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MDOF Hybrid Shake Table Testing of Response Modification Devices

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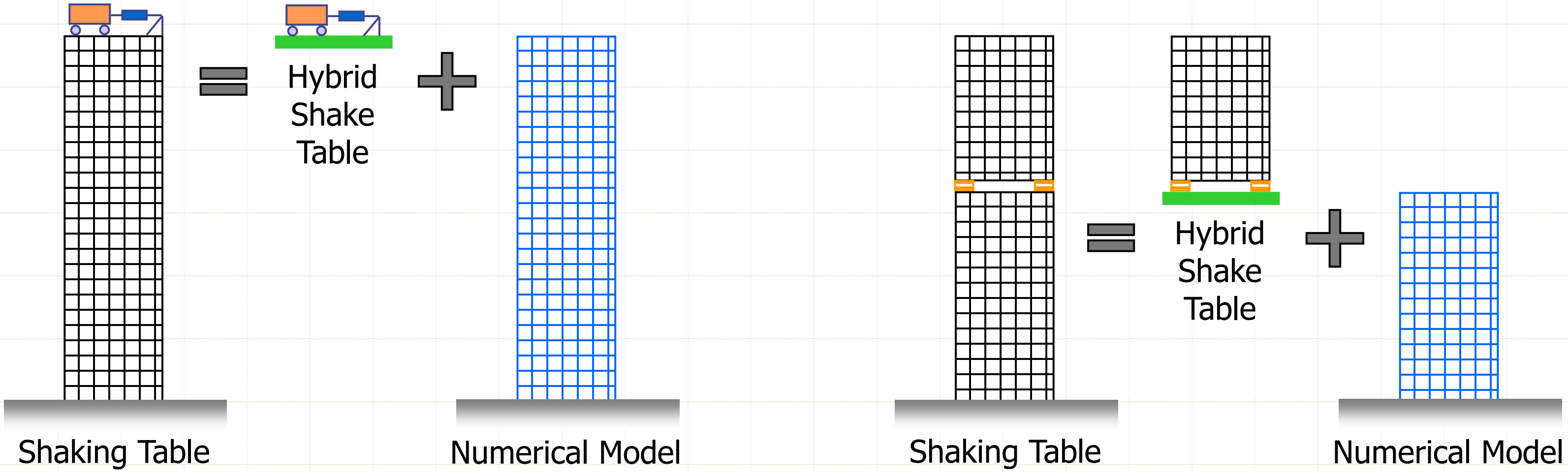
Outline of Presentation

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

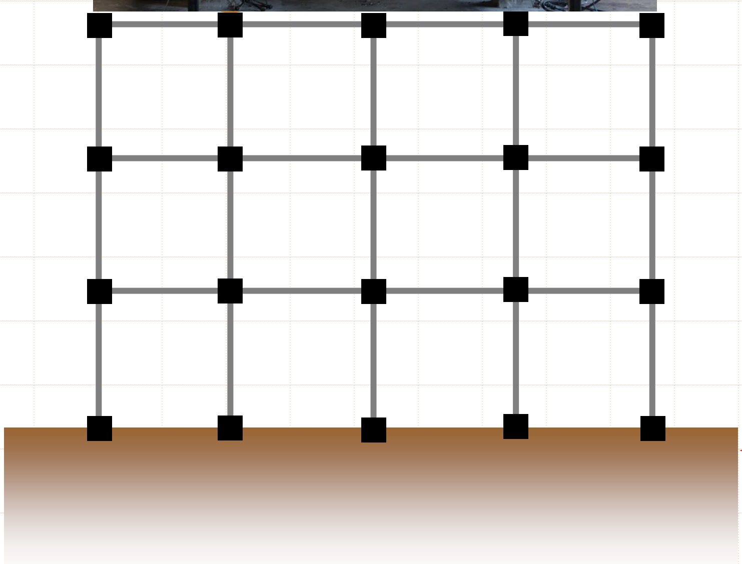
Motivation

- 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

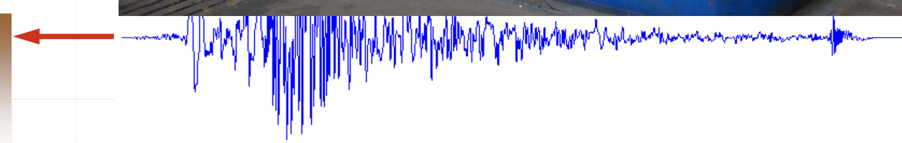


Hybrid Shake Table Testing

$$\mathbf{M}\cdot\ddot{\mathbf{u}} + \mathbf{C}\cdot\dot{\mathbf{u}} + \mathbf{P}_r\left(\mathbf{u},\dot{\mathbf{u}},\ddot{\mathbf{u}}\right) = \mathbf{P}(t)$$

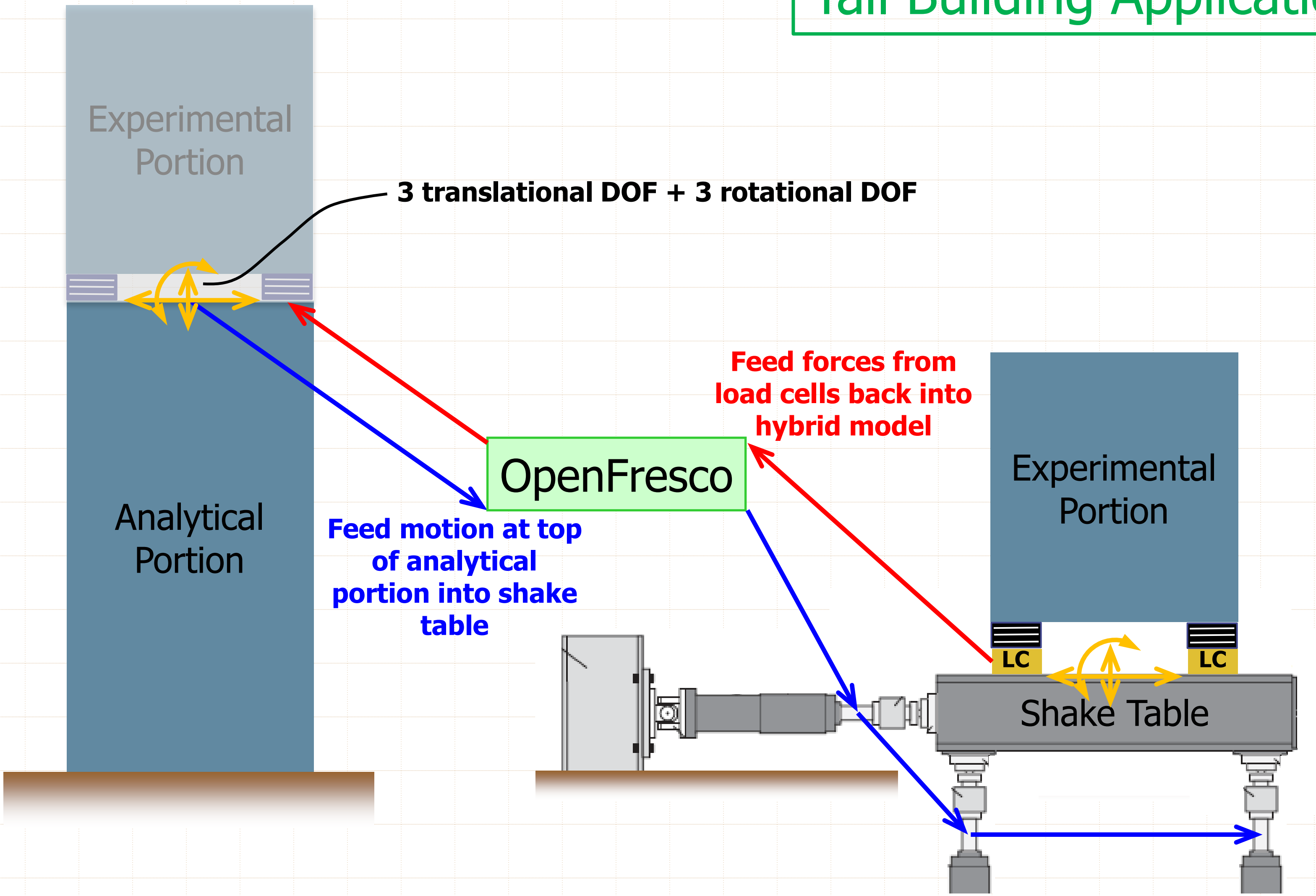


- Inertia
- Energy Dissipation
- Resistance



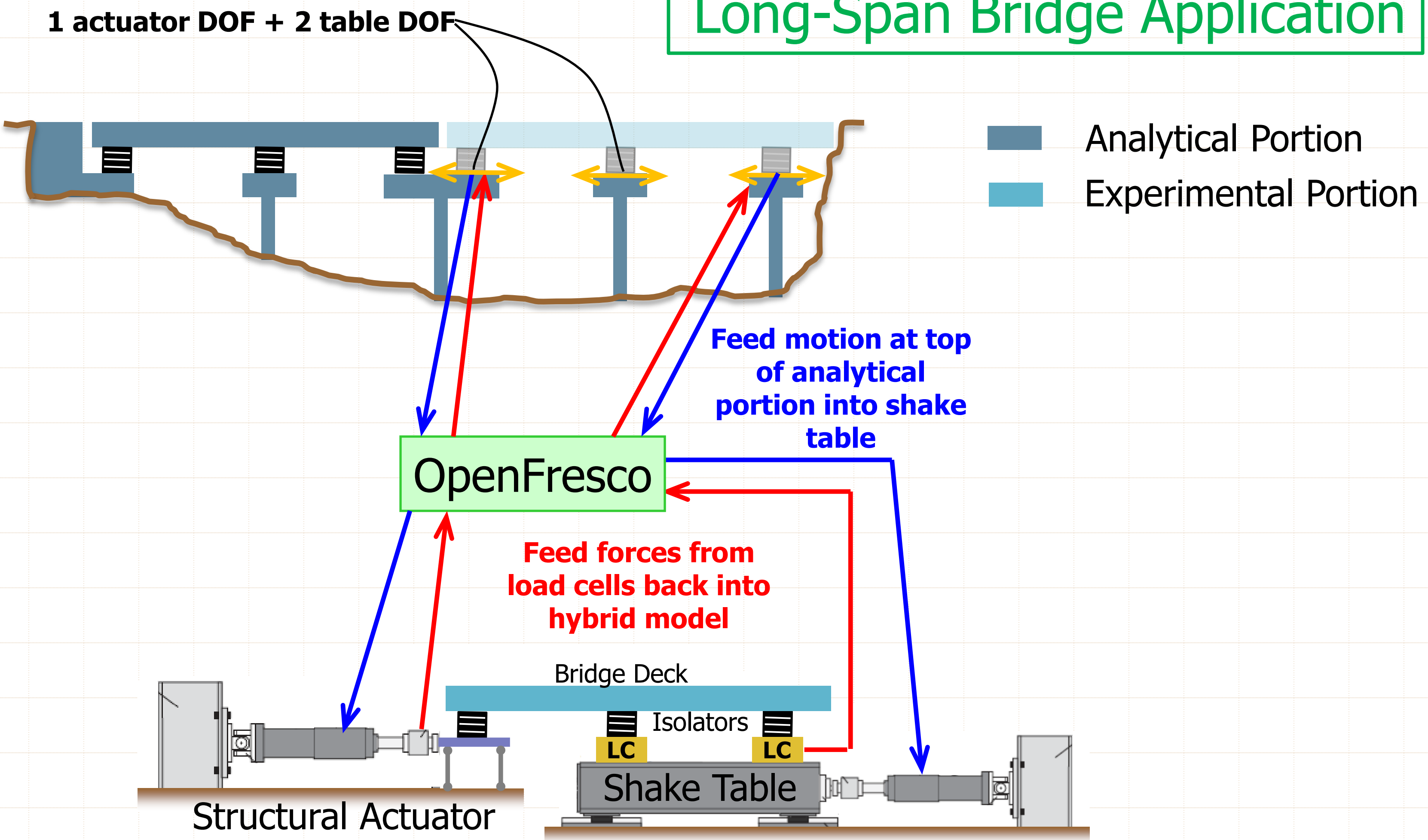
Hybrid Shake Table Configuration

Tall Building Application



Hybrid Shake Table Configuration

Long-Span Bridge Application



Equations of Motion

1. Slow test

$$\mathbf{M}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

2. Rapid test

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} - \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}^{E} - \mathbf{C}^{E}\dot{\mathbf{U}}_{i+1}^{E}$$

3. Real-time test

$$\mathbf{M}^{A}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}^{A}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{\mathbf{0},i+1}$$

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}$$

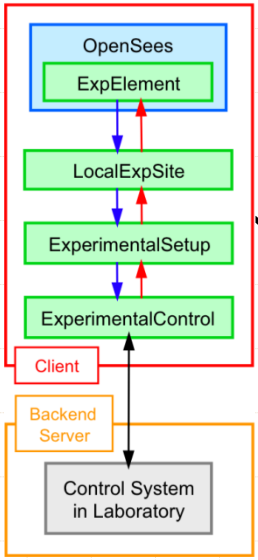
4. Smart shaking table test

$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{\mathbf{t},i+1}, \dot{\mathbf{U}}_{\mathbf{t},i+1}, \ddot{\mathbf{U}}_{\mathbf{t},i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{\mathbf{t},\,i+1}$$

Important Analysis Parameters

- OpenSees or OpenSeesSP as comp. driver
- Using AlphaOSGeneralized ($\rho_{inf} = 0$)
- Next time try KRAlphaExplicit method
- 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

OpenFresco Middleware

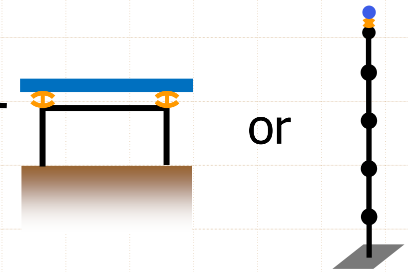
TCP/IP or SCRAMNetGT

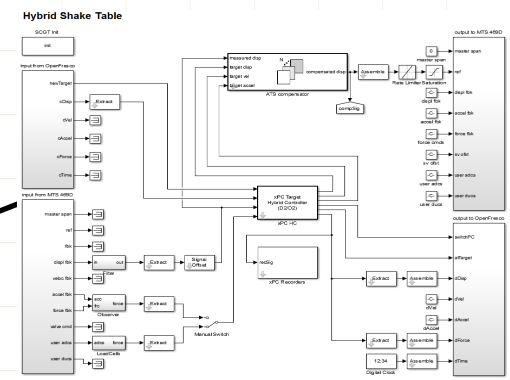
xPC-Target real-time Predictor-Corrector

SCRAMNetGT | SCRAMNetGT

MTS 469D Controller | MTS FlexTest Controller

Physical Specimen in Laboratory

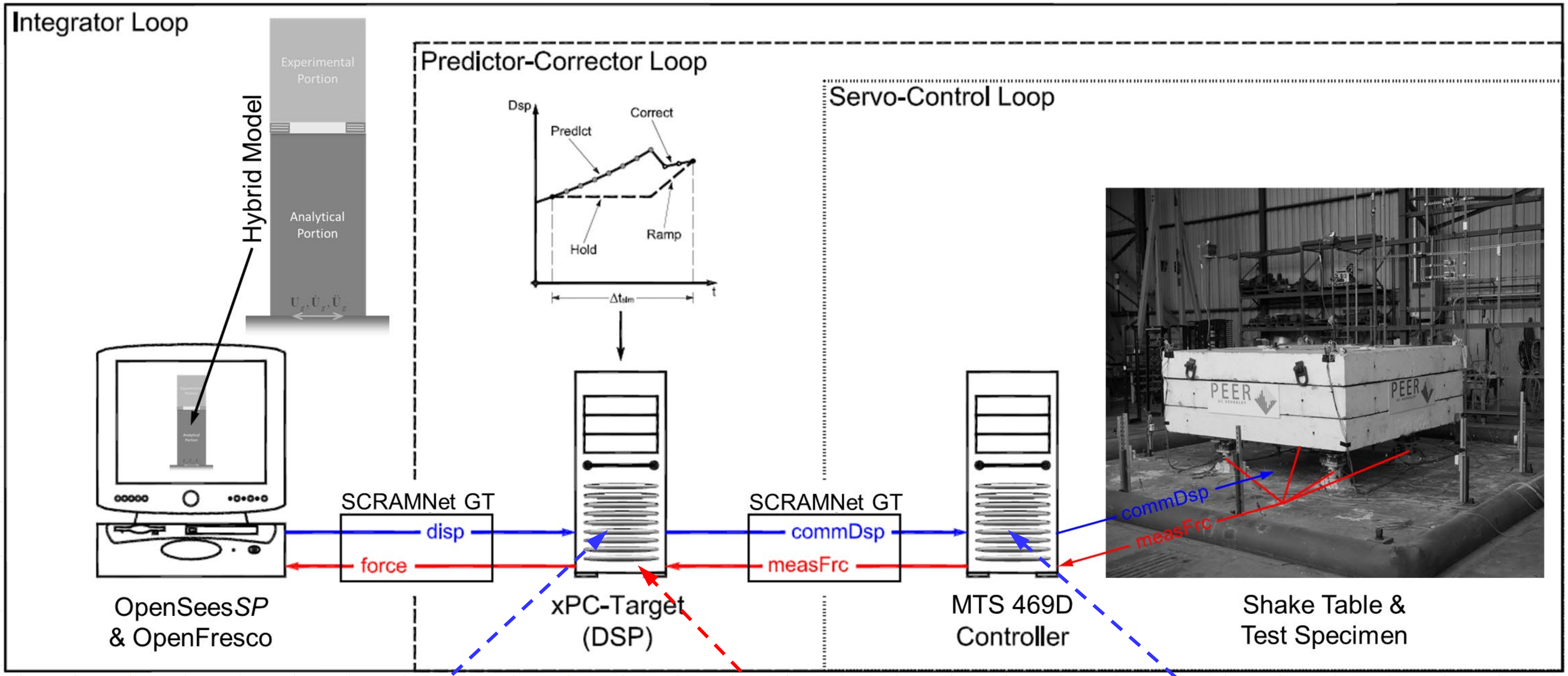




Improving Stability & Accuracy

- 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

Three-loop architecture



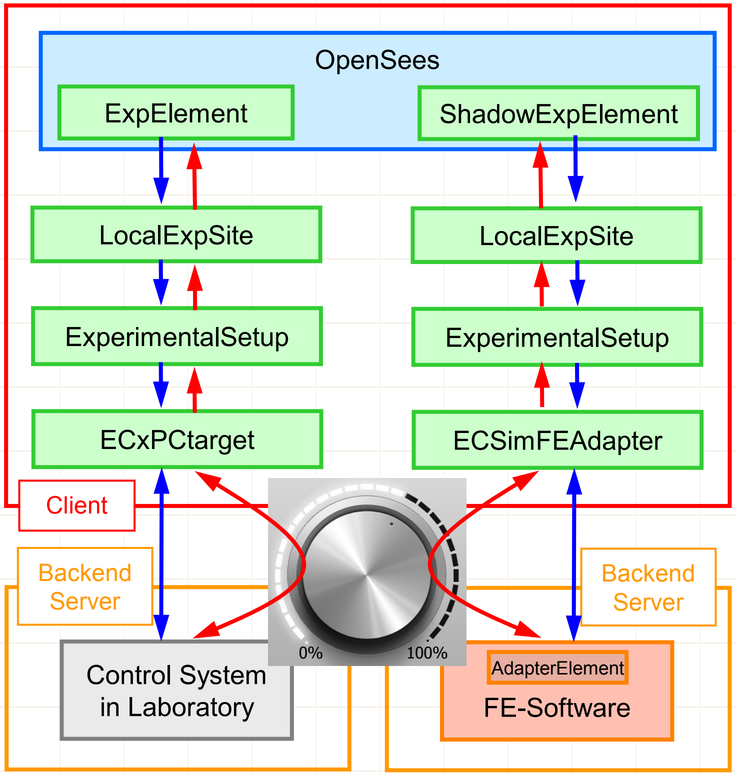
ATS delay compensator

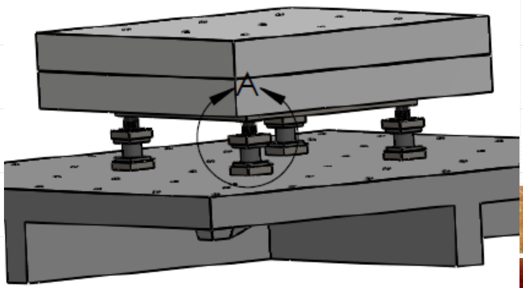
filtering & noise reduction

TVC or other adv. ctrl. & force balancing

Test Rehearsal

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

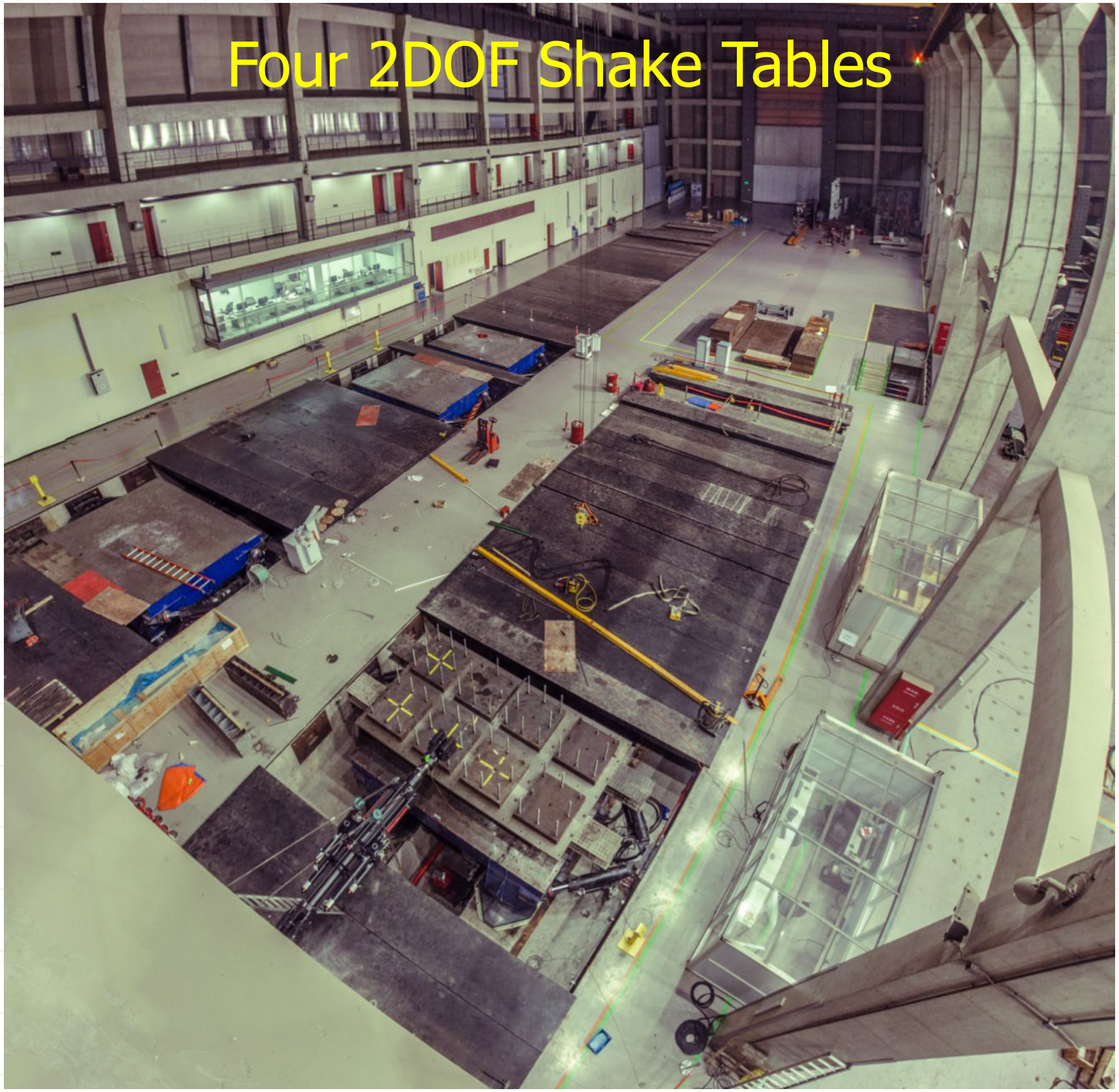




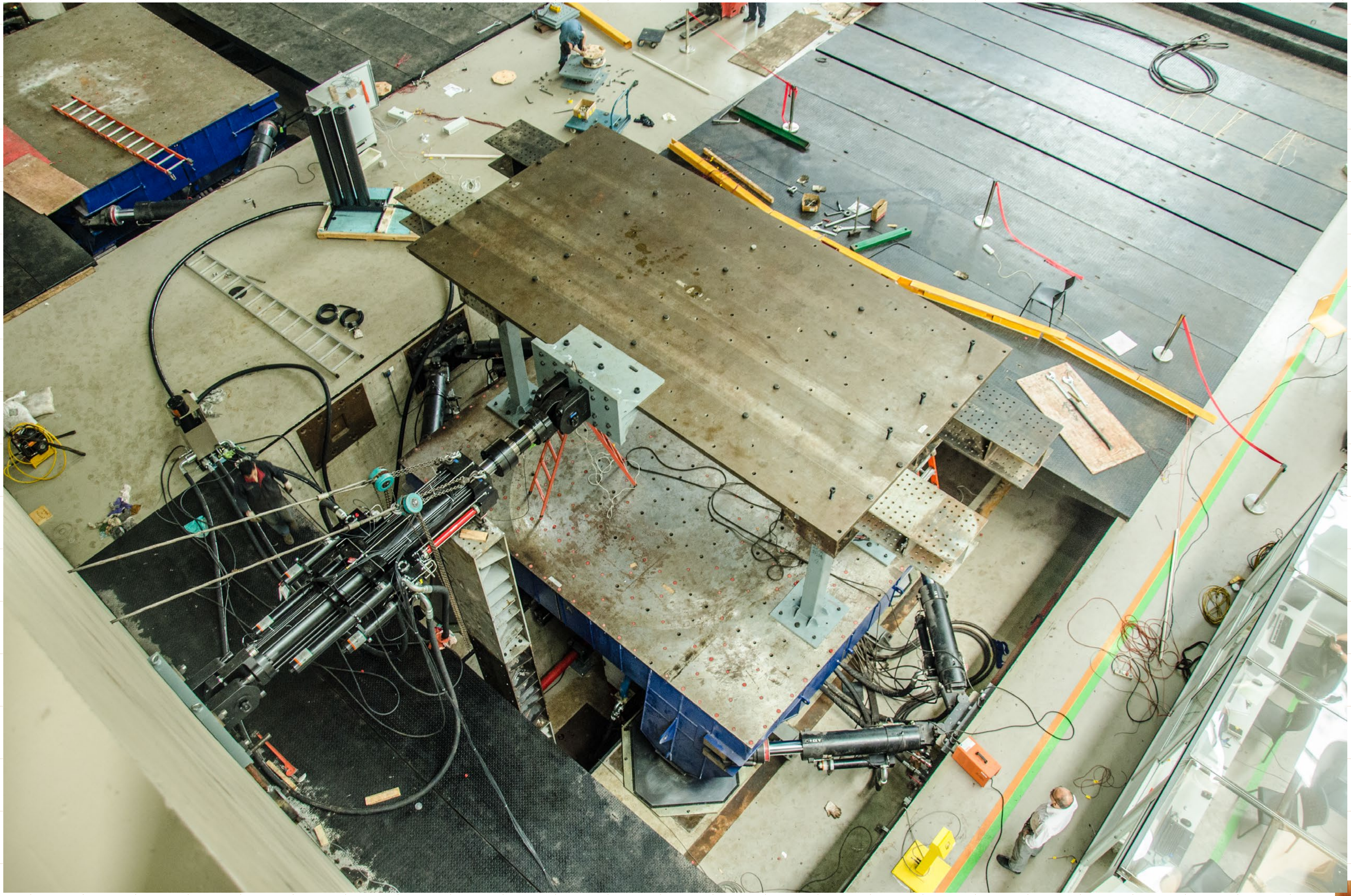
Safety Precautions

- 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

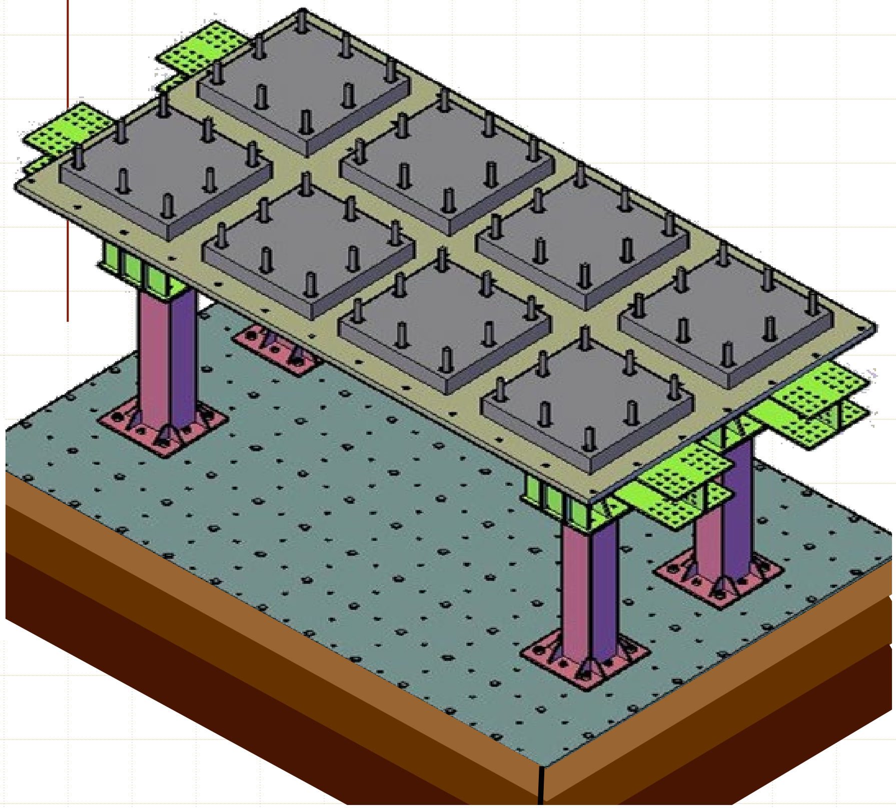
Bridge Application



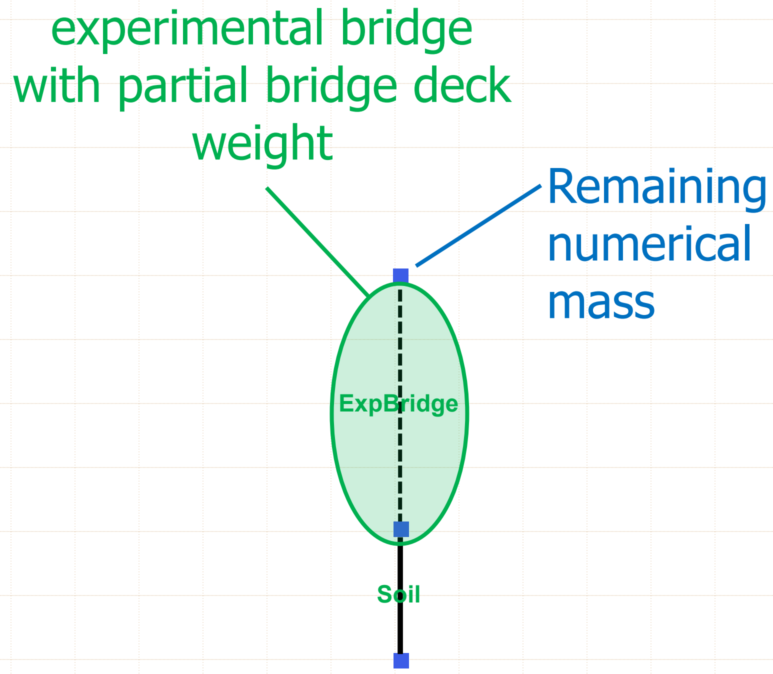
Shake Table + Structural Actuator



Hybrid Model Development

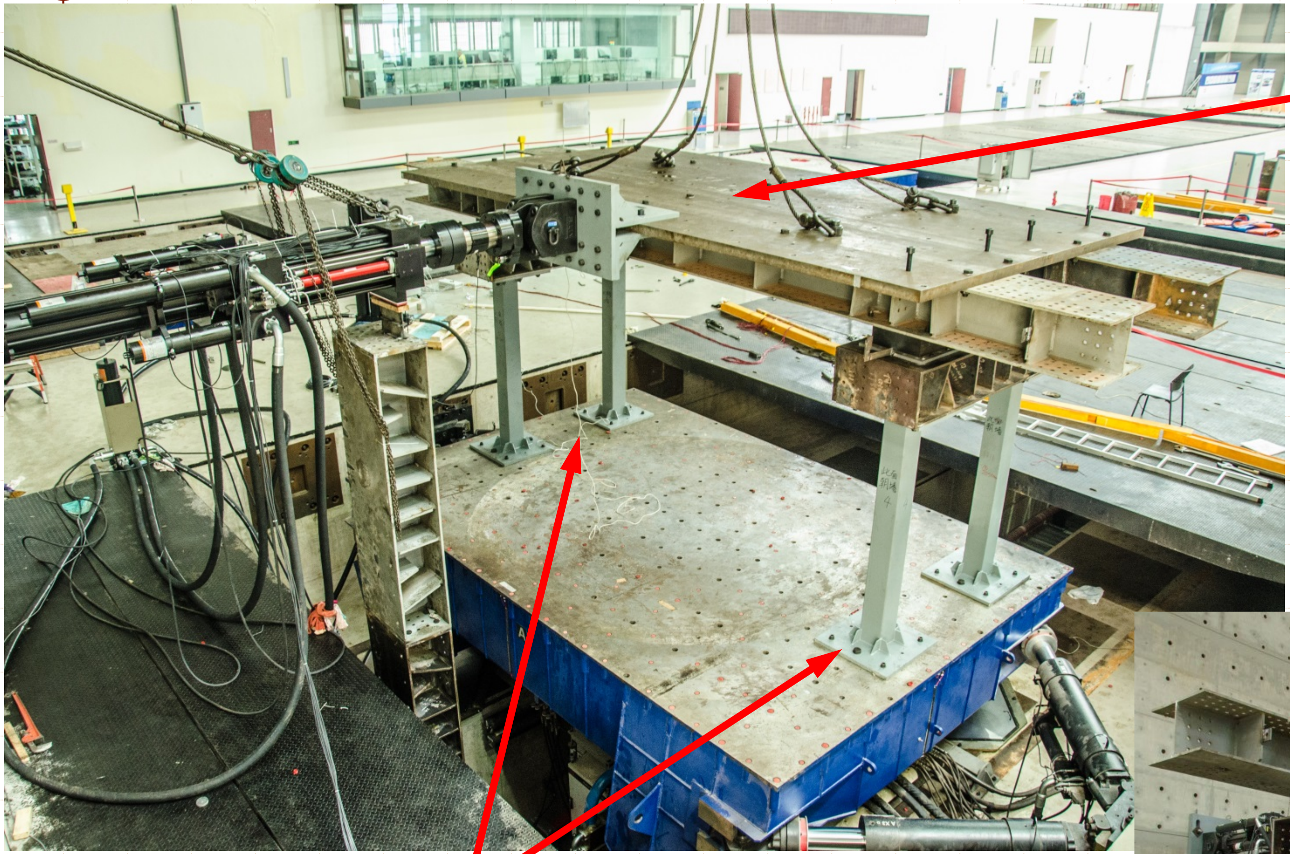


Actual Bridge Configuration (with foundation + soil)



Simplified Hybrid OpenSees Model of Bridge (Stage 2)

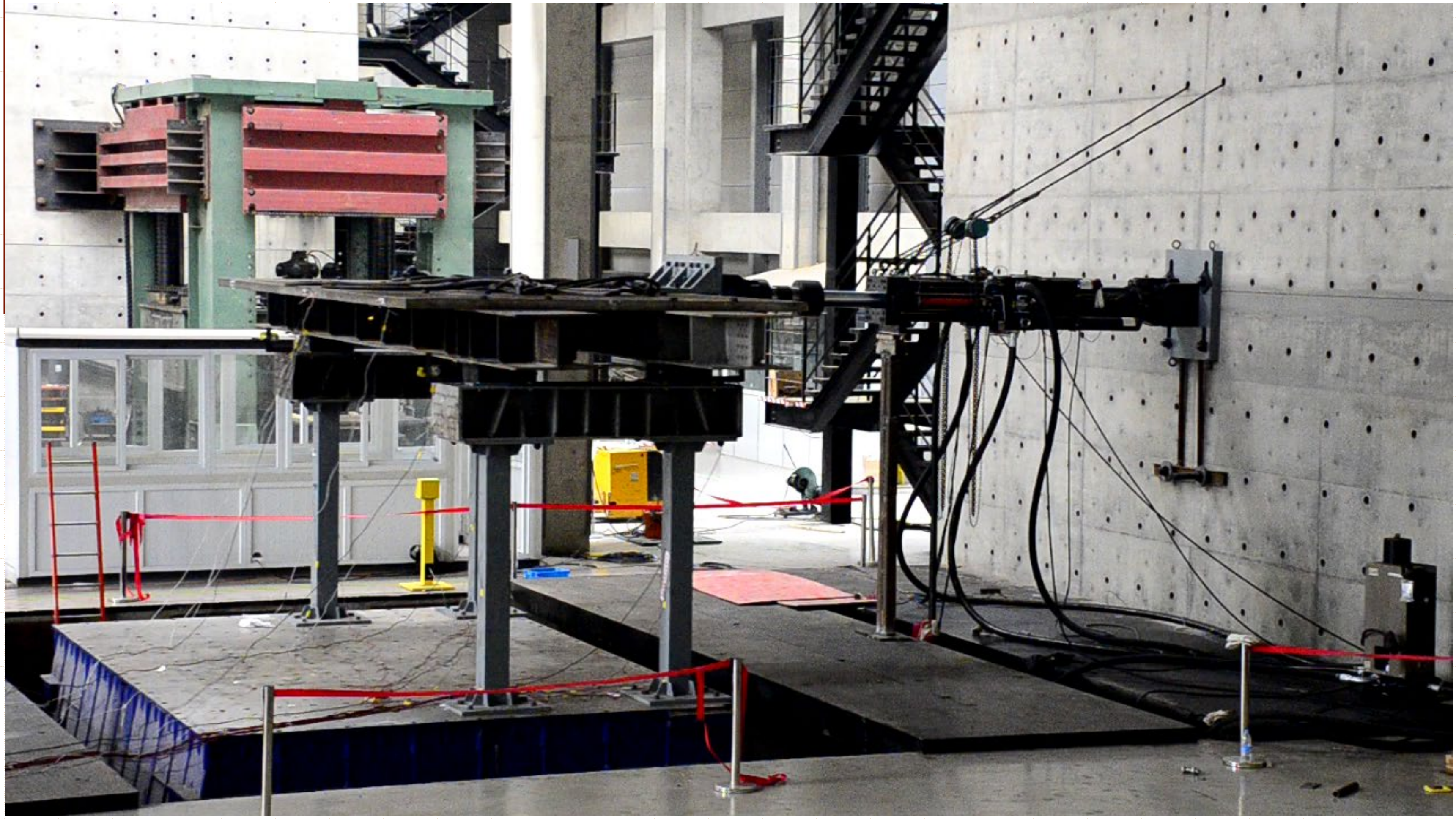
Experimental Setup



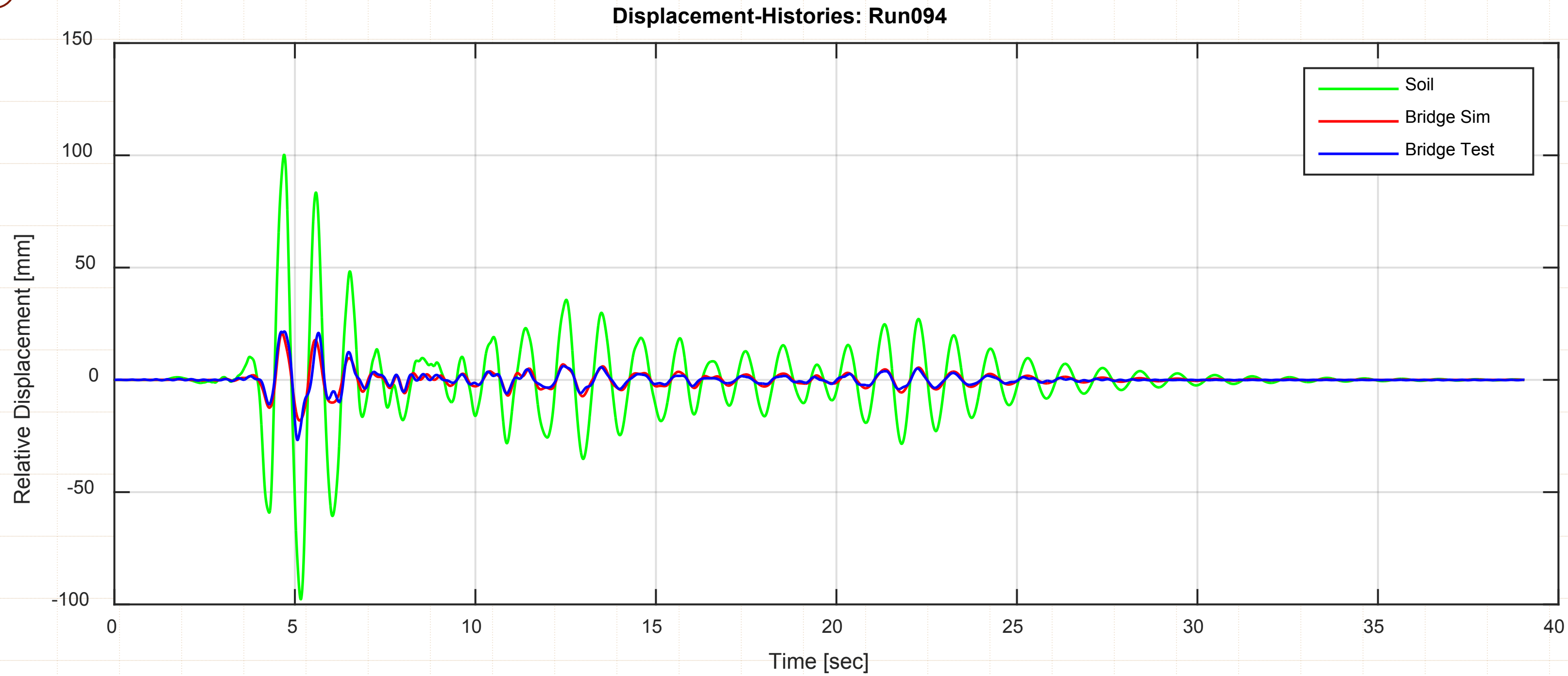
Partial-weight bridge deck

Using table observer to get shear forces at bottom of columns (load cells would be better)

Movie of Test

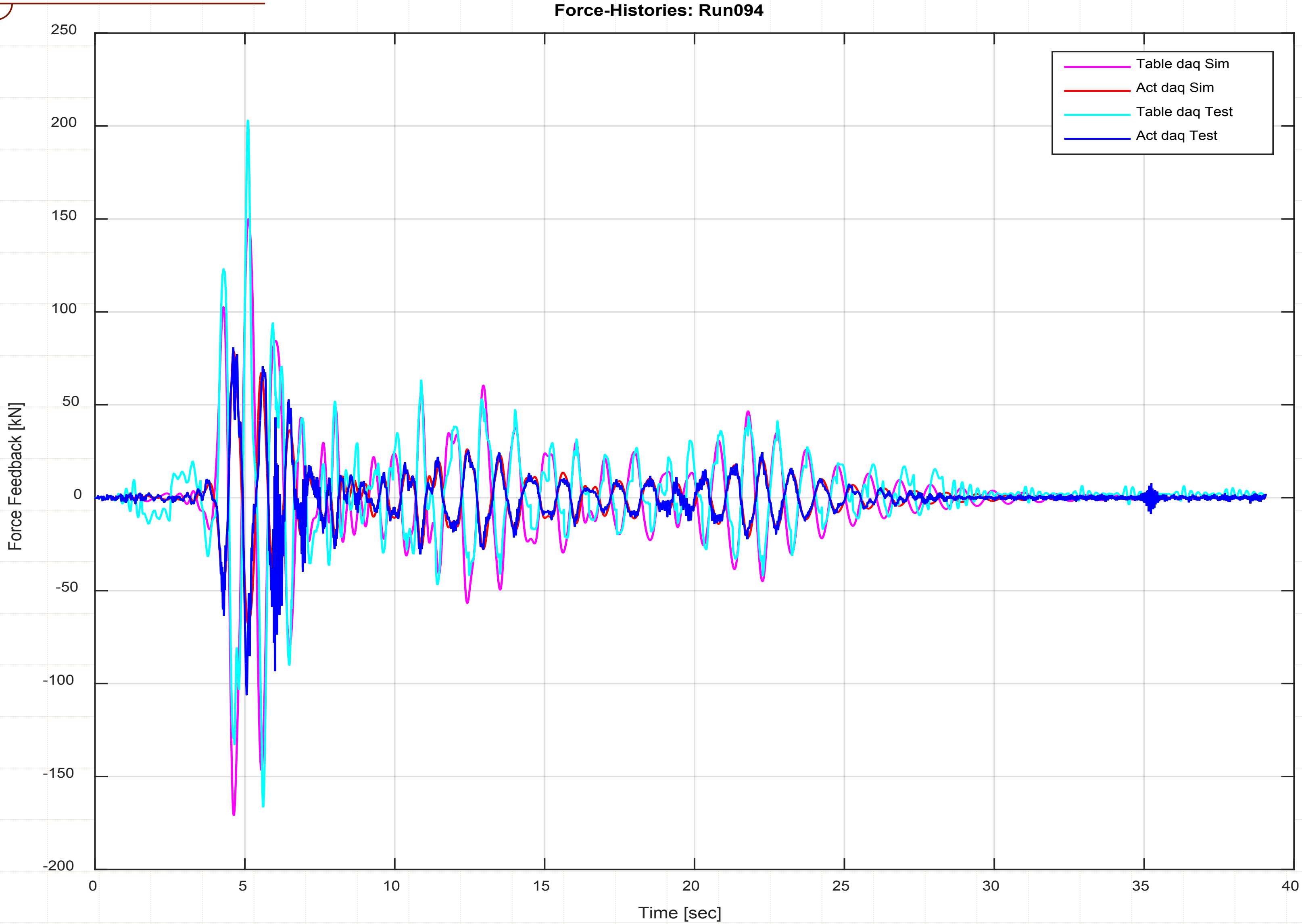


Displ. Response Comparison

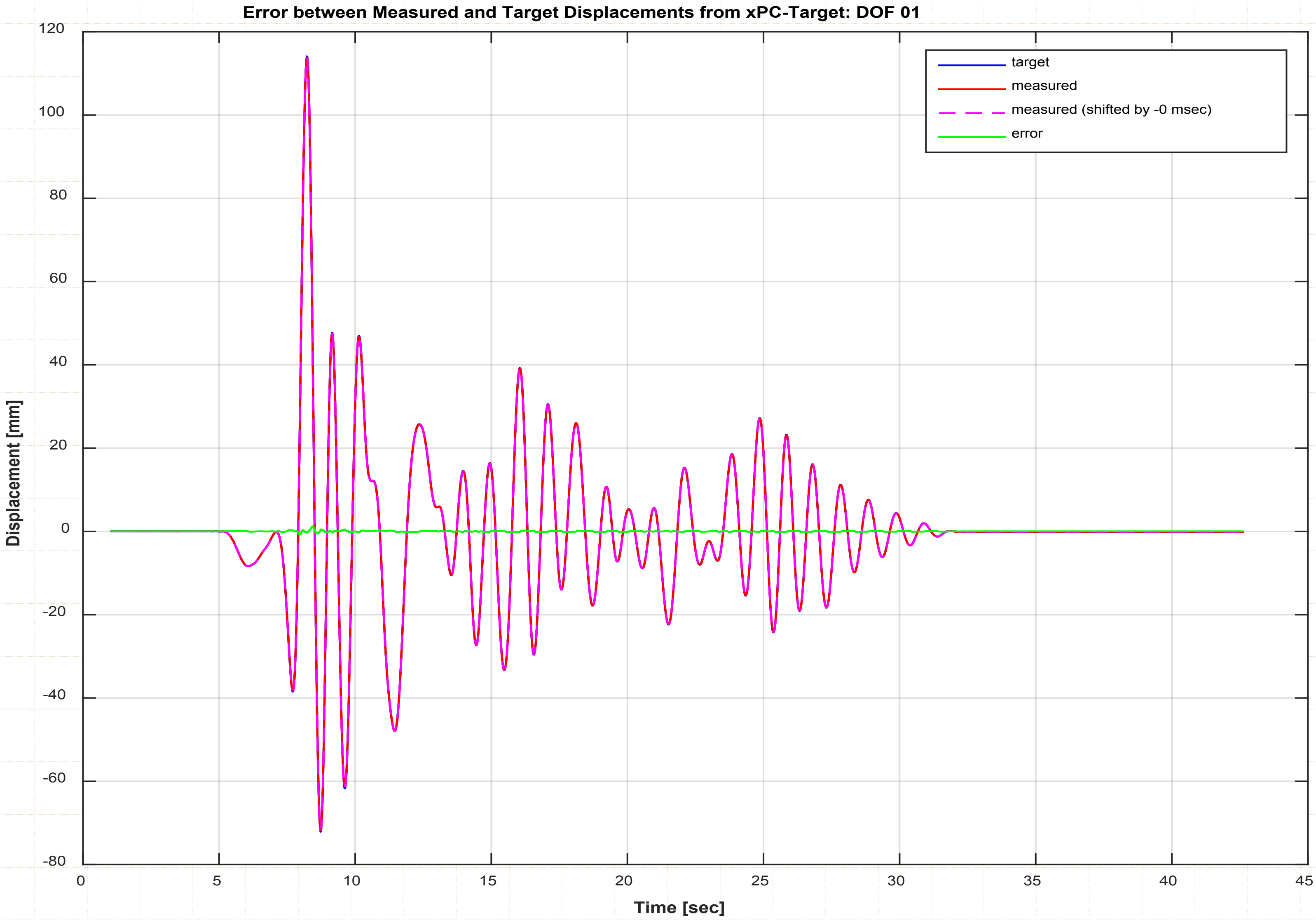


- Accuracy is assessed using
  - FFTs of tracking error
  - Tracking Indicator (by Mercan and Ricles)
  - RMS Error histories
  - Comparison with purely numerical simulation

Force Response Comparison



Delay Assessment

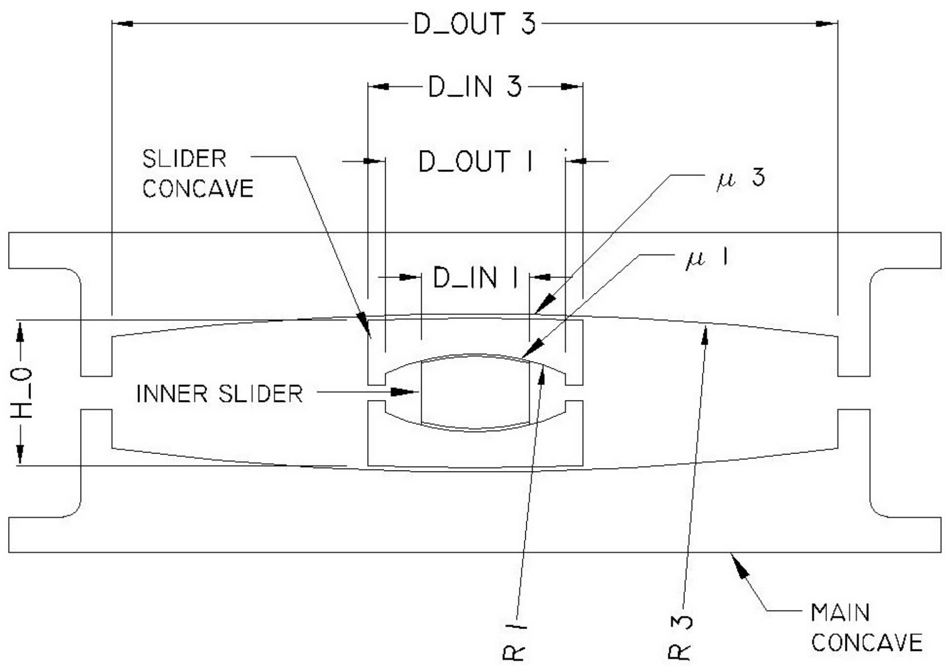


Building Application

PEER Shake Table Facility

- 20 ft x 20 ft table size
- Still the largest 6 DOF shake table in the US
- Can test structures, weighing 100,000 lbs, to horizontal accelerations of 1.5 g
- +/- 5 in. horizontal displacement capacity
- +/- 2 in. vertical displacement capacity
- +/- 40 in./sec velocity capacity

Triple Friction Pendulum Bearings



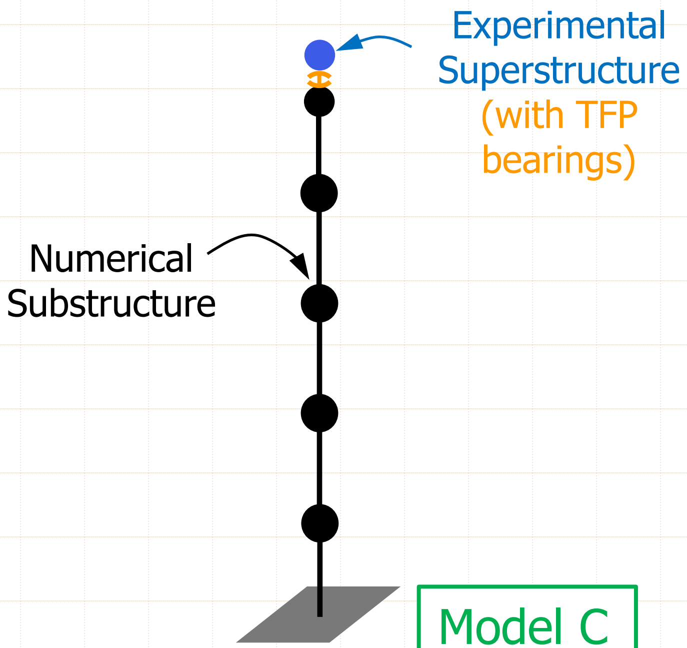
L1 (in.)	L2 (in.)	L3 (in.)
2.175	17.17	17.17

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

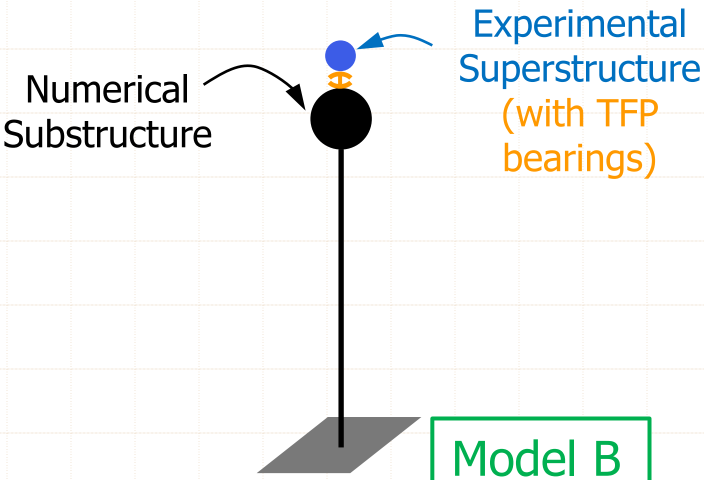
	Inner sliding surfaces	Outer sliding surfaces
Dish radius (inch)	3	18.64
Height (inch)	1.65	2.94
Outer diameter (inch)	2.60	9
Inner diameter (inch)	1.75	3

Analytical Substructure Parameters

Models without rotational DOF



Model C



Model B

15-DOF Shear Building

W_{tmd} = 53 kip

W_{bldg} = 450 kip

f_{x1} = 1 Hz

f_{y1} = 1.25 Hz

f_{z1} = 9.8 Hz

3-DOF Equivalent Model

W_{tmd} = 53 kip

W_{bldg} = 0.886*450 kip

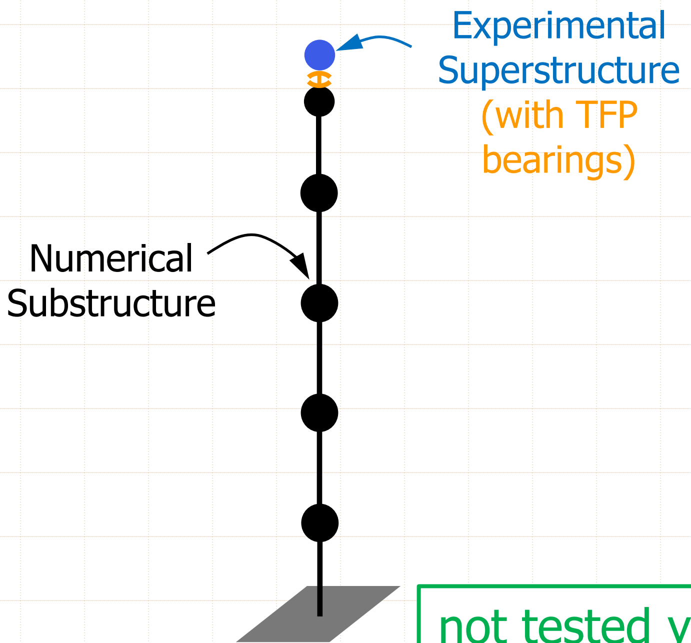
f_{x1} = 1 Hz

f_{y1} = 1.25 Hz

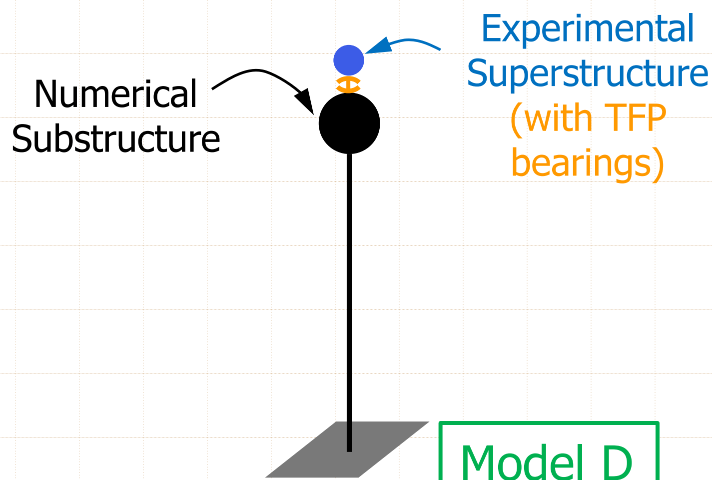
f_{z1} = 11 Hz

Analytical Substructure Parameters

Models with rotational DOF



not tested yet



Model D

<u>30-DOF Flexural Building</u>

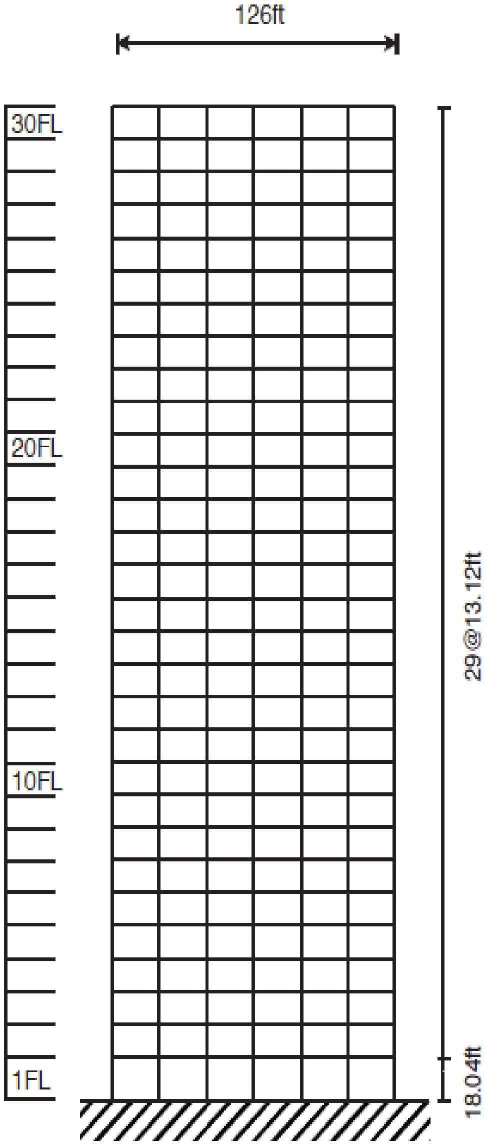
W_{tmd} = 53 kip
W_{bldg} = 450 kip
f_{x1} = 1 Hz
f_{y1} = 1.25 Hz
f_{z1} = 9.8 Hz

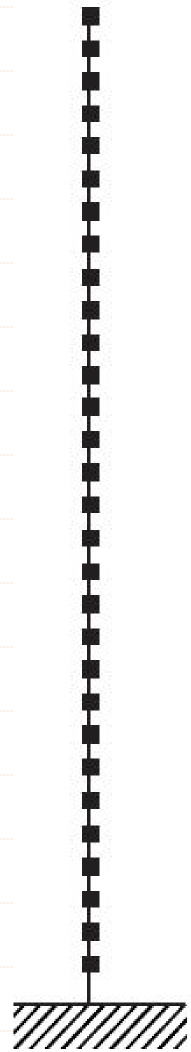
<u>5-DOF Equivalent Model</u>

W_{tmd} = 53 kip
W_{bldg} = 0.849*450 kip
f_{x1} = 1 Hz
f_{y1} = 1.25 Hz
f_{z1} = 11 Hz

Analytical Substructure Parameters

Tall Building Model E





30-DOF Shear Building

W_{tmd} = 53 kip

W_{bldg} = 63000 kip

SF = 120

SL = sqrt(SF)

SI = SL^4

ST = sqrt(SL)

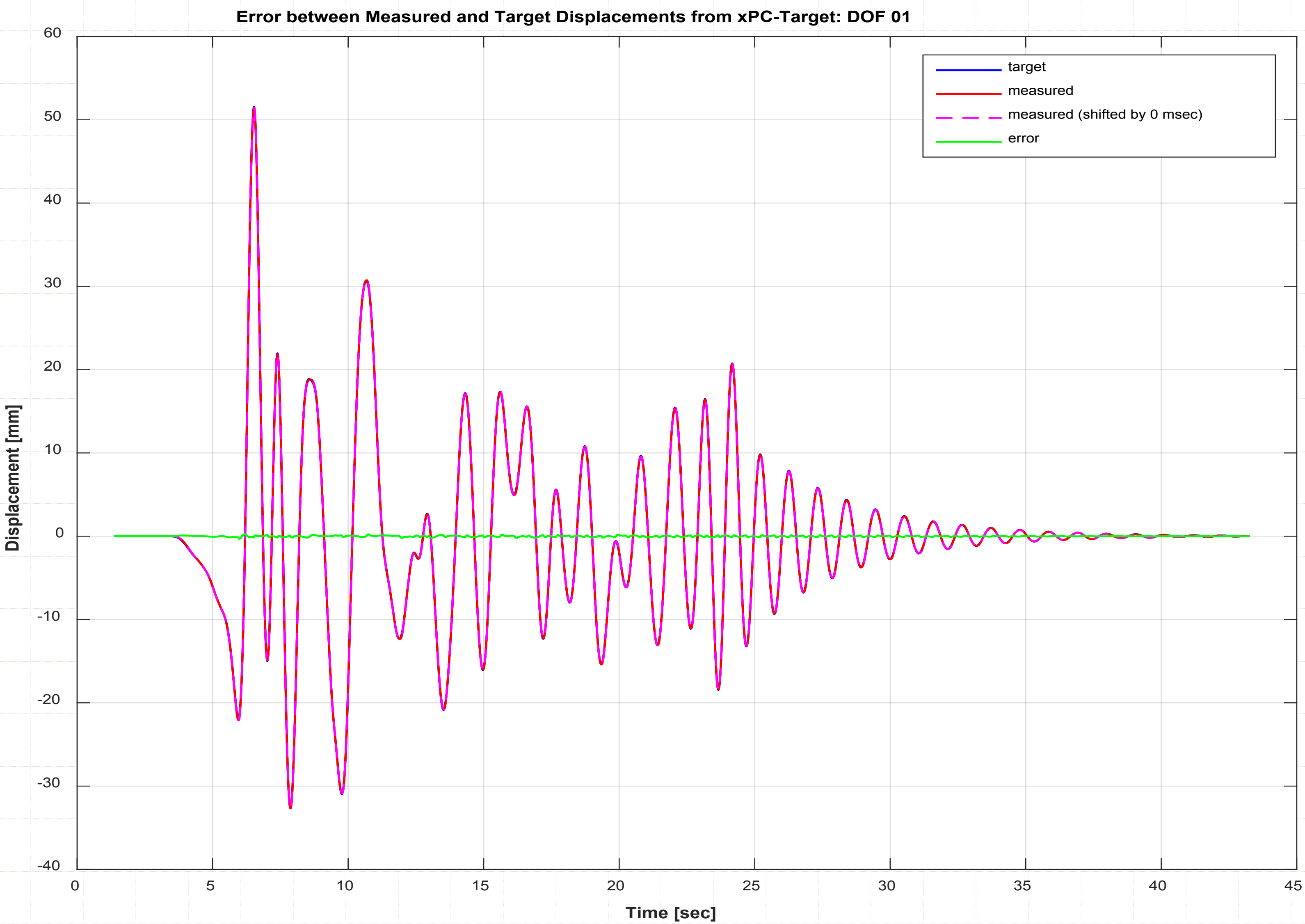
SV = SL/ST

f_{x1} = 0.27 Hz

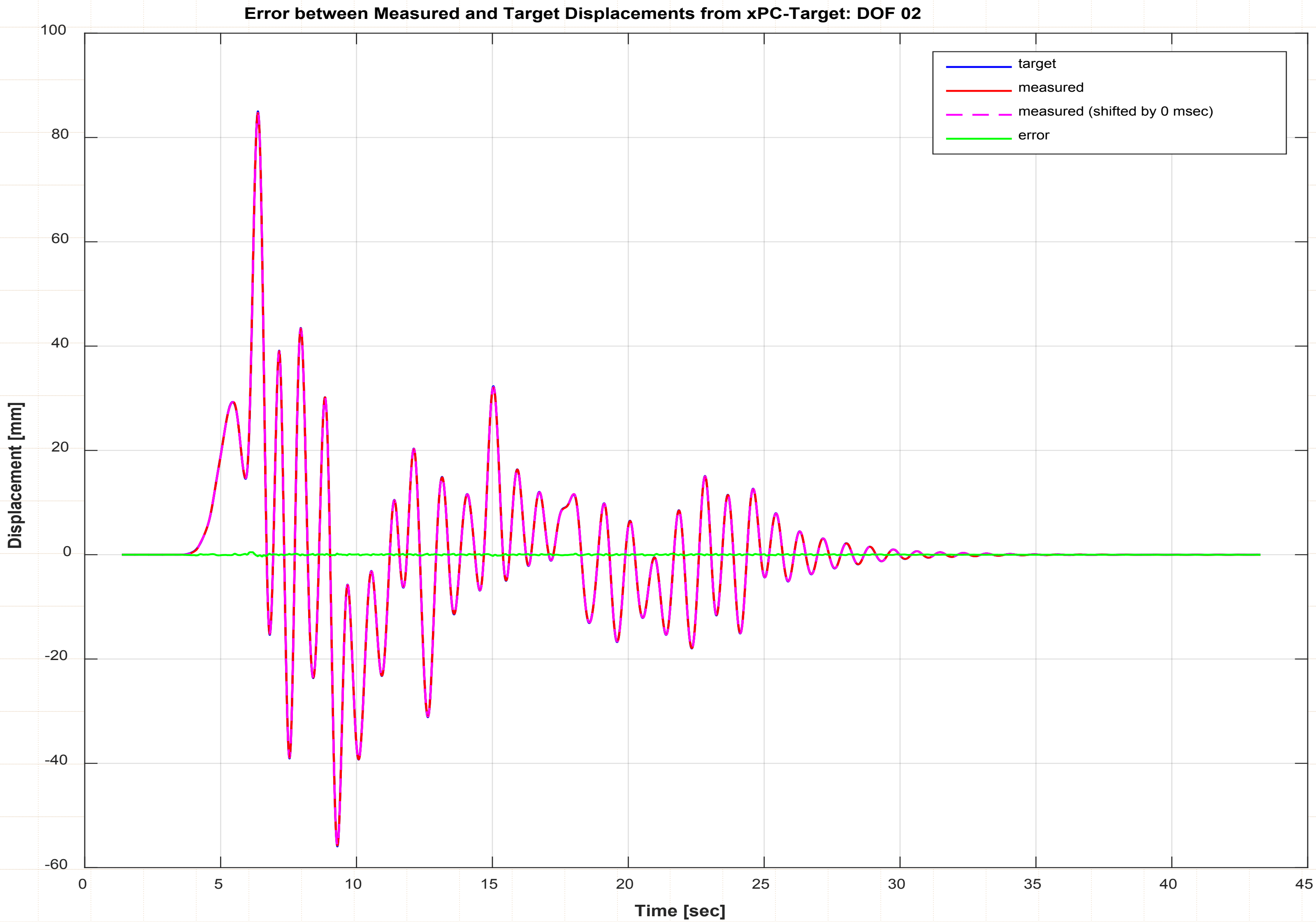
T_{x1} = 3.7 sec

Movie of Test

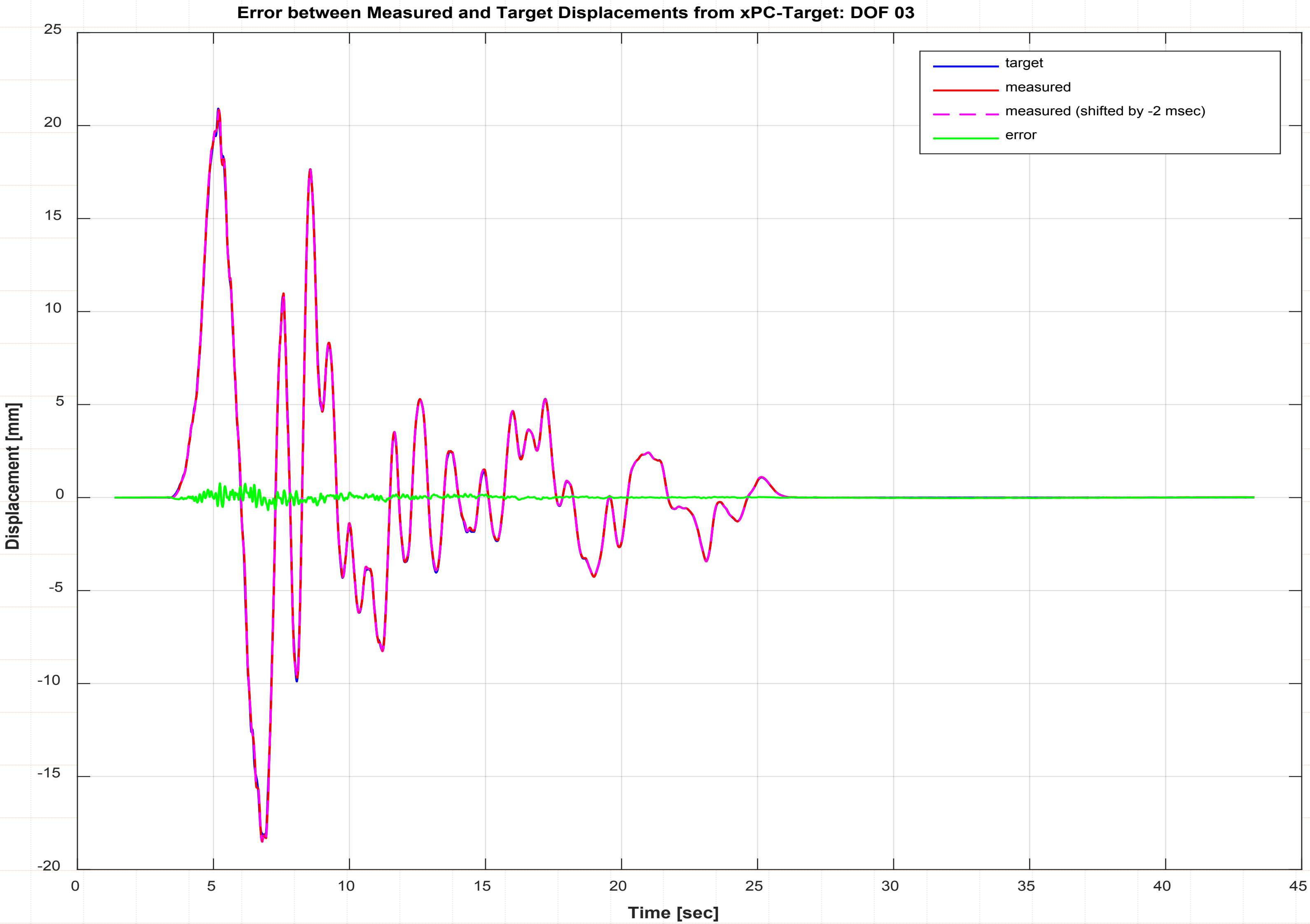
Delay Assessment



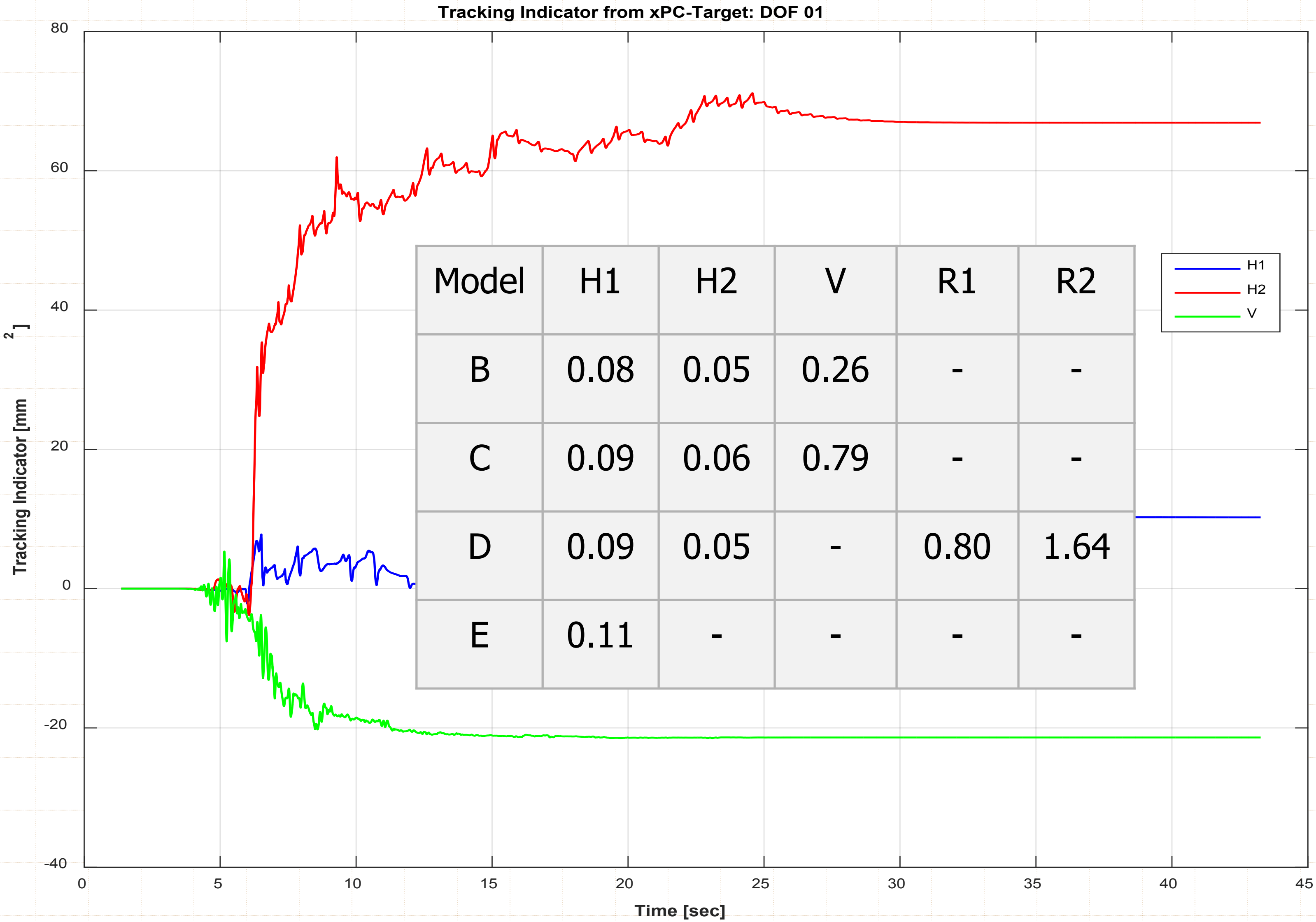
Delay Assessment



Delay Assessment

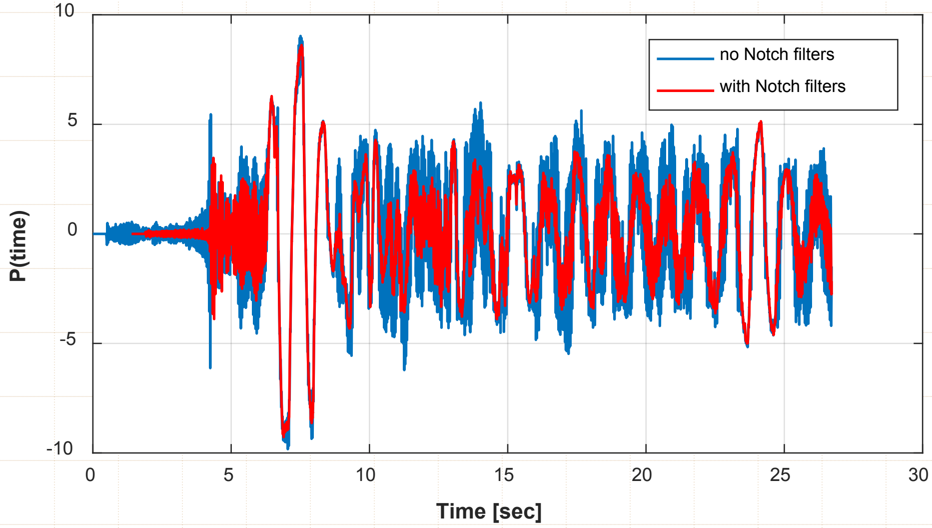


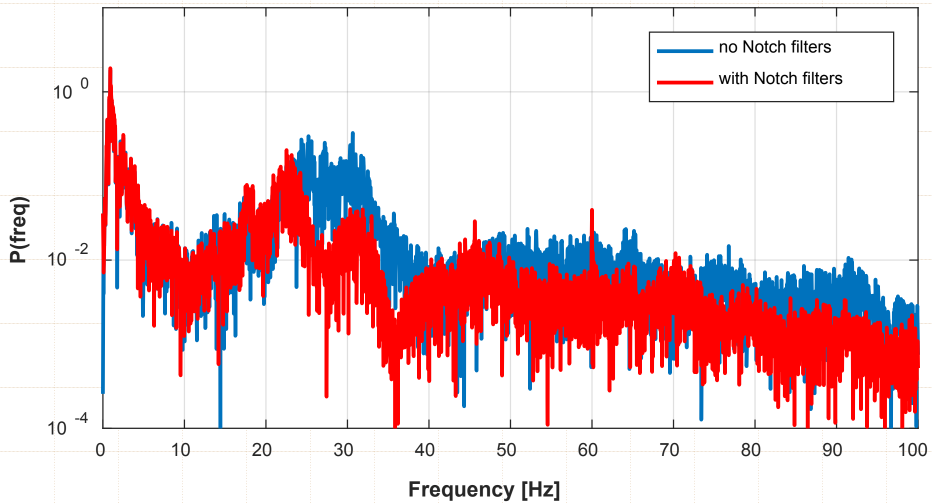
Tracking Indicator & NRMSE[%]



Model	H1	H2	V	R1	R2
B	0.08	0.05	0.26	-	-
C	0.09	0.06	0.79	-	-
D	0.09	0.05	-	0.80	1.64
E	0.11	-	-	-	-

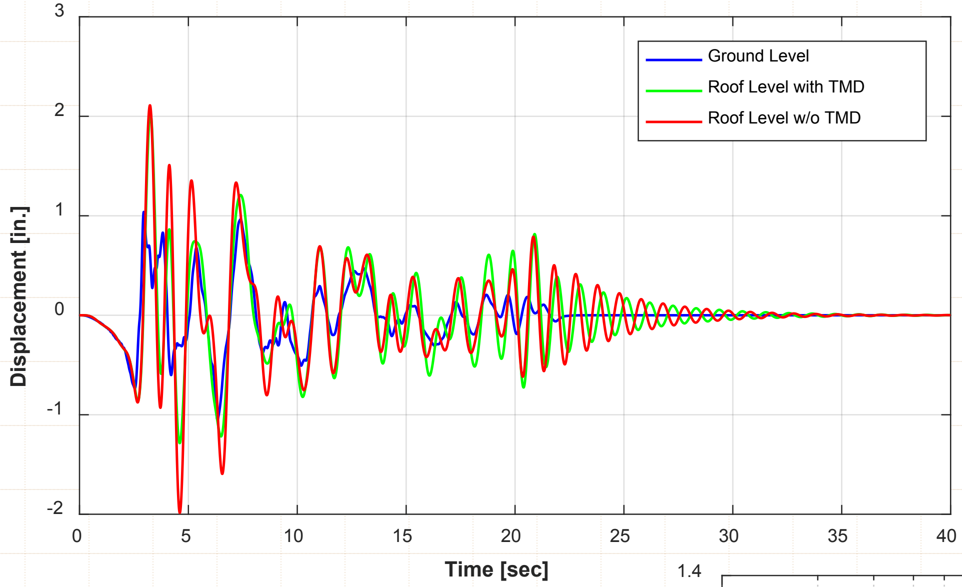
Filtering of Force Feedback

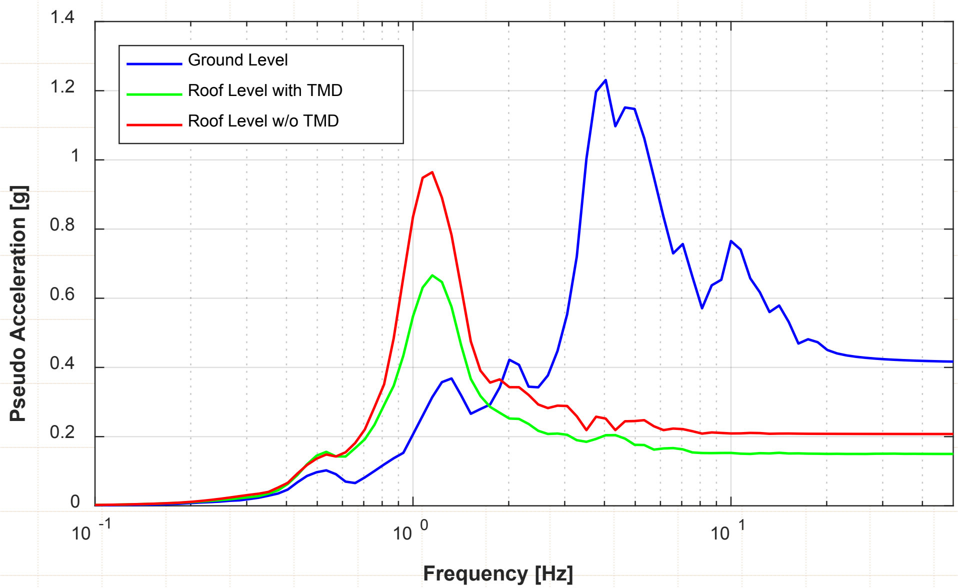




- Future work required
- Investigate other filtering techniques
- Investigate Kalman filtering techniques (can this be applied to force feedbacks using an predictive analysis model in parallel?)

Building Response Modification





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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