System Level Performance Evaluation of New Bridge Bent Design Using Hybrid Simulation

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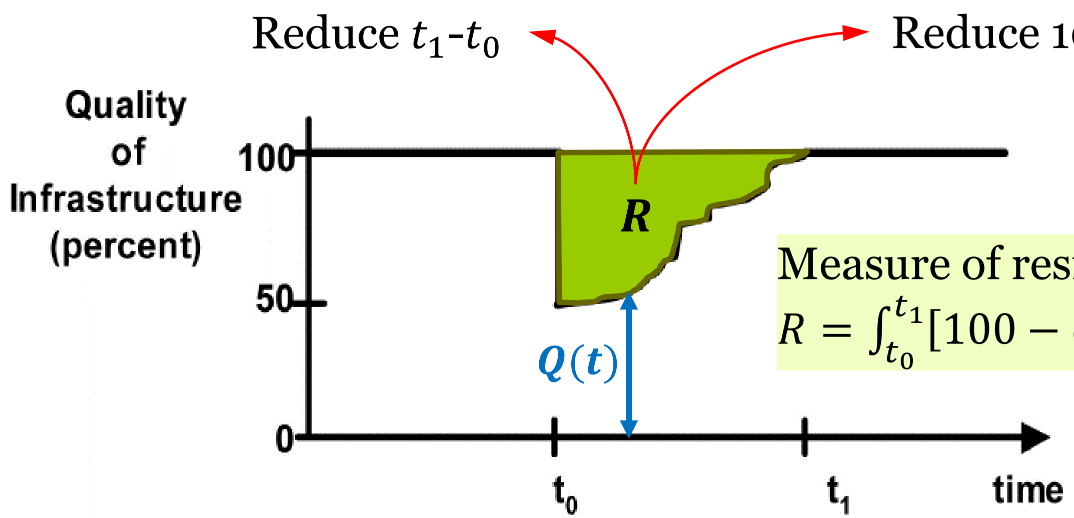
Resiliency

A seismic resilient system has:

- Reduced failure probabilities;
- Reduced consequences (casualties, damage, losses, …) from failures; and
- Reduced time to recovery (restoration of the system to its “normal” performance).



Measure of resiliency:

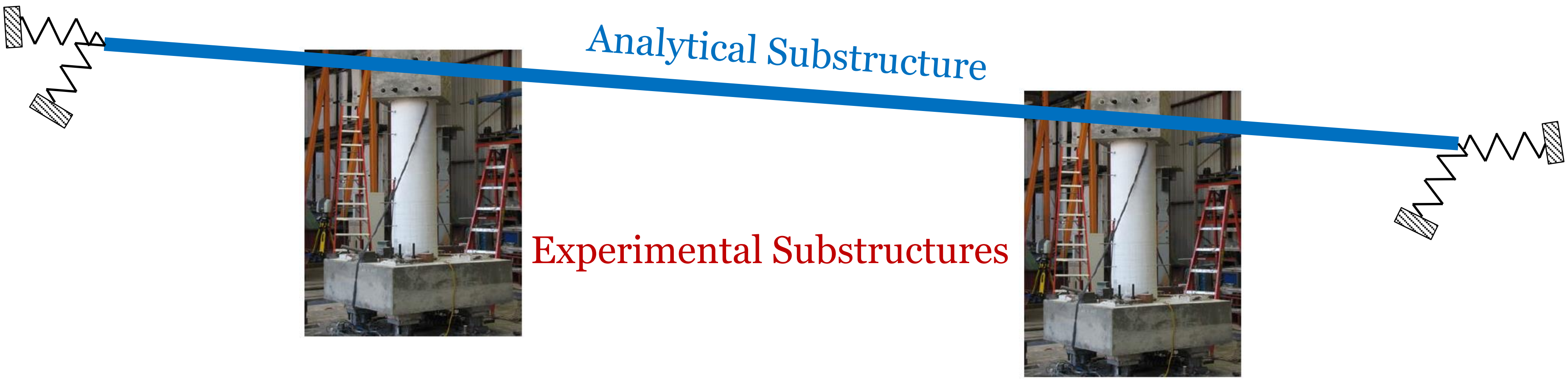
$R = \int_{t_0}^{t_1} [100 - Q(t)]dt$ → **min.**

Bridge Seismic Resilience

Ability of a bridge to:

- ✓ Minimize earthquake-induced damage;
- ✓ Maintain functionality & minimize repair cost & downtime after moderate to strong earthquakes.

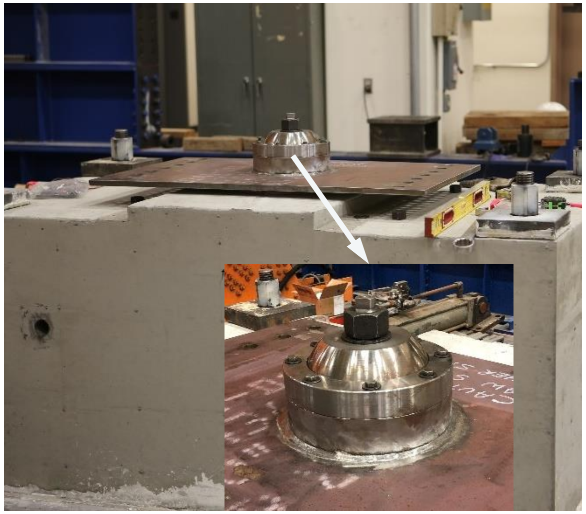
Why Hybrid Simulation (HS) ?



- Analytical substructures: Modeled with confidence
- Experimental substructures: Difficult to model due to lack of prior data, complex geometry &/or boundary conditions, material inelastic behavior, etc.

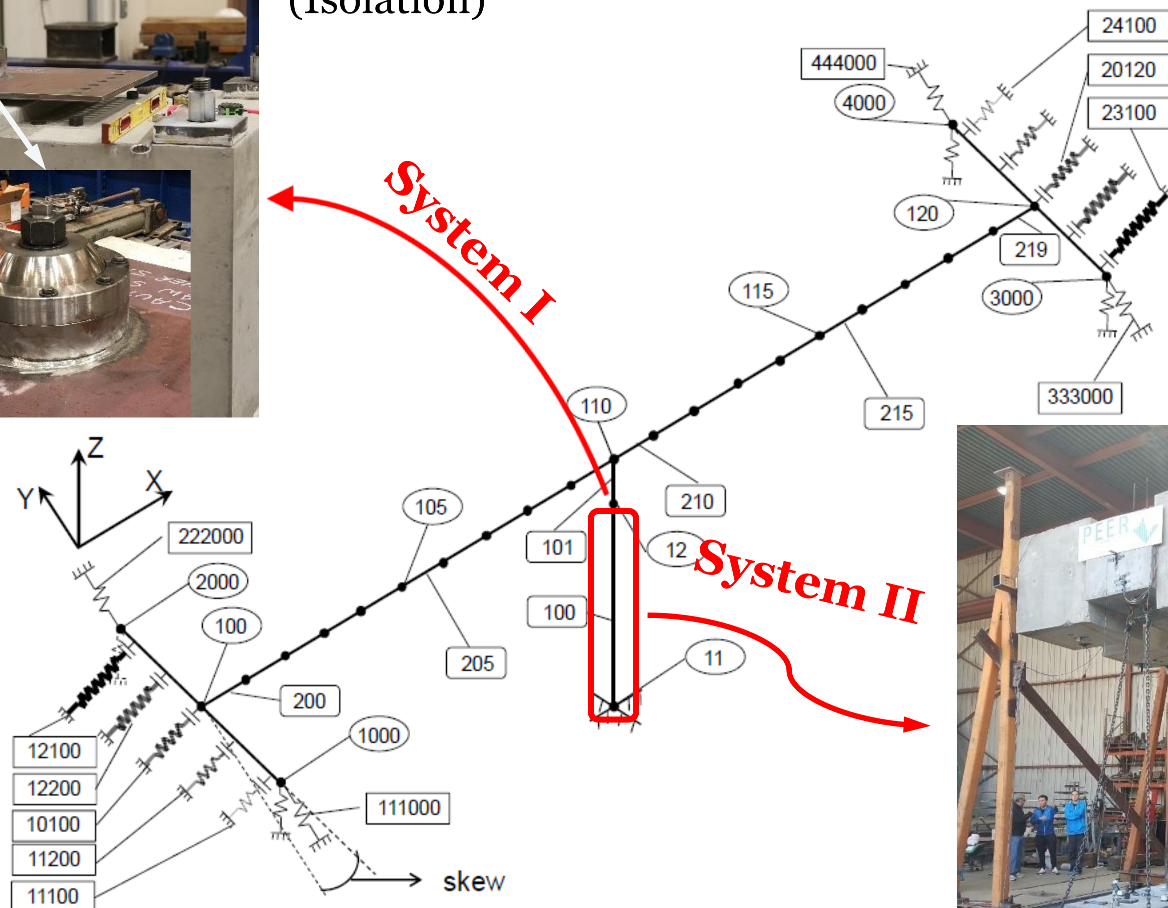
Limited data of technologies employed in resilient bridges & difficulty to test a complete bridge → HS a feasible approach to simulate the seismic response of resilient bridges.

Resilient Bridge Systems



V-connector
(Isolation)

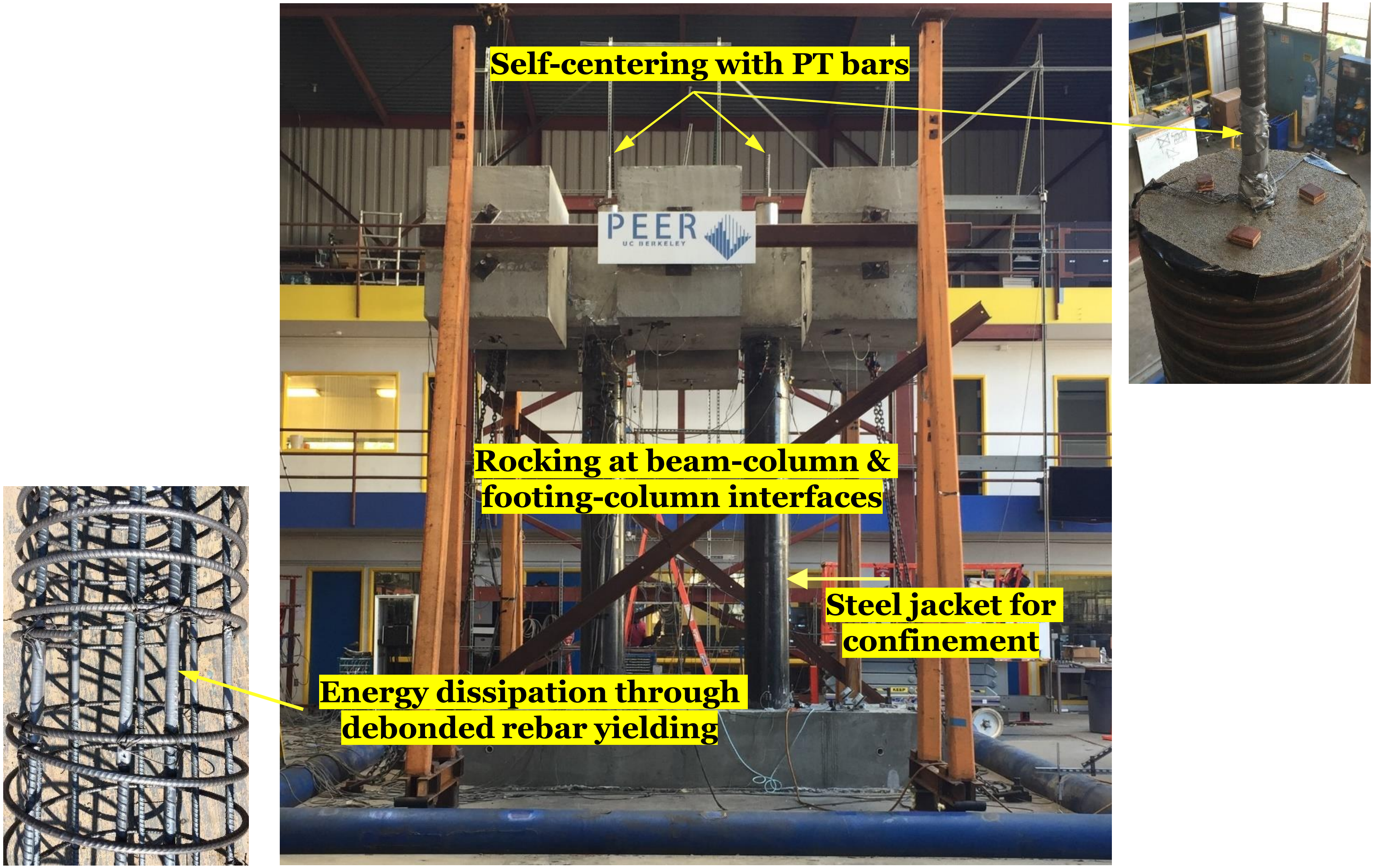
[Kaviani et al., 2012]



Self-centering, rocking &
energy dissipating columns

HS on System I was completed in 2018. Focus of this study was System II.

Innovative Design Features



Collaborative research with UC San Diego

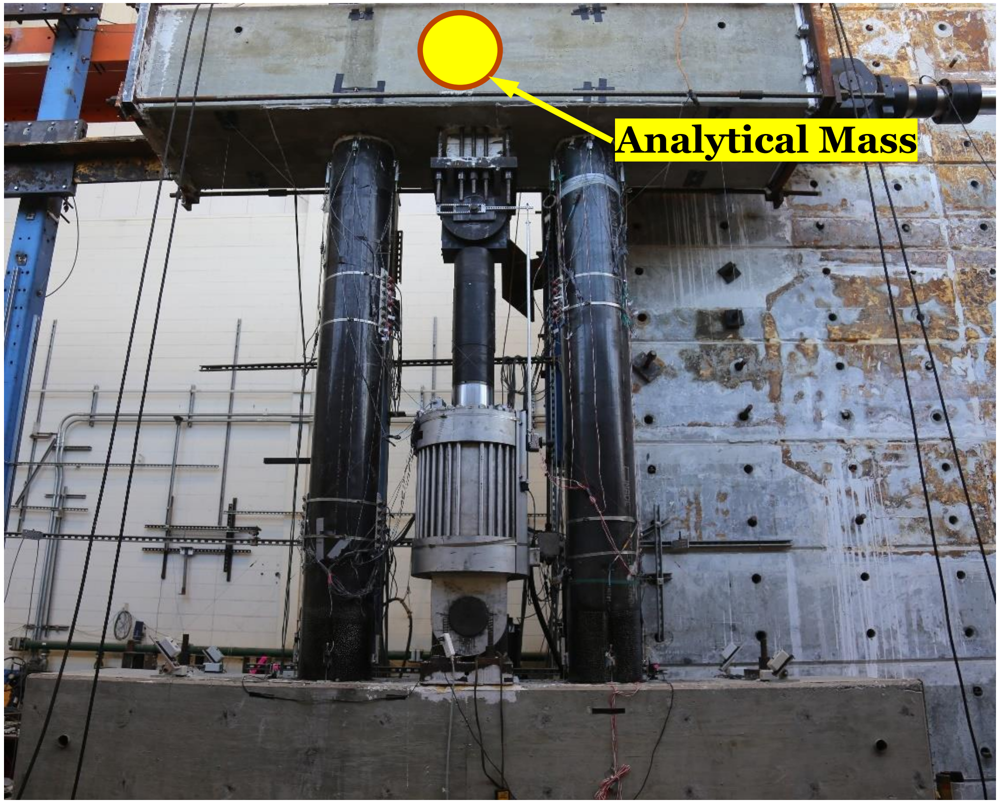
Shaking Table Test

Test setup

- ❑ 35%-scale specimen with two-column bridge bent of an existing CA highway bridge;
- ❑ Inertia force at the cap beam with affixed 6 concrete blocks;
- ❑ <u>Total of 12 GMs</u>: A horizontal & the vertical components;
- ❑ Tests conducted using PEER 6-DOF shaking table.

Hybrid Simulation Phase I

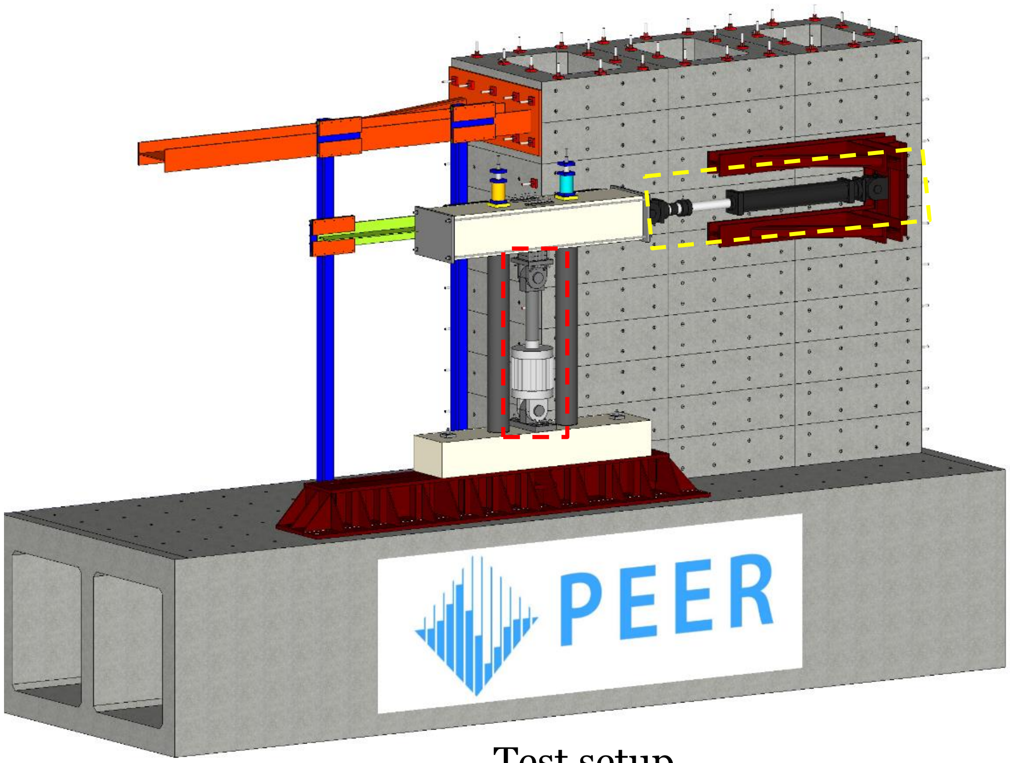
Shaking Table



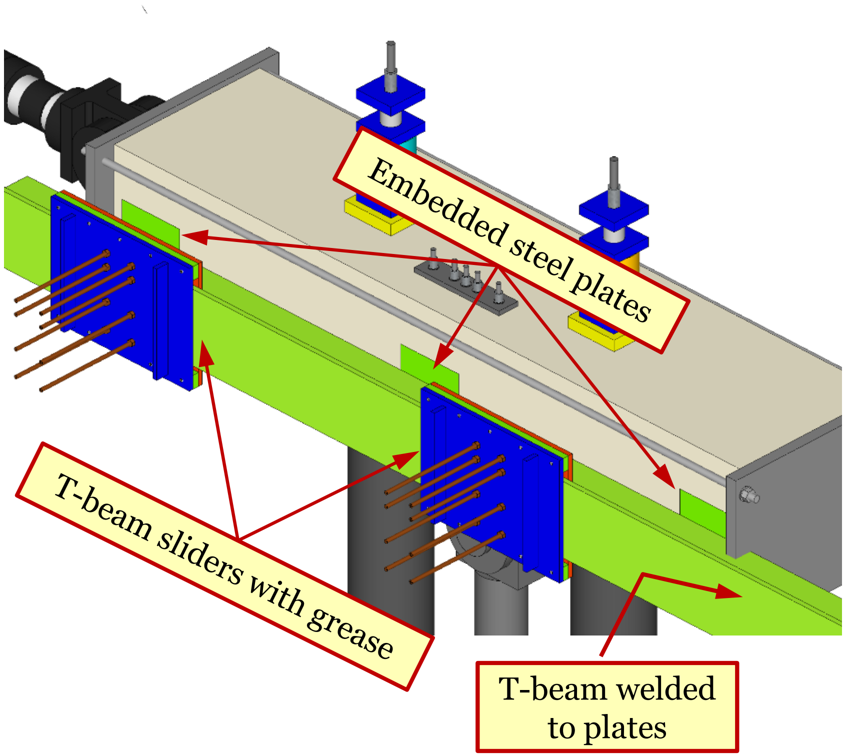
Hybrid Simulation Phase I

In Phase I, results from HS were compared against the shaking table tests.

Phase I Test Setup



Test setup



Lateral support detailing

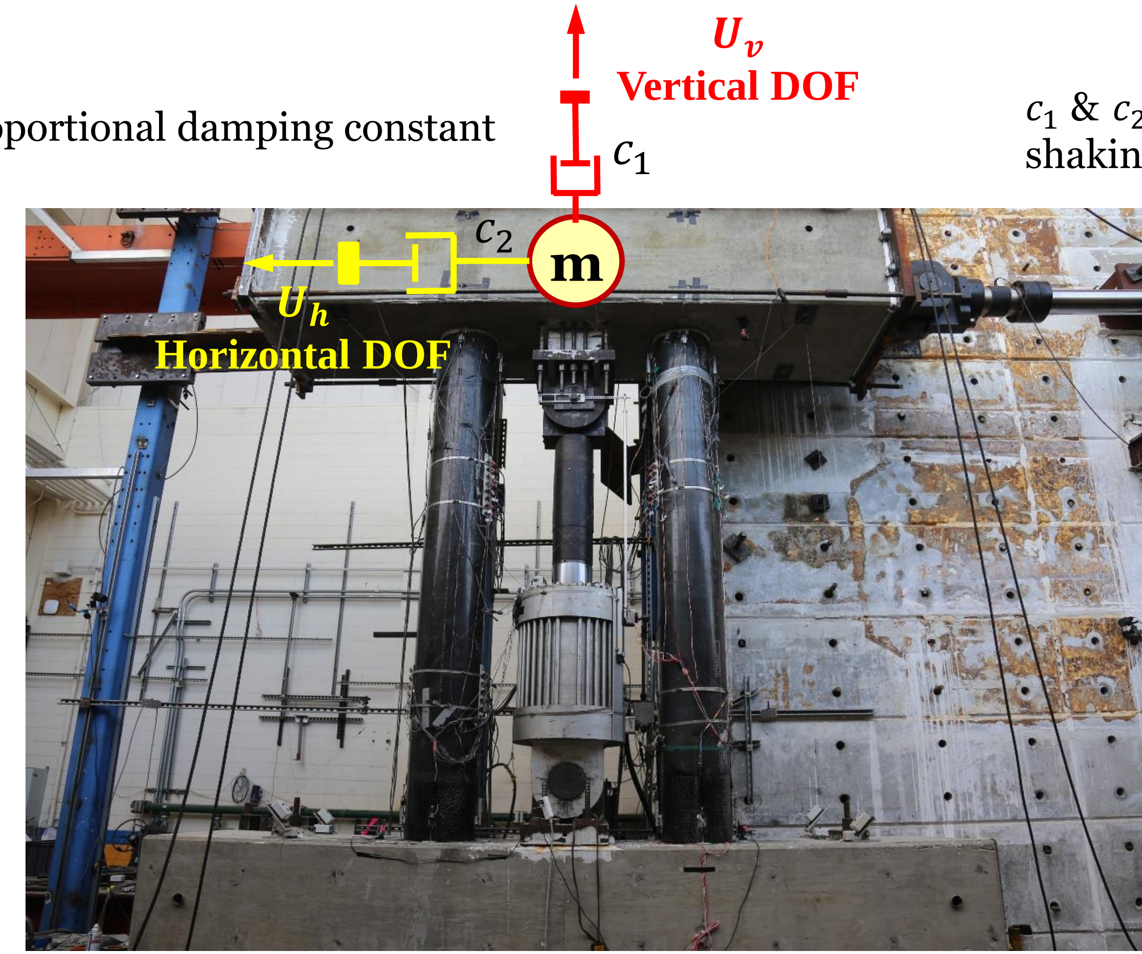
- A horizontal actuator applies lateral displacements (negligible top moment from the shaking table tests).
- For the vertical component of GM, a vertical actuator applies gravity & earthquake vertical forces.

Hybrid Simulation Phase I

$c_i = \alpha m$

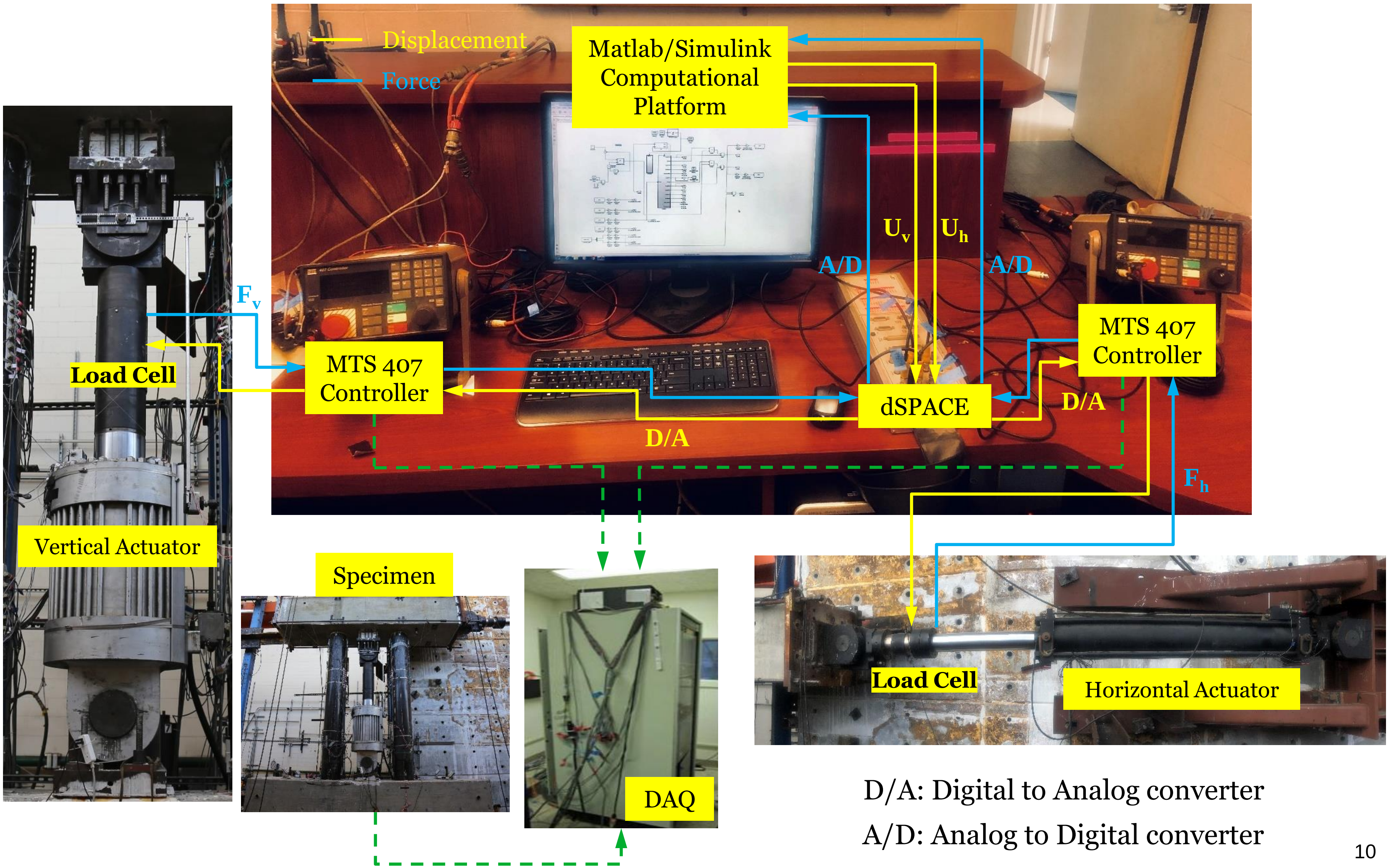
α: mass proportional damping constant

c_1 & c_2 estimated from shaking table tests



Responses from 2 directions represented by 2 independent & uncoupled differential equations of motion
→ Horizontal & vertical DOFs are formulated separately.

Hybrid Simulation System



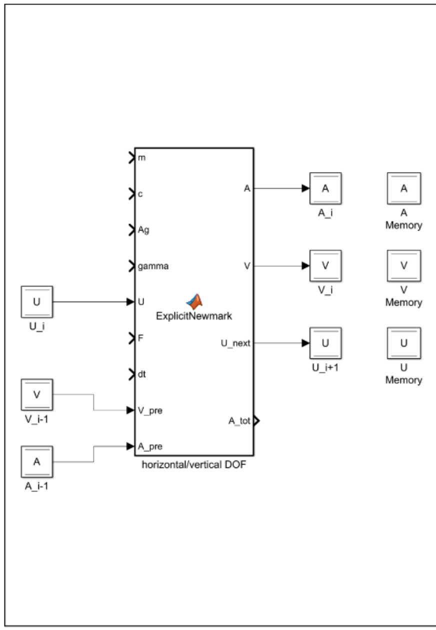
D/A: Digital to Analog converter

A/D: Analog to Digital converter

Hybrid Simulation System

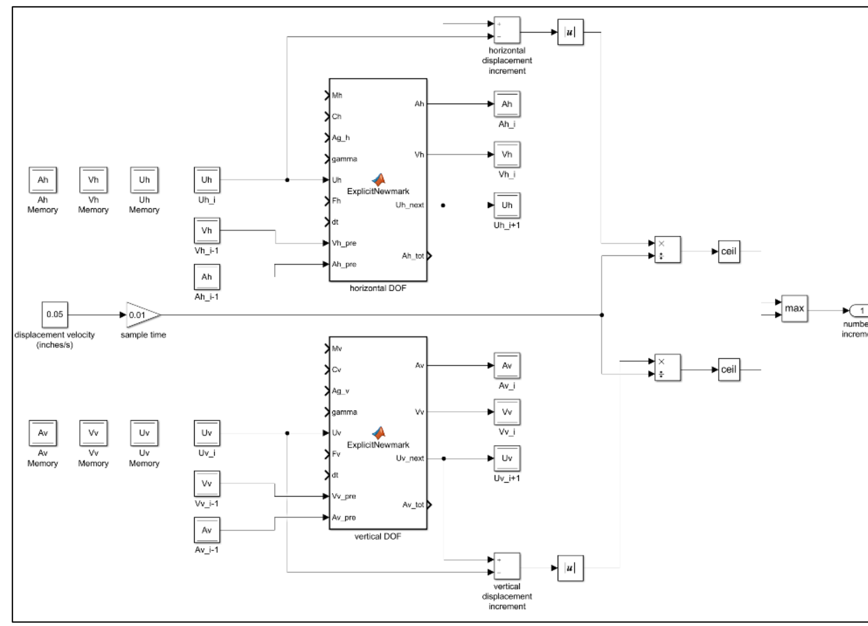
The computational platform Matlab/Simulink has two tasks:

- Numerical integration by Matlab function block using non-iterative method;
- Displacement interpolation between 2 adjacent time steps to regulate displacement application with constant velocity & avoid sudden application of large displacement commands.




```
function [A,V,U_next,A_tot] =
ExplicitNewmark(m,c,Ag,gamma,U,F,dt,V_pre,A_pre)
% Expicit Newmark algorithm for SDOF system

% Inputs: m - mass corresponds to SDOF system
%         c - damping ratio
%         Ag - ground acceleration at step i
%         gamma - Newmark velocity coefficient
%         U - displacement at step i
%         F - measured resisting force at step i
%         dt - time step, deltaT
%         V_pre - velocity at step i-1
%         A_pre - acceleration at step i-1
% Outputs: A - acceleration at step i
%          V - velocity at step i
%          U_next - displacement at step i+1
%          A_tot - total acceleration at step i

% compute acceleration A at step i
P = -m*Ag;
m_eff = m + dt*gamma*c;
P_eff = P - F - c*(V_pre + dt*(1 - gamma)*A_pre);
A = P_eff/m_eff;

% compute velocity V at step i
V = V_pre + dt*((1 - gamma)*A_pre + gamma*A);

% compute displacement U_next at step i+1
U_next = U + dt*V +0.5*(dt^2)*A;

% compute total acceleration A_tot at step i
A_tot = A + Ag;
```

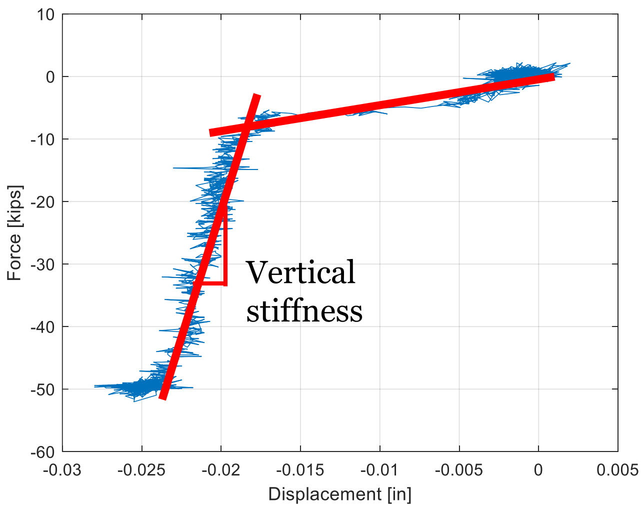
Numerical integration



Displacement interpolation

Gravity Loading

Before HS, a gravity load of 47 kips representing the six mass blocks is applied.



Force-displacement plot

Actuator-specimen connection details

- Limitations of experimental setup → switch from disp. control to force control in vl. dir.;
- Applied vertical force obtained by multiplying specimen's vertical stiffness with calculated vertical displacement considering effect of vertical ground motion component.

Hybrid Simulation Phase I

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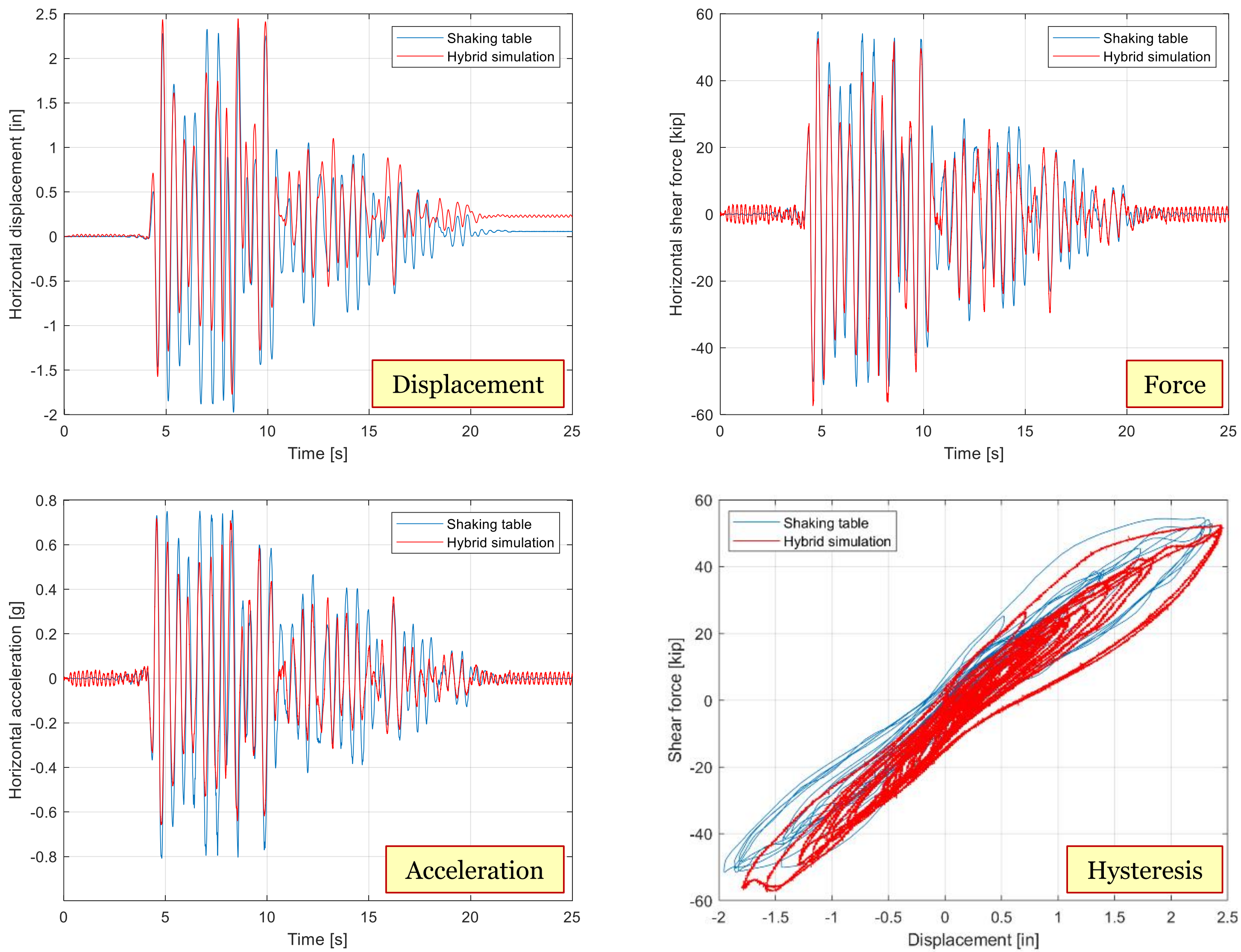
Ground Motions used in Hybrid Simulation
(from accelerometers mounted on the shaking table)

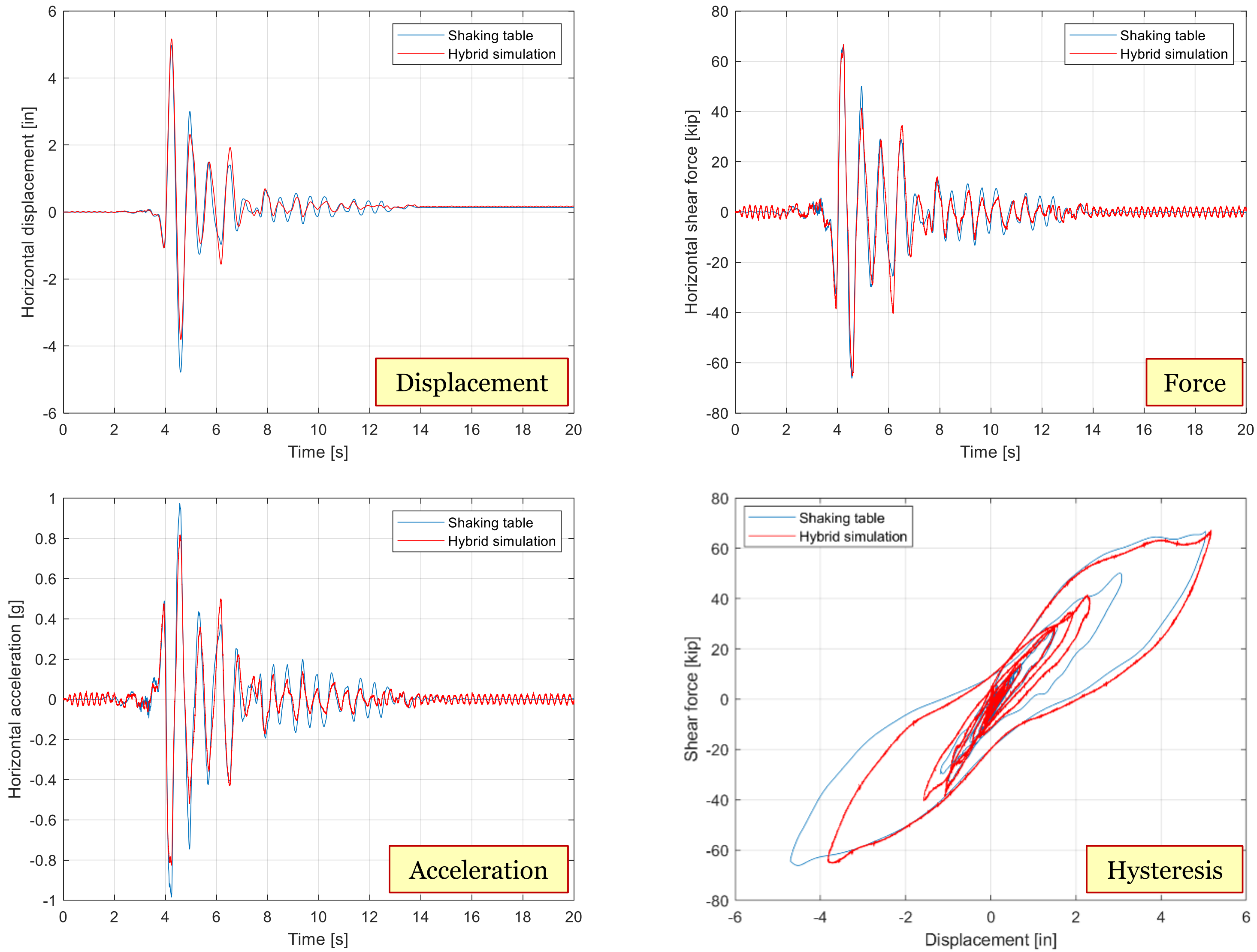
EQ #	Event Name	Station Name	Unscaled PGA [g]	Scale Factor	Expected Drift [%]
01	For checking shaking table tests and not used in HS				
02	Landers, 1992	Lucerne	0.72	0.9	0.6
03	Tabas, 1978	Tabas	0.85	-0.9	1.8
04	Kocaeli, 1999	Yarimca	0.30	1.0	0.6
05	Northridge, 1994	RRS	0.85	0.8	4.0
06	Duzce, 1999	Duzce	0.51	1.0	1.8
07	Northridge, 1994	NFS	0.72	-1.2	4.0

Phase I Results



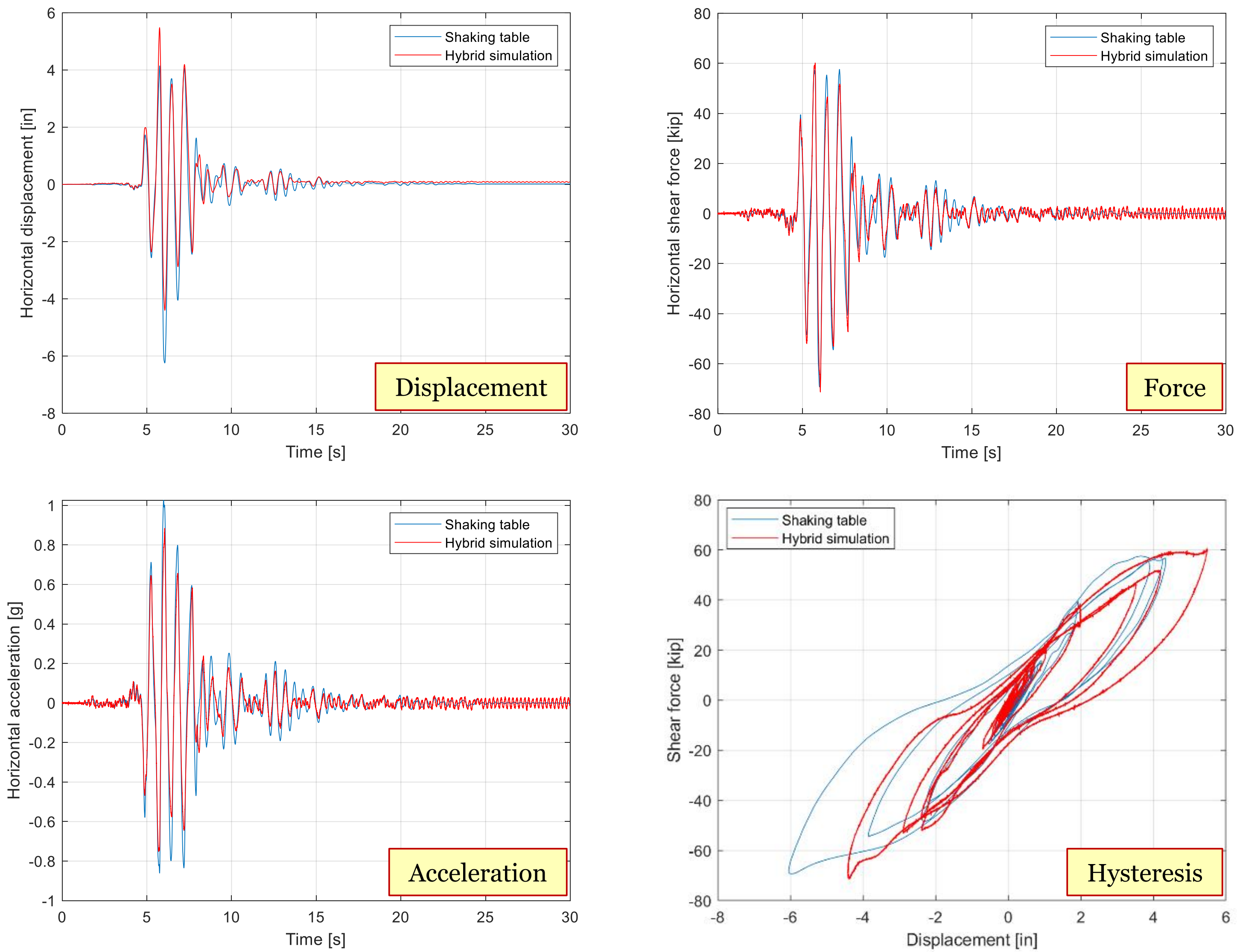
EQ3 (Actual HS drift ratio: 1.85% vs. 1.8%)

Phase I Results



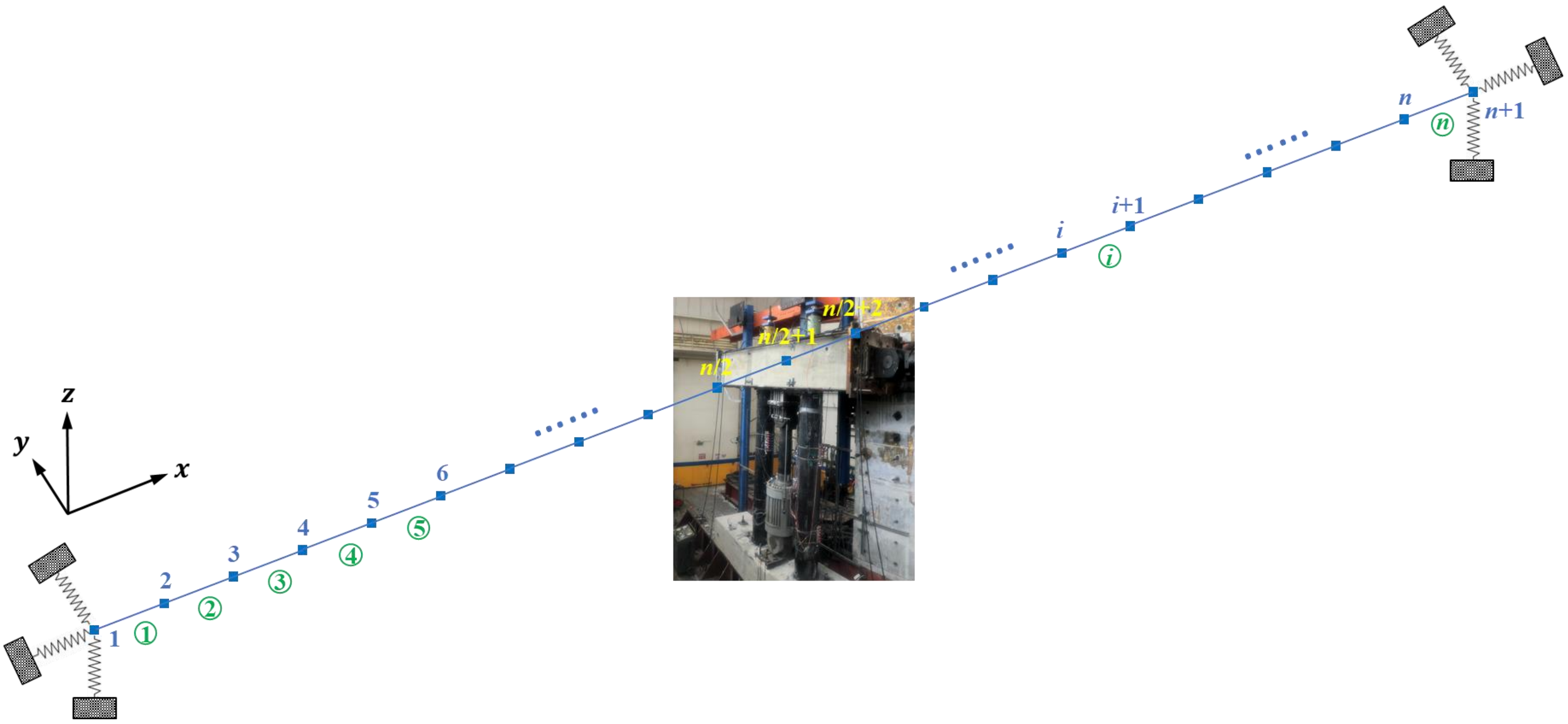
EQ5 (Actual HS drift ratio: 3.92% vs. 4.0%)

Phase I Results



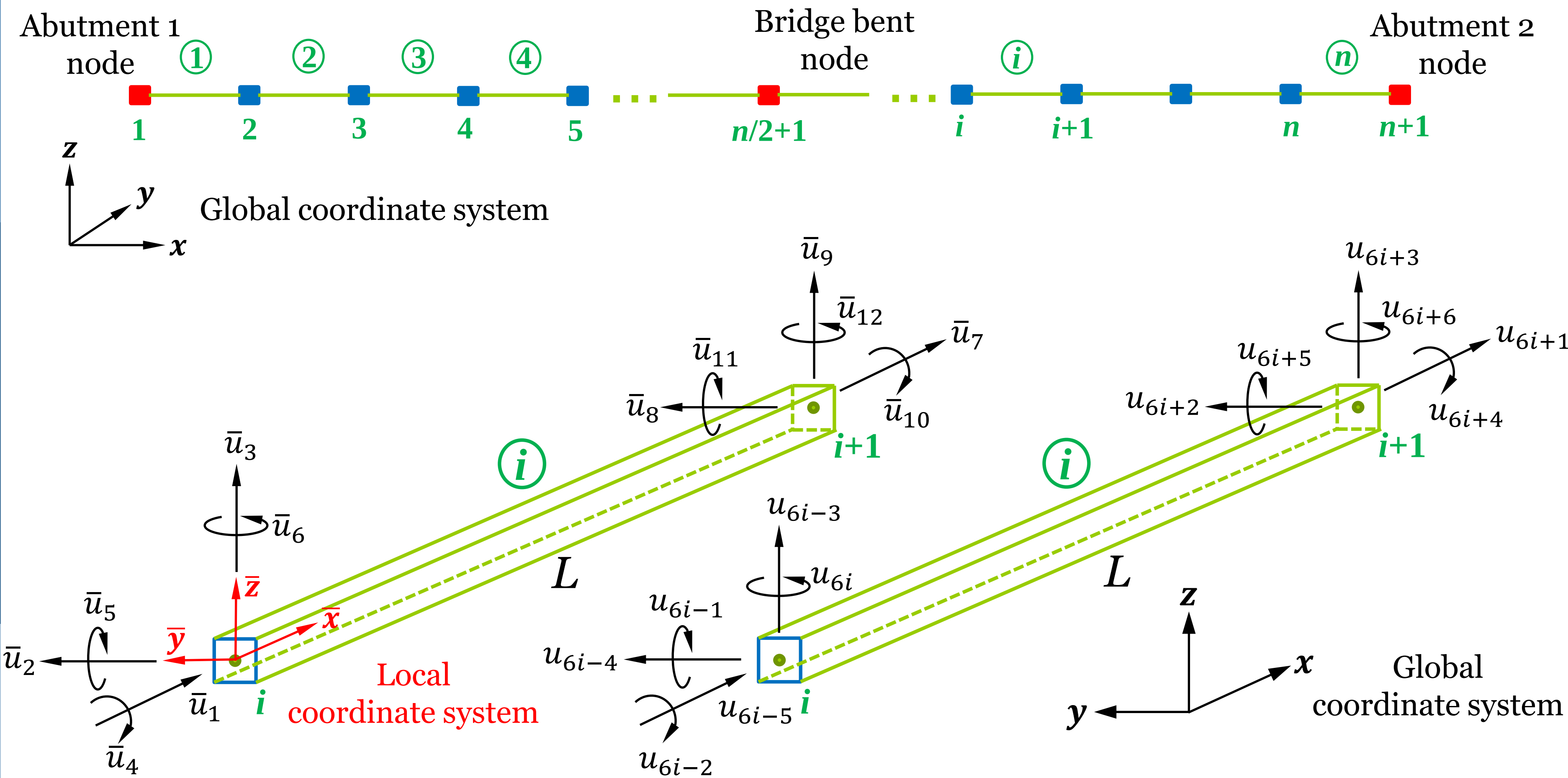
EQ7 (Actual HS drift ratio: 4.2% vs. 4.0%)

Hybrid Simulation Phase II



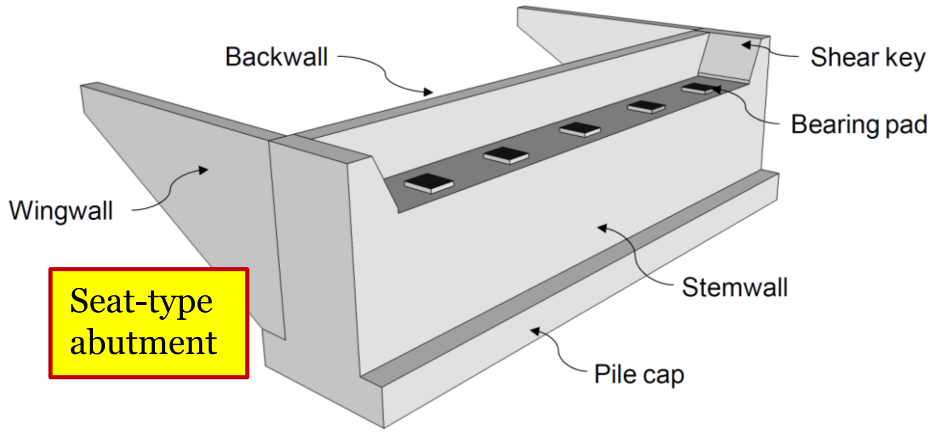
In Phase II, the bridge bent is simulated as the experimental substructure while the rest of the bridge is modeled analytically to consider the system level response of the bridge.

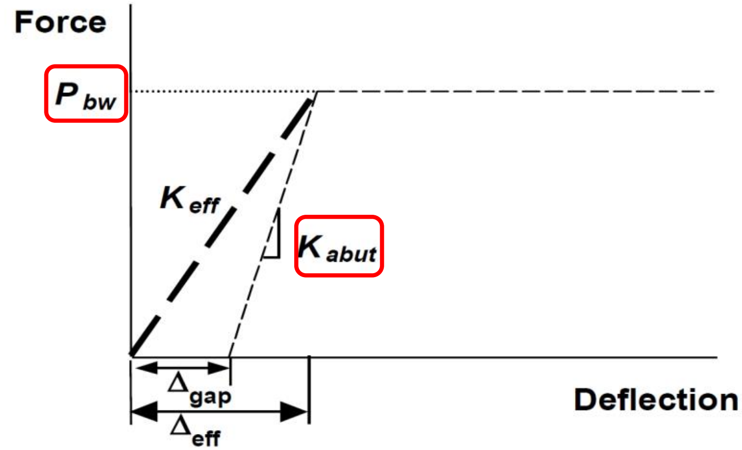
Bridge Deck Modeling



- 3D linear elastic frame element used for the bridge deck without coordinate transformation;
- Direct stiffness implementation method used to formulate the stiffness matrix; and
- Consistent mass matrix employed.

Simplified Abutment Modeling





According to Caltrans SDC (2013):

$$K_{abut} = 25\frac{kip/in}{ft} \times w_{bw} \times \left(\frac{h_{bw}}{5.5\ ft}\right)$$

$$P_{bw} = A_e \times 5.0\ ksf \times \frac{h_{bw}}{5.5}$$

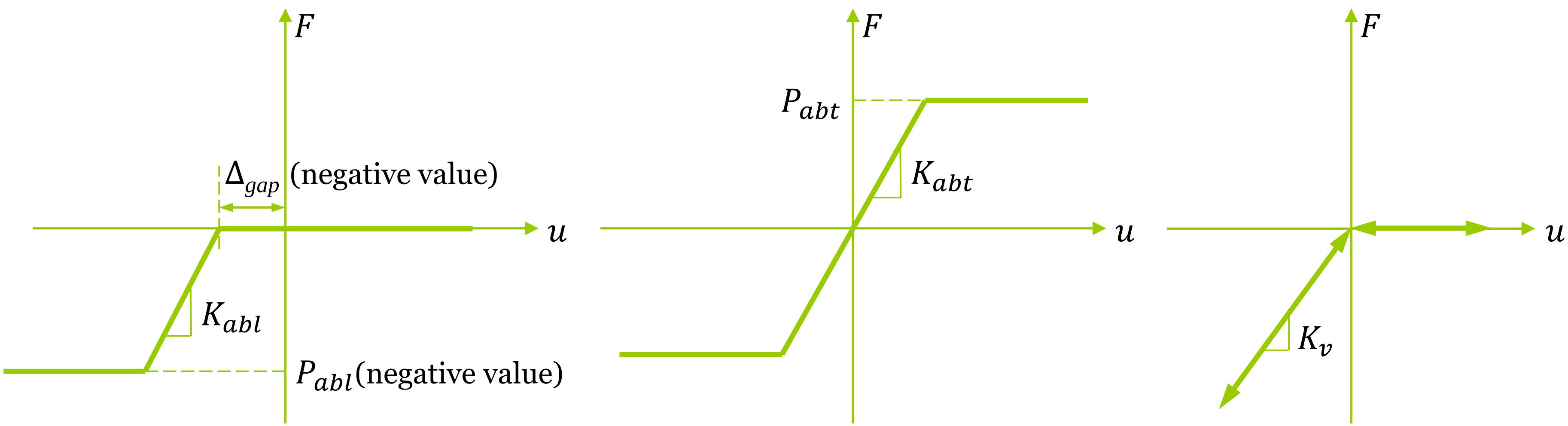
$$A_e = h_{bw} \times w_{bw}$$

Jack Tone Road Overcrossing

- Abutment height h_{bw} and width w_{bw} were obtained from the prototype bridge geometry;
- Gap distance Δ_{gap} was taken to be 1 in.; and
- Wall effectiveness coefficient C_L and participation coefficient C_w were taken to be 2/3 and 4/3 in the transverse direction (Maroney and Chai, 1994).

Simplified Abutment Modeling

- Use 3 nonlinear springs —longitudinal, transverse & vertical— at each end of the bridge deck;
- **Longitudinal to represent the abutment backwall**: a compression-only spring with an elastic perfectly-plastic gap material;
- **Transverse to represent the backfill, wingwall & pile system**: a spring with an elastic perfectly-plastic material;
- **Vertical to represent the bearing pad** : a compression-only elastic spring;



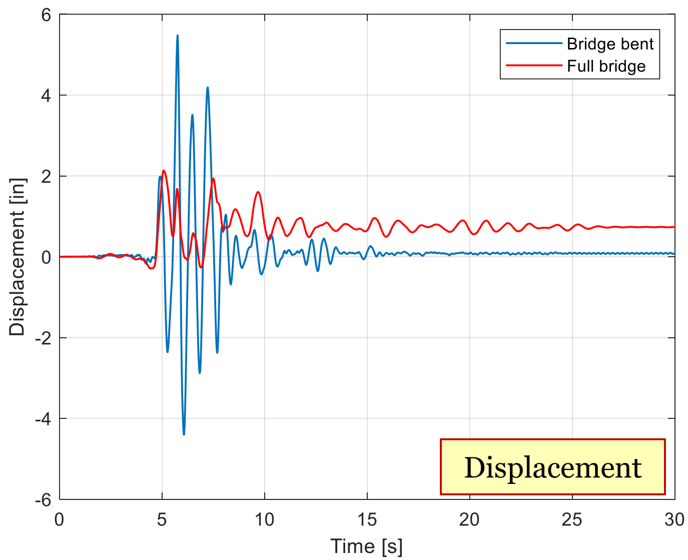
Longitudinal spring | Transverse spring | Vertical spring

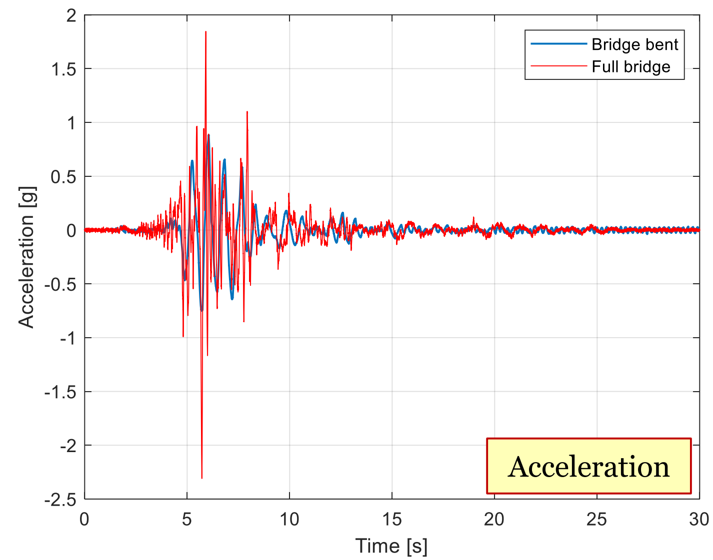
The resisting forces added to global resisting force vector after state-determination:

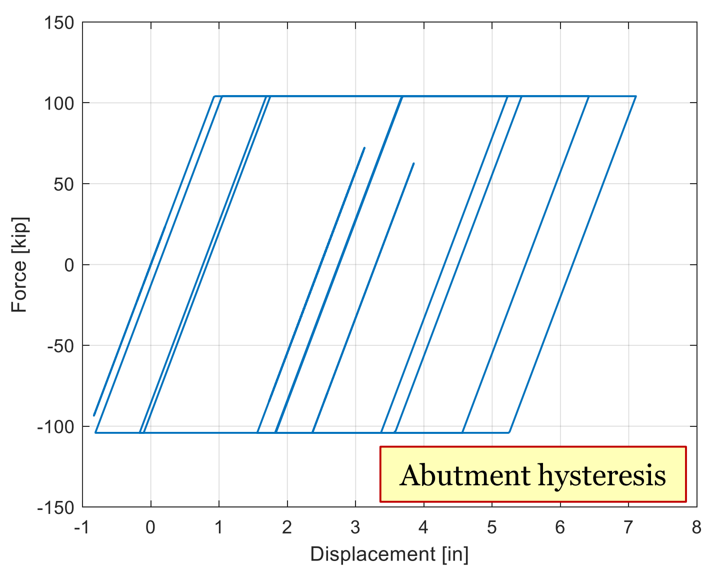
$$\boldsymbol{P}_r = \sum_{el} \boldsymbol{P}_r^{(el)} = \boldsymbol{P}_{r,deck} + \boldsymbol{P}_{r,abutment} + \boldsymbol{P}_{r,specimen}$$

Phase II Results

Repeat EQ7 on the full bridge system







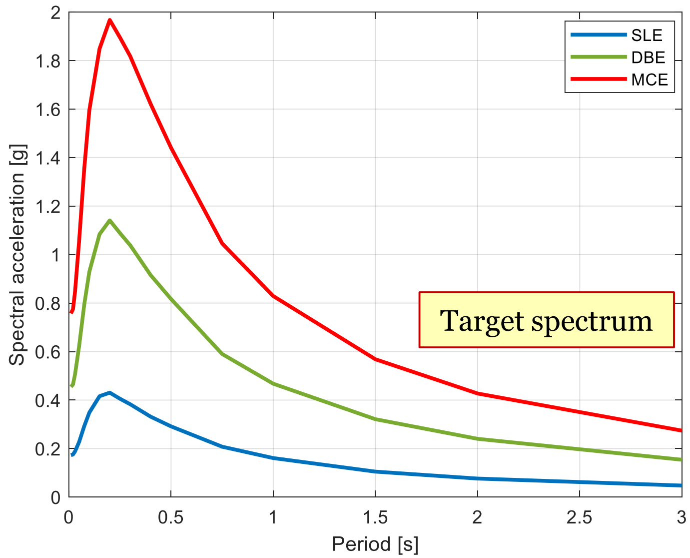
Observations:

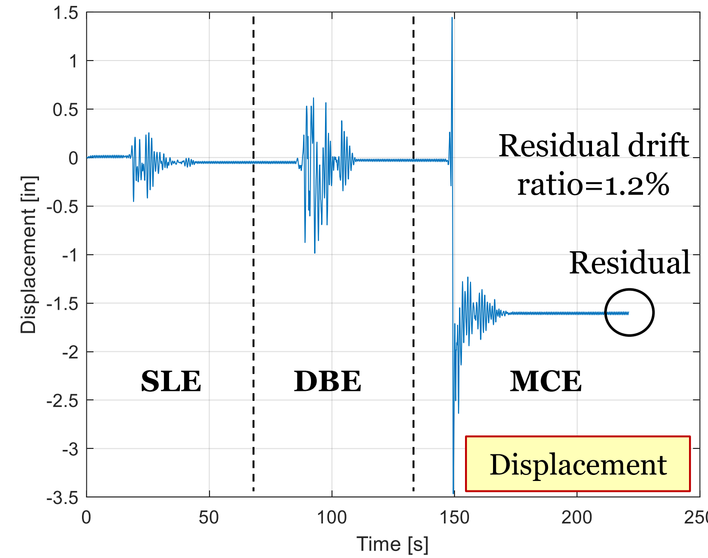
Bridge bent: Phase I; Full bridge: Phase II

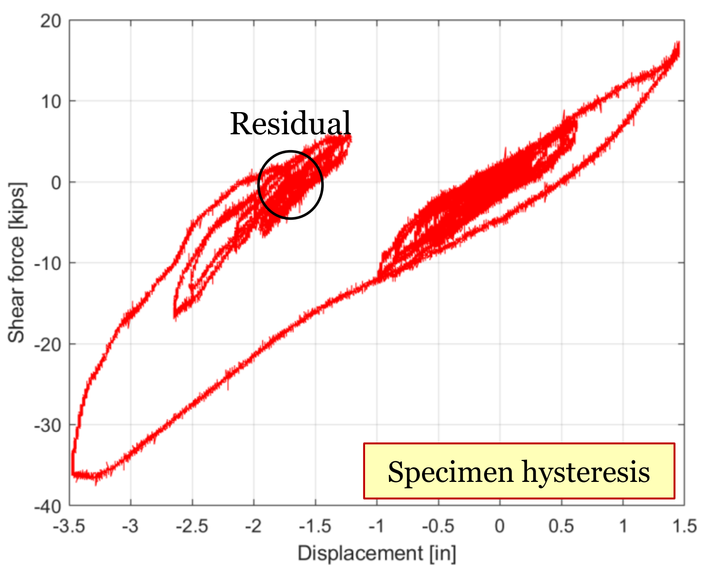
- Period elongation, as expected, is obvious;
- Smaller peak displacement but larger residual displacement; and
- Significant abutment yielding during the full bridge test is observed.

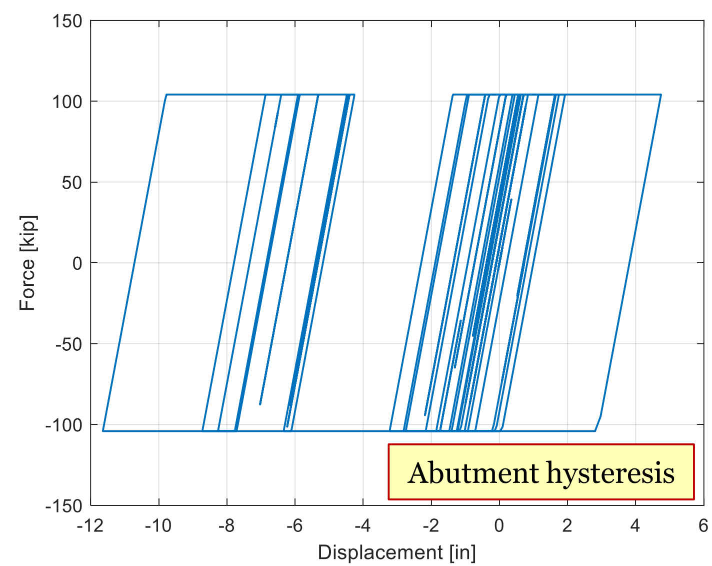
Phase II Results

Three combined motions with increasing intensity





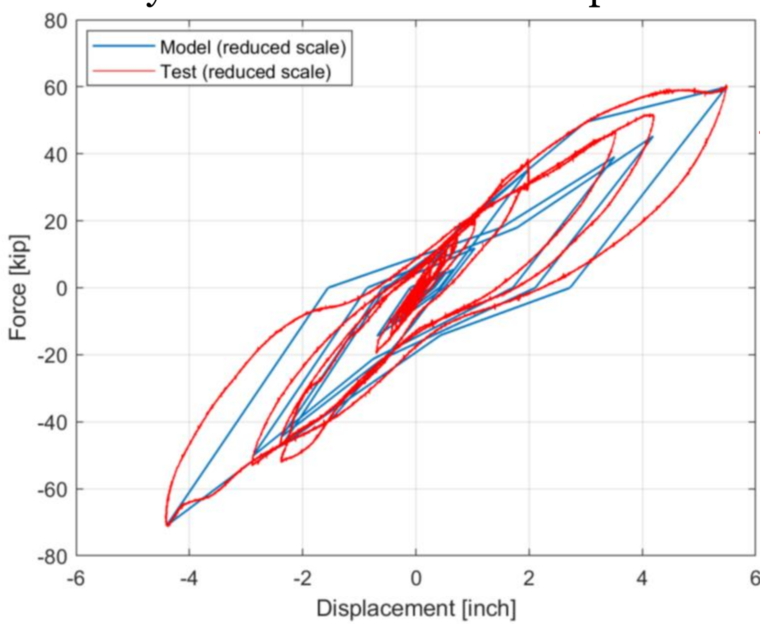


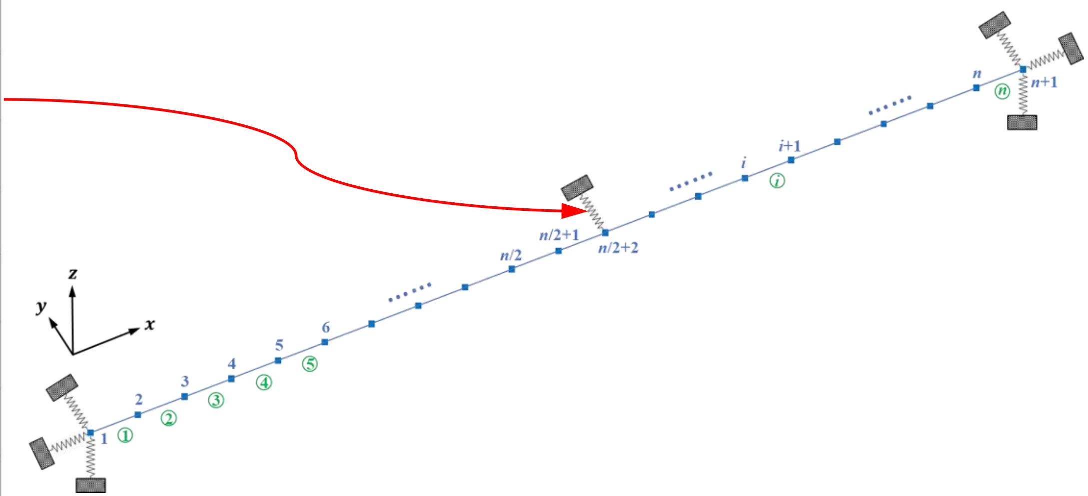


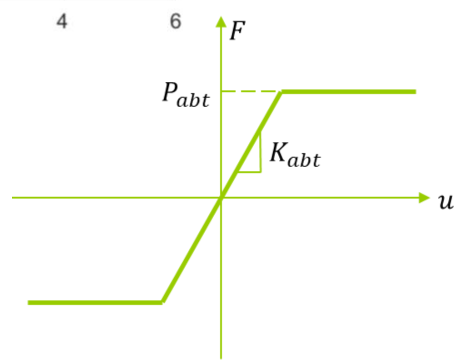
Parametric Study

- Investigate the effect of abutments on the bridge bent behavior via a parametric study; and
- The bridge bent is modeled using a zero-length spring whose hysteretic response is calibrated against a representative test run.

Hysteretic material from OpenSees



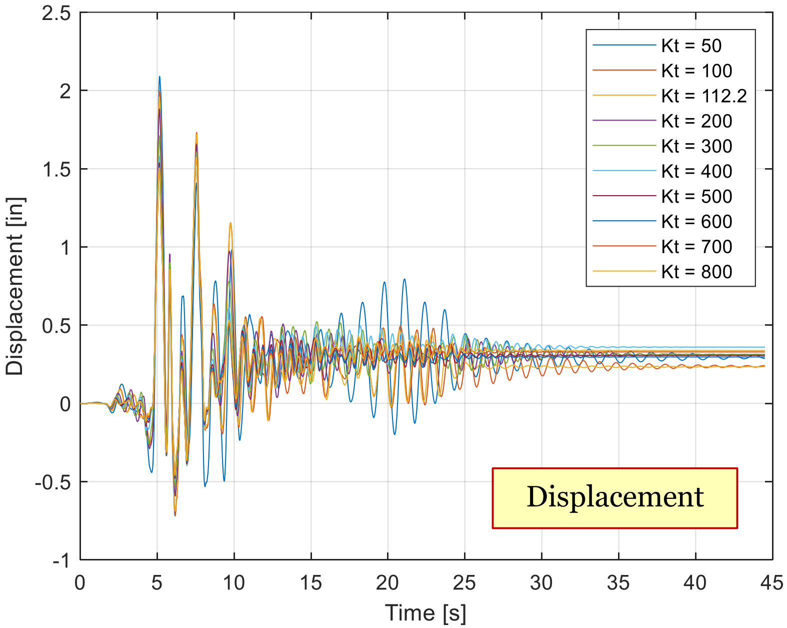


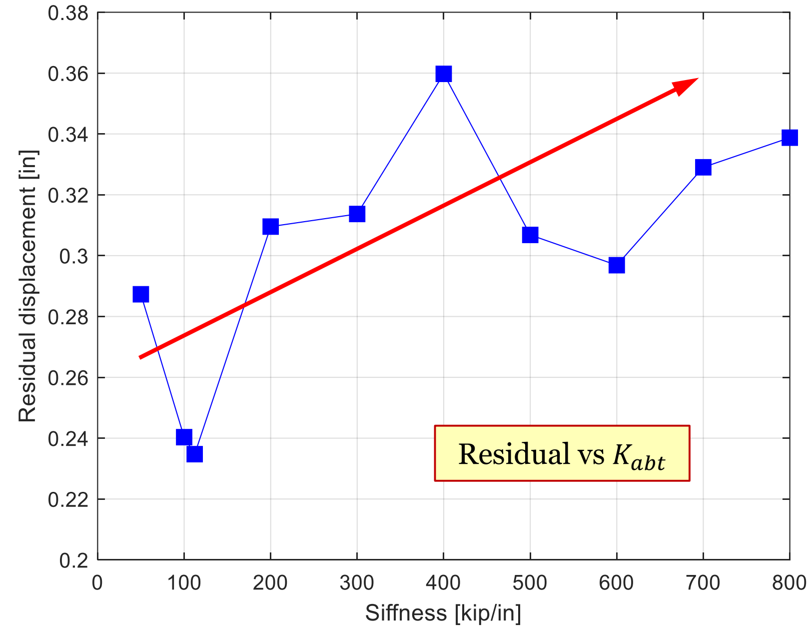


- Keep K_{abt} constant & vary P_{abt} for effect of yield strength;
- Keep P_{abt} constant & vary K_{abt} for effect of initial stiffness.

Parametric Study

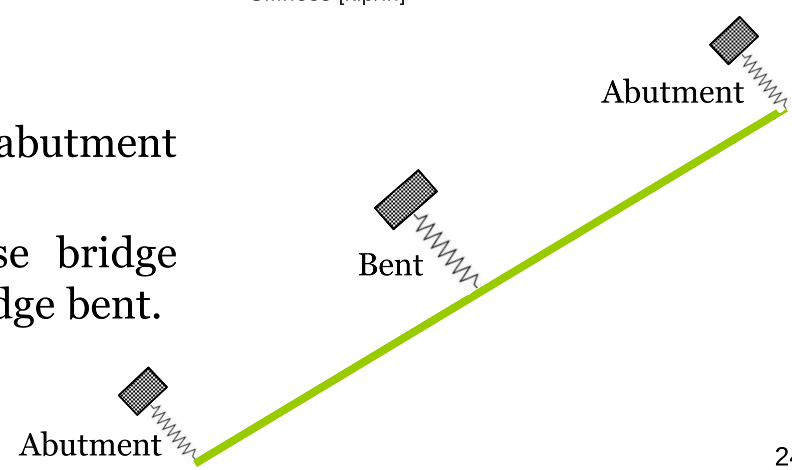
Effect of initial stiffness K_{abt}





Observations:

- Residual displacement increases "on average" as abutment stiffness increases;
- As the abutment stiffness increases, transverse bridge response is controlled by abutment instead of bridge bent.



Parametric Study

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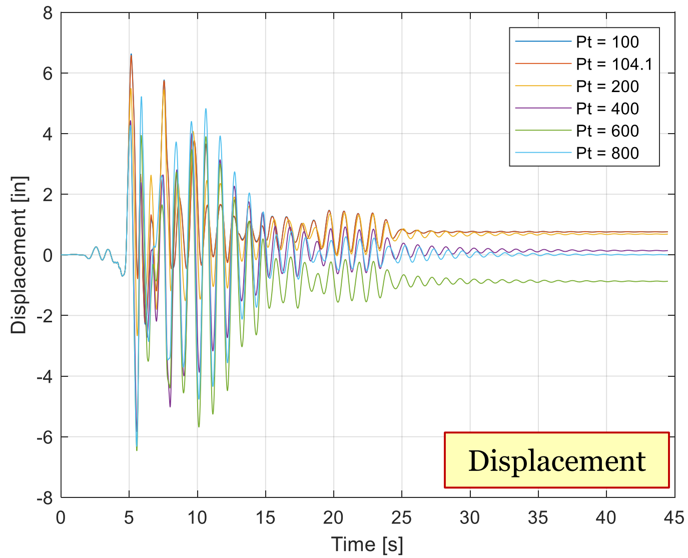
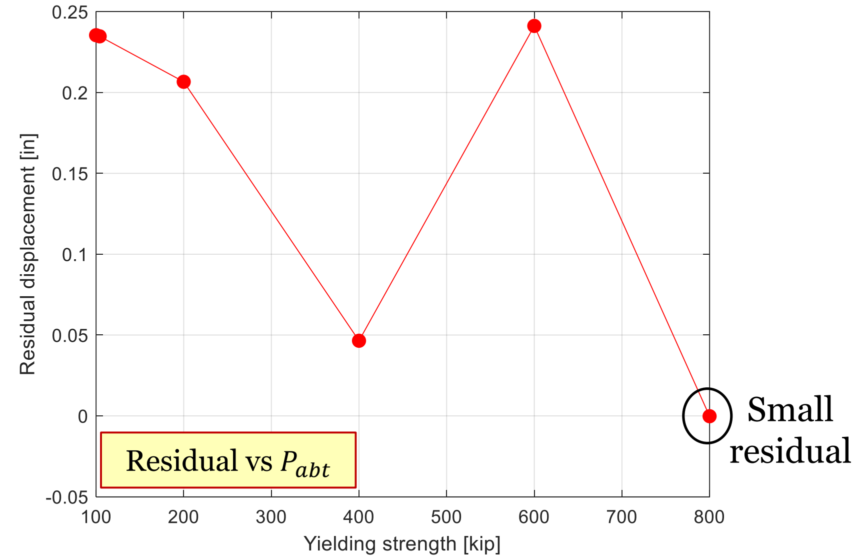
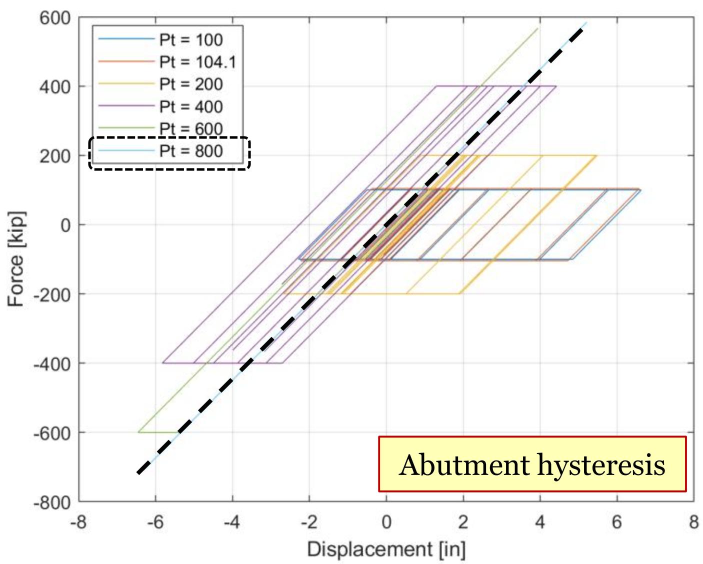
Effect of yield strength P_{abt}







Observations:

- The residual displacement is close to zero when the abutment remains elastic;
- This proves that the large residual displacement during the system level test is due to the abutment yielding; and
- There is no clear trend of the relationship between the residual displacement and the abutment yield strength P_{abt}.

Summary and Conclusions

- A HS system is developed using Matlab/Simulink as a computational platform for single & multi-degree of freedom analytical substructures;
- Phase I HS of a "resilient bridge" bent design is conducted & compared against shaking table tests. Good matching of the test results indicates:
  - Reliability of the developed HS system;
  - Confidence of HS in to test new structural/geotechnical systems.
- The bridge bent shows larger residual displacement during the system level test (Phase II) compared to the bent test (Phase I) due to yielding of the abutment;
- Attention should be given to the bridge system response including not only bridge bents and deck, but also abutments for optimal bridge performance; and
- Findings from standalone bridge bent & system level HS tests increase our understanding for damage-free bridges towards resilient transportation networks.

Thank You !