Mitigation of Collapse Risk in Vulnerable Concrete Buildings:

Column Tests

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Introduction

- Older (pre-1976) reinforced concrete (RC) buildings contain columns that survive axial failure after loss of lateral shear strength while others may collapse

Research Objectives

- **Identify** older RC columns that may experience *axial collapse following shear failure*
- **Develop/Modify** tools to determine drift at axial failure of older RC columns
- **Incorporate** observed behavior into structural simulation software and evaluation tools

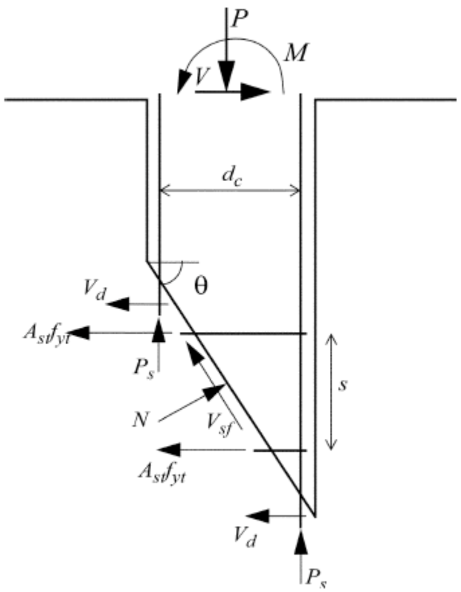
Background- UCB Tests

- Column specimens:
  - 18”x18” cross-section
  - Symmetric 8-bar long. steel configuration (#8, #9, or #10 bars)
  - Height = 116” (a/d = 3.2)
  - Uni-directional displacement testing
  - Double curvature testing configuration
  - Older (pre-1976) transverse reinforcement design #3 @18” or (2) #3 @ 12” (including diamond ties) with 90° hooks
- Results used to calibrate model to predict drift at axial failure (Elwood/Moehle model)

Berkeley Specimens

Specimen ID	Longitudinal Reinforcement	Transverse Reinforcement	Axial Load	$P/f'_c A_g$	$(\Delta/L)_a$
3CLH18	(8) #10 – 3.1%	#3 @ 18" – 0.07%	113	0.09	2.1
3CMH18	(8) #10 – 3.1%	#3 @ 18" – 0.07%	340	0.26	2.1
3CMD12	(8) #10 – 3.1%	(2) #3 @ 18" – 0.18%	340	0.26	2.1
3SLH18	(8) #10 – 3.1%	#3 @ 18" – 0.07%	113	0.09	3.1
2CLH18	(8) #8 – 1.9%	#3 @ 18" – 0.07%	113	0.07	3.1
2CMH18	(8) #8 – 1.9%	#3 @ 18" – 0.07%	340	0.28	1.0
2SLH18	(8) #8 – 1.9%	#3 @ 18" – 0.07%	113	0.07	3.6
3SMD12	(8) #10 – 3.1%	(2) #3 @ 18" – 0.18%	340	0.28	2.1
2CLD12	(8) #9 – 2.5%	(2) #3 @ 12" – 0.18%	150	0.15	5.0
2CHD12	(8) #9 – 2.5%	(2) #3 @ 12" – 0.18%	600	0.61	1.9
2CVD12	(8) #9 – 2.5%	(2) #3 @ 12" – 0.18%	-50/600	-0.05/0.61	2.9
2CLD12M	(8) #9 – 2.5%	(2) #3 @ 12" – 0.18%	150	0.15	5.1

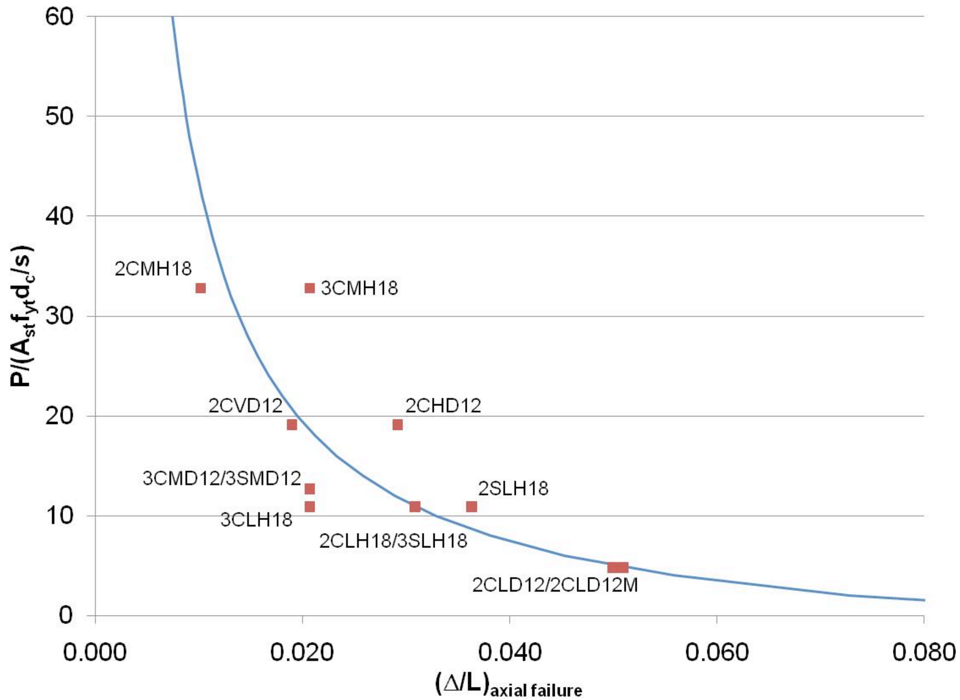
Elwood/Moehle Model



Basis for development of model equation (FBD of column post-shear failure)

$$\left(\frac{\Delta}{L}\right)_{axial} = \frac{4}{100}\frac{1+(\tan\Theta)^2}{\tan\Theta + P\left(\frac{s}{A_{st}f_{yt}d_c\tan\Theta}\right)}$$

Axial capacity model equation

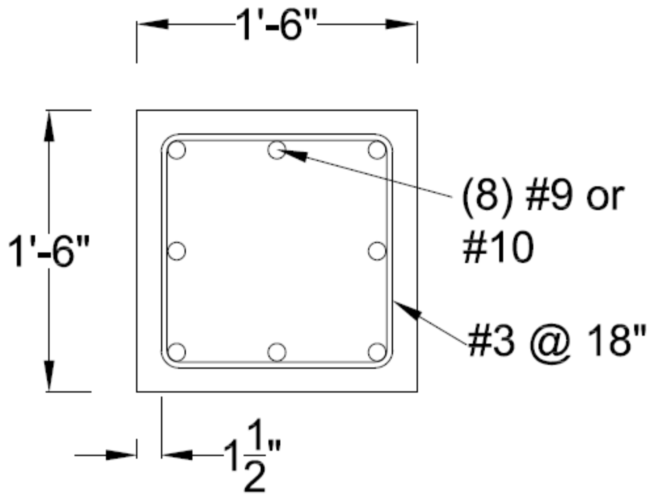


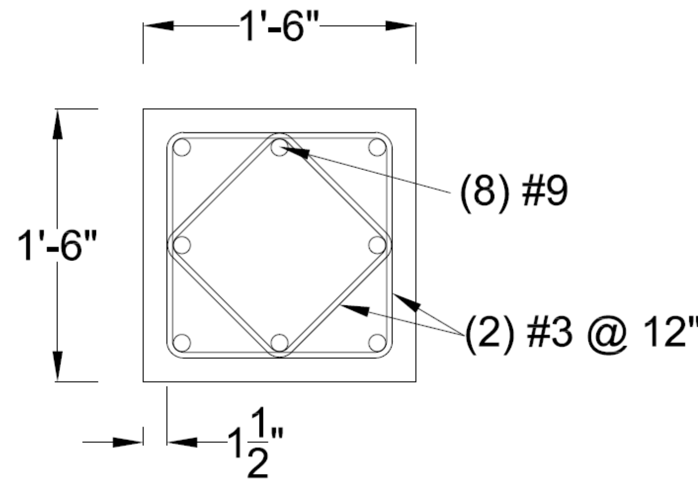
Axial capacity model plotted with Berkeley test data

GC Testing Parameters

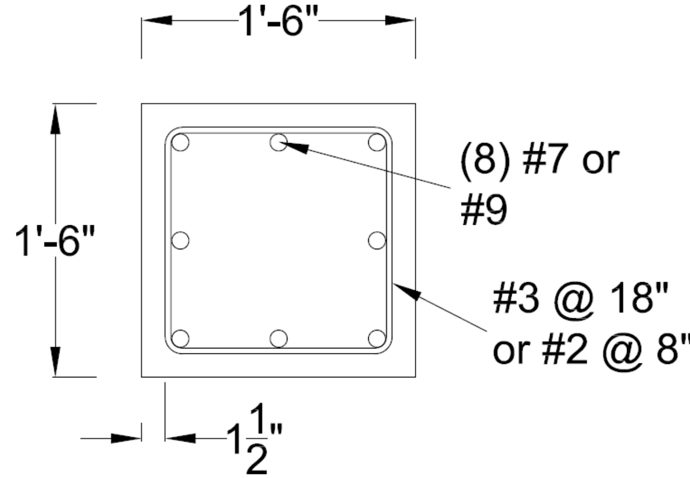
- Aspect ratio
- Number of displacement reversals applied to column
- Type of displacement protocol to which column is subjected
  - Uni-directional: 3 full cycles at each increment of drift
  - Bi-directional: 3 full cycles at each increment on each principal axis

Experimental Program





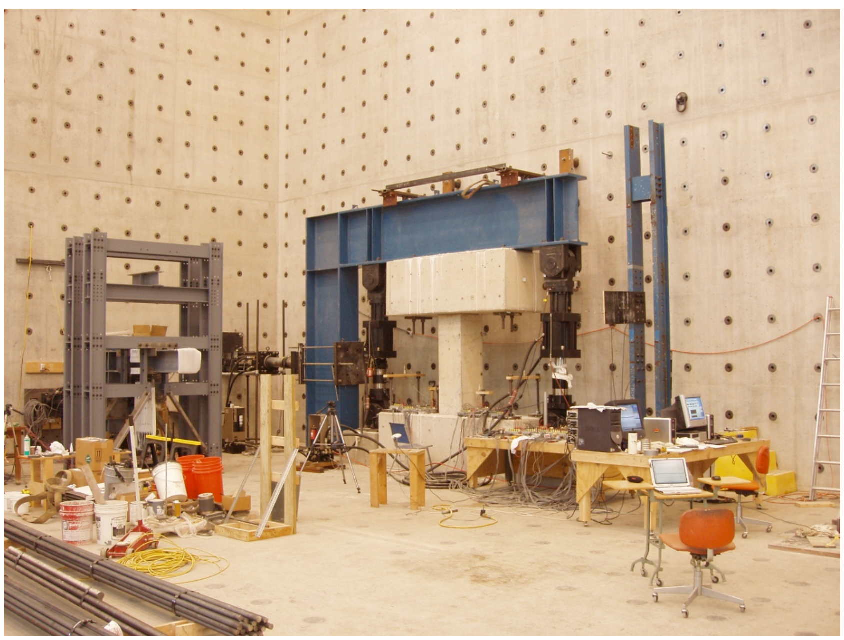
Kansas specimens



Purdue specimens

Testing Facilities

- Robert L. and Terry L. Bowen Laboratory at Purdue University and at the University of Minnesota's Multi-Axial Subassemblage Testing (MAST) Laboratory
- The MAST system uses a cruciform-shaped steel cross head on which forces are applied by 4 horizontal (2 each in X & Y directions) hydraulic actuators and 4 vertical hydraulic actuators
  - Control of 6 degrees of freedom of the cross head
  - Application of 1320 kips force and 20 inches of stroke – Z-direction
  - Application of 880 kips force and 16 inches of stroke – X & Y-directions



Bowen laboratory

MAST laboratory (Photo courtesy of University of Minnesota)

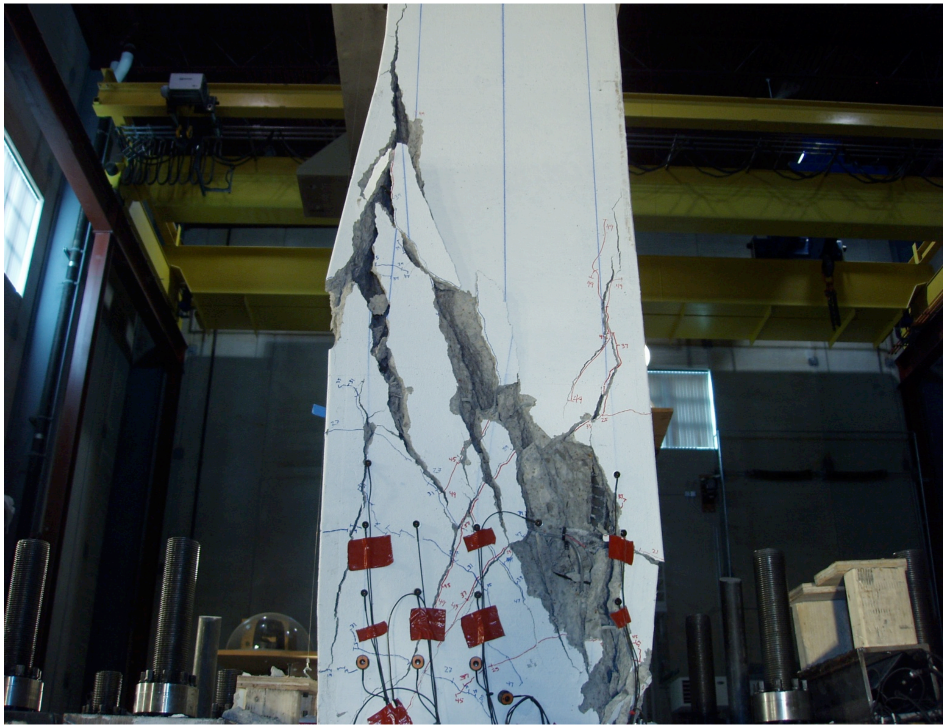
Kansas Test Specimens- Uniaxial Displacement Protocol

Specimen ID	Longitudinal Reinforcement	Transverse Reinforcement	Aspect Ratio	Axial Load (k)
Kansas 1	(8) #9 – 2.5%	#3 @ 18” – 0.07%	3.2	500
Kansas 2	(8) #9 – 2.5%	#3 @ 18” – 0.07%	3.2	340
Kansas 3	(8) #10 – 3.0%	#3 @ 18” – 0.07%	3.2	500
Kansas 4	(8) #9 – 2.5%	(2) #3 @ 12” – 0.18%	3.2	150

Purdue Test Specimens

Specimen ID	Longitudinal Reinforcement	Transverse Reinforcement	a/d	Axial Load	P/f'_cA_g	Displ. Proto.
Purdue 1	(8) #7 – 1.5%	#3 @ 18” – 0.07%	1.6	340	0.37	Uni
Purdue 2	(8) #7 – 1.5%	#2 @ 8” – 0.07%	1.6	340	0.37	Uni
Purdue 3	(8) #7 – 1.5%	#3 @ 18” – 0.07%	1.6	220	0.21	Bi
Purdue 4	(8) #9 – 2.5%	#3 @ 18” – 0.07%	1.6	500	0.44	Uni
Purdue 5	(8) #9 – 2.5%	#3 @ 18” – 0.07%	1.6	500	0.45	Bi
Purdue 6	(8) #9 – 2.5%	(2) #3 @ 12” – 0.18%	3.2	150	0.11	Bi
Purdue 7	(8) #9 – 2.5%	(2) #3 @ 12” – 0.18%	3.2	?	?	?
Purdue 8	(8) #9 – 2.5%	#3 @ 12” – 0.10%	3.2	?	?	?

Test Results

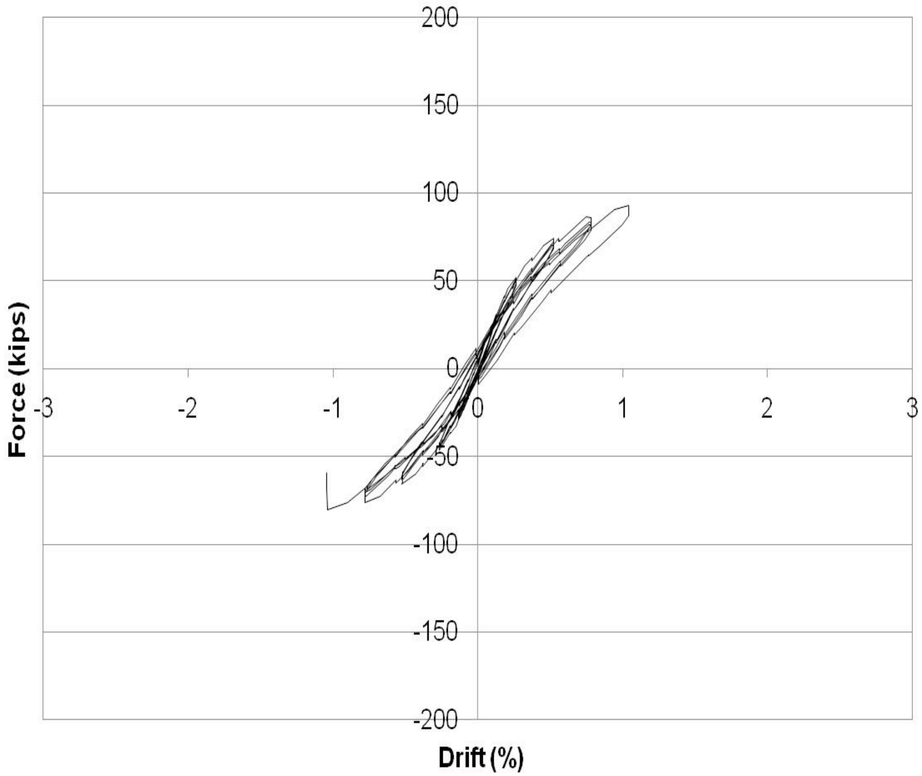


Kansas 1 after axial failure

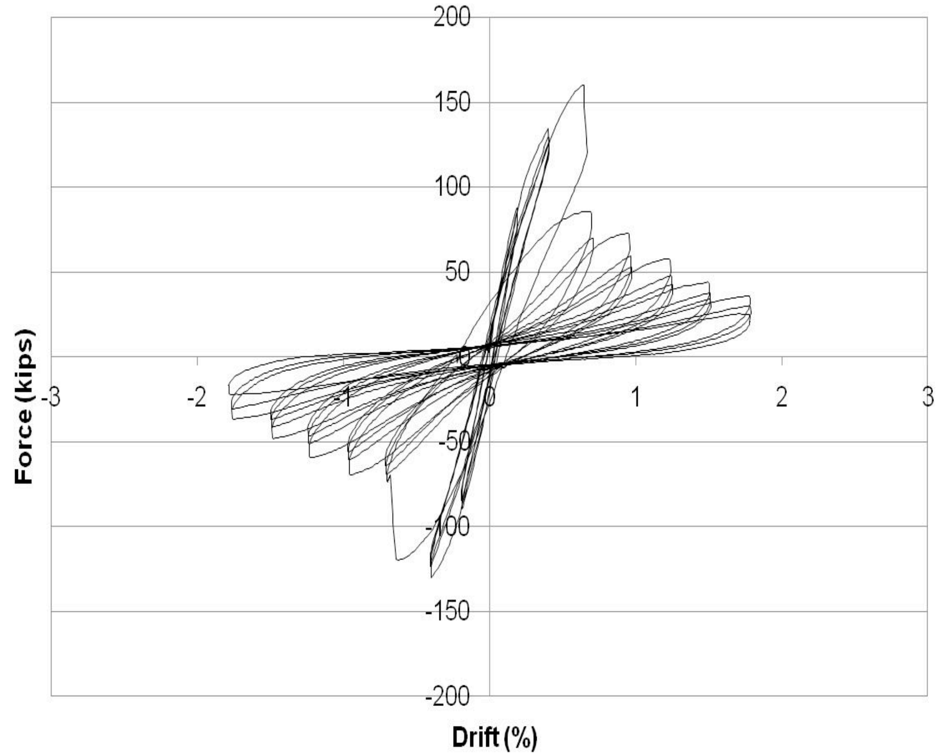
Purdue 1 after axial failure

Test Results

- Decreasing the aspect ratio increases the drift at axial failure- Uni-directional



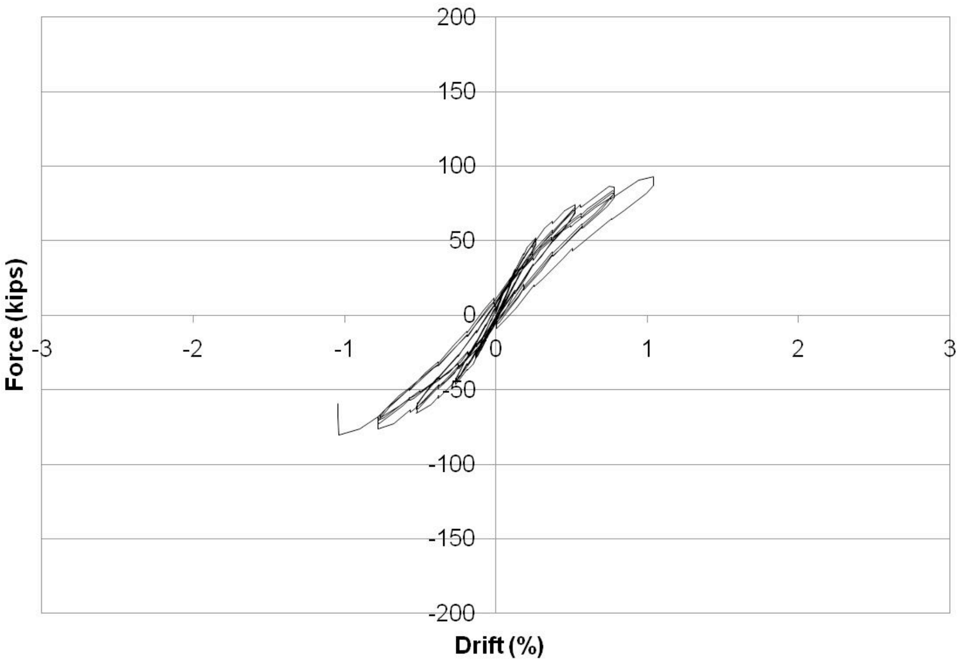
Load-drift response of Kansas 1



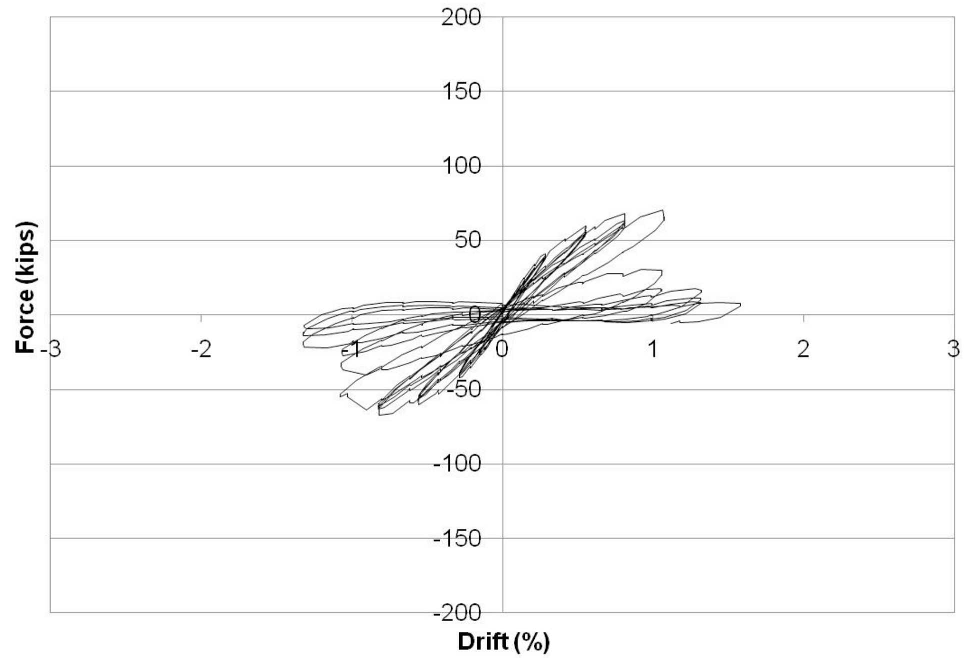
Load-drift response of Purdue 4

Test Results

➢Increasing the amount of longitudinal reinforcement increases the drift at axial failure- Uni-directional



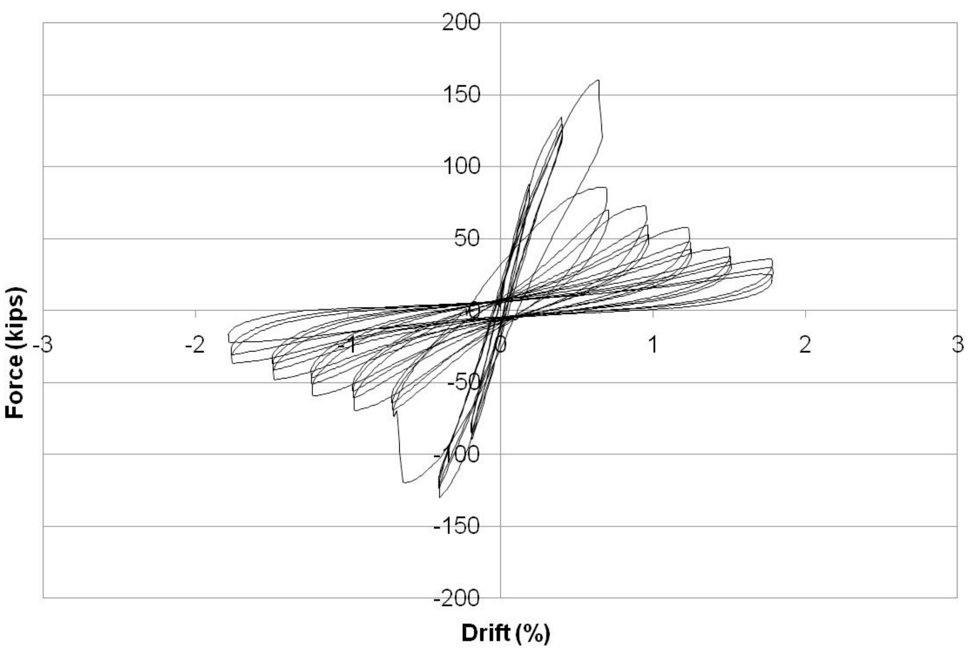
Load-drift response of Kansas 1



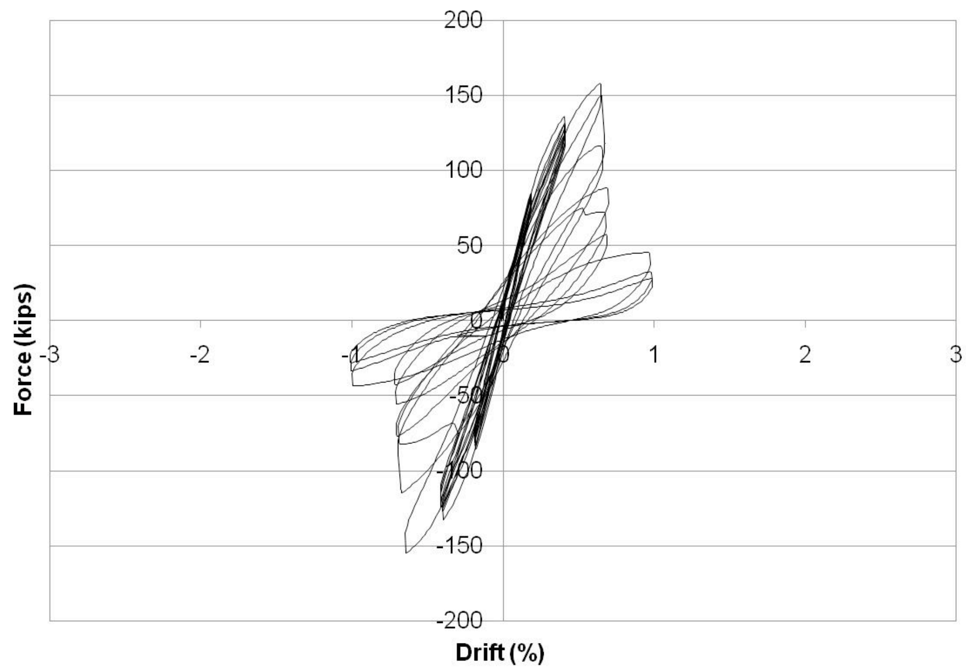
Load-drift response of Kansas 3

Test Results

➢Columns subjected to a uni-directional displacement protocol reach higher drift levels before axial failure occurs than those subjected to a bi-directional displacement protocol

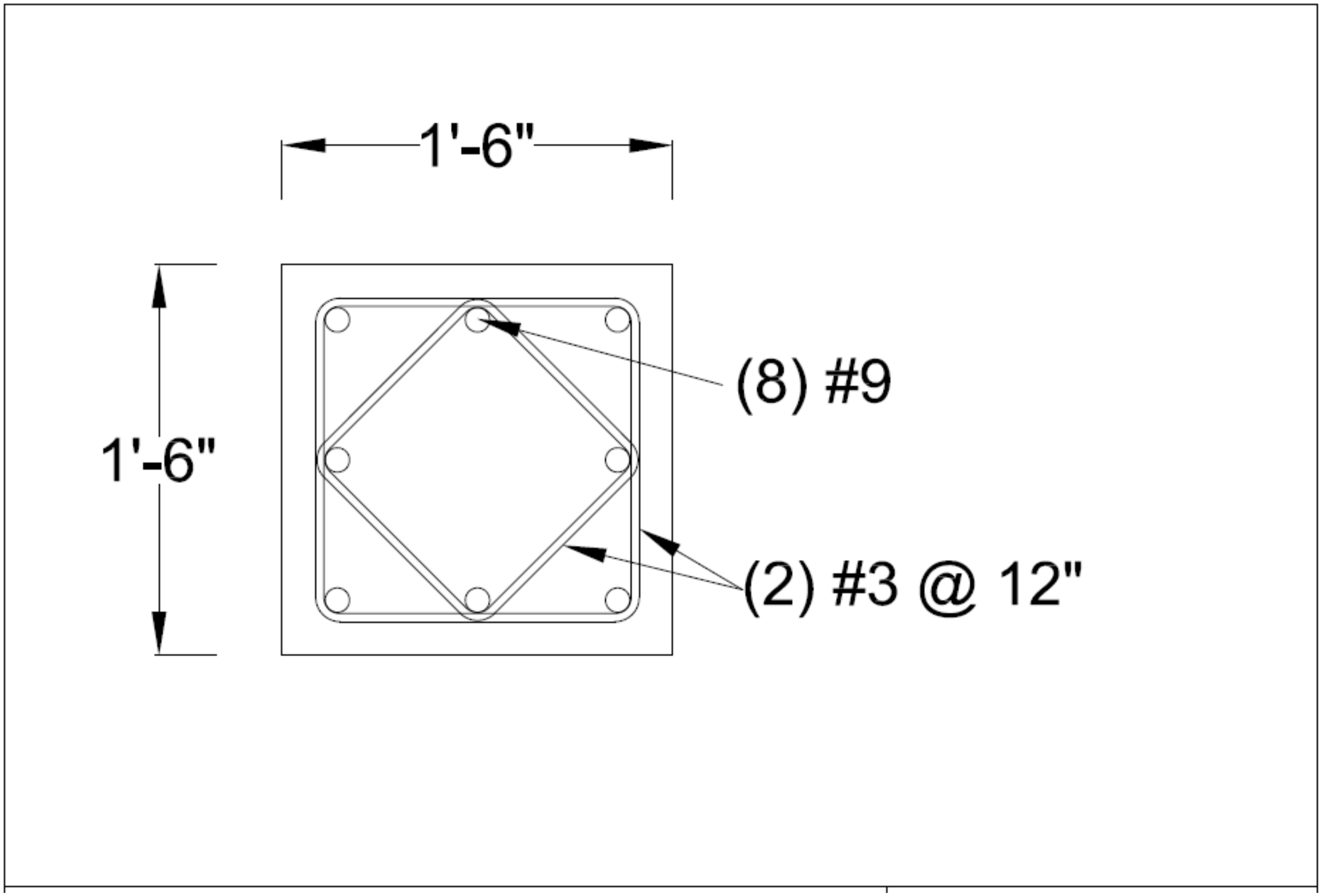


Load-drift response of Purdue 4



Load-drift response of Purdue 5

Purdue 6 & 7

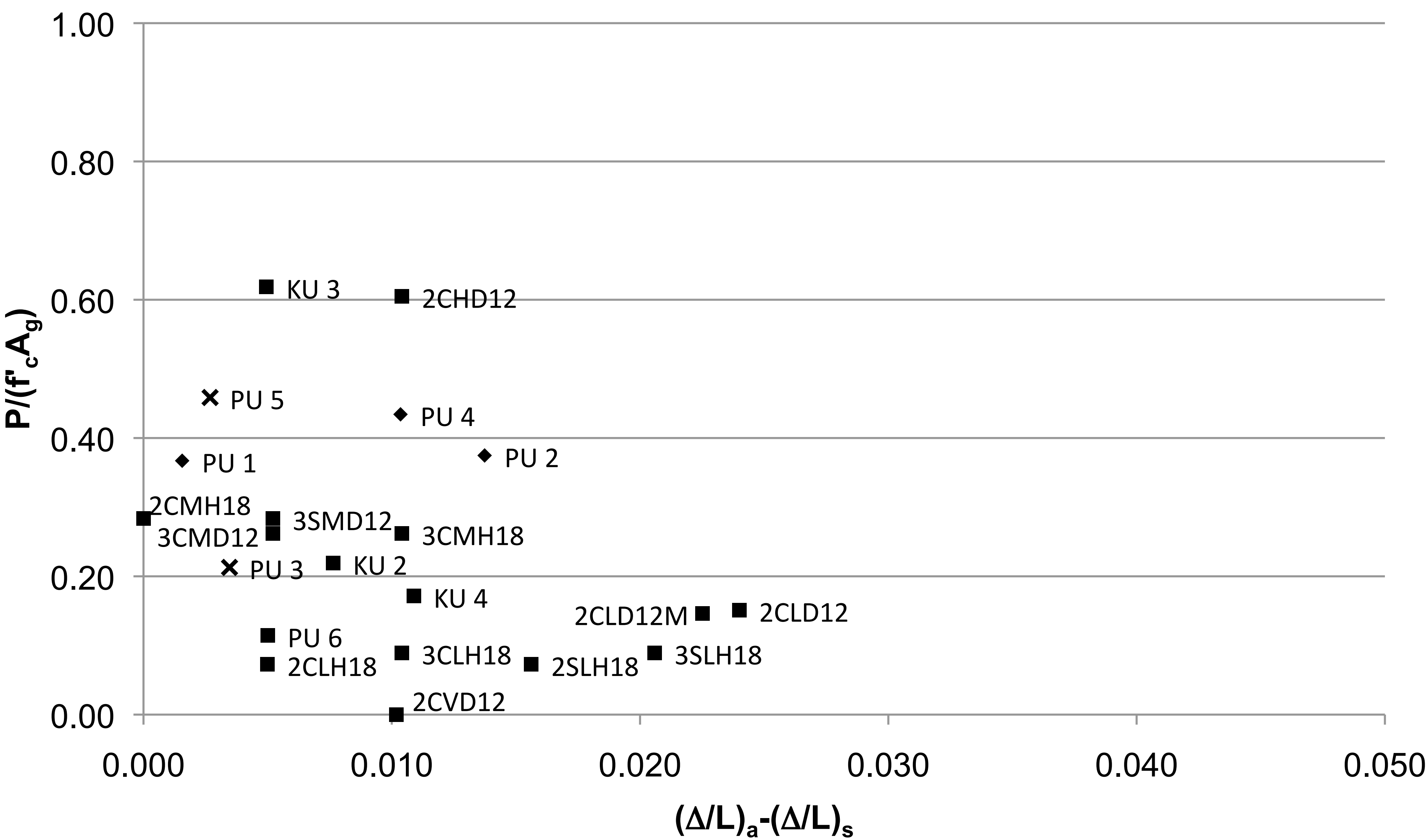


Effect of bi-directional displacement protocol

- Aspect ratio: 3.2
- Tie spacing 12 in.
- Axial load ratio 0.11
- Long. Reinf. 2.5%

Specimen ID	Shear Failure Drift (%)	Max. Drift (%)
Purdue 6	1.8	2.25
Kansas 4	2.0	3.1
2CLD12M	2.8	5.1
2CLD12	2.6	5.0

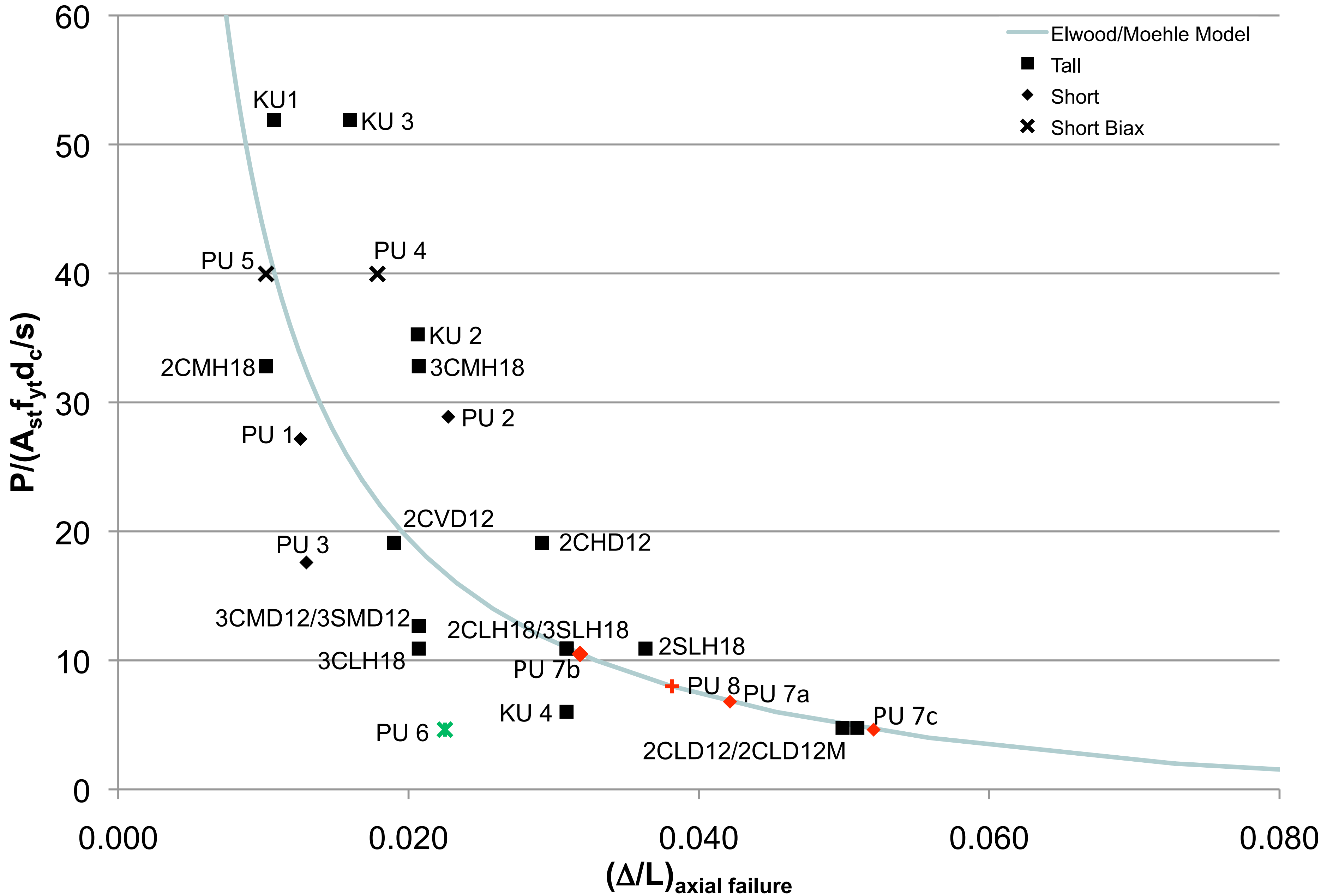
Residual Drift



Specimen 7 Alternatives

Specimen ID	P (kips)	Displ. Proto.	$P/f'_c A_g$	V_n (kips)	V_n/V_p	Elwood Drift (%)	ASCE 41 $(\Delta/L)_a-(\Delta/L)_s$
PU 7a	220	Regular	0.17	80	~1	4	1.6
PU 7b	340	Regular	0.26	85	~1	3	1.3
PU 7c	150	Other (?)	0.11	75	~1	5	1.8

Elwood/Moehle Drift



Conclusions

- Bi-directional displacement protocol results in axial failure at lower drift levels than uni-directional displacement protocol

- Outdated tie design, #3 @18” and 90 degree hooks:
  - axial failure at drift level ≤ 2%
  - $P/f'_c A_g > 0.3$ may lead to simultaneous shear/axial failures