Hybrid Simulation of Bridges with Innovative Column Designs

YINGJIE WU
SELIM GÜNAY
KHALID M. MOSALAM

PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

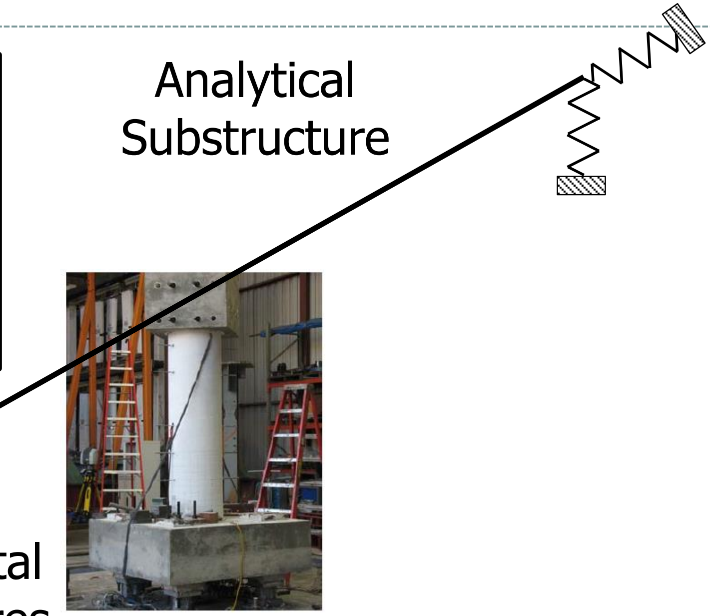
UNIVERSITY OF CALIFORNIA, BERKELEY

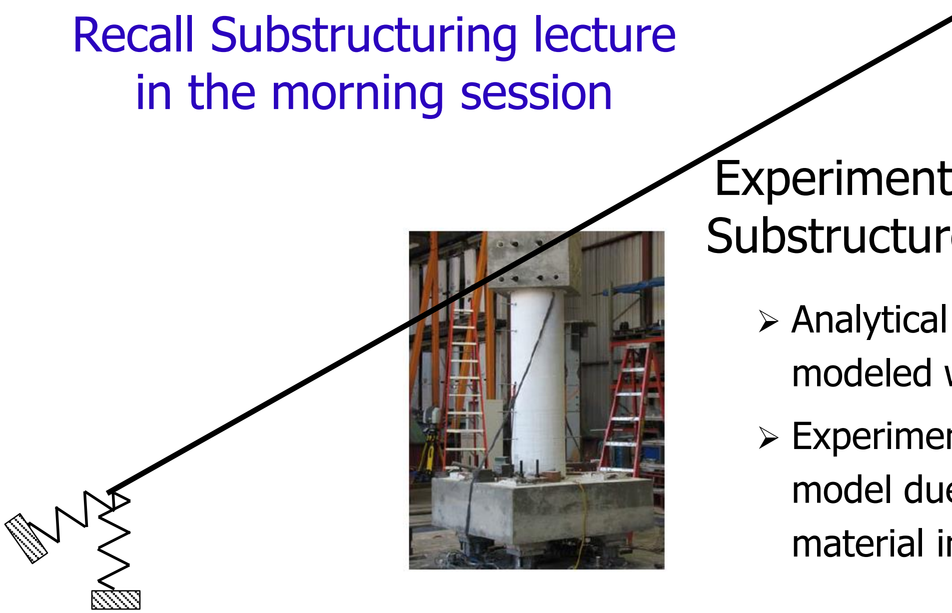
Outline

- ❑ Introduction
- ❑ Hybrid Simulation of a Bridge with a V-connector
- ❑ Hybrid Simulation of a Bridge with Self Centering, Rocking and Energy Dissipating Columns

Introduction

Recall Substructuring lecture in the morning session





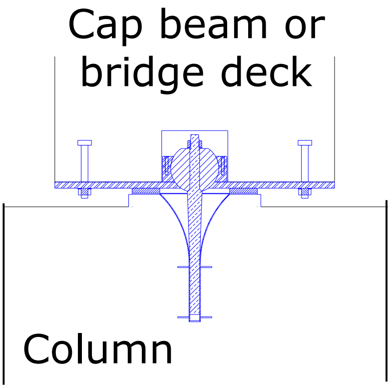
- Analytical substructures are generally those that can be modeled with confidence
- Experimental substructures are those that are difficult to model due to lack of prior data, complicated geometry, material inelastic behavior, boundary conditions, etc.

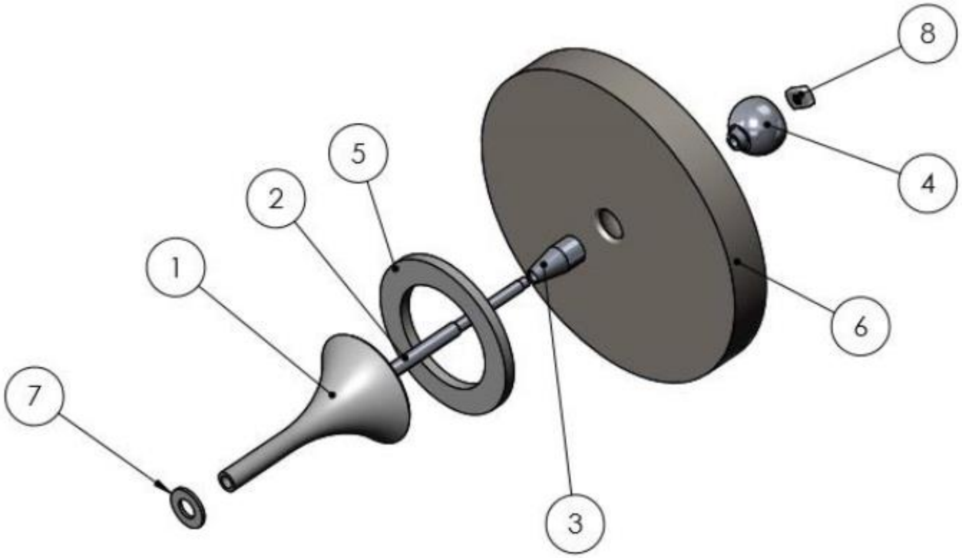
- There is generally limited data for innovative column designs
- It is practically not possible to test a complete bridge
- Hybrid simulation is a great tool to simulate the seismic response of bridges with innovative column designs

Hybrid Simulation of a Bridge with a V-connector

What is a V-connector?

- An innovative connecting device designed as the joint between column and superstructure or between column and footing in a bridge.
- Elongates the period and assures elastic response of bridge components
- Enables accelerated bridge construction and rapid retrofit or replacement by allowing prefabrication of the connected structural parts at different places and then assembling at construction site.

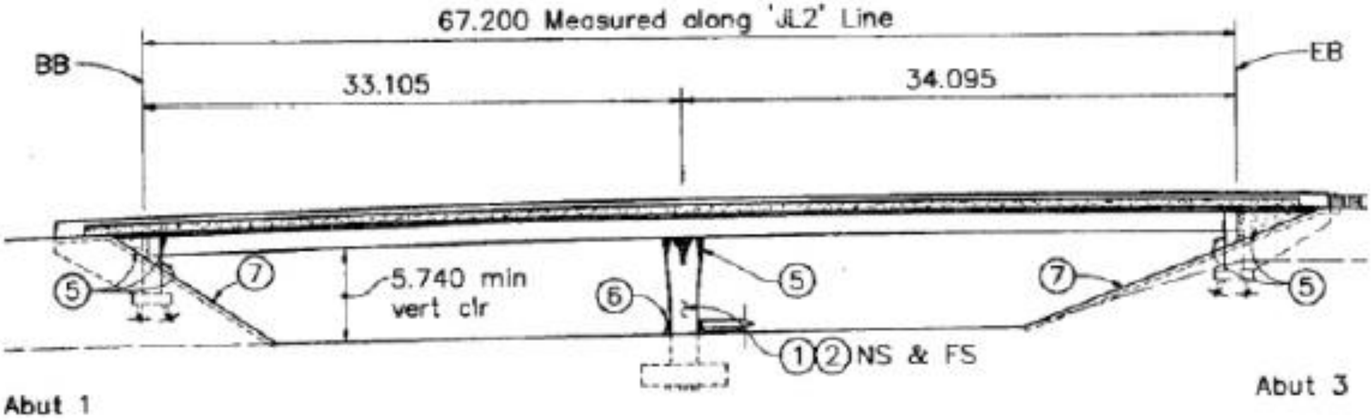




1	V-tube
2	S-Pin: body
3	Shear-Reinforce Ring
4	Ball Hinge-end
5	Low-friction washer
6	Top-Pad
7	Tube-Reinforce Ring
8	Pin-fix nut

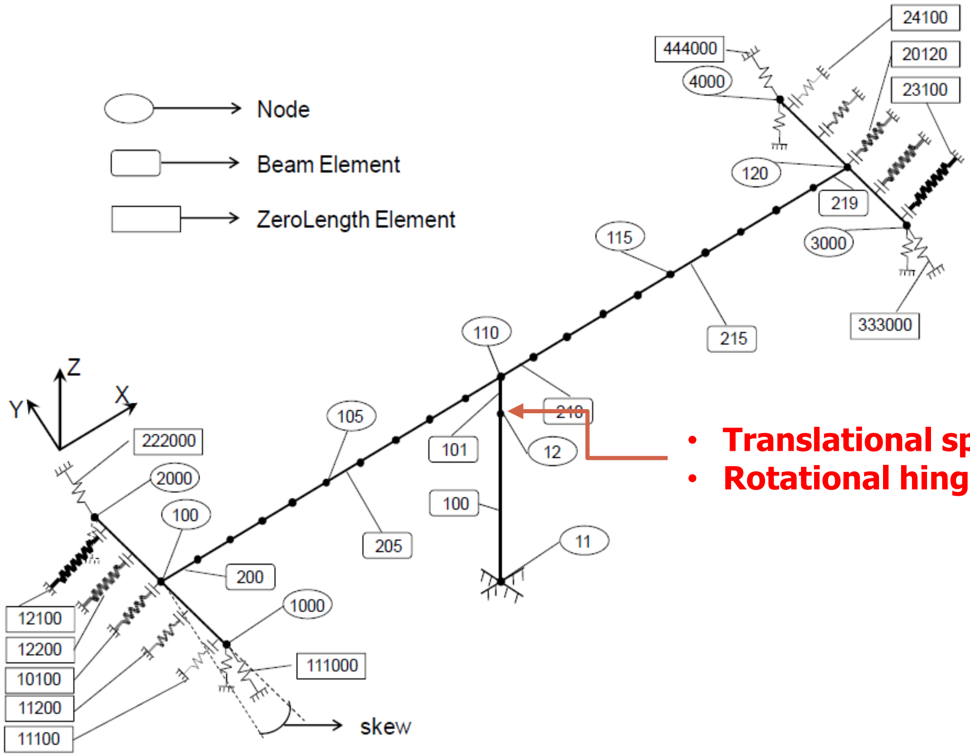
Prototype Bridge

Jack Tone Road Overcrossing

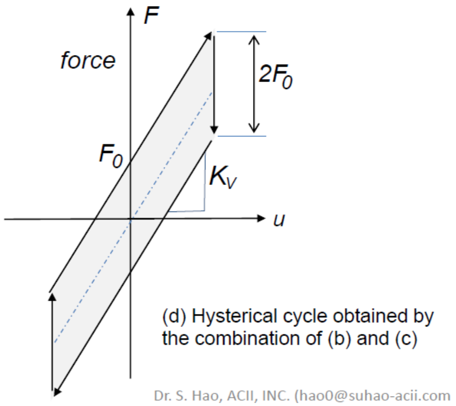


This bridge, with a single column bridge bent, is suitable for hybrid simulation (HS), because it allows testing the V-connector as an experimental substructure and the rest of the bridge as an analytical substructure.

Full Bridge Modeling with V-connectors



- **Translational springs**
- **Rotational hinges**



Dr. S. Hao, ACII, INC. (hao0@suhao-acii.com

Modeling of translational springs

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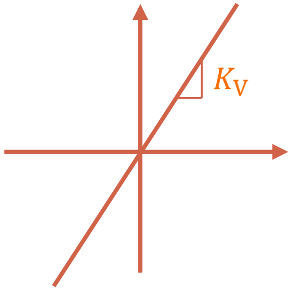

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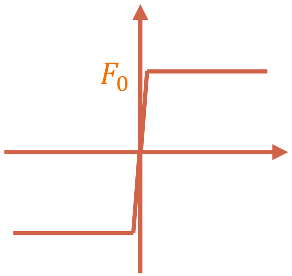


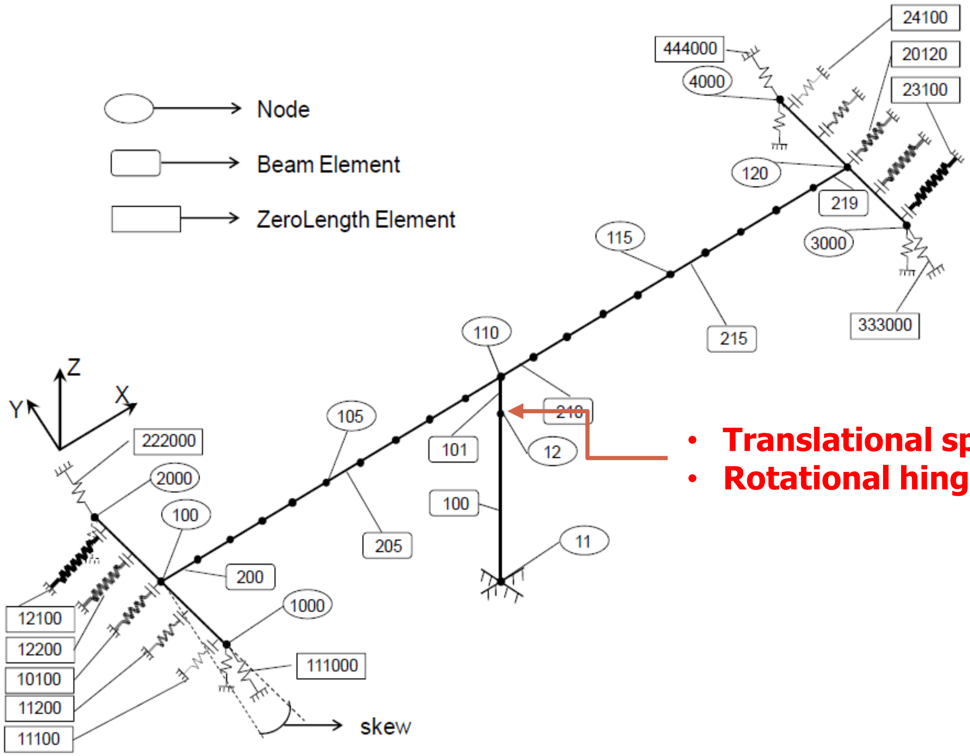
Linear elastic (V-connector rod)

Rigidly plastic (Friction due to washer)

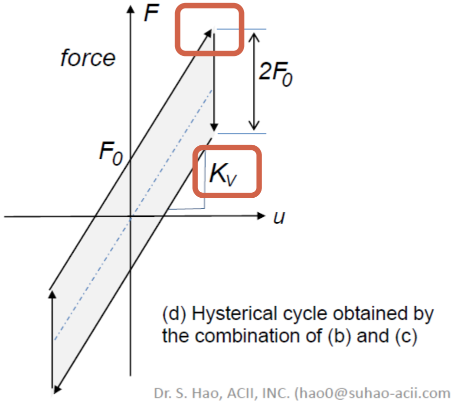
To include the V-connector in the bridge model:

- Translational spring elements are added between the column top and bridge deck along the longitudinal and transverse directions
- Flexural connection between the column top and bridge deck is modeled as rotational hinges with zero stiffness

Procedure for Finding K_v that Leads to Elastic Column Response



- **Translational springs**
- **Rotational hinges**



Modeling of translational springs

To keep the column response in elastic range, V-connector stiffness K_v needs to be reduced, because:

- ➢ Reducing the stiffness increases the effective period of the bridge, reducing the accelerations and the inertia forces acting on the bridge.
- ➢ Smaller K_v reduces the maximum force experienced by the V-connector. Since this force is equal to the maximum force that the column experiences (due to equilibrium), column force reduces.

Ground Motions

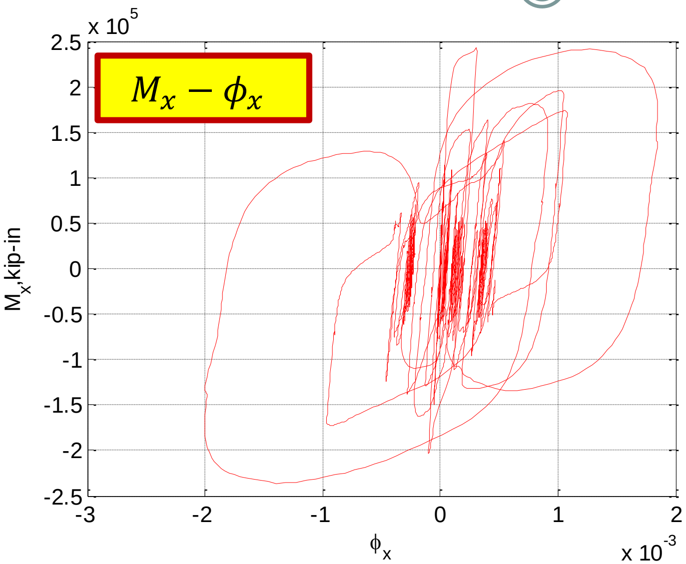
Test	Event	Date	Station	SF
GM1	Coalinga	1983/05/09	Harris Ranch – Hdqtrs (temp)	2.50
GM2	Imp. Valley	1979/10/15	EC Meloland Overpass FF	0.80
GM3	Morgan Hill	1984/04/24	Coyote Lake Dam (SW abut)	0.70
GM4	Northridge	1994/01/17	Rinaldi Receiving Station	0.56
GM5	Northridge	1994/01/17	Sylmar – Olive View Med FF	-0.80
GM6	Northridge	1994/01/17	Rinaldi Receiving Station	0.90
GM7	Kobe	1995/01/16	Takatori	0.77
GM8	Kobe	1995/01/16	Takatori	-0.90

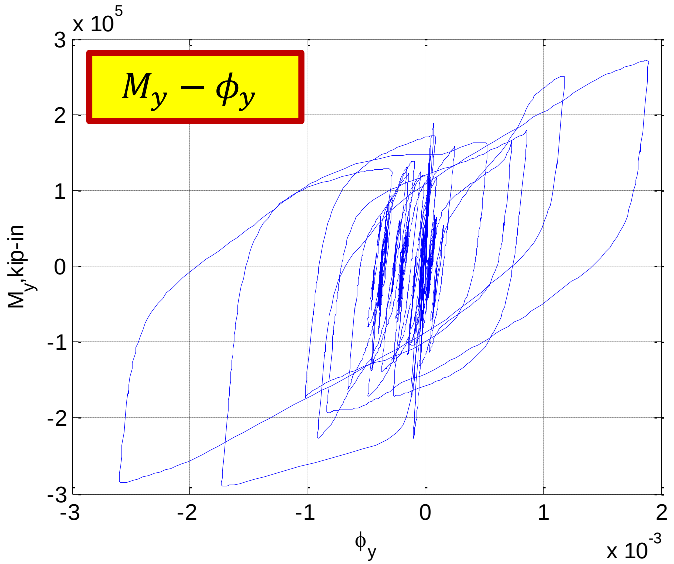
Reference: Gabriele Guerrini & José I. Restrepo (2013) "Seismic Response of Composite Concrete-Dual Steel Shell Columns for Accelerated Bridge Construction"

Analysis Results

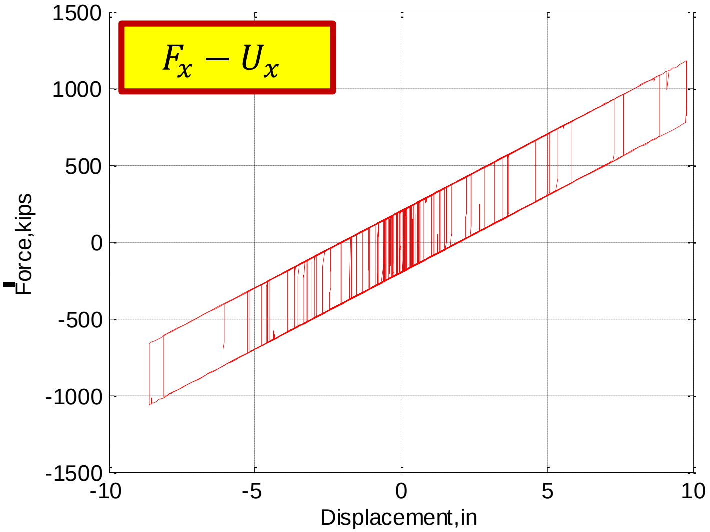
$K_v = \mathbf{100}\text{kips/in}$

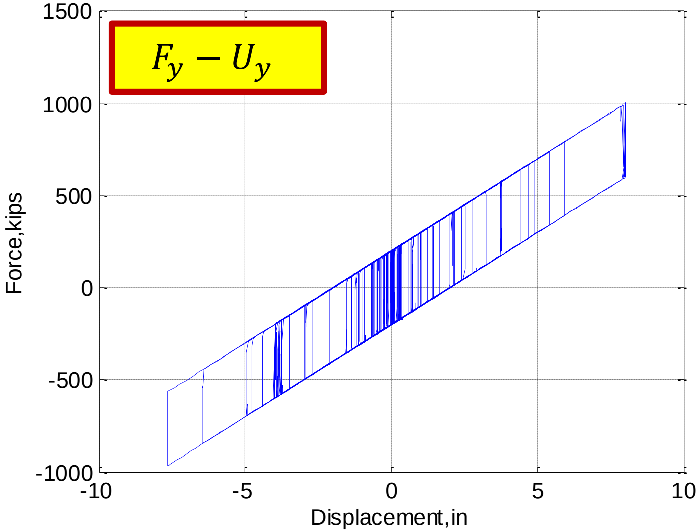
Column base moment-curvature





V-connector force-displacement

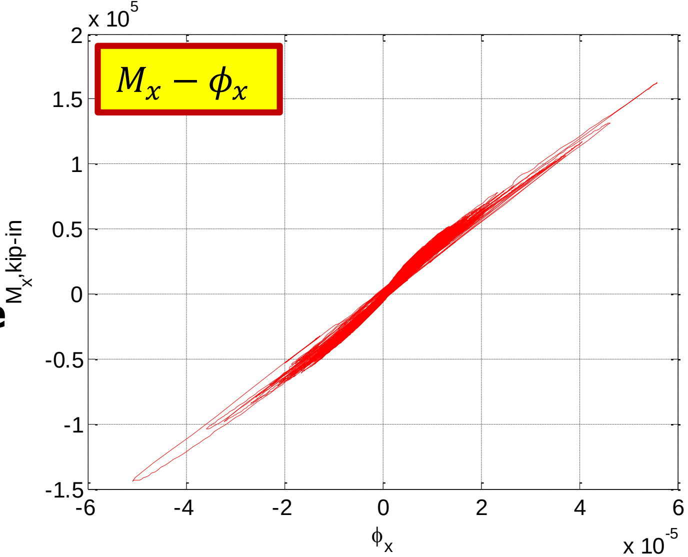


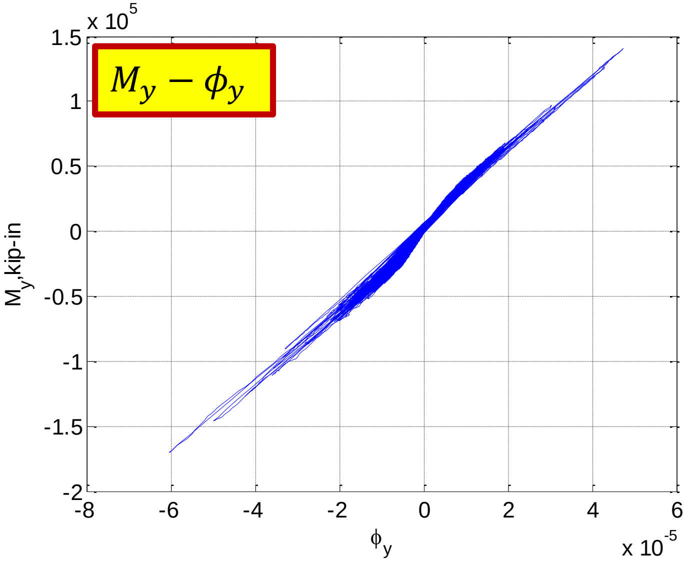


Analysis Results

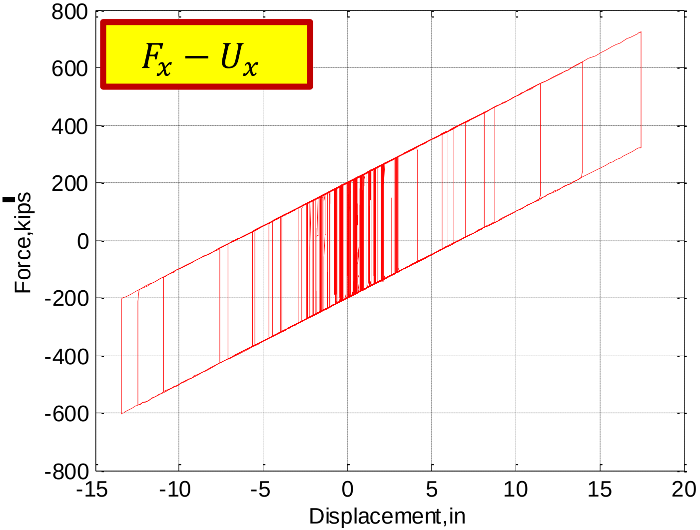
$K_v = \mathbf{30}\text{kips/in}$

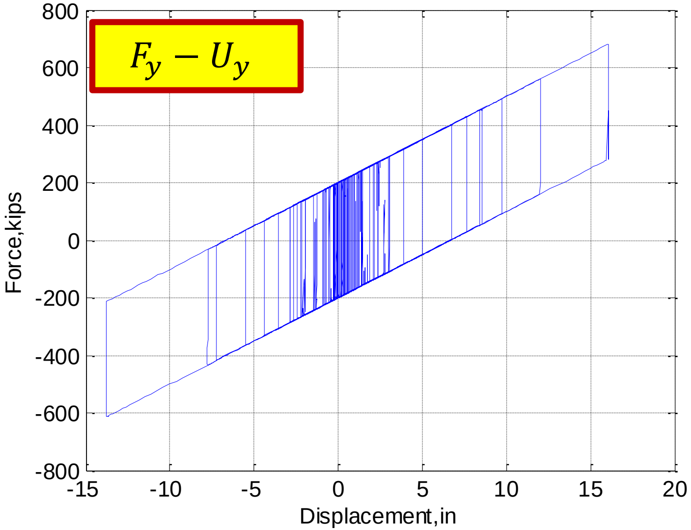
Column base moment-curvature





V-connector force-displacement

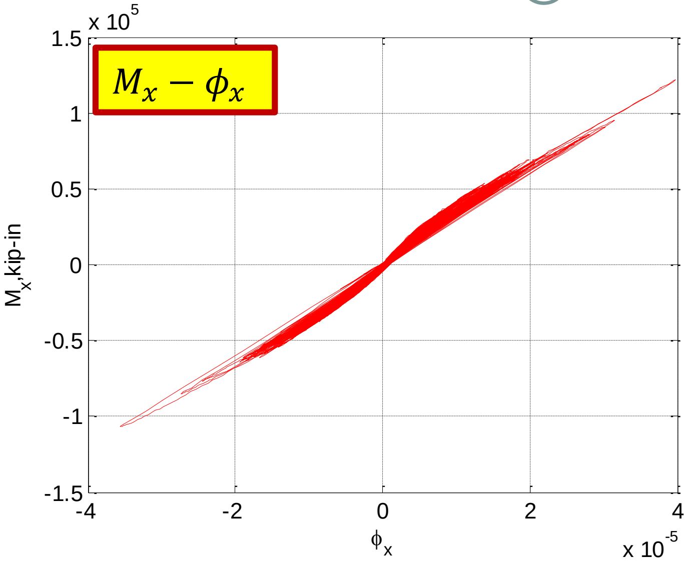


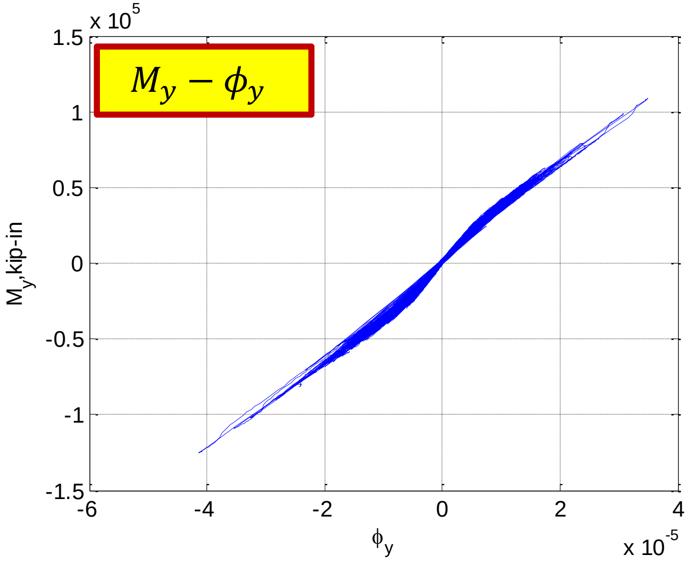


Analysis Results

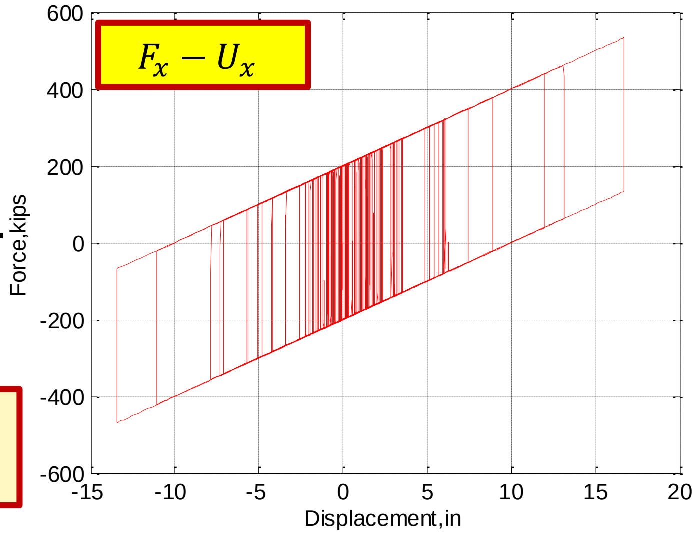
$K_v = \mathbf{20}\text{kips/in}$

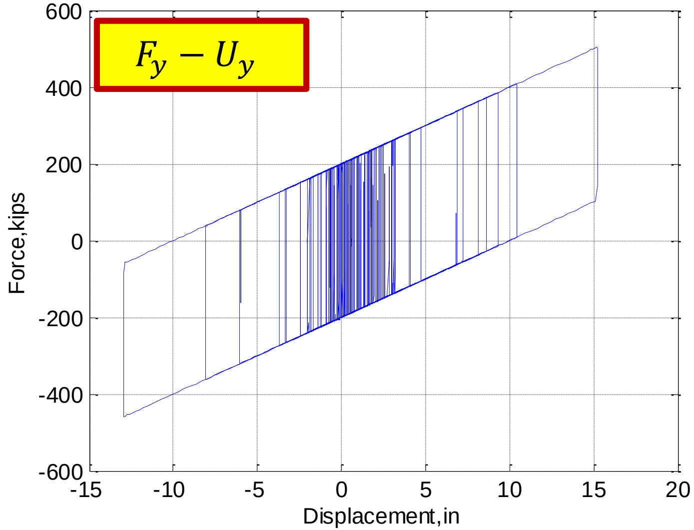
Column base moment-curvature





V-connector force-displacement





Washer friction coefficient = 10%

Analysis Results

Deformations and Forces for Different K_v values

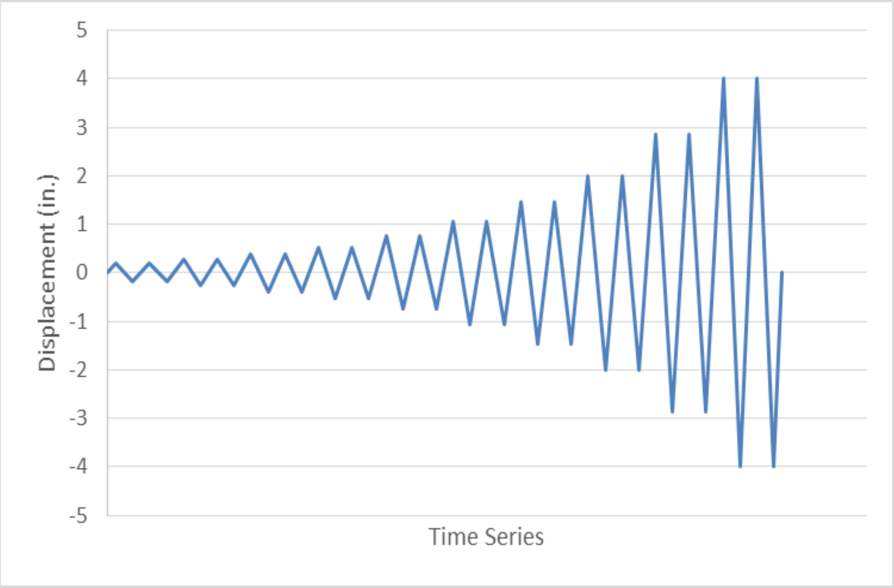
K_V(kip/in)	T_n(s)	V-connector deformations (in)		Column Forces (kip)	
		Longitudinal	Transverse	Longitudinal	Transverse
100	1.86	9.8	8.0	1100	1000
30	3.28	17.5	16.0	900	650
20	4.00	16.7	15.2	520	480

According to these results, a V-connector with K_v = 30 kip/in is the most suitable choice.

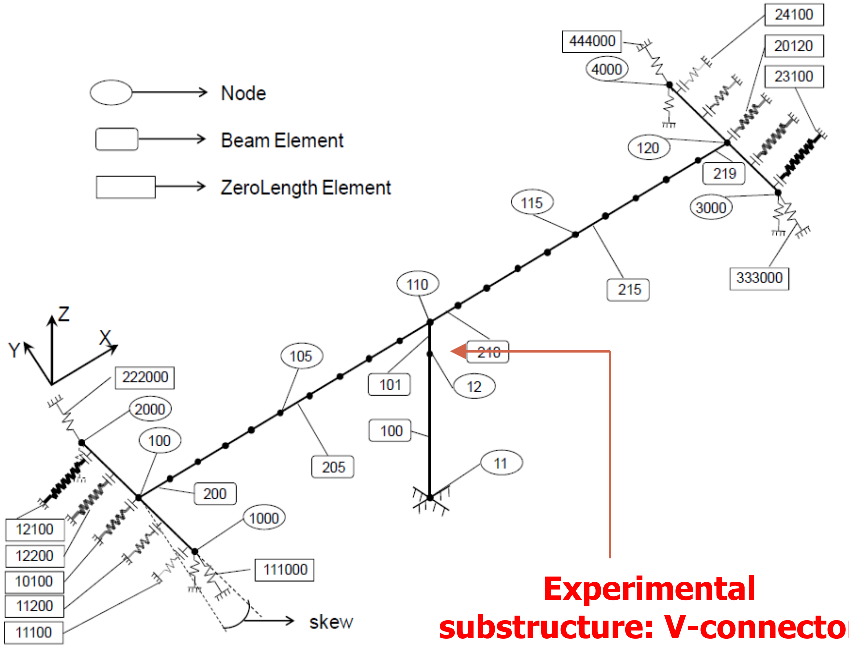
- ☐ V-connector is designed according to the desired stiffness and friction values
- ☐ To accommodate the loading equipment capacities, V-connector is designed to be 1/3 scale

Test Plan

Phase I Cyclic: Conduct cyclic test on the V-connector, to validate the assumed force-displacement relation

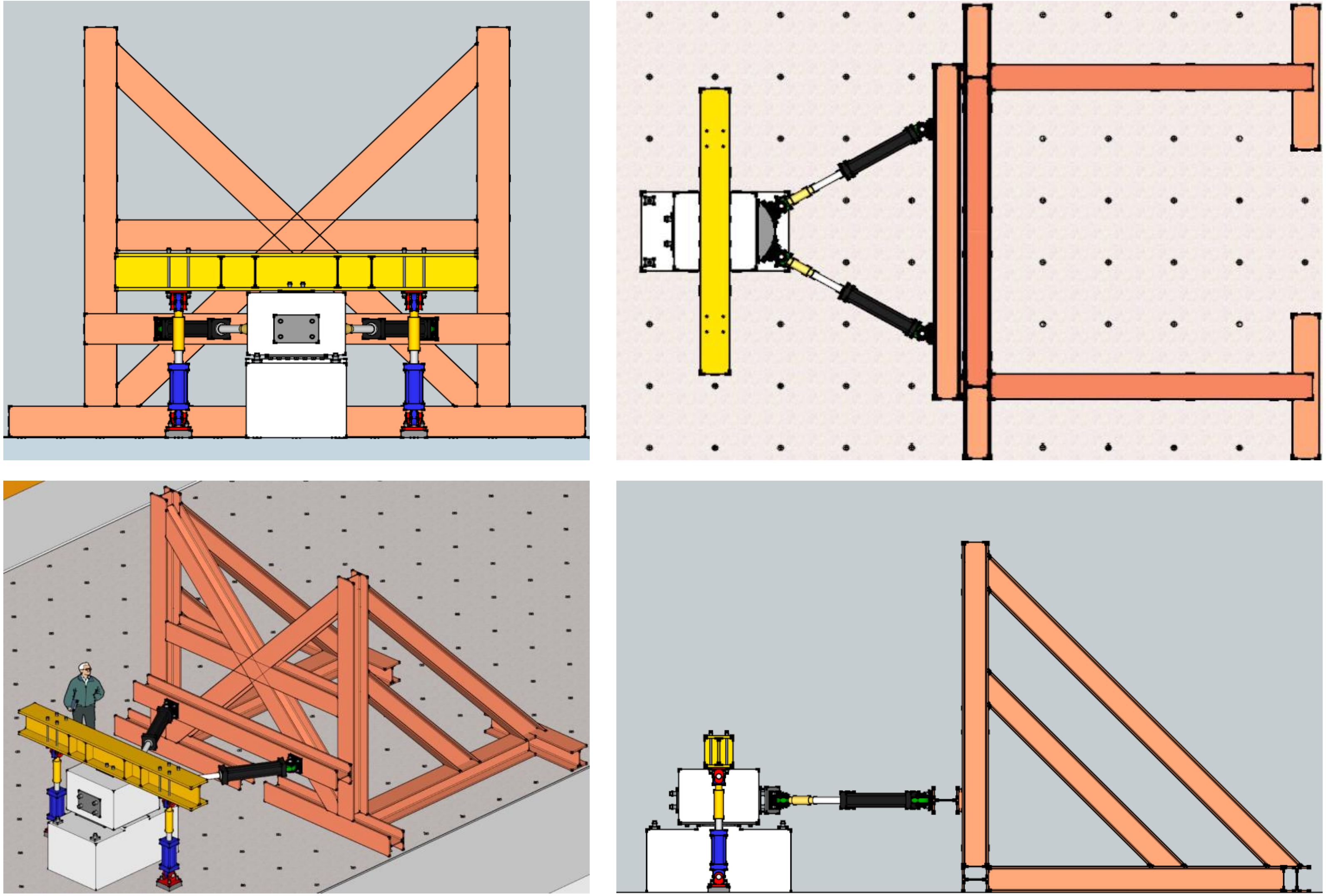


Phase II HS: Test the V-connector using hybrid simulation, model everything else analytically



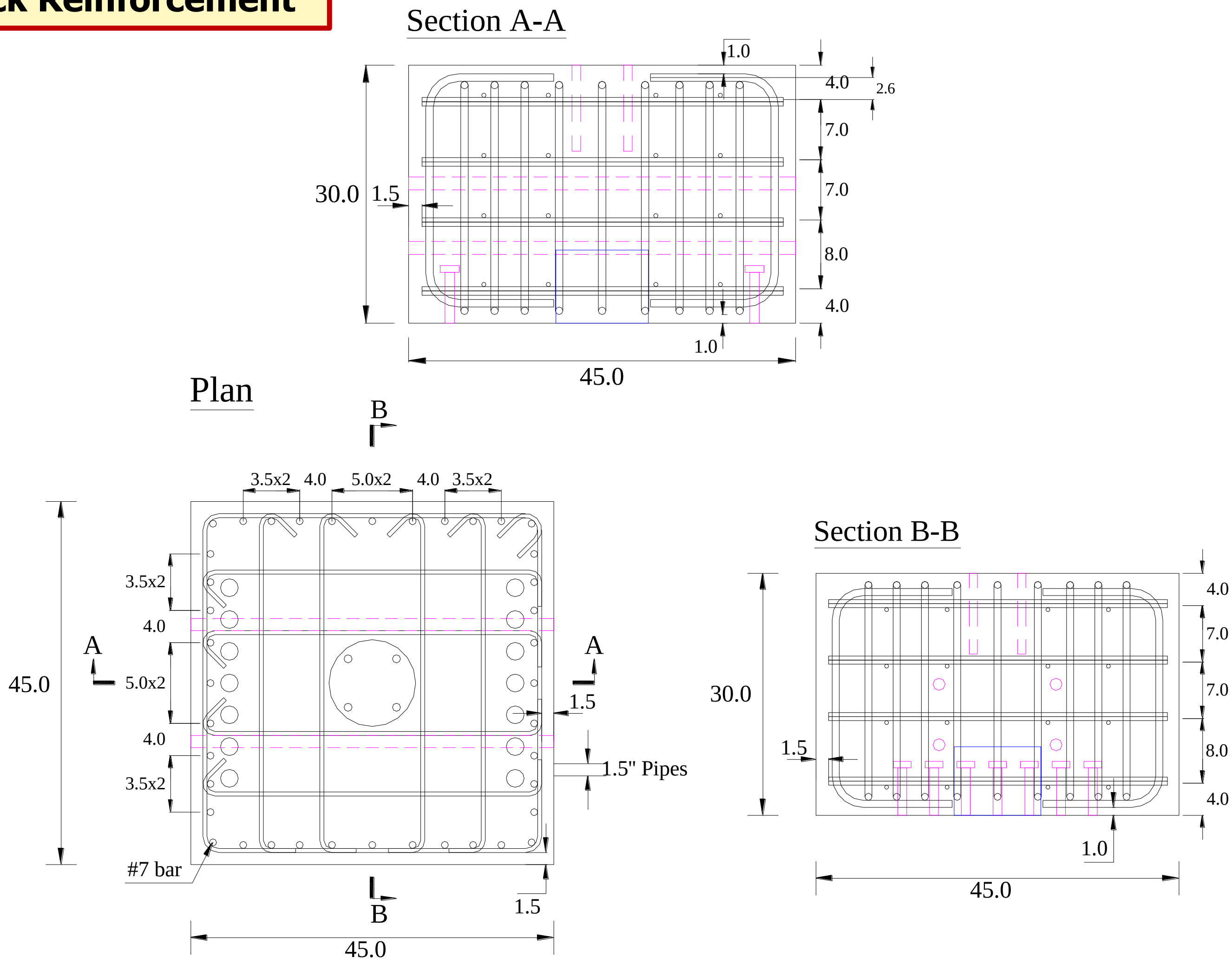
Experimental substructure: V-connector

Test Setup



Reinforcement Details

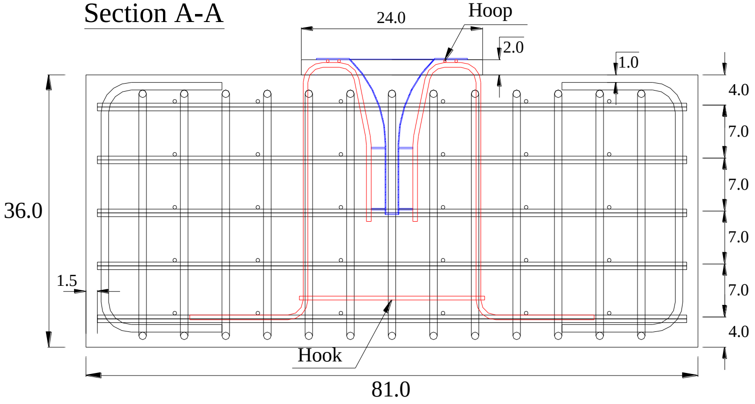
Top Block Reinforcement



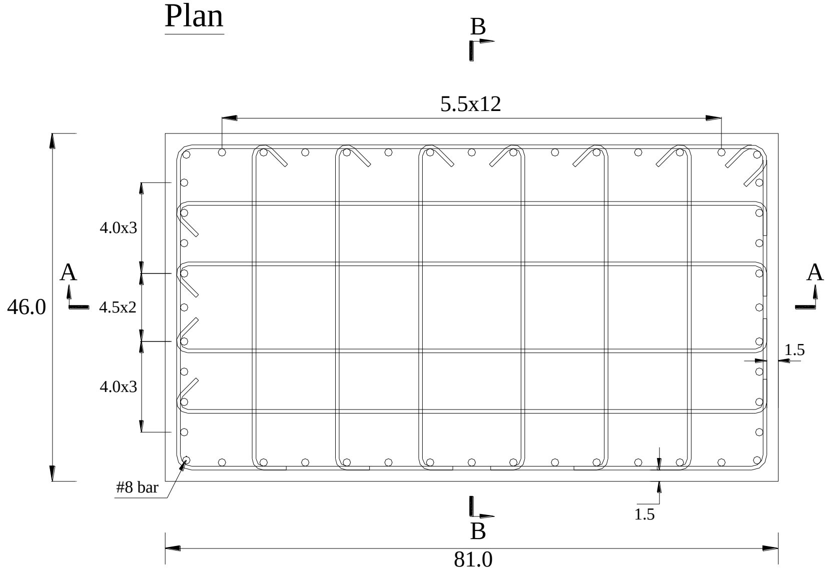
Reinforcement Details

Bottom Block Reinforcement

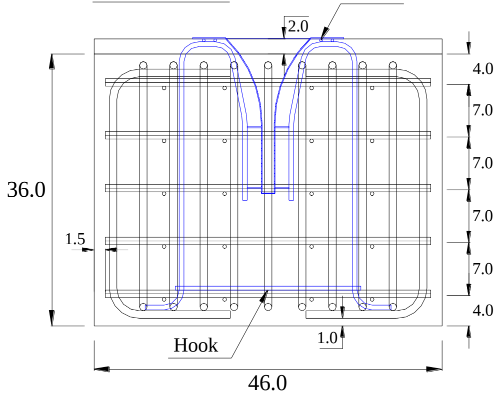
Section A-A



Plan



Section B-B



V-connector Assembly

Step 1: Connect the bottom block with embedded V-tube and Teflon washer to the strong floor

Embedded V-tube

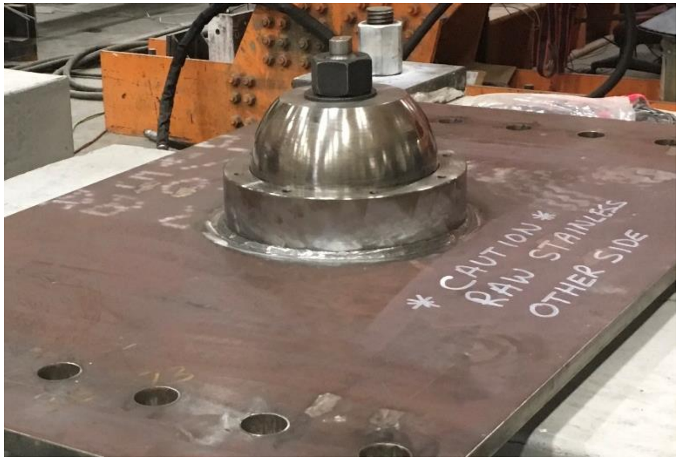
Teflon Washer

Step 2: Place the top pad with the hinge holder

Top pad with hinge holder

V-connector Assembly

Step 3: Insert the V-connector rod with hinge through the hinge holder



V-connector rod and the hinge

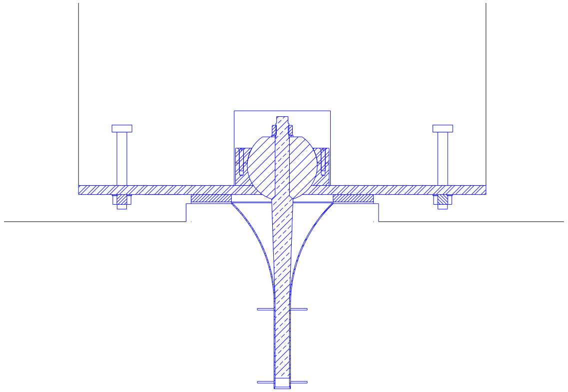
Step 4: Tighten the hinge fixing nut

V-connector Assembly

Step 5: Place the top block

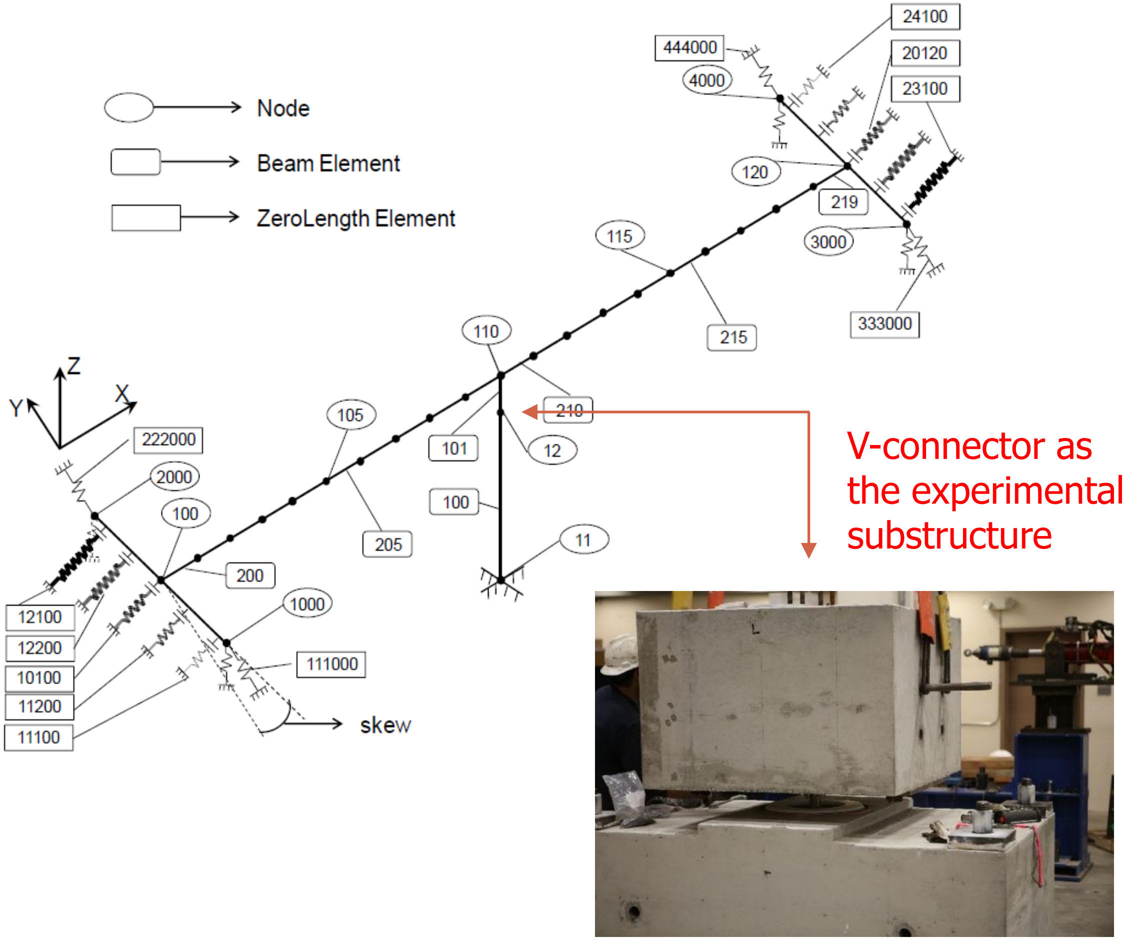
Hollow portion

Step 6: Tighten up the nuts beneath



Section cut

Phase II Hybrid Simulation Details



V-connector as the experimental substructure

- V-connector as the experimental substructure
- All the rest is simulated as the analytical substructure
- Column inelastic response is modeled, however the column is designed to remain elastic, therefore it is part of the analytical substructure
- Alpha OS as the numerical integration
- Computed displacements scaled by 1/3 before applying to the specimen
- Measured forces are multiplied by 9 (S^2) before using in the numerical integration

Hybrid Simulation of a Bridge with Self-Centering, Rocking and Energy Dissipating Columns

Phase I: Column Design and Shaking Table Testing
(UCSD, PI: Jose Restrepo)

Phase II: Hybrid Simulation
(UC Berkeley, PI: Khalid Mosalam)

Innovative Design Features

Steel jacket for confinement

Shaking Table Testing

- ❑ Shaking table tests completed on the PEER 6-DOF shaking table
- ❑ A blind prediction competition is organized from these tests:

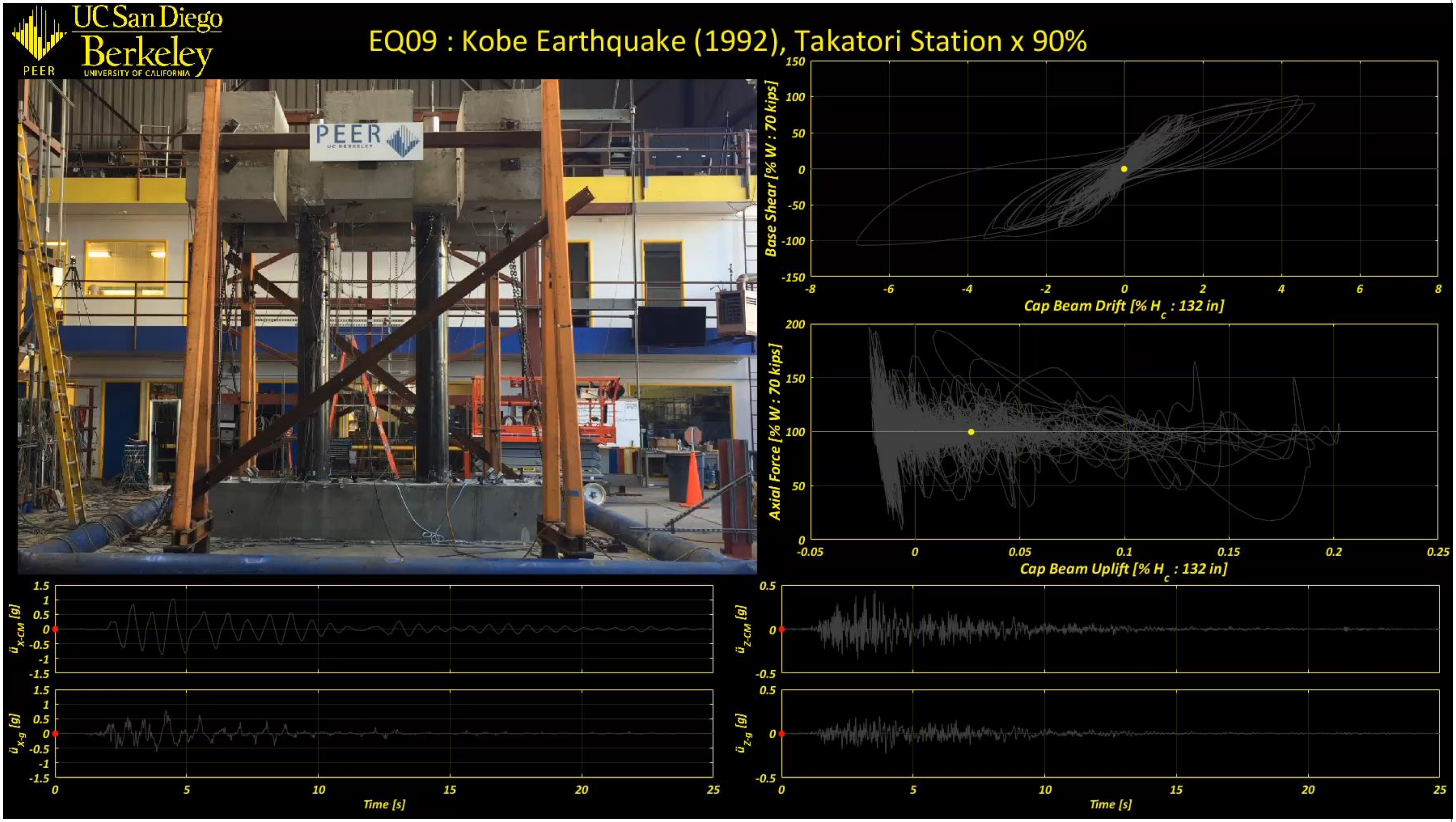
  http://peer.berkeley.edu/prediction_contest/

Shaking Table Testing

Ground Motions

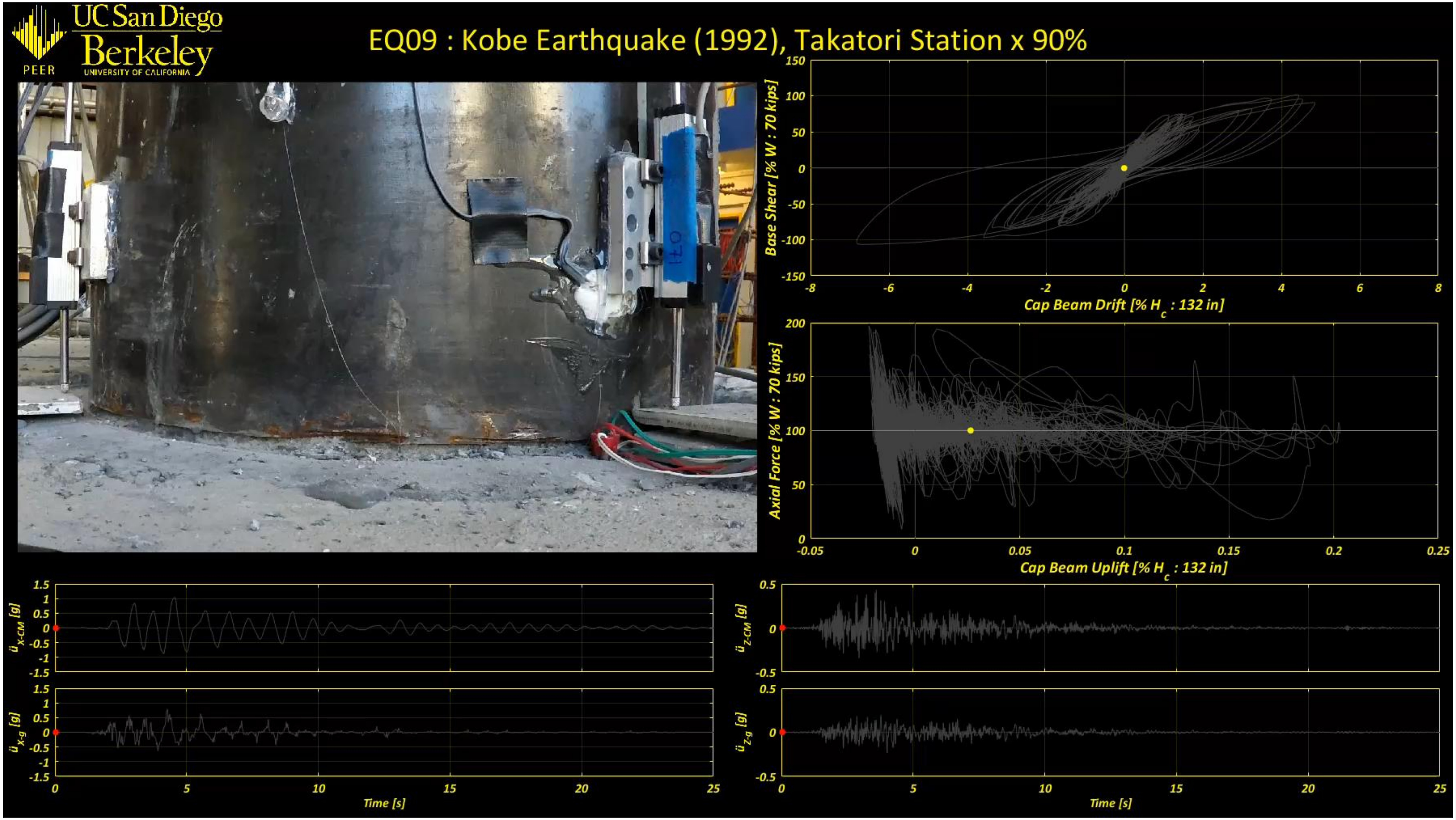
EQ #	Event Name	Station Name	Unscaled PGA [g]	Scale Factor	Expected Drift [%]
1	Landers, 1992	Lucerne	0.72	0.9	0.6
2	Landers, 1992	Lucerne	0.72	0.9	0.6
3	Tabas, 1978	Tabas	0.85	-0.9	1.8
4	Kocaeli, 1999	Yarimca	0.3	1.0	0.6
5	Northridge, 1994	RRS	0.85	0.81	4
6	Duzce, 1999	Duzce	0.51	1	1.8
7	Northridge, 1994	NFS	0.72	-1.2	4
8	Kobe, 1995	Takatori	0.76	-0.8	5
9	Kobe,1995	Takatori	0.76	0.9	7
10	Tabas, 1978	Tabas	0.85	-0.9	-
11	Northridge, 1994	RRS	0.85	0.81	-
12	Kobe, 1995	Takatori	0.76	-0.8	-

Shaking Table Testing



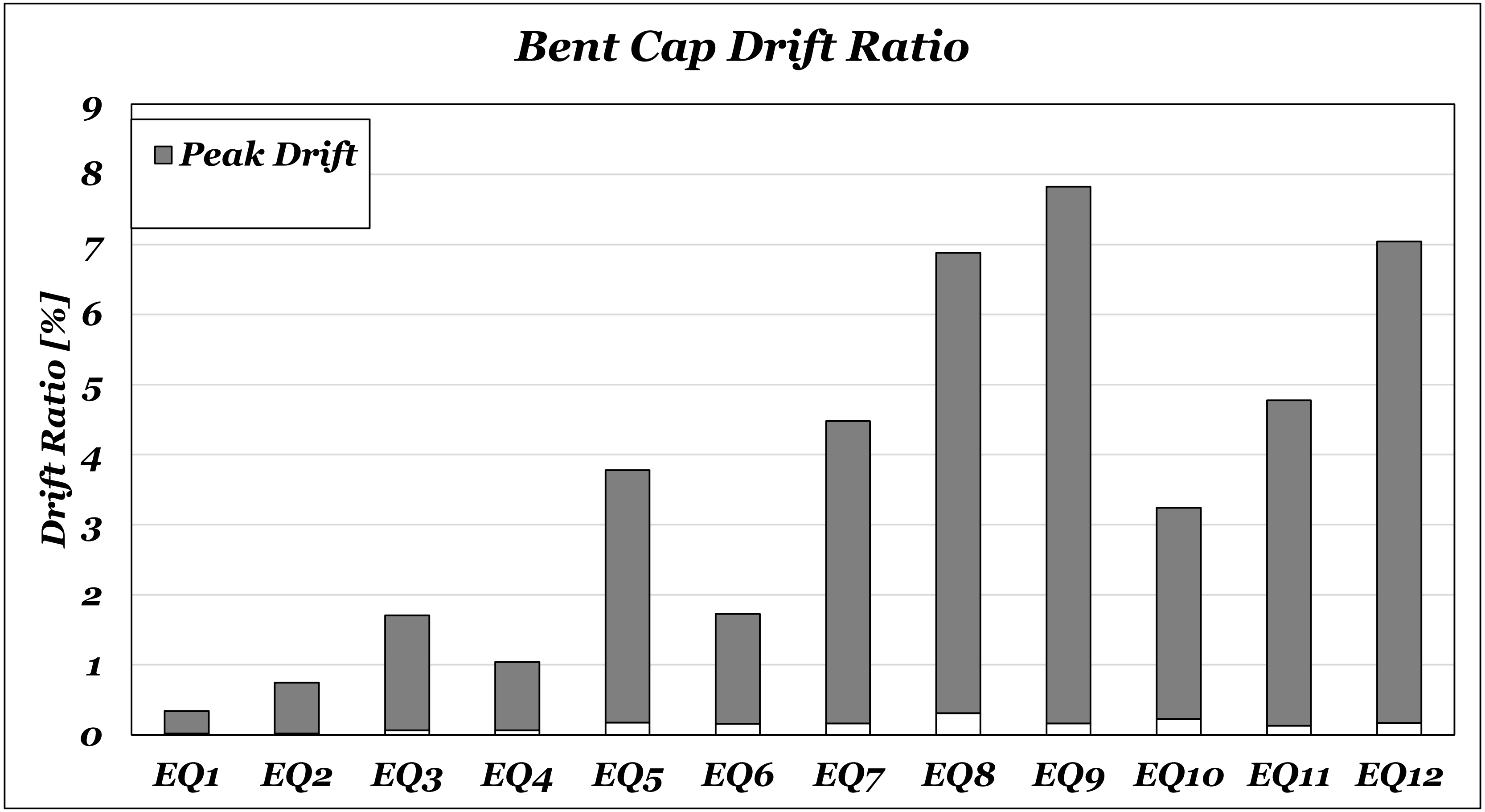
Courtesy of Arpit Nema, UC San Diego

Shaking Table Testing



Courtesy of Arpit Nema, UC San Diego

Shaking Table Testing



Courtesy of Arpit Nema, UC San Diego 28

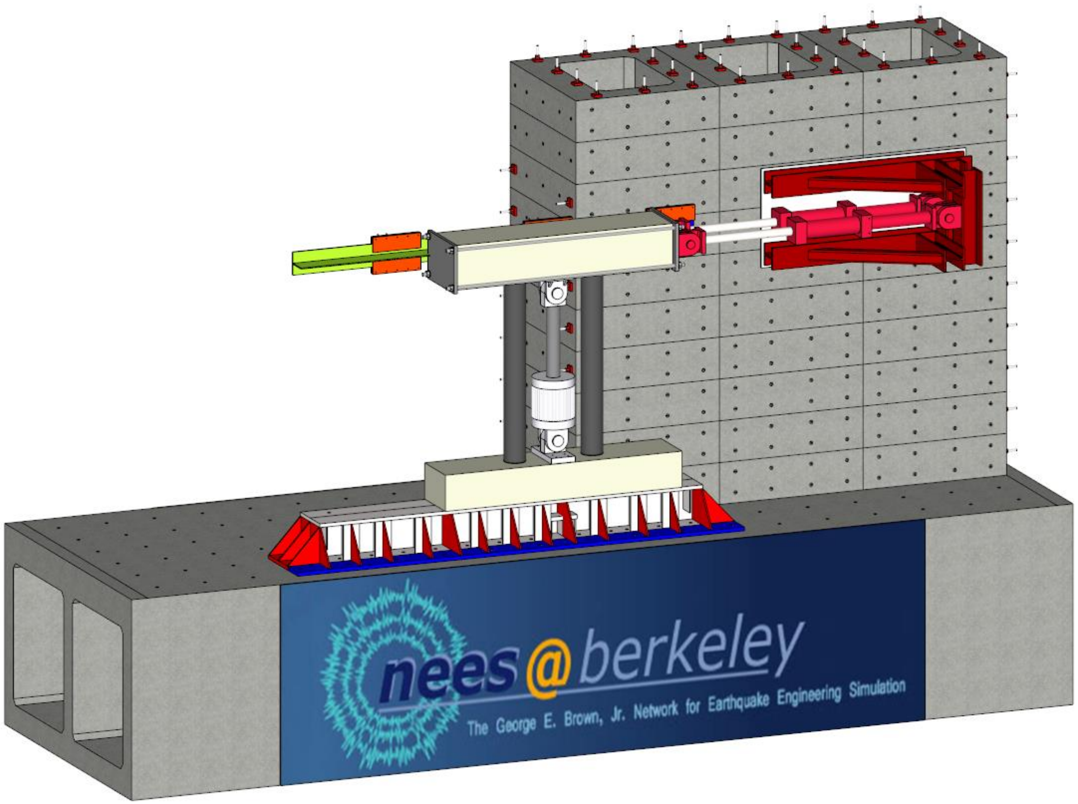
Hybrid Simulation: Substructuring

Shaking Table

Hybrid Simulation Phase I

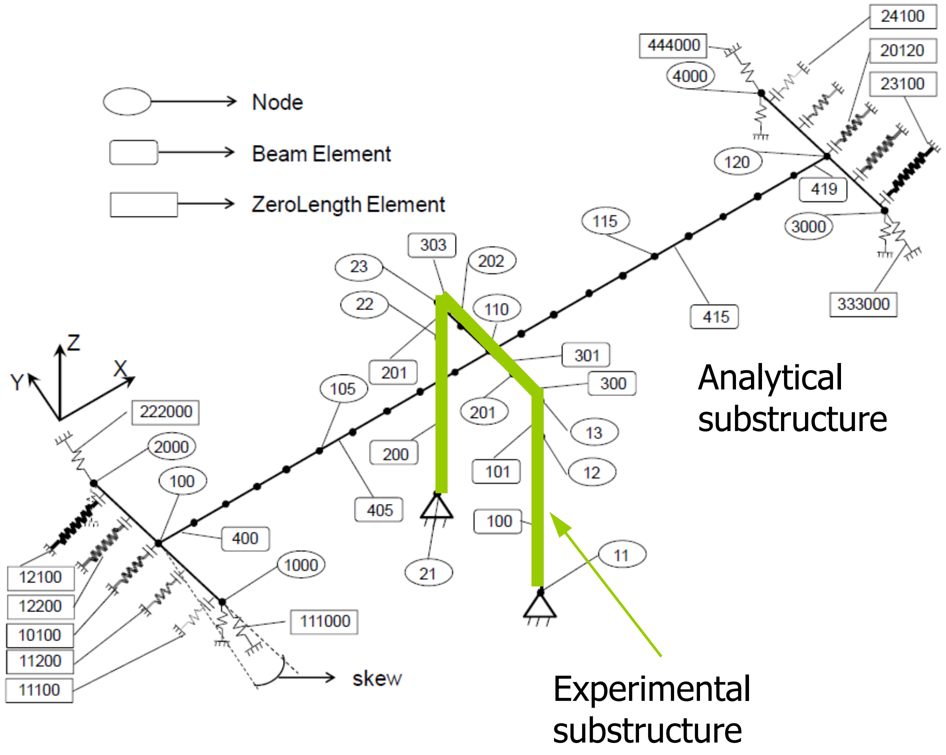
Direct comparison of shaking table and hybrid simulation results

Hybrid Simulation Phase I



- From the shaking table test results, moment at the top is found to be negligible
- Single actuator is used to apply the lateral displacements
- As there is a vertical component of the ground motion, a vertical actuator is used to apply vertical forces due to gravity & earthquake

Hybrid Simulation Phase II



Analytical substructure

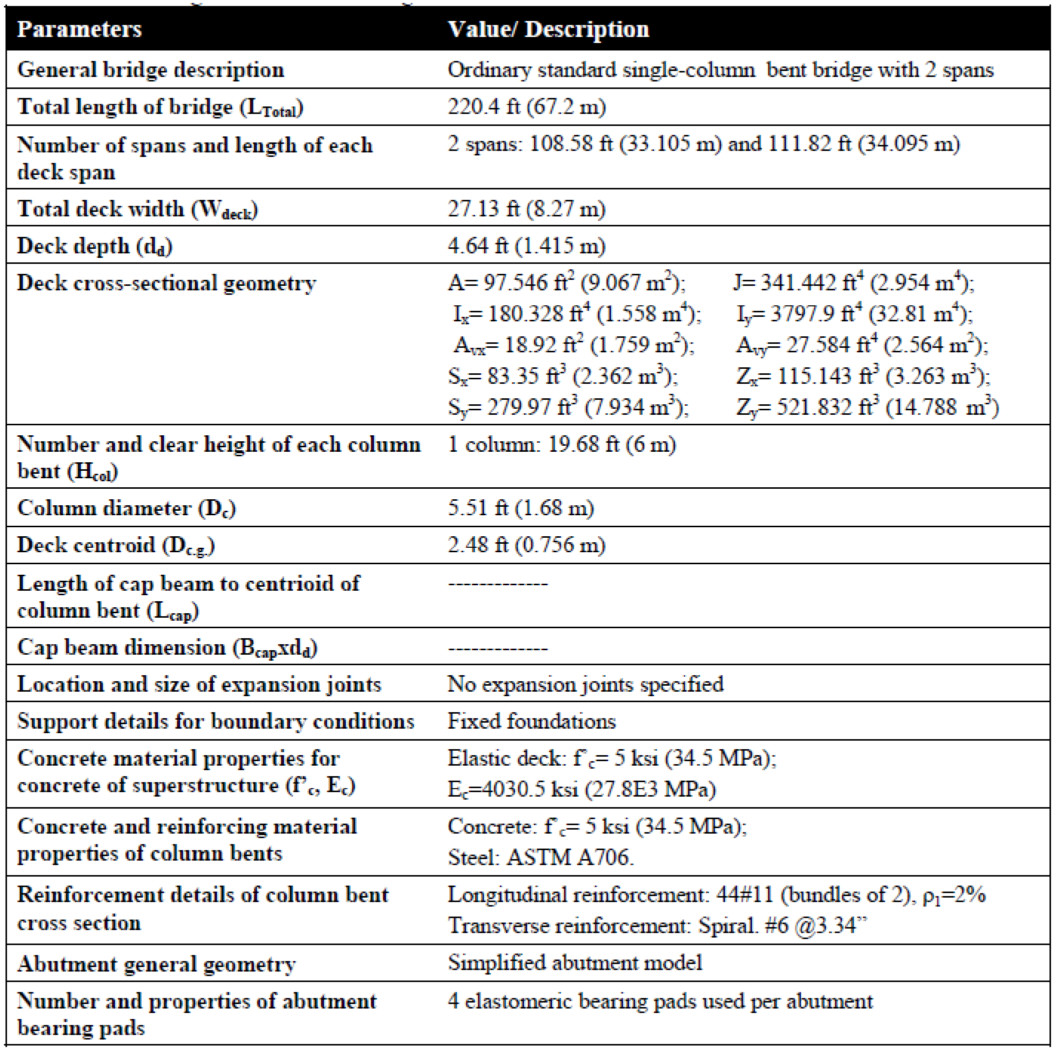
Experimental substructure

In Phase II, rest of the bridge will be modeled analytically to consider the system level response of the bridge

Thank You !

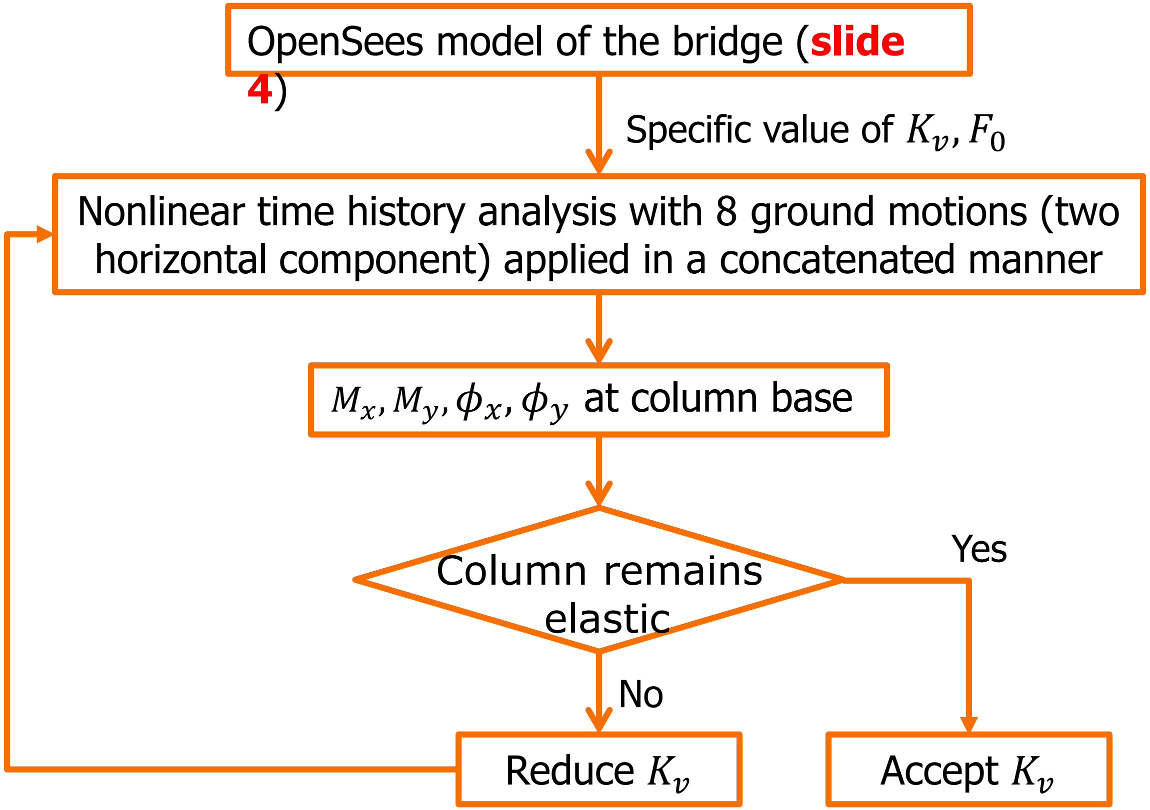
Prototype Bridge

Structural and geometrical parameters of the prototype bridge



Parameters	Value/ Description
General bridge description	Ordinary standard single-column bent bridge with 2 spans
Total length of bridge (L_{Total})	220.4 ft (67.2 m)
Number of spans and length of each deck span	2 spans: 108.58 ft (33.105 m) and 111.82 ft (34.095 m)
Total deck width (W_{deck})	27.13 ft (8.27 m)
Deck depth (d_d)	4.64 ft (1.415 m)
Deck cross-sectional geometry	$A= 97.546\ ft^2\ (9.067\ m^2)$; $J= 341.442\ ft^4\ (2.954\ m^4)$; $I_x= 180.328\ ft^4\ (1.558\ m^4)$; $I_y= 3797.9\ ft^4\ (32.81\ m^4)$; $A_{vx}= 18.92\ ft^2\ (1.759\ m^2)$; $A_{vy}= 27.584\ ft^4\ (2.564\ m^2)$; $S_x= 83.35\ ft^3\ (2.362\ m^3)$; $Z_x= 115.143\ ft^3\ (3.263\ m^3)$; $S_y= 279.97\ ft^3\ (7.934\ m^3)$; $Z_y= 521.832\ ft^3\ (14.788\ m^3)$
Number and clear height of each column bent (H_{col})	1 column: 19.68 ft (6 m)
Column diameter (D_c)	5.51 ft (1.68 m)
Deck centroid ($D_{c.g.}$)	2.48 ft (0.756 m)
Length of cap beam to centrioid of column bent (L_{cap})	-------------
Cap beam dimension ($B_{cap}xd_d$)	-------------
Location and size of expansion joints	No expansion joints specified
Support details for boundary conditions	Fixed foundations
Concrete material properties for concrete of superstructure (f'_c, E_c)	Elastic deck: $f'_c= 5$ ksi (34.5 MPa); E_c=4030.5 ksi (27.8E3 MPa)
Concrete and reinforcing material properties of column bents	Concrete: $f'_c= 5$ ksi (34.5 MPa); Steel: ASTM A706.
Reinforcement details of column bent cross section	Longitudinal reinforcement: 44#11 (bundles of 2), ρ_1=2% Transverse reinforcement: Spiral. #6 @3.34"
Abutment general geometry	Simplified abutment model
Number and properties of abutment bearing pads	4 elastomeric bearing pads used per abutment

Procedure for Finding K_v that Leads to Elastic Column Response



OpenSees model of the bridge (**slide 4**)

Specific value of K_v, F_0

Nonlinear time history analysis with 8 ground motions (two horizontal component) applied in a concatenated manner

M_x, M_y, ϕ_x, ϕ_y at column base

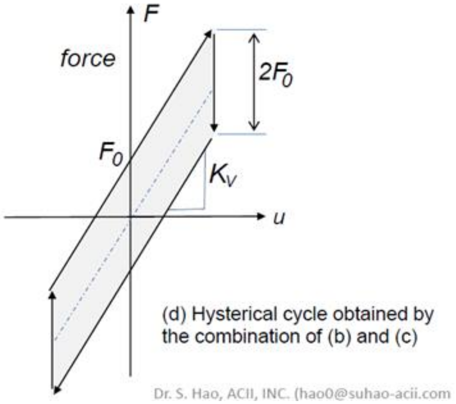
Column remains elastic

Yes

No

Reduce K_v

Accept K_v



(d) Hysterical cycle obtained by the combination of (b) and (c)

Dr. S. Hao, ACII, INC. (hao0@suhao-acii.com)

Here F_0 (the friction) is chosen to be 10% of the maximum axial force, about 200kips