FEMA P695 Study on Coupled Composite Plate Shear Walls / Concrete Filled

Update / Progress Report

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LAYOUT

1. Design of Archetype Structures
2. Modeling of Composite Plate Shear Walls
3. Modeling of Coupling Beams
4. Analyses, Cross-checks and Spot-Checks

DESIGN OF ARCHETYPE STRUCTURES

- Design approach
  - Lateral load resistance with good ductility
  - Seismic energy dissipated by coupling beams
  - Preferred yield mechanism
    - Yielding of coupling beams over the height of the structure
    - Followed by yielding at the bottom of individual walls
  - Individual walls should be stronger than coupling beams to ensure yielding of coupling beams prior to yielding of walls

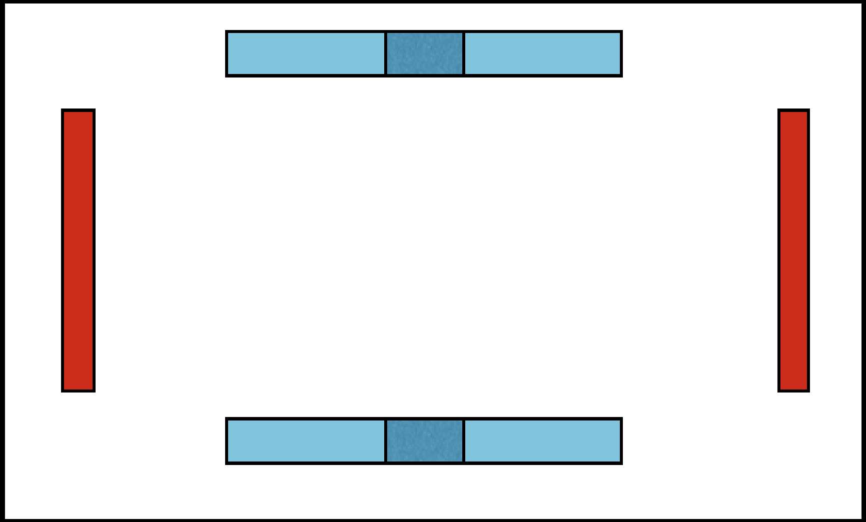
DESIGN OF ARCHETYPE STRUCTURES

Table 1. Archetype performance groups summary table

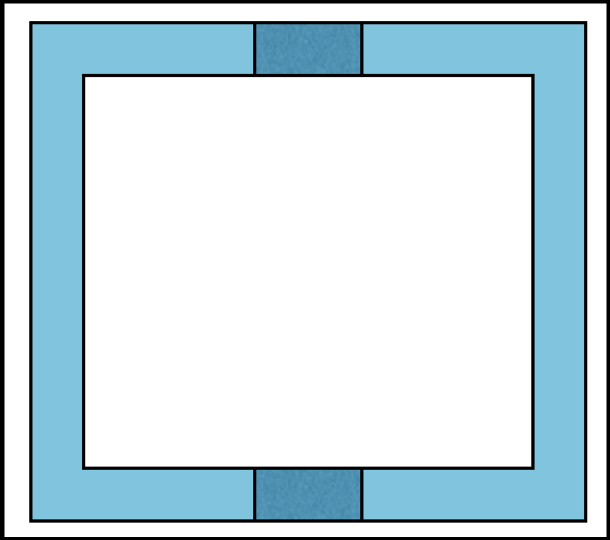
Performance Group Summary				
Group No.	Grouping Criterial			Number of Archetypes
	Basic Configuration	Design Load Level		
		Gravity	Seismic	
PG-1	Type I	Typical	SDC D_{max}	6 (8 & 12 Story)
PG-2			SDC D_{min}	2 (8 & 12 Story)
PG-3	Type II	Typical	SDC D_{max}	6 (18 & 22 story)
PG-4			SDC D_{min}	2 (18 & 22 story)

Design of Archetype Structures

Configuration Type 1

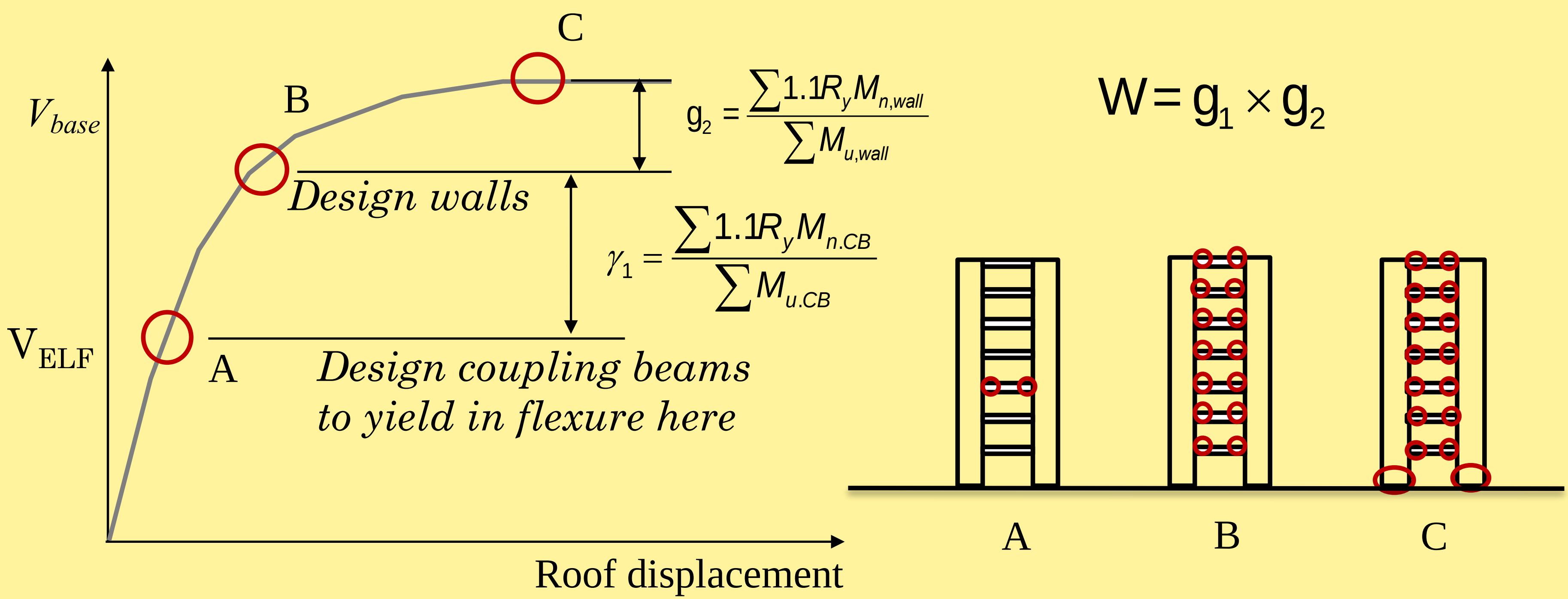


Configuration Type 2



Parameter	Value
Coupling beam length-to-depth ratio	3, 4, or 5
Story height	First story 17ft, All other stories 14ft
Seismic Weight	Floor load of 120 psf
Coupled Wall Length	30 ft - 40 ft. (depending on height etc)
Floor Dimensions	120 ft x 200 ft
Base Shear Amplification Factor	4

Design of Archetype Structure



Design of Archetype Structures

Purdue University

Table 4. 8 story archetype structures

Case	No. Stories	L/d	Cs	Coupled Wall Length, in	Wall Thickness, tsc, in	Plate Thickness, tp, in	CB Length, in	CB Section, in	Uncoupled Wall Length, in	Performance Group
PG-1A	8	3	0.076	144	20	9/16	72	20x24x 3/8(f), 3/8(w)	252	1
PG-1B		4		132	24	9/16	96	24x24x 1/2(f), 3/8(w)	240	1
PG-1C		5		120	24	5/8	120	24x24x 1/2(f), 3/8(w)	240	1
PG-2B	8	4	0.024	144	10	3/16	72	10x18x 3/16(f), 1/4(w)	240	2

Table 5. 12 story archetype structures

Case	No. Stories	L/d	Cs	Coupled Wall Length, in	Wall Thickness, tsc, in	Plate Thickness, tp, in	CB Length, in	CB Section, in	Uncoupled Wall Length, in	Performance Group
PG-1D	12	3	0.057	204	18	9/16	72	18x24x 5/16(f), 3/8(w)	348	1
PG-1E		4		192	22	9/16	96	22x24x 7/16(f), 3/8(w)	336	1
PG-1F		5		180	24	9/16	120	24x24x 1/2(f), 3/8(w)	324	1
PG-2E	12	4	0.017	204	8	3/16	72	8x18x 3/16(f), 1/4(w)	336	2

Design of Archetype Structures

Purdue University

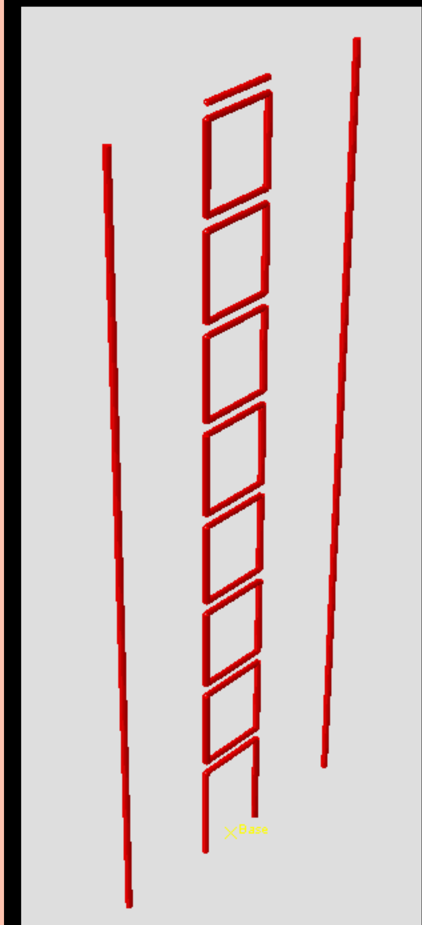
Table 6. 18 story archetype structures

Case	No. Stories	L/d	Cs	C wall depth, in (c-c)	C wall width, in (c-e)	$t_{sc,f}$, in	$t_{sc,w}$, in	$t_{p,bot}$, in	$t_{p,top}$, in	CB Length, in	CB Section, in	Performance Group
PG-3A		3		360	180	18	14	1/2	5/16	72	18x24x 5/16(f), 3/8(w)	3
PG-3B	18	4	0.042	360	168	24	14	1/2	5/16	96	24x24x 7/16(f), 3/8(w)	3
PG-3C		5		360	156	26	16	9/16	5/16	120	26x24x 1/2(f), 3/8(w)	3
PG-4B	18	4	0.014	360	162	12	12	3/16	3/16	72	12x18x 1/4(f), 1/4(w)	4

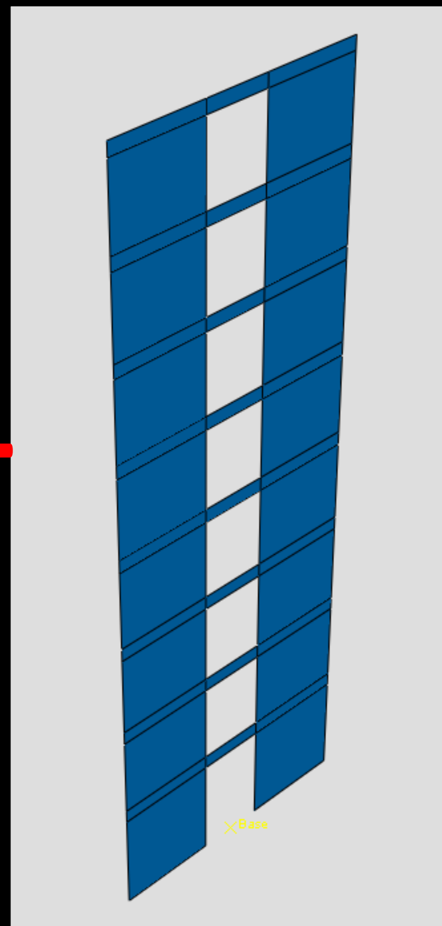
Table 7. 22 story archetype structures

Case	No. Stories	L/d	Cs	C wall depth, in (c-c)	C wall width, in (c-e)	$t_{sc,f}$, in	$t_{sc,w}$, in	$t_{p,bot}$, in	$t_{p,top}$, in	CB Length, in	CB Section, in	Performance Group
PG-3D		3		360	204	20	14	1/2	3/8	72	20x24x 3/8(f), 3/8(w)	3
PG-3E	22	4	0.036	360	192	24	14	1/2	3/8	96	24x24x 7/16(f), 3/8(w)	3
PG-3F		5		360	180	28	16	9/16	3/8	120	28x24x 9/16(f), 3/8(w)	3
PG-4E	22	4	0.012	360	162	14	10	3/16	3/16	72	14x18x 1/4(f), 1/4(w)	4

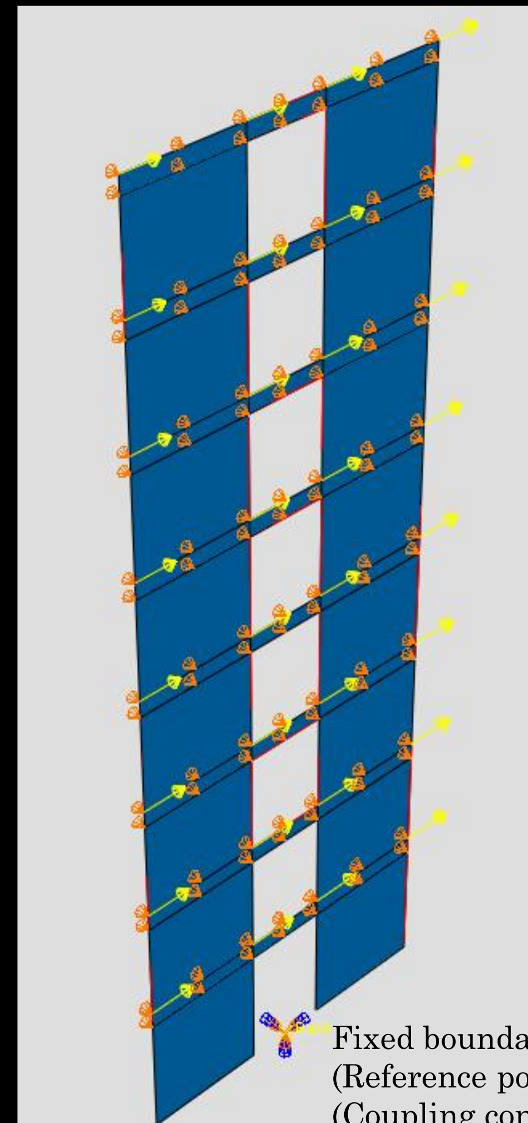
Design of Archetype Structure



Truss elements
T3D2

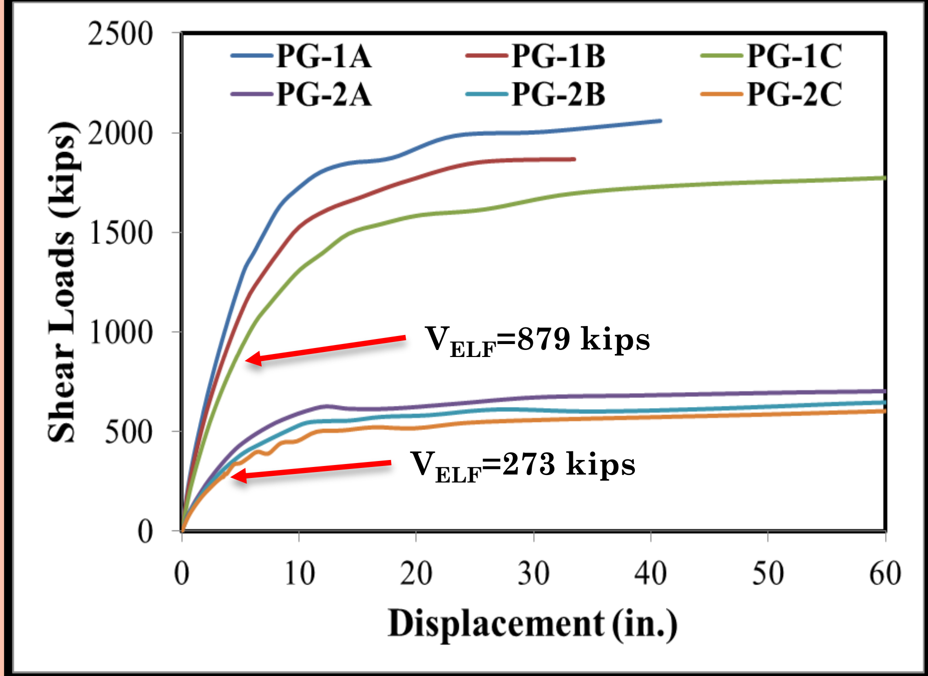


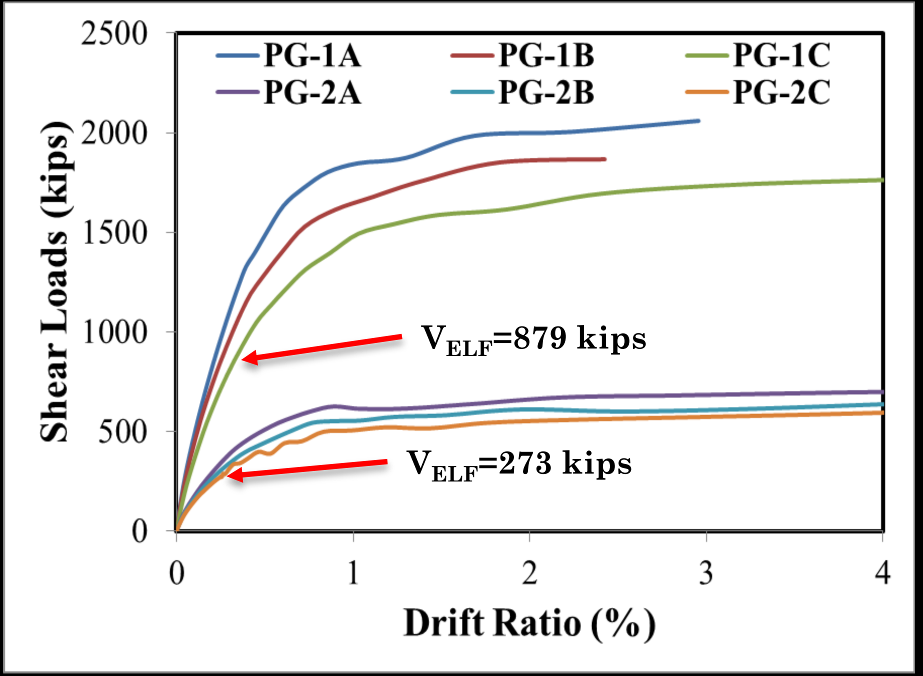
Layered composite shell
elementsS4R



Design of Archetype Structures

Pushover analysis results:

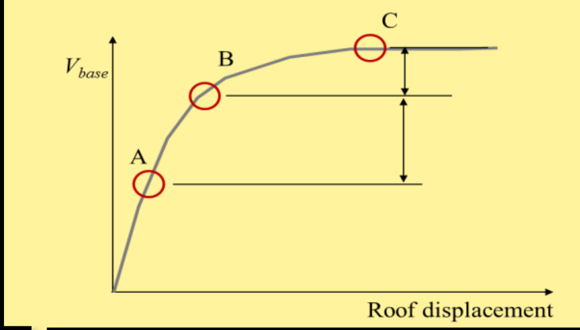


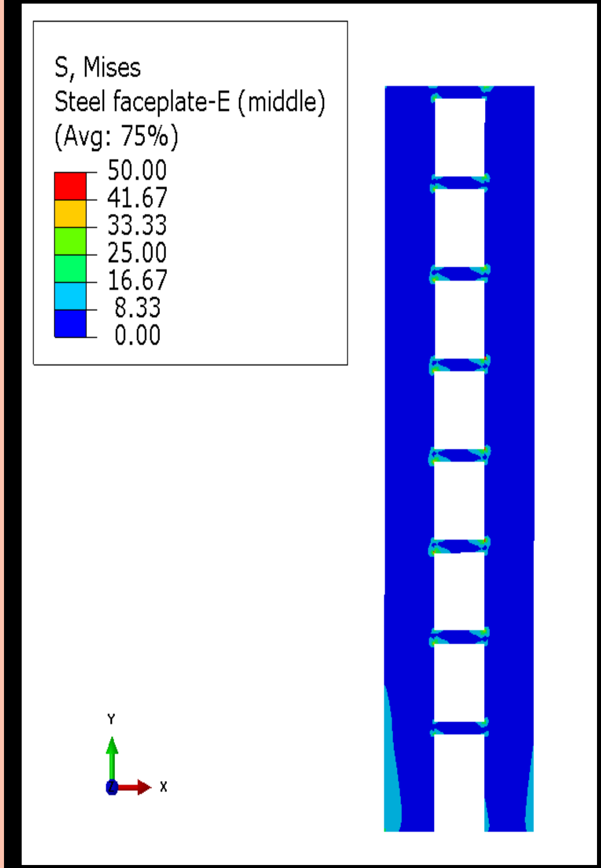


	PG-1A	PG-1B	PG-1C	PG-2A	PG-2B	PG-2C
Ω_0	2.34	2.17	2.34	3.04	2.89	2.15

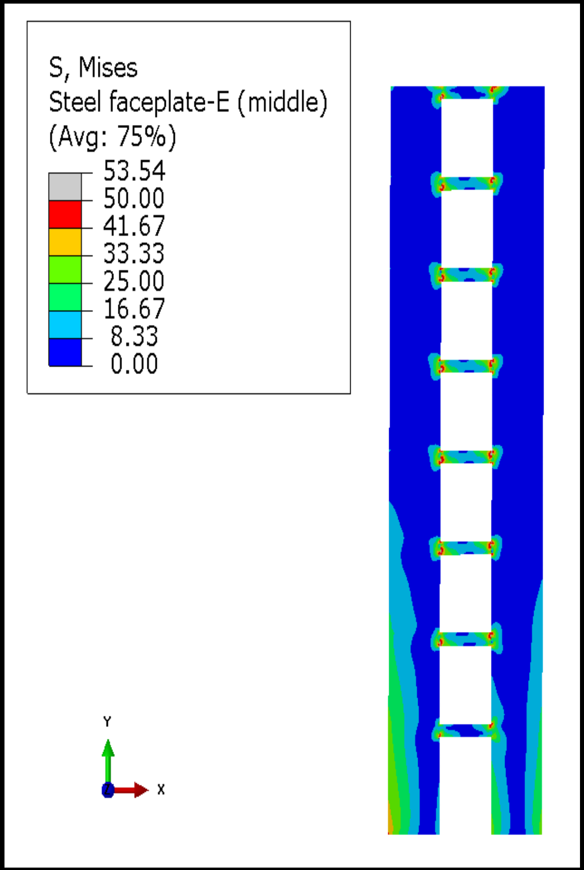
Design of Archetype Structures

Pushover analysis results:





A



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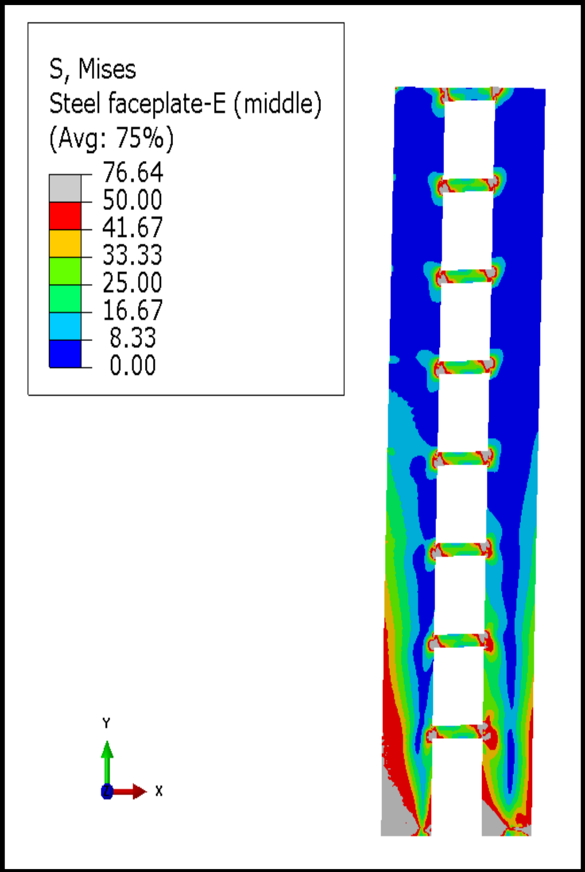

C

Design of Archetype Structures

- Design approach
  - Wall overstrength factor (CSA 2004)

$$W = g_1 \times g_2$$

$$\gamma_1 = \frac{\sum 1.1 R_y M_{n.CB}}{\sum M_{u.CB}}$$

$$g_2 = \frac{\sum 1.1 R_y M_{n,wall}}{\sum M_{u,wall}}$$

$M_{n.CB}$: nominal flexural capacity of coupling beams

$M_{u.CB}$: flexural demand on coupling beam calculated using ELF

$M_{n.W}$: nominal flexural capacity of composite wall account for axial force

$M_{u.W}$: flexural demand on wall calculated using ELF amplified by g_1

LAYOUT

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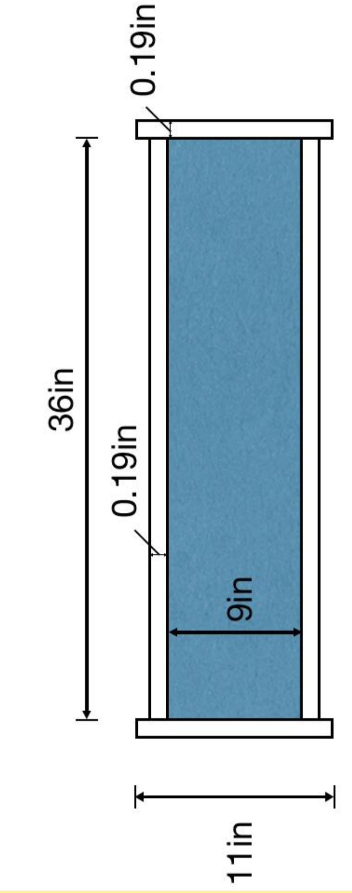
Modeling of CPSW

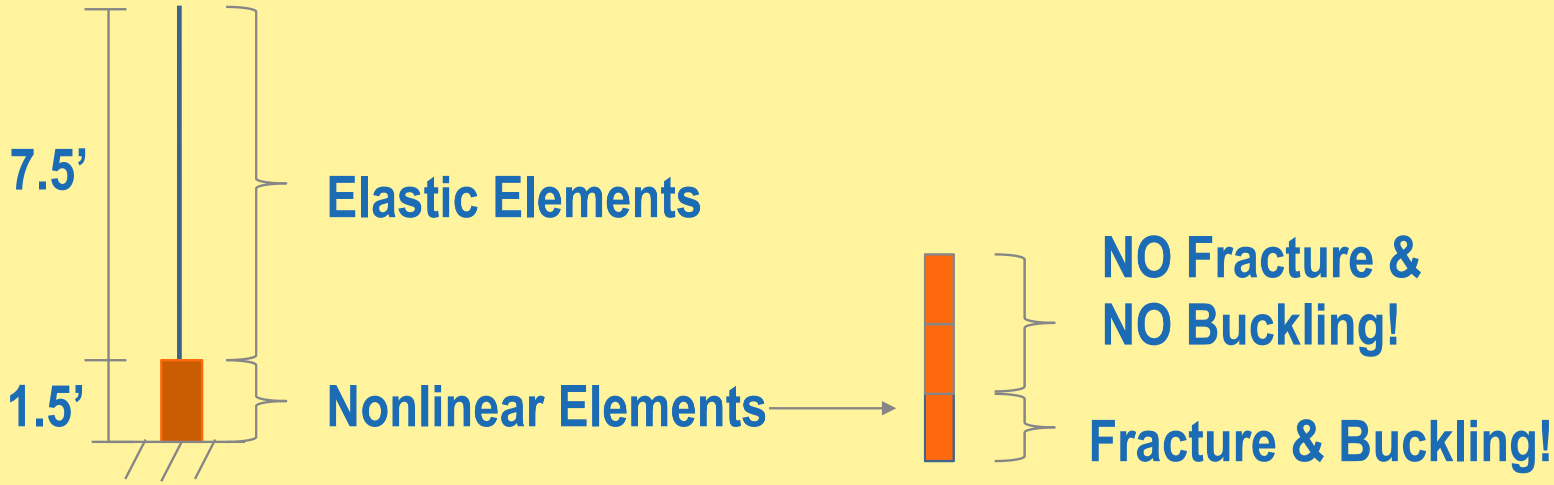
- Specimens Tested at Purdue …

	Name	Day of Testing Concrete Strength, psi	3/16" Plate Fy, ksi	3/16" Plate Fu, ksi	P applied, kip
SP1	CW-42-55-10-T	6508.0	61.2	71.6	210
SP2	CW-42-55-20-T	7789.0	61.2	71.6	505
SP3	CW-42-14-20-T	8741.0	61.2	71.6	560
SP4	CW-42-14-20-TS	8408.0	61.2	71.6	540
SP5	CW-42-55-30-T	7386.0	61.2	71.6	710



Modeling of CPSW

- Lp is 16" from similarity using fiber analysis but increased to 18" for strain hardening.
- Only bottom element has both fracture and buckling
- Elements are 6" displacement based with 3 NIP over plastic hinge.
- 1" fiber in size was chosen for the cross-section.



Modeling of CPSW

Material Inputs - Steel

- Backbone Curve:
- Backbone Curves from Coupon Test for this cross section
- Cyclic Buckling:
- So following parameters were chosen based on the behavior observed from test:

  $\beta = 1.0$ $\gamma = 1.0$ $r = 0.4$ $Lsr = 20.8$

- Low Fatigue Life:
- So following parameters were chosen based on the behavior observed from test:

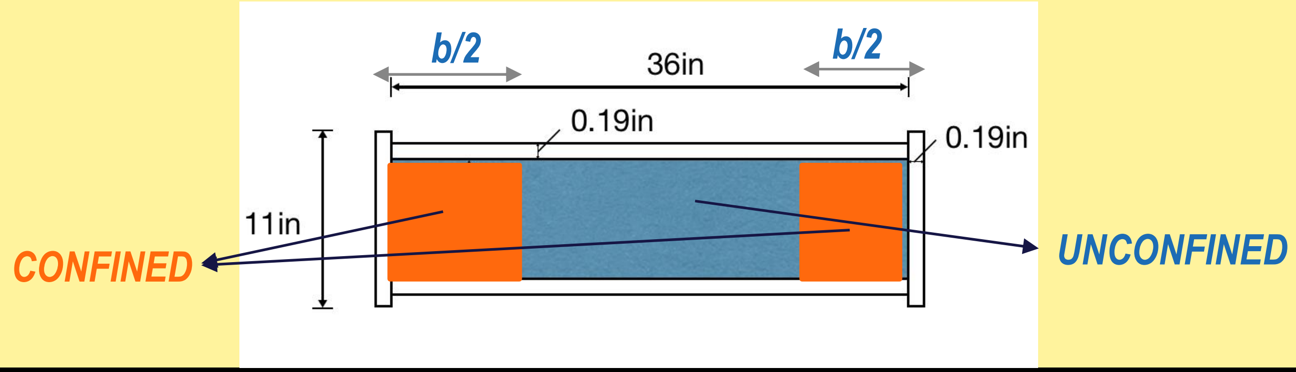
  $c = 0.515$ $\varepsilon'f = 0.21$ $Cd = 0.3$ (for cyclic degradation)

	Steel
Fy (ksi)	61.2
Fu (ksi)	71.6
Es (ksi)	22500
Esh (ksi)	1221.75
εsh	2.82E-3
εu	0.15

Modeling of CPSW

Material Inputs - Concrete

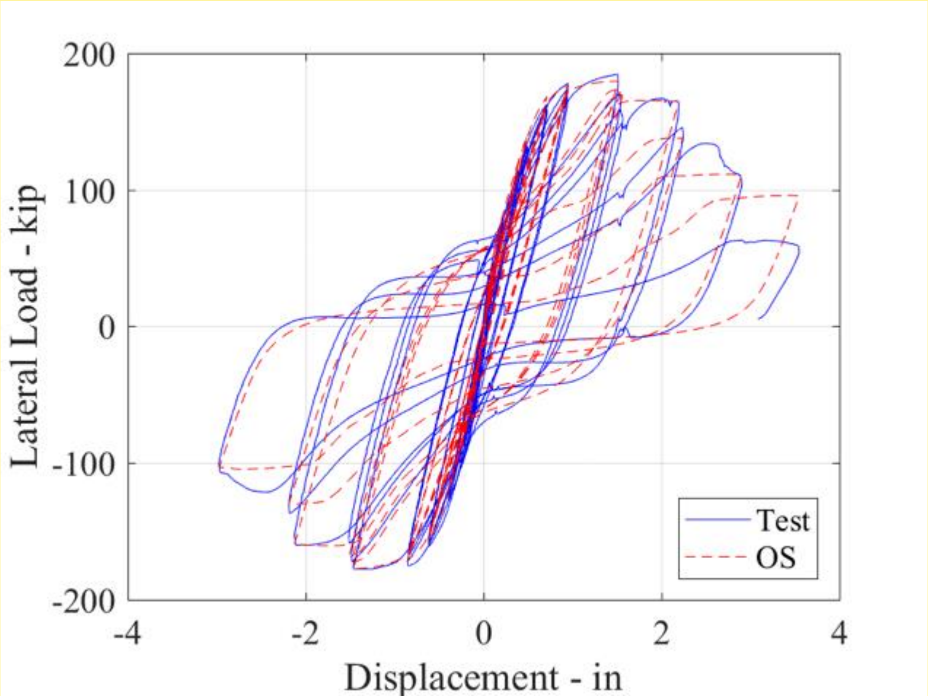
Specimen	fpc, ksi (unconfined/ confined)	Ec, ksi	eps_c0	fp_cu, ksi	eps_cu, ksi	Lambda
SP1	6.508/8.61	4598	2.831E-3/3.754E-3	5.88/7.79	0.04	0.7
SP2	7.789/9.752	5031	3.096E-3/3.877E-3	6.924/8.67	0.04	0.1
SP3	8.7411/10.77	5329	3.28E-3/4.04E-3	7.7/9.495	0.04	0.7
SP4	8.408/10.42	5227	3.22E-3/3.98E-3	7.43/9.21	0.04	0.7
SP5	7.386/9.31	4899	3.02E-3/3.8E-3	6.59/8.305	0.04	0.05



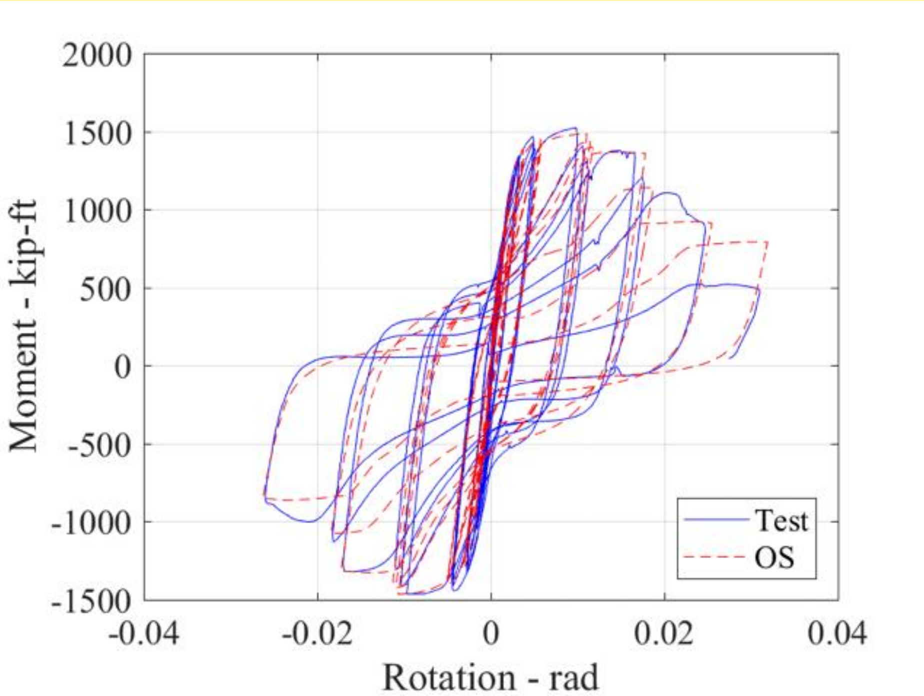
Modeling of CPSW

CW-42-55-10-T (SP1)

Lateral Force vs Top Displacement



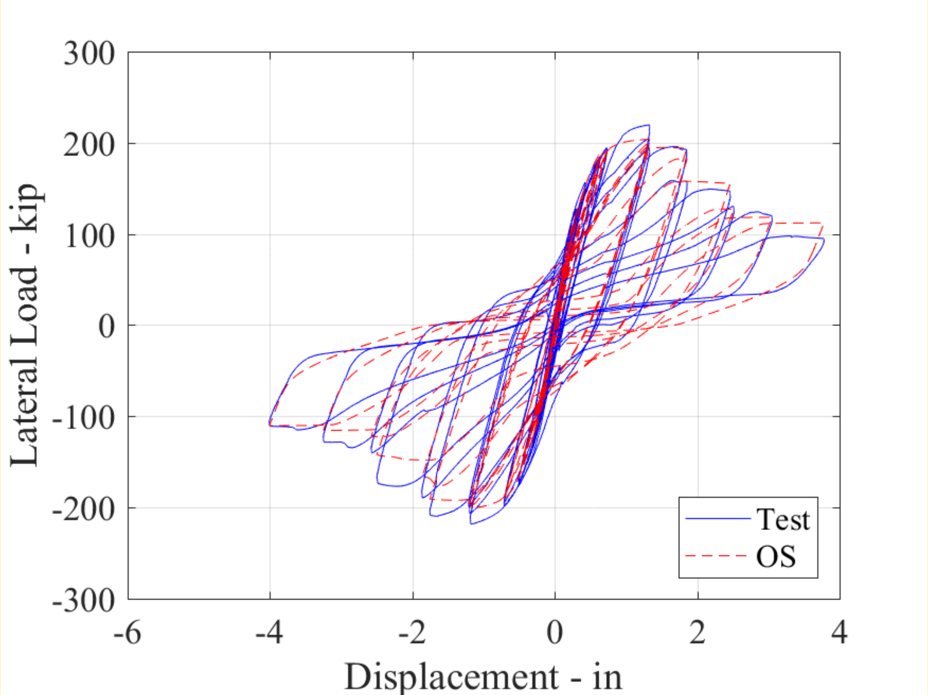
Moment vs Rotation



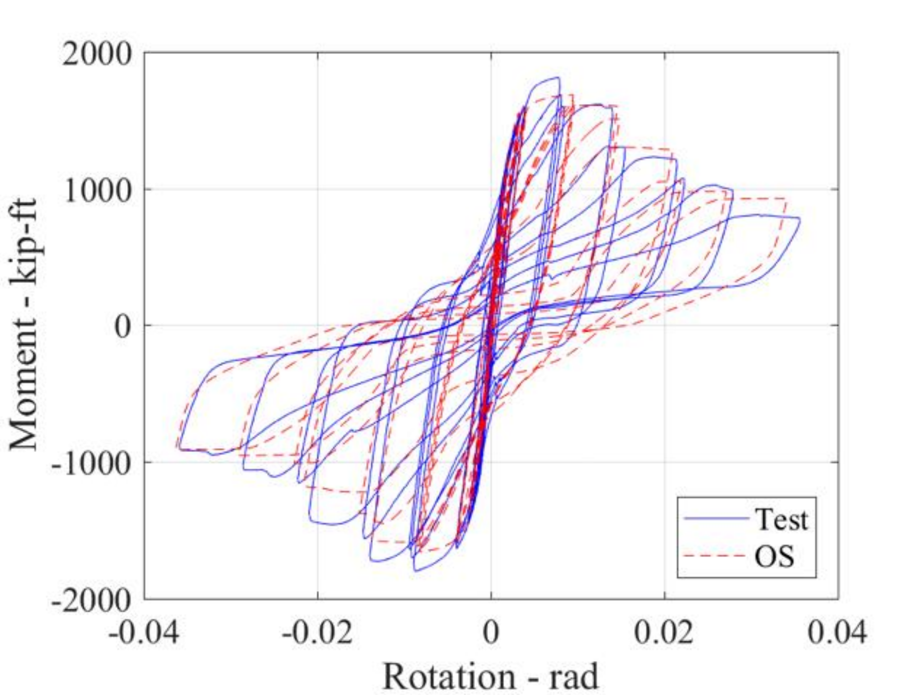
Modeling of CPSW

CW-42-55-20-T (SP2)

Lateral Force vs Top Displacement

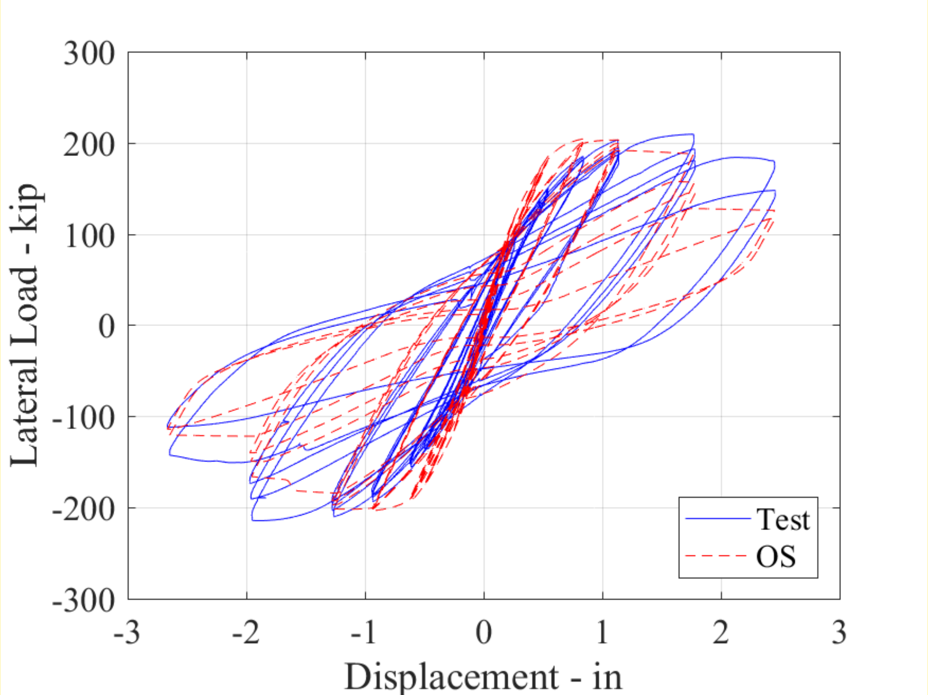


Moment vs Rotation

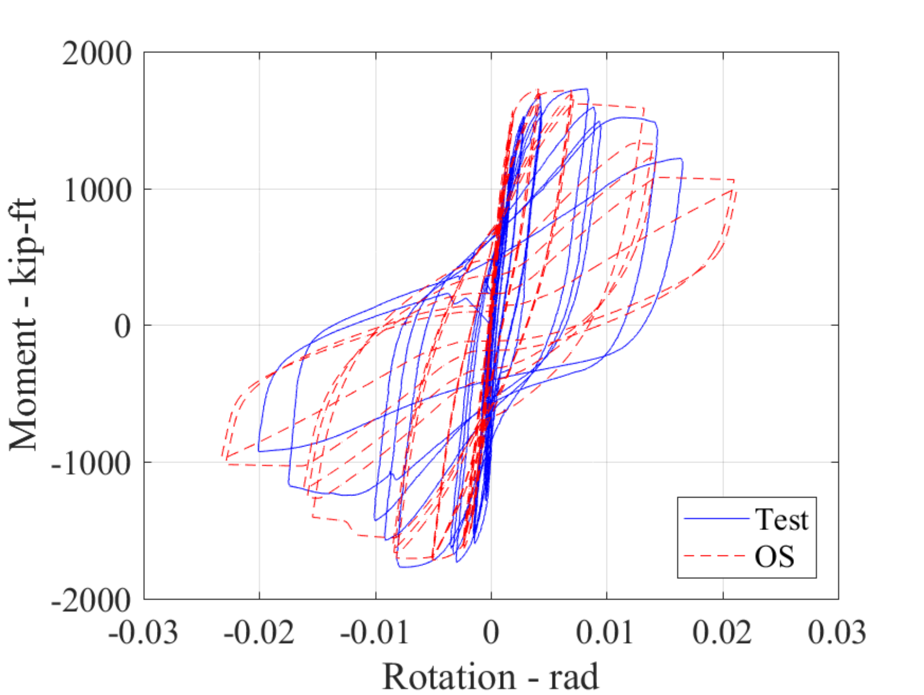


CW-42-55-30-T (SP5)

Lateral Force vs Top Displacement



Moment vs Rotation



LAYOUT

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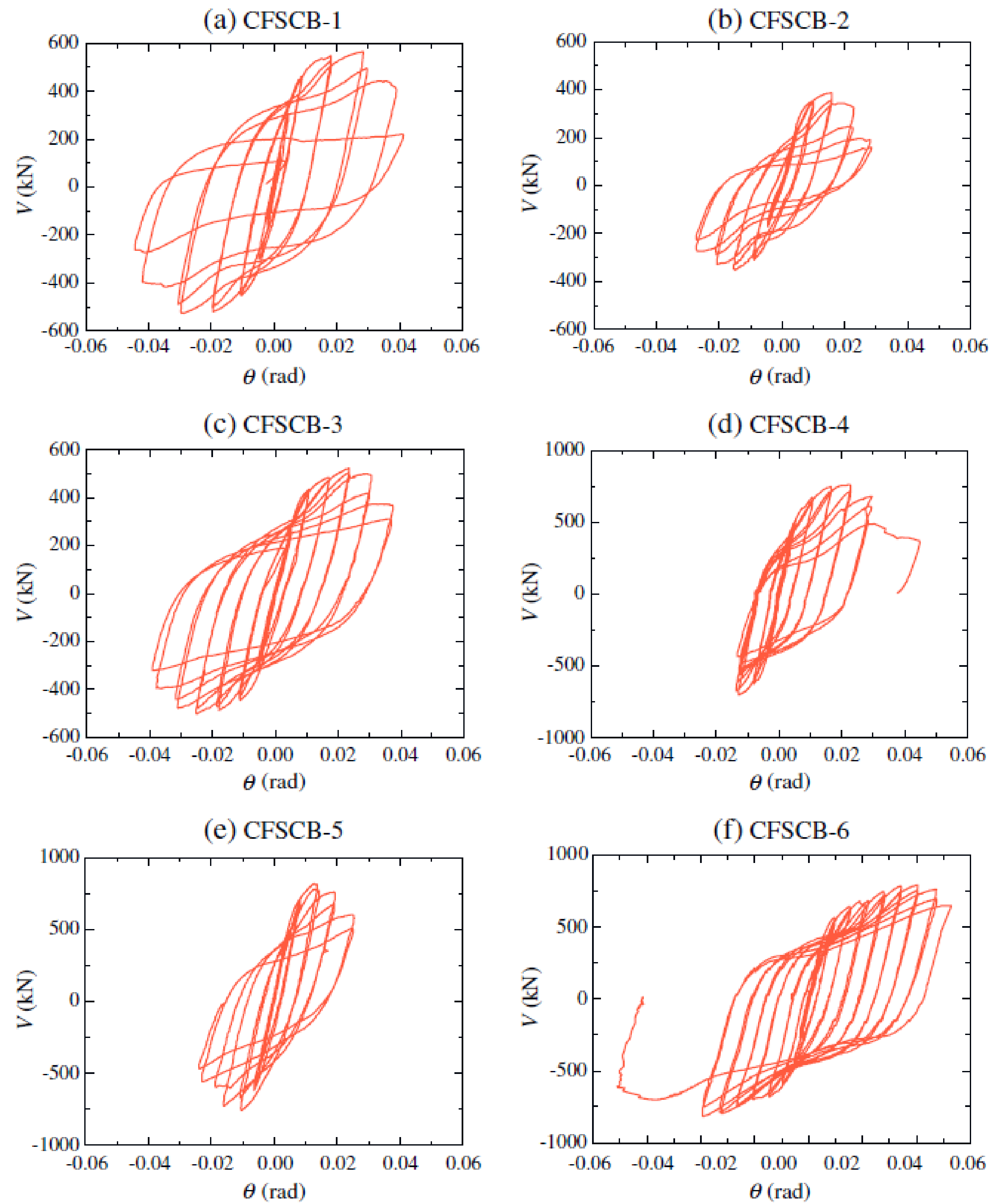
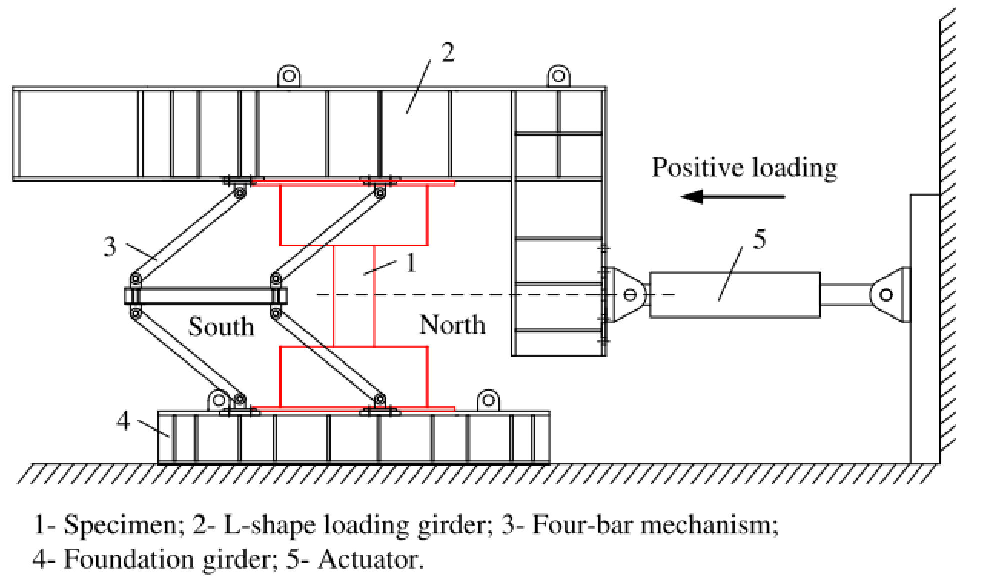
MODELING OF C

- Specimens …
- Specimen 1, 2, and 3 (L/d = 2.5)
- Specimen 4, 5, and 6 (L/d = 1.33)



Modeling of Coupling Beams

- Two flexural dominated coupling beams were selected. One with constant steel plate thickness and one with different plate thickness.
- Only bottom element has both fracture and buckling
- Five elements are 6” displacement based with 3 NIP over plastic hinge.
- Rotational spring at the boundary in order simulate the possible rotation at the base.
- 1” fiber in size was chosen for the cross-section.



1- Specimen; 2- L-shape loading girder; 3- Four-bar mechanism; 4- Foundation girder; 5- Actuator.

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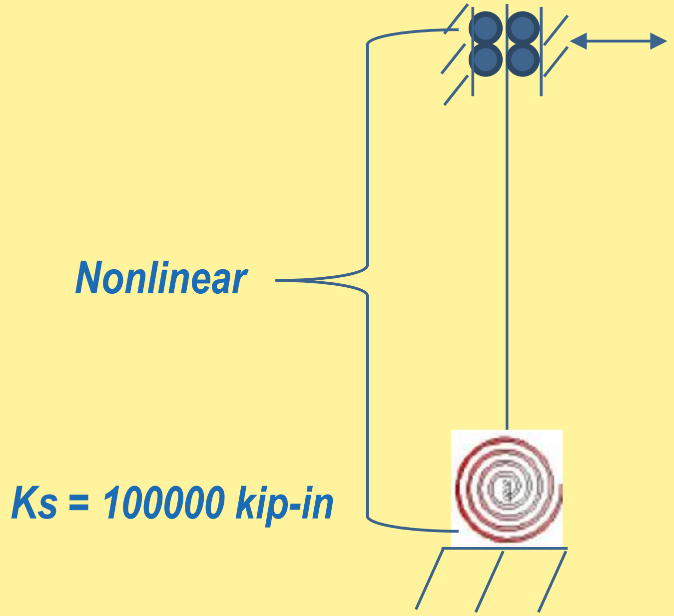


Modeling of Coupling Beams

Material Inputs - Steel

	Steel
Fy (ksi)	42.5
Fu (ksi)	66.5
Es (ksi)	29732
Esh (ksi)	29
εsh	1.53E-3
εu	0.15

- Backbone Curve:
- Backbone Curves from Coupon Test for this cross section
- Cyclic Buckling:
- So following parameters were chosen based on the behavior observed from test:

  $\beta = 1.0$ $\gamma = 0.5$ $r = 0.3$ $Lsr = 10$
- Low Fatigue Life:
- So following parameters were chosen based on the behavior observed from test:

  $c = 0.515$ $\varepsilon'_f = 0.21$ $C_d = 0.4$ (for cyclic degradation)

Modeling of Coupling Beams

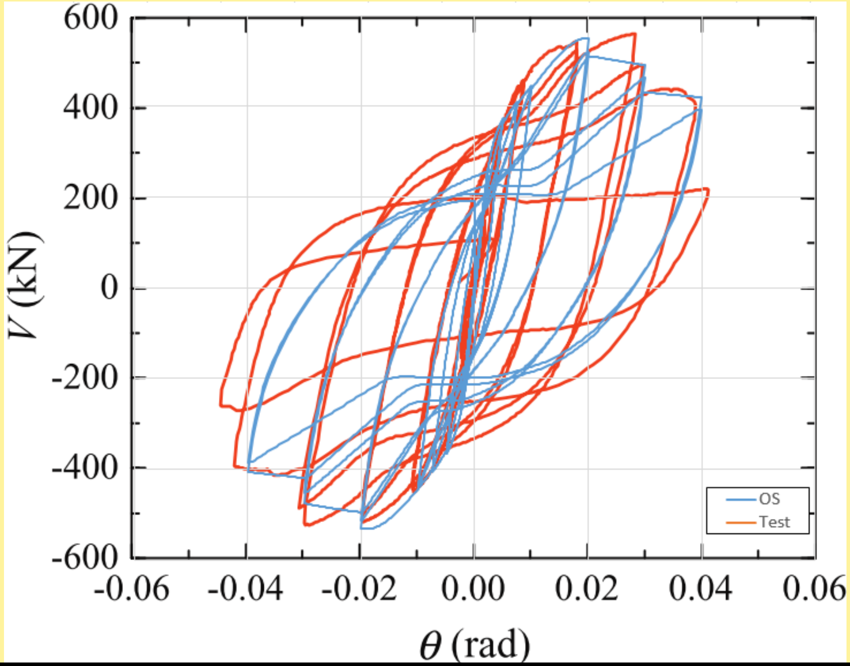
Material Inputs - Concrete

Specimen	fpc, ksi (confined)	Ec, ksi	eps_c0	fp_cu, ksi	eps_cu, ksi	Lambda
CFSCB-1	8.04	4897	3.28E-3	6.29	0.04	0.05
CFSCB-3	8.92	4897	3.64E-3	6.56	0.04	0.05

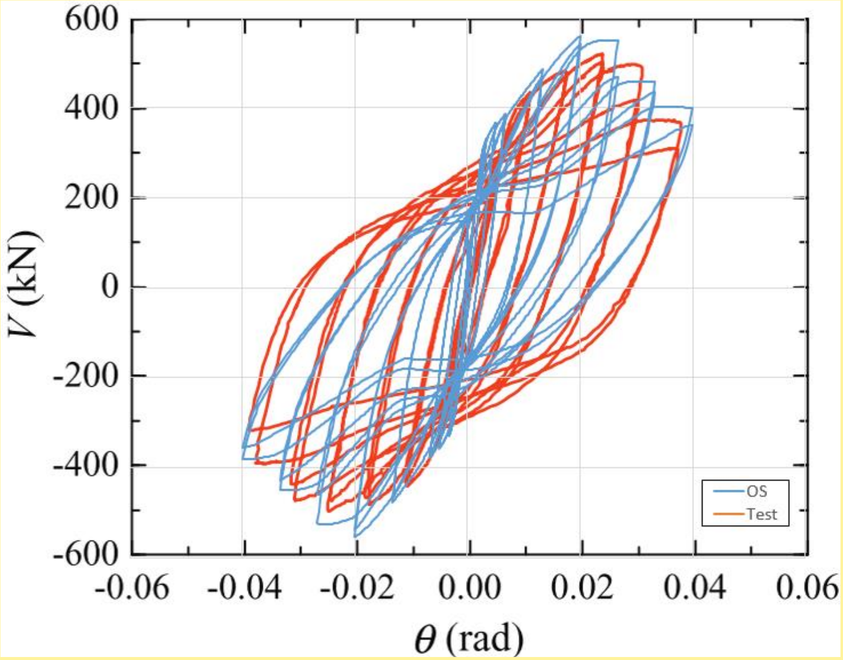
Modeling of Coupling Beams

Shear Force vs Rotation Comparison

CFSCB-1



CFSCB-3



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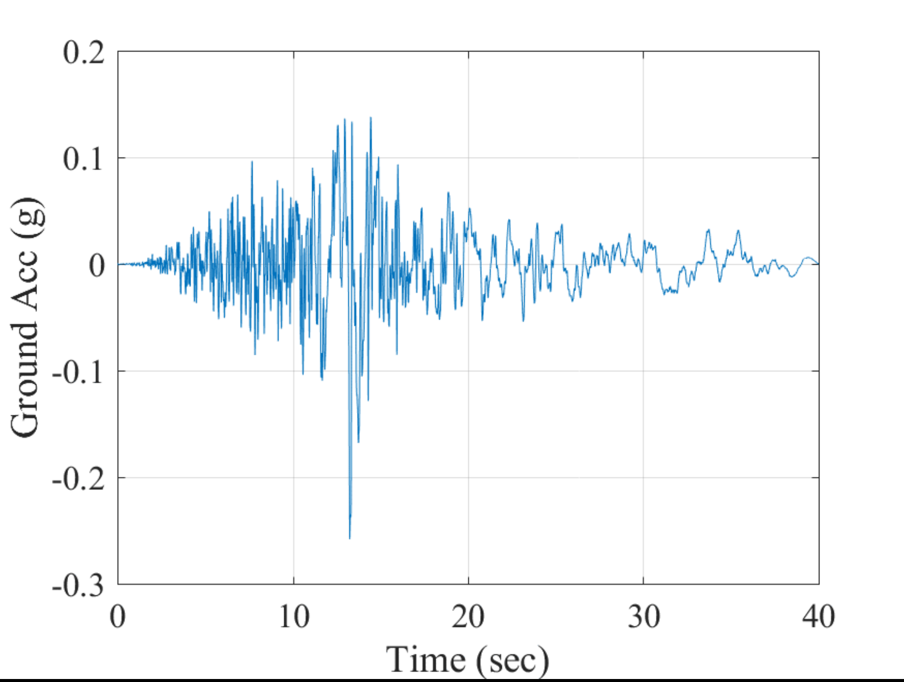
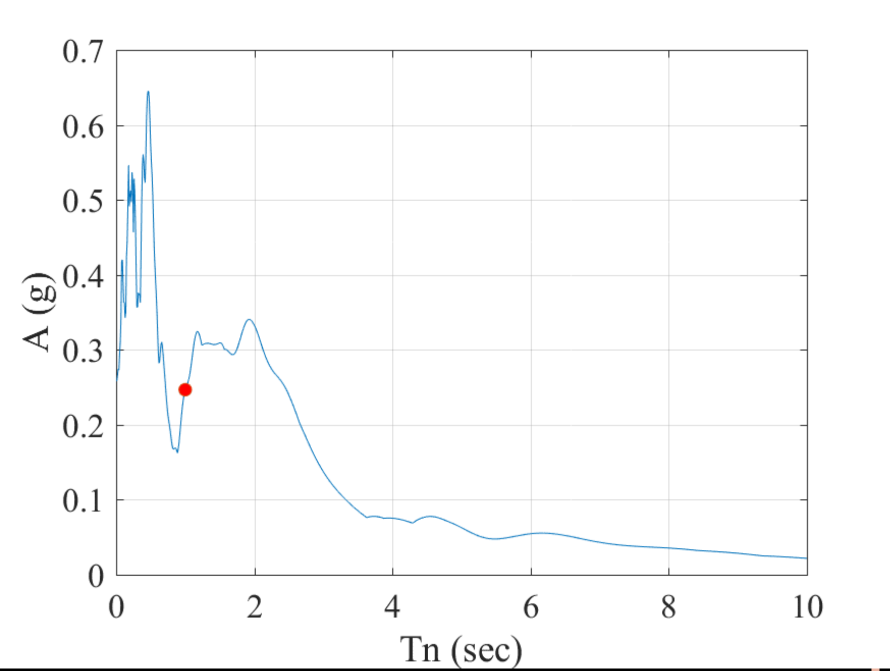
Seismic Analysis

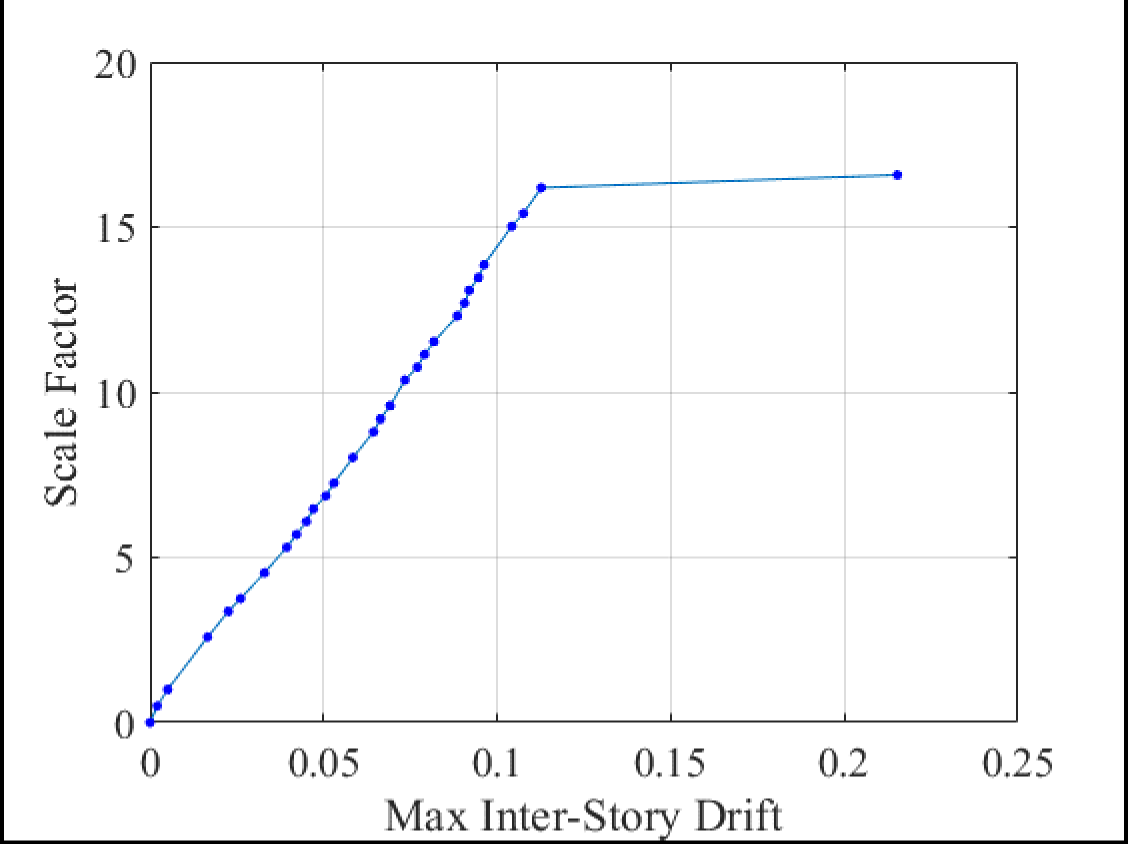




- The spectral acceleration for BICC090 earthquake is 0.25 for the period of archetype which is 1 second

SEISMIC ANALYSIS

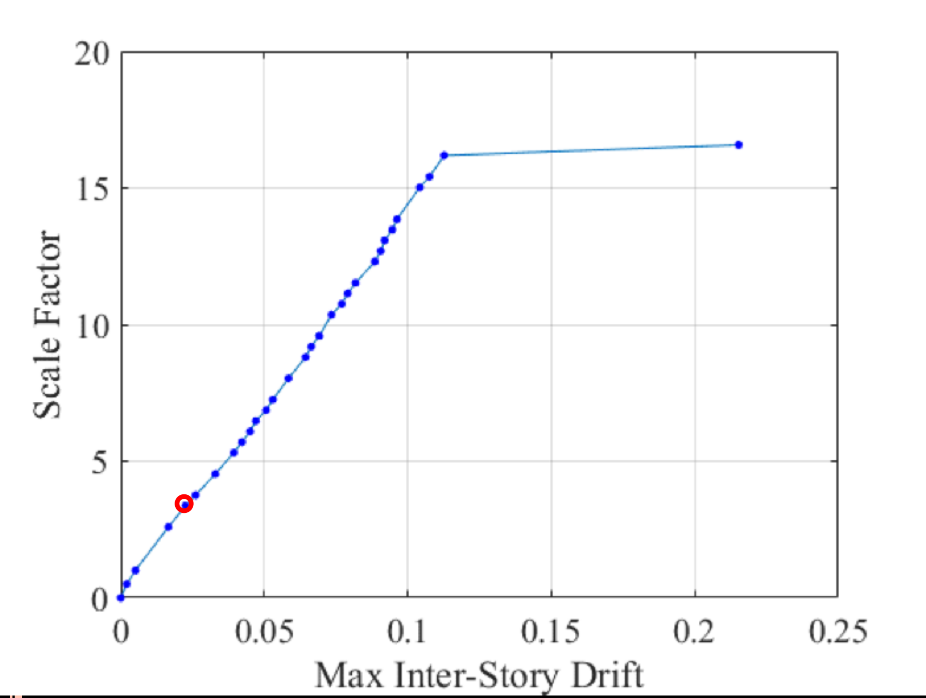
BICC090 EQ and Spectral Acceleration:

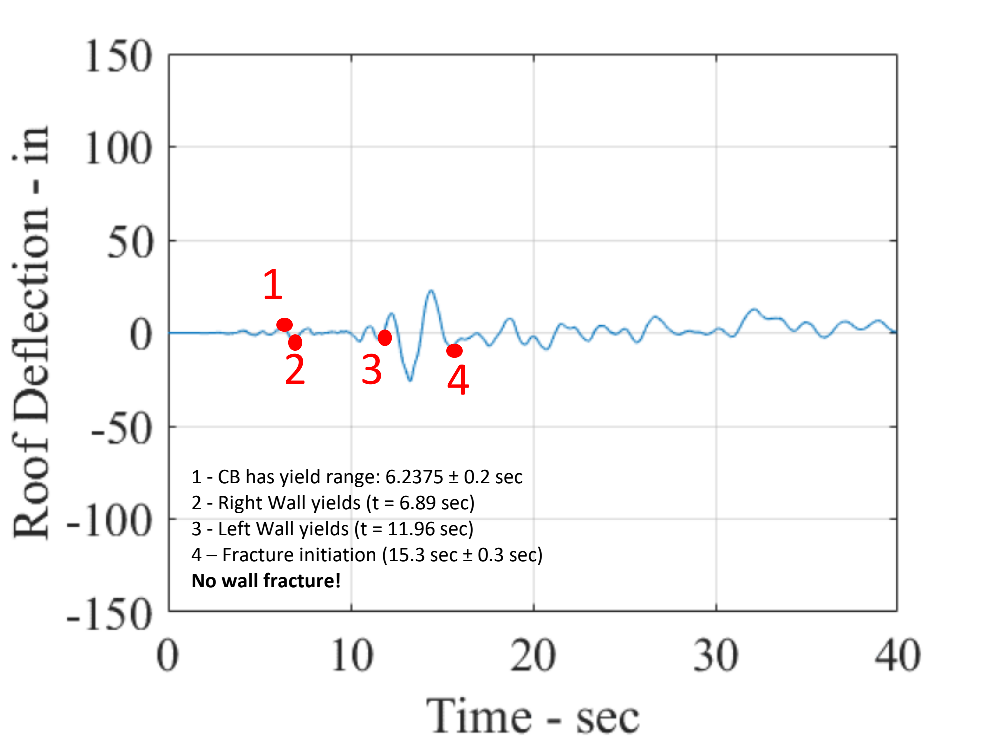


Last point is where OpenSees code indicated as collapse.

SEISMIC ANALYSIS

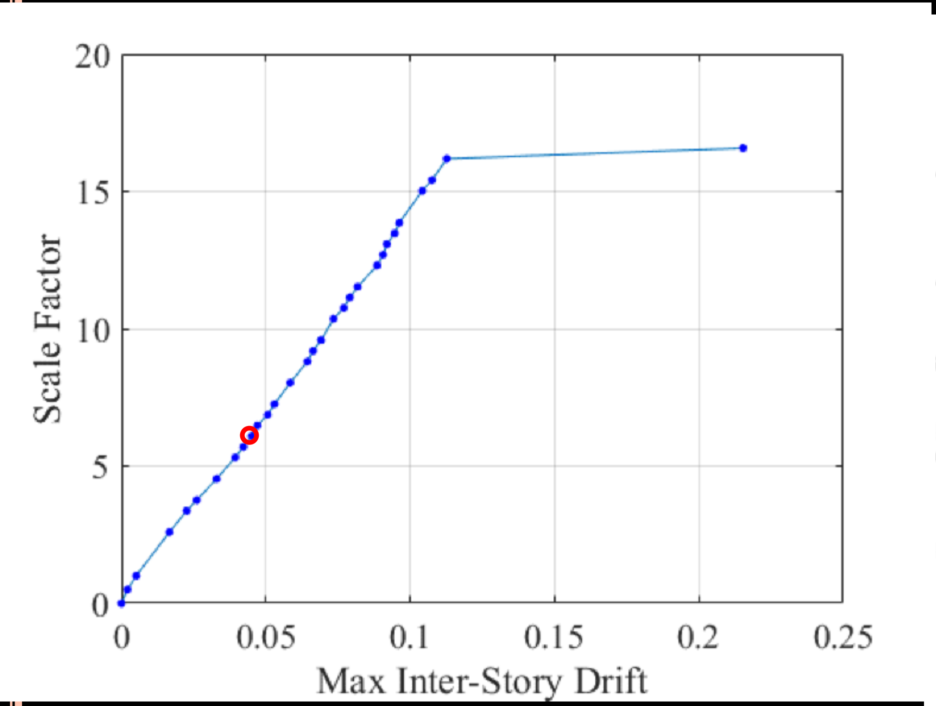
Scale Factor → 3

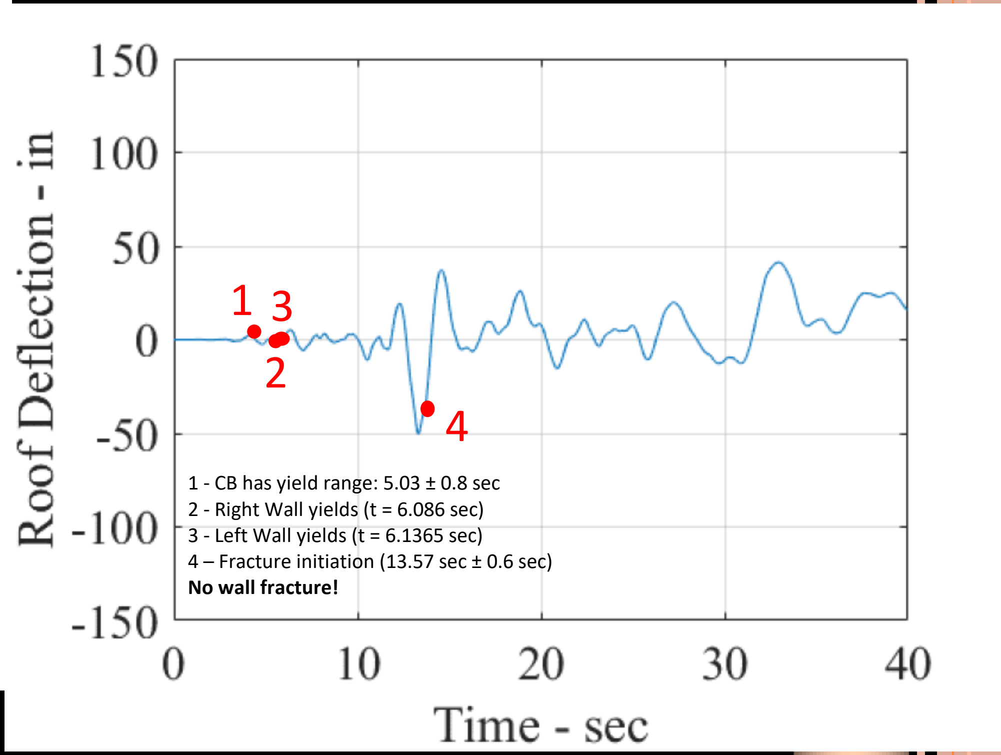




Seismic Analysis

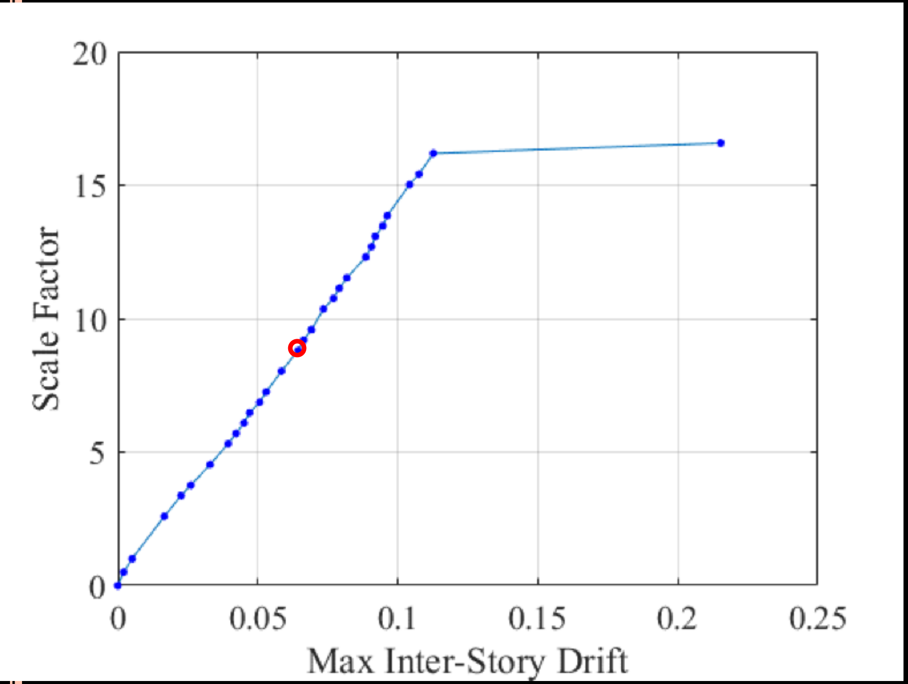
- Scale Factor → 6

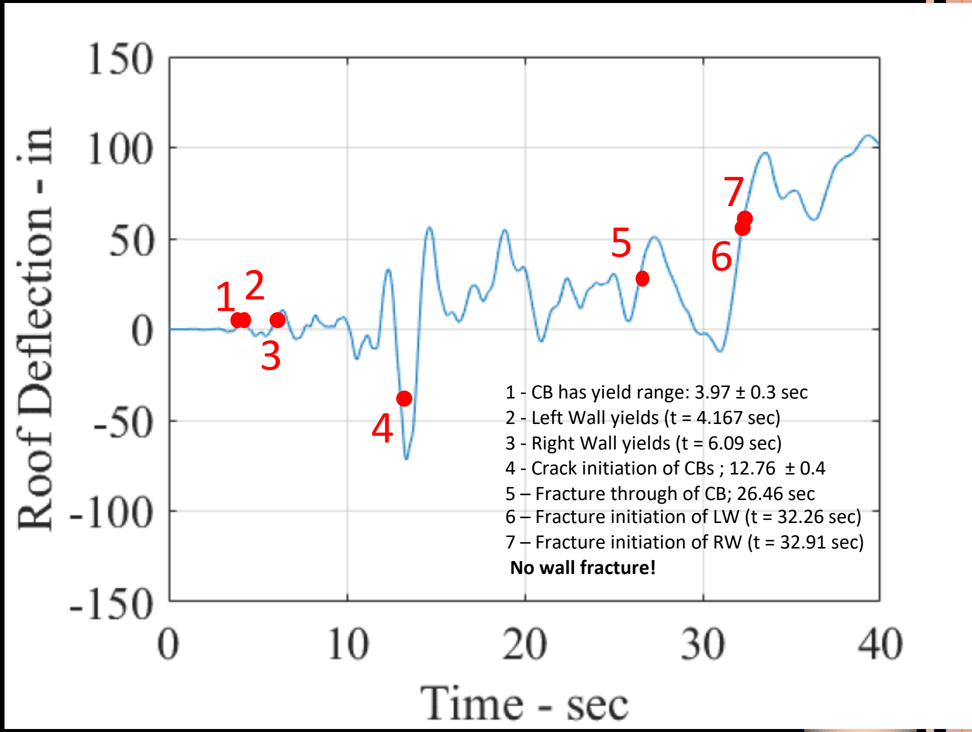




SEISMIC ANALYSIS

- Scale Factor --> 9





Seismic Analysis

- IDA Analysis Status Report

- Each point in IDA curve takes 1 – 3 hour (depends on earthquake) using OpenSees with fiber hinge models
- However, each earthquake run in parallel in super computer. Therefore, total run time for one curve takes 4-5 hours.
- Analyses ongoing… and new results being generated everyday

Seismic Analysis

CROSS CHECKING RESULTS

- OpenSEES Models with slightly different steel and concrete material models and different types of elements for the coupling beams
  - CPSW modeled with fiber element, but effective stress-strain curves for steel and concrete materials derived from results of benchmarked 3D finite element models of the tested specimens
  - Coupling beams modeled with concentrated plasticity hinge element calibrated to results from 3D finite element models of tested specimens and full-scale members

SEISMIC ANALYSIS

- SPOT CHECKING RESULTS

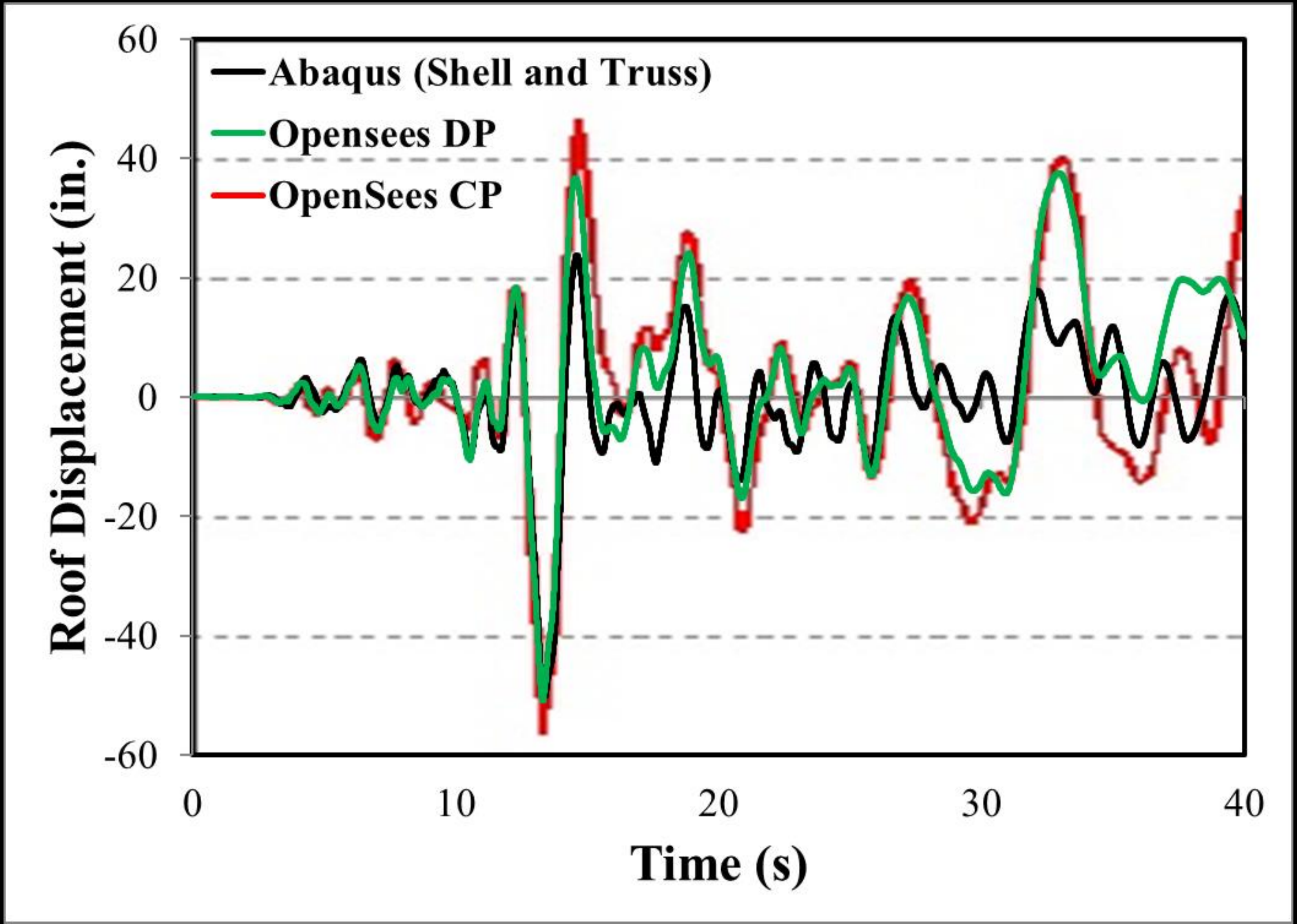
- ABAQUS Models of the coupled core wall system

  - Layered composite shell elements for the walls and coupling beams. Steel and concrete plies within the layered shell elements. Material properties calibrated using test data and 3D FEM analyses.

  - Truss elements to model the flange plates of the walls and the coupling beams. Material properties calibrated to model local buckling, fracture, etc. using test data and 3D FEM analyses

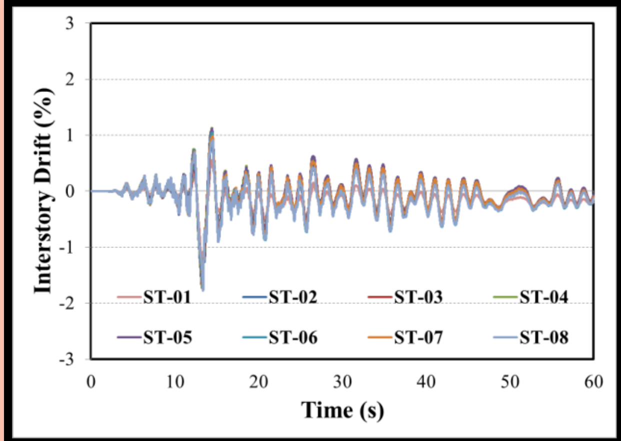
Seismic Analysis

- 16-2-BICC090, Scale Factor 6

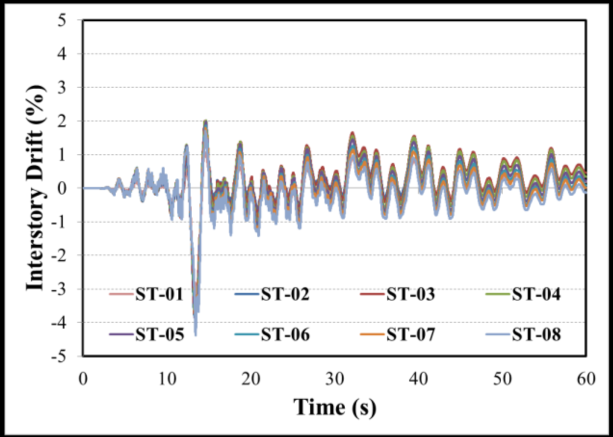


Seismic Analysis

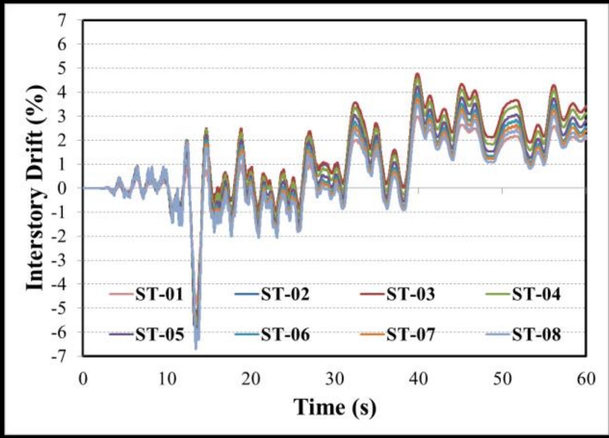
Scale Factor 3



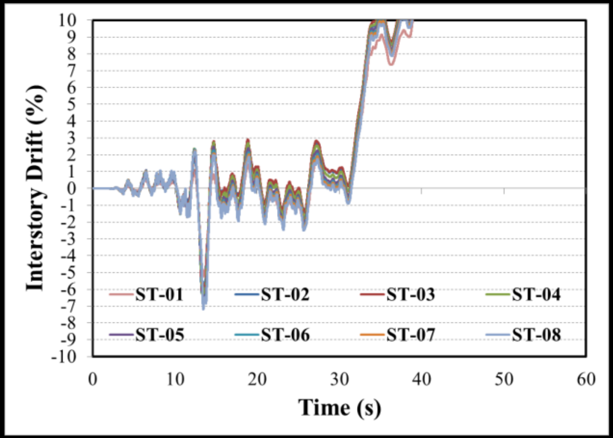
Scale Factor 6



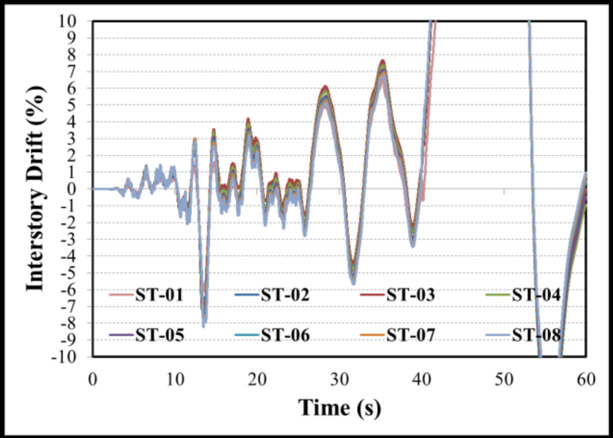
Scale Factor 9



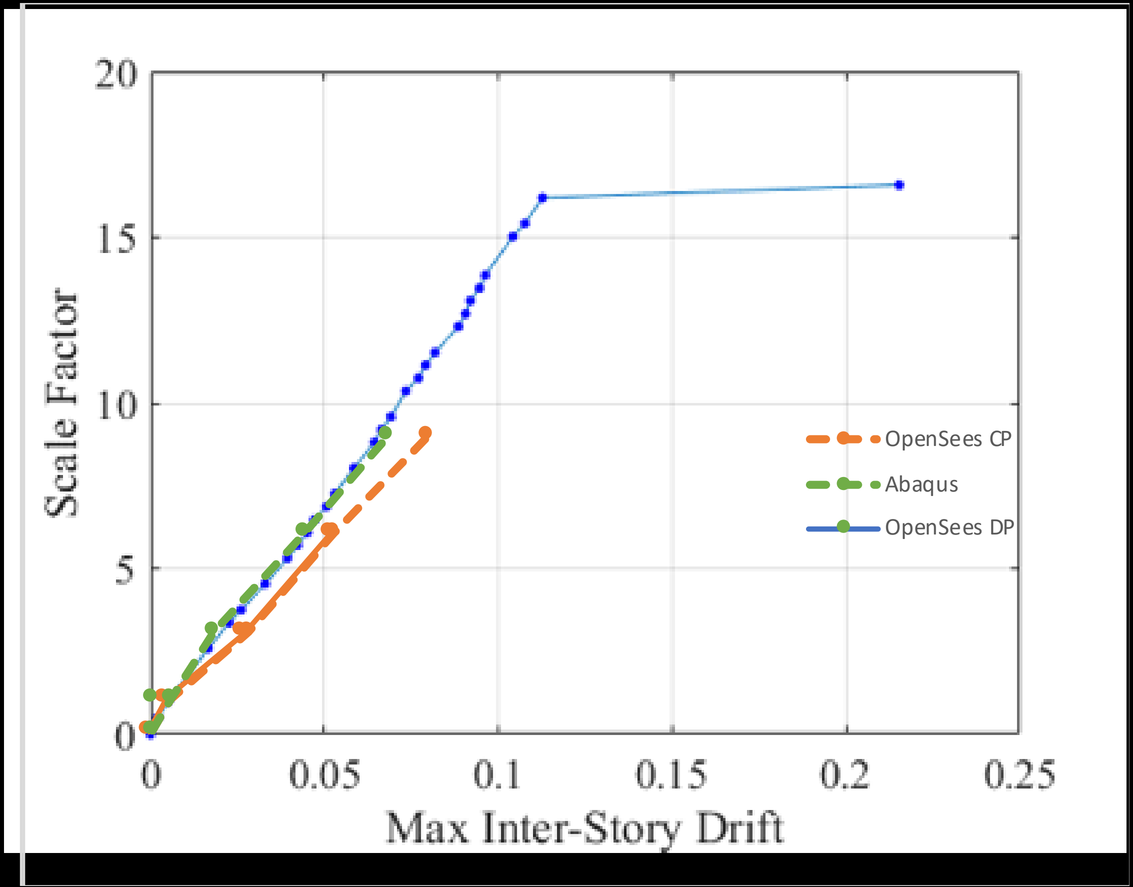
Scale Factor 10



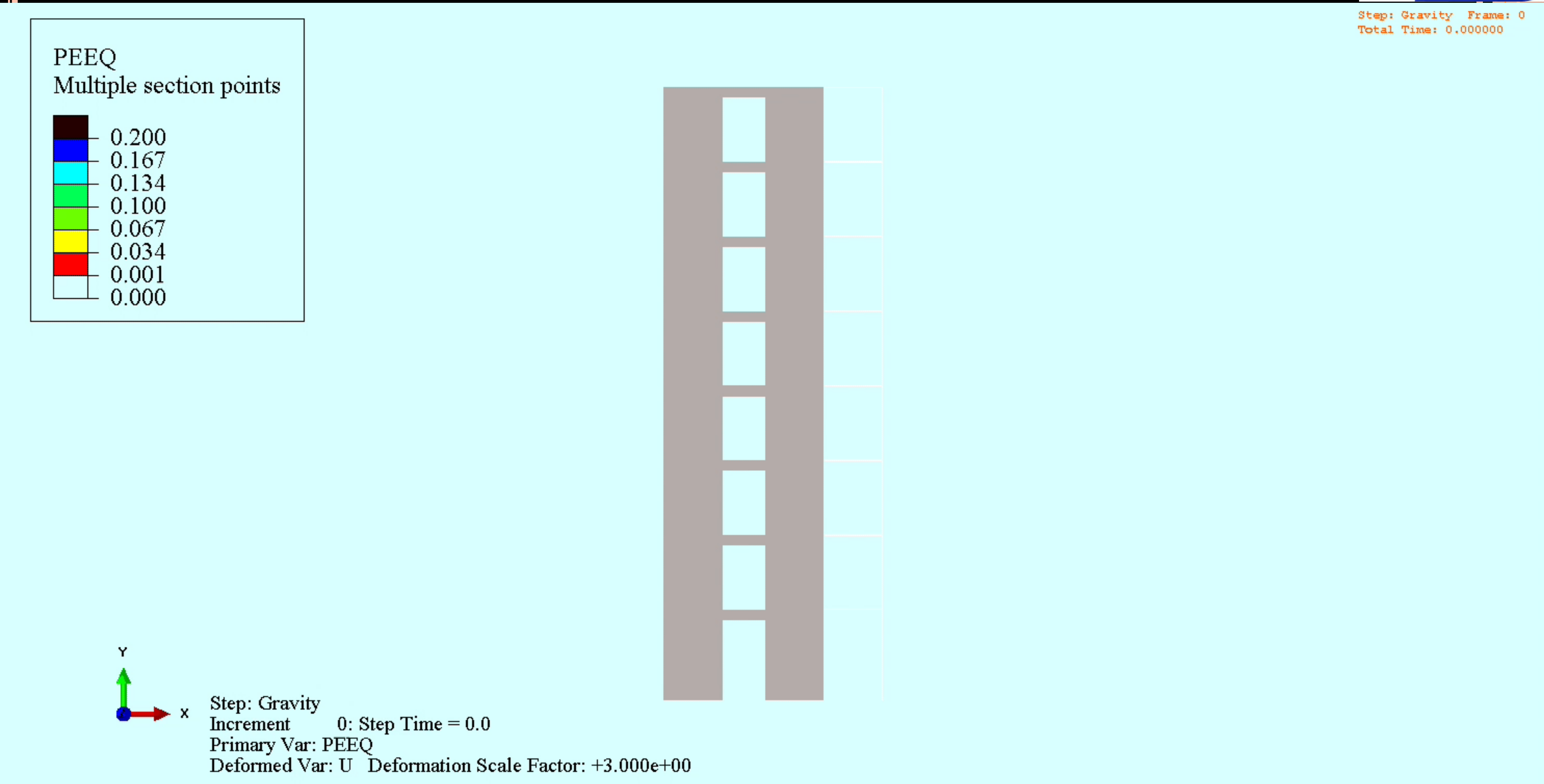
Scale Factor 12



Seismic Analysis



SEISMIC ANALYSIS



Path Forward / Projected Schedule

1. Present preliminary results to IT4 during Sept. 5-6 meeting in Seattle. Collect comments from IT4.
2. Address comments and prepare ballot for IT4 in PUC format. Ballot to be submitted to IT4 in Oct. 2018
3. IT4 ballots and comments collected in Nov. 2018
4. Attend PUC meeting in December 2018, present the IT4 ballot results along with comments and resulting actions
5. Collect verbal comments from PUC December meeting.
6. Address all comments from IT4 and PUC, and submit ballot in PUC format in Jan. 2019 along with all backup information for first PUC ballot.