Structural Response of Bent Caps in Reinforced Concrete Box-Girder Bridges

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Sponsor:

Caltrans

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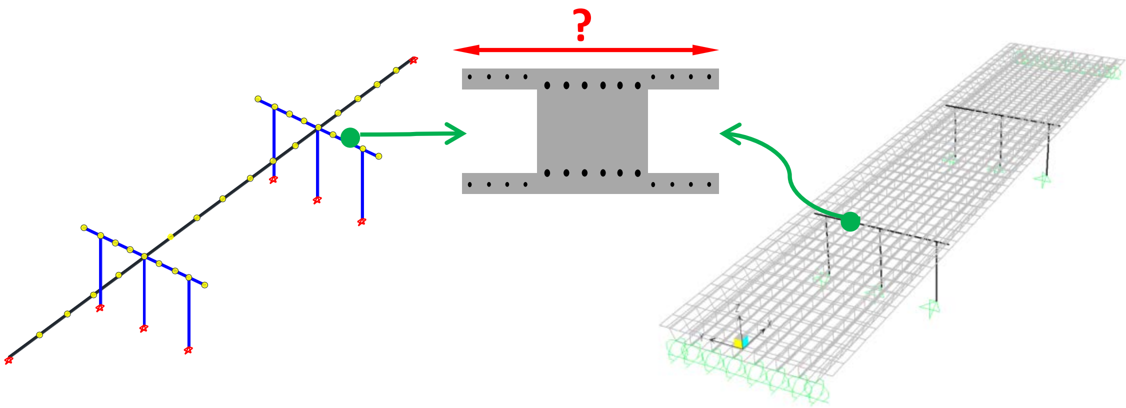
Motivation

Bent Cap Response

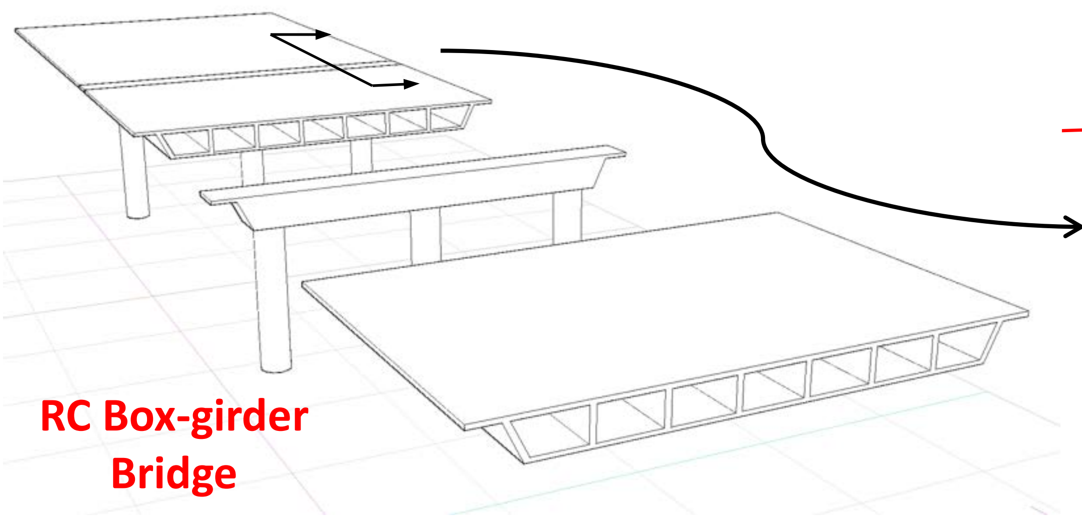
- **Bent caps damage in past events**
  - *e.g. San Fernando 1971, Whittier 1987, Chi-Chi 1999*
- **Post-event repair is not feasible**
  - *$$$ + long down time*
- **Why accurate bent cap response important?**
  - *Modeling and analysis*
  - *Optimized design (new bridges)*
  - *Retrofit design (old bridges)*

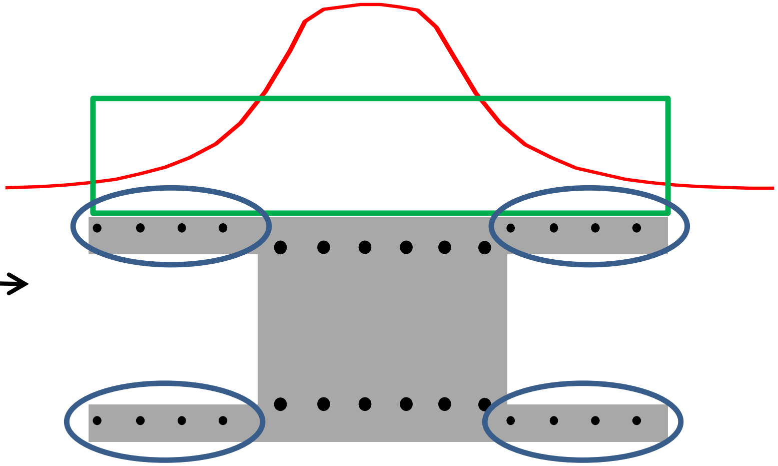


Courtesy of Hamid Saadatmanesh, Simpson Strong-Tie

Problem Statement

1. What is box-girder slab contribution to bent cap?
   strain-based effective slab width approach
2. How can bent cap capacity accurately estimated?
   slab reinforcement inclusion
3. Could column over-design migrate damage to bent cap?
   informed retrofit decisions





Methodology

Stage 1: Pre-test analyses:

- FE analyses of prototype bridge
- FE analyses of test specimen

Stage 2: Experimental program (2 large-scale specimens):

- Quasi-static testing of SP1 (as-built & repaired)
- Hybrid Simulation testing of SP2 (retrofitted)

Stage 3: Post-test analyses:

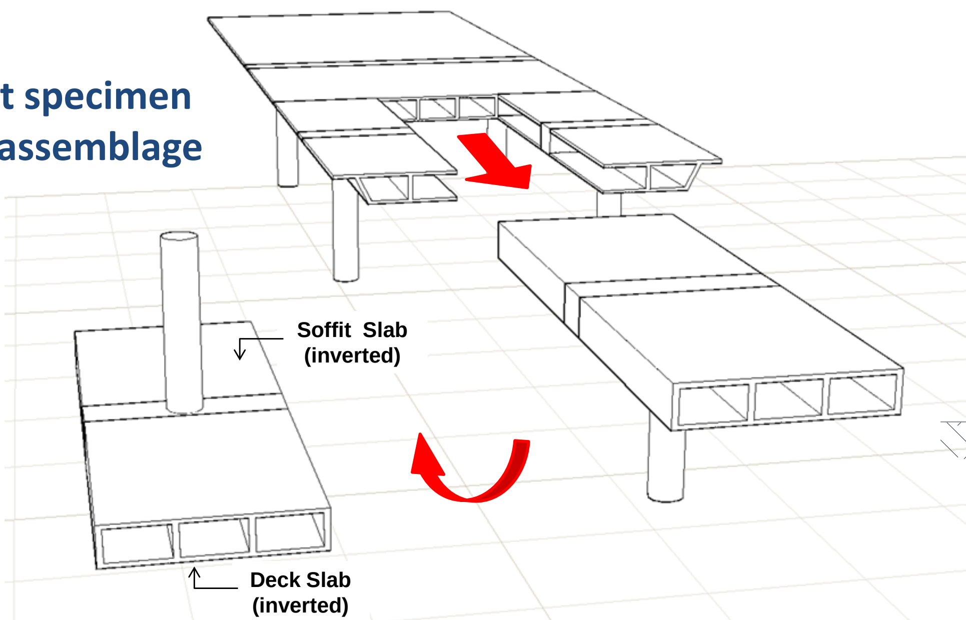
- FE model calibration/parametric study
- Design implications

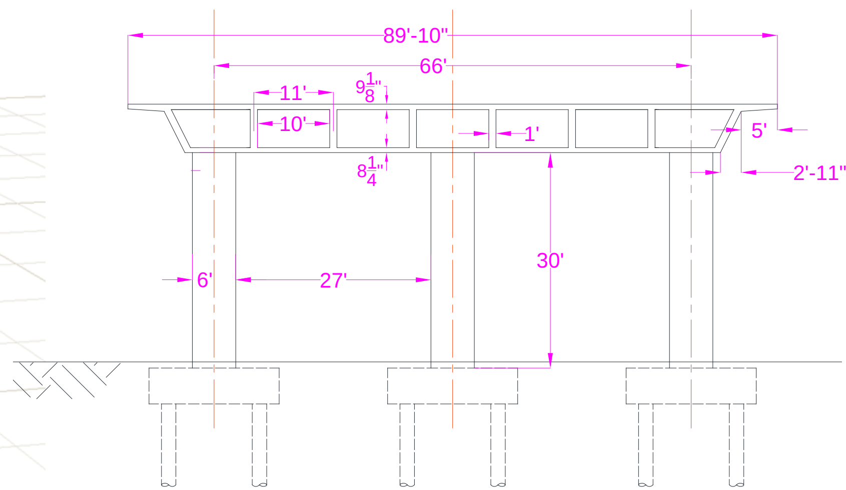
Prototype Bridge

Adopted from Caltrans Academy Bridge

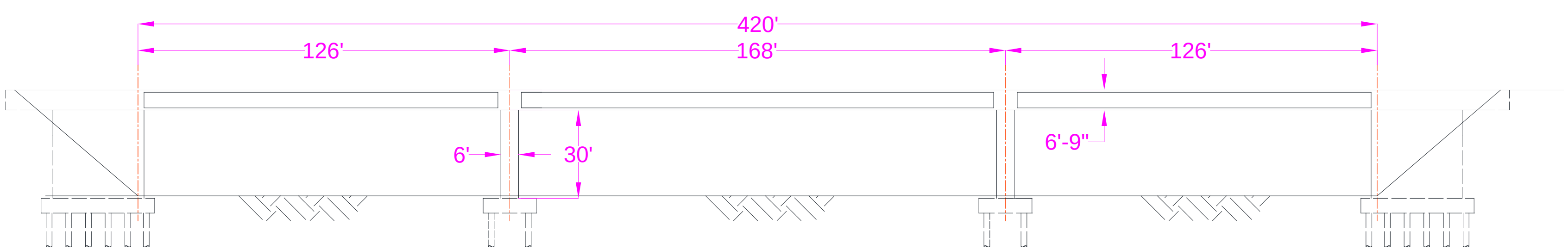
(Typical RC box-girder bridge in CA)

Test specimen subassemblage





Cross-Section

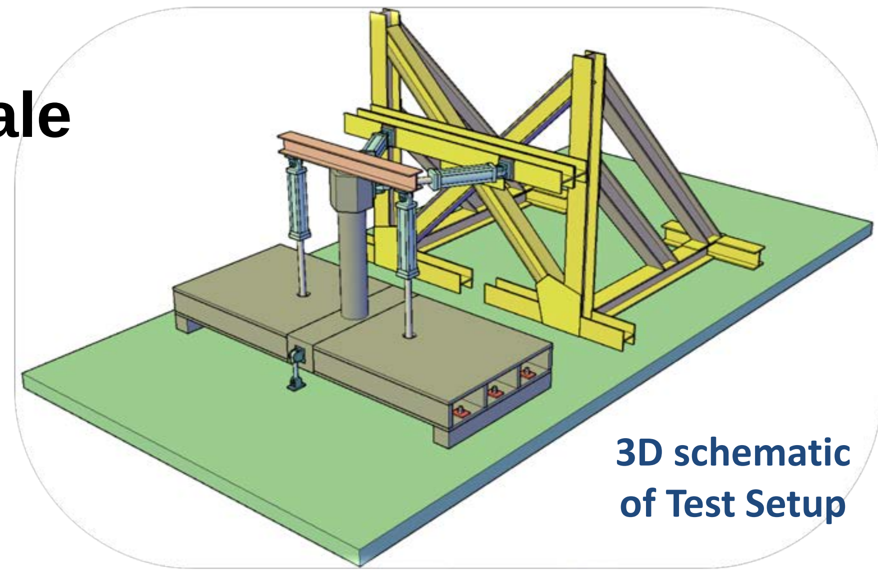


Elevation View

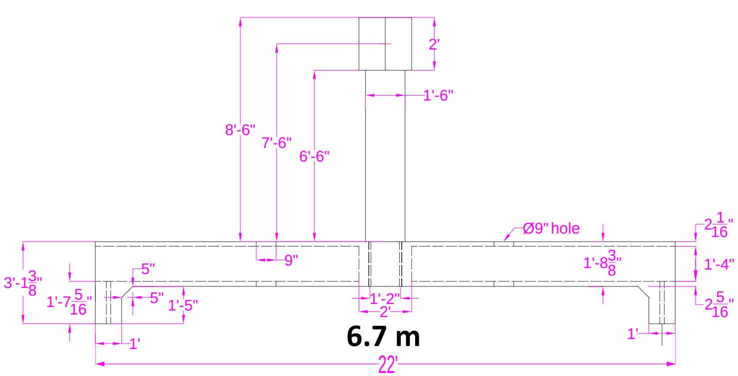
Specimen Design & Test Setup

1/4 scale

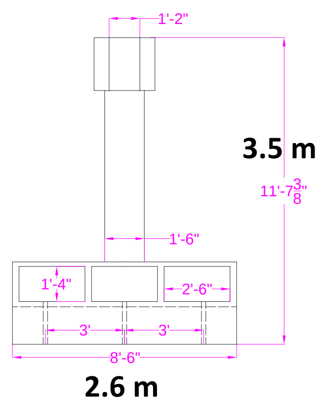
- Design acc. to AASHTO, Caltrans SDC, and ACI-318
- Two Specimens tested in an inverted position at UC Berkeley Structures Laboratory
- Gravity & lateral loads applied at the column top



3D schematic of Test Setup



Elevation



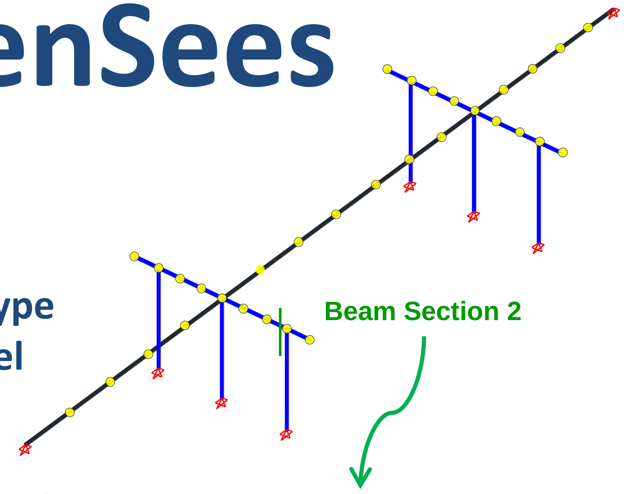
Side View

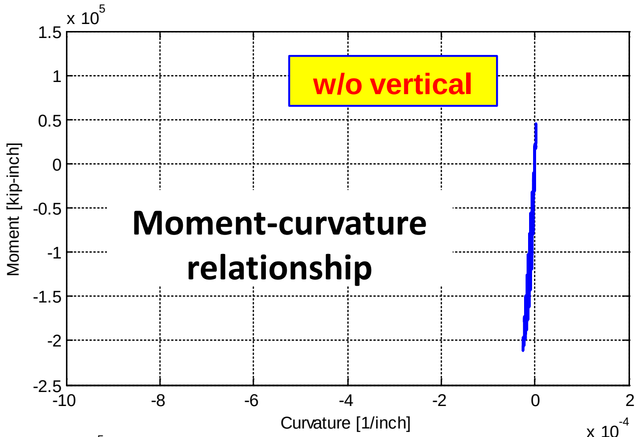
Summary of specimen reinforcement

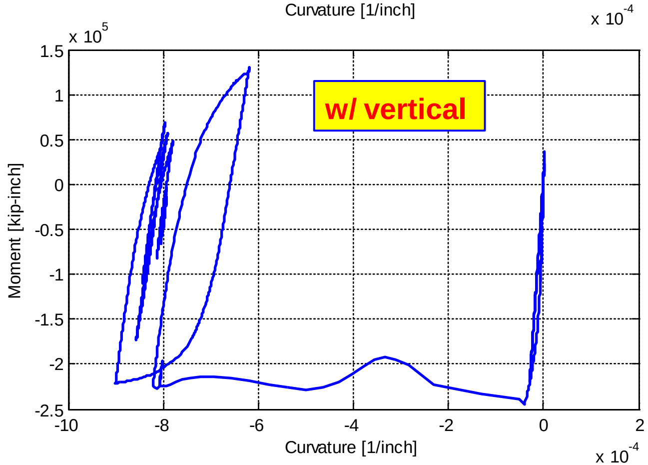
Column	16 #6 longitudinal bars
	#3 spiral at 2-1/2 in.
Cap beam	8 #5 negative reinforcement
	8 #5 positive reinforcement
	#3 stirrups 4 branches at 5 in. spacing
Box-girder	#3 in transverse dir. at 4 in. spacing
	#3 in longitudinal dir. at 2-1/2 in. spacing
	#3 single branch tie at 4 in. spacing

Pre-test FEA: OpenSees

- **Objectives**:
  - Choose GMs with most severe effect on bent cap beam
  - Select final GMs for loading protocol
- Prelim. nonlinear time history analysis of prototype w/ & w/o vl. excitation
- > 80 ground motions (GMs) from PEER NGA database (**Criteria**: Magnitude > 6 & Distance to fault < 20 km)





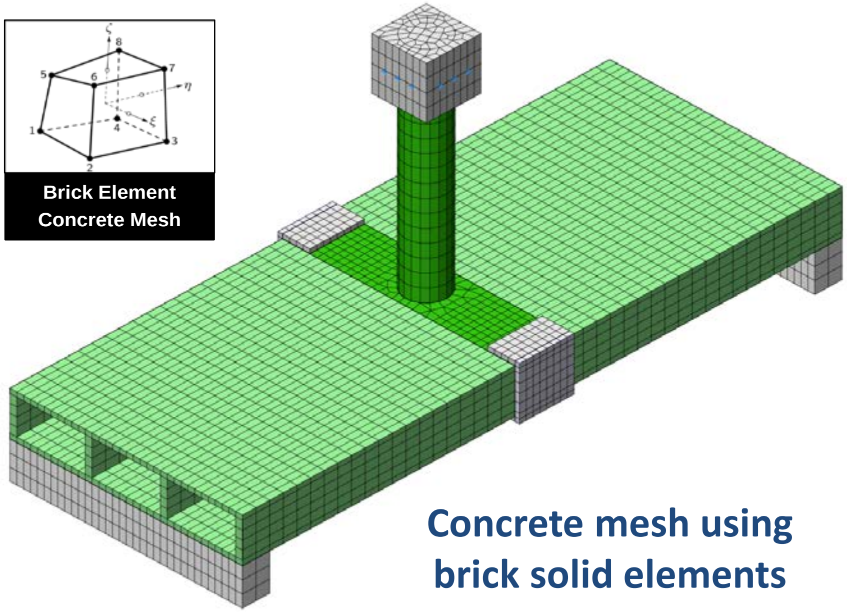


Summary of critical GMs causing bent cap beam failure

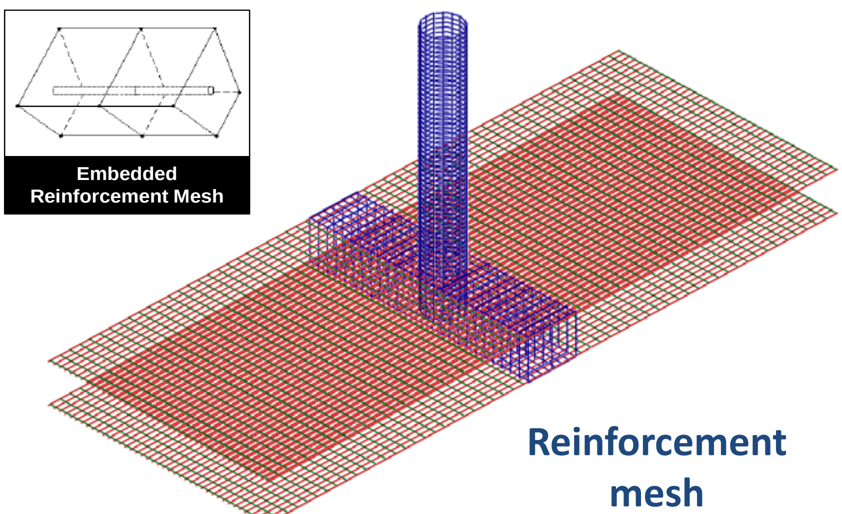
GM	Earthquake	Year	Magnitude	Station
#1	Nahanni- Canada	1985	6.76	Site 1
#2	Loma Prieta	1989	6.93	LGPC
#3	Northridge-01	1994	6.69	Rinaldi
#4	Kobe- Japan	1995	6.90	Takarazuka
#5	Chi-Chi- Taiwan	1999	7.62	TCU068

Pre-test FEA: DIANA

- ❑ **Objectives:**
  - Behavior & mode of failure
  - Setup design & instrumentation
- ❑ Pushover Analysis
  - Vertical & lateral direction
  - Different constant gravity load (0% → 23% column axial capacity)
- ❑ Time-history Analysis



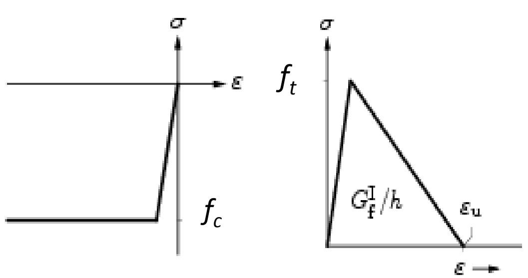
Concrete mesh using brick solid elements



Reinforcement mesh

Total Strain-Based Crack Model

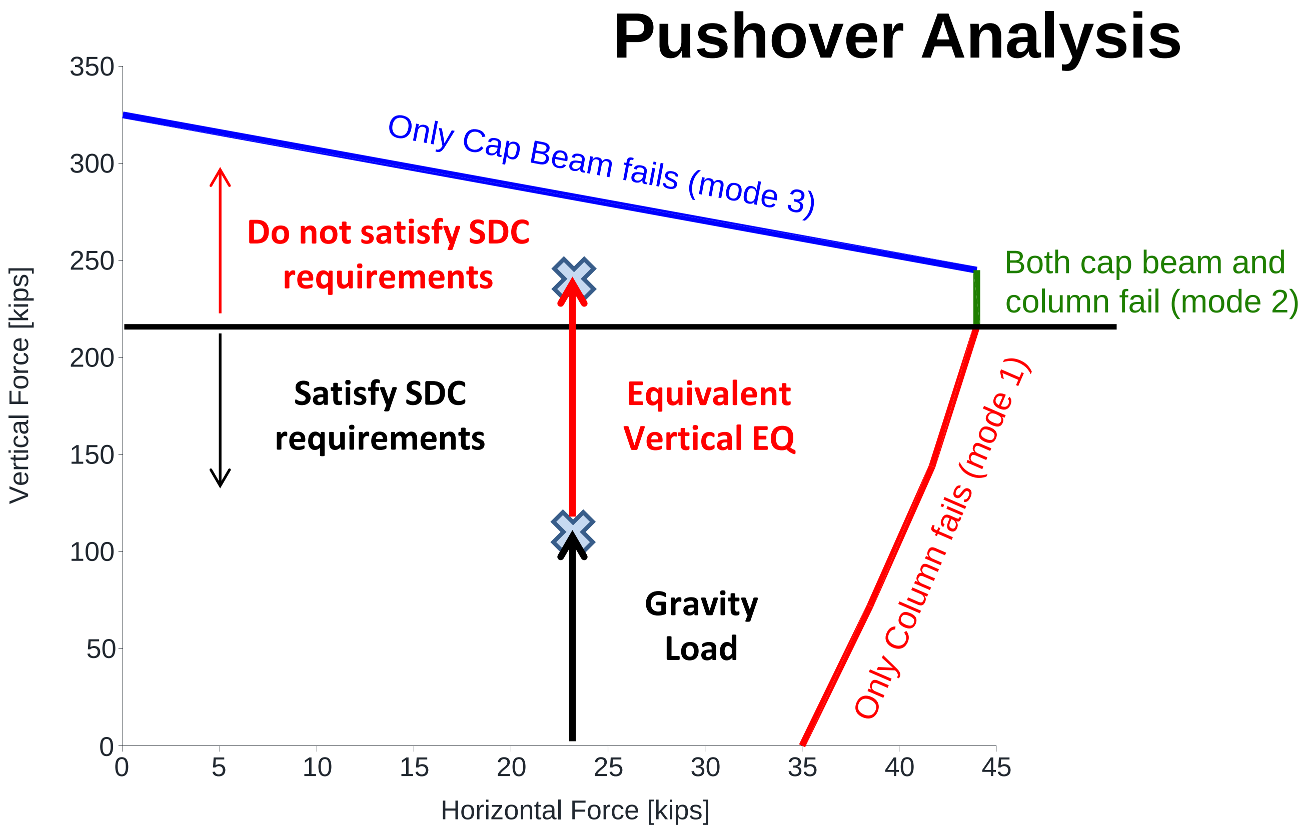
Concrete Material Model

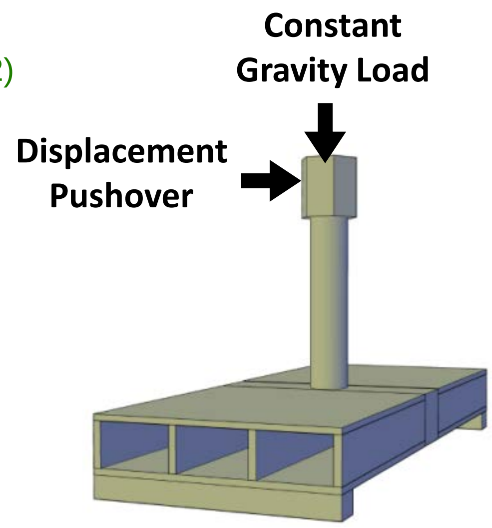


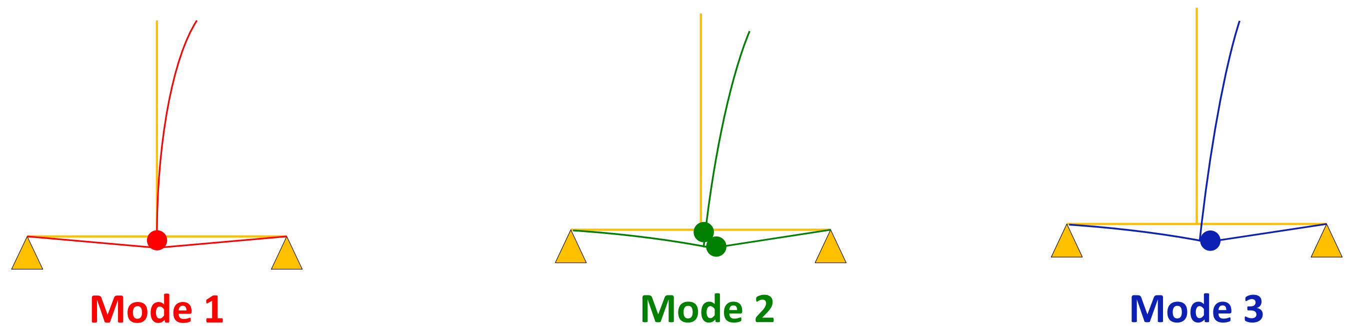
Constant Compression

Linear Tension Softening

Pre-test FEA: DIANA







Experimental Program

- **Objectives**:
  - Global subassemblage behavior (*force, disp., stiffness*)
  - Local Bent cap & column behavior (*moment, curvature, strains*)
  - Box-girder behavior (*effective slab width*)
- **Two identical specimens → Repair & Retrofit?**

Final test Matrix

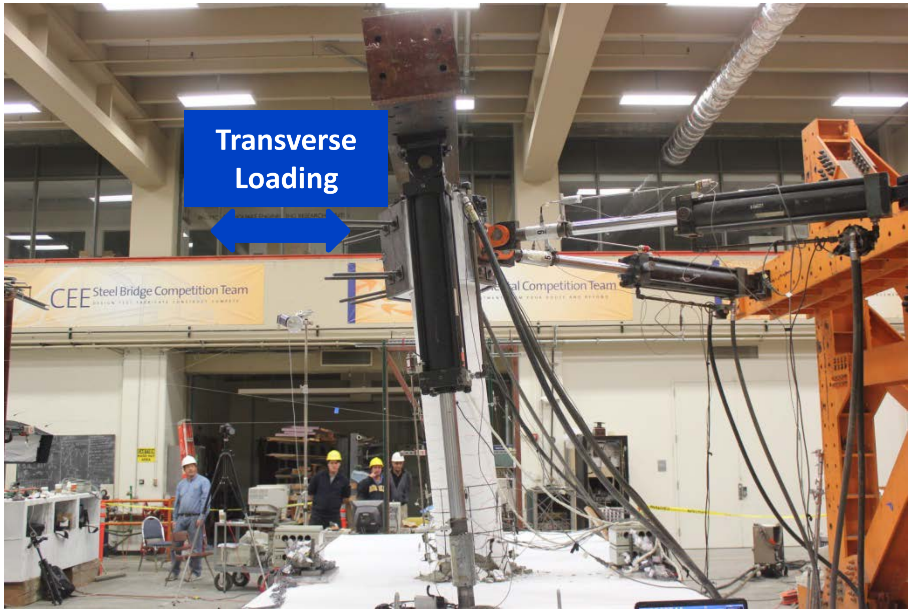
Test Set	Status	Type	Direction	Gravity	Different Scale Runs
SP1-1	As-built	Cyclic	Bidirectional	5%	0.25μ, 0.35μ, 0.50μ, 0.70μ, 1.0μ
SP1-2	As-built	Cyclic	Bidirectional	10%	1.4μ, 2.0μ, 2.8μ, 4.0μ, 5.6μ, 8.0μ
SP1-3	Repaired	Cyclic	Bidirectional	10%	1.4μ, 2.0μ, 2.8μ, 4.0μ, 5.6μ
SP1-4	Repaired	HS Trials	Bidirectional	0%	20%, 50% Rinaldi Ground Motion (GM)
SP1-5	Repaired	HS Trials	Bidirectional	10%	50%, 80%, 100% Rinaldi GM
SP2-1	Retrofitted	HS	Bidirectional	10%	25%, 50%, 75%, 100% Rinaldi GM
SP2-2	Retrofitted	HS	Transverse	15%	125%, 150%, 175%, 200% Rinaldi GM

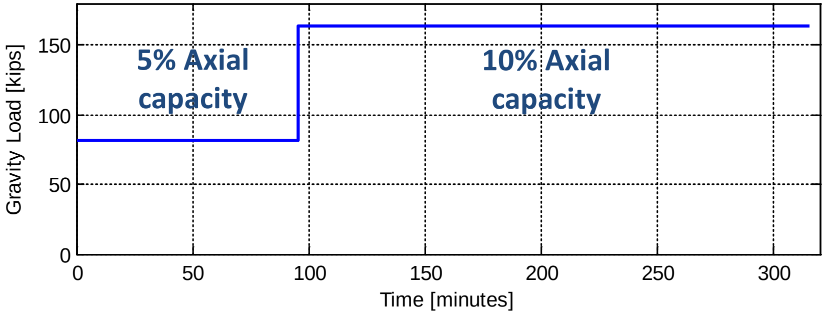
Cyclic Tests: As-built SP1

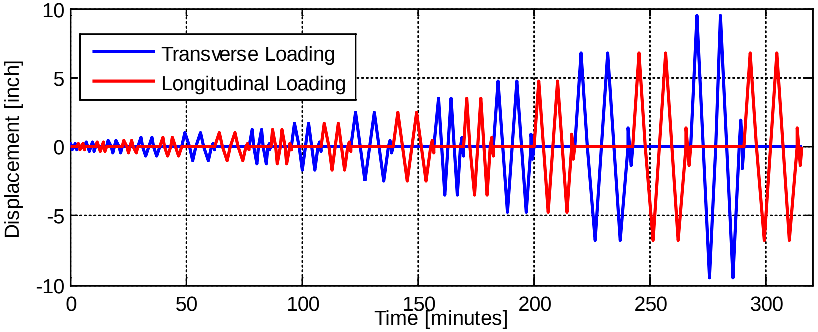
Cyclic Loading
Test Setup

Cyclic Tests: As-built SP1

Bidirectional Cyclic Loading Protocol



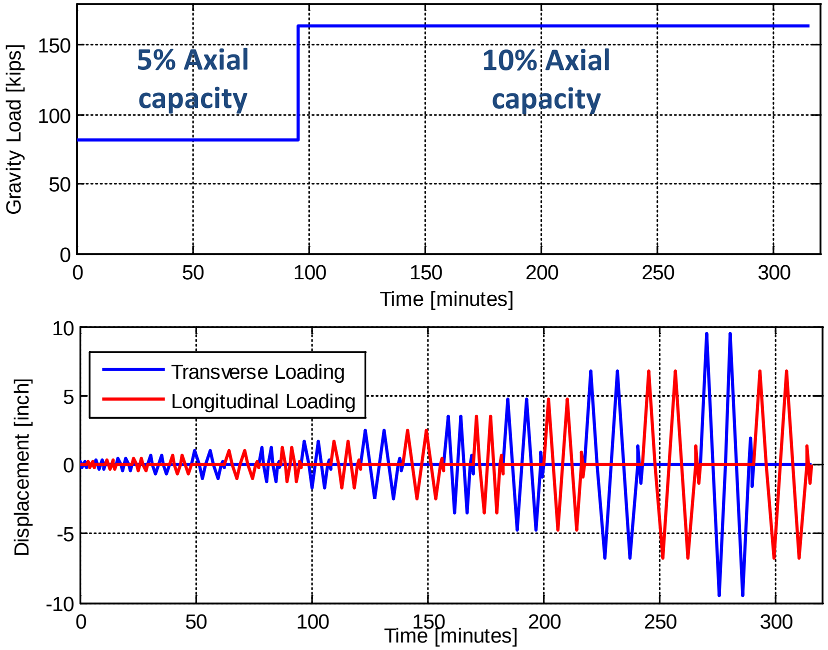




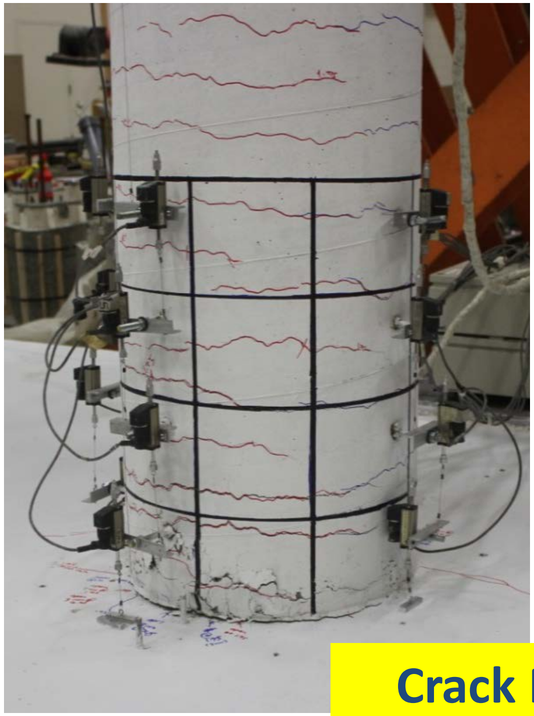
Cross-loading adopted from FEMA 461

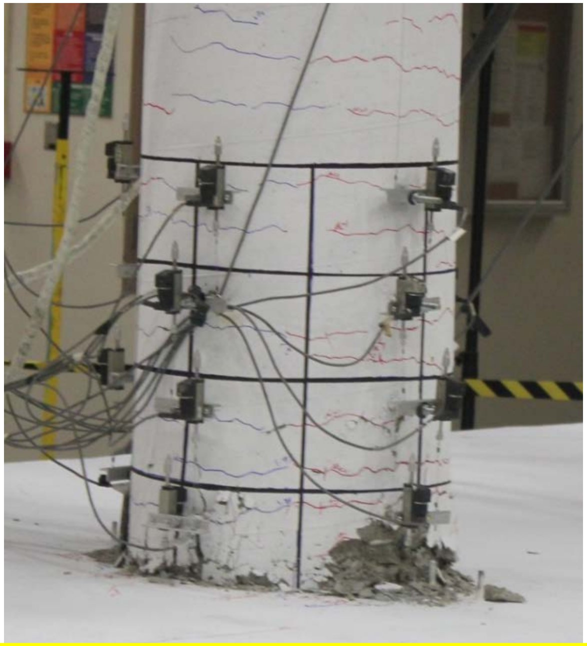
Cyclic Tests: As-built SP1

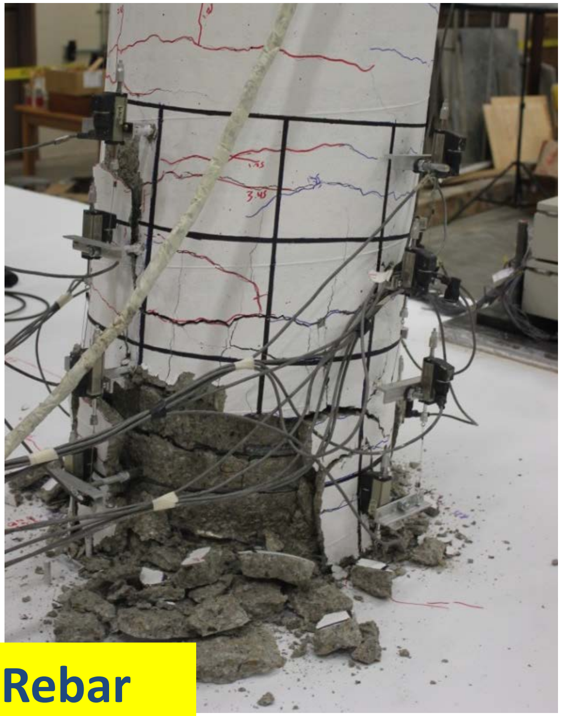
Bidirectional Cyclic Loading Protocol



Cyclic Tests: As-built SP1



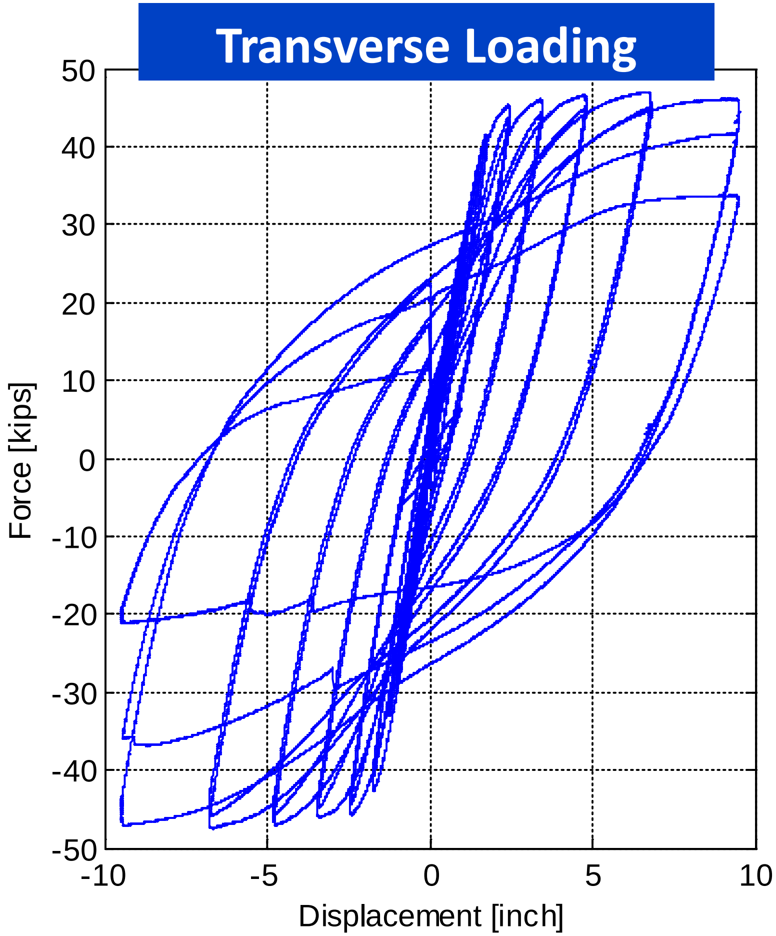


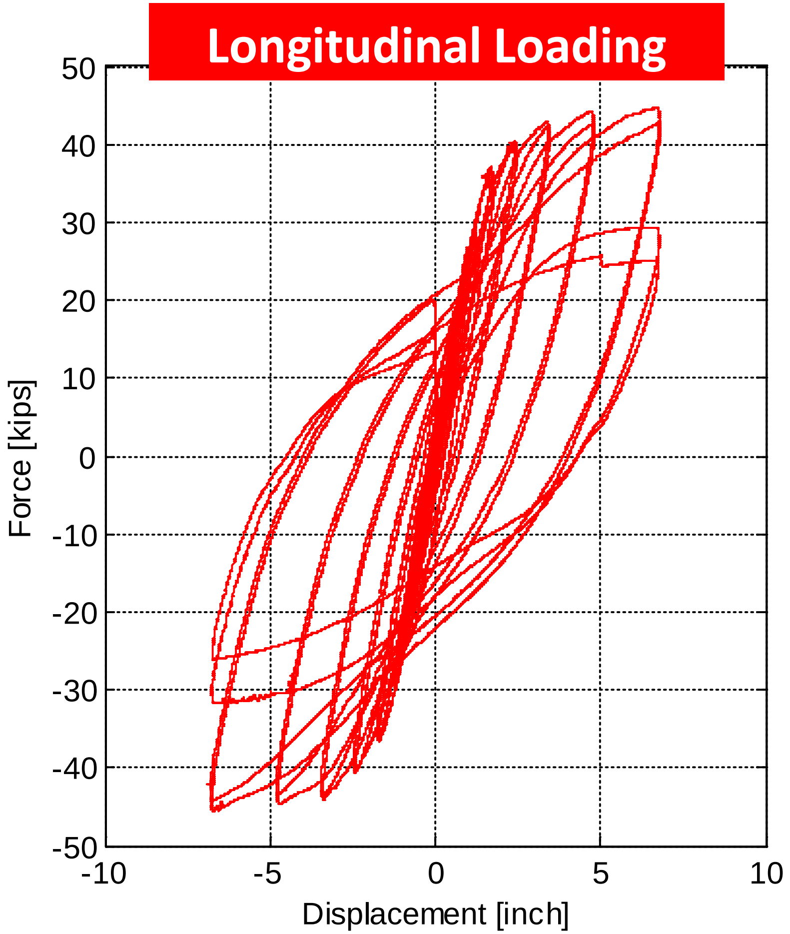


Crack Propagation, Cover Spalling & Rebar Rupture in Column Plastic Hinge Region

Cyclic Tests: As-built SP1

Global Behavior

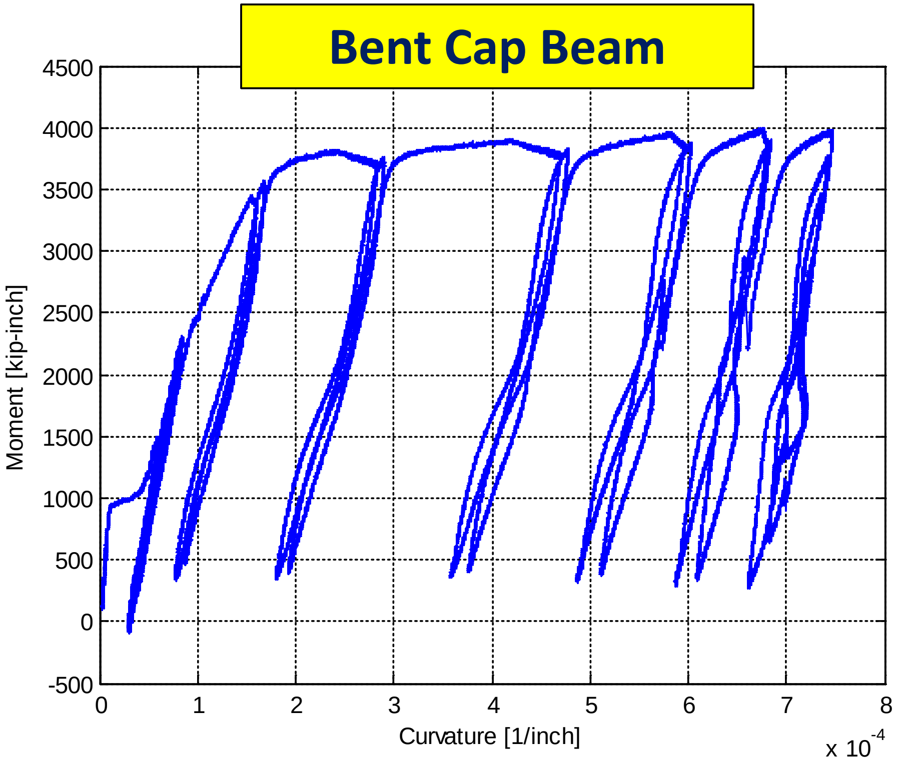


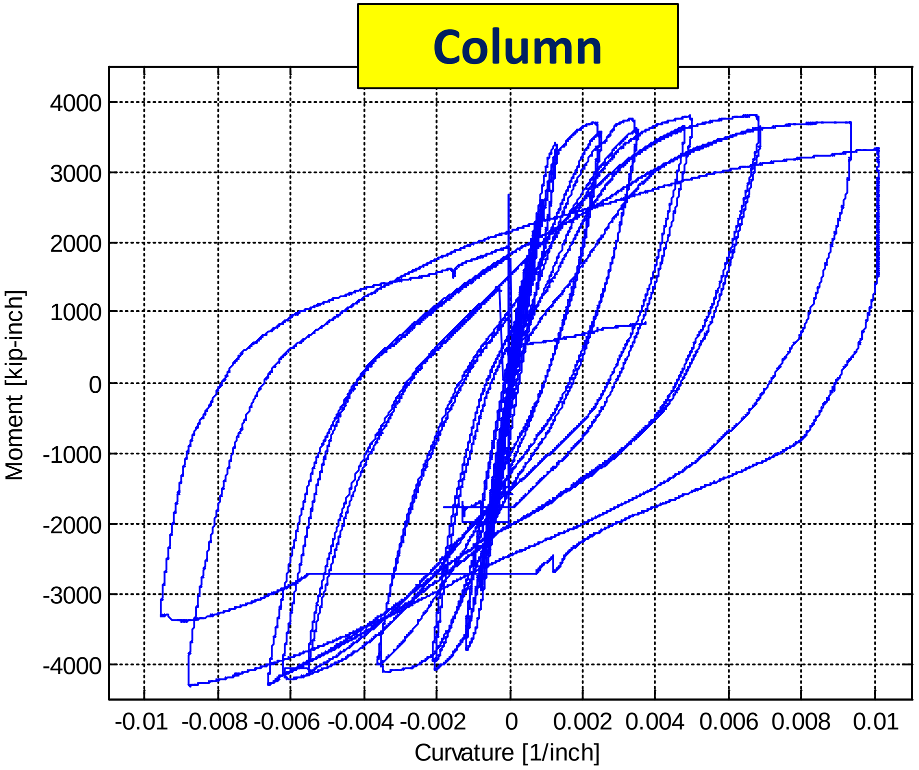


Subassemblage Force-Displacement Relationship

Cyclic Tests: As-built SP1

Local Behavior





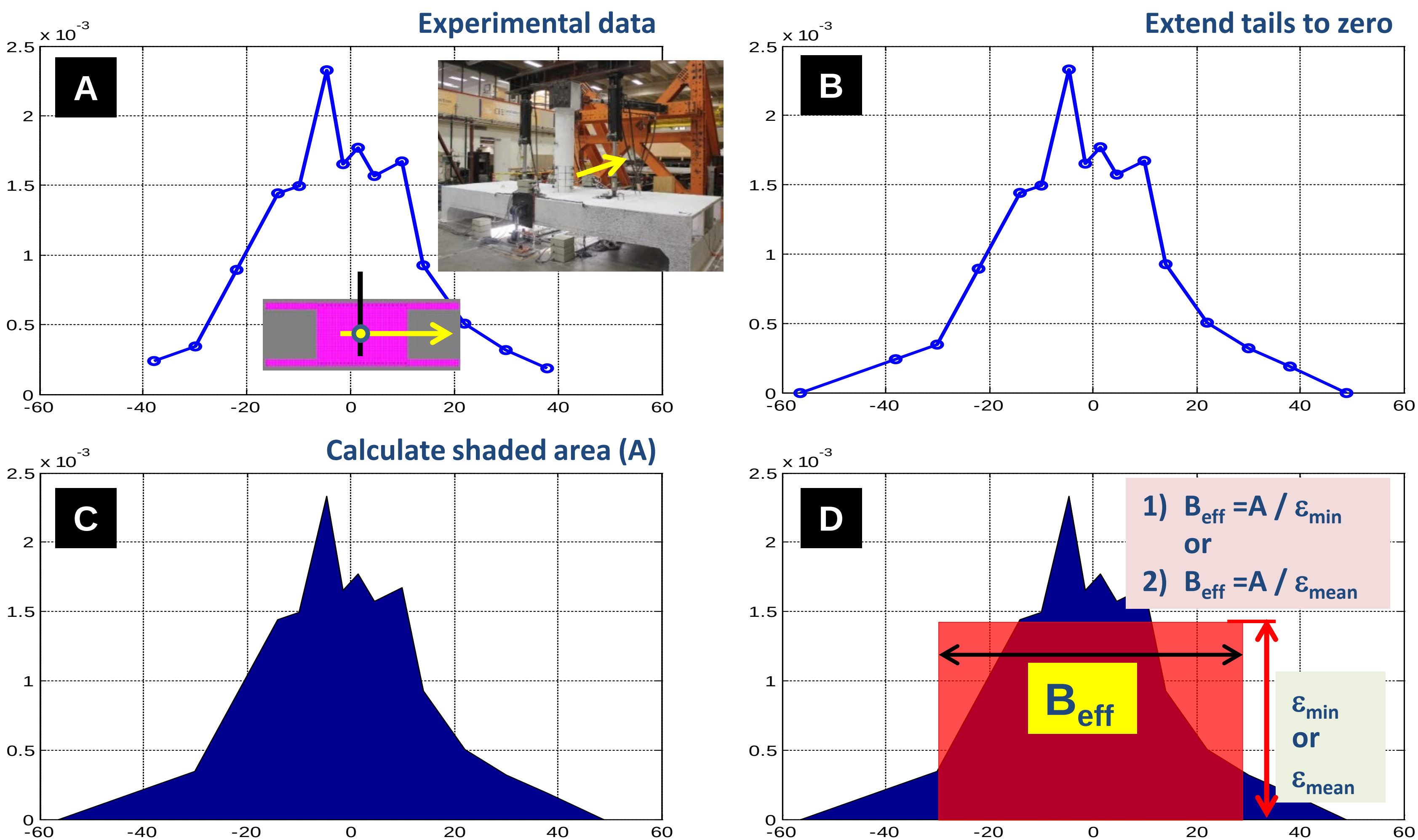
Moment-Curvature Relationship

- Yielding of rebars & hairline cracks
- NO spalling or PH formation

- Rupture of rebars
- cover spalling & PH formation

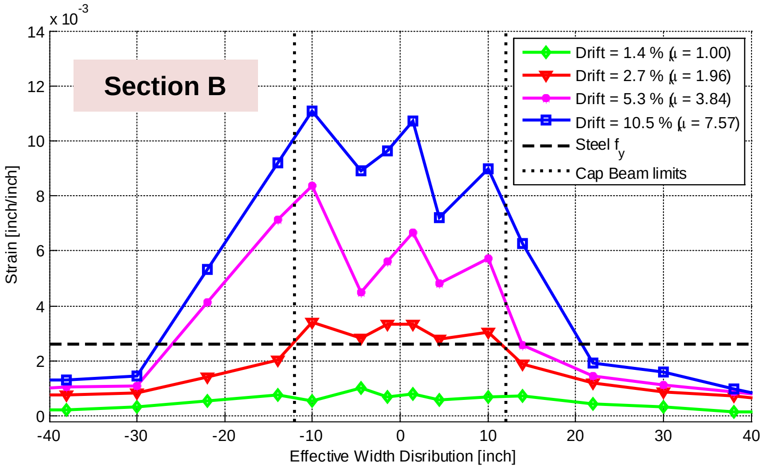
Cyclic Tests: As-built SP1

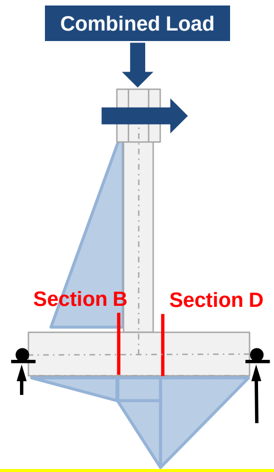
Effective Slab Width

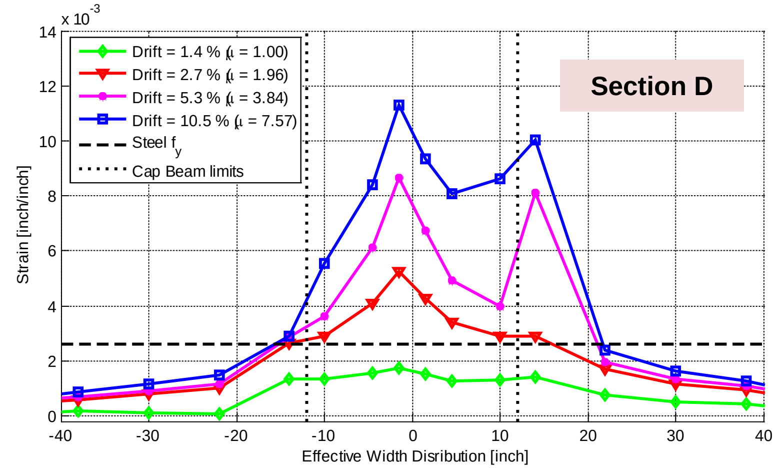


Procedure for estimating effective width from strain distribution

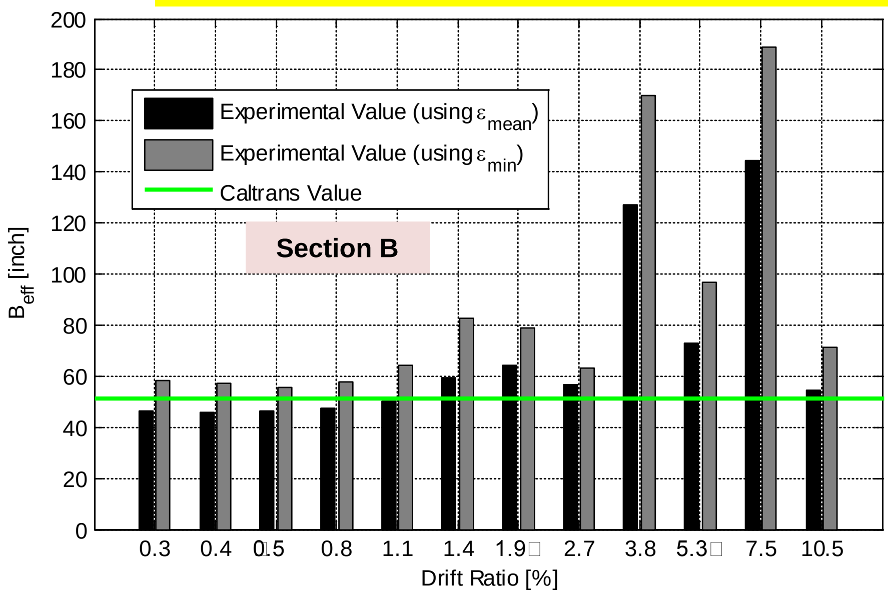
Cyclic Tests: As-built SP1

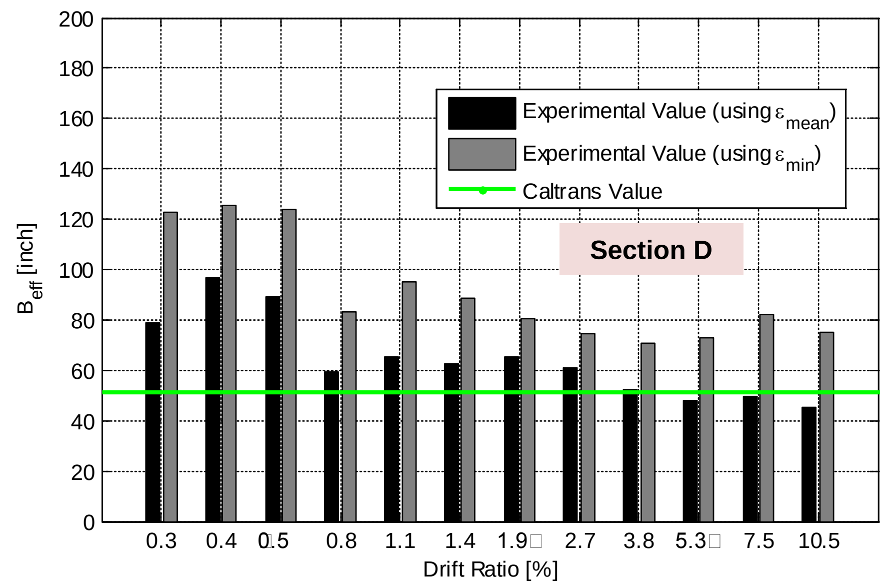






Strain Distribution & Effective Slab Width during TRANSVERSE Loading



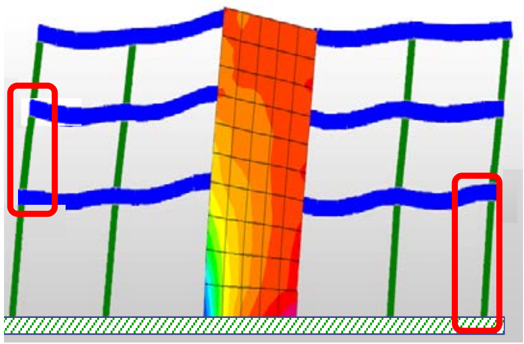


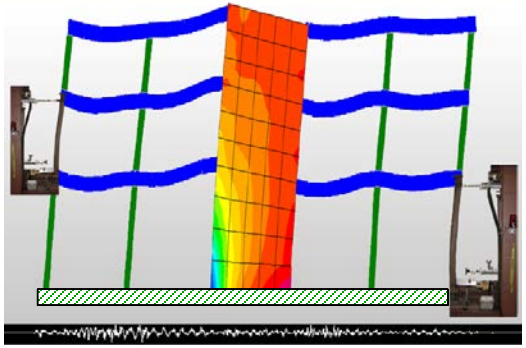
Cyclic Tests: Repaired SP1

Repair Procedure

HS Tests: Background

WHAT is Hybrid Simulation?





Analytical Simulation + **Experimental Simulation** = **Hybrid Simulation (HS)**

TYPES?

Slow Hybrid Simulation vs. Real-time Hybrid Simulation

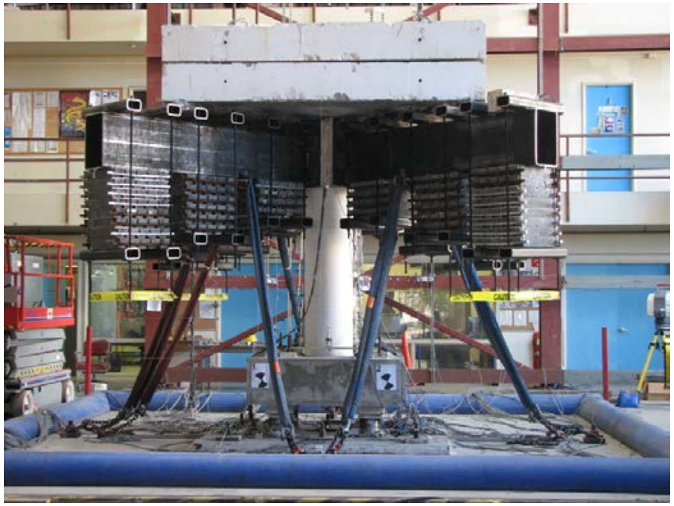
HS Tests: Background

WHY Hybrid Simulation?

More convenient & feasible than shaking table tests

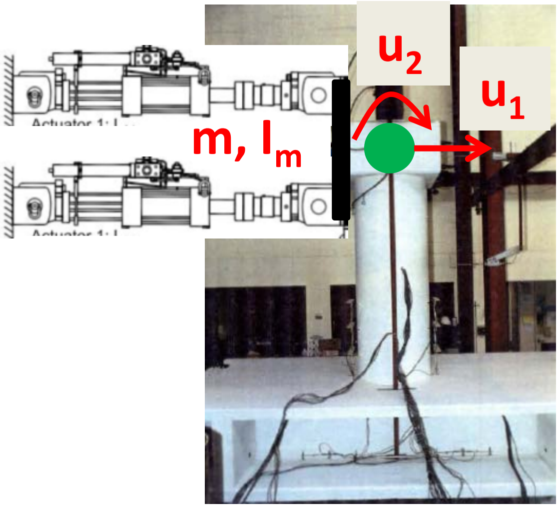
- ✓ Mass modeling
- ✓ Larger structures
- ✓ Observing the damage progression
- ✓ Modeling physical boundary conditions

Shaking Table



VS.

Hybrid Model

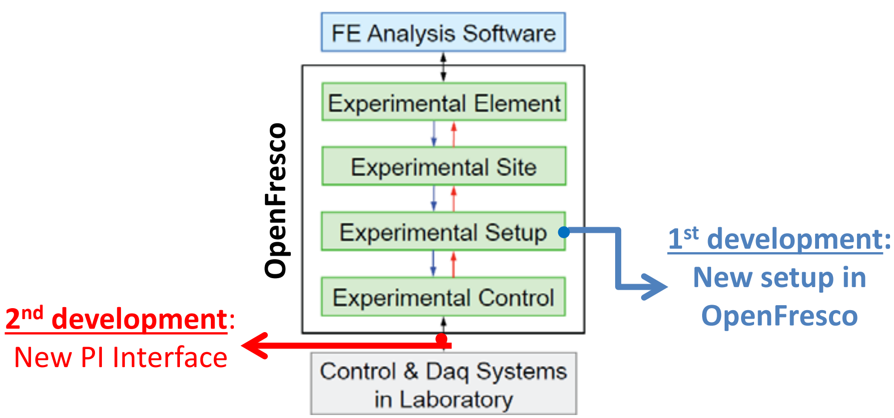


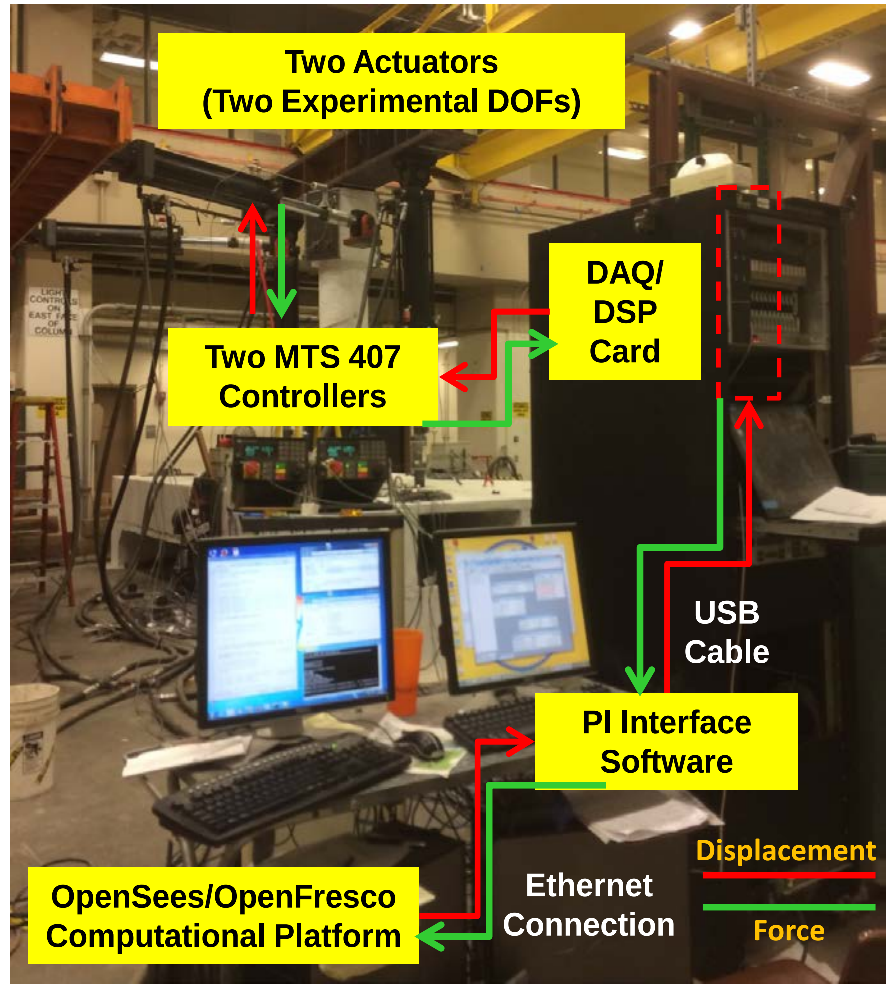
HS Tests: Hybrid System

- ❑ Slow HS Test Components:
  - <u>Physical Substructure:</u> specimen subassemblage
  - <u>Computational Substructure:</u> MDOF mass & damping
- ❑ How HS works?

$$\mathbf{M}\ddot{\mathbf{U}}_{i+1}+\mathbf{C}\dot{\mathbf{U}}_{i+1}+\mathbf{P}_r(\mathbf{U}_{i+1})=\mathbf{P}_{i+1}$$

- ❑ Communication Loop?

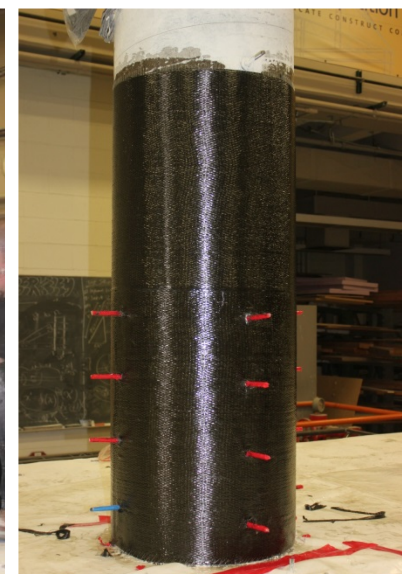




Main components of HS system

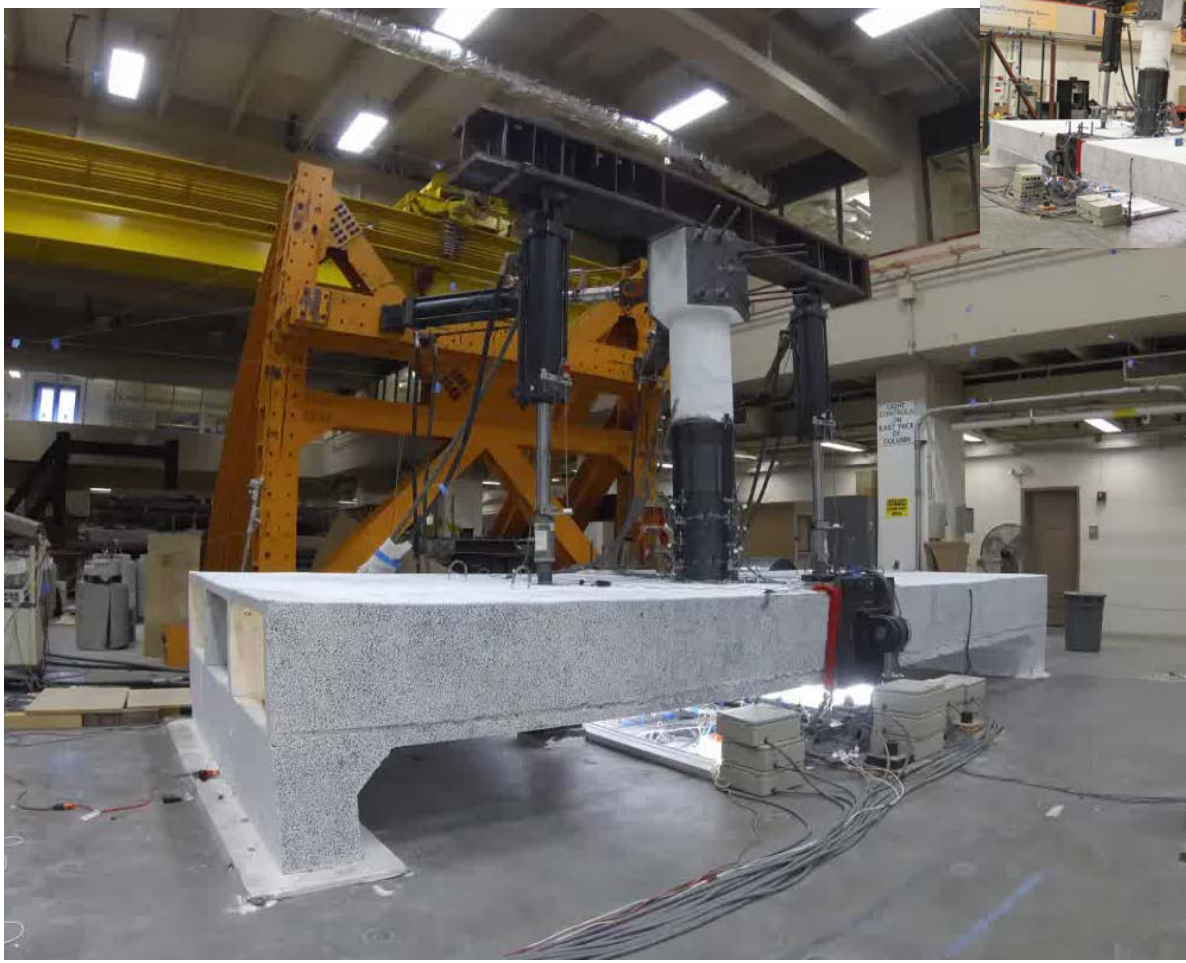
HS Tests: Retrofitted SP2

Retrofit Procedure



HS Tests: Retrofitted SP2

HS Test In-progress



HS Tests: Retrofitted SP2

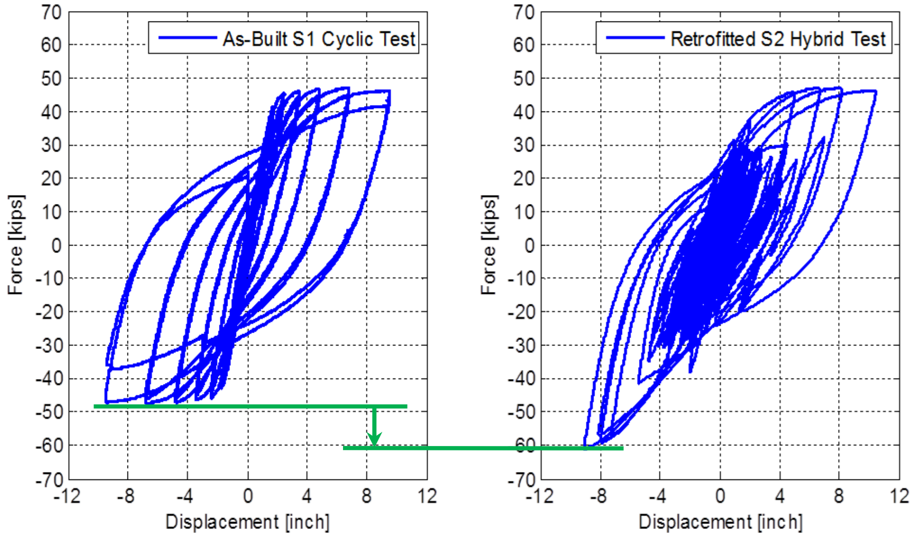
Retrofitted SP2 Damage after HS Tests

Bent cap concrete crushing in compression

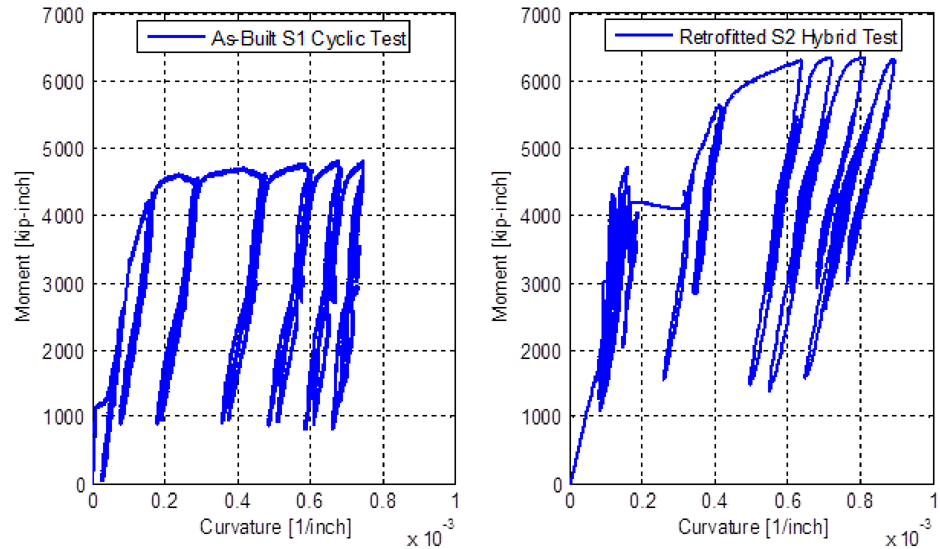
HS Tests: Retrofitted SP2

As-built SP1 vs. Retrofitted SP2

- ❑ Retrofit increased overall SYSTEM capacity by ~25%
- ❑ Increased demand from column + higher gravity (15%) → bent cap failure



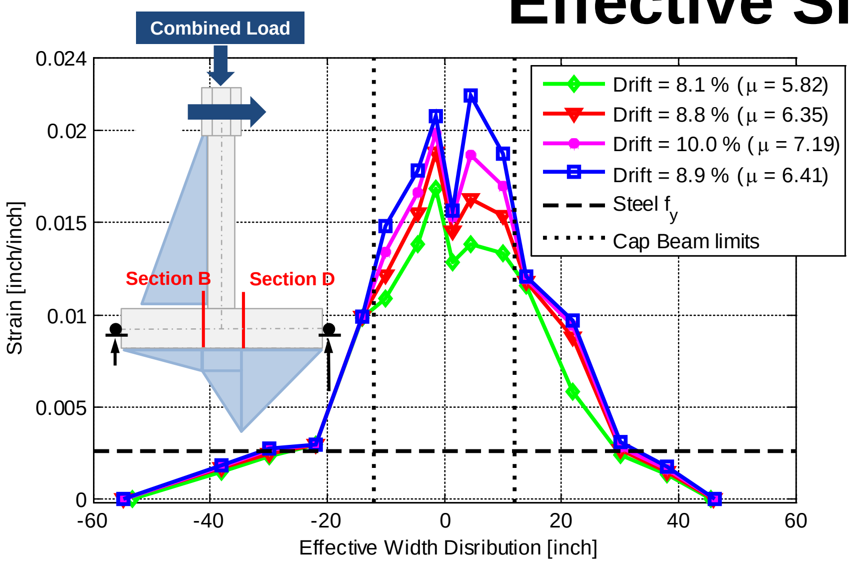
Force-displacement relationship (transverse)

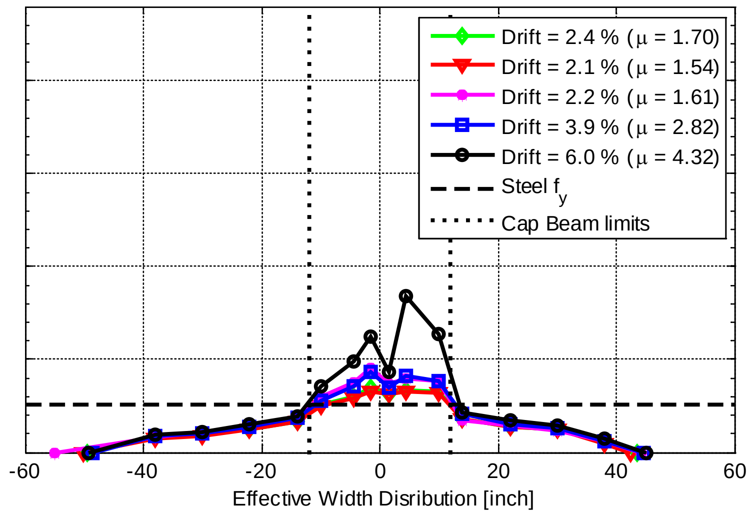


Bent cap moment-curvature relationship

HS Tests: Retrofitted SP2

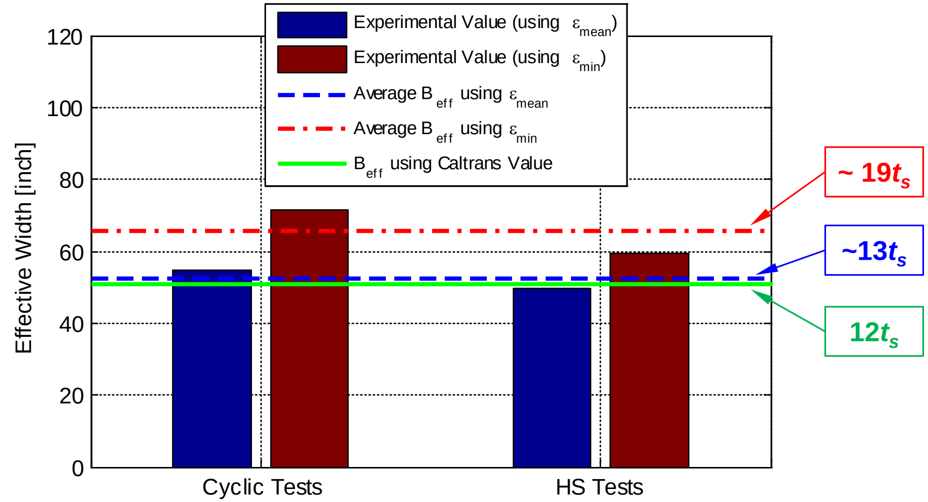
Effective Slab Width





Strain distribution from transverse-only up to 200% (left) & bidirectional up to 100% (right) at Section B

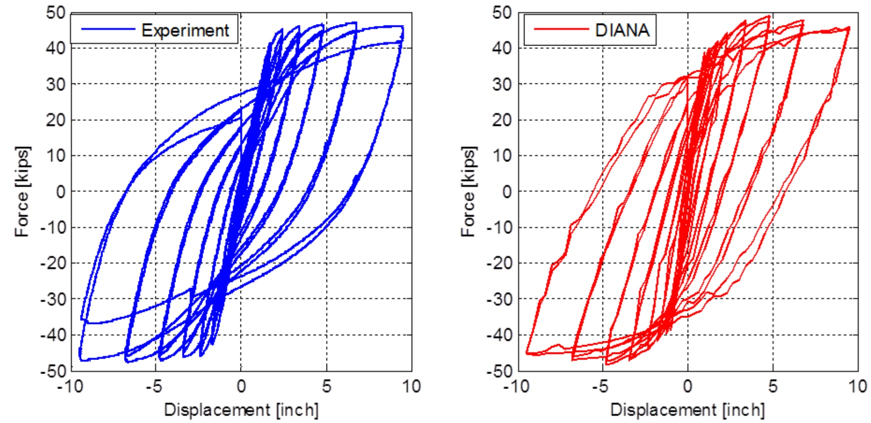
Overall mean values for effective slab width from SP1 cyclic & SP2 HS tests



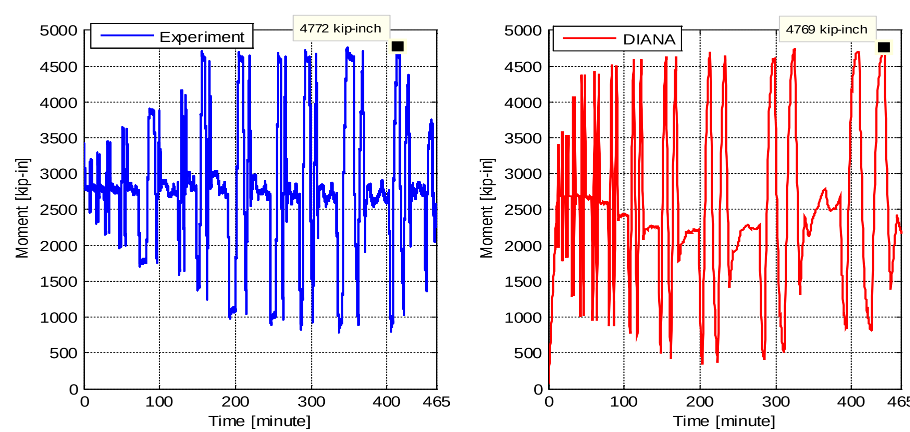
Post-test FEA

- Calibrate FE model
  - *using SP1 experiments*
- Extensive parametric study
  - *e.g. different beam designs*
- Section Analysis

Final FE Calibrated Model



Force-displacement relationship (transverse dir.)



Bent cap beam moment history

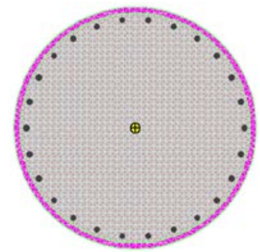
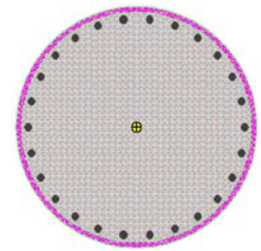
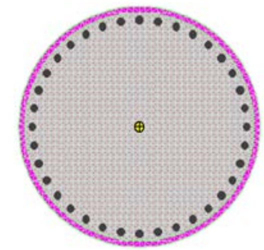
Bent cap beam capacity [kip-in] using section analysis

Section Analysis	$12t_s$	w/o slab rft.	4504
		w/ slab rft.	5977
	$18t_s$	w/o slab rft.	4566
		w/ slab rft.	6855
SP2 HS Tests			**6535**

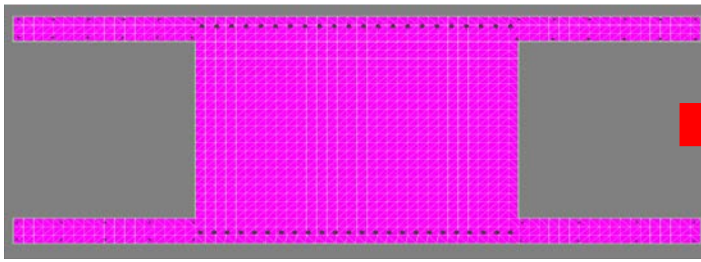
Design Implications

- Design example using Academy Bridge Prototype
- 3 column design scenarios ($\rho_{long.}$ ~ 1.4%, 2.6%, 3.5%)
- 3 configurations for bent cap for capacity check:
  - $12t_s$ w/o slab rft
  - $12t_s$ w/ slab rft
  - $18t_s$ w/ slab rft

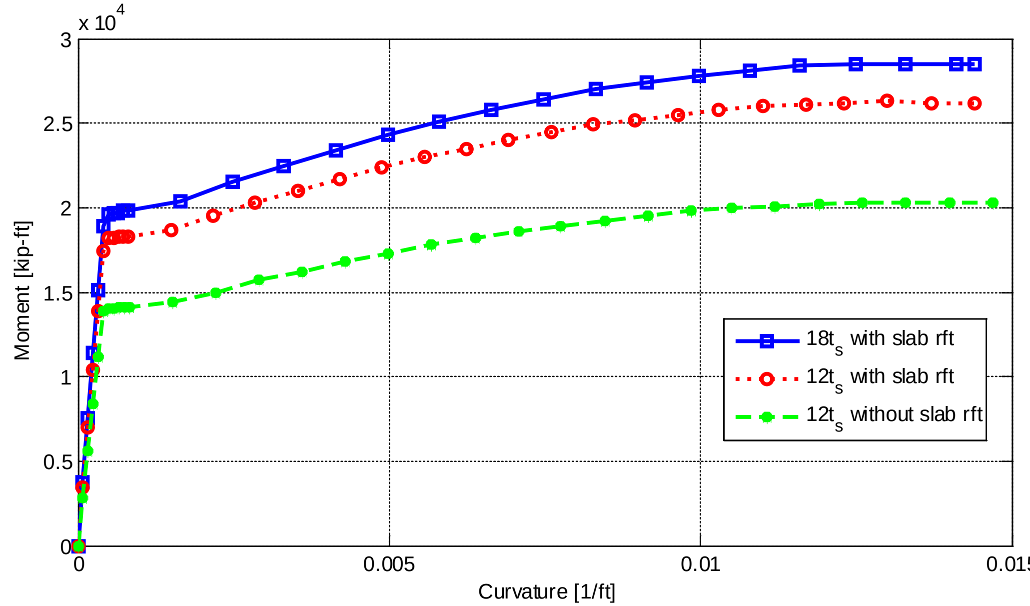
Amplified demands due to higher column capacity (design requirements or retrofit decision)

Column Cross-section			
Diameter	6 ft	6 ft	6 ft
Long. Rft.	26 #14	26 #18	36 #18
Rft. Ratio	1.44%	2.56%	3.53%
Hoops	#8 @ 5 in.	#8 @ 5 in.	#8 @ 5 in.
Ultimate Moment M_p [kip-ft]	14,510	21,140	26,200
Overstrength Moment M_o [kip-ft]	17,410	25,370	31,440
Cap Beam M_{+ve} Demand [kip-ft]	14,970	21,820	27,040
Cap Beam M_{-ve} Demand [kip-ft]	15,670	22,830	28,300

Design Implications



Section analysis for moment-curvature
(e.g. results of negative moment side)



Caltrans & AASHTO Seismic Capacity Check → Revised design required if NOT satisfied!

Case	Column Design	Moment Demand [kip-ft]	**12t_s w/o slab rft**		**12t_s w/ slab rft**		**18t_s w/ slab rft**	
			Capacity	Satisfy Capacity Check?	Capacity	Satisfy Capacity Check?	Capacity	Satisfy Capacity Check?
1	1.44%	15,670		YES		YES		YES
2	2.58%	22,830	**20,270**	NO	**26,170**	YES	**28,460**	YES
3	3.50%	28,300		NO		NO		YES

Conclusions

- $12t_s$ code value conservative & revised effective slab width of $18t_s$ recommended to account for box-girder contributions;
- Transverse deck & soffit slab reinforcement within effective width should be included in bent cap capacity estimation;
- Overdesigned column retrofit may migrate damage to bent cap and/or superstructure;
- Accurate bent cap effective width & capacity check crucial for economical design & informed repair/retrofit decisions.

Thank You! Questions?