MDOF Hybrid Shake Table Testing for Bridge and Building Structures

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PEER

MTS

**ASES** ADVANCED STRUCTURAL ENGINEERING SOLUTIONS

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EU-US-Asia workshop on hybrid testing
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Outline of Presentation

1. Motivation
2. Hybrid Shake Table Testing
3. Stability and Accuracy Considerations
4. Test Rehearsal and Safety Precautions
5. Bridge Application
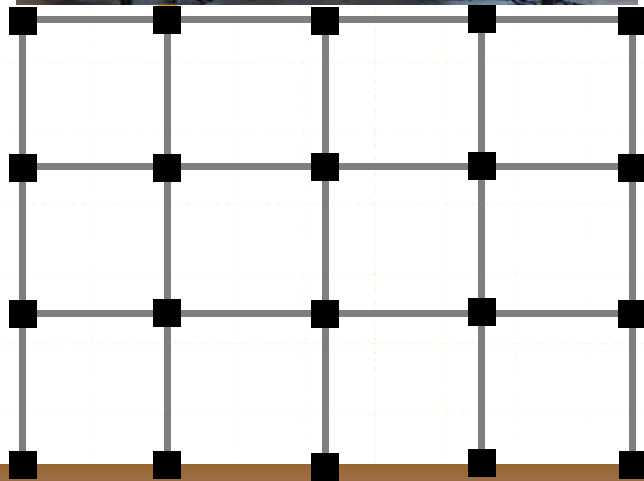6. Building Application
7. Summary & Conclusions

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Motivation

✦ Many structures exhibit significant rate of loading effects

✦ Need testing to occur at or near real time

✦ Large systems such as tall buildings, long-span bridges, or SFSI are difficult to test on shake tables

Shaking Table   Numerical Model   Shaking Table   Numerical Model

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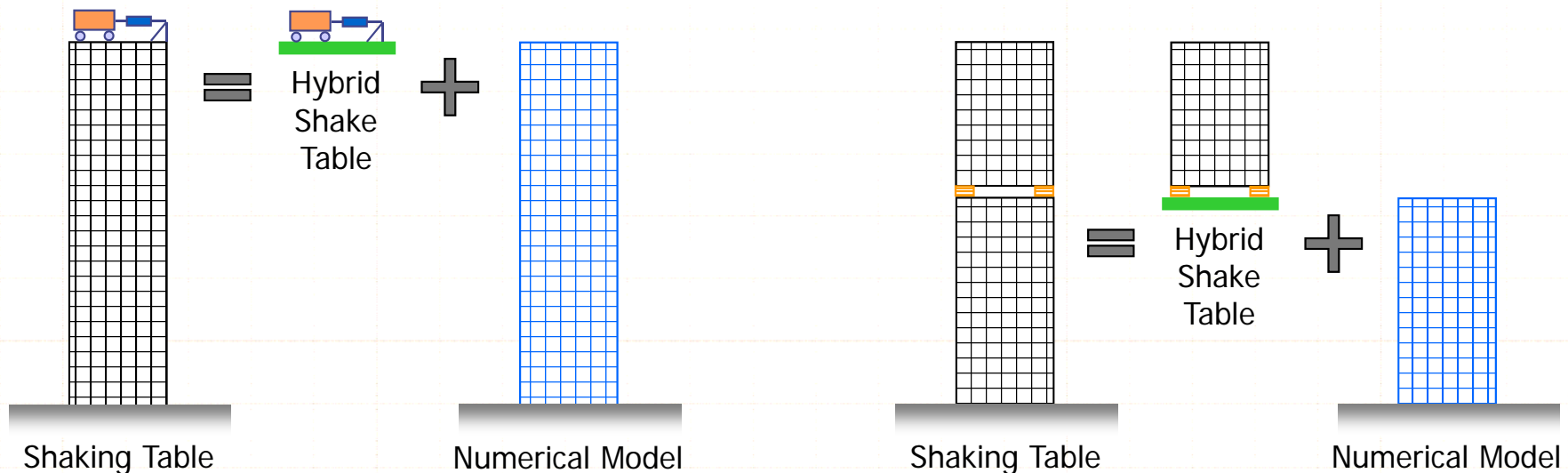
Hybrid Shake Table Testing

$$\mathbf{M} \cdot \ddot{\mathbf{u}}_t + \mathbf{C} \cdot \dot{\mathbf{u}}_t + \mathbf{P_r}\left(\mathbf{u}_t, \dot{\mathbf{u}}_t, \ddot{\mathbf{u}}_t\right) = \mathbf{P_0}$$
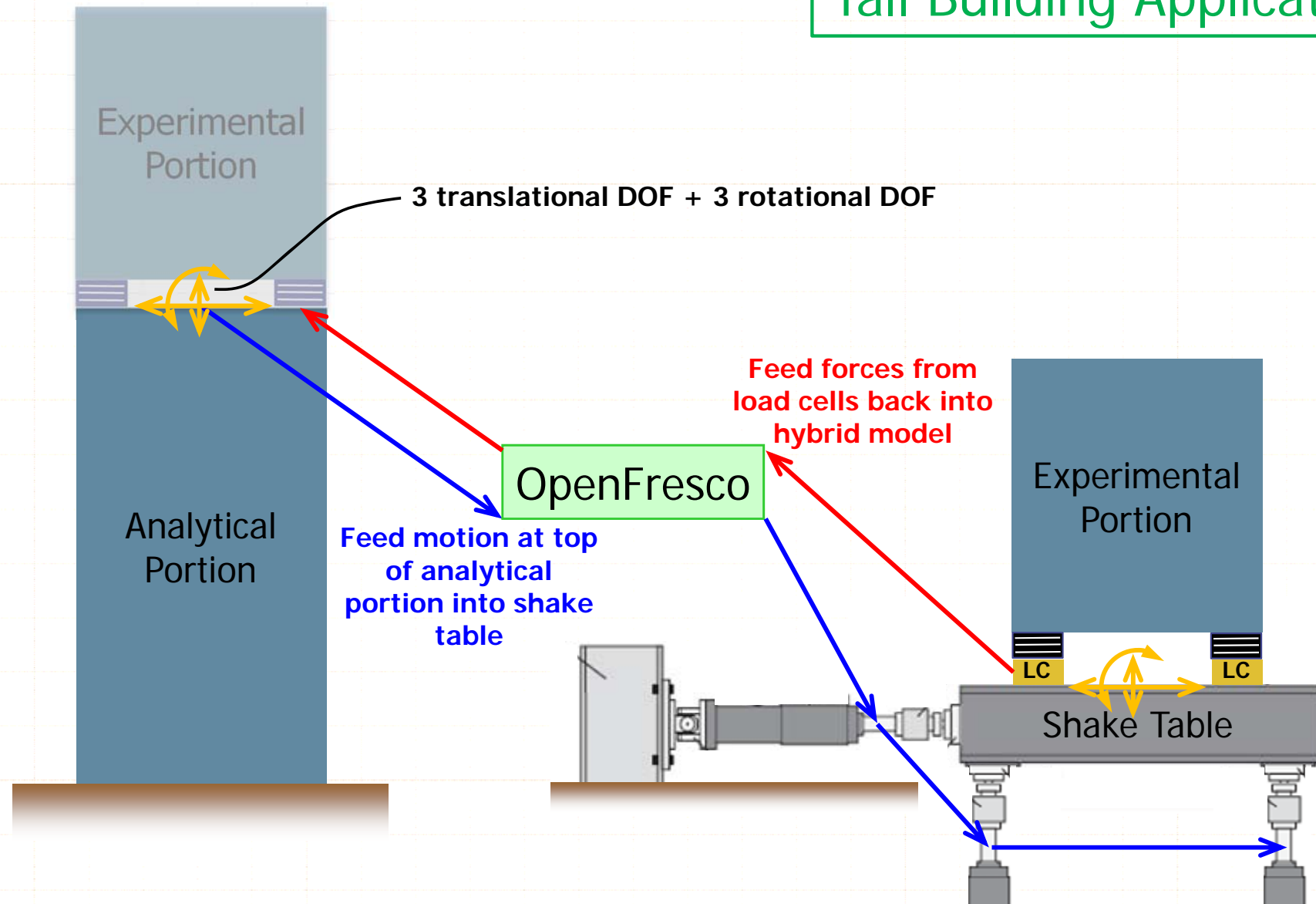
- Inertia
- Energy Dissipation
- Resistance

$$\ddot{\mathbf{u}}_g, \dot{\mathbf{u}}_g, \mathbf{u}_g$$
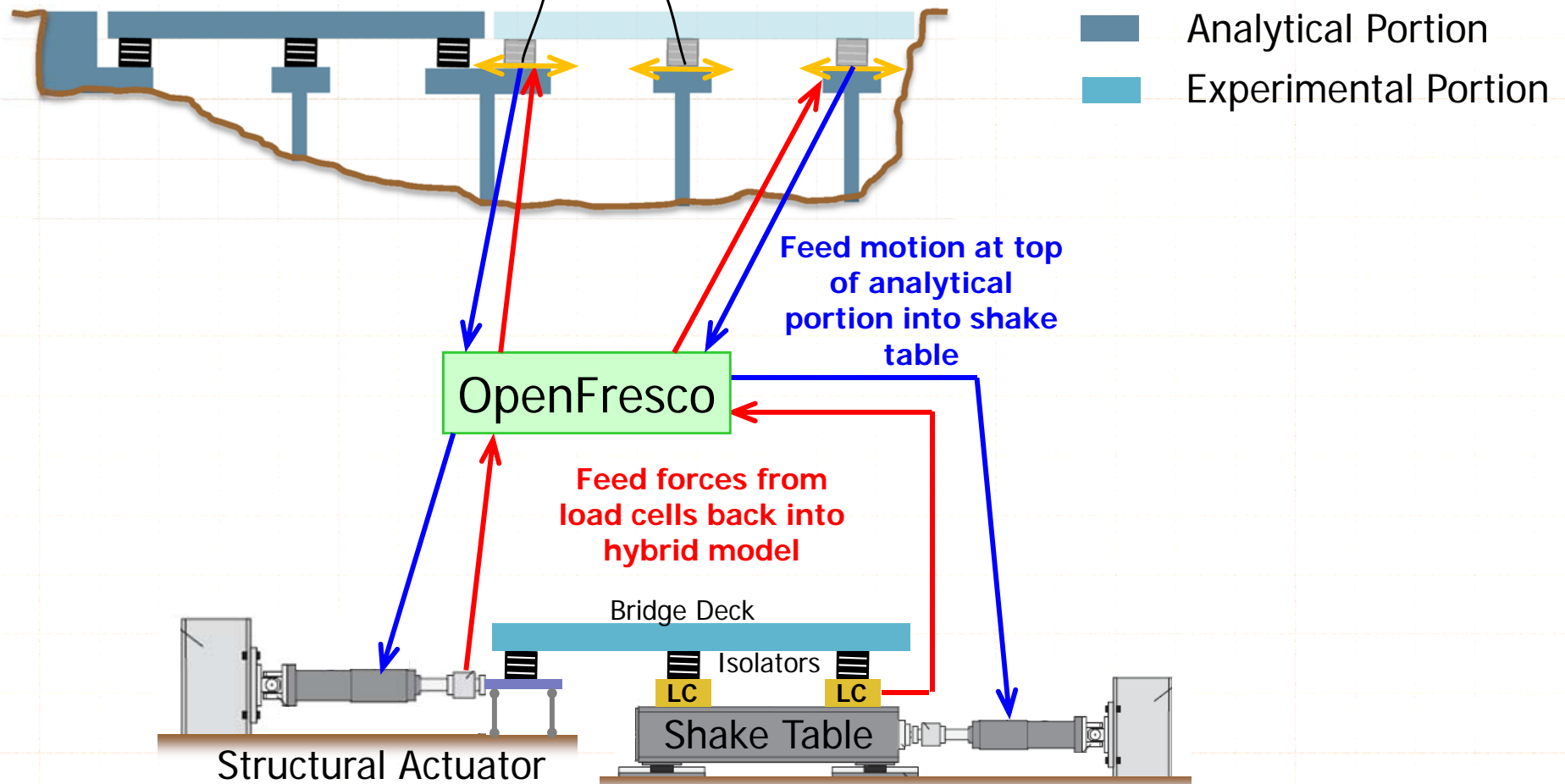
Hybrid Shake Table Configuration

Tall Building Application

Experimental Portion

3 translational DOF + 3 rotational DOF

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Analytical Portion

Feed motion at top of analytical portion into shake table

Feed forces from load cells back into hybrid model

Experimental Portion

LC   LC

Shake Table

Hybrid Shake Table Configuration

1 actuator DOF + 2 table DOF

Long-Span Bridge Application

Analytical Portion
Experimental Portion

Feed motion at top of analytical portion into shake table

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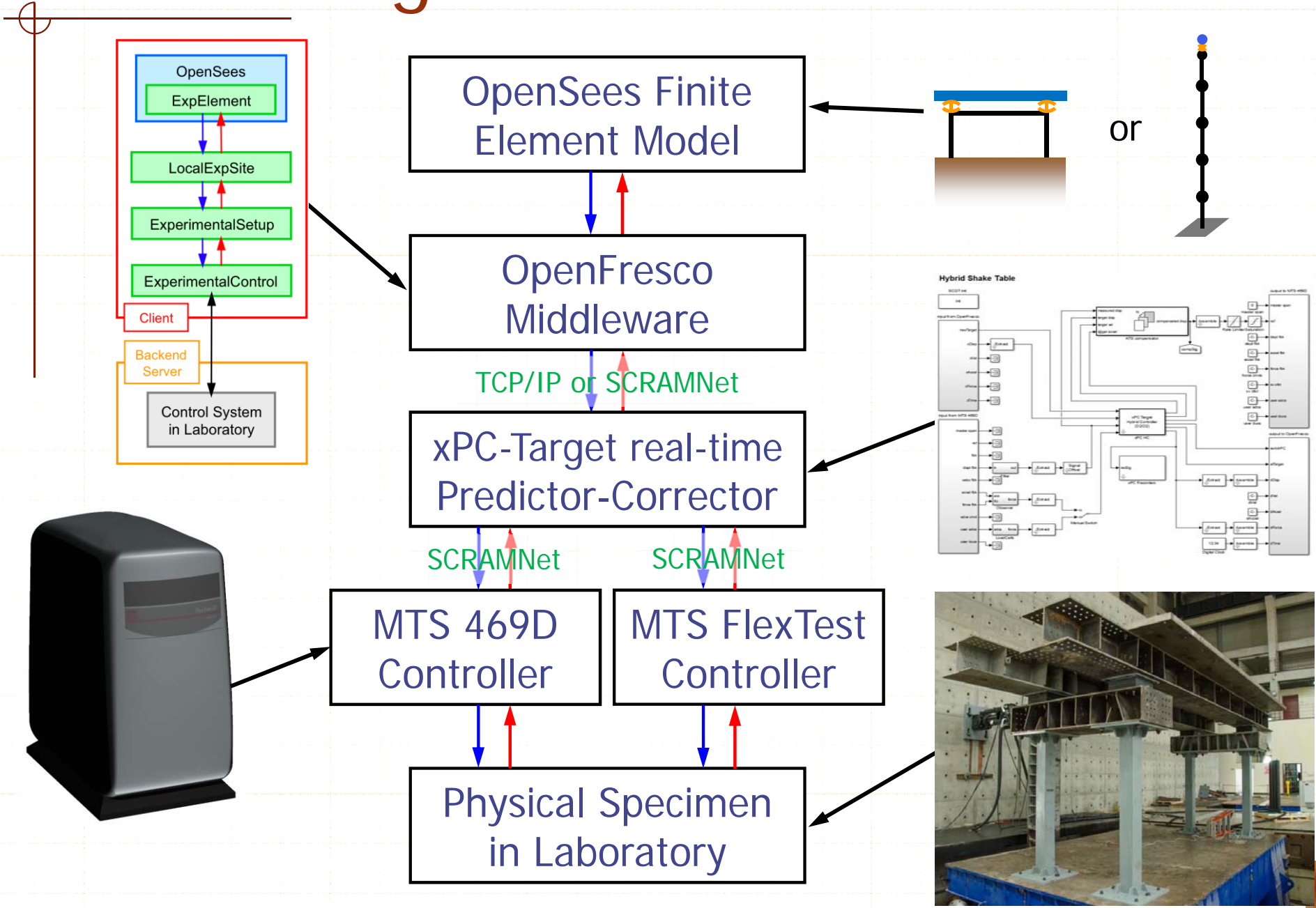**Feed forces from load cells back into hybrid model**

Bridge Deck

Isolators

LC   LC

Shake Table

Structural Actuator

Important Analysis Parameters

- OpenSees or OpenSeesSP as comp. driver
- Using AlphaOSGeneralized ($\rho_{inf} = 0$)
- No iterations necessary
- Using MultipleSupport excitation pattern in OpenSees to get absolute response
- Gravity loads on test specimen always present → apply gravity loads to numerical portion before connecting with shake table + apply disp. commands relative to start of test

Connecting to MTS 469D + FlexTest

OpenSees Finite Element Model

or

OpenFresco Middleware

TCP/IP or SCRAMNet

xPC-Target real-time Predictor-Corrector

SCRAMNet   SCRAMNet

MTS 469D Controller   MTS FlexTest Controller

Physical Specimen in Laboratory

OpenSees
ExpElement
LocalExpSite
ExperimentalSetup
ExperimentalControl
Client
Backend Server
Control System in Laboratory

Improving Stability & Accuracy

- ✦ Delay compensation is essential for real-time hybrid simulations (RTHS)

- ✦ Use Adaptive Time Series (ATS) delay compensator (by Y. Chae)

- ✦ Modify ATS to use target velocities and accelerations computed by predictor-corrector algorithm instead of taking derivatives of target displacements

- ✦ Use stabilization and loop-shaping

- ✦ Sensor noise reduction by filtering fbk

Test Rehearsal

✦ Use FE-Adapter element method to simultaneously connect hybrid model to a numerically simulated test specimen
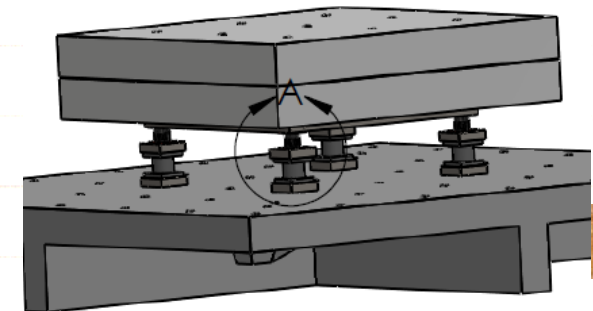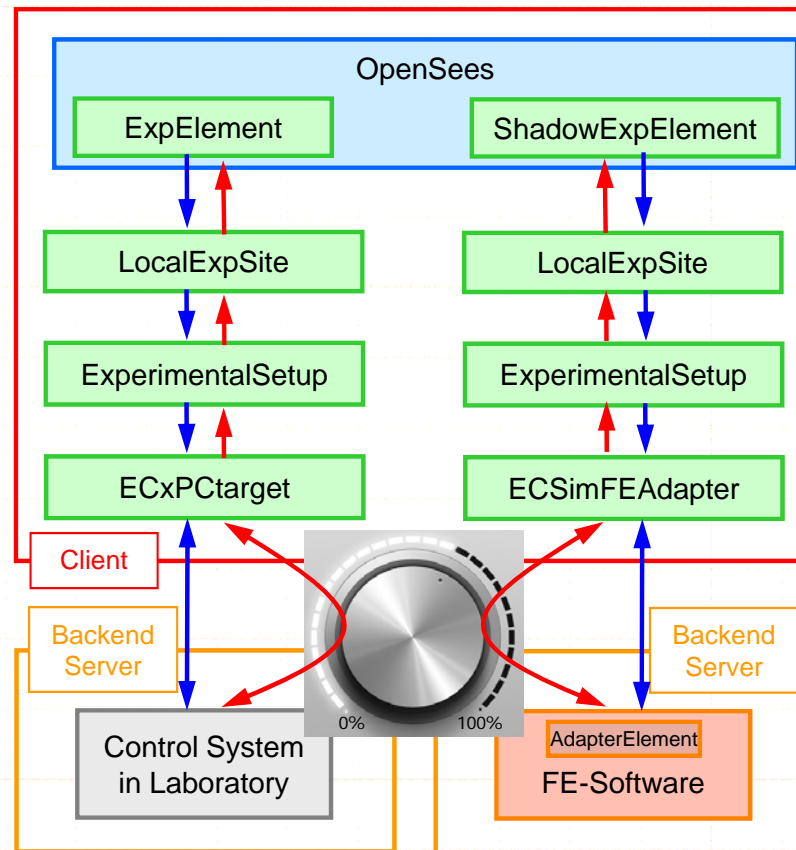
Safety Precautions

- **At analysis side**
  - Set limit on displacement command (saturation and possibly rate limit)
  - Set limit on actuator force so that once the limit is exceeded, the analysis model sends displacement commands to ramp both table and actuator to starting positions
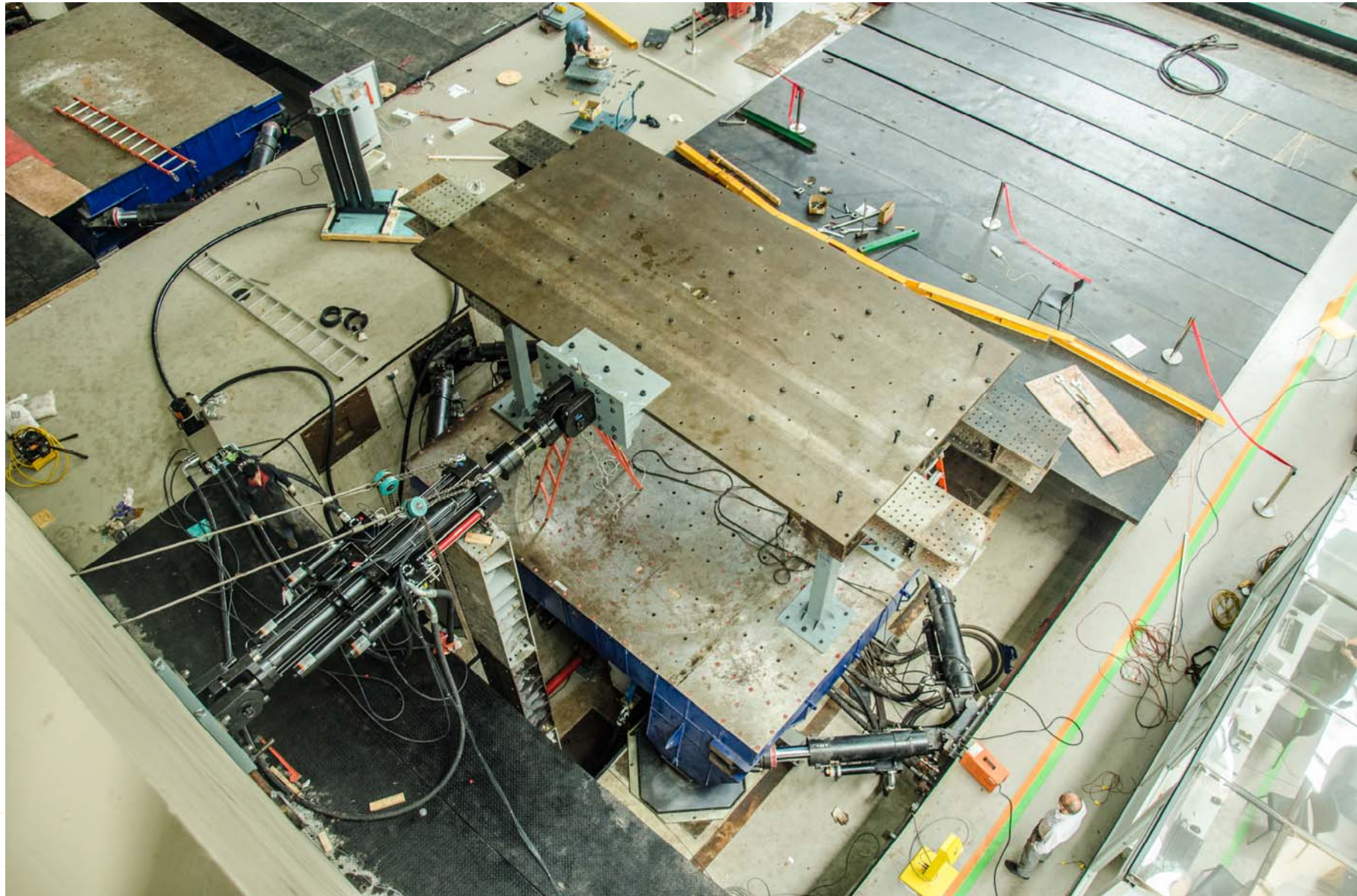
- **At controller side**
  - Set both displacement and force limits so that once the limit is exceeded, the actuator pressure is switched to low, therefore, limiting the actuator force that can be applied to the specimen

Bridge Application

Four 2DOF Shake Tables

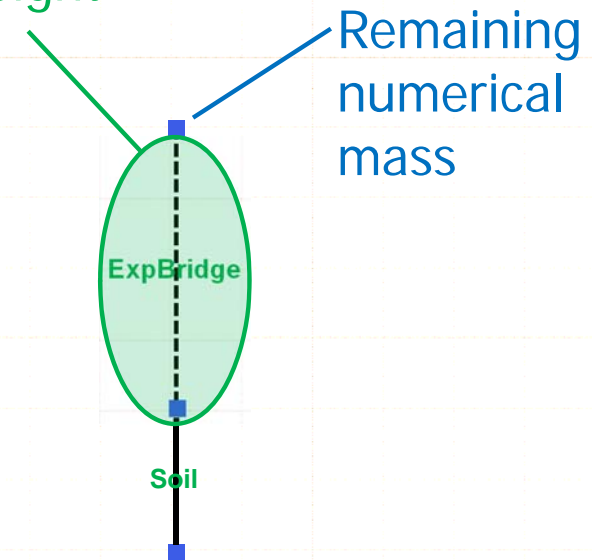# Shake Table + Structural Actuator
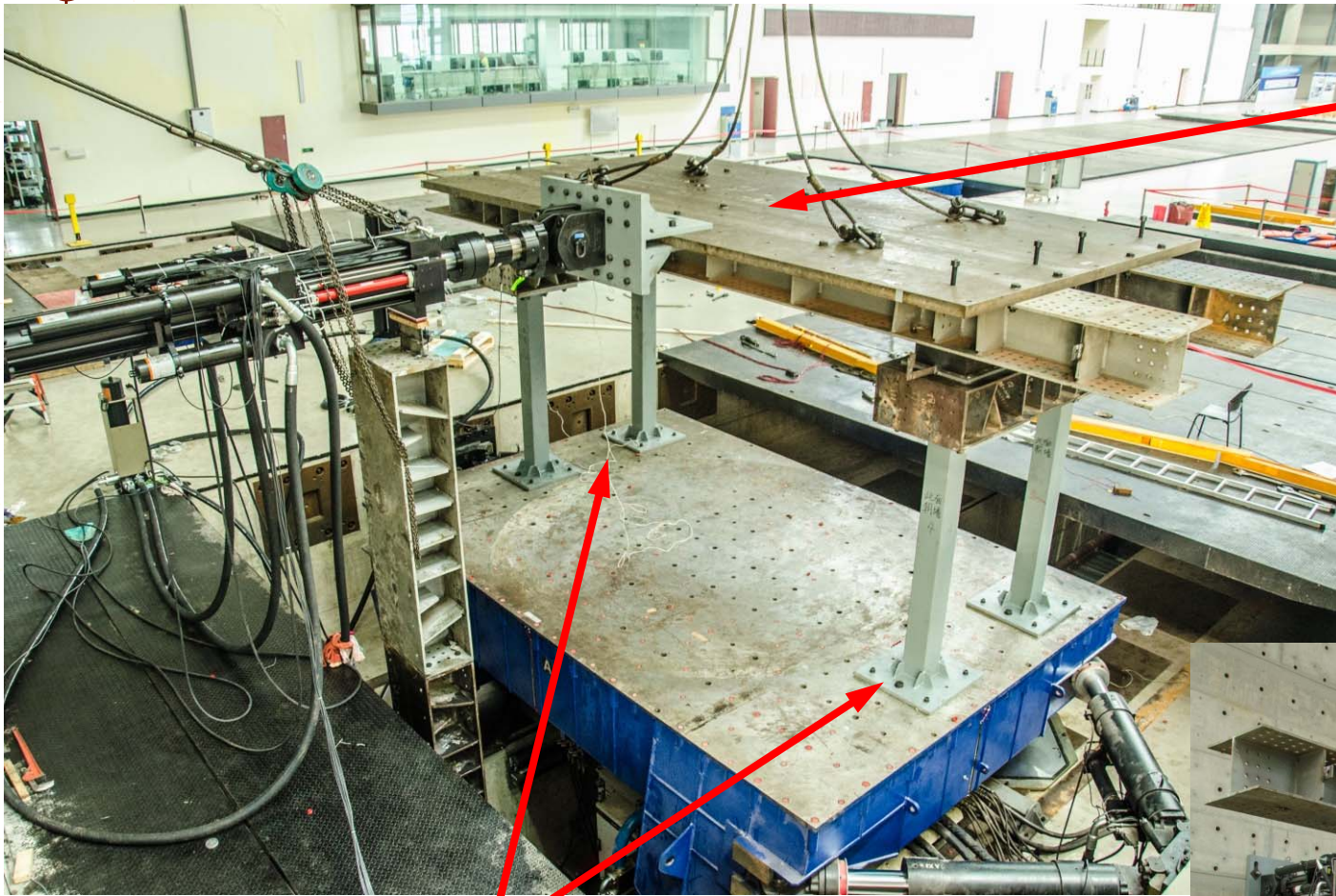
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Hybrid Model Development

experimental bridge
with partial bridge deck
weight

Remaining
numerical
mass

ExpBridge
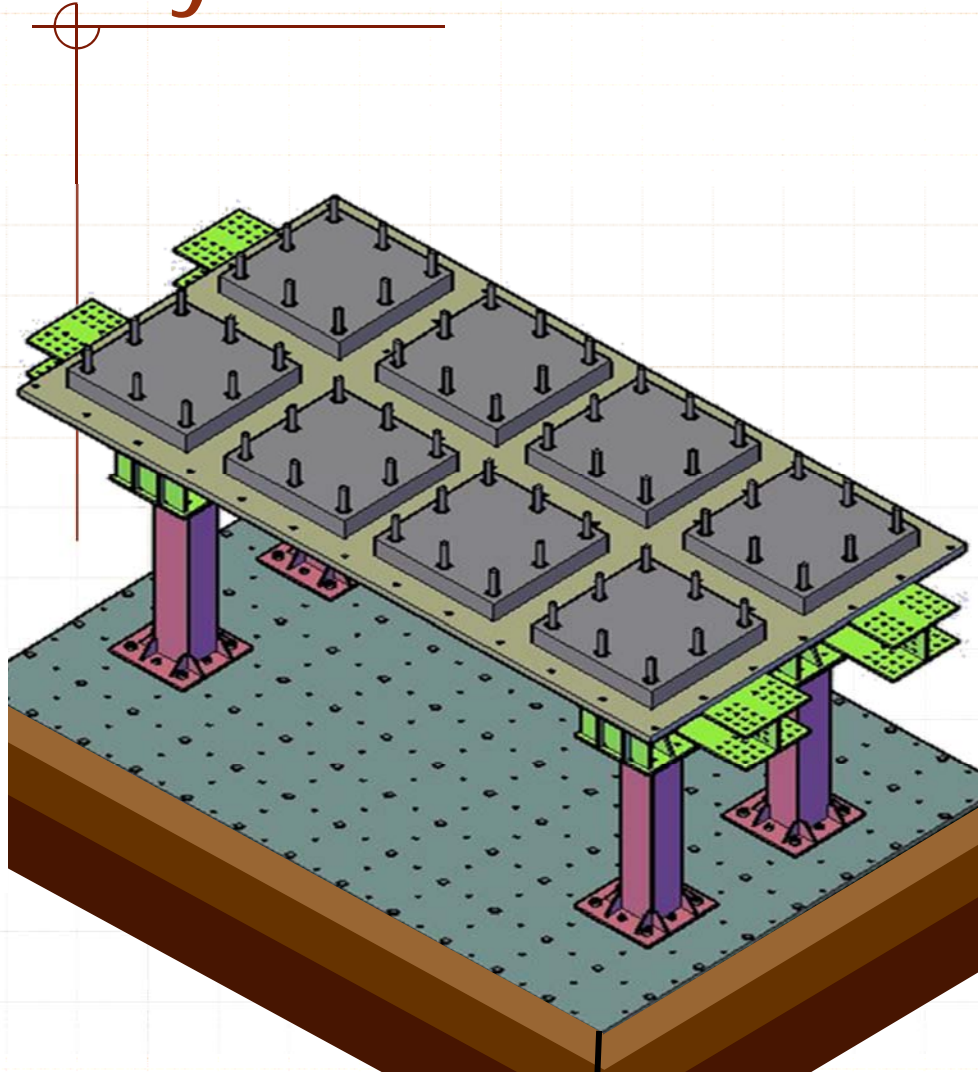
Soil

Actual Bridge Configuration
(with foundation + soil)

Simplified Hybrid OpenSees
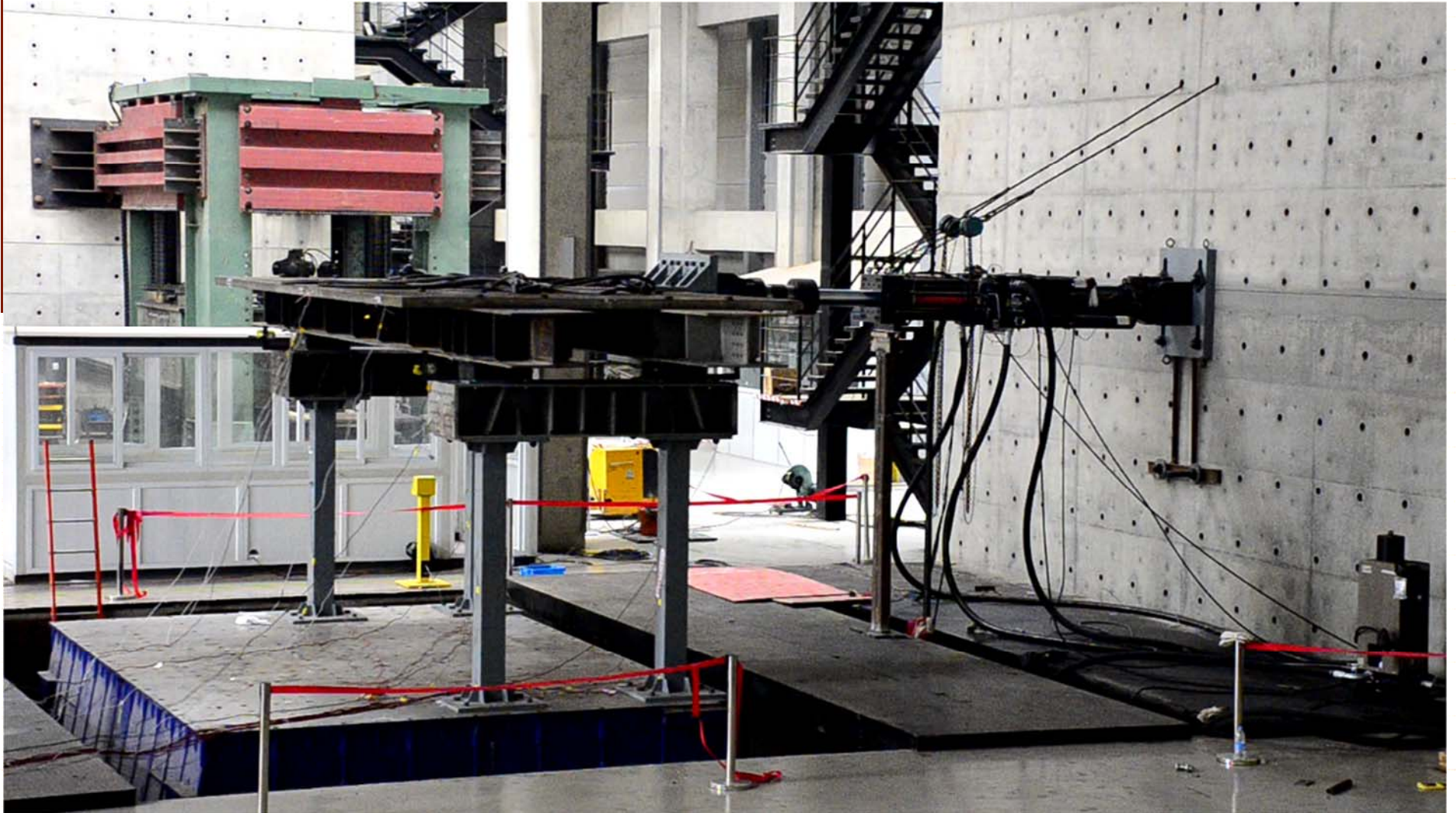**Model of Bridge (Stage 2)**

Experimental Setup

Partial-weight bridge deck

Using table observer to get shear forces at bottom of columns (load cells would be better)
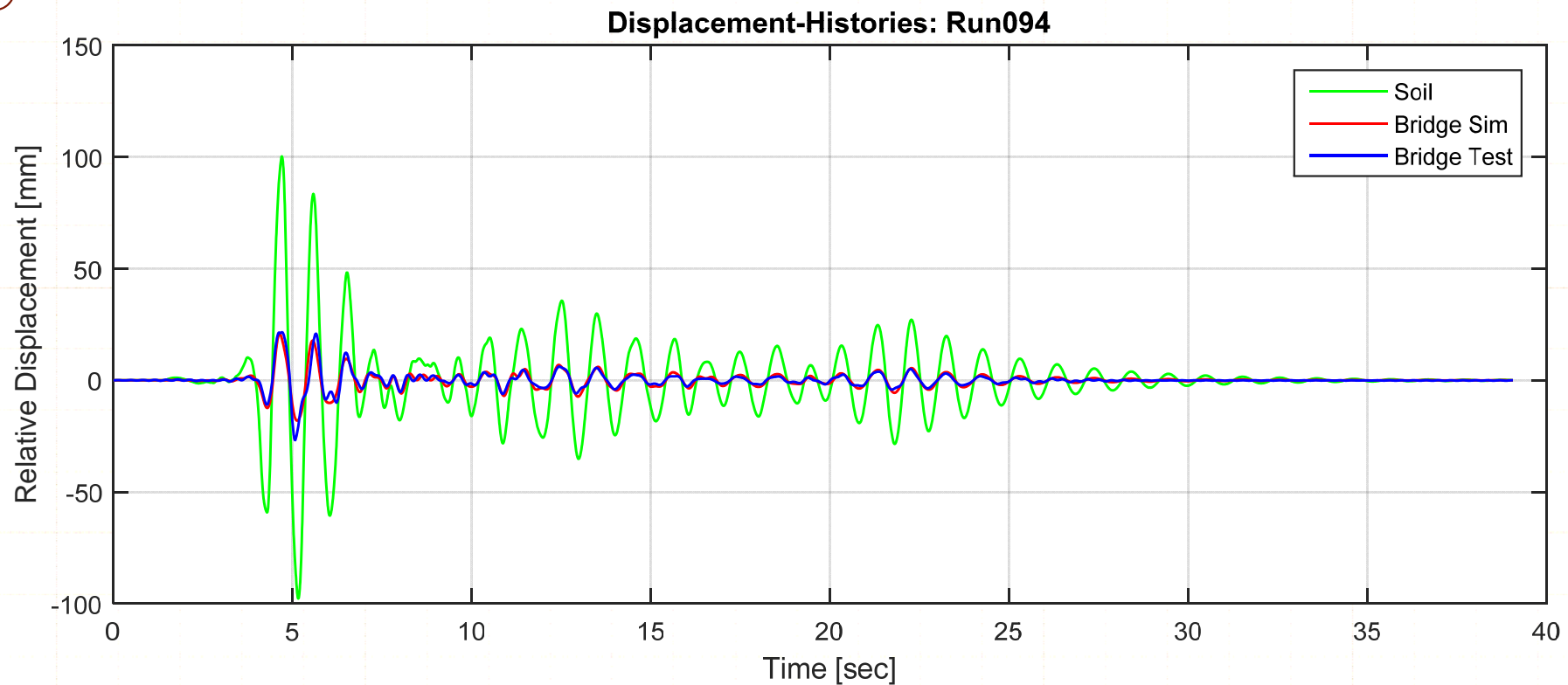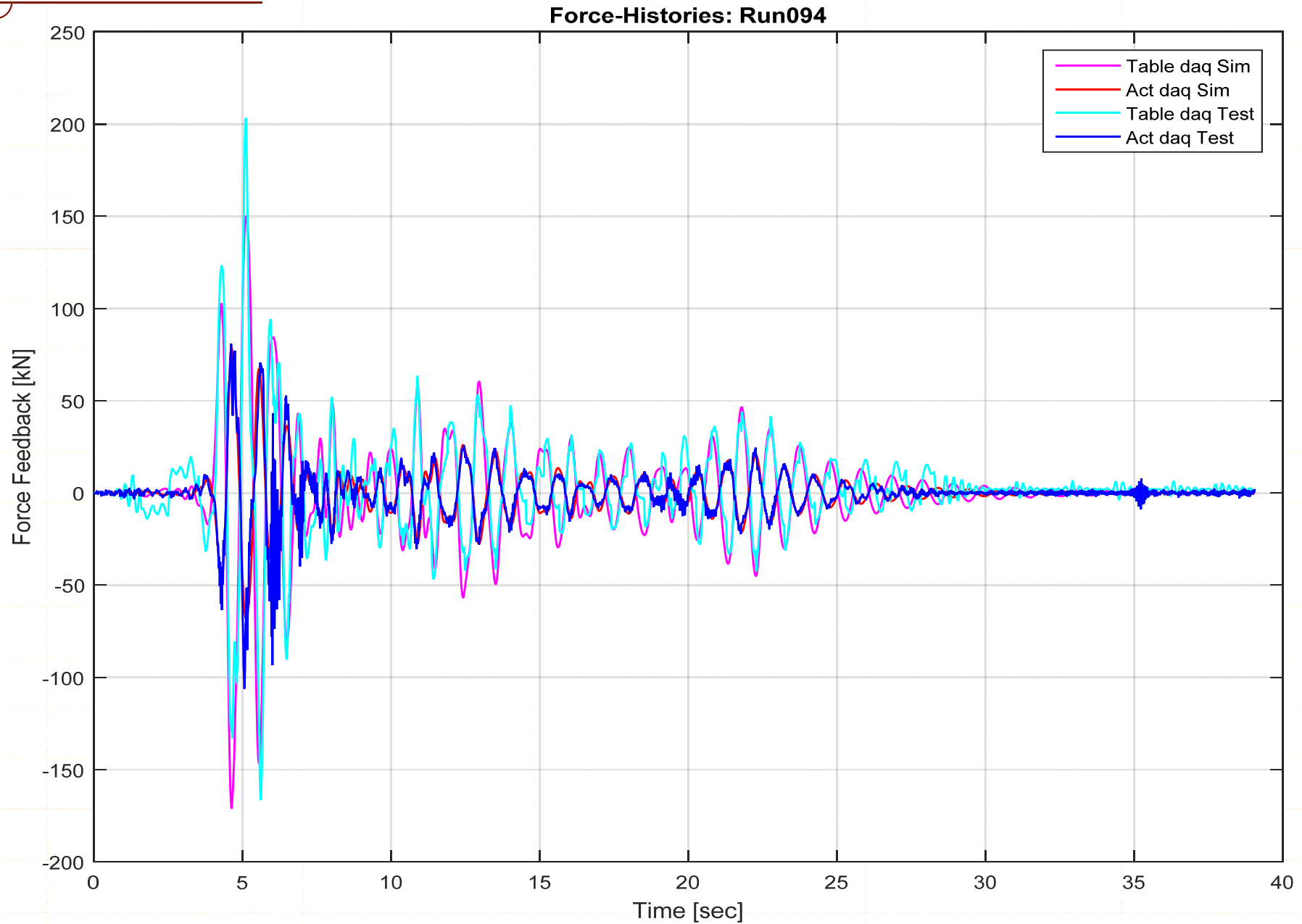
Movie of Test
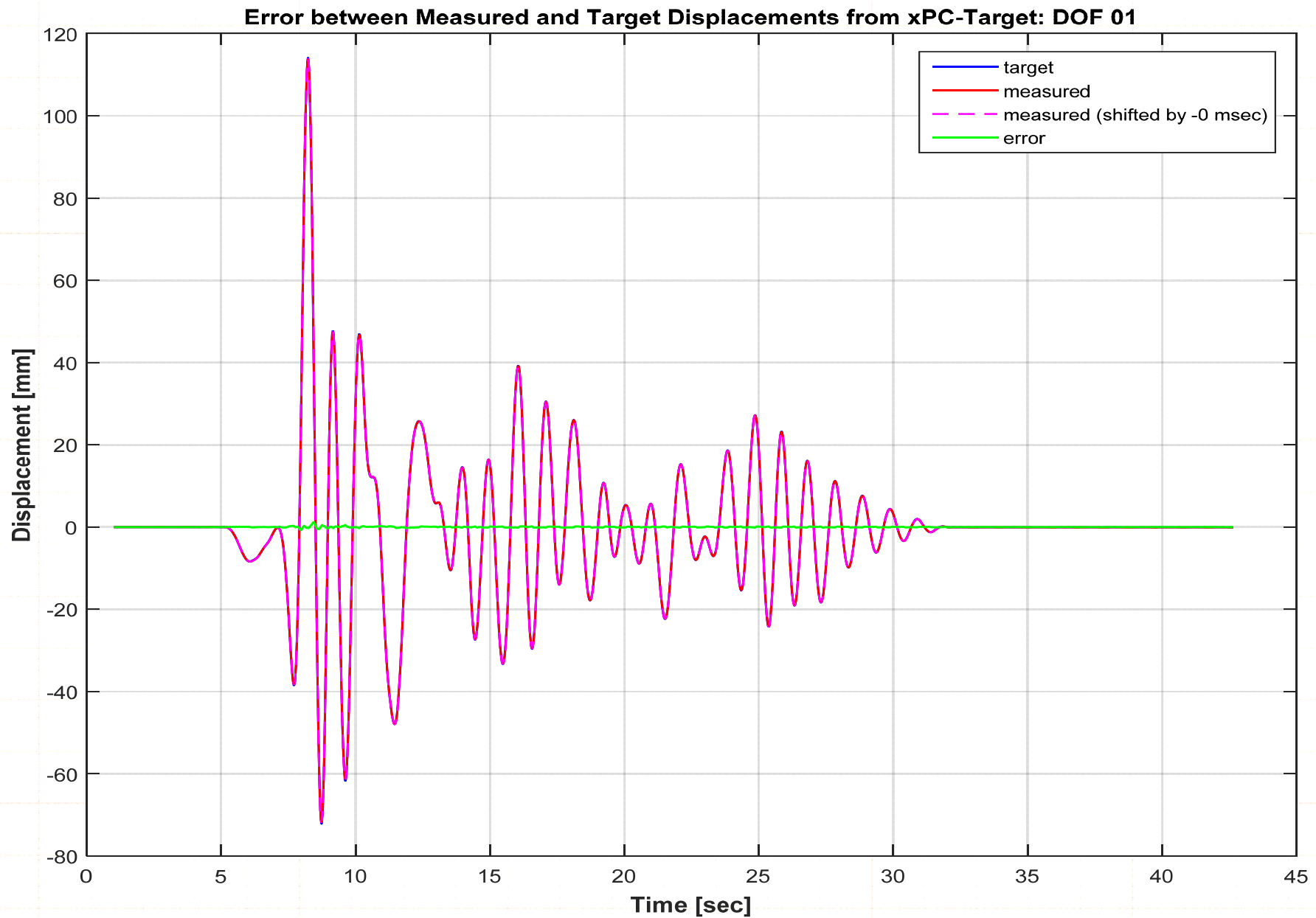
Displ. Response Comparison

Displacement-Histories: Run094

- ✦ **Accuracy is assessed using**
  - FFTs of tracking error
  - Tracking Indicator (by Mercan and Ricles)
  - RMS Error histories
  - Comparison with purely numerical simulation
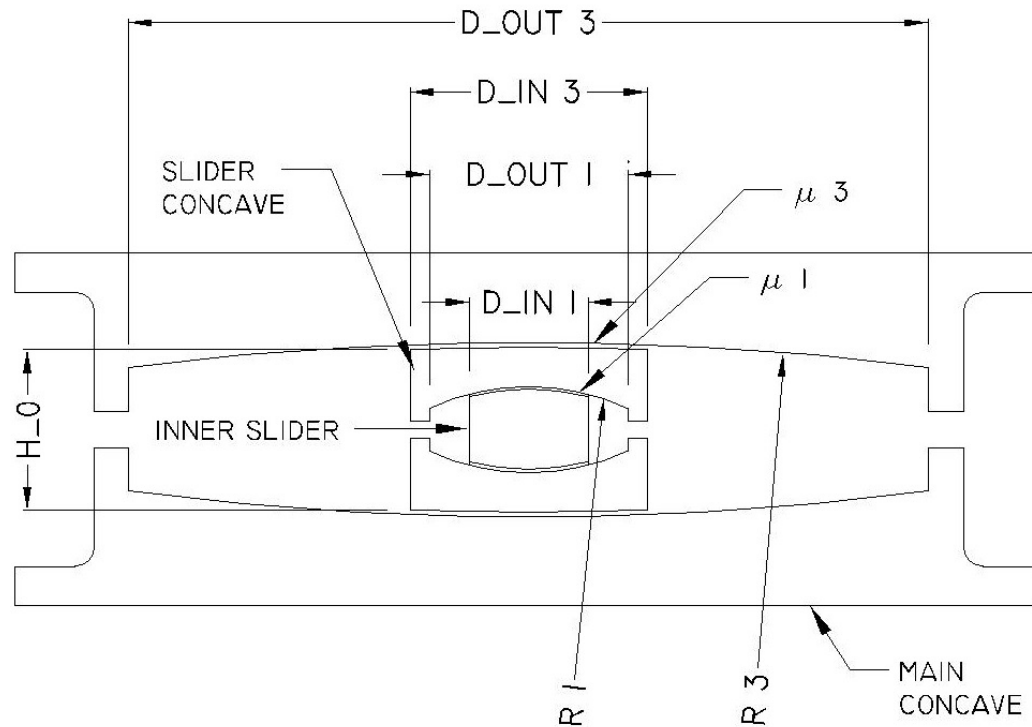
Force Response Comparison

Force-Histories: Run094

Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 01

Building Application

Triple Friction Pendulum Bearings

L1 (in.)	L2 (in.)	L3 (in.)
2.175	17.17	17.17

T1 (s)	T2 (s)	T3 (s)
0.67	1.41	1.87

	Inner sliding surfaces	Outer sliding surfaces
Dish radius (inch)	3	18.64
Height (inch)	1.65	2.94
Outer diameter (inch)	2.60	9
Inner diameter (inch)	1.75	3

Analytical Substructure Parameters

Experimental
Substructures
(with TP isolation
bearings)

Analytical
Substructures

Analytical
Substructures

Experimental
Substructures
(with TP isolation
bearings)
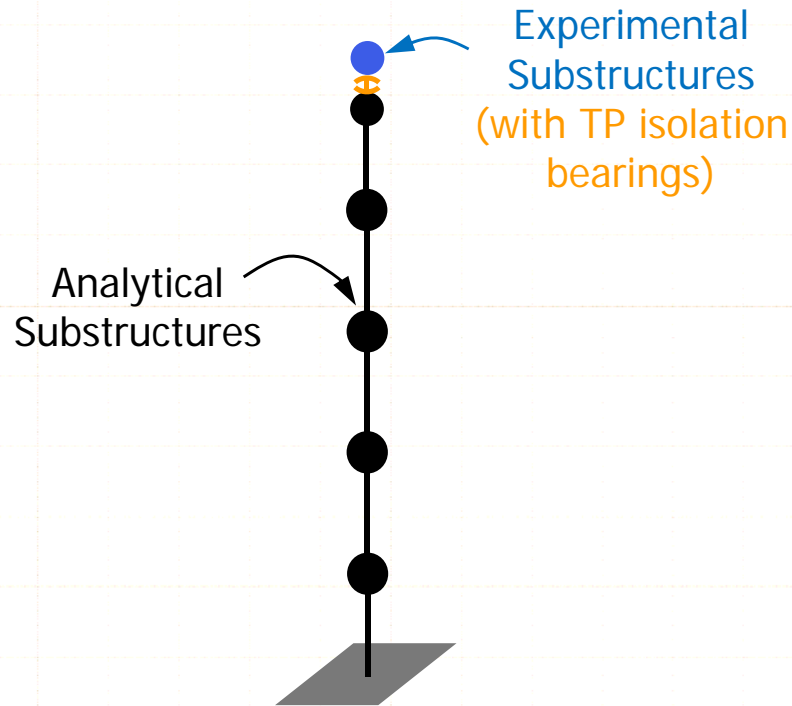
<u>15-DOF Shear Building</u>

$W_{tmd} = 53$ kip

$W_{bldg} = 450$ kip

$f_{x1} = 1$ Hz

$f_{y1} = 1.25$ Hz

$f_{z1} = 9.8$ Hz
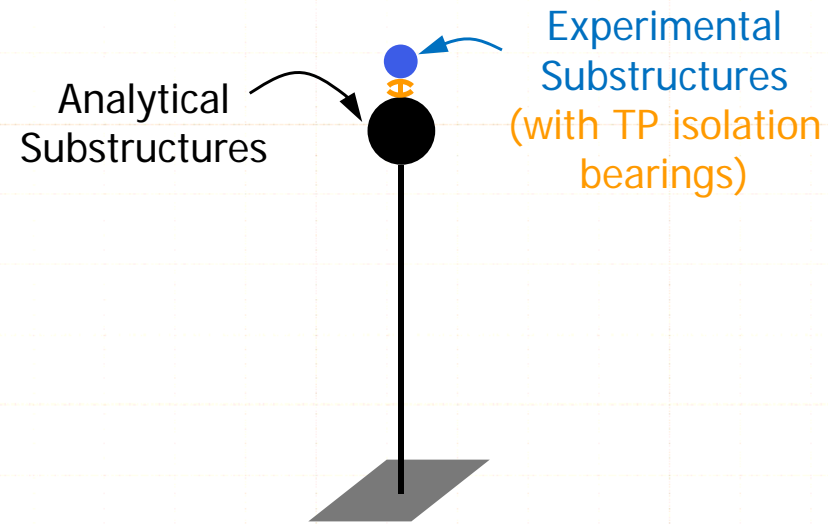
<u>3-DOF Equivalent Model</u>

$W_{tmd} = 53$ kip

$W_{bldg} = 0.886*450$ kip

$f_{x1} = 1$ Hz

$f_{y1} = 1.25$ Hz

$f_{z1} = 11$ Hz

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Movie of Test

Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 01

Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 02

Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 03

Tracking Indicator

Tracking Indicator from xPC-Target: DOF 01
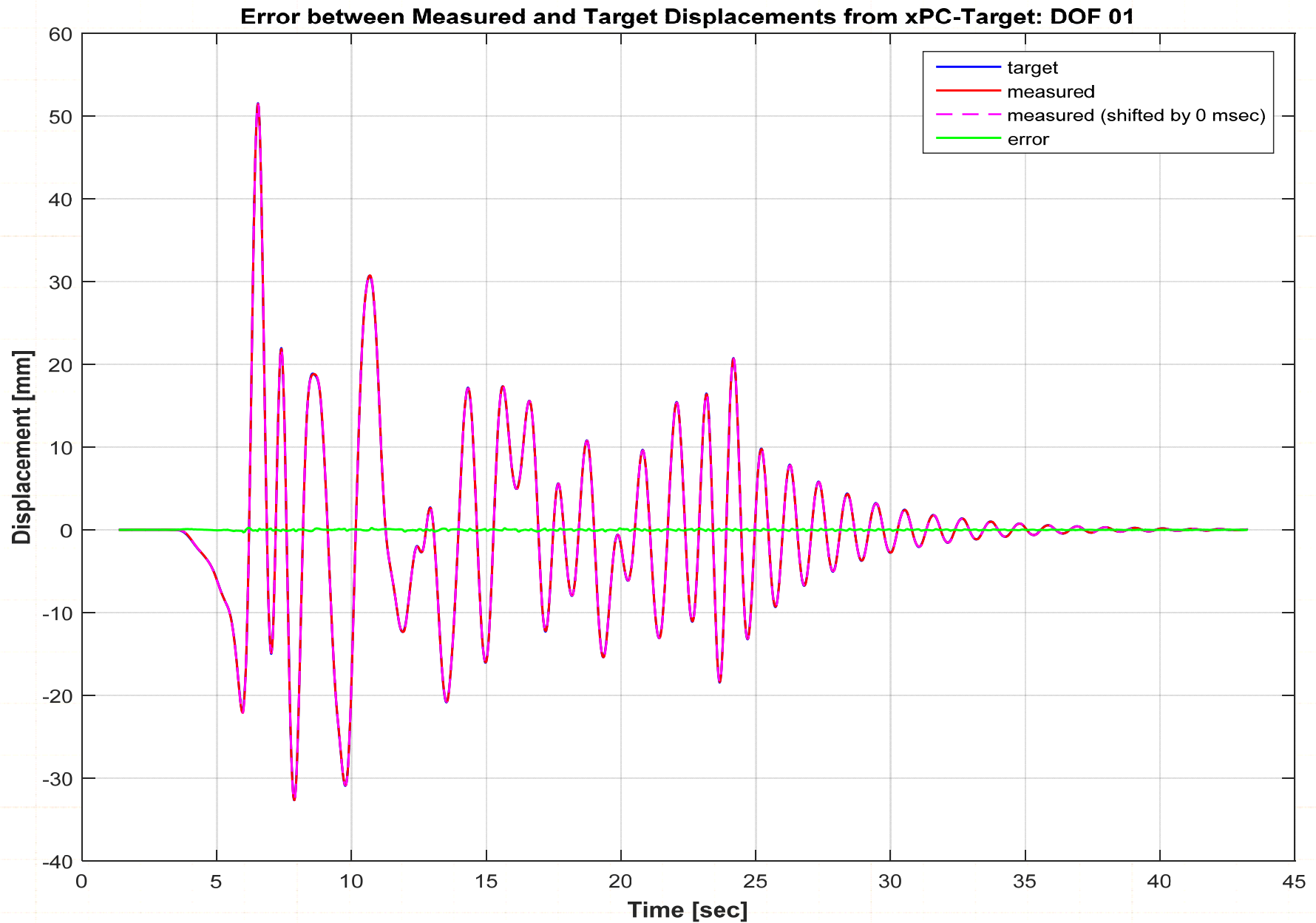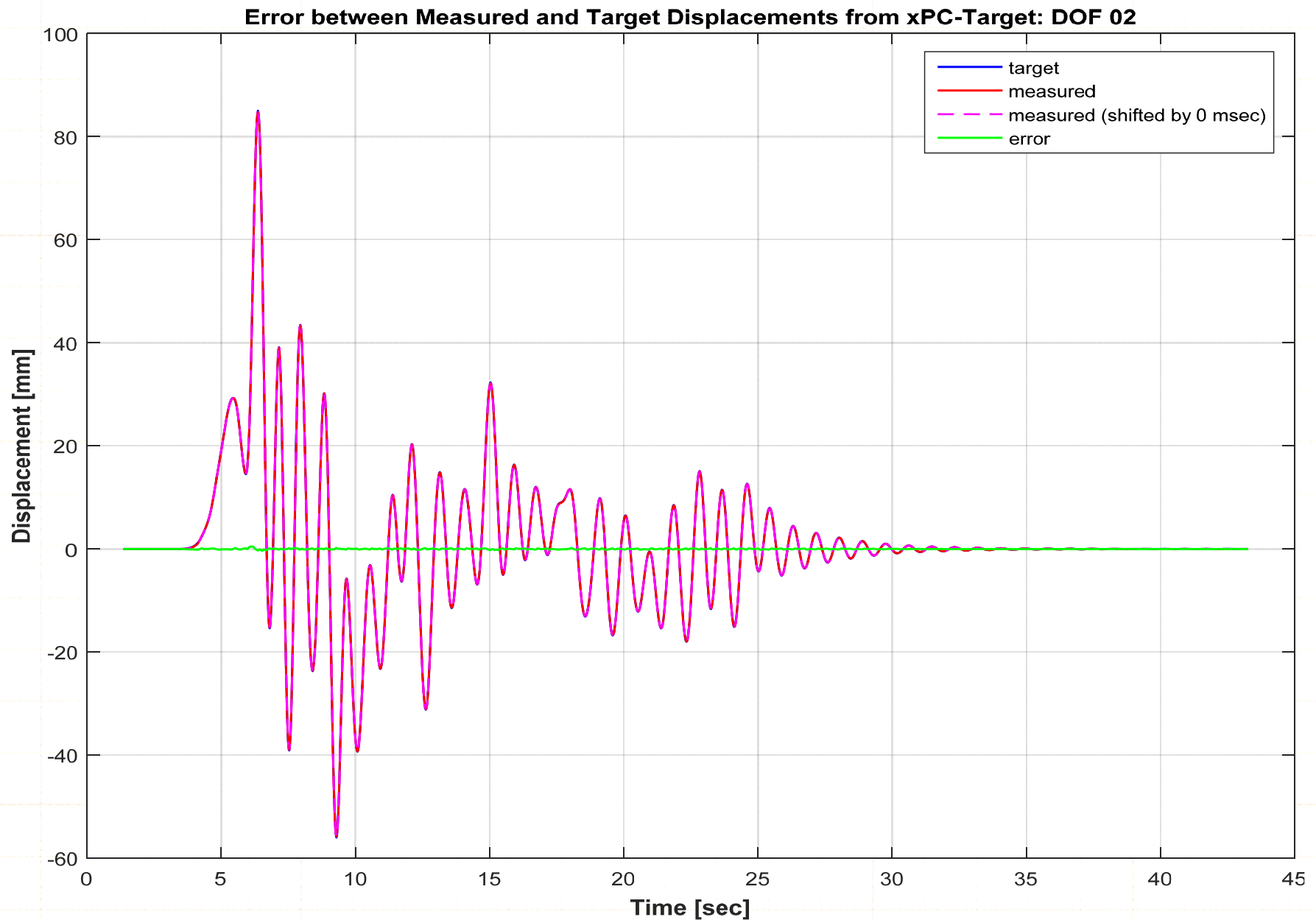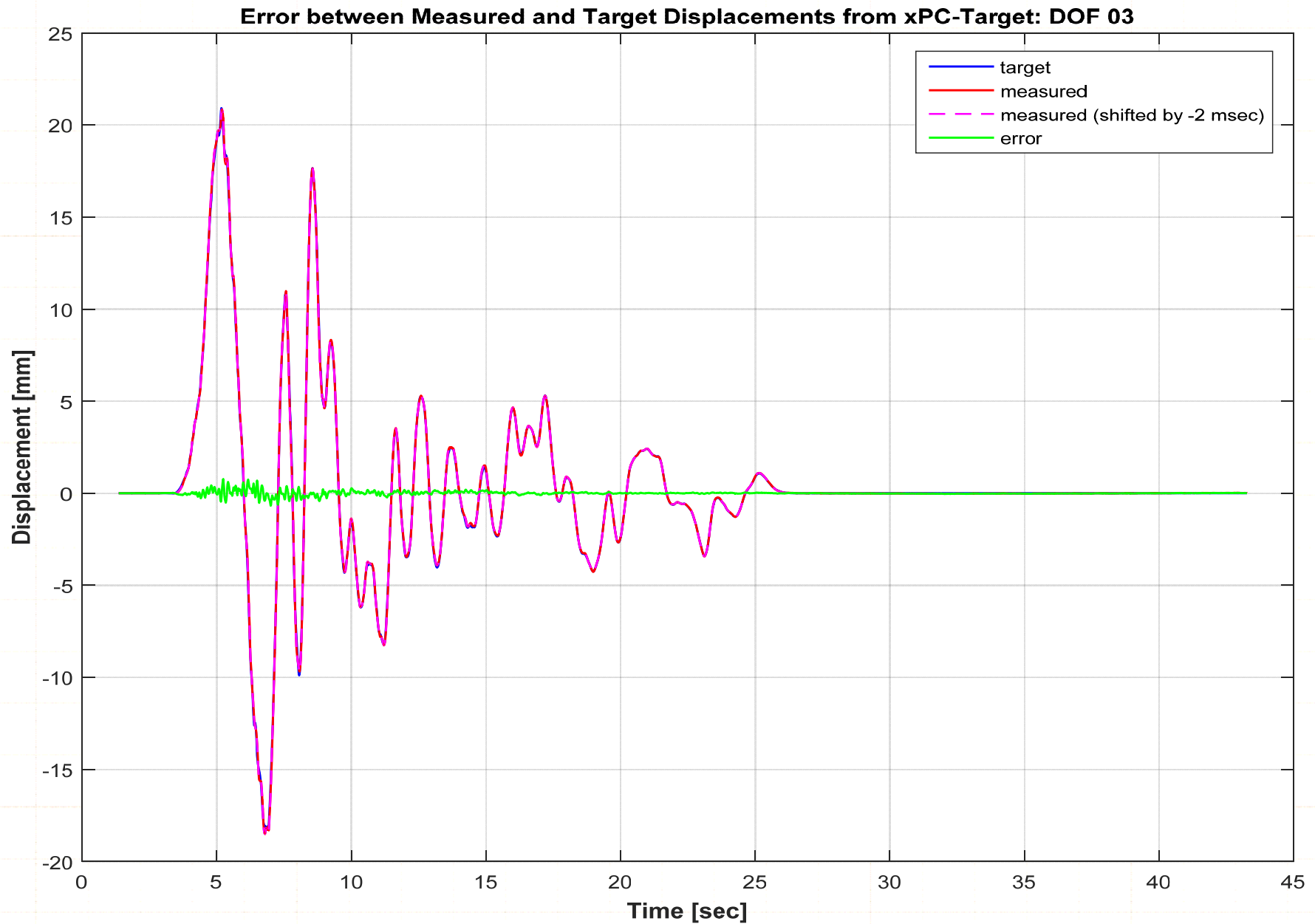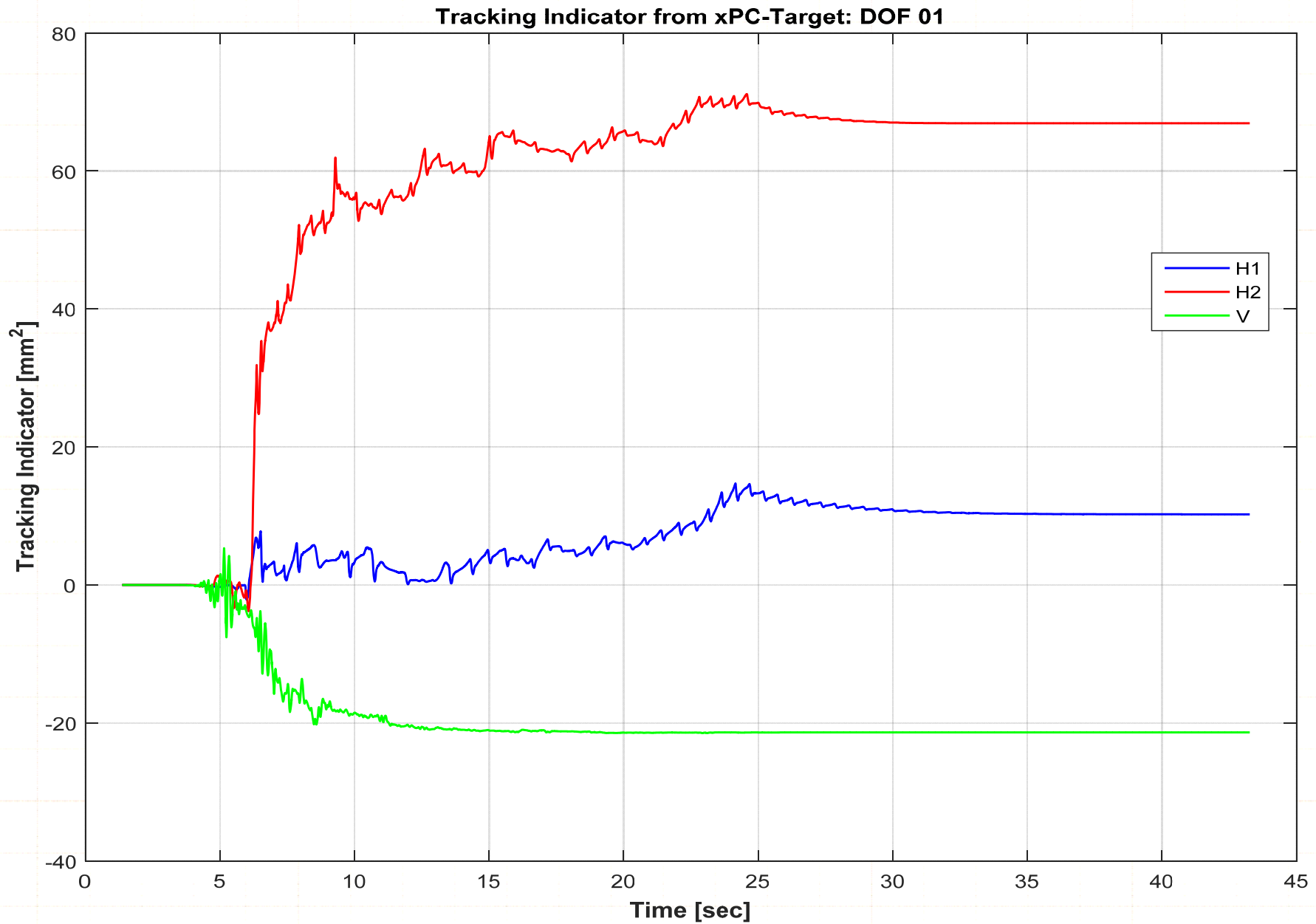
Summary & Conclusions

- Ability to drive a MDOF shake table through a finite element model

- Shake table platform can thus represent a floor or the roof of a building, the motion on top of a bridge column, or the ground surface on top of a soil domain

- Performed large-scale RTHS where a shake table is combined with a dynamic structural actuator applied to a bridge

- Ability to perform parameter studies

Summary & Conclusions

- Use whenever the dynamics of the test specimen significantly affects the response of the supporting structure or soil and, therefore, alters the required input to the shake table as testing progresses

- ATS delay compensator worked very well

- Need to further investigate sensor noise reduction methods to improve feedback signals (look into Kalman filters)

Questions?
Thank you!

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