Capabilities and Advancements of Hybrid Simulation using LHPOST

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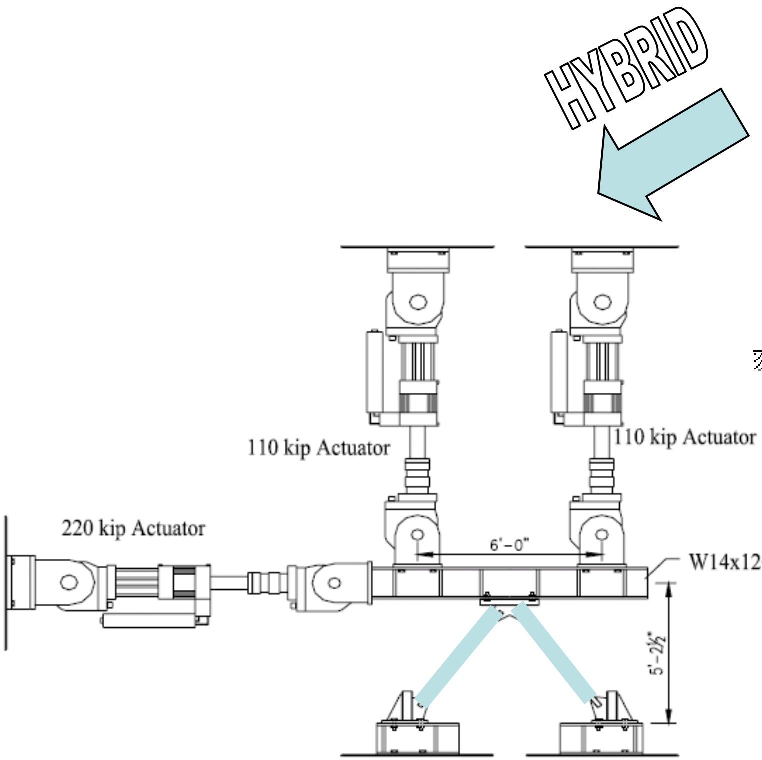
December 11, 2017

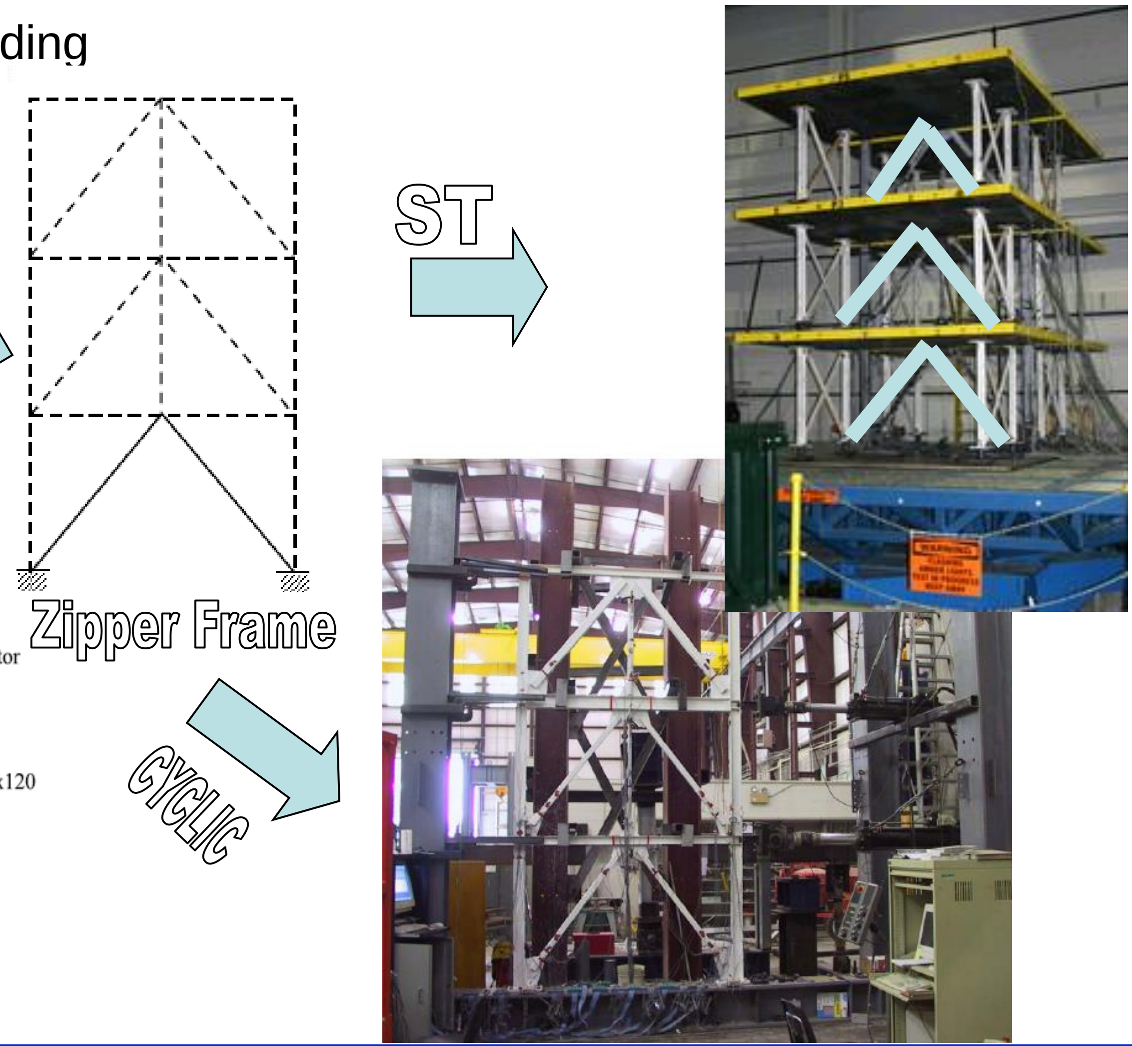
Overview

- Background on Hybrid Simulation
  - Various forms of implementation of hybrid simulation
  - Sources and monitoring of errors
  - Potential Applications of Hybrid Simulation
- Shake Table Substructures
  - Includes restoring forces and inertial forces
- Hardware available at NHERI-UCSD
  - Control system, ScramNet, and Matlab xPC Environment
  - External actuators
- User Requirements and Preparation
- Recent Hybrid Testing Activities at NHERI-UCSD

Experimental Methods

- Experimental Methods for Seismic Performance Evaluation
  - Quasi-Static or Cyclic Loading
  - Shake Table
  - Hybrid Simulation



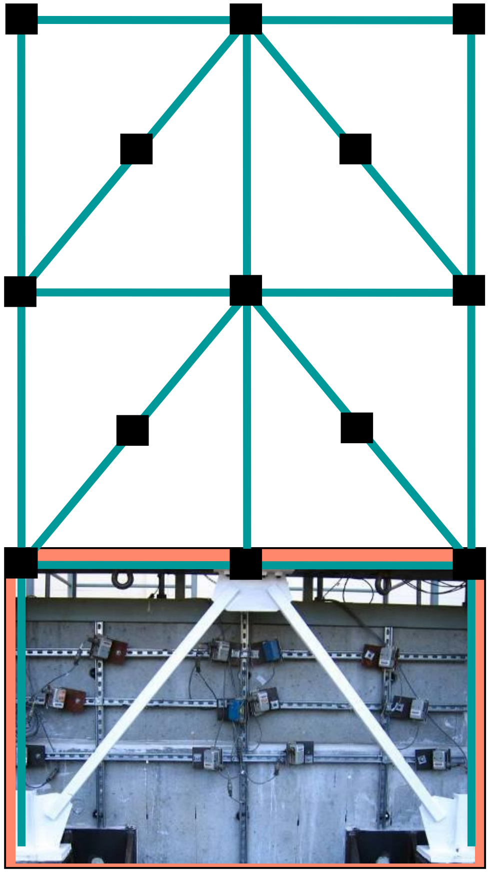


Hybrid Simulation

- Equation of motion for prototype structure

$$ma + cv + r = f$$

- Hybrid simulation combines:
  - Physical models of structural resistance
  - Computer models of structural damping and inertia
- Enables seismic testing of large- or full-scale structural models
- Solve equation of motion using numerical integration algorithms



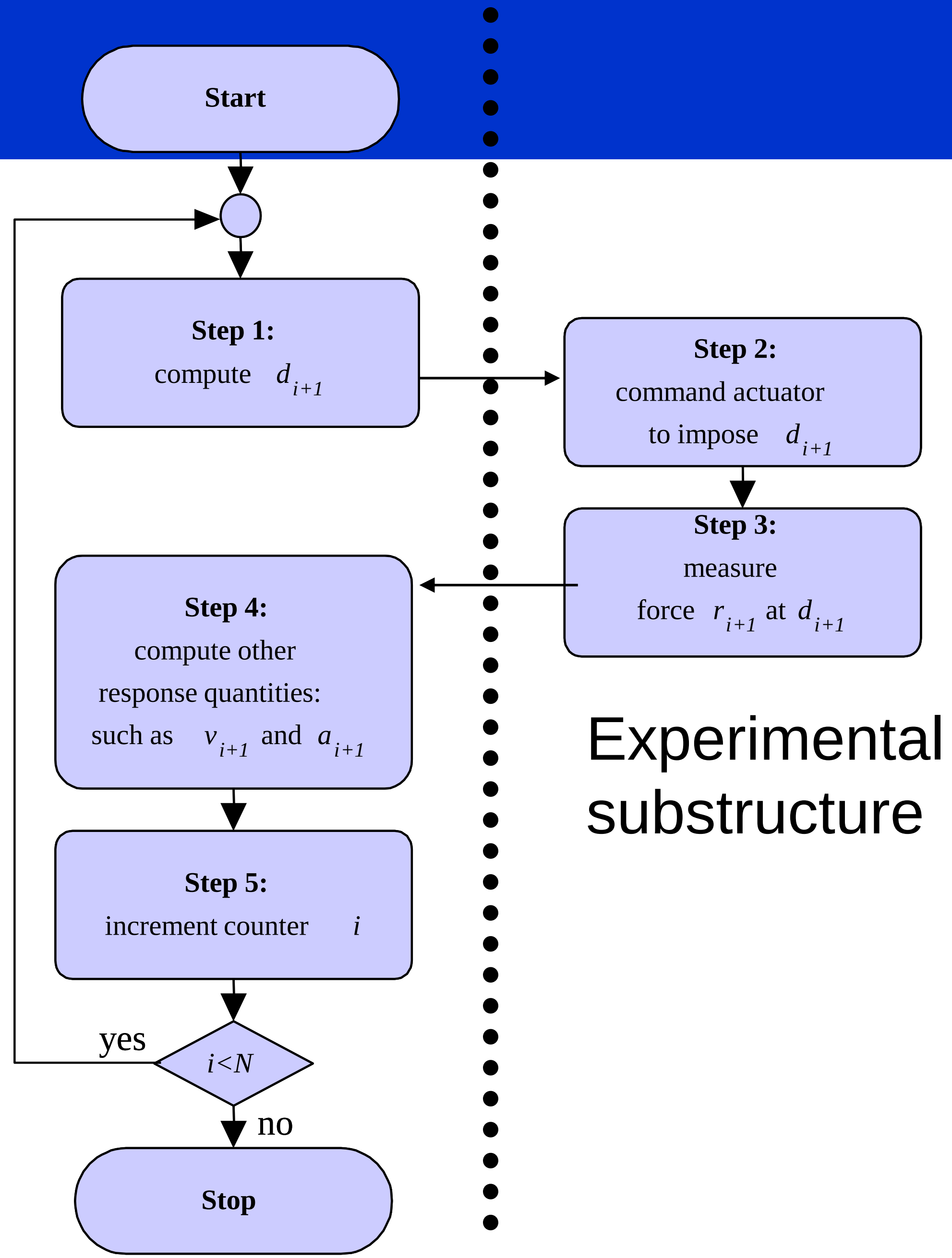
Test Procedure

Time-stepping integration algorithm e.g., Newmark Explicit

$$ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}$$

$$d_{i+1} = d_i + \Delta t v_i + \frac{1}{2}\Delta t^2 a_i$$

$$v_{i+1} = v_i + \frac{1}{2}\Delta t \left(a_i + a_{i+1}\right)$$



Implementation Issues

- Integration Algorithms
  - Implicit or explicit
  - Integration time step
  - Accuracy and stability
- Rate of testing
  - Time scaling
  - Pseudo-dynamic vs. dynamic
  - Material strain rate effects
  - Observation of damage
- Experimental Errors
  - Actuator tracking errors
  - Propagation of errors

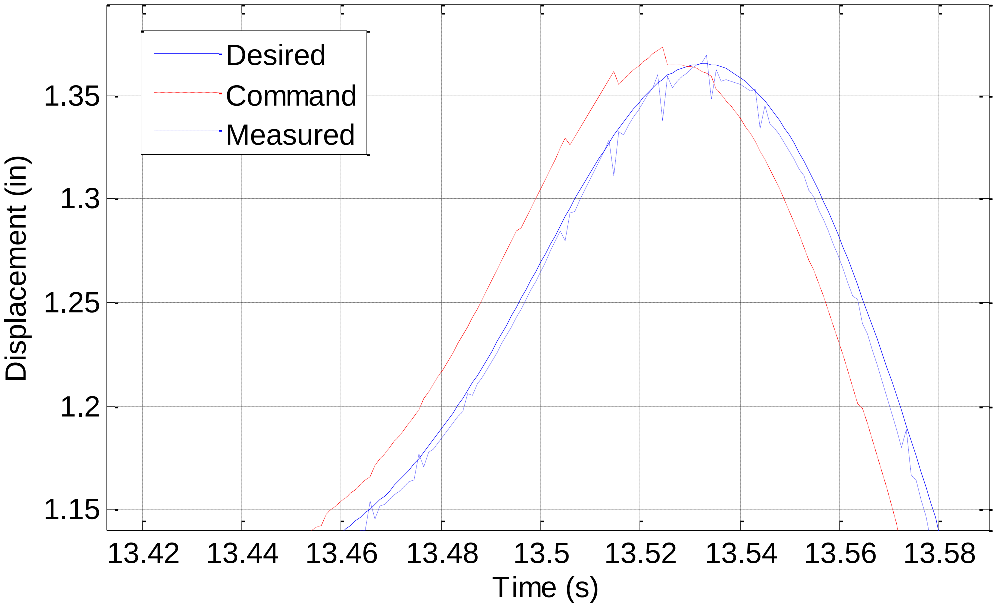
Central Difference

Newmark's Method

$$ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}$$

$$d_{i+1} = d_i + \Delta t v_i + \frac{1}{2}\Delta t^2 a_i$$

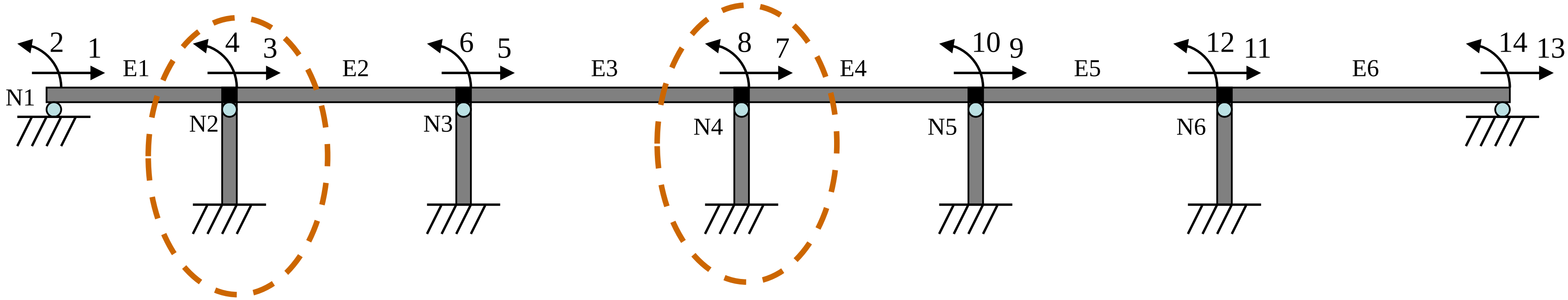
$$v_{i+1} = v_i + \frac{1}{2}\Delta t\left(a_i + a_{i+1}\right)$$



Hybrid Structural Model

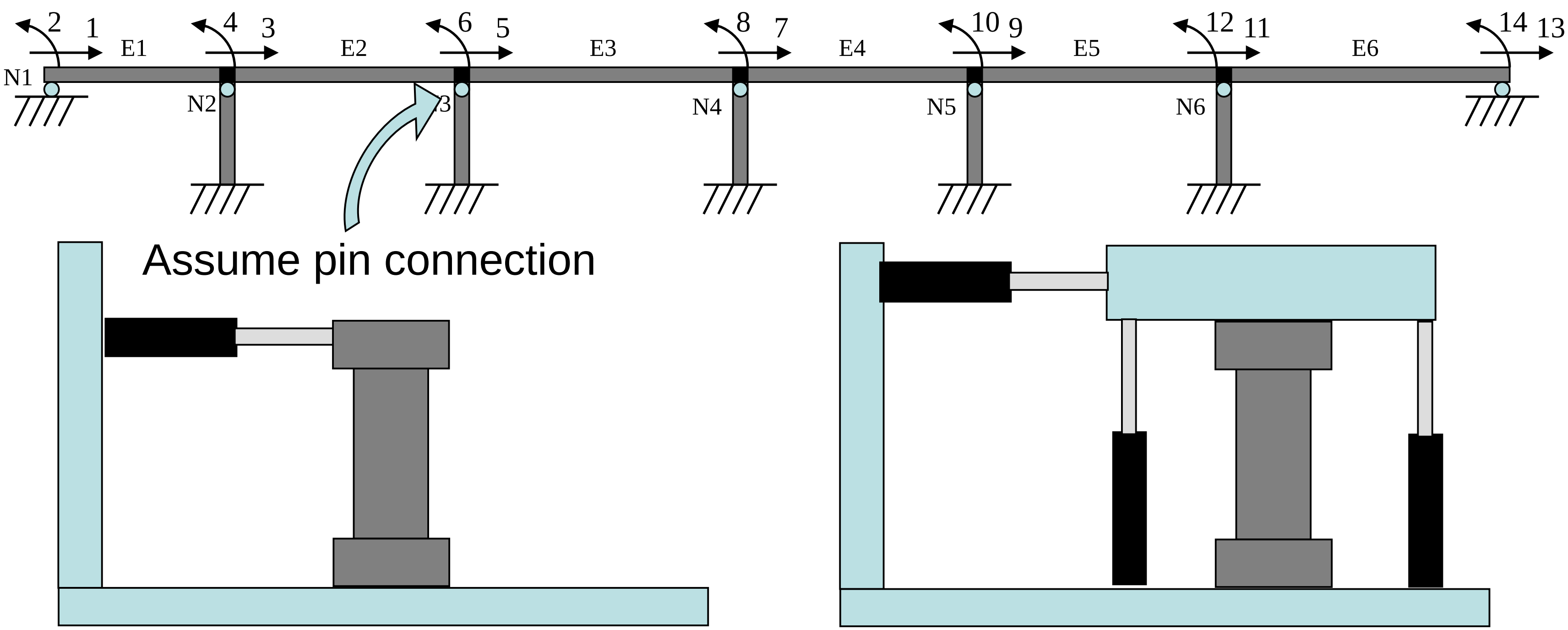
➢ Modeling

- Selection of experimental substructures
  - ✓ components of structure that are difficult to model
- Interface boundary conditions between physical and numerical model
- Size and scale of experimental substructure limited by equipment capabilities
  - ✓ substructures can be tested at different scales



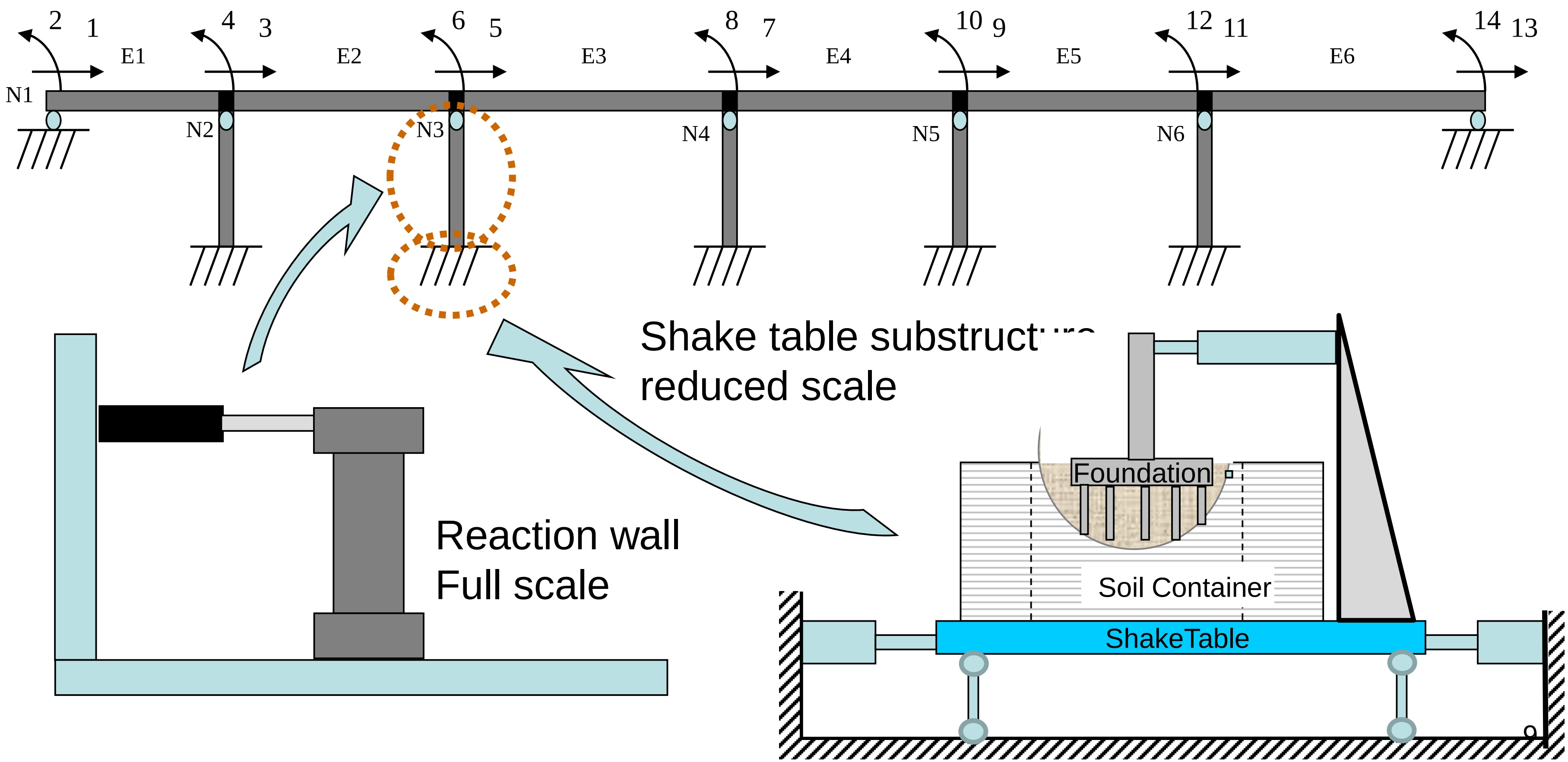
Hybrid Structural Model

- **Modeling Assumptions**
  - Assume force release at boundary to simplify experimental setup
  - Consider available equipment in laboratory



Structural Modeling

- **Various configuration possible**
  - Substructures at different length scales



Errors in Hybrid Simulation

Mitigation of errors key to successful hybrid simulation

Numerical Errors

- **Similar to numerical simulations, hybrid simulation employs numerical integrators to solve equation of motion**
  - e.g., Newmark's Method in explicit form

$$ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}$$

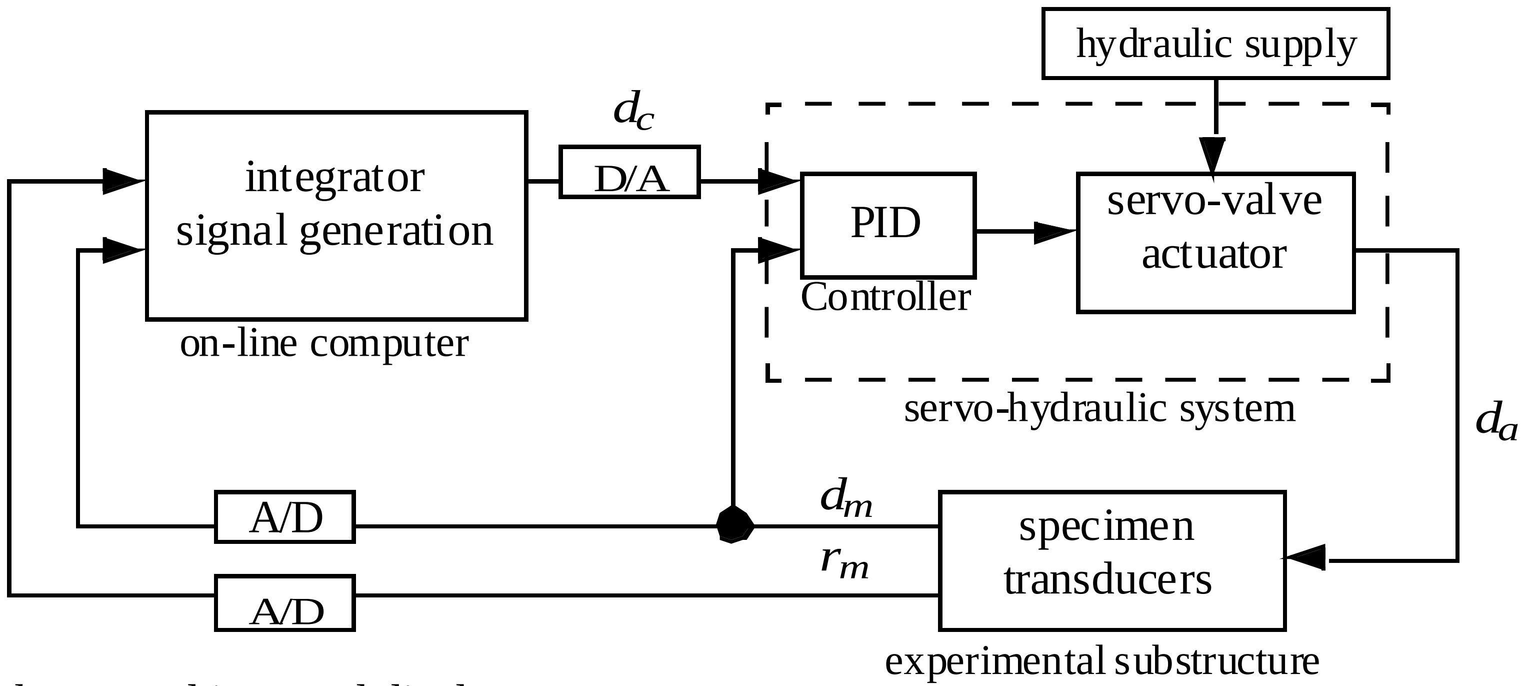
$$d_{i+1} = d_i + \Delta t v_i + \frac{1}{2}\Delta t^2 a_i$$

$$v_{i+1} = v_i + \frac{1}{2}\Delta t\left(a_i + a_{i+1}\right)$$

- **Satisfy dynamic equilibrium and kinematics**
- **Selection of integration algorithm and time step critical to stability and accuracy**

Errors in Hybrid Simulation

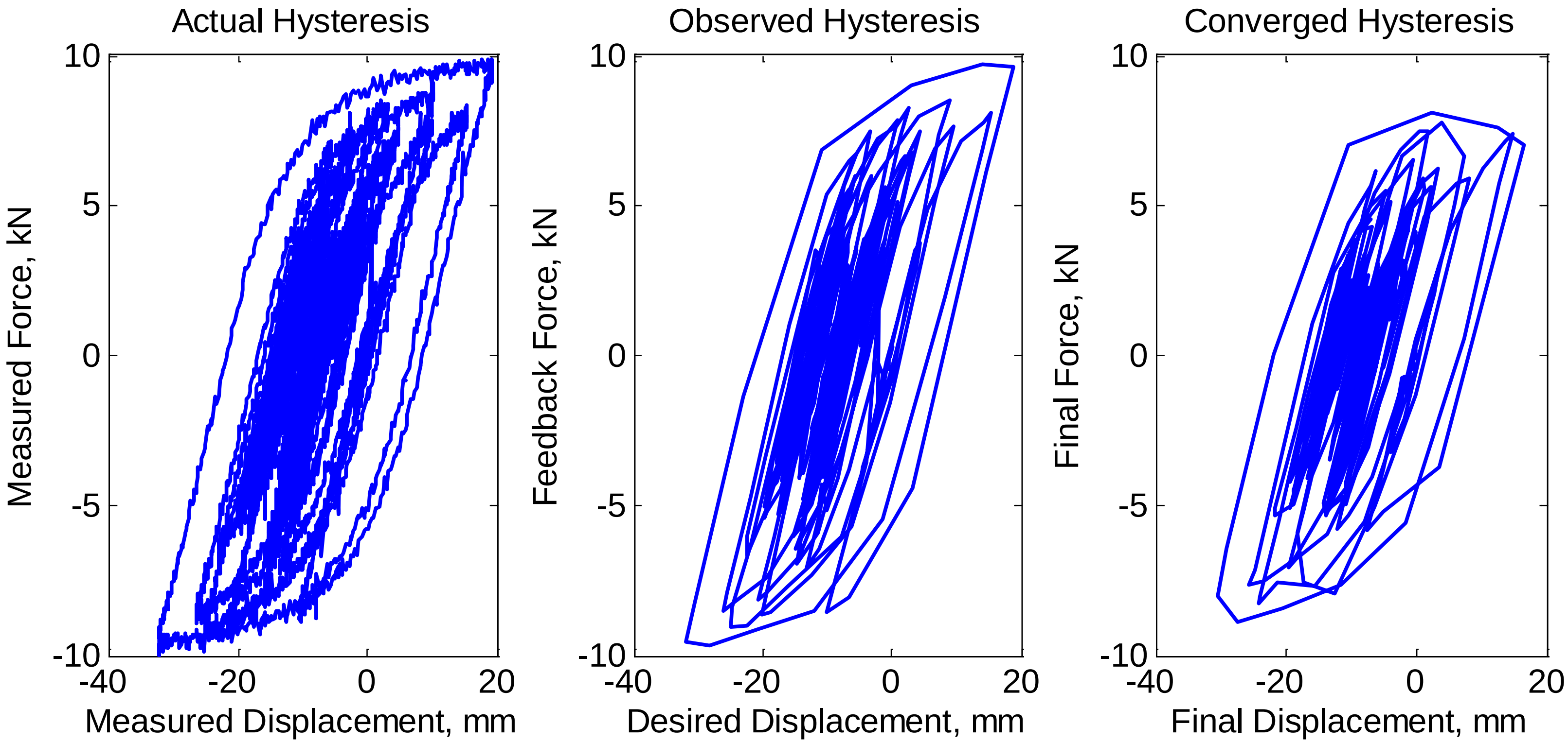
Experimental Errors



d_a = actual imposed displacement
d_c = command displacement
d_m = measured displacement
r_m = measured restoring force

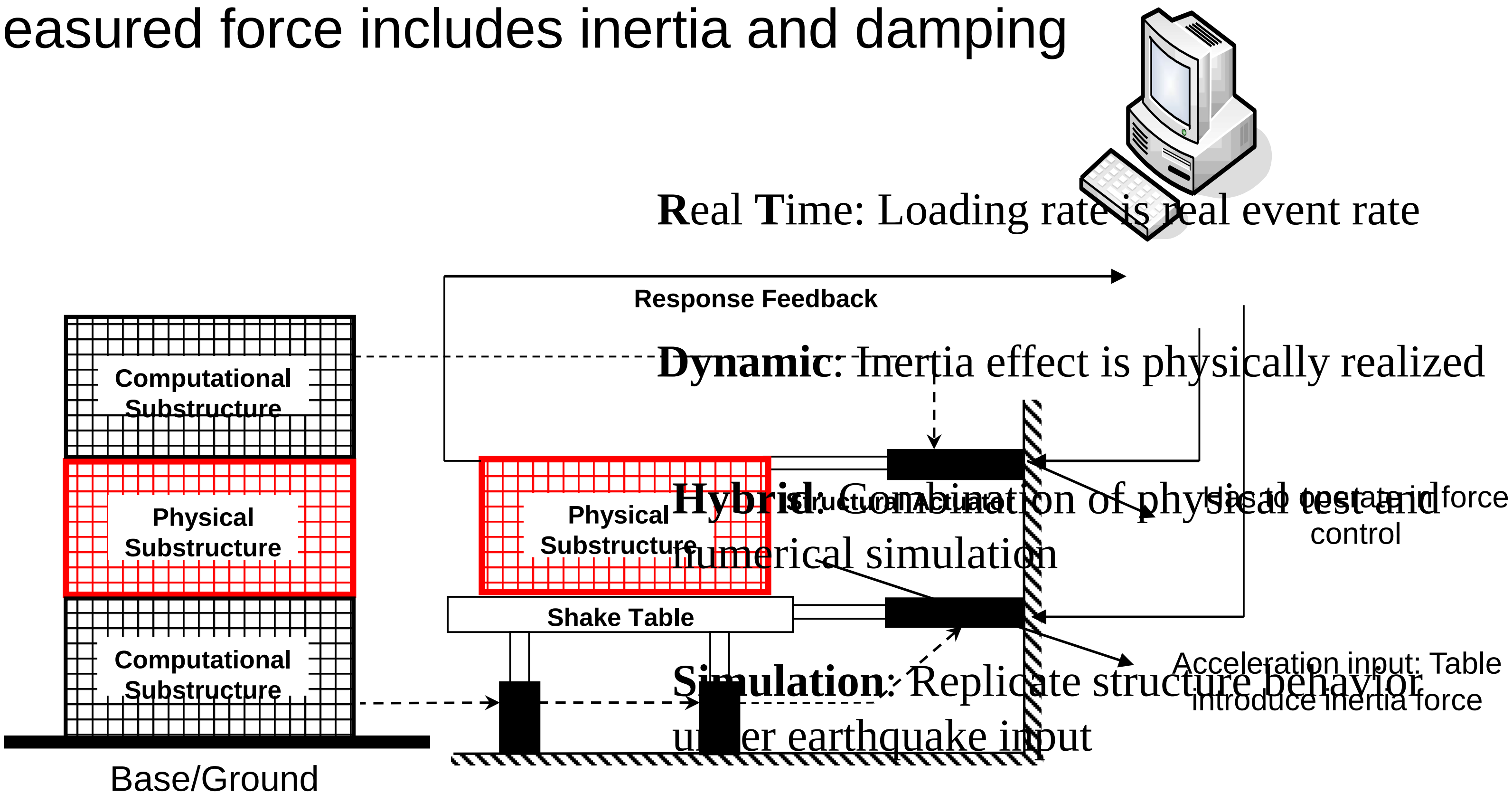
Errors in Hybrid Simulation

Difference between observed and measured behavior of specimen due to experimental errors can propagate through simulation



Real-Time Dynamic Hybrid Simulation

- **Real-time Dynamic Hybrid Simulation** combines use of shake tables, actuators and computational models
- Measured force includes inertia and damping



Real **T**ime: Loading rate is real event rate

Dynamic: Inertia effect is physically realized

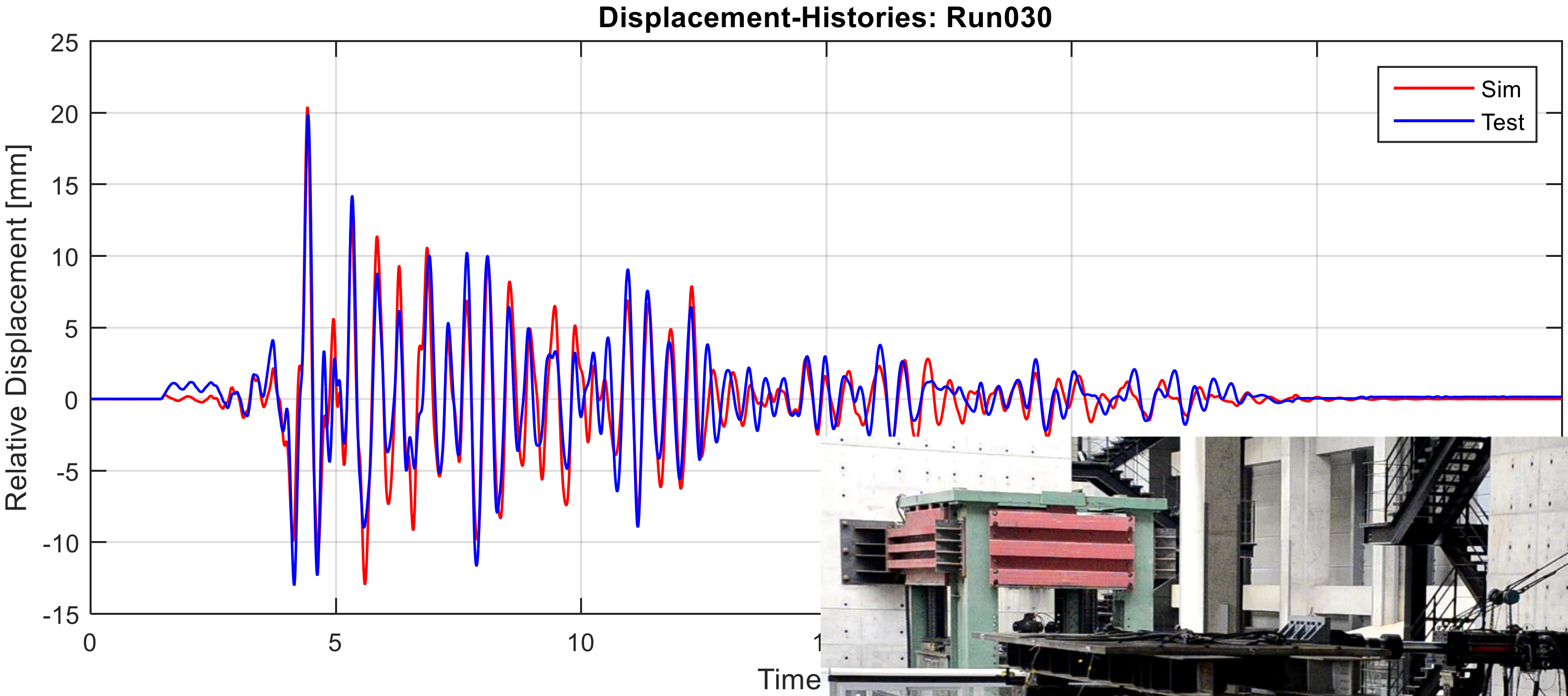
Hybrid: Combination of physical test and numerical simulation

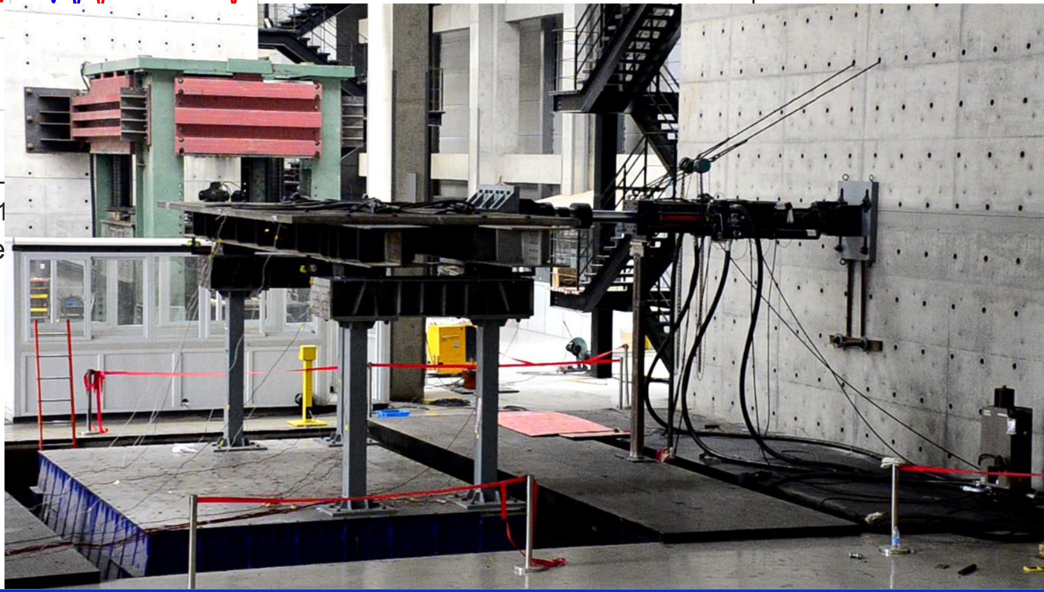
Simulation: Replicate structure behavior under earthquake input

(Reinhorn and Shao)

Real-time Dynamic Hybrid Simulations

- **Large scale RTDHS conducted at Tongji University**

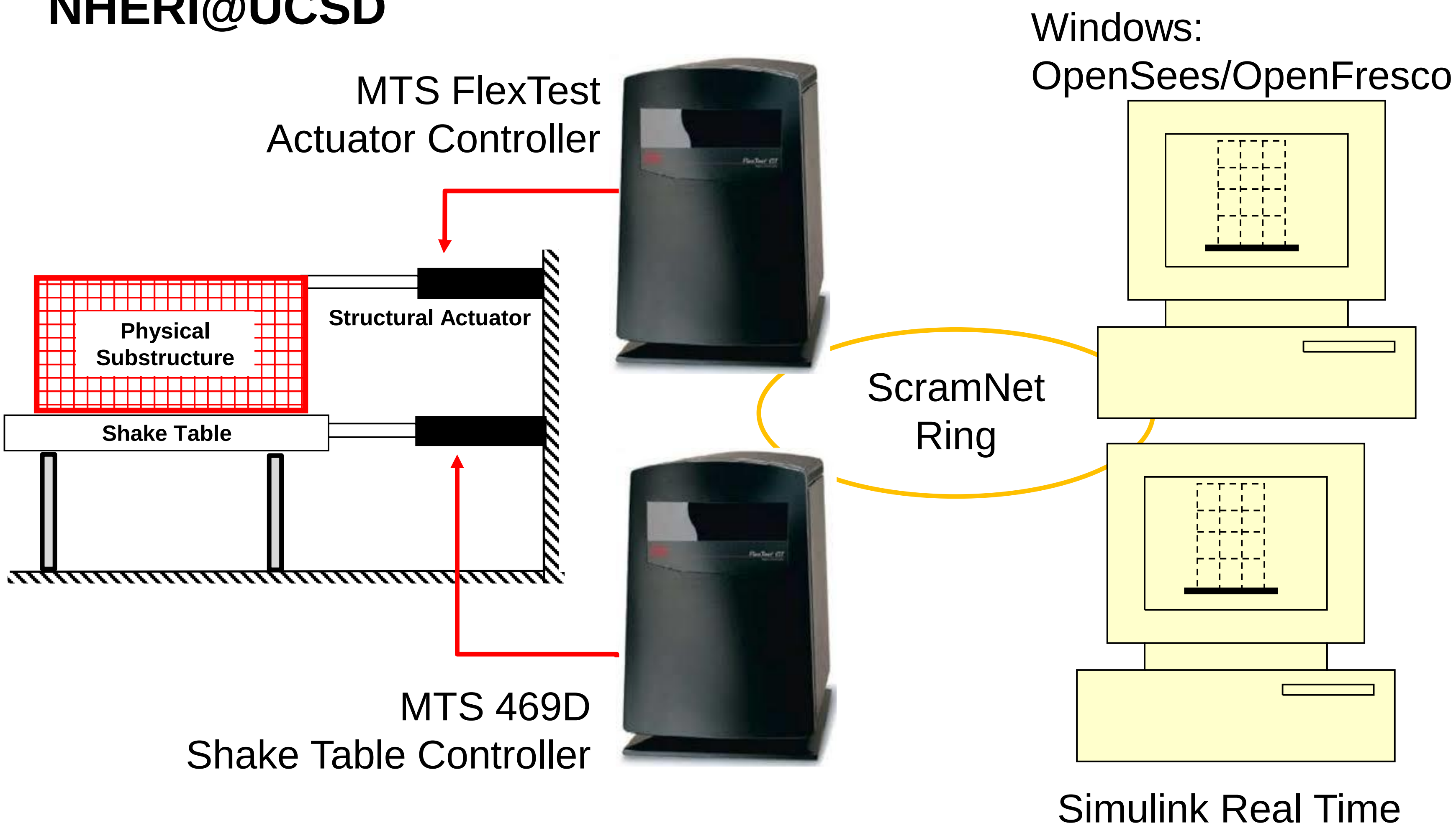




(Schellenberg et al.)

Hybrid Simulation Control System

- **Real time integrated computational capabilities available at NHERI@UCSD**

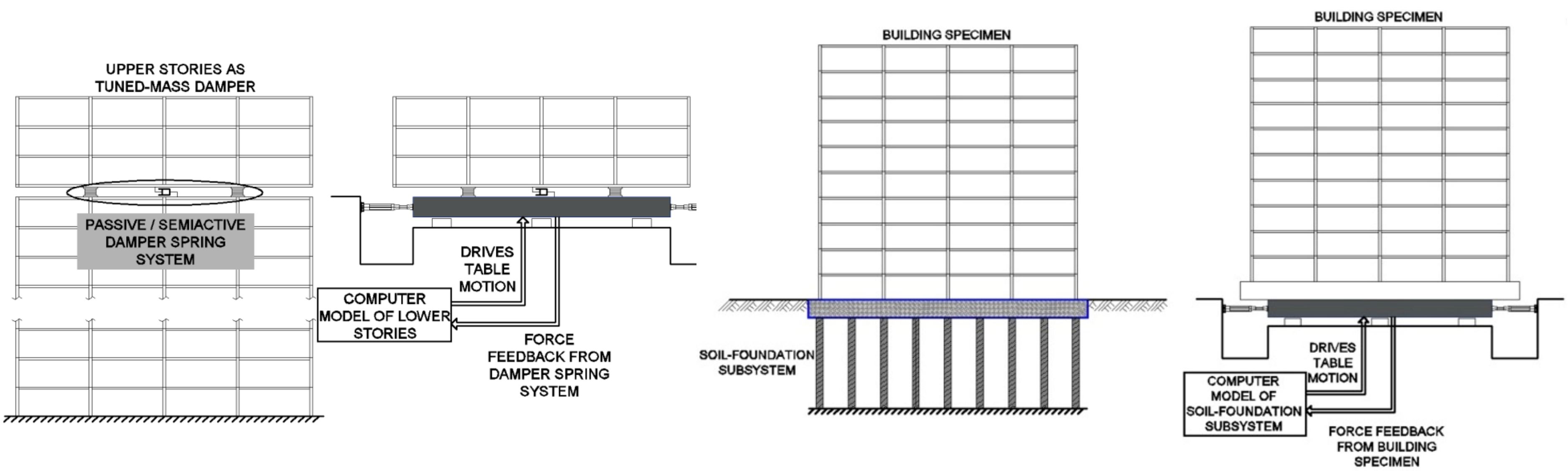


Real-time Hybrid Simulation Control System

- **Hardware integrated through ScramNet Reflective Shared Memory for real-time communication between**
  - Exchange of data on the order of microseconds
- **MTS 469D Shake Table Controller**
  - Can be set to take control commands from ScamNet
- **Multi-channel MTS FlexTest Actuator Controller**
- **xPC Target/Simulink Real-Time**
  - User programmable environment using Matlab- Simulink that runs in real-time
  - Send commands and receive feedback from actuator controllers through ScramNet
- **50-ton dynamic actuator**

Application of Hybrid Simulation

- Simulate large and complex structures that exceed capabilities of the shake table such as long span bridges and tall buildings
  - Test a critical part of the structure at large scale
  - Numerically capture system level response
- Some type of structures exhibit rate dependent effects and distributed inertial forces requiring dynamic testing

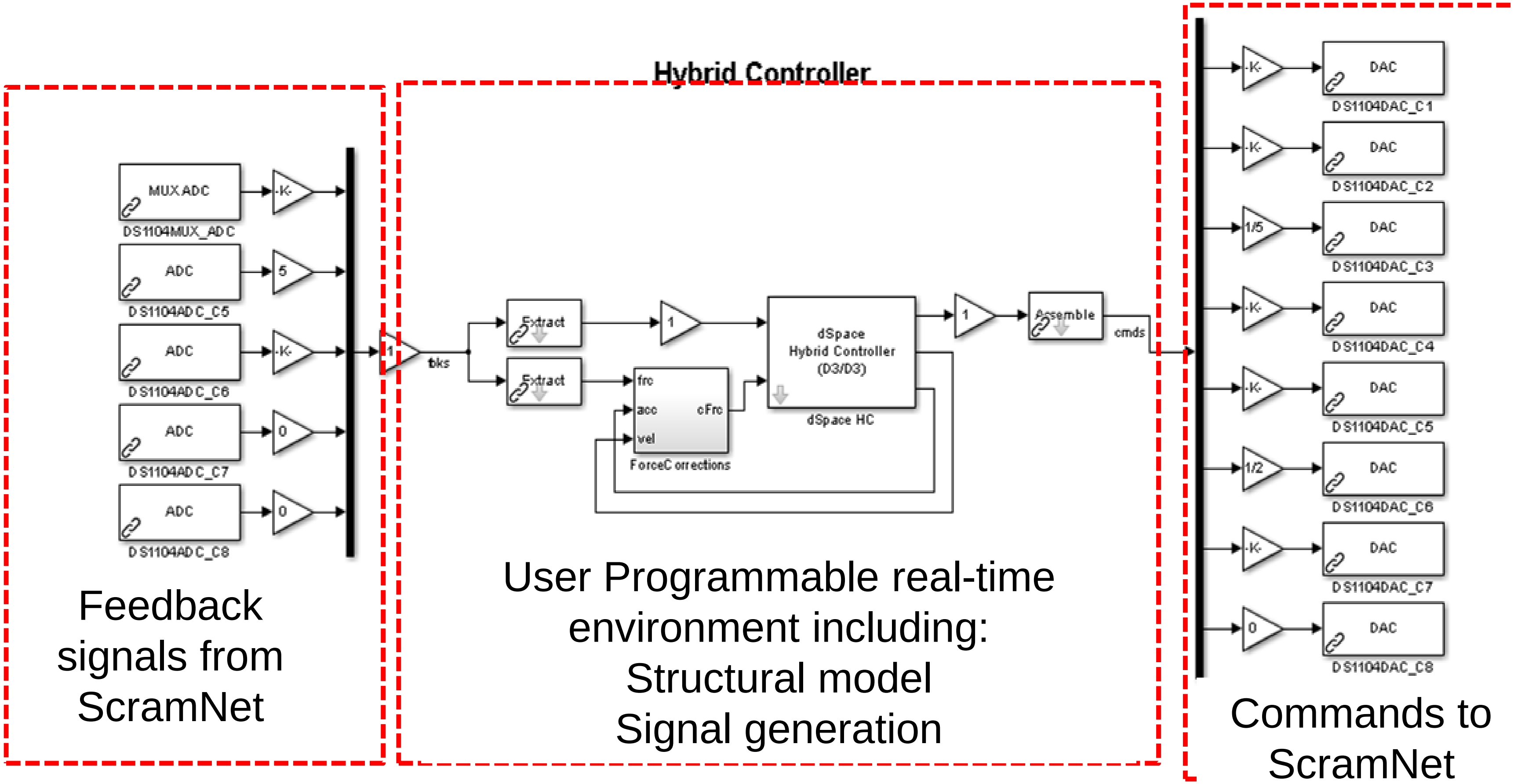


Real-time Hybrid Simulation Control System

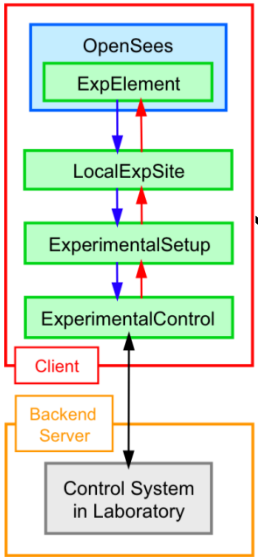
- **For hard real-time, users can program numerical structural model in Simulink**
- **Potential to interface with real time programs in other operating systems and program for structural analysis through ScramNet**
  - Applications with OpenSees/OpenFresco have been verified
- **Structural analysis software provides the advantage of access to libraries of integrators, elements etc.**
- **Delay and error compensation is critical to hybrid simulation and can be implemented in real-time environment**

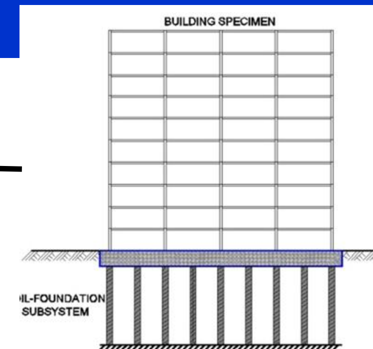
Real-time Hybrid Simulation Control System

- **User defined structural model and boundary conditions can be implemented in Simulink for ‘hard’ real-time**



Advanced Numerical Models using OpenSees/OpenFresco



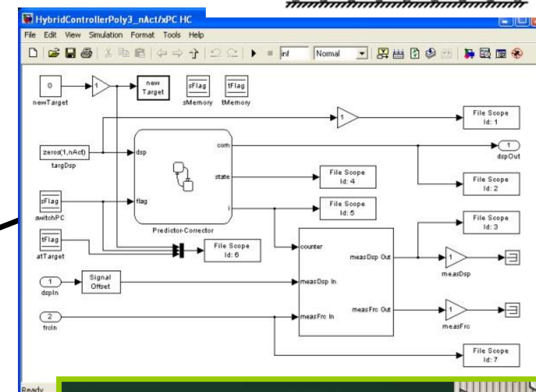


OpenSees Finite Element Model

OpenFresco Middleware

TCP/IP or SCRAMNet

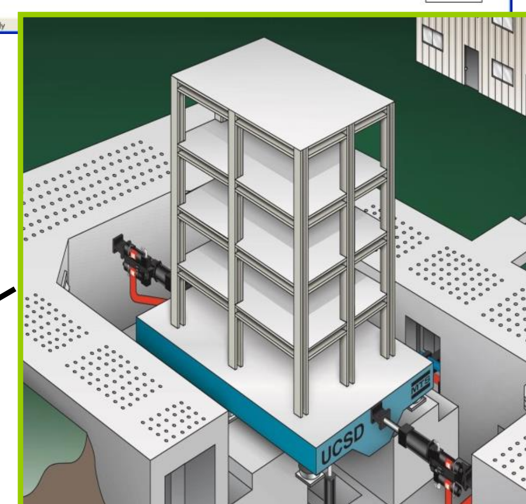
xPC-Target real-time Predictor-Corrector



SCRAMNet

MTS 469D real-time Controller

Physical Specimen on Shake Table

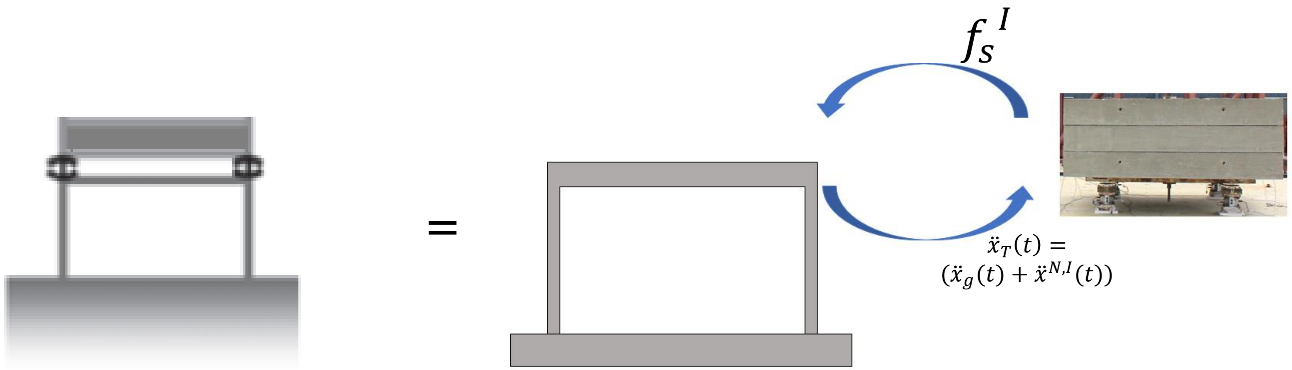


User Preparation

- Selection of structural model
  - ✓ Computer modeling, substructures and boundary conditions
- Design of experimental setup within capacity of facility
- Selection of integration and error compensation algorithm and their implementation in real-time software
- Communication link between computer model and hardware for custom software applications
- Pre-test simulation with numerical model of test setup
- Low level simulations to verify system performance and feedback loops
  - ✓ Include time for development and implementation of algorithms
- Execute test sequence

Recent Applications

- **Hybrid Simulation Commissioning Tests using LHPOST**
  - Collaborative development effort with NHERI SimCenter
  - Data workflow and curation with NHERI DesignSafe



$$M^N\ddot{x}(t) + C^N C\dot{x}(t) + K^N x(t) = -M^N L\ddot{x}_g(t) + f_s{}^I$$

$$M^E\ddot{x}(t) + C^E\dot{x}(t) + K^E x(t) = -M^E L\ddot{x}_T = -M^E L(\ddot{x}_g(t) + \ddot{x}^{N,I}(t))$$

where $f_s{}^I$ only affects the interface DOF

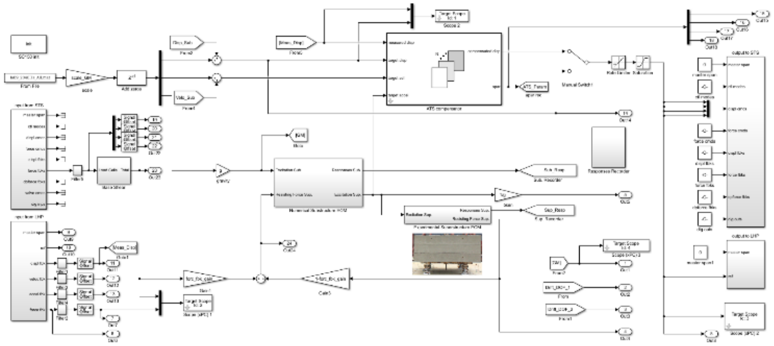
Assuming no mass in the interface of the experimental

Recent Applications

- **Hybrid Simulation Commissioning Tests using LHPOST**
  - Two different approaches were implemented for the hybrid simulation computational drivers models programmed fully in Simulink RT and using OpenSees/OpenFresco)
  - Displacement control of shake table
  - Two different integrator algorithms were used: the generalized Alpha-Operator-Splitting and the explicit KR-alpha (adapted to shake table sub-structuring)
  - Application of adaptive time delay compensation was used (ATS compensator, Chae et al (2013))
  - SDOF and MDOF numerical models were implemented

Hybrid Simulation using LHPOST

- **Simulink Real-Time as computational driver**



Simulink RT
(xPC-Target)

SCRAMNet+ SCRAMNet+

MTS 469D Controller

MTS STS Controller

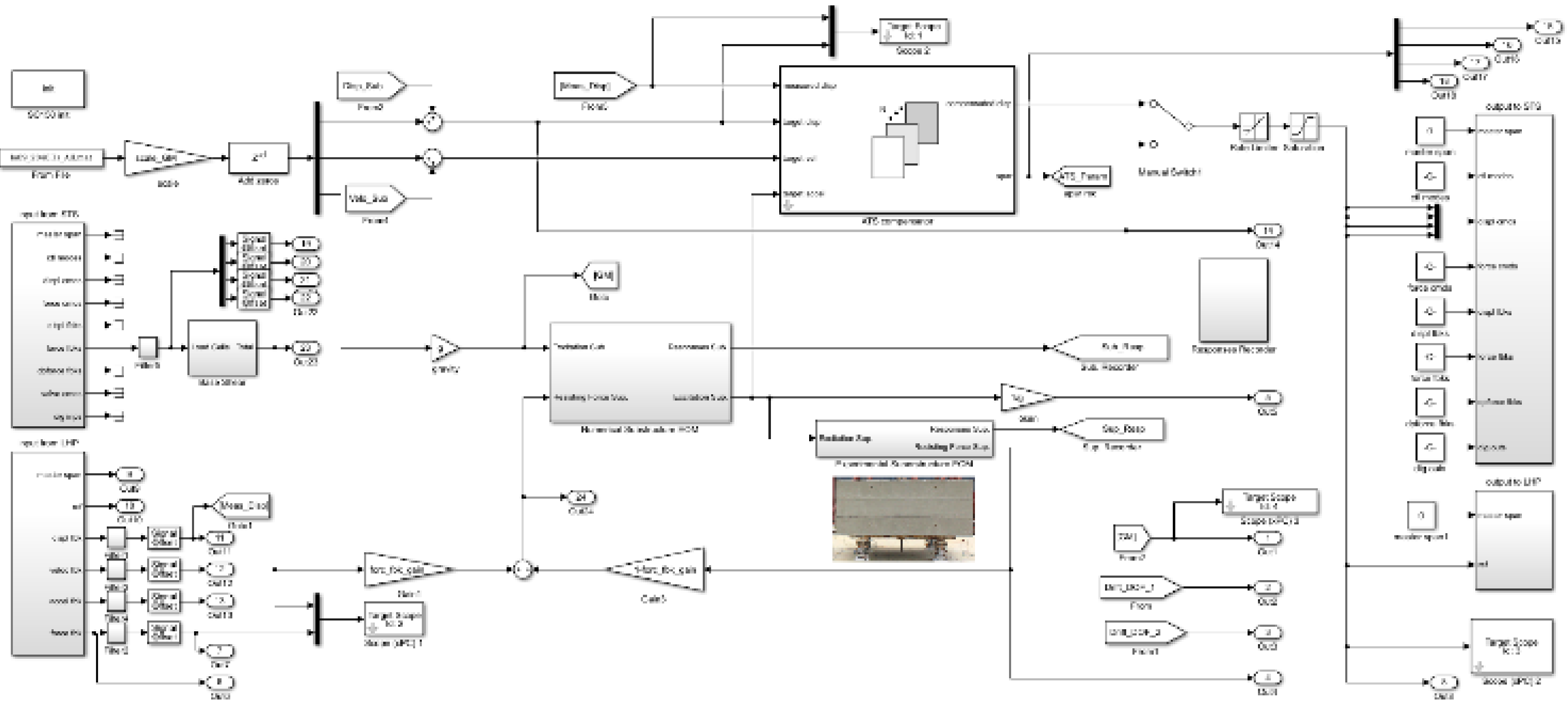
to servo valve

from load cells

Physical Specimen on LHPOST

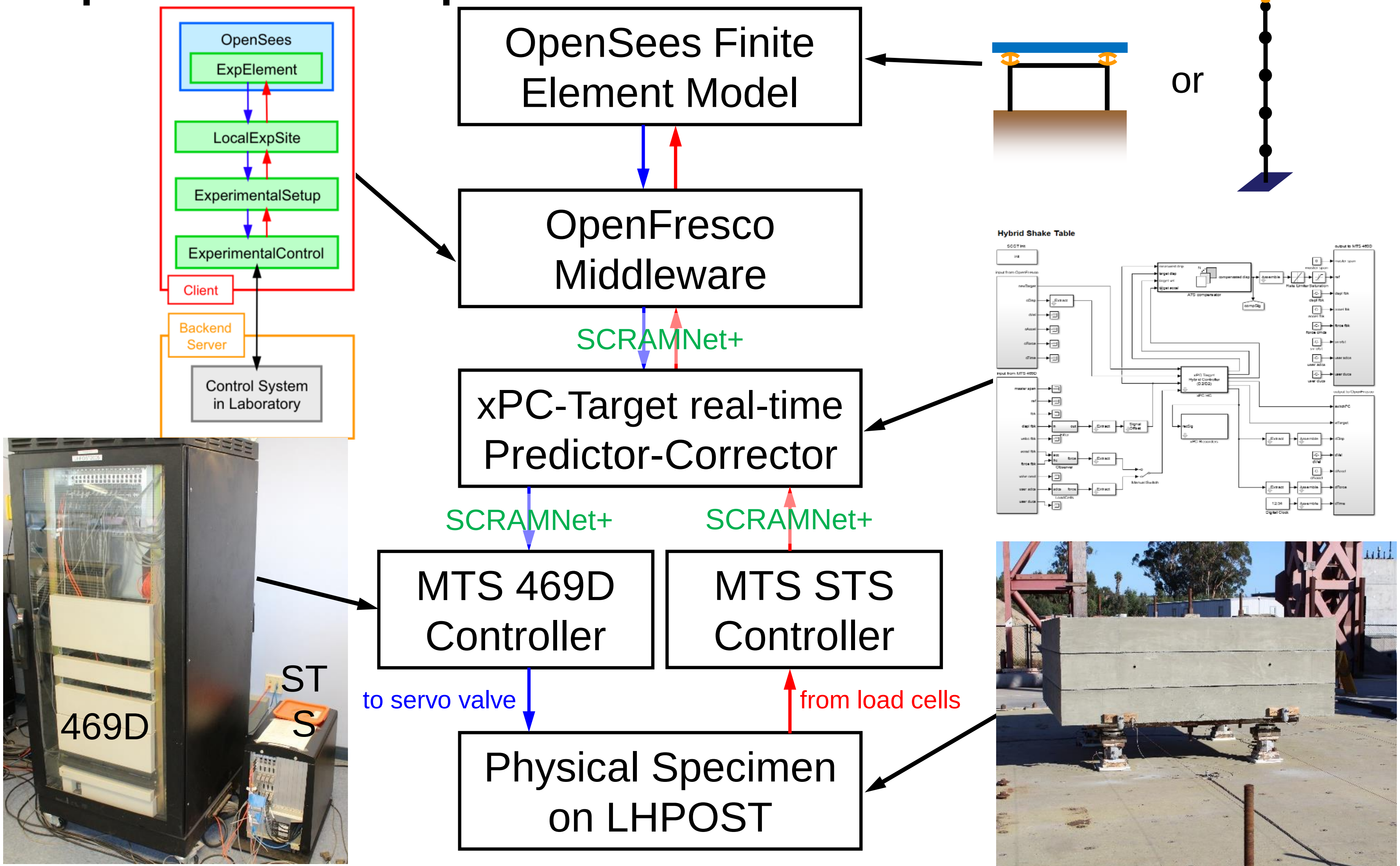
Hybrid Simulation using LHPOST

➢ **Simulink Real-Time as computational driver**



Hybrid Simulation using LHPOST

- **OpenSees as computational driver**



Hybrid Simulation using LHPOST

- **Comparison of two configurations**
  - Hard Real-Time vs Soft Real-Time
  - OPS-OPF have access to all the library that includes: MDOF systems, different integration algorithms, different material models and other nonlinear effects.
  - OPS-OPF requires the implementation of a predictor corrector algorithm.

➢ Experimental Setup

- Rigid Mass (56 kip) over four triple friction pendulum bearings

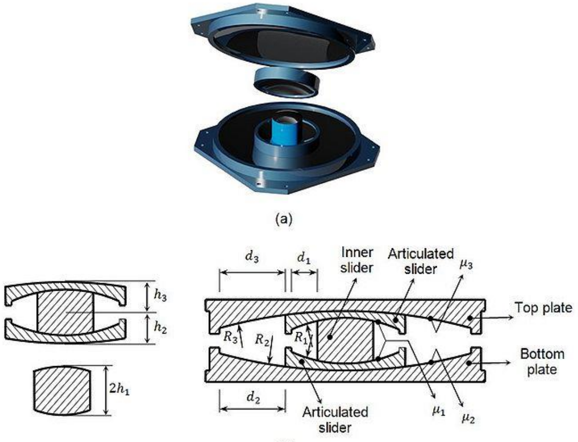
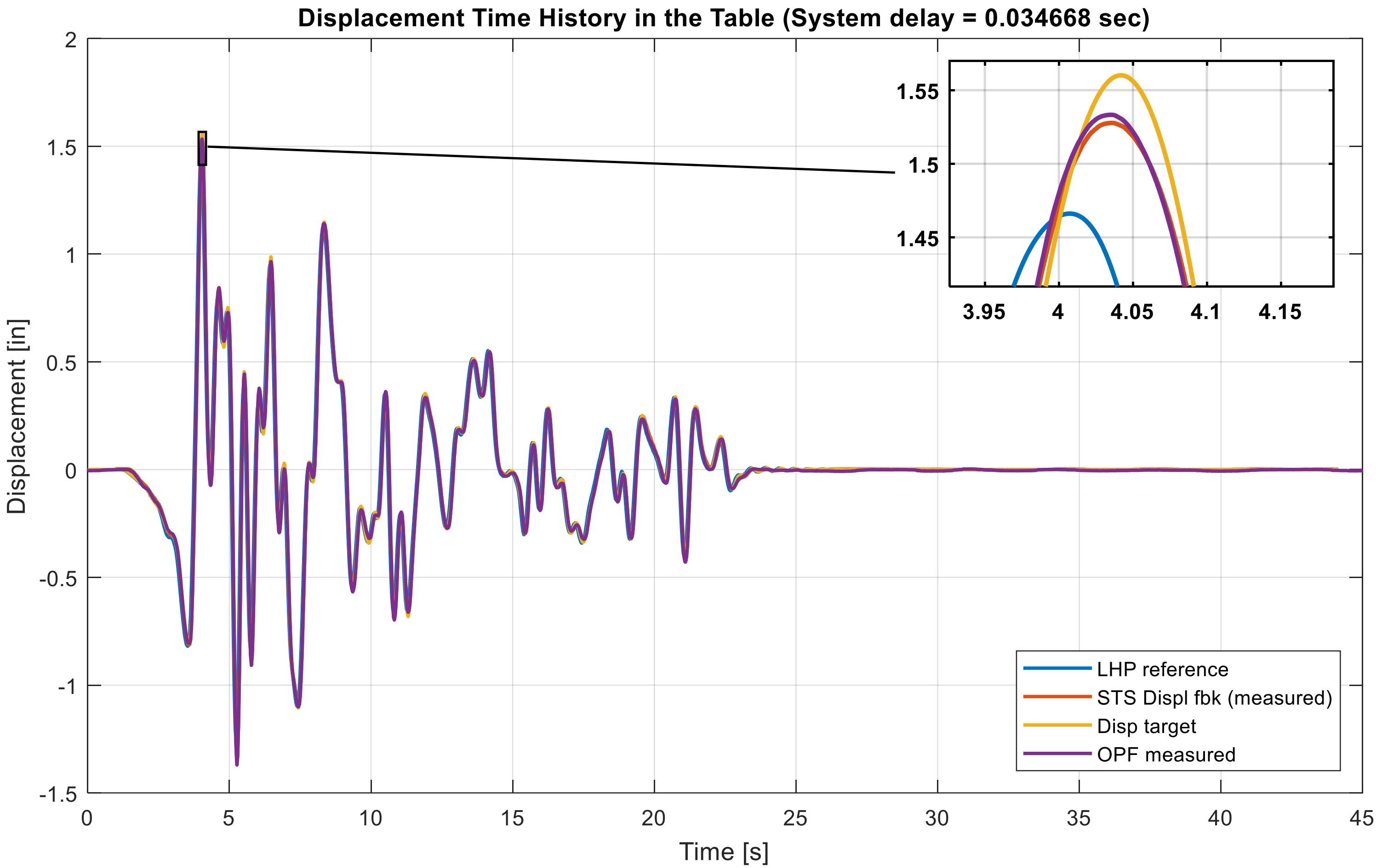


Figure 1: Triple friction pendulum bearing
(a) Three-dimensional view
(b) Section view and basic parameters

Hybrid Simulation using LHPOST

➢ Experimental Results

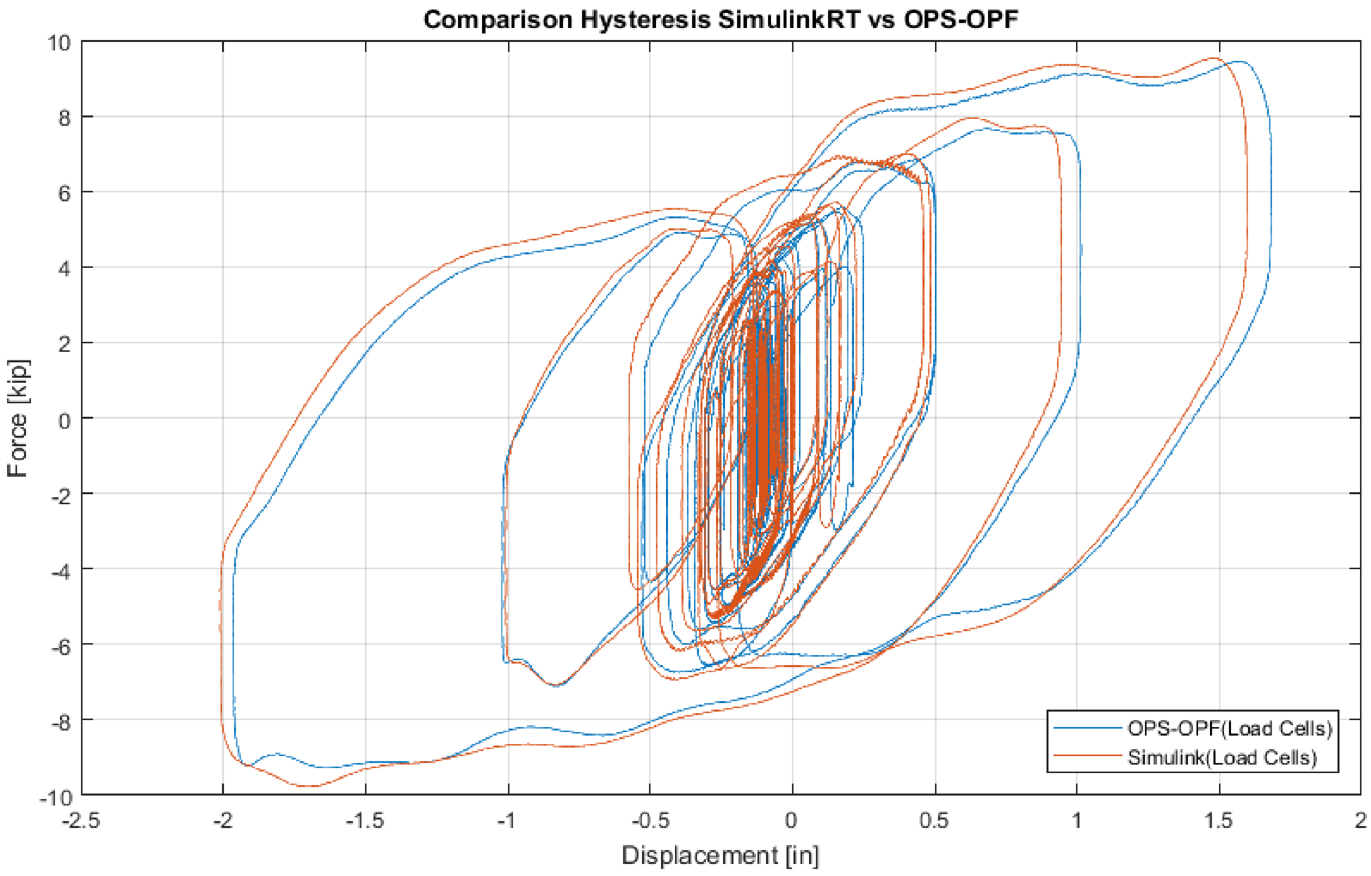


The time delay (average 34 ms) introduced by the shake table system was alleviated with an ATS compensator.

Hybrid Simulation using LHPOST

➢ Experimental Results

The results using OPS-OPF and Simulink Real Time as the computational driver compare well.



Concluding Remarks

- **Hybrid simulation can be a cost-effective and reliable approach to expand testing capabilities**
- **Control of numerical and experimental errors is critical to accuracy and stability of a hybrid test**
- **NHERI@UCSD can provide expertise to support the implementation of hybrid simulation**
- **Hybrid Commissioning tests demonstrate new capabilities that can expand the complexity of large-scale geotechnical and structural systems that can be tested on LHPOST.**

Acknowledgements

- NSF NHERI support for capacity enhancement
- Andreas Schellenberg, NHERI SimCenter
- UCSD: Manuel Vega (PhD), Humberto Caudana (Post-Doc), Darren McKay (NHERI Site Operations)