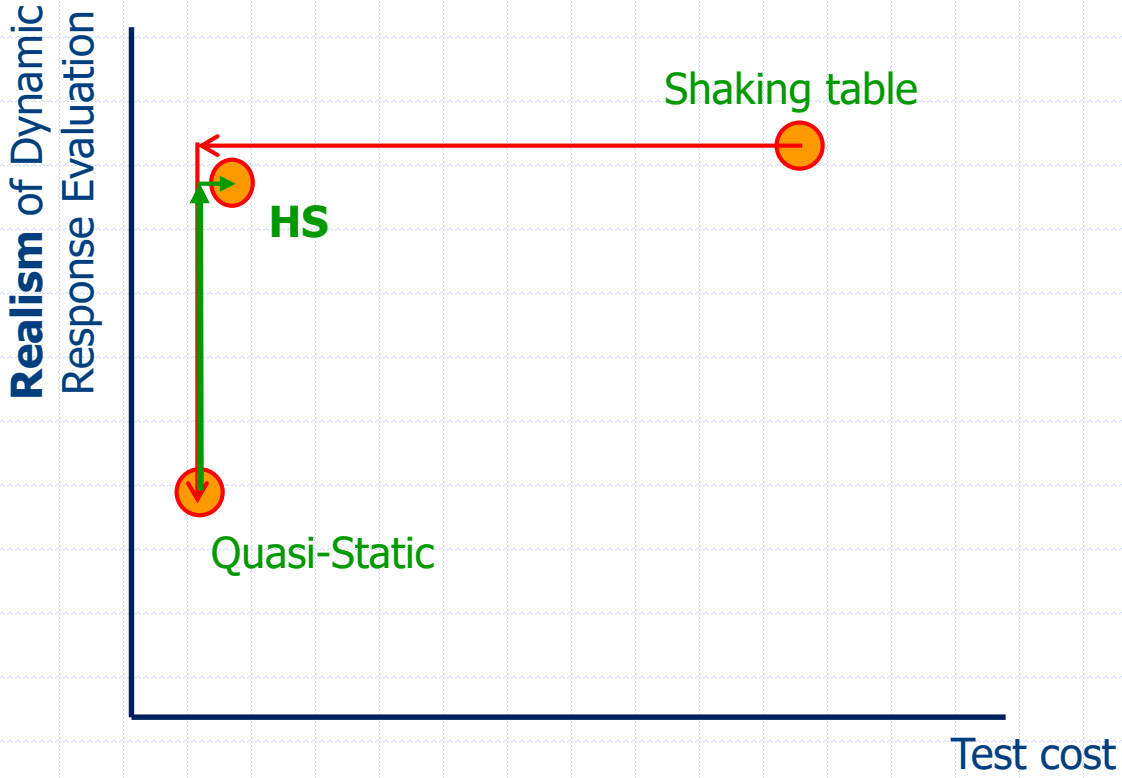
- Introduction
- Substructuring
- Integration Methods
- Simulation Errors
- Geographically distributed Hybrid Simulation
- Real-time Hybrid Simulation

Introduction

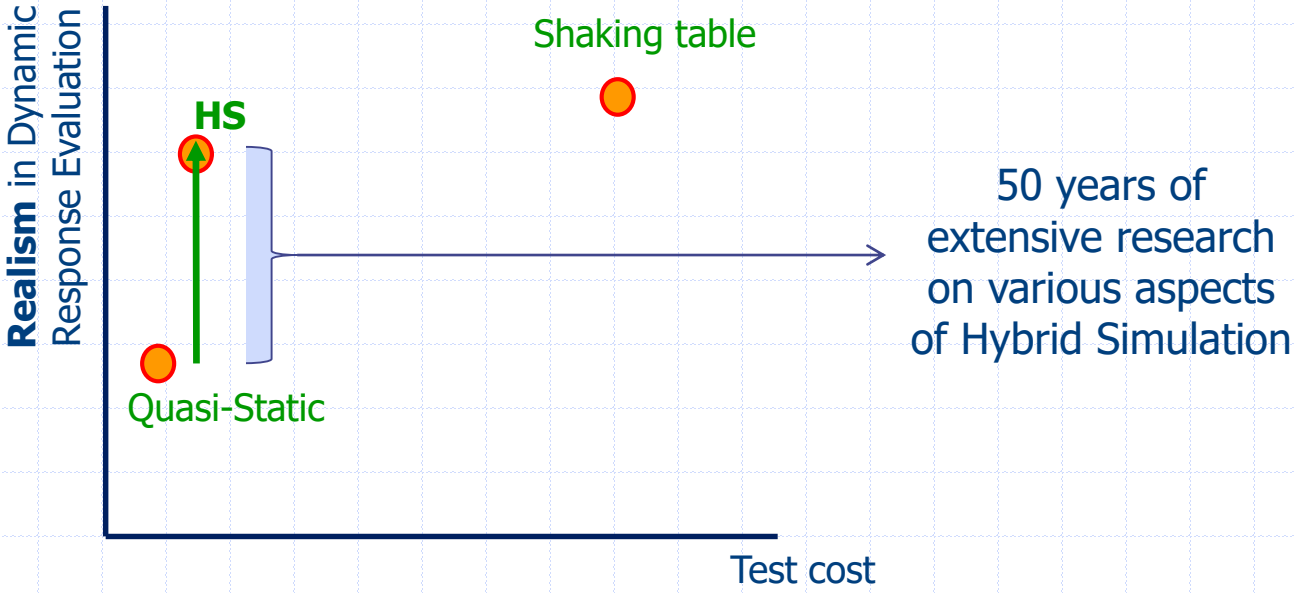
Laboratory Testing in
Structural & Earthquake Engineering

- Shaking Table Testing
- Quasi-Static Testing
- Hybrid Simulation

Introduction

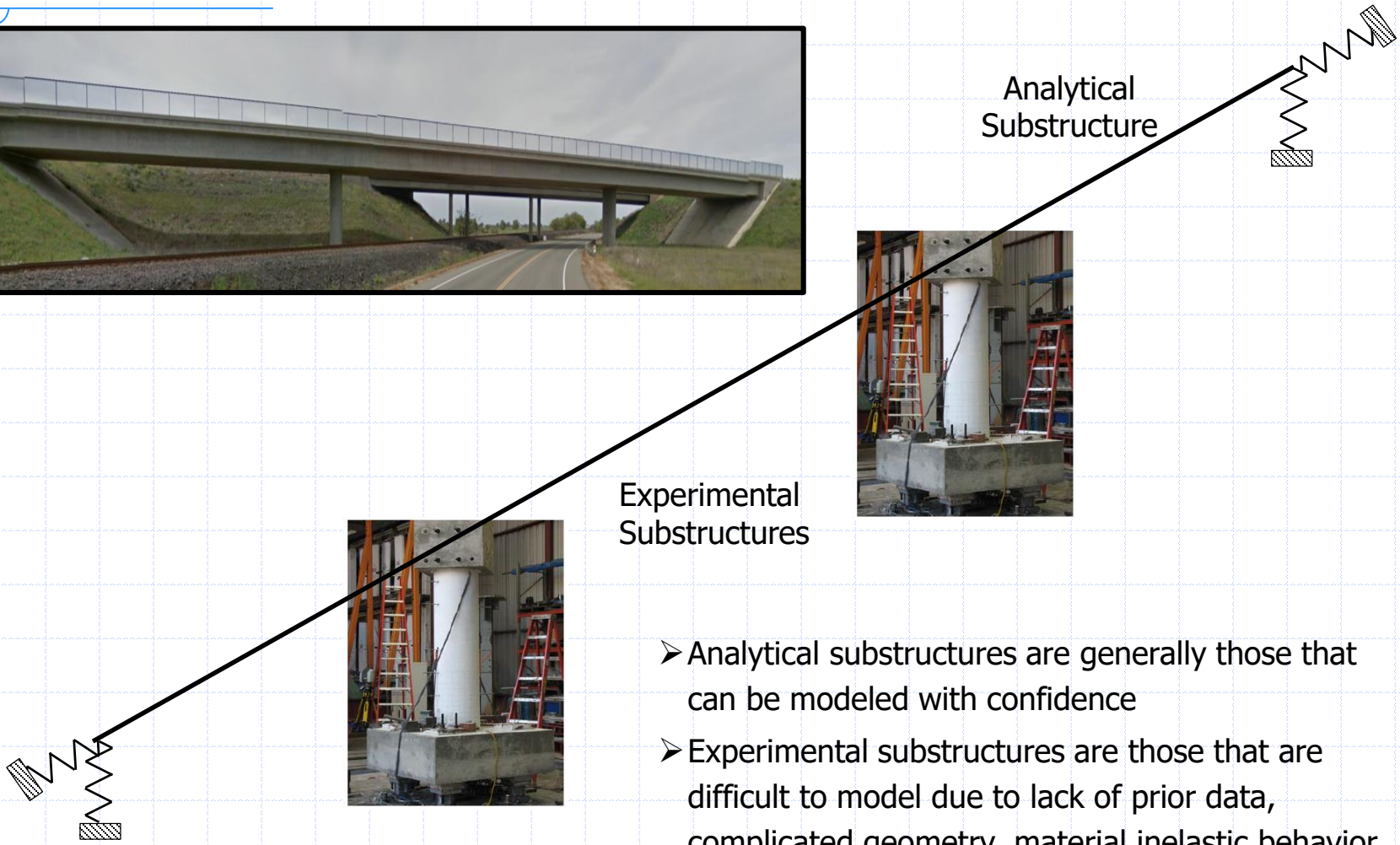


Introduction



- **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



- Analytical substructures are generally those that can be modeled with confidence
- Experimental substructures are those that are difficult to model due to lack of prior data, complicated geometry, material inelastic behavior, boundary conditions, etc.

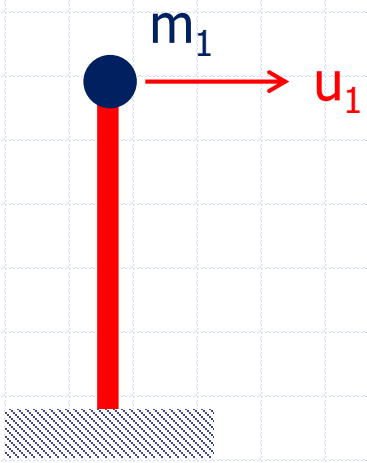
Substructuring

- Analytical substructures can vary between no analytical substructure (only mass and damping modeling) to analytical substructures with many degrees of freedom

- Substructuring and the boundary conditions between analytical and experimental substructures define the experimental degrees of freedom and how the experimental degrees of freedom will be controlled

Substructuring Cases

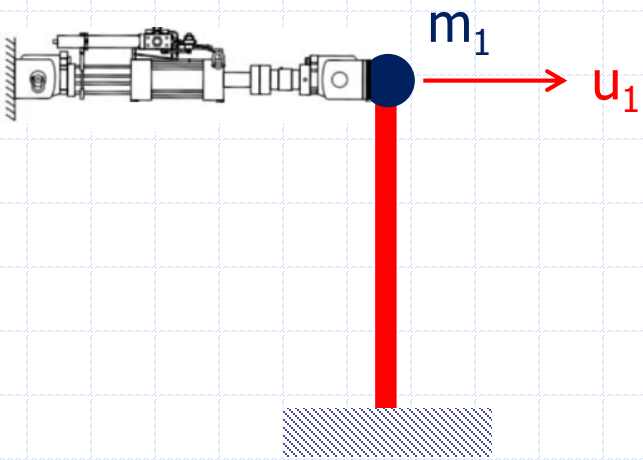
CASE 1: CANTILEVER COLUMN with MASS [No MASS MOMENT of INERTIA or ANALYTICAL SUBSTRUCTURE]



Red : Experimental
Blue: Analytical

Substructuring Cases

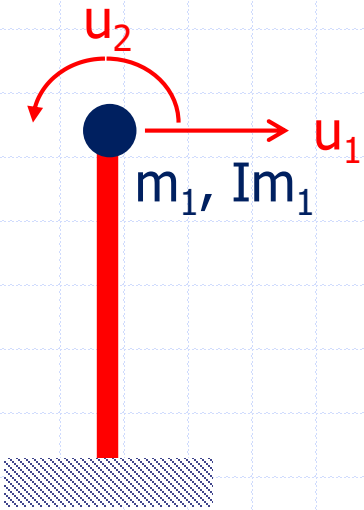
CASE 1: CANTILEVER COLUMN with MASS [No MASS MOMENT of INERTIA or ANALYTICAL SUBSTRUCTURE]

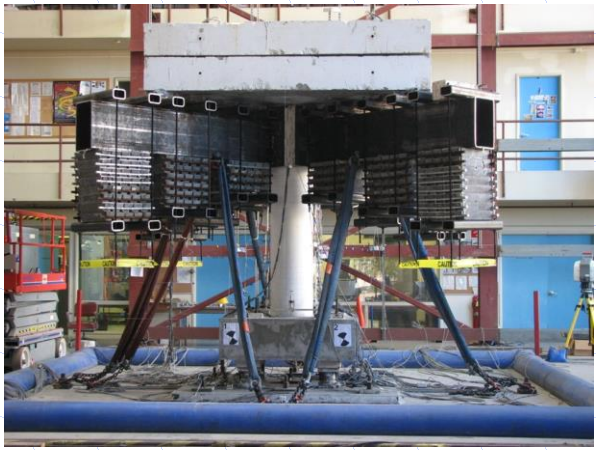


Red : Experimental
Blue: Analytical

Substructuring Cases

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

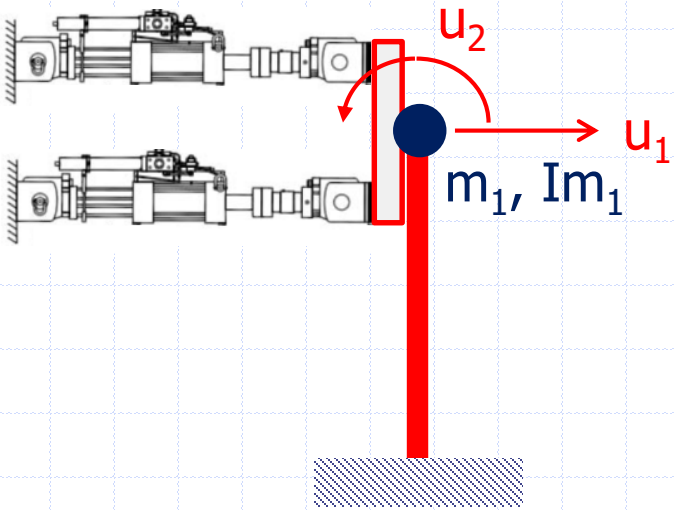




Red : Experimental
Blue: Analytical

Substructuring Cases

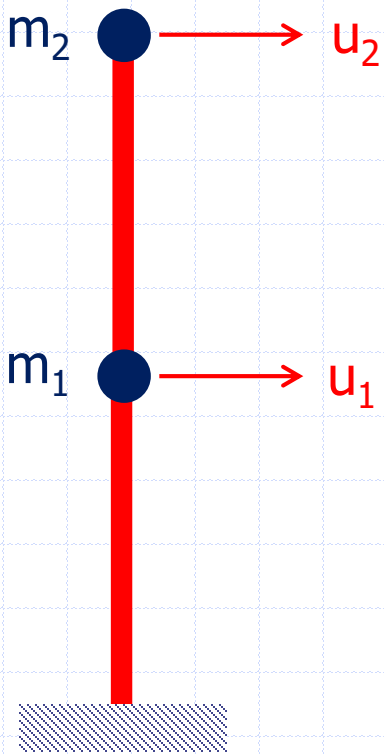
CASE 2: CANTILEVER COLUMN with MASS and MASS MOMENT of INERTIA [No ANALYTICAL SUBSTRUCTURE]



Red : Experimental
Blue: Analytical

Substructuring Cases

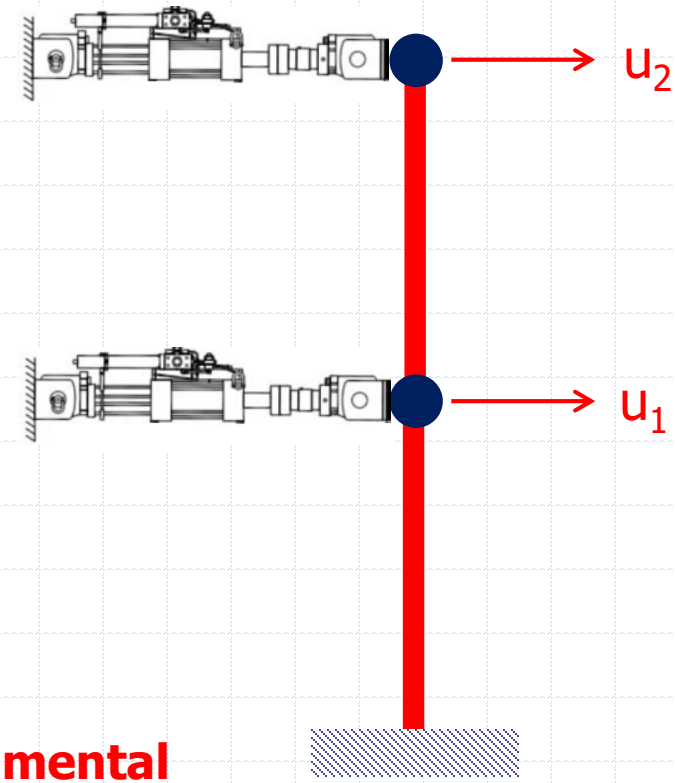
CASE 3: TWO COLUMNS without ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

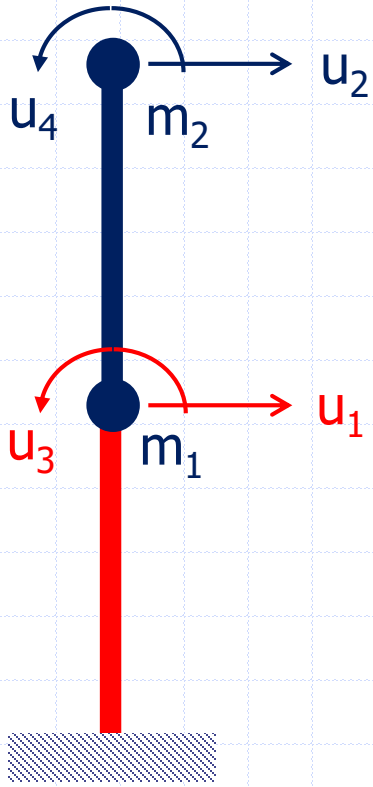
CASE 3: TWO COLUMNS without ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

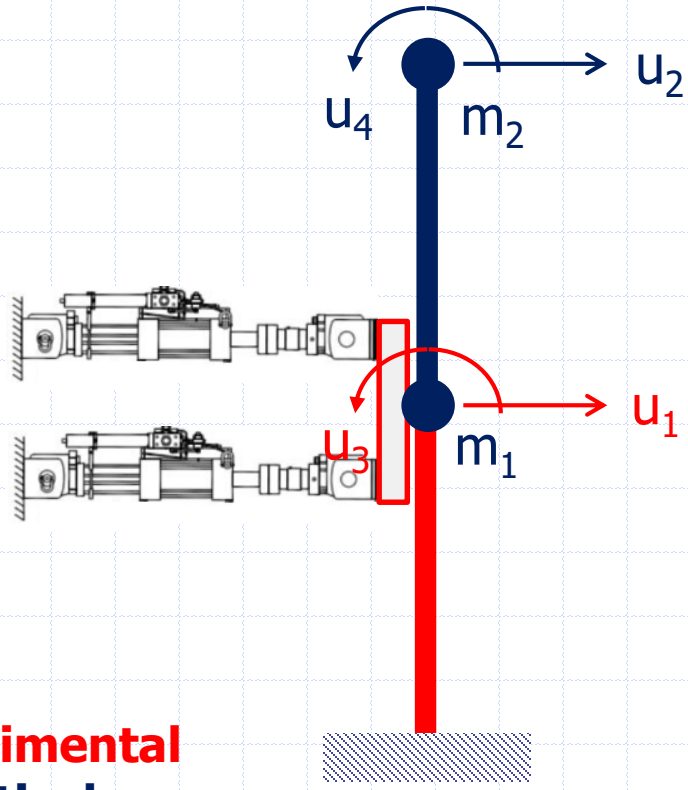
CASE 4: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

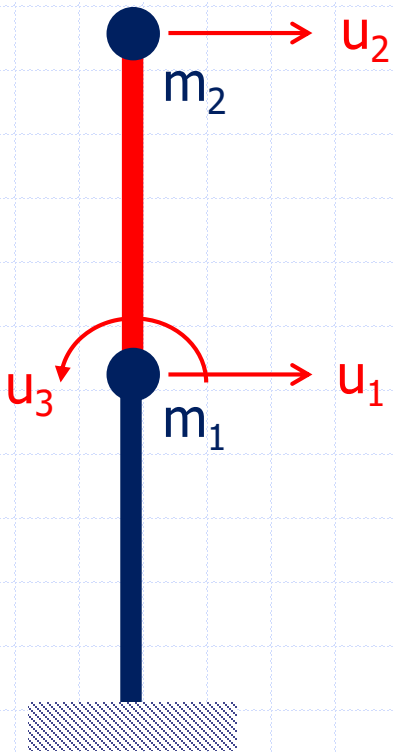
CASE 4: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

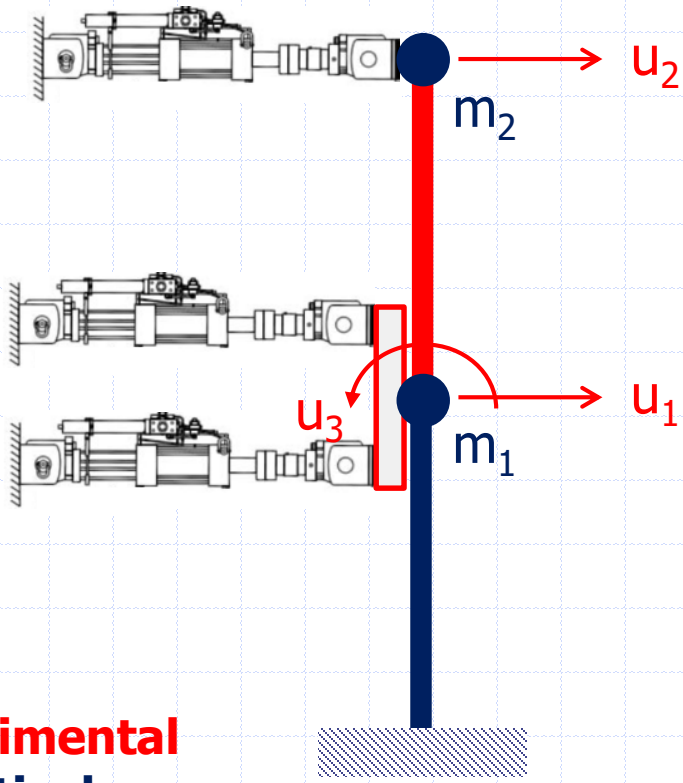
CASE 4-1: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

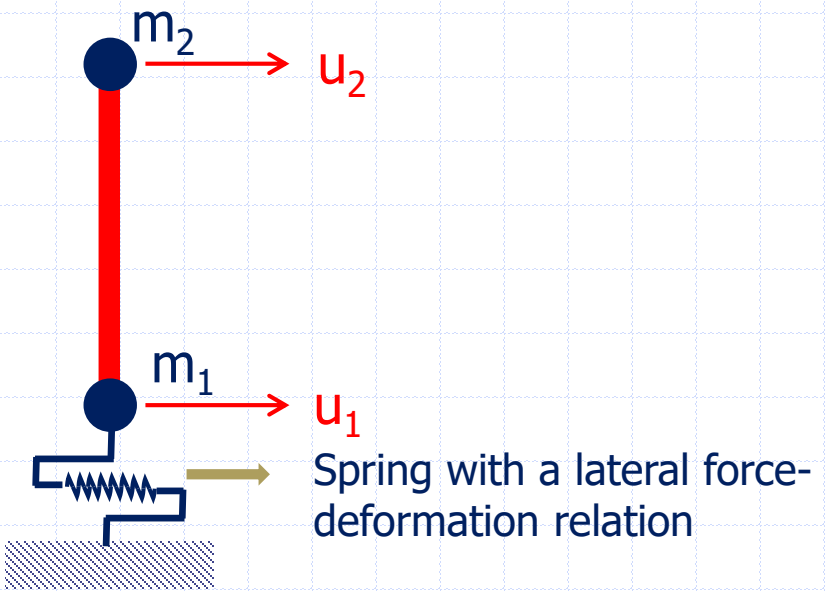
CASE 4-1: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

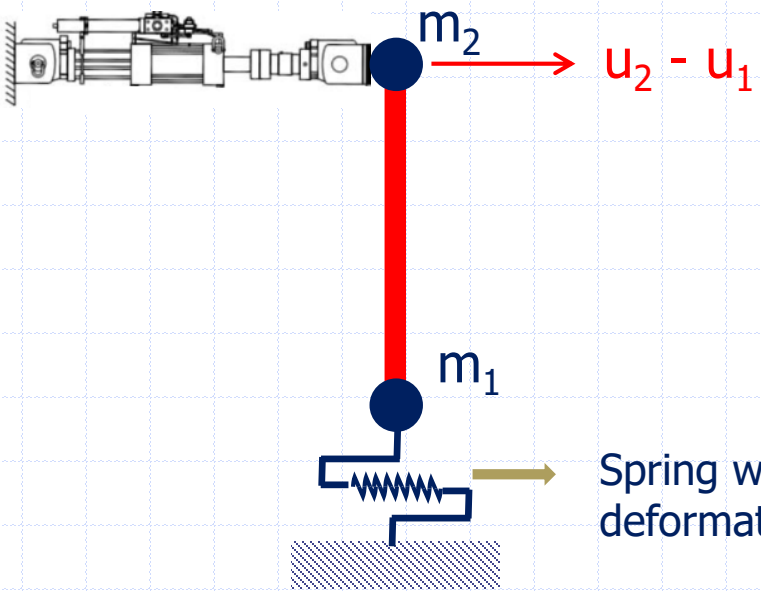
CASE 4-2: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

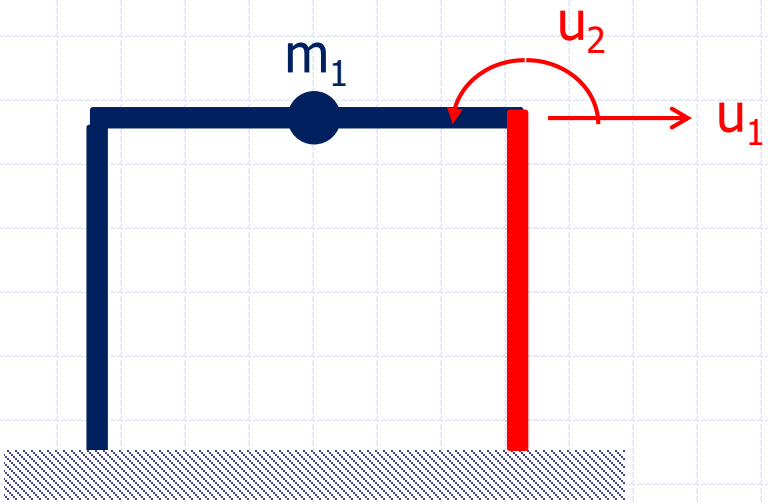
CASE 4-2: TWO COLUMNS with an EXPERIMENTAL and an ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

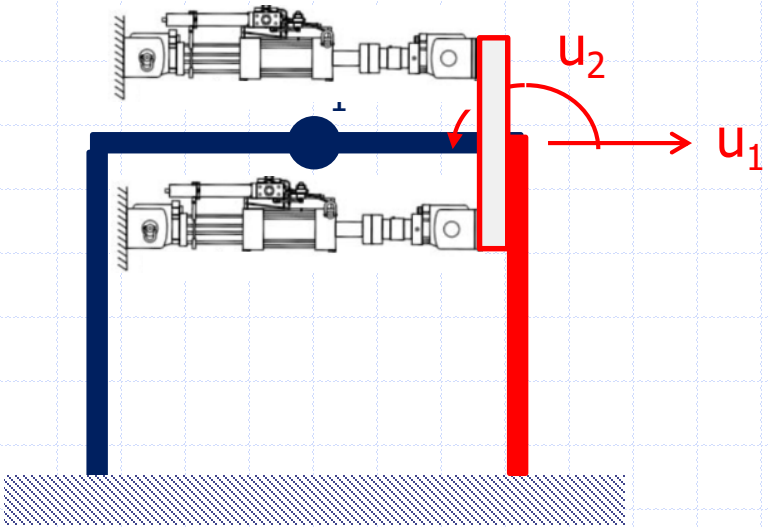
CASE 5: PORTAL FRAME with ONE OF THE COLUMNS AND BEAM AS ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

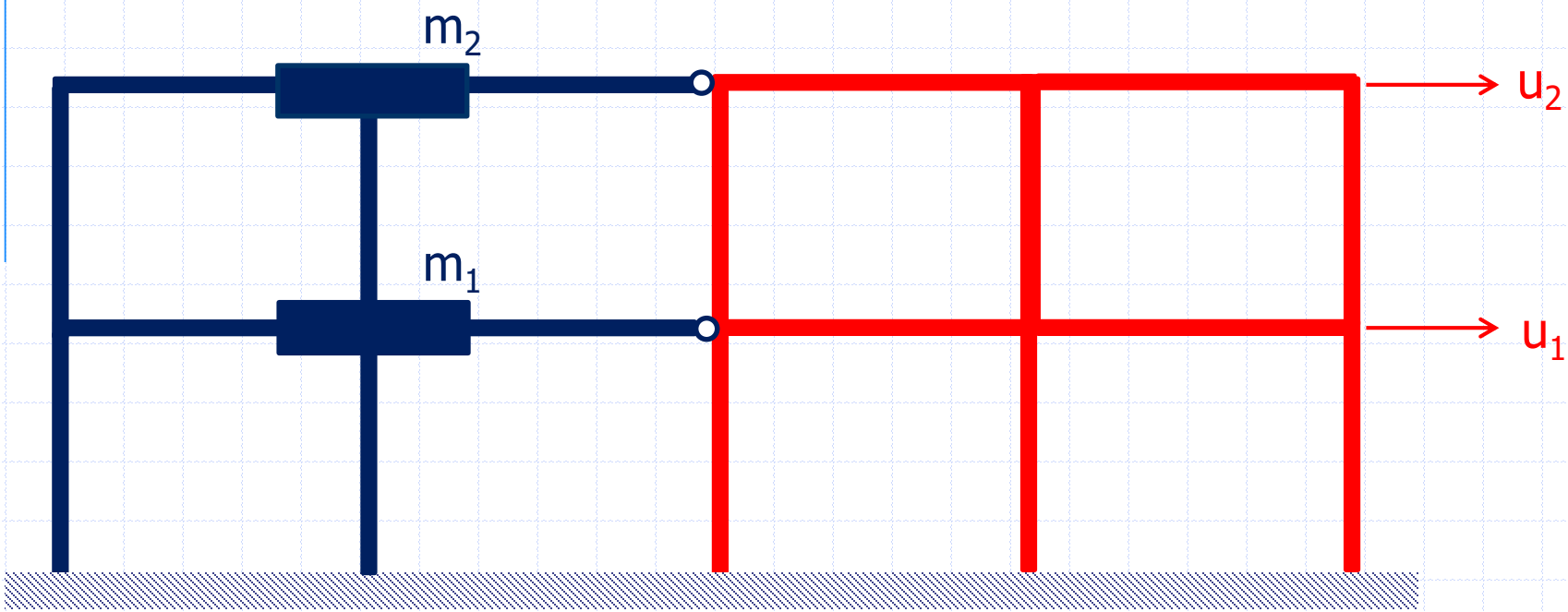
CASE 5: PORTAL FRAME with ONE OF THE COLUMNS AND BEAM AS ANALYTICAL SUBSTRUCTURE



Red : Experimental
Blue: Analytical

Substructuring Cases

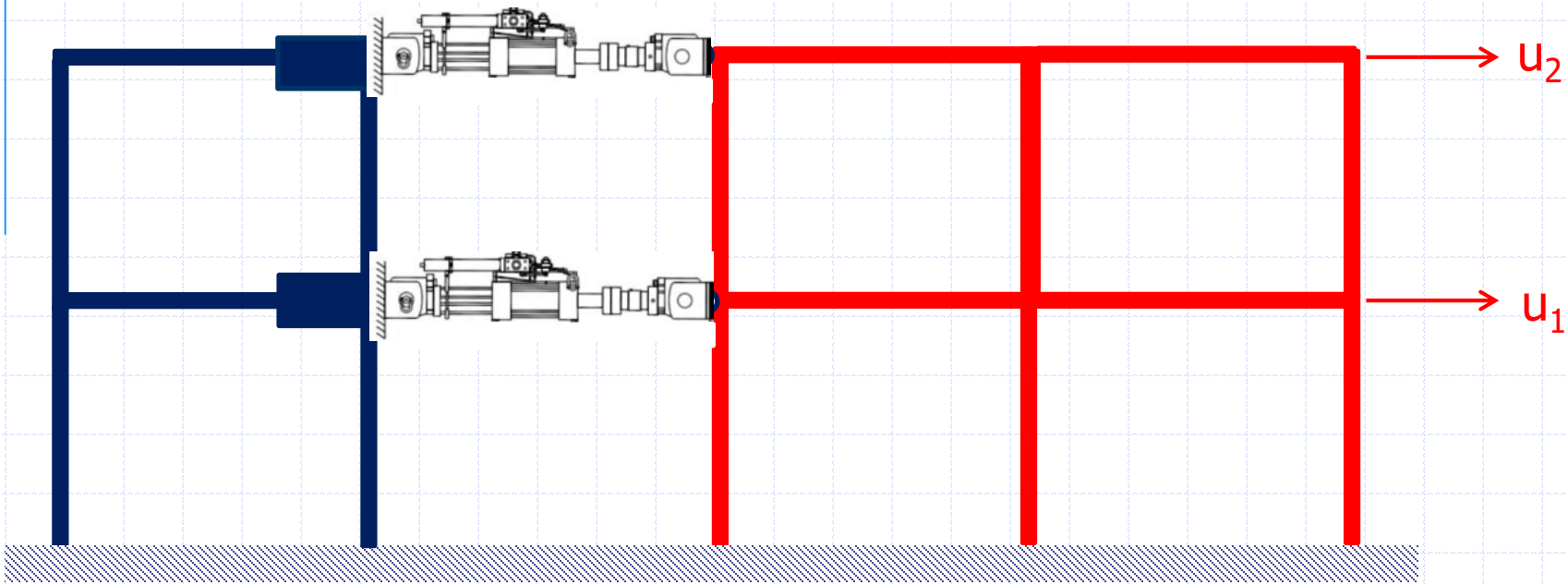
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Substructuring Cases

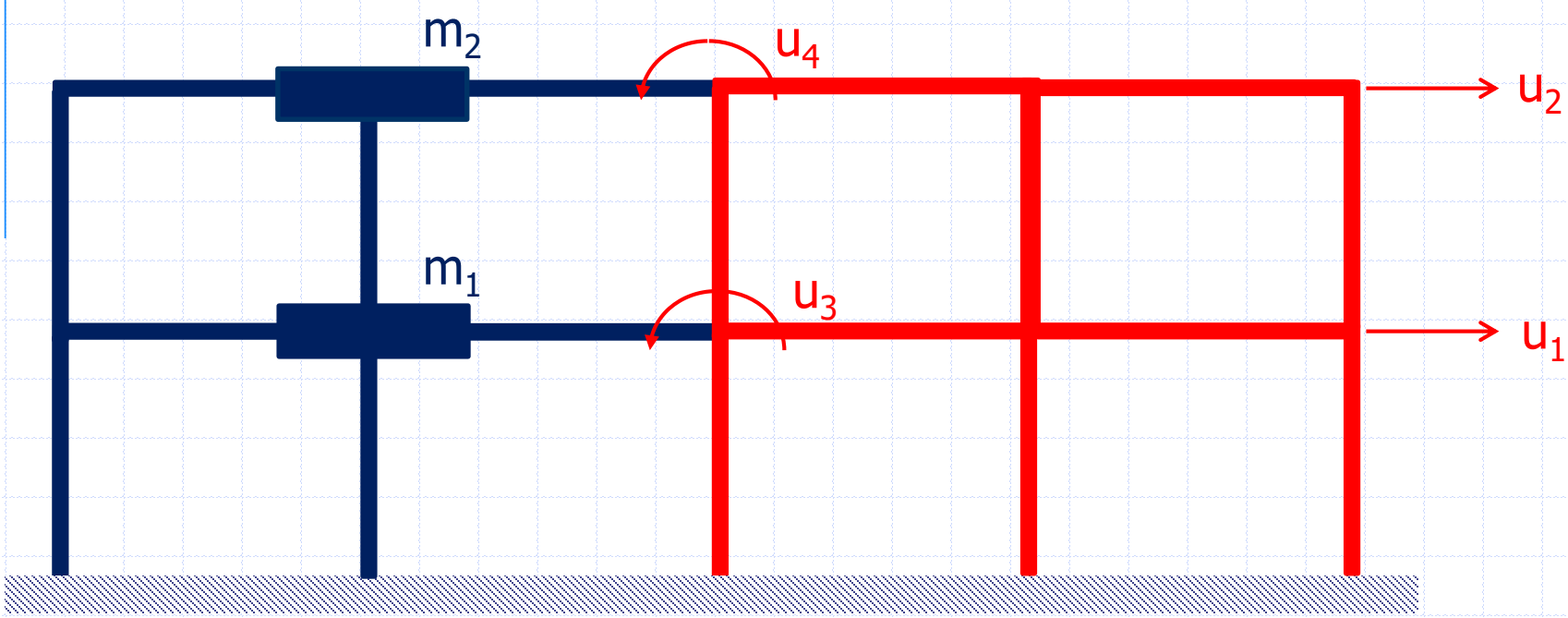
CASE 6: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



Red : Experimental
Blue: Analytical

Substructuring Cases

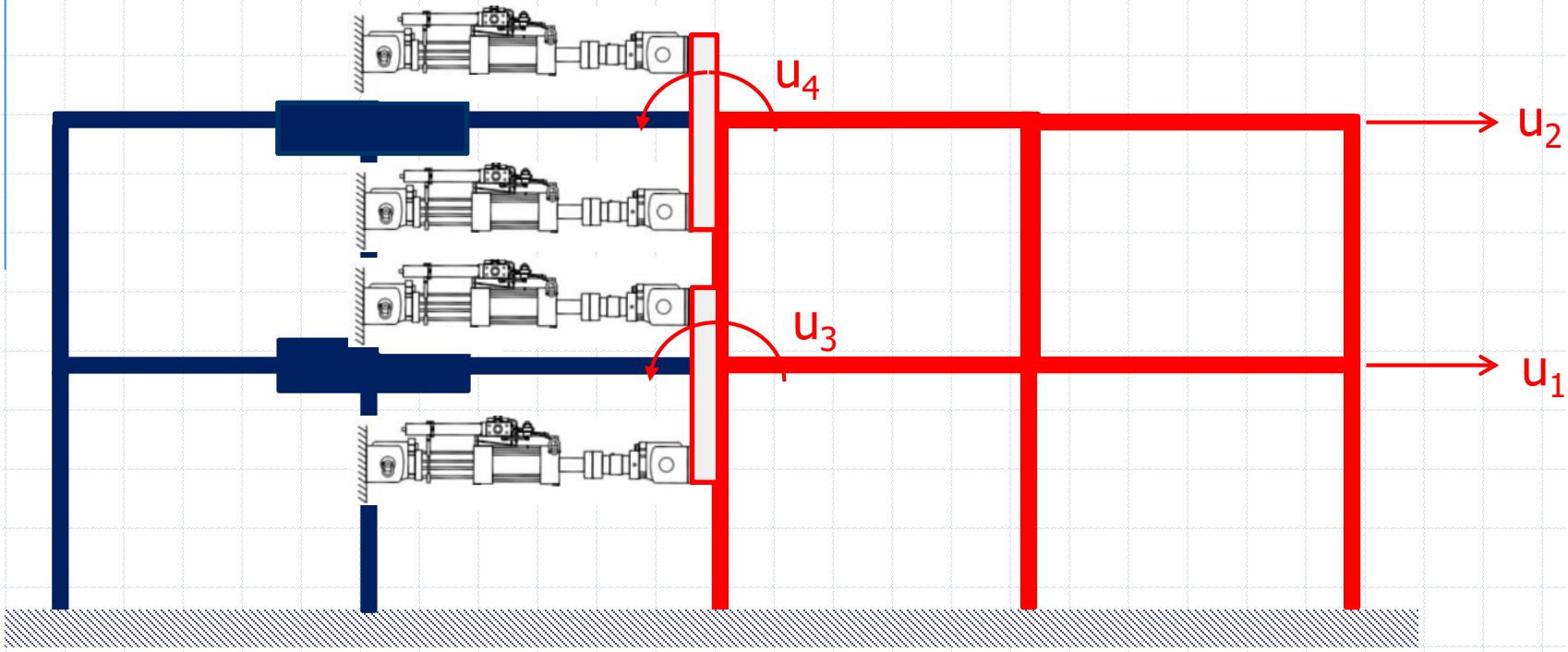
CASE 6-1: MULTI-BAY MULTI-STORY FRAME with ANALYTICAL SUBSTRUCTURING



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

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

$$\dot{\mathbf{u}}_{i+1} = \dot{\mathbf{u}}_i + \Delta t\left[(1-\gamma)\ddot{\mathbf{u}}_i + \gamma\,\ddot{\mathbf{u}}_{i+1}\right]$$

Difference equations

γ and β define the variation of accelerations over a time step

γ=1/2 and β=1/4 : constant average acceleration

γ=1/2 and β=1/6 : linear acceleration

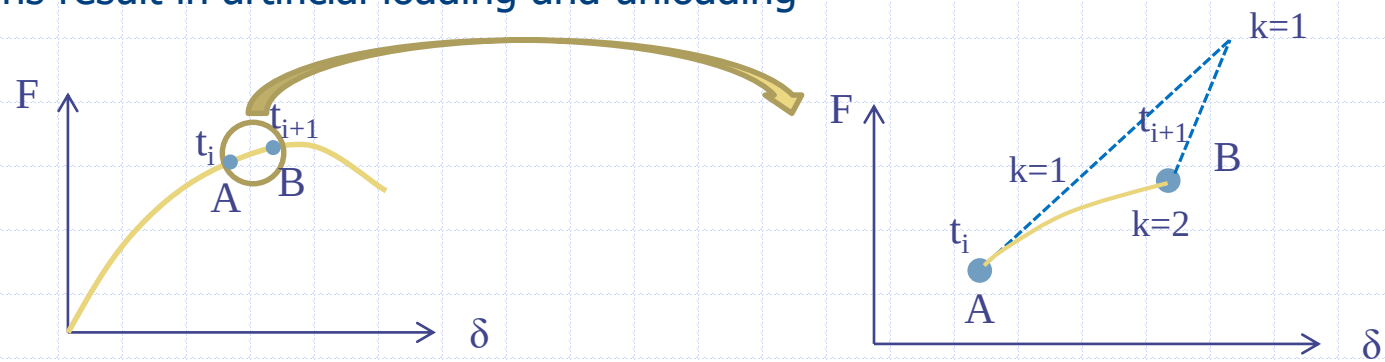
Equilibrium and difference equations represent a <u>nonlinear system of equations</u>, $f(\mathbf{u}_{i+1}) = \mathbf{p}_{i+1} - \mathbf{m}\ddot{\mathbf{u}}_{i+1} - \mathbf{c}\dot{\mathbf{u}}_{i+1} - \mathbf{p}_{\mathbf{r}}(\mathbf{u}_{i+1}) = \mathbf{0}$

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

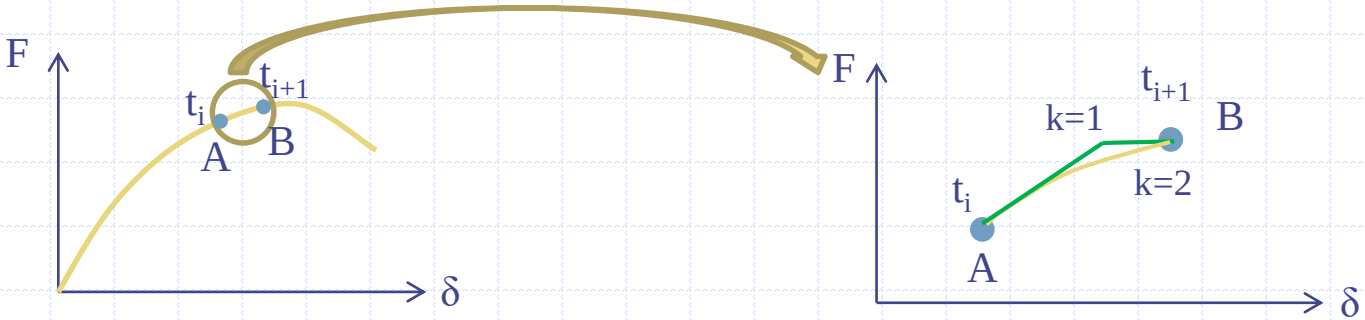
Integration Methods

Iterations of Implicit Newmark are not suitable for hybrid simulation:

- Iterations may not converge
- Iterations result in artificial loading and unloading



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



Integration Methods

HS compatible integrators

- Explicit Newmark Integration
- Operator Splitting Method

Do not require iterations

- Implicit Newmark Integration with Fixed Number of Iterations

Explicit Newmark

Algorithm

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) Impose the displacements $\mathbf{u}_{i+1}$ and compute/measure forces $\mathbf{p_r}(\mathbf{u}_{i+1})$

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

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

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

Explicit Newmark

- Becomes explicit by setting β = 0
- Initial and tangent stiffness matrices are not required

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

- Iterations are not required
- Computationally very efficient

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

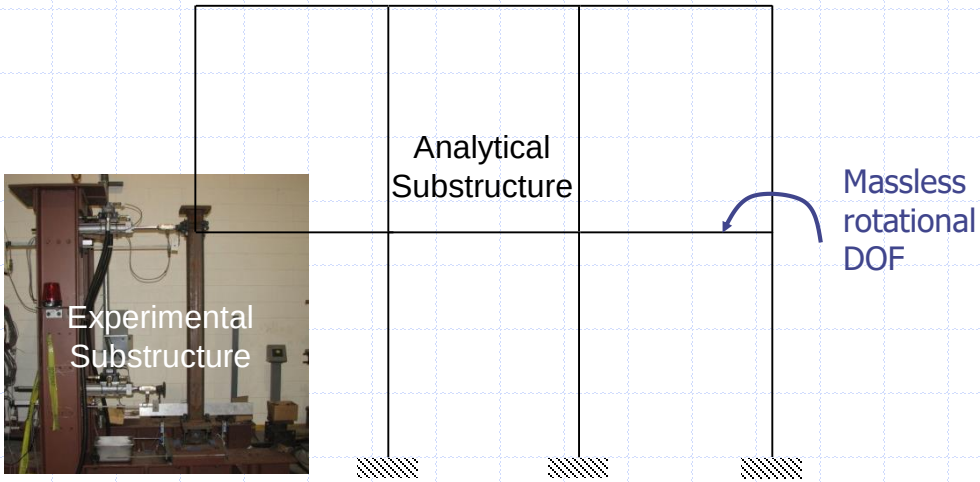
$$\mathbf{m}_{\mathbf{eff}}\ddot{\mathbf{u}}_{i+1} = \mathbf{p}_{\mathrm{eff}}$$

  - m_{eff} is constant during the solution
  - m_{eff} needs to be factored only once

- No numerical damping is present to suppress higher-mode participation.

Explicit Newmark

- Conditionally stable: $dt/T_n < \Pi$
- Not applicable to structures with massless DOF



- If stability condition is satisfied, most suitable method for both slow and real-time hybrid simulation

Alpha – Operator Splitting (OS) Method

- Iterations are not required (one predictor, one corrector)
- Eliminates the iterations by ignoring the $\ddot{u}_{i+1}$ term in the displacement difference equation
- Tangent stiffness matrix is not required

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

$$\mathbf{m}_{\mathbf{eff}} = \mathbf{m} + (1-\alpha)\Delta t\,\gamma\,\mathbf{c} + \Delta t^2\beta(1+\alpha)\mathbf{K}^I$$

$$\mathbf{p}_{\mathbf{eff}} = (1-\alpha)\mathbf{p}_{i+1} + \alpha\mathbf{p}_i - (1-\alpha)\mathbf{p}_{\mathbf{r}}(\tilde{\mathbf{u}}_{i+1}) - \alpha\mathbf{p}_{\mathbf{r}}(\tilde{\mathbf{u}}_i) - \left[(1-\alpha)\mathbf{c}\Delta t(1-\gamma) + \alpha\Delta t^2\beta\mathbf{K}^I\right]\ddot{\mathbf{u}}_i - \mathbf{c}\dot{\mathbf{u}}_i$$

- Computationally efficient
  - m_{eff} is constant during the solution
  - m_{eff} needs to be factored only once
- Unconditionally stable for softening response
- Numerical damping is present
- Quite suitable for slow and real-time hybrid simulation

Implicit Newmark Integration with Fixed Number of Iterations

- Uniform displacement increments between iterations
- Number of iterations constant → No convergence problems
- Number of iterations should be determined with prior analyses
- Very suitable for slow hybrid simulation
- Restricted use in real-time hybrid simulation

- integration time step = 0.01 sec
- # of iterations =10

} Each iteration needs to be physically completed in 1 msec

Not always possible

Simulation Errors

ERROR SOURCES

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

Errors due to Structural Modeling

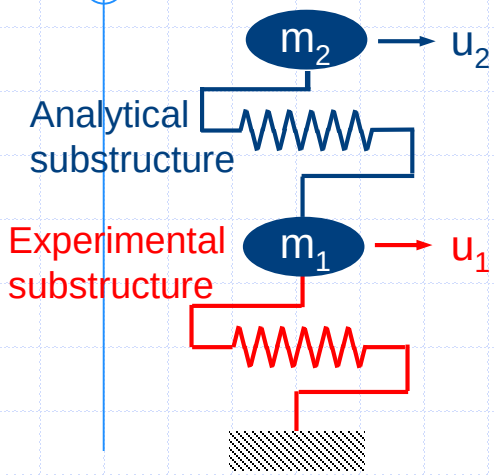
- Structural Idealization
  - Discrete parameter system
  - Lumped mass vs Consistent Mass Matrices

- Modeling Damping
  - Viscous Damping is represented analytically
  - Spurious moments may be introduced when initial stiffness proportional damping is used

Errors due to Numerical Methods

- Use of initial stiffness matrix instead of tangent stiffness matrix for experimental substructures may lead to errors
- Experimental errors increase with the number of iterations
- Higher modes are more susceptible to error propagation than the lower modes. Therefore numerical damping is desirable for suppressing higher mode errors
- However, numerical damping may lead to errors if it reduces lower mode participation

Experimental 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 resisting 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

Experimental 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.
- **<u>Examples</u>**:
  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.

Experimental Errors

Systematic errors:

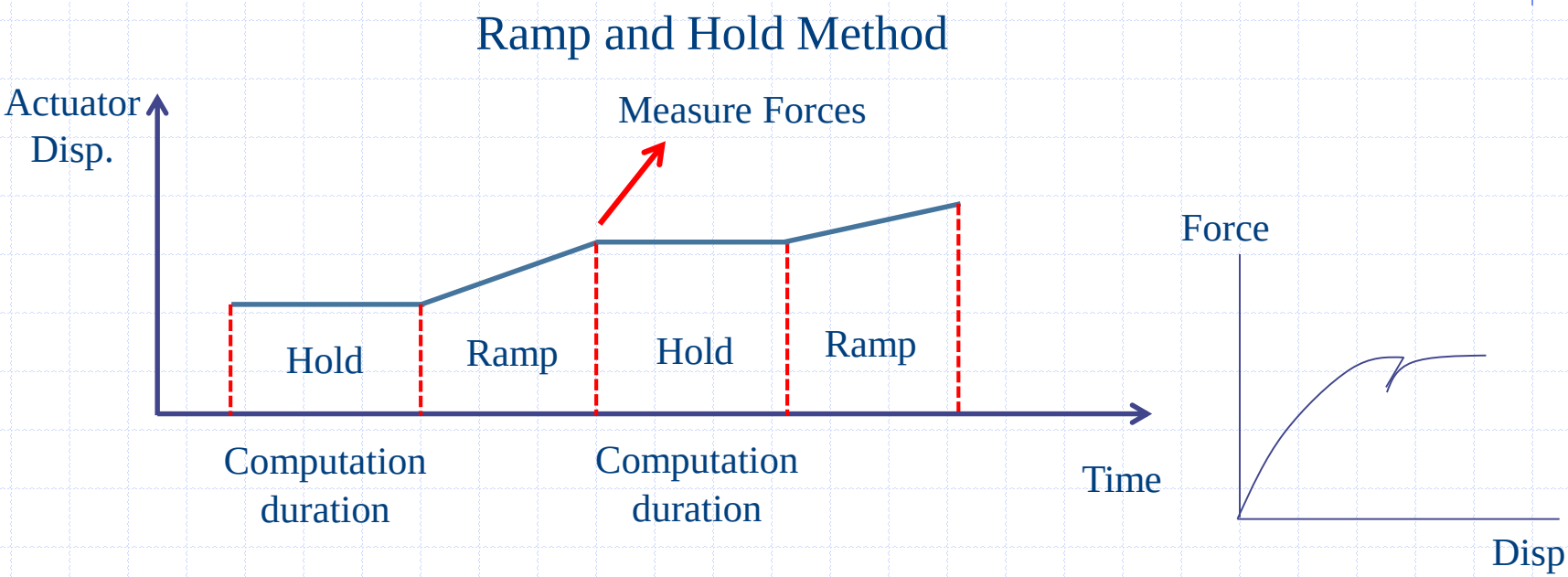
- They may lead to error propagation and numerical instability
- **Examples**:
  1. Measurement errors
  2. Hybrid simulation technique (ramp and hold, continuous, real-time)
  3. Servo-hydraulic closed control loop

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

Experimental Errors

Hybrid Simulation Technique

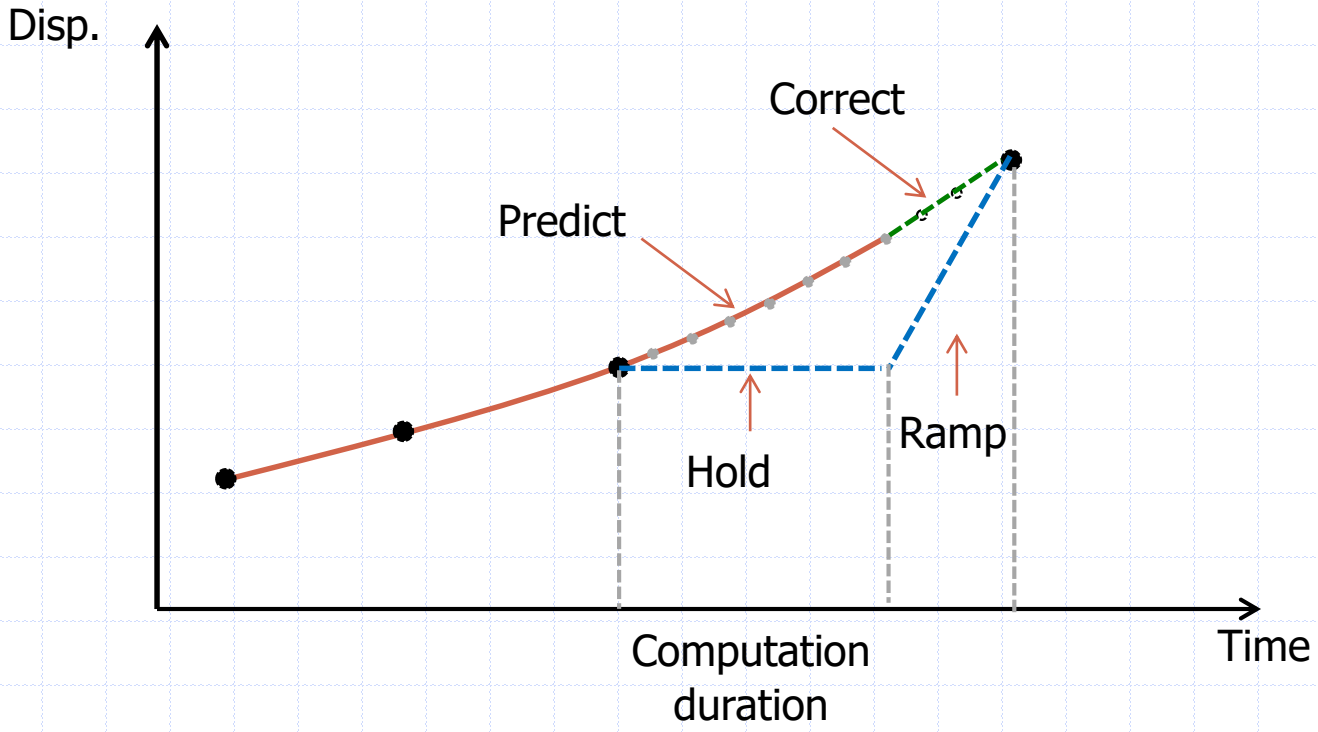


- Force relaxation during hold phase

Experimental Errors

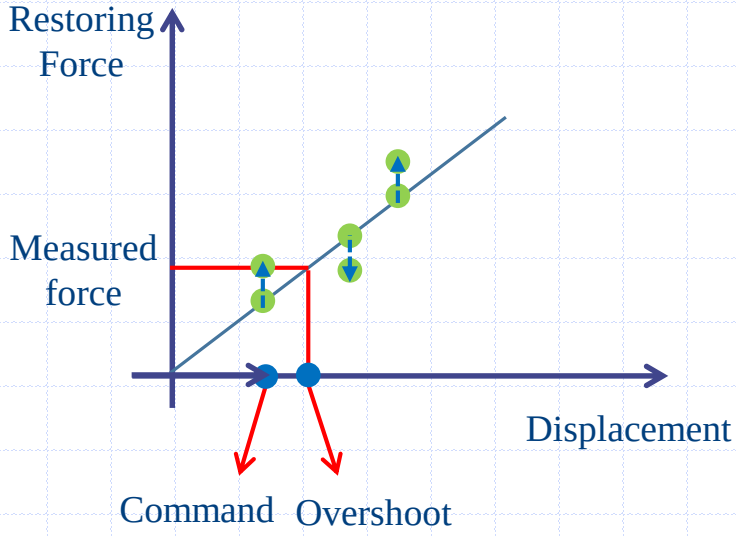
Hybrid Simulation Technique

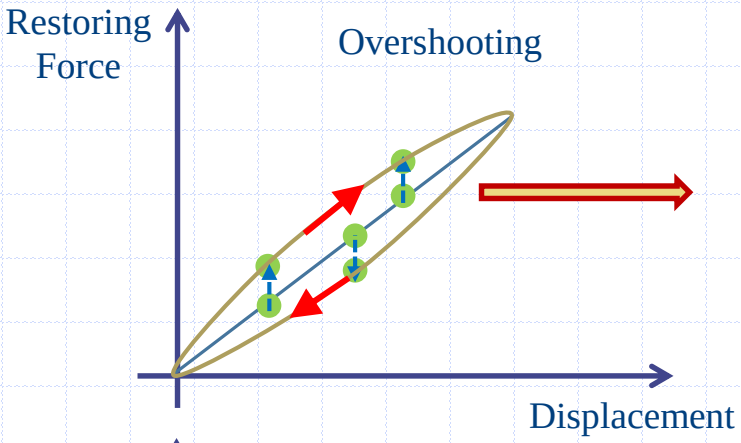
Continuous Testing (Predictor-Corrector Algorithms)

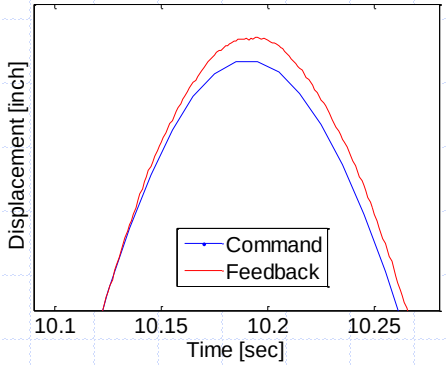


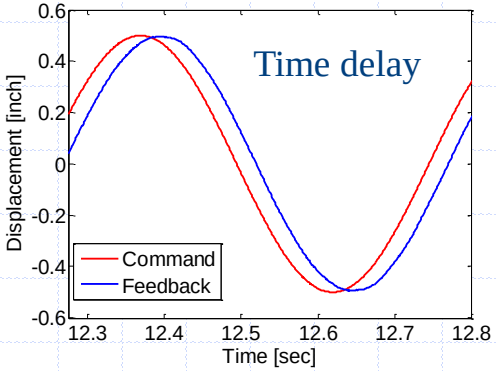
Experimental Errors

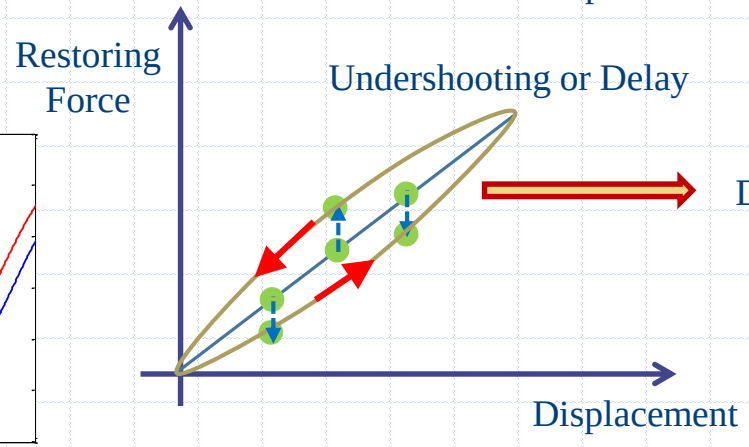
Control-loop errors









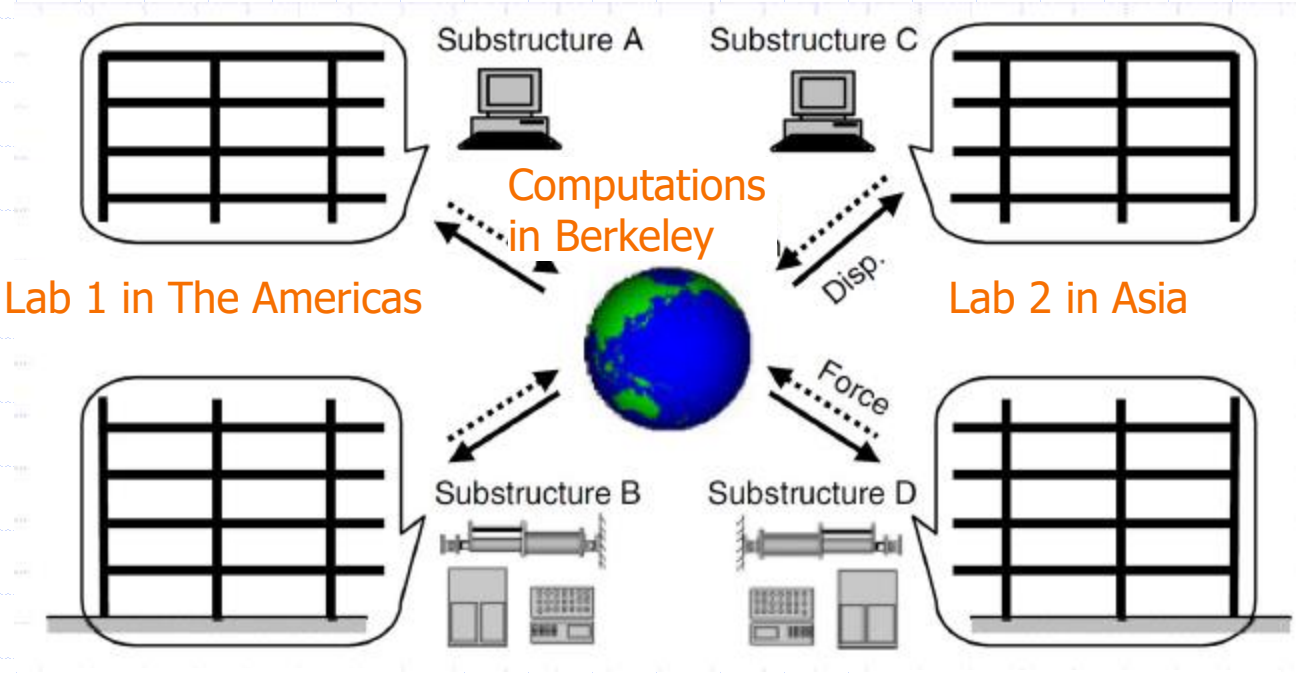


Simulation Errors

Methods to Reduce the Effects of Errors

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

Geographically Distributed HS



Lab 1 in The Americas

Lab 2 in Asia

Lab 3 in Europe

Lab 4 in Australia

Real-time Hybrid Simulation (RTHS)

- **<u>Requirement for real time</u>**:

  Loading rate = Computed velocity

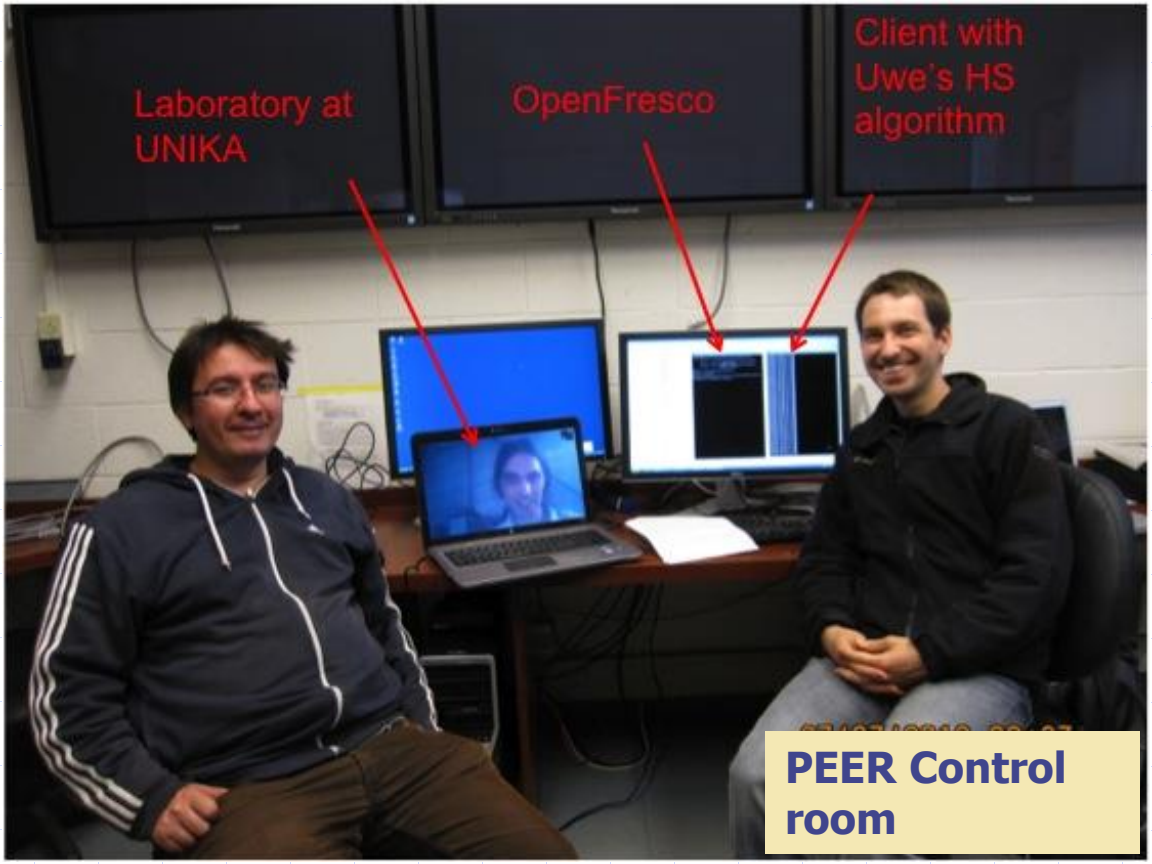
- Slow HS: Sufficient for most cases when rate effects are not important.

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

Thank you!

Geographically Distributed HS

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



PEER Control room

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/