Hybrid Shake Table Test of a Midlevel Seismic Isolated Structure (NEES08)

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PEER NSF MTS NEES NEEScomm McMaster University

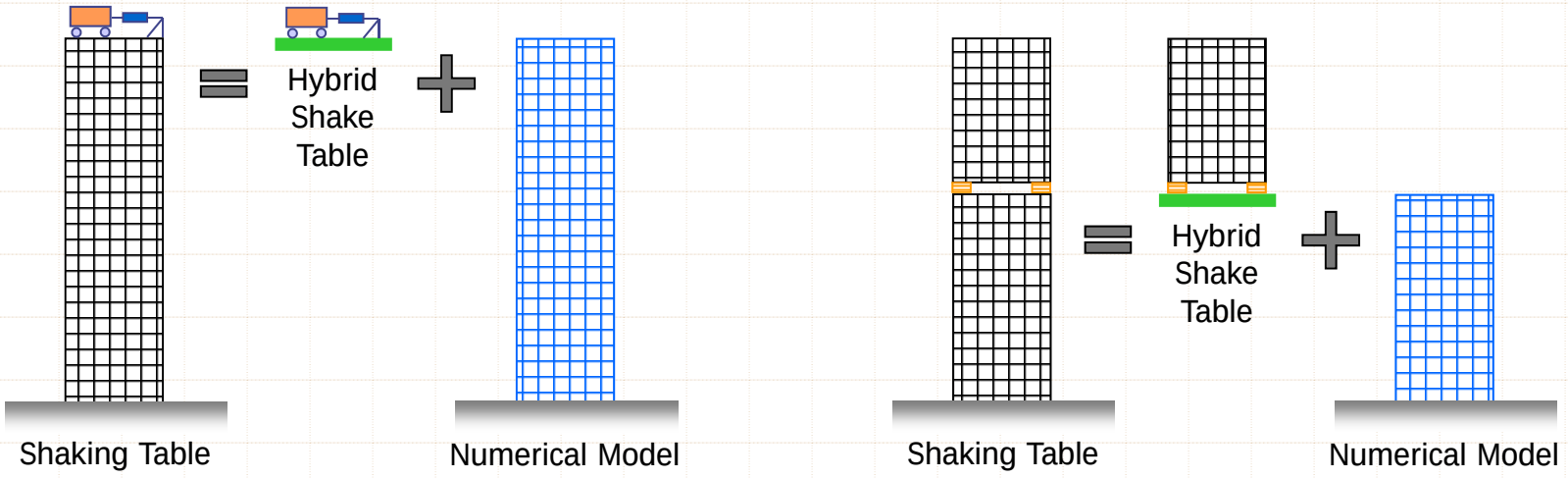
OpenFresco

Outline of Presentation

1. Motivation
2. Midlevel Seismic Isolation
3. Introduction to Hybrid Simulation
4. Hybrid Shake Table
5. Test Specimen and TFP bearings
6. Test Program and Parameters
7. Preliminary Results
8. 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 or SFSI are difficult to test on shake tables

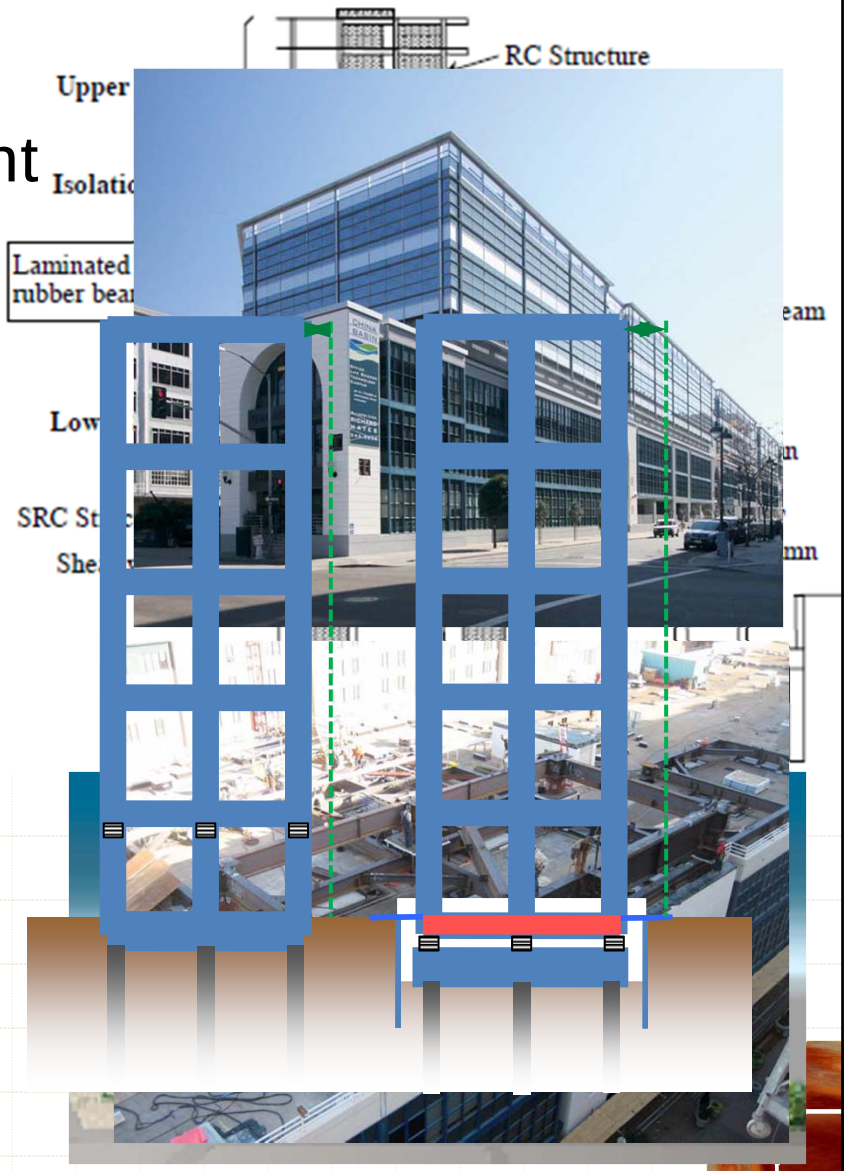


Motivation

- Enables us to perform dynamic tests of full-scale specimens without exceeding size, strength and weight limitations of shake table.
- With very little effort we can perform a wide range of parameter studies by changing the properties of the analytical portion of the hybrid model.

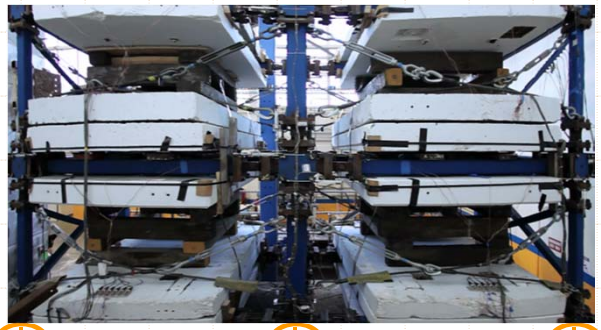
Midlevel Seismic Isolation

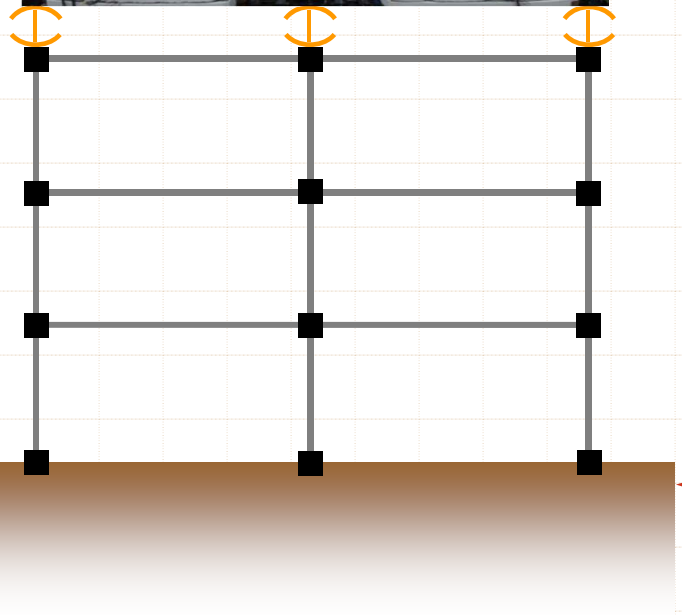
- Provide architectural flexibility
  - transitions between different structural systems
- Facilitate addition of new stories
  - minimally increase seismic demands on the existing building
  - exploit untuned mass-damper effect
- Decrease cost of isolation
  - Moat and clearance space

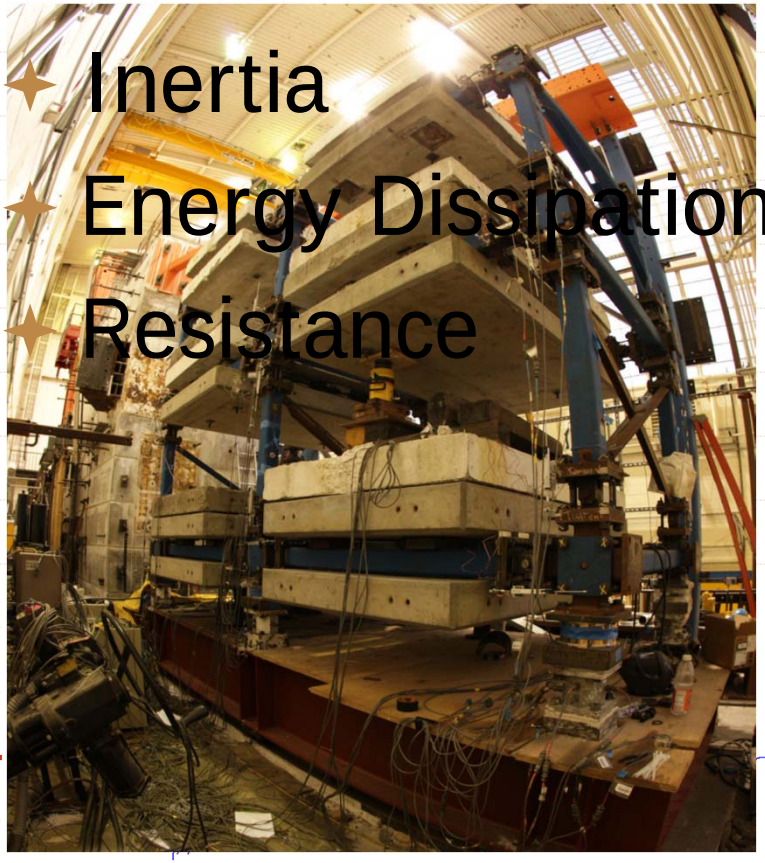


Hybrid Simulation

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



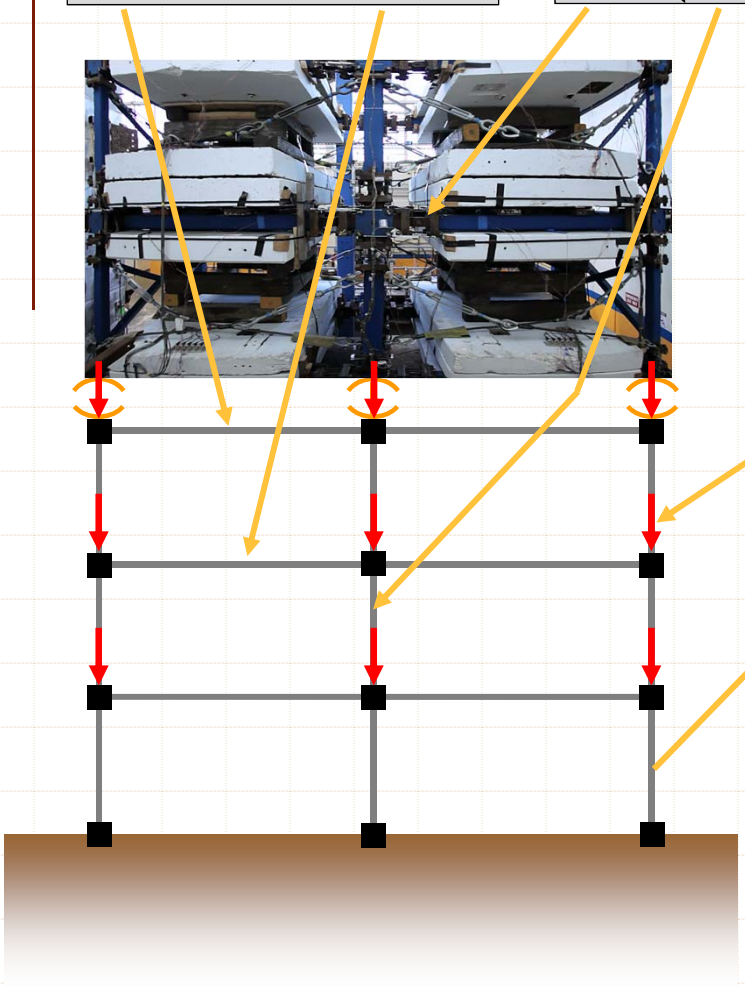




- Inertia
- Energy Dissipation
- Resistance

Hybrid Simulation

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



Dynamic Loading:

- Seismic
- Wind
- Blast/Impact
- Wave
- Traffic

Static Loading:

- Gravity
- Prestress

analytically add nonlinear geometric effects to measured resisting forces

analytical model of structural energy dissipation and inertia

physical model of structural resistance

Equations of Motion

1. Slow test

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

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

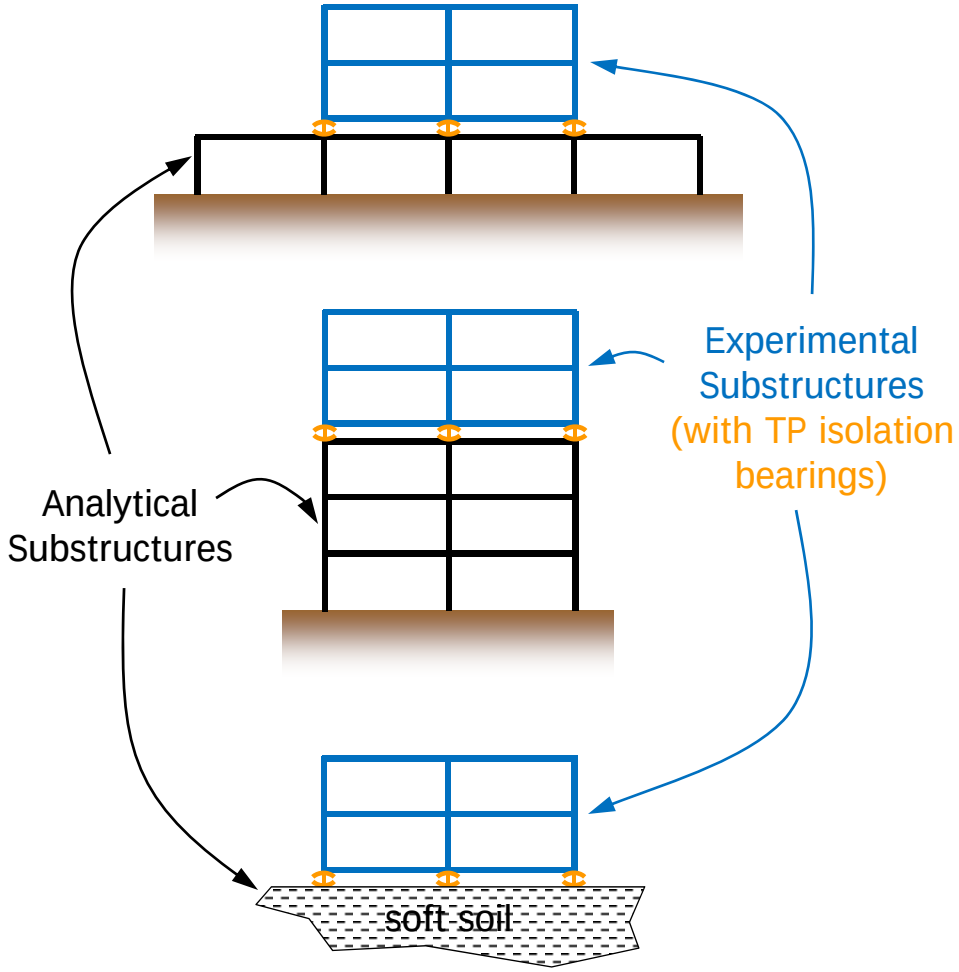
$$\mathbf{M}^{A}\ddot{\mathbf{U}}_{i+1} + \mathbf{C}^{A}\dot{\mathbf{U}}_{i+1} + \mathbf{P}_{\mathbf{r}}^{A}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}\right) + \mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{i+1} - \mathbf{P}_{0,i+1}$$

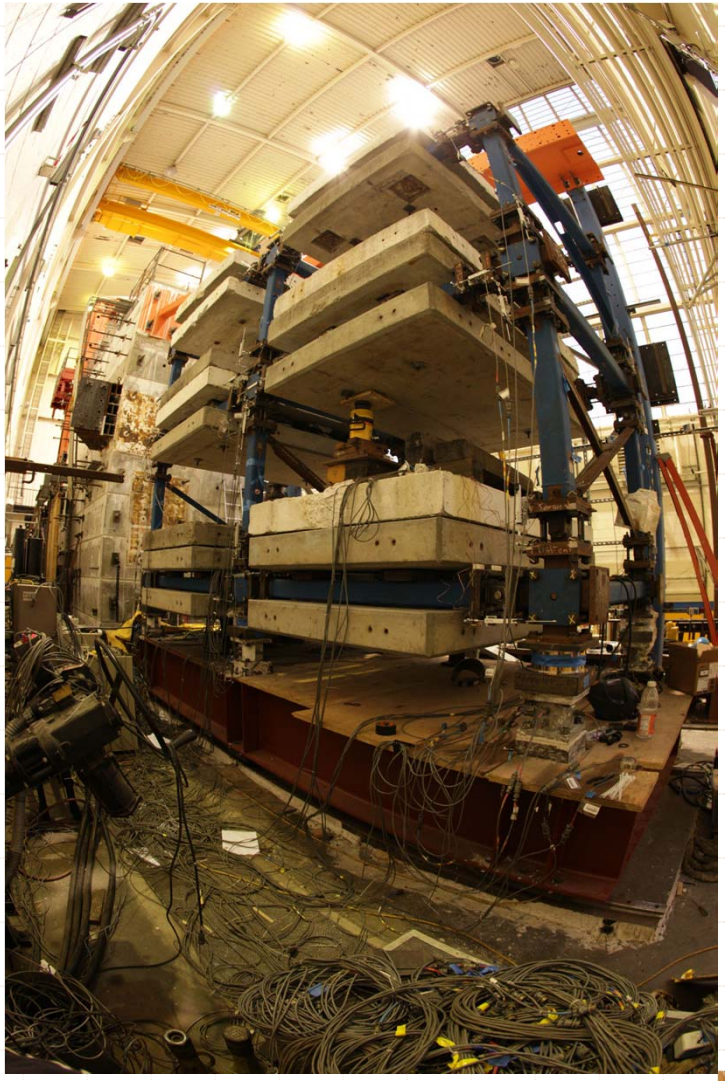
$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{i+1}, \dot{\mathbf{U}}_{i+1}, \ddot{\mathbf{U}}_{i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{i+1}$$

4. Smart shaking table test

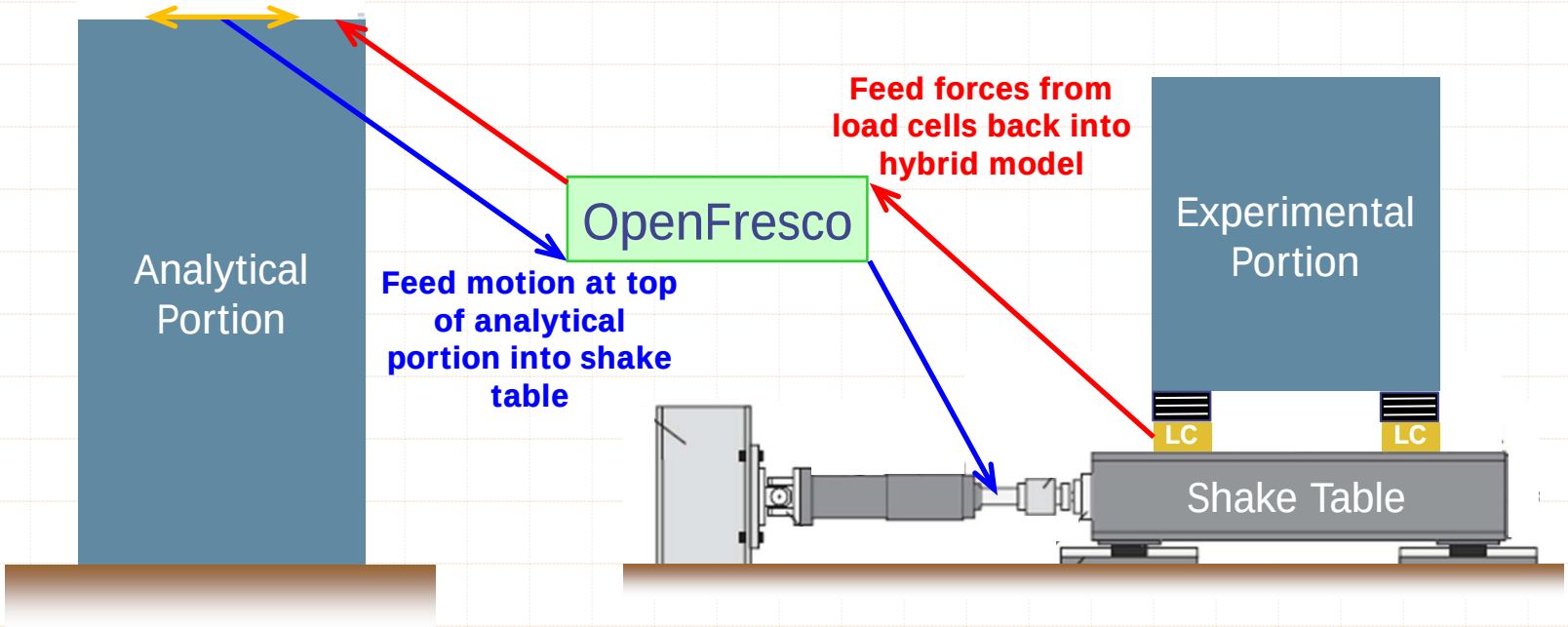
$$\mathbf{P}_{\mathbf{r}}^{E}\left(\mathbf{U}_{\mathbf{t},i+1}, \dot{\mathbf{U}}_{\mathbf{t},i+1}, \ddot{\mathbf{U}}_{\mathbf{t},i+1}\right) = \mathbf{P}_{\mathbf{r},i+1}^{E} + \mathbf{M}^{E}\ddot{\mathbf{U}}_{\mathbf{t},i+1}$$

Hybrid Shake Table Test

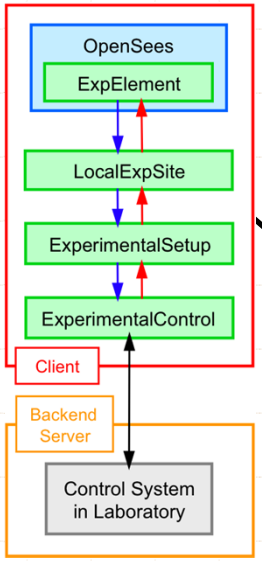




Hybrid Shake Table Configuration



Connecting to MTS 493 controller



OpenSees Finite Element Model

OpenFresco Middleware

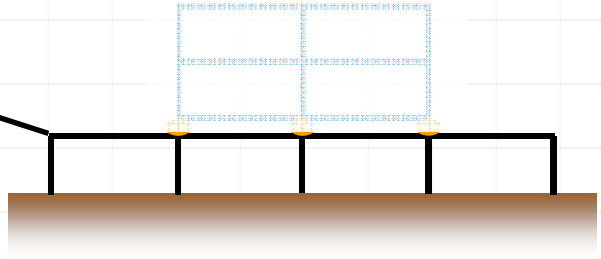
SCRAMNet

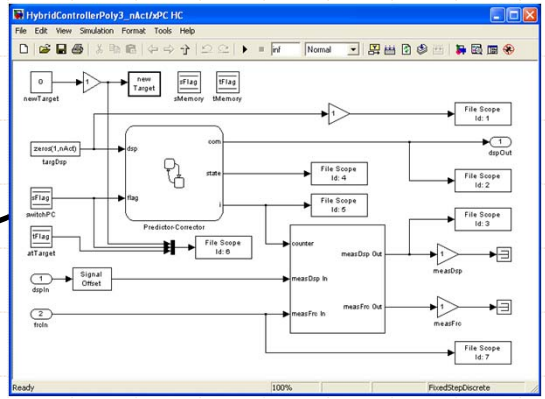
xPC-Target real-time Predictor-Corrector

SCRAMNet

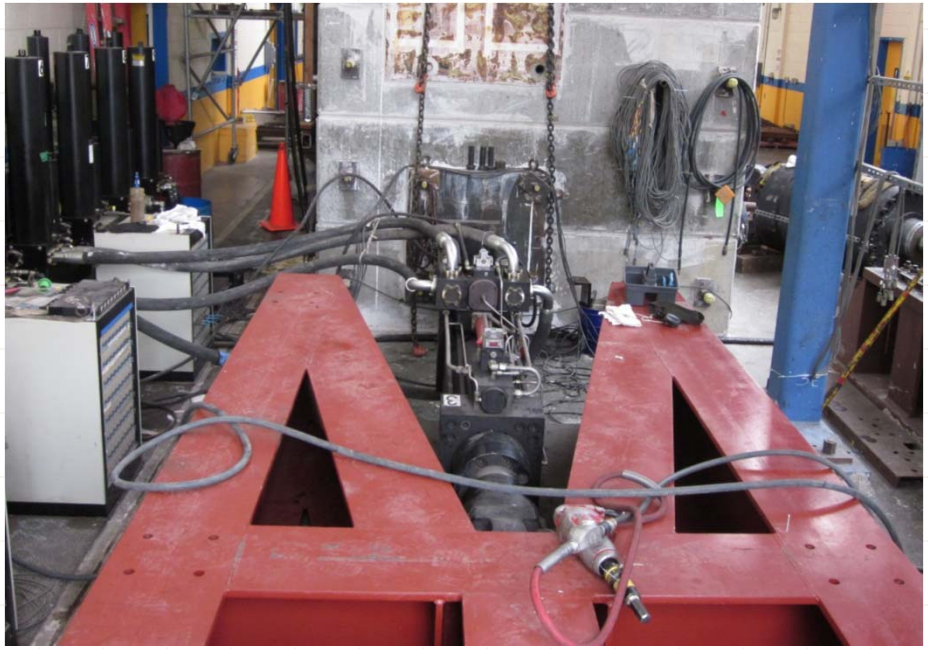
MTS 493 real-time Controller

Physical Specimen in NEES Lab



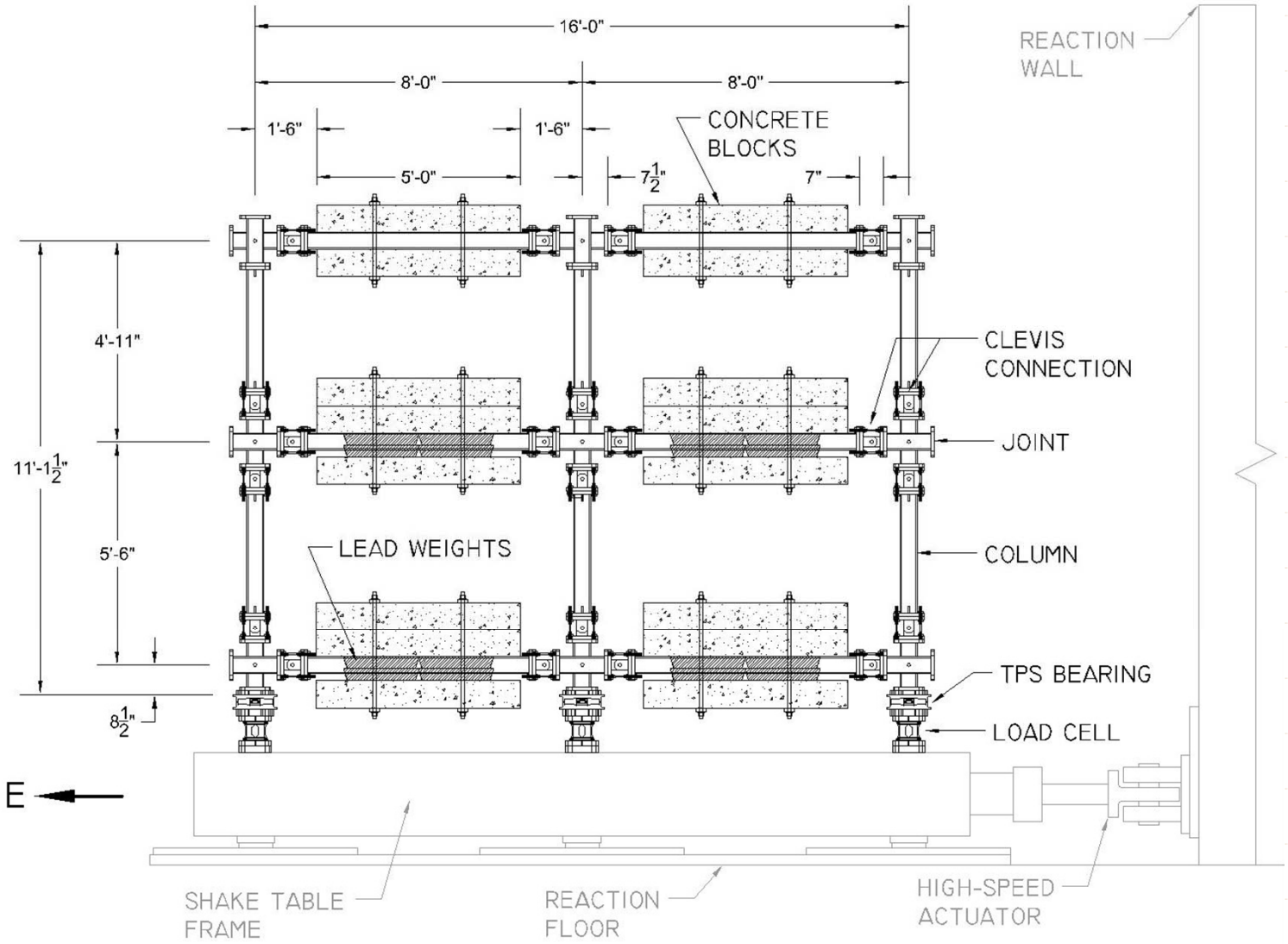


Shake Table

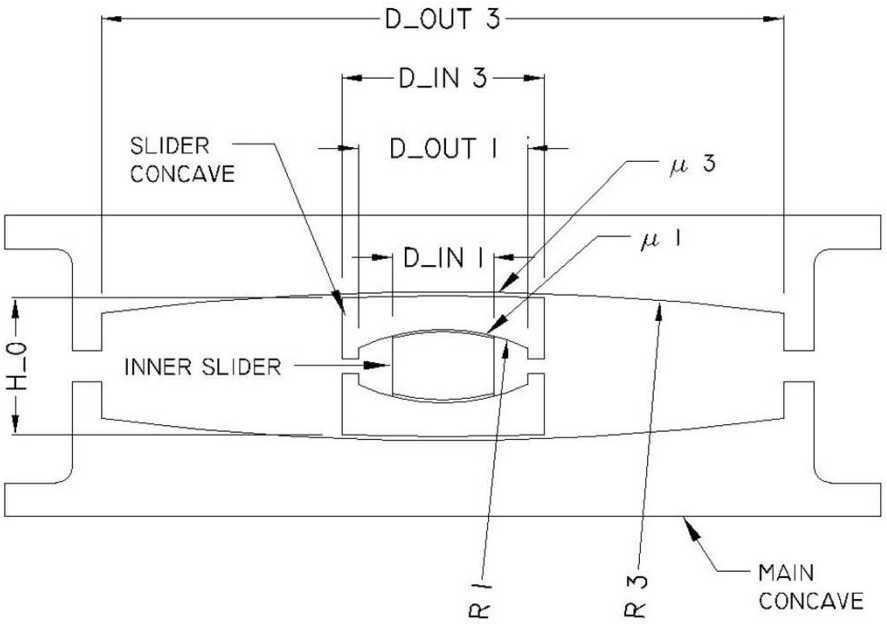


- 5.8m x 2.1m platform
- Linear bearings with μ < 10%
- Actuator with 1000kN, ±0.5m and ±1m/sec capacity

Specimen


16'-0"
8'-0"
8'-0"
1'-6"
1'-6"
5'-0"
7½"
7"
CONCRETE BLOCKS
REACTION WALL
4'-11"
11'-1½"
5'-6"
8½"
CLEVIS CONNECTION
JOINT
LEAD WEIGHTS
COLUMN
TPS BEARING
LOAD CELL
E
SHAKE TABLE FRAME
REACTION FLOOR
HIGH-SPEED ACTUATOR

Triple Friction Pendulum Bearings



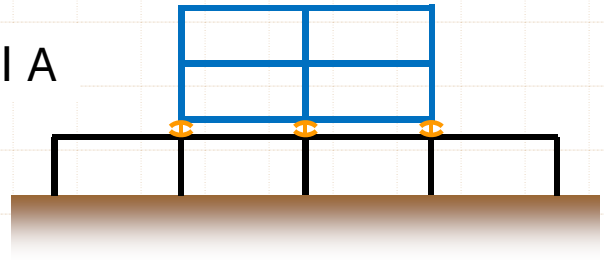
T_{eff} = 1.4 sec @ 10cm

PROPERTY	VALUE
R 1	3.00"
R 3	18.64"
D_IN 1	1.5"
D_IN 3	3.0"
D_OUT 1	2.5"
D_OUT 3	9.0"
H_0	6.0"
μ 1	2%
μ 3	9%

1/3rd scale

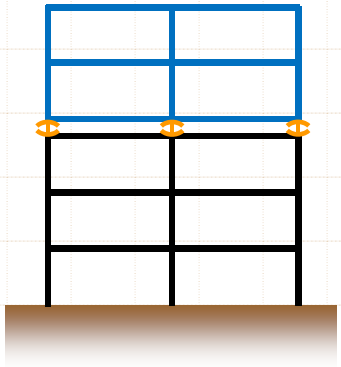
Analytical Substructure Parameters

Model A



W_{floor} (kN)	T_1	ζ_1
445	1.01	0.03
445	0.51	0.03
445	0.25	0.03
445	0.13	0.03

Model B



W_{floor} (kN)	T_1	T_2	T_3	$\zeta_{1,3}$
142	1.02	0.36	0.25	0.03
142	0.51	0.18	0.13	0.03
142	0.25	0.09	0.06	0.03

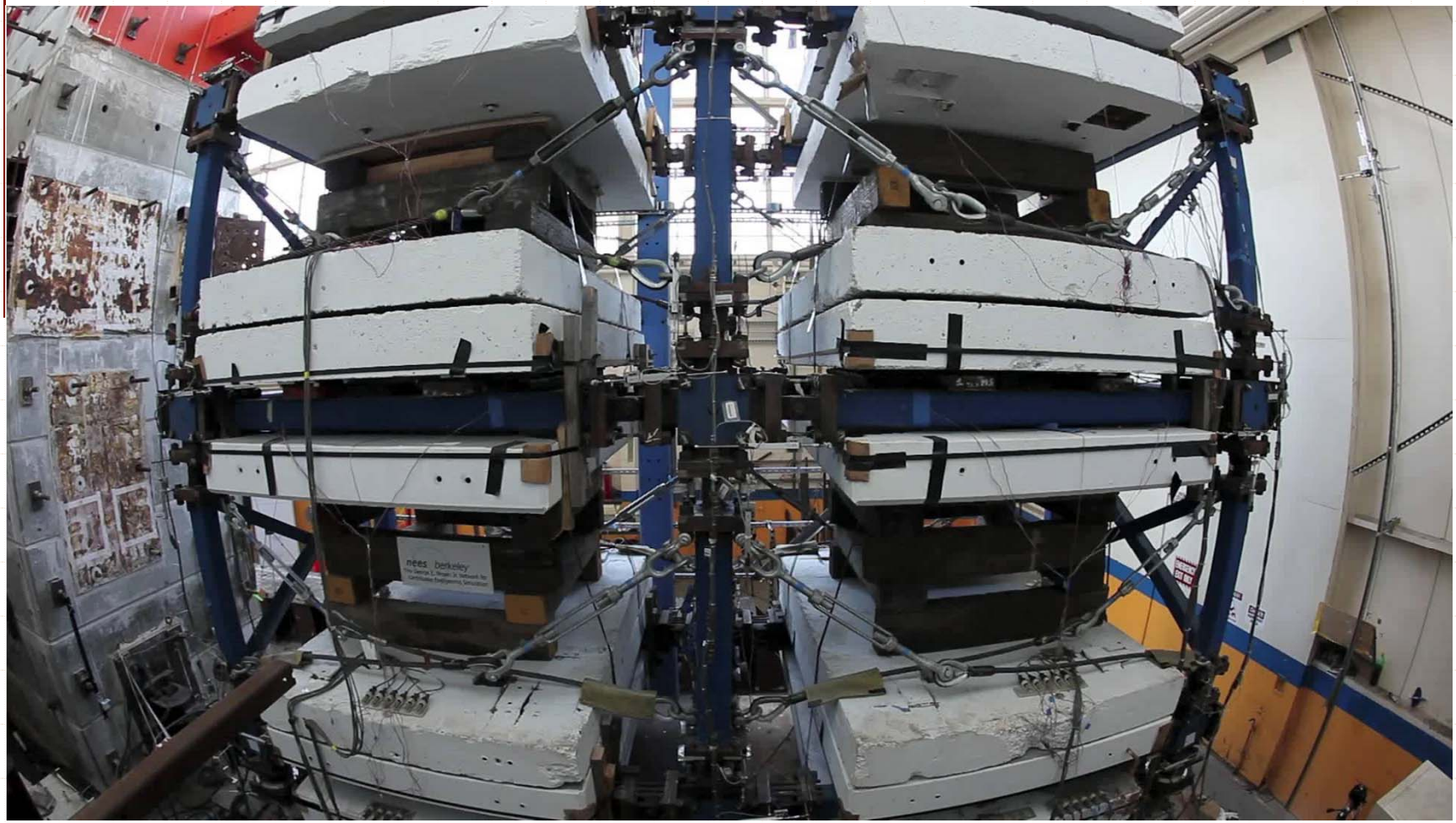
Important Analysis Parameters

- OpenSees as computational driver
- Using Newmark Explicit ($\beta = 0$, $\gamma = 0.5$)
- No iterations necessary
- But conditionally stable
  - $dt < T_{min}/\pi = 0.06/\pi = 0.01997$ sec
  - choose $dt_{int} = dt_{sim} = 5/1024 = 0.00488$ sec
- Using MultipleSupport excitation pattern in OpenSees to get absolute response
- SCRAMNet experimental control is used to reduce communication delays

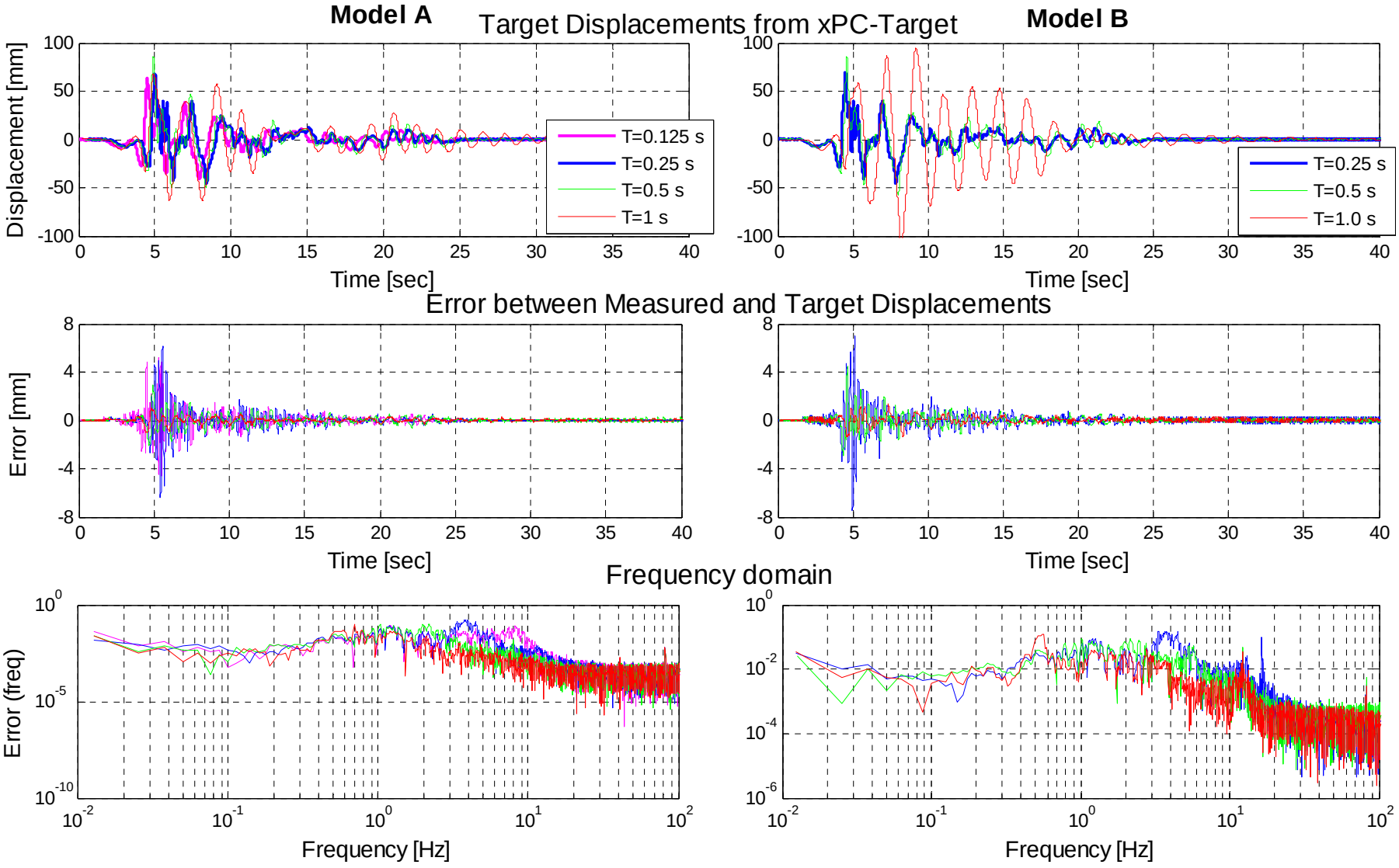
Ground Motion

- Loma Prieta Gilroy #4 Array
  - DBE 10% chance of exceedance in 50 years
- Scaled so expected bearing displ. was just within the maximum displ. of the bearings (18 cm) under the MCE level, or 2% chance of exceedance in 50 years

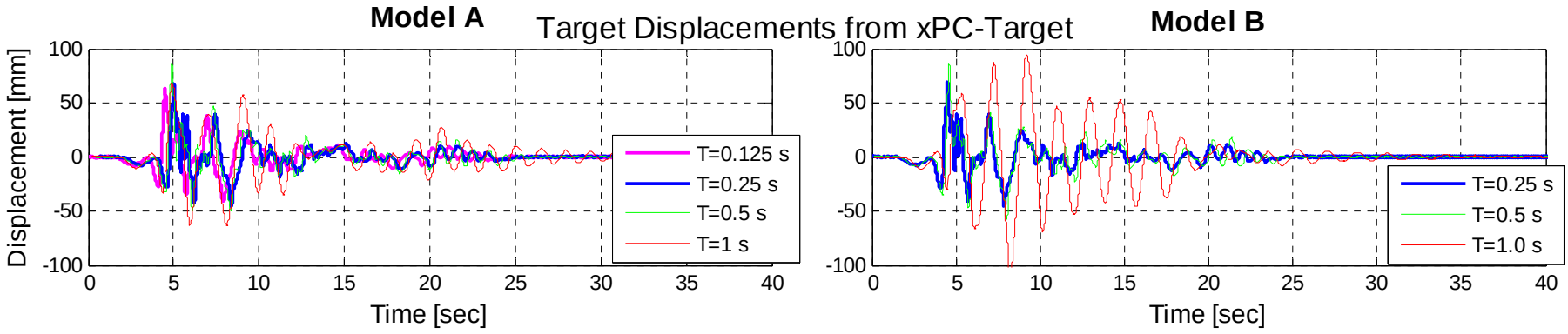
Movie of Test

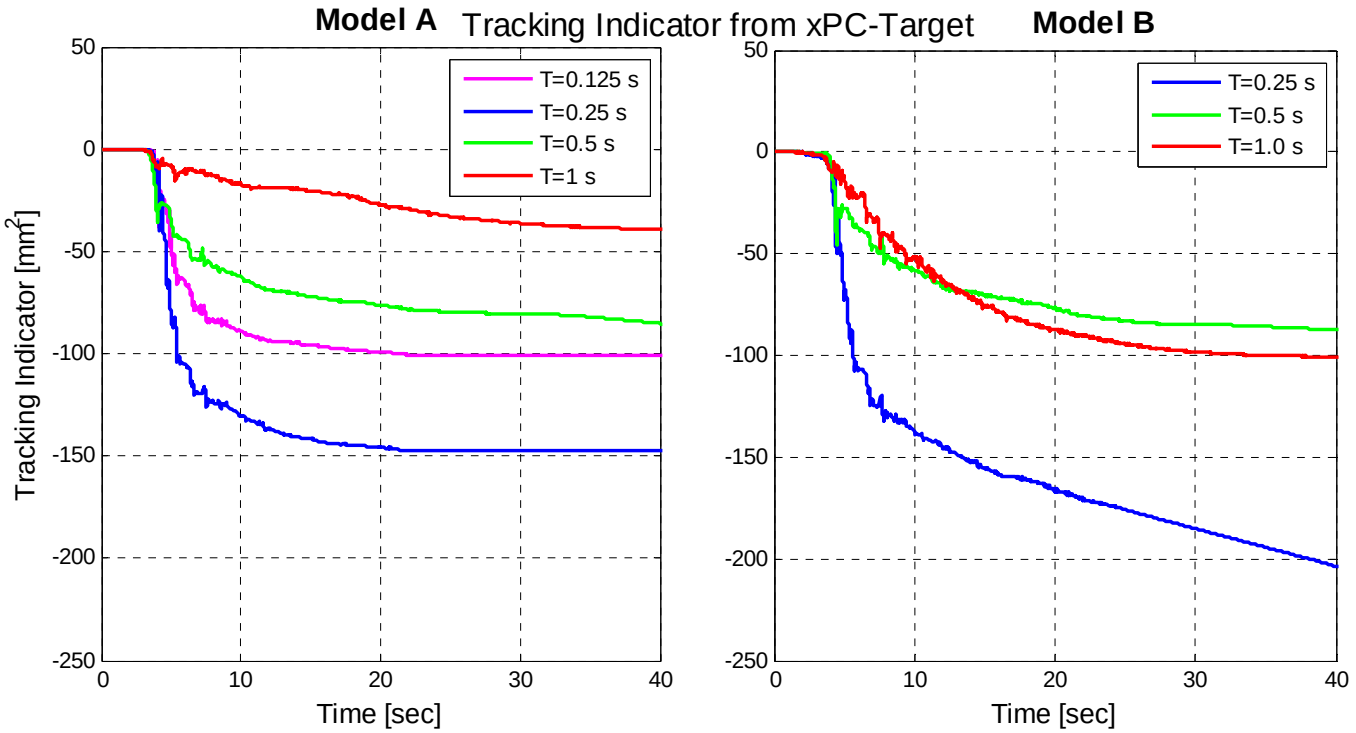


Shake Table Displacements

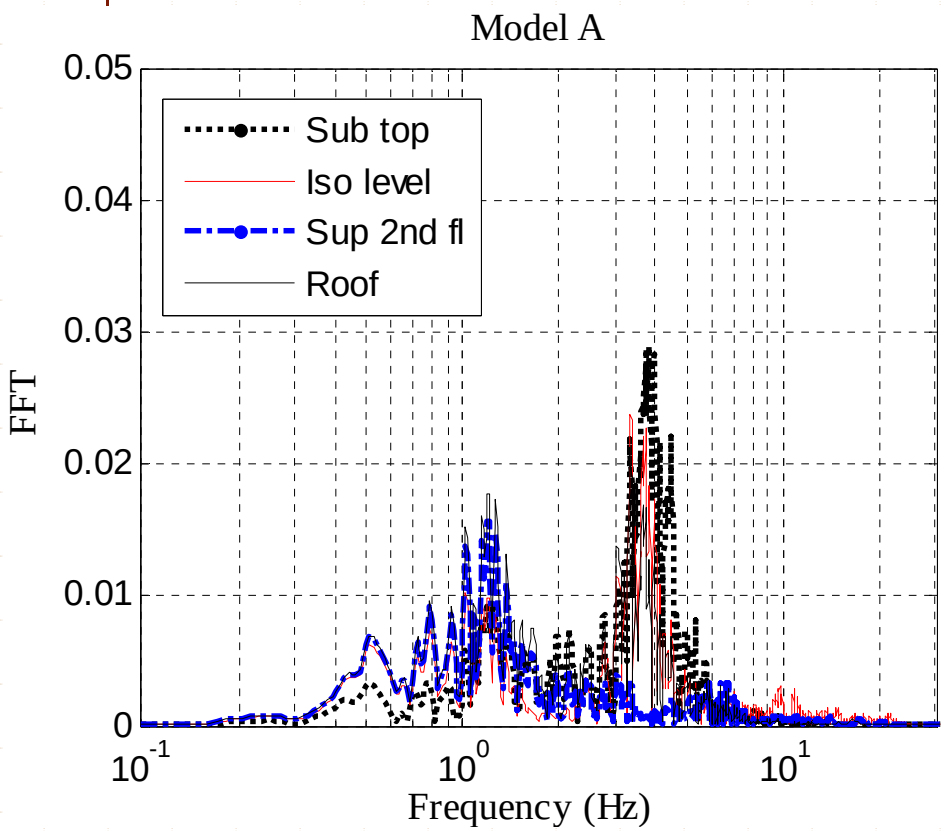


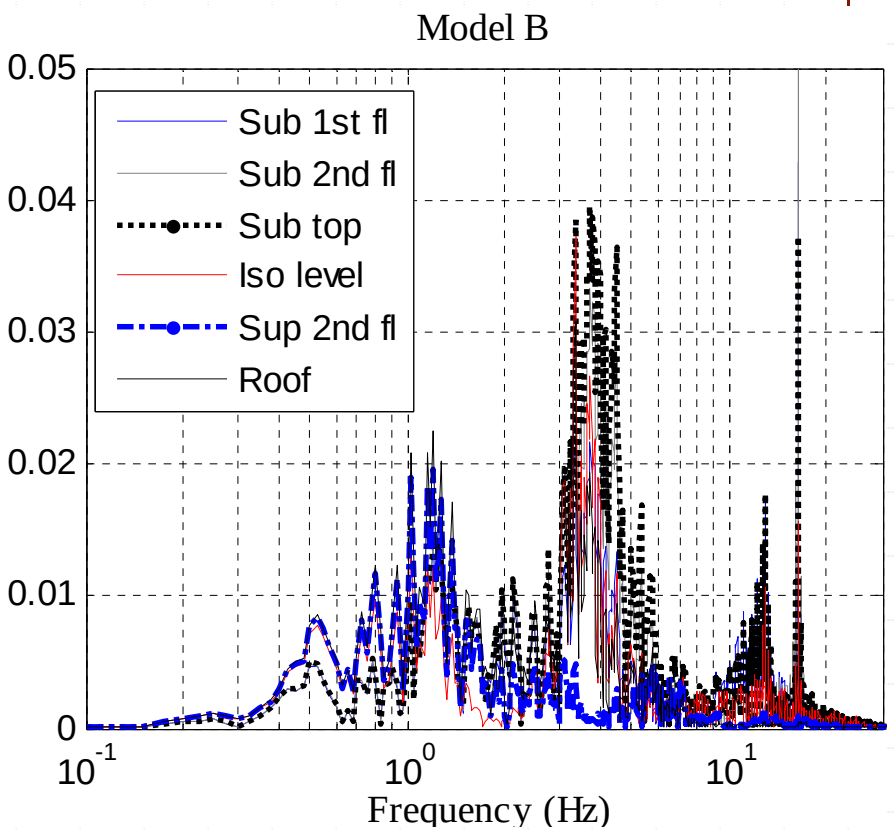
Tracking Indicators



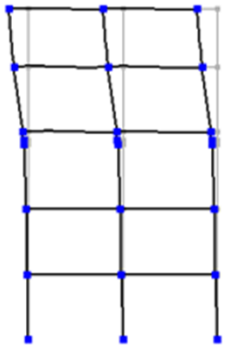
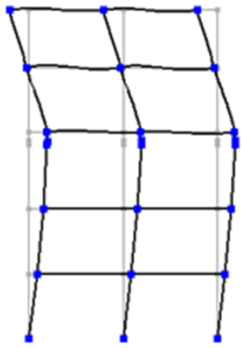
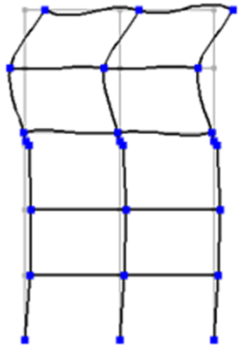
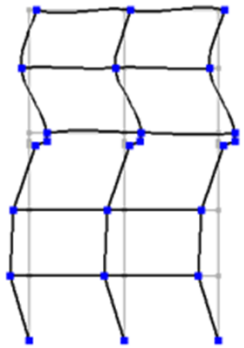
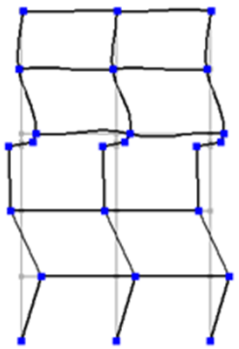
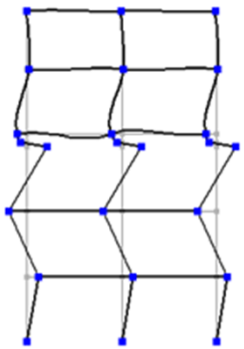
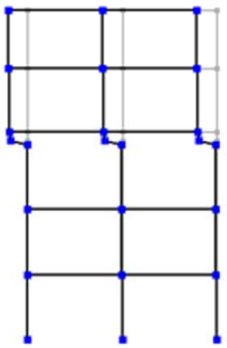
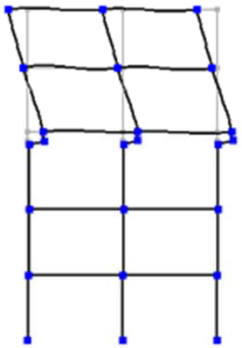
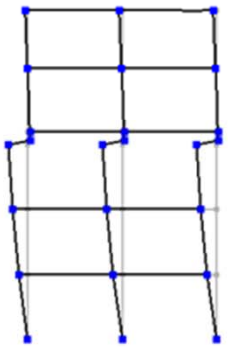
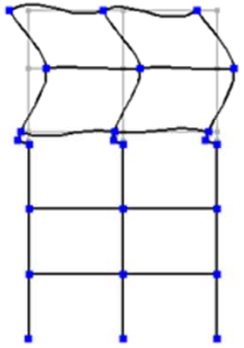
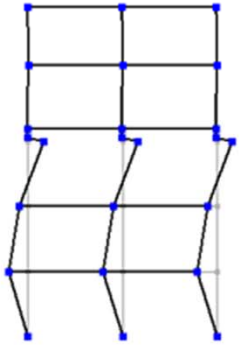
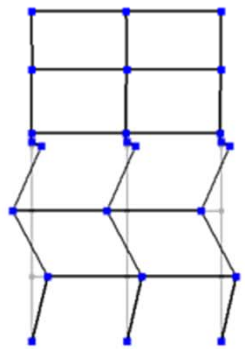


FFTs of acc. histories for T = 0.25 sec

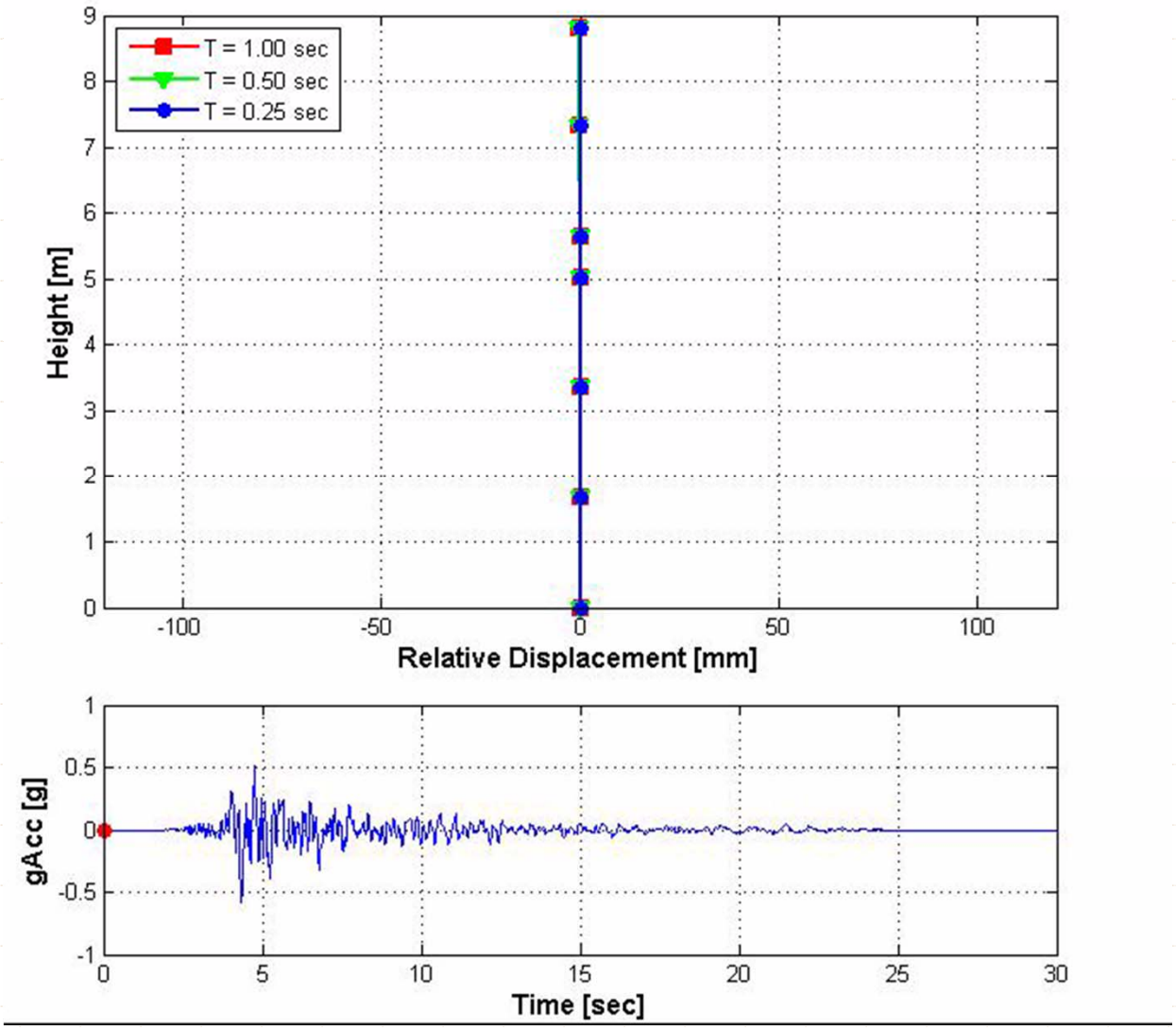




Mode shapes and frequencies

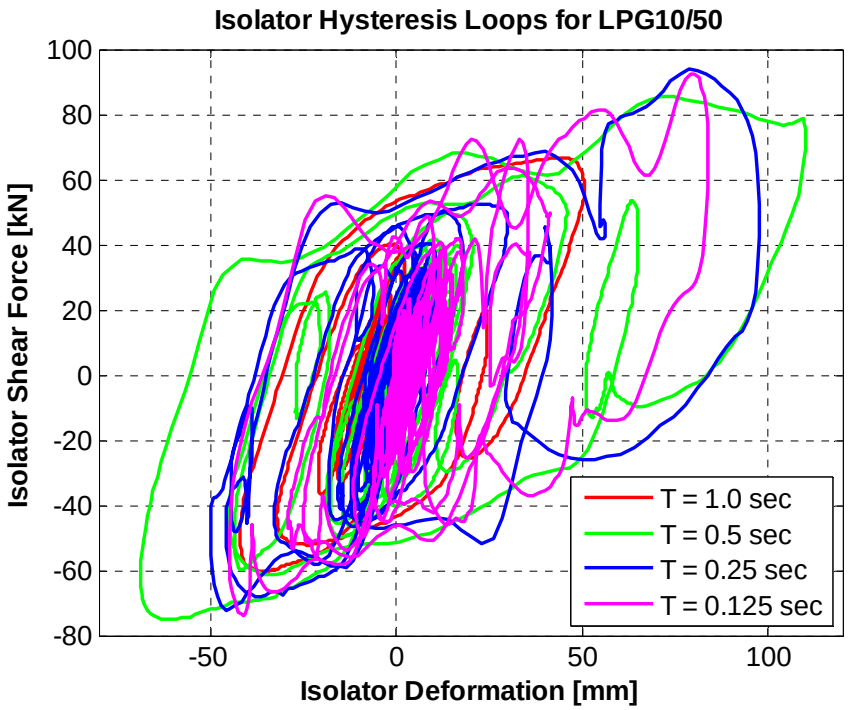
Mode	1	2	3	4	5	6
k_{iso} = initial	 1.7 Hz	 3.6 Hz	 7.0 Hz	 9.6 Hz	 14.2 Hz	 17 Hz
k_{iso} = 2nd sliding stage	 0.51 Hz	 3.4 Hz	 4.0 Hz	 7.6 Hz	 11.0 Hz	 15.9 Hz

Relative Displacement Model B

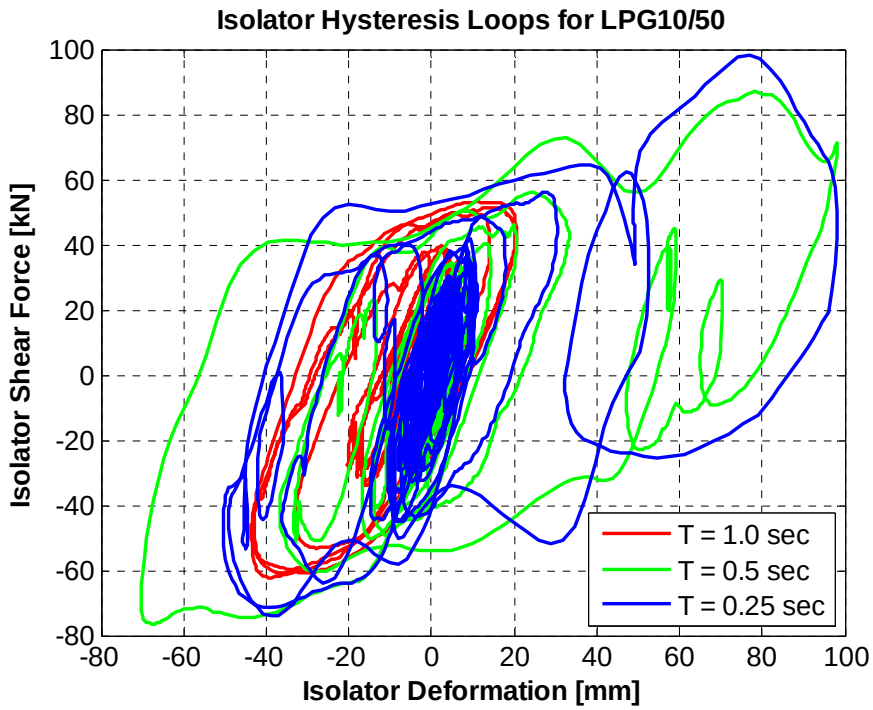


Isolator Hysteresis Loops

Model A

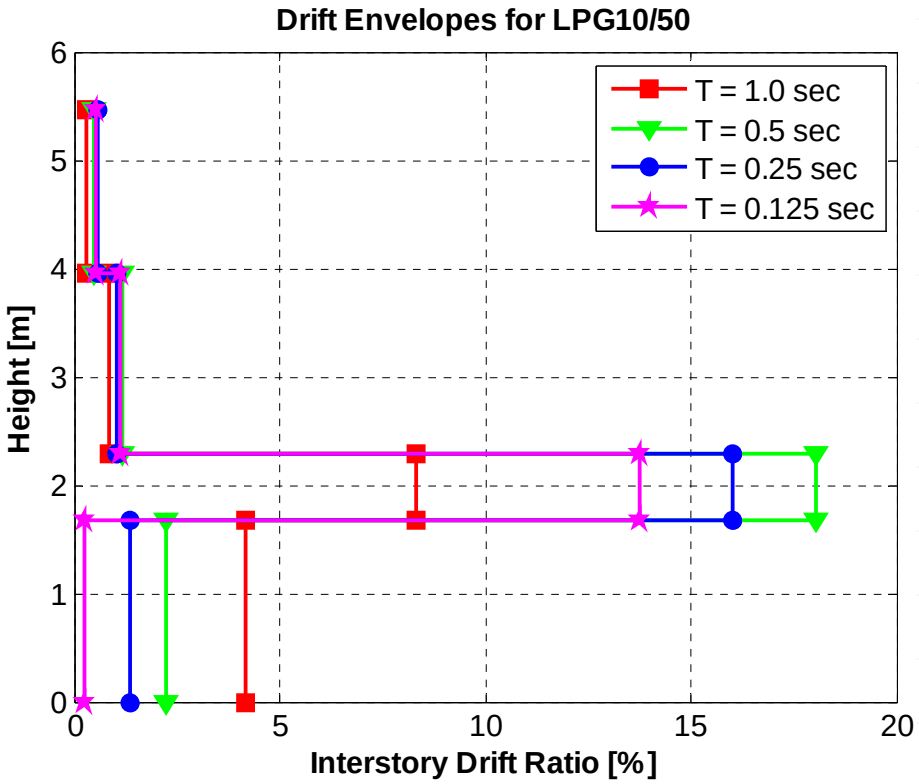


Model B

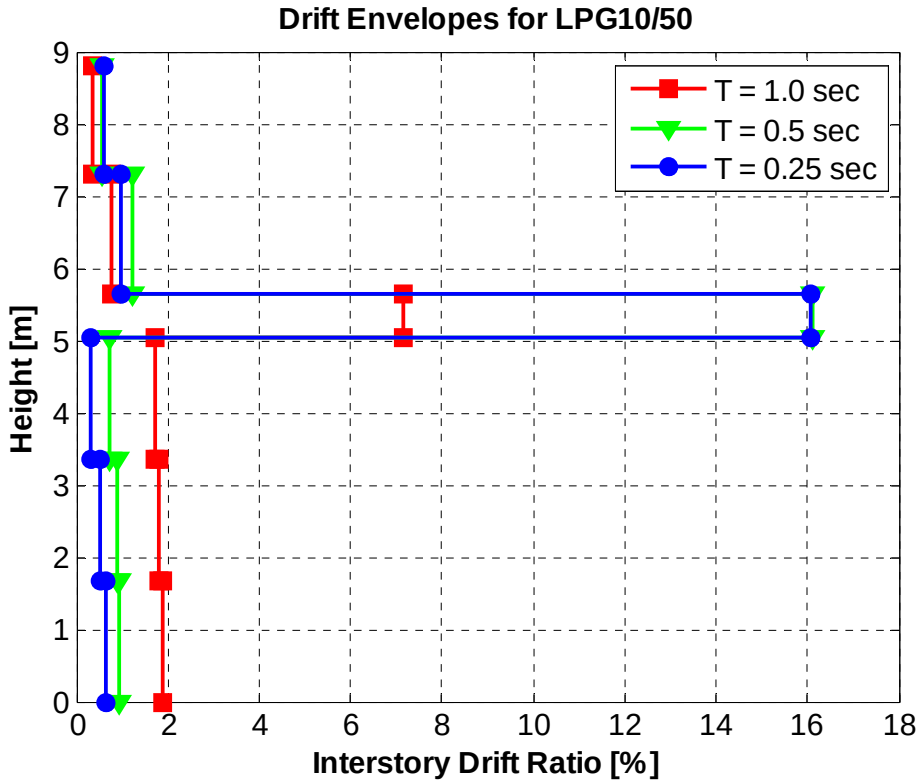


Drift Envelopes

Model A

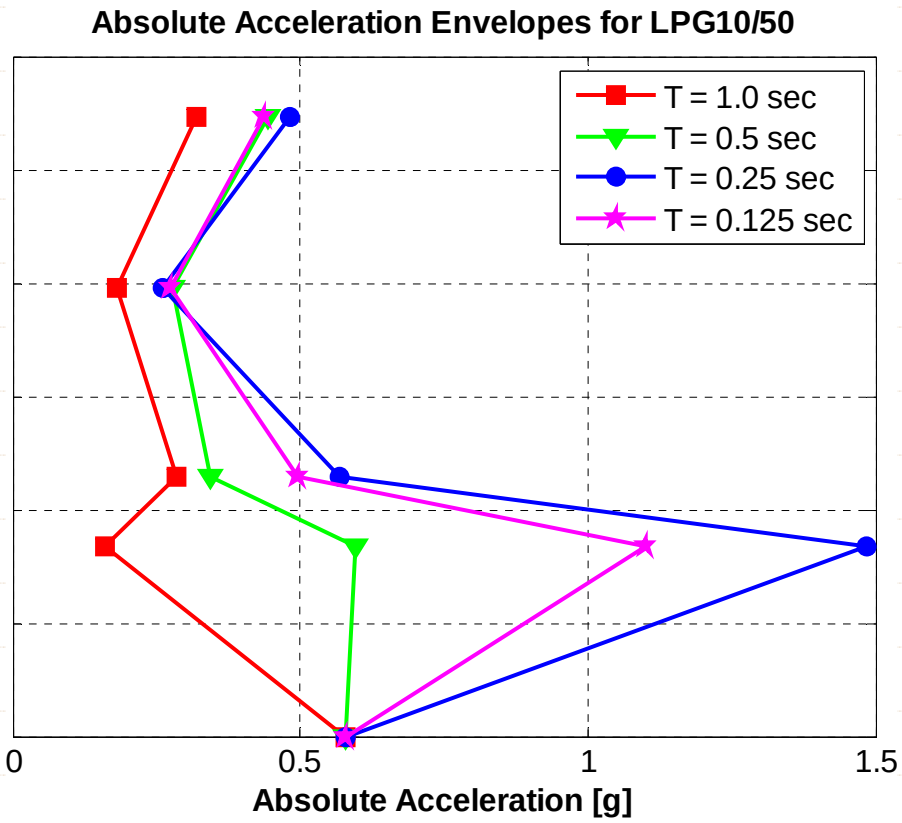


Model B

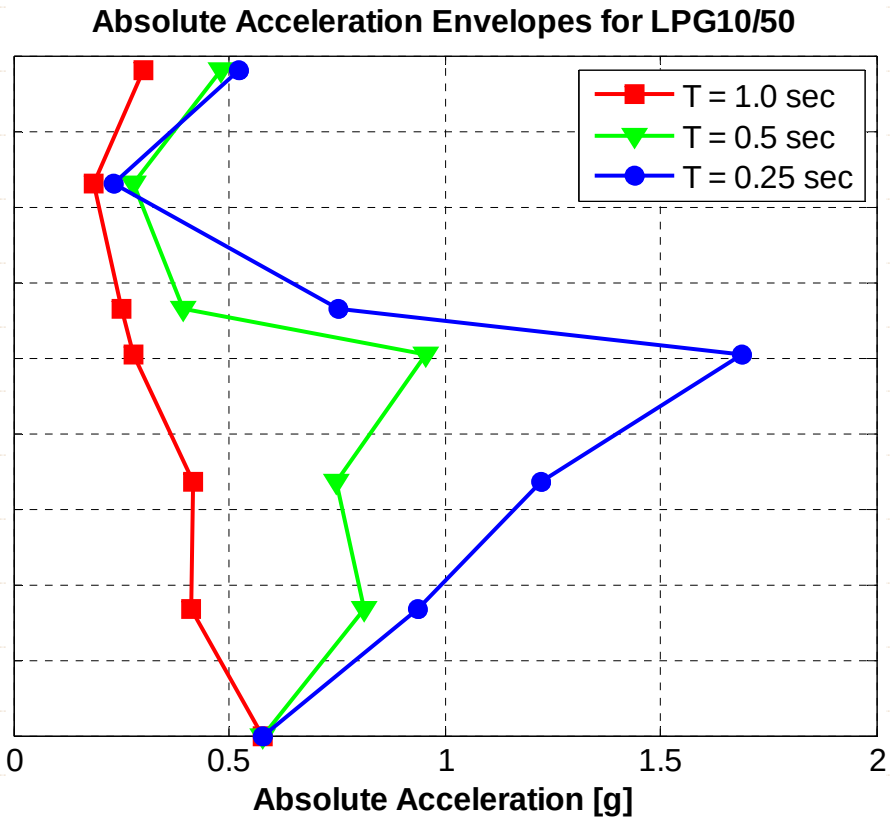


Response Envelopes

Model A



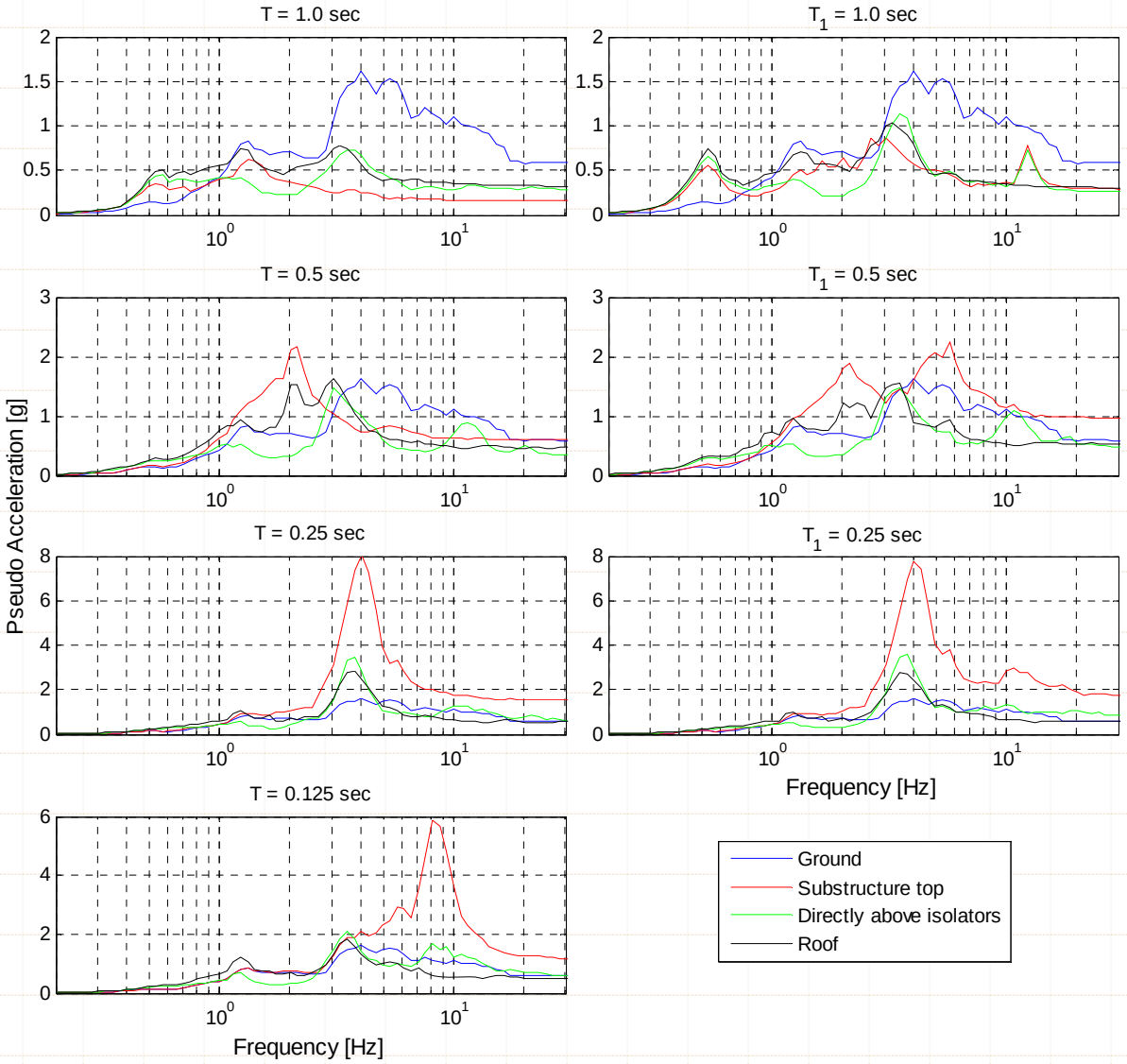
Model B



Floor Response Spectra

Model A

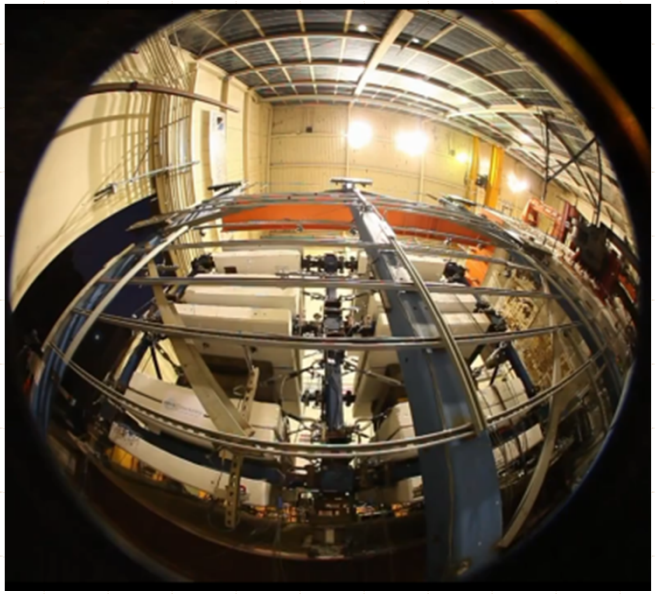
Model B



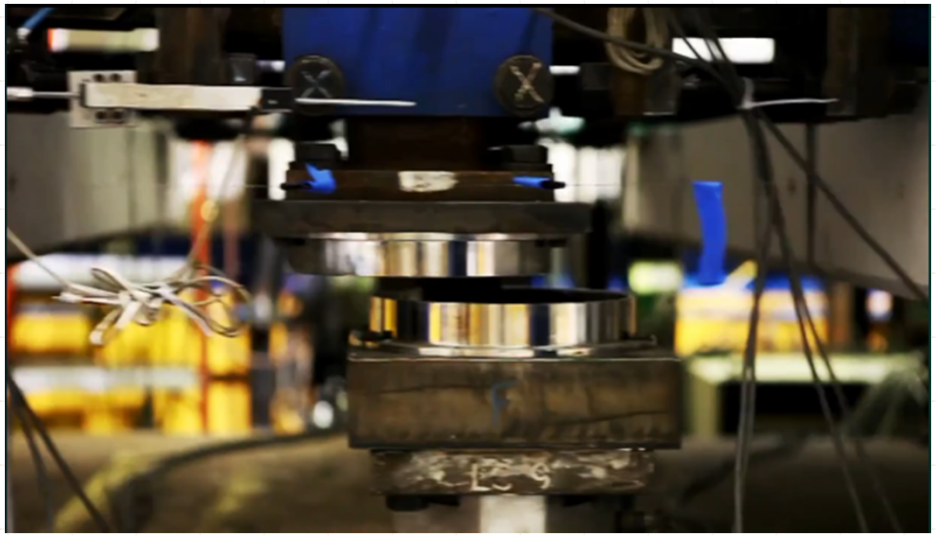
Conclusions

- Efficiently test portion of the structure though hybrid simulation
- Hybrid testing reproduced desired input
- Isolation displacement was larger for short period substructures
- The level of superstructure response is tied only to the peak acceleration levels coming from the substructure, with larger accelerations resulting in larger superstructure responses

Earthquake Exhibit: Life on a Dynamic Planet



CALIFORNIA ACADEMY OF SCIENCES



EARTHQUAKE

Questions?
Thank you!

http://openfresco.berkeley.edu/

The development of OpenFresco and the TIPS project have been sponsored in parts by the National Science Foundation through grants from the NEES Consortium, Inc.

OpenFresco