Performance of Retrofitted Reinforced Concrete Bridge Columns in Cascadia Subduction Zone Earthquakes

Christopher Motter
William Nickelson
Sean McGuiness
Stacia Bell
Adam Phillips
Zachary Quesnel
Ruben Jerves

Washington State University

October 30, 2023

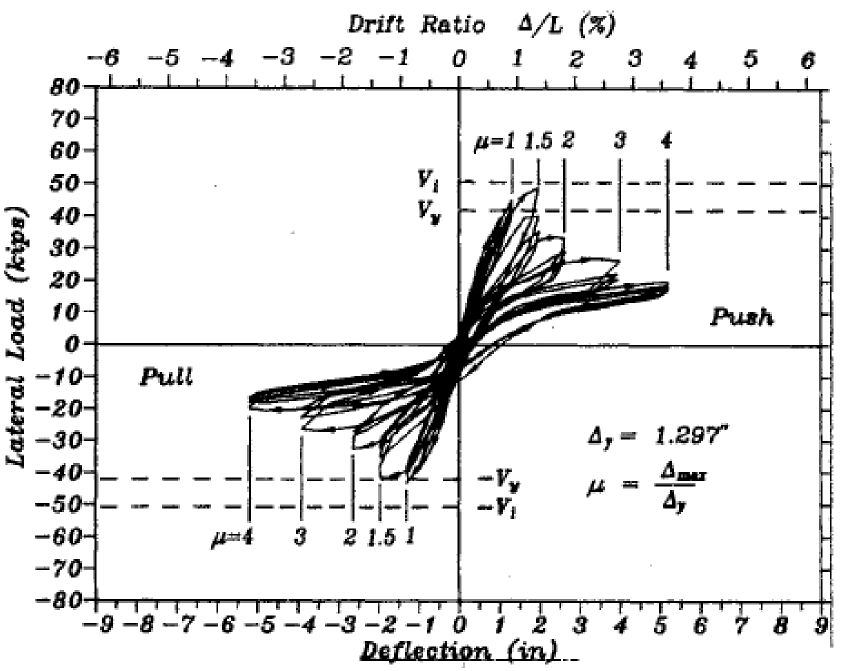
Presentation Overview

- Motivation
- Column experimental study
- Reinforcement fatigue
- Column modeling
- SDOF nonlinear time history analyses and column fragility

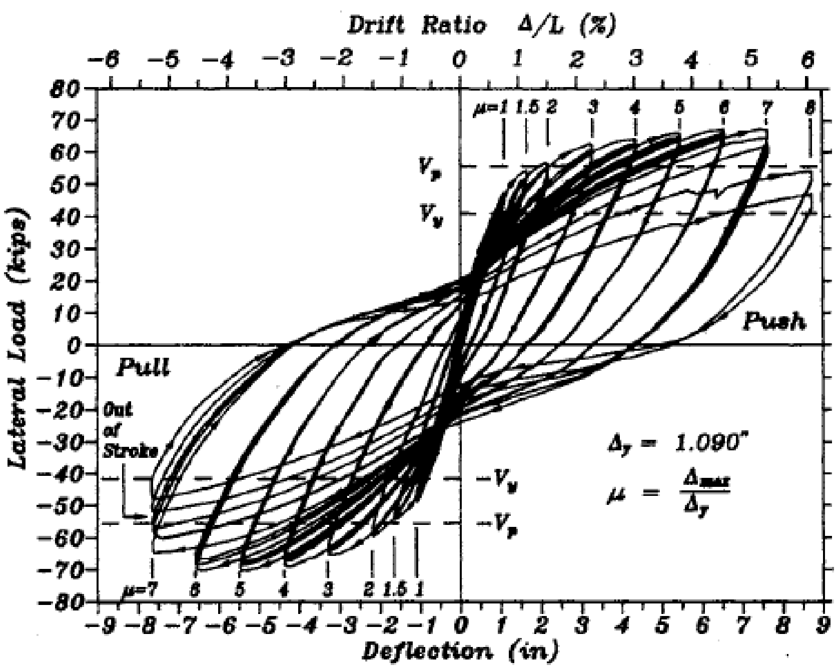
Motivation

- Need for retrofit: Circular columns tested as cantilevers
  - Loading protocol consistent with strike-slip earthquakes

No retrofit:



Retrofit:

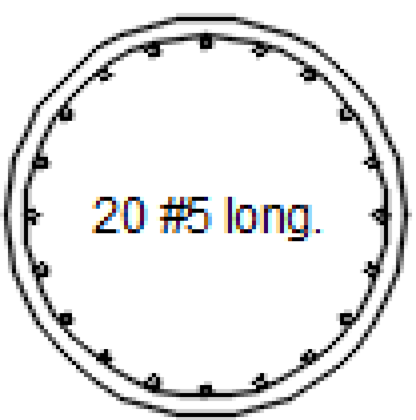


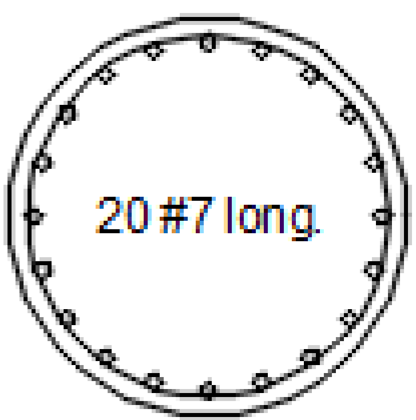
Chai, Priestley, Seible (1991)

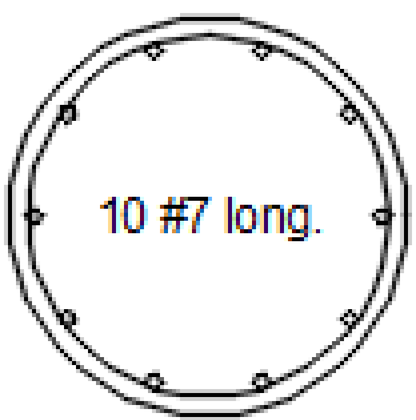
Retrofitted Column Experimental Study

Test Matrix – Steel Jacket

Column I.D.	Long. Bar Size	# Long. Bars	A_s/A_g	$P/(A_g f'_c)$	H/D	Loading Protocol
C(S)-4.0-#7(1.3)-0.05	#7	10	0.0133	0.05	4.0	Cyclic
C(S)-4.0-#5(1.4)-0.05	#5	20	0.0137	0.05	4.0	Cyclic
C(S)-4.0-#7(2.7)-0.05	#7	20	0.0265	0.05	4.0	Cyclic
C(S)-4.0-#7(1.3)-0.05-EQ	#7	10	0.0133	0.05	4.0	EQ
C(S)-4.0-#7(1.3)-0.15	#7	10	0.0133	0.15	4.0	Cyclic
C(S)-6.0-#7(1.3)-0.05	#7	10	0.0133	0.05	6.0	Cyclic

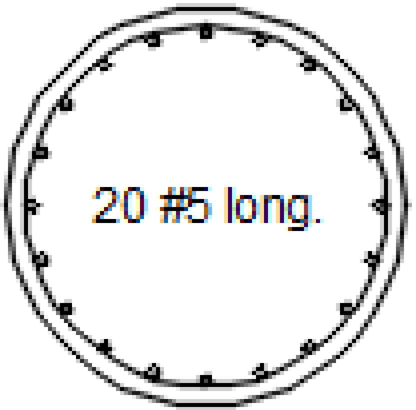


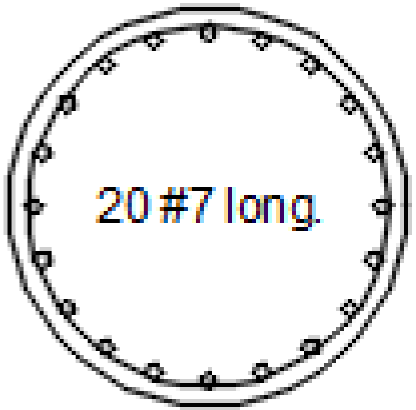


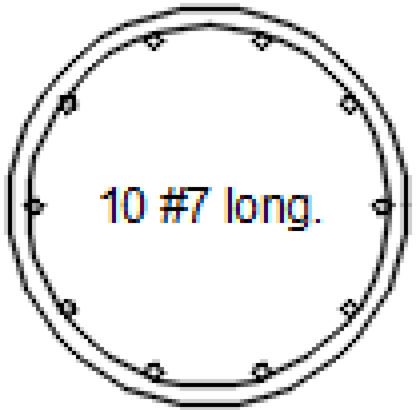


Test Matrix – FRP Jacket

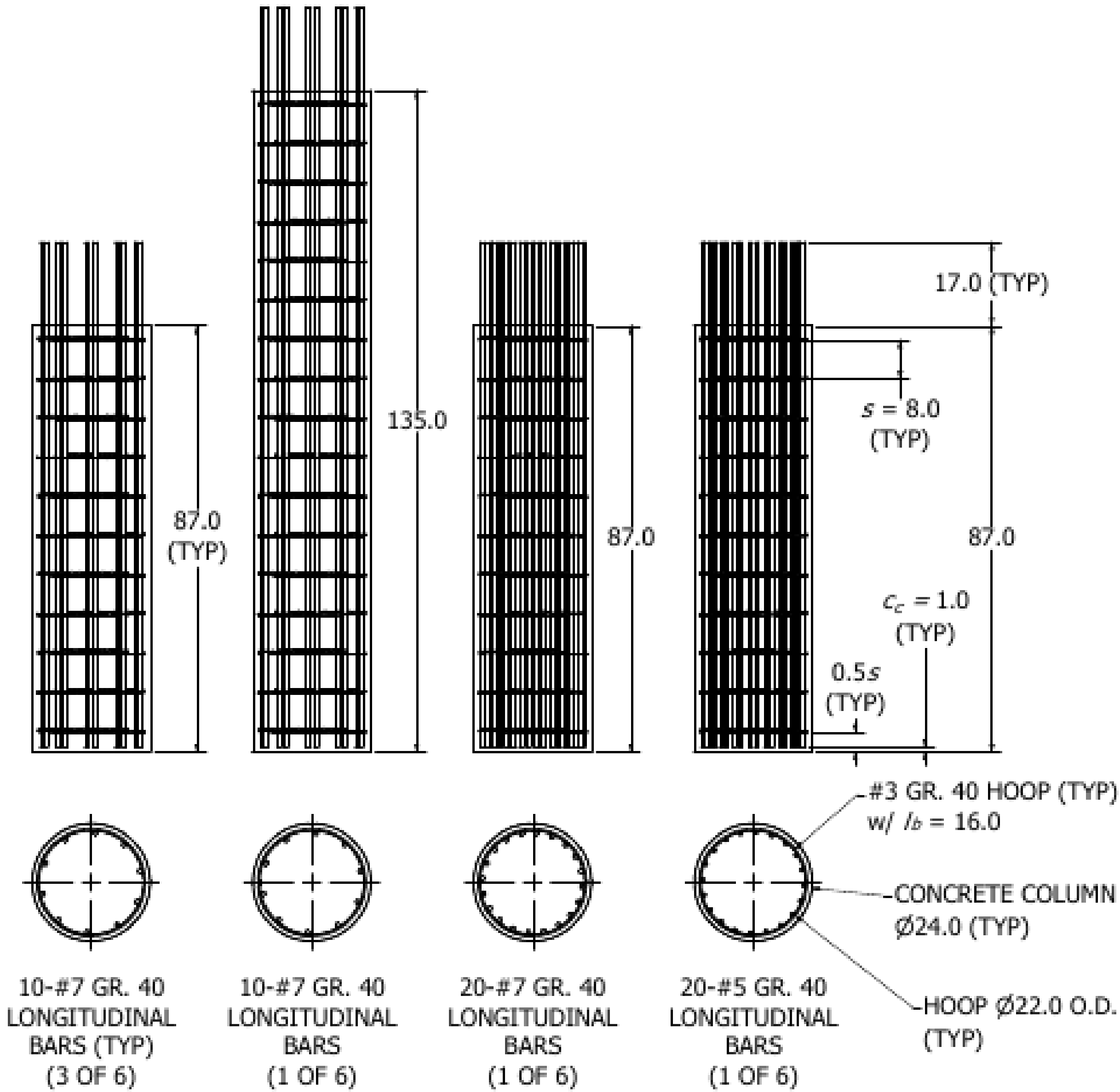
Column I.D.	Long. Bar Size	# Long. Bars	A_s/A_g	$P/(A_g f_c')$	H/D	Loading Protocol
C(CFRP)-4.0-#7(1.3)-0.05	#7	10	0.0133	0.05	4.0	Cyclic
C(CFRP)-4.0-#5(1.4)-0.05	#5	20	0.0137	0.05	4.0	Cyclic
C(CFRP)-4.0-#7(2.7)-0.05	#7	20	0.0265	0.05	4.0	Cyclic
C(CFRP)-4.0-#7(1.3)-0.05-EQ	#7	10	0.0133	0.05	4.0	EQ
C(CFRP)-4.0-#7(1.3)-0.05-2X	#7	10	0.0133	0.05	4.0	2x Cyclic
C(CFRP)-4.0-#7(1.3)-0.15	#7	10	0.0133	0.15	4.0	Cyclic



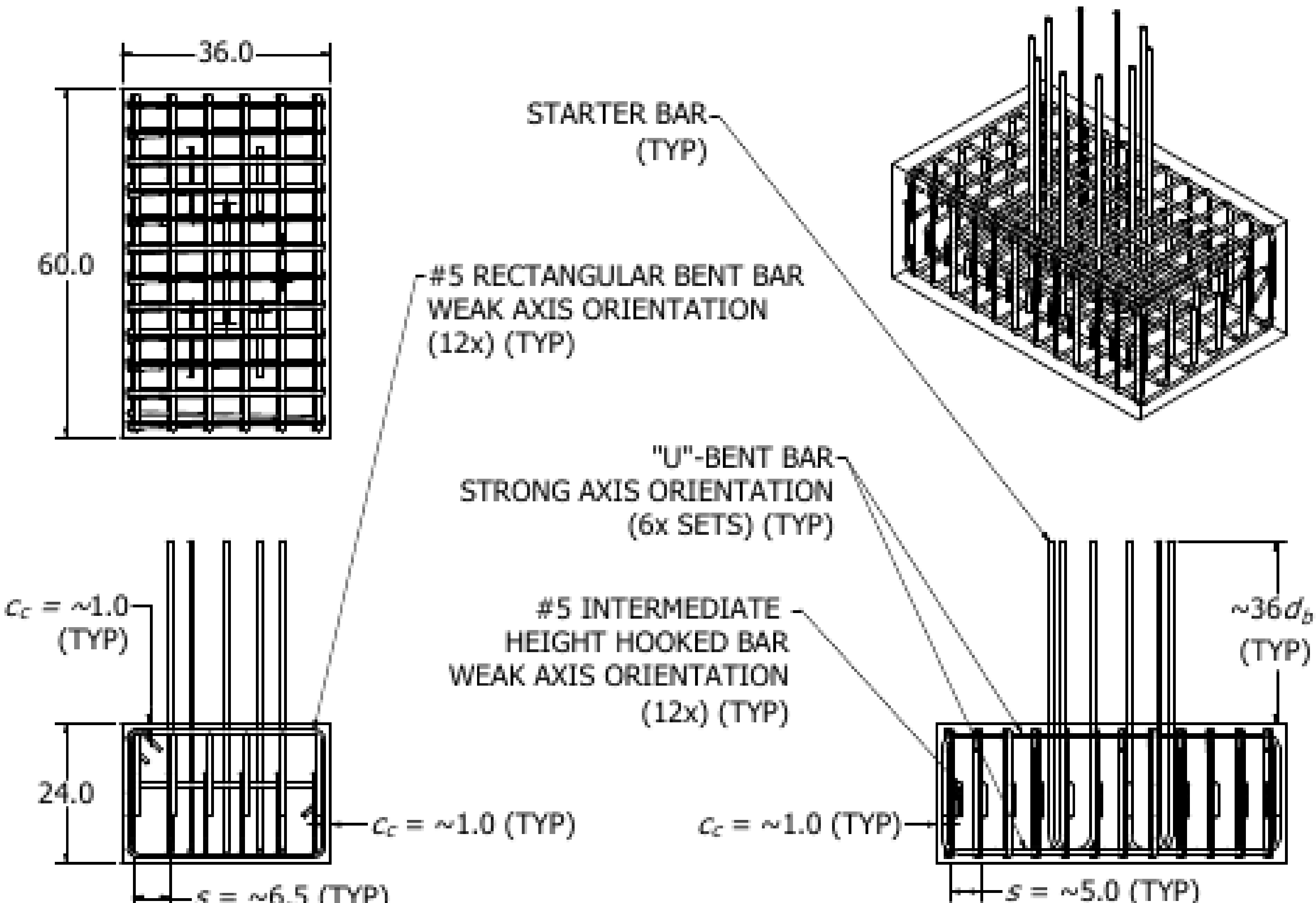




Column Drawings



Footing Drawings



Construction

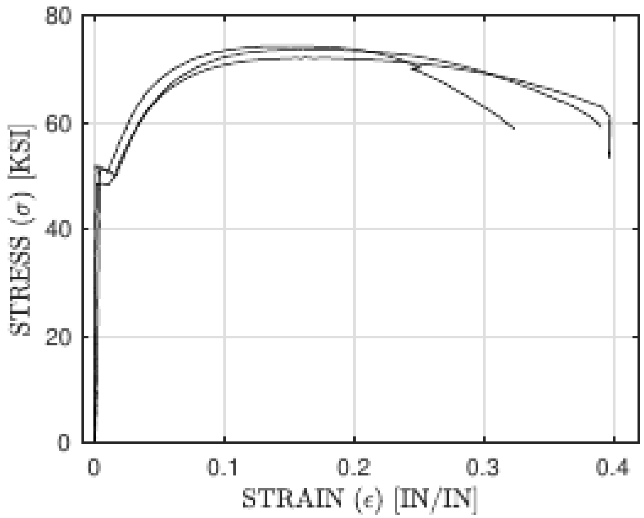
Construction

Construction

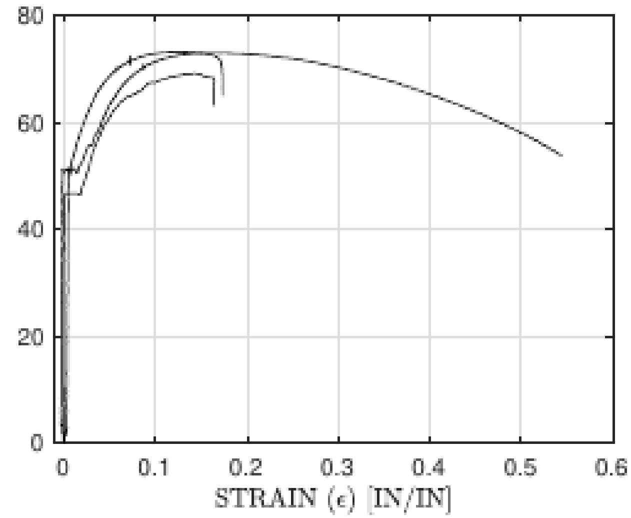
Construction

Construction

Steel Reinforcement Properties



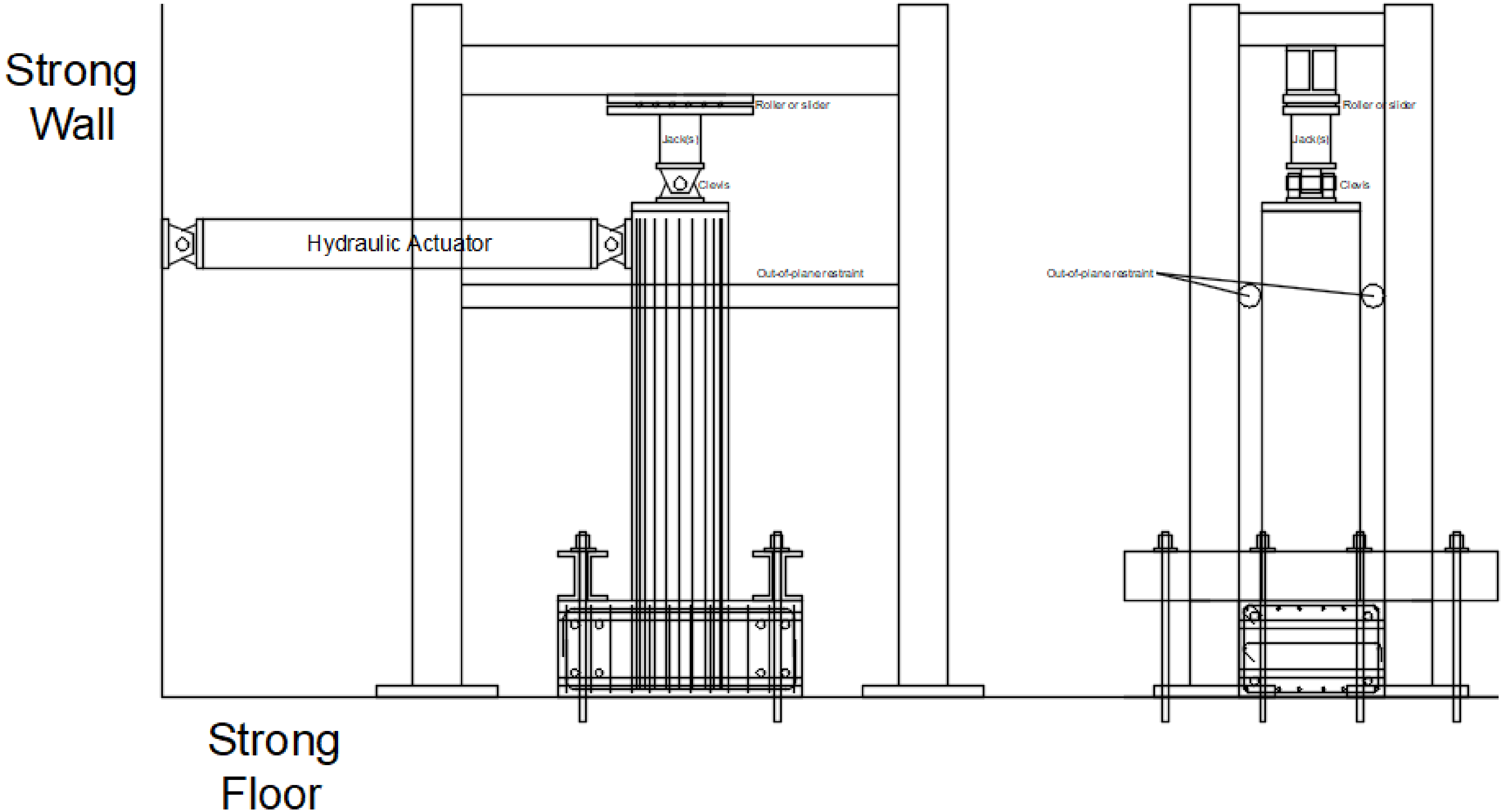
(a) #5 Stress–Strain Relationship



(b) #7 Stress–Strain Relationship

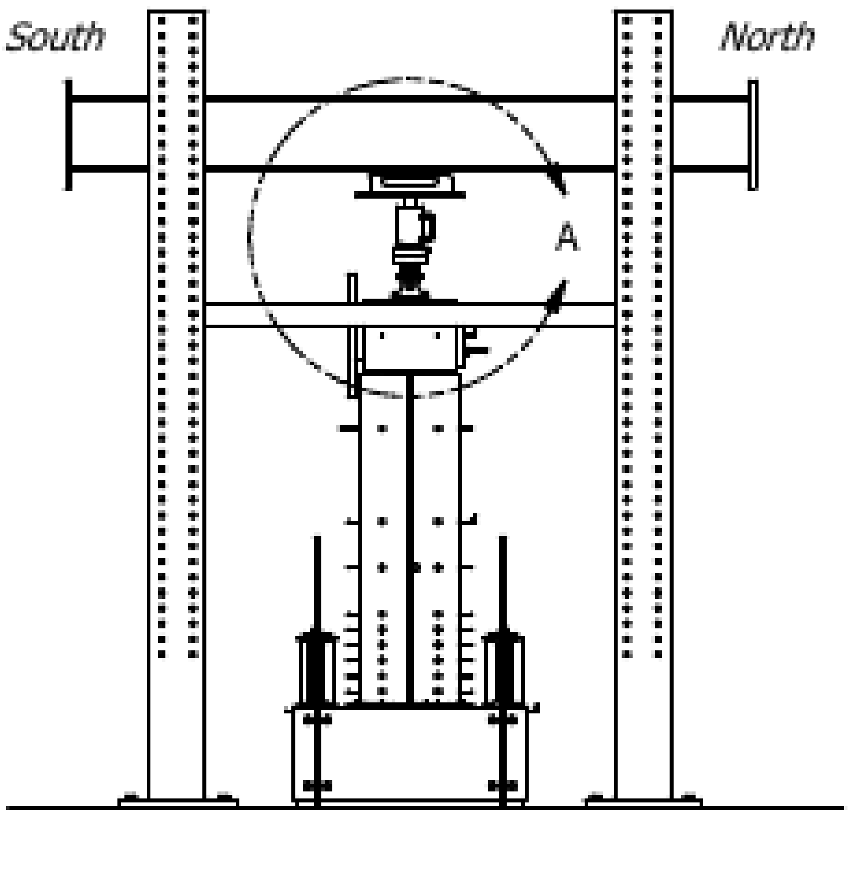
#5 Grade 40				#7 Grade 40			
Sample I.D.	f_y [ksi]	f_u [ksi]	Elongation [%]	Sample I.D.	f_y [ksi]	f_u [ksi]	Elongation [%]
#5 Test 1	48.5	72.0	39	#7 Test 1	46.5	69.0	16
#5 Test 2	52.0	74.5	32	#7 Test 2	51.0	73.0	17
#5 Test 3	51.0	74.0	39	#7 Test 3	51.5	73.0	54
Average	50.5	73.5	36.7		49.8	71.7	29

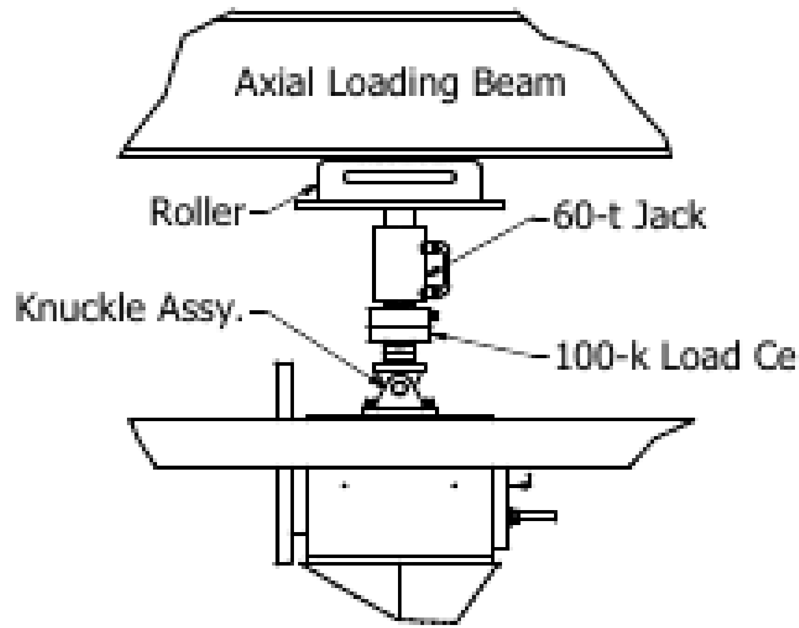
Test Set-Up


Strong Wall
Roller or slider
Jack(s)
Clevis
Hydraulic Actuator
Out-of-plane restraint
Roller or slider
Jack(s)
Clevis
Out-of-plane restraint
Strong Floor

Test Set-Up

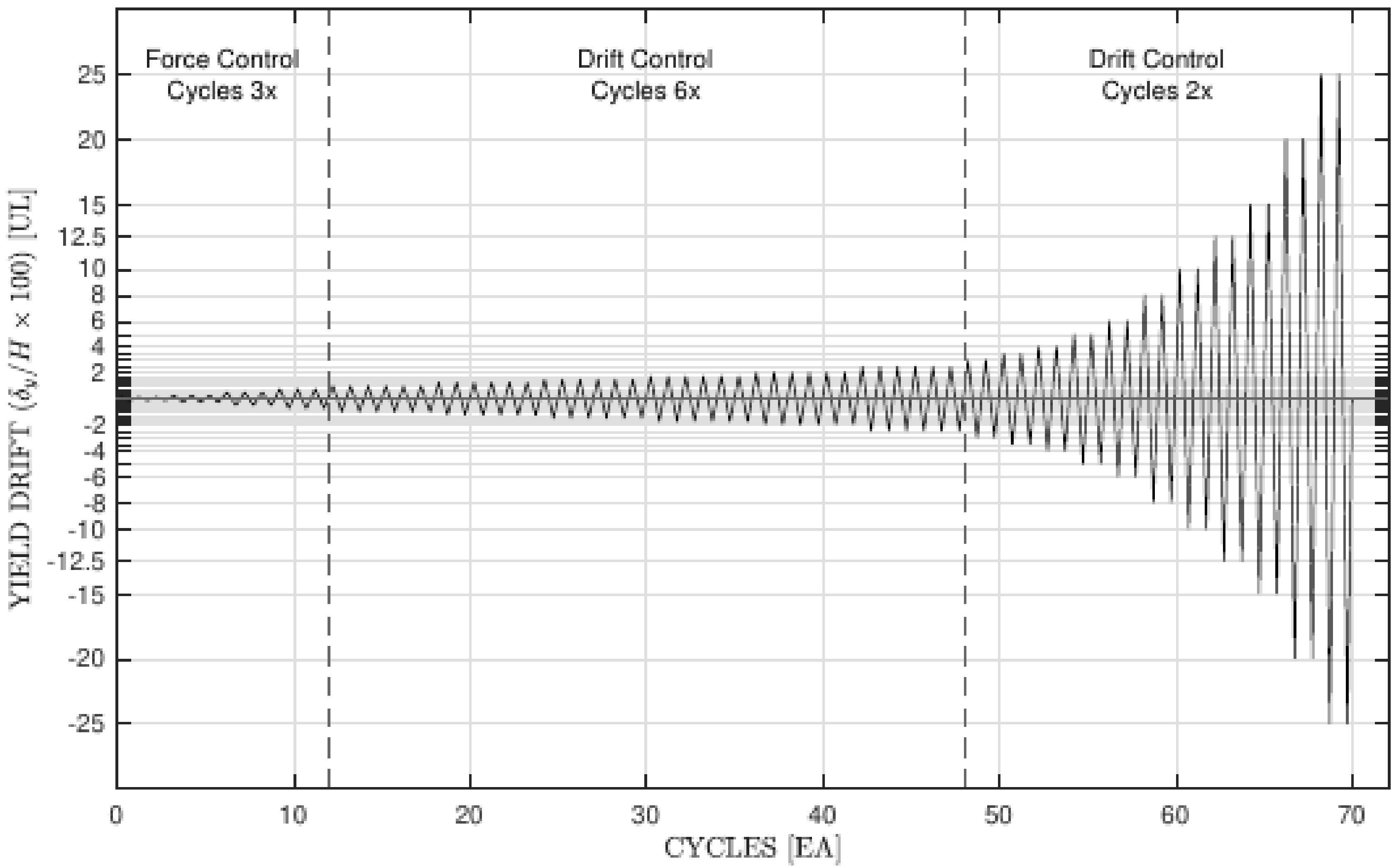
Test Set-Up: Axial Load Application





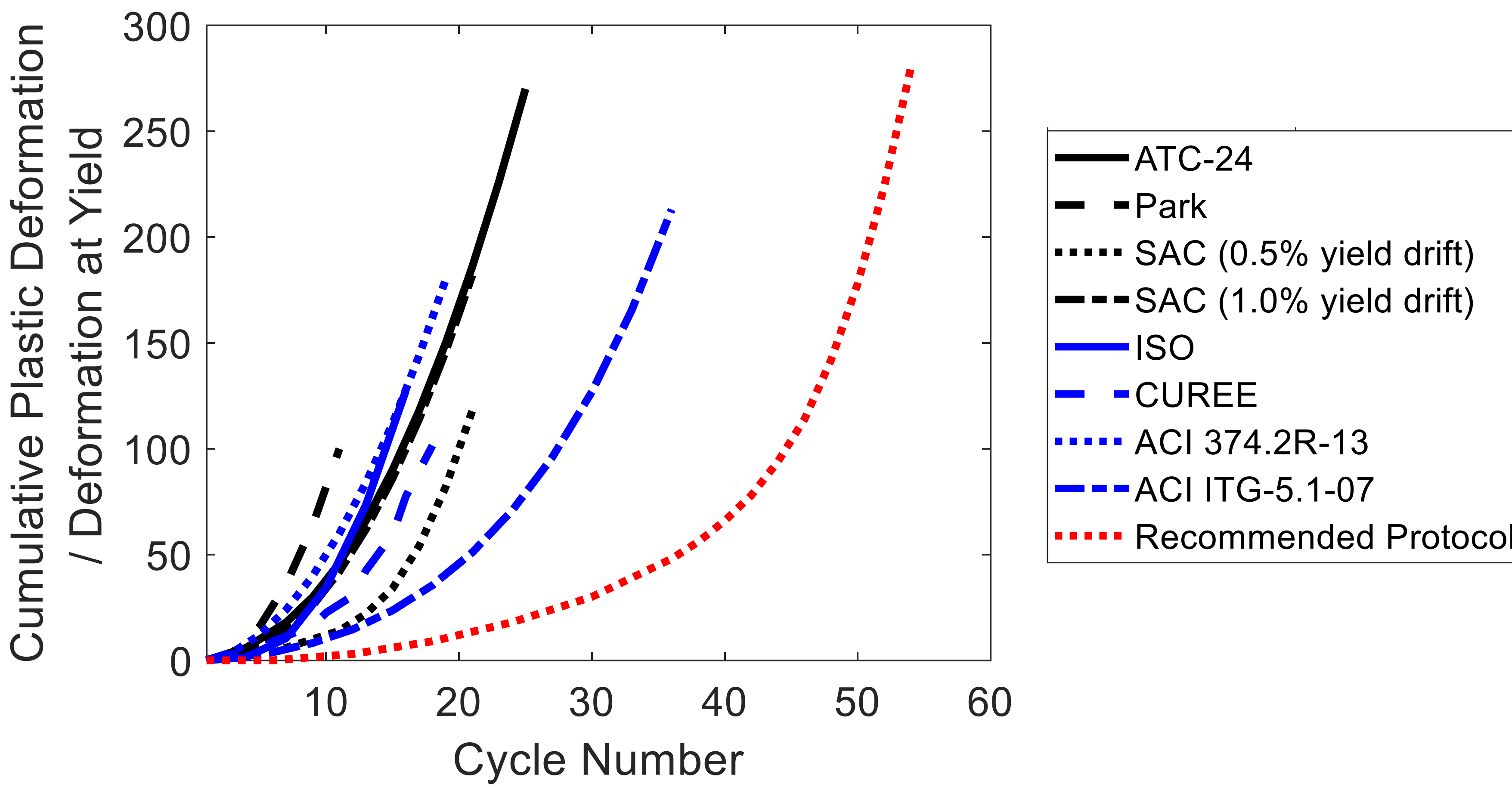
DETAIL A
SCALE 2:1

Loading Protocol

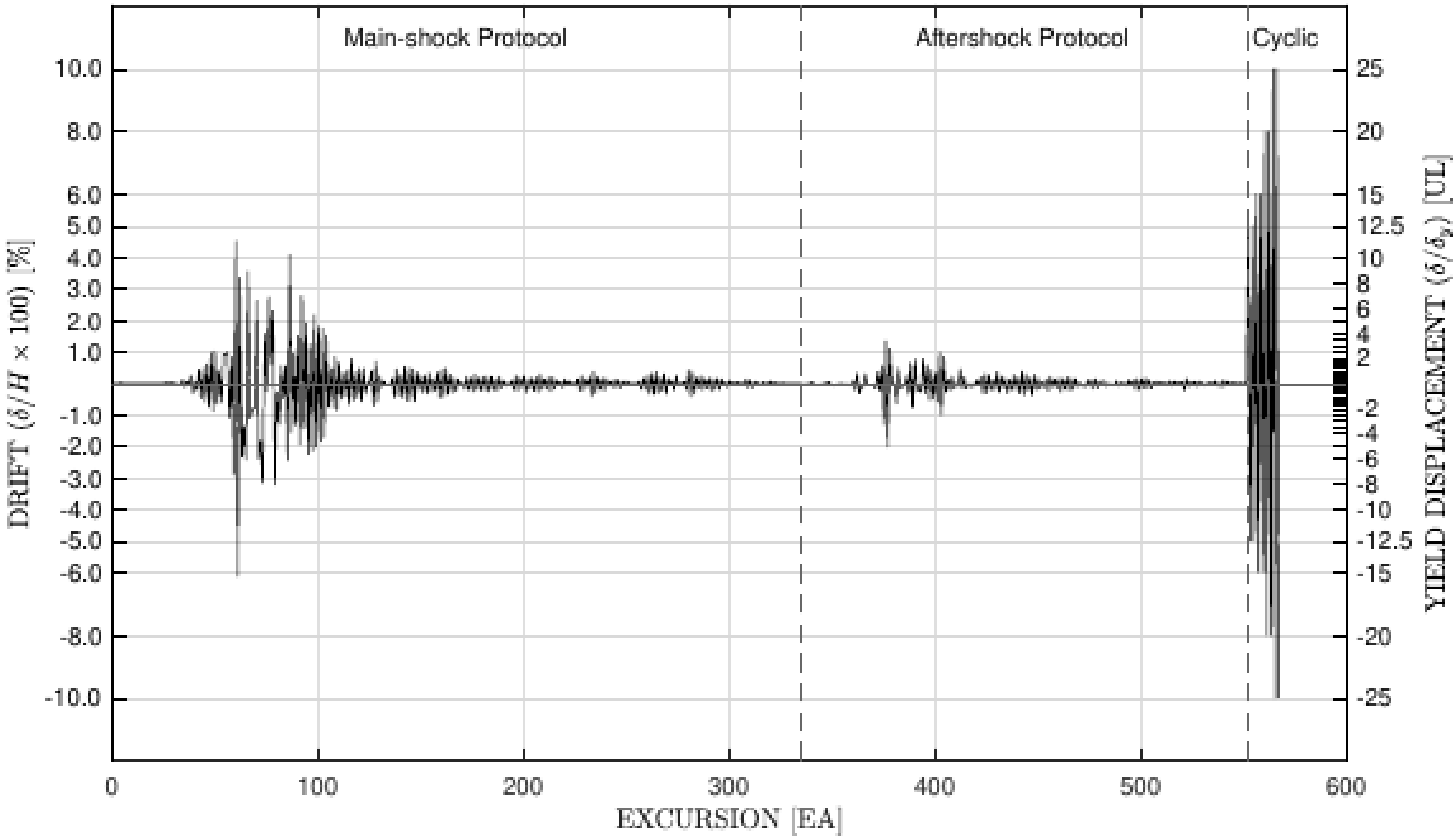


Loading Protocol

- Loading protocol:

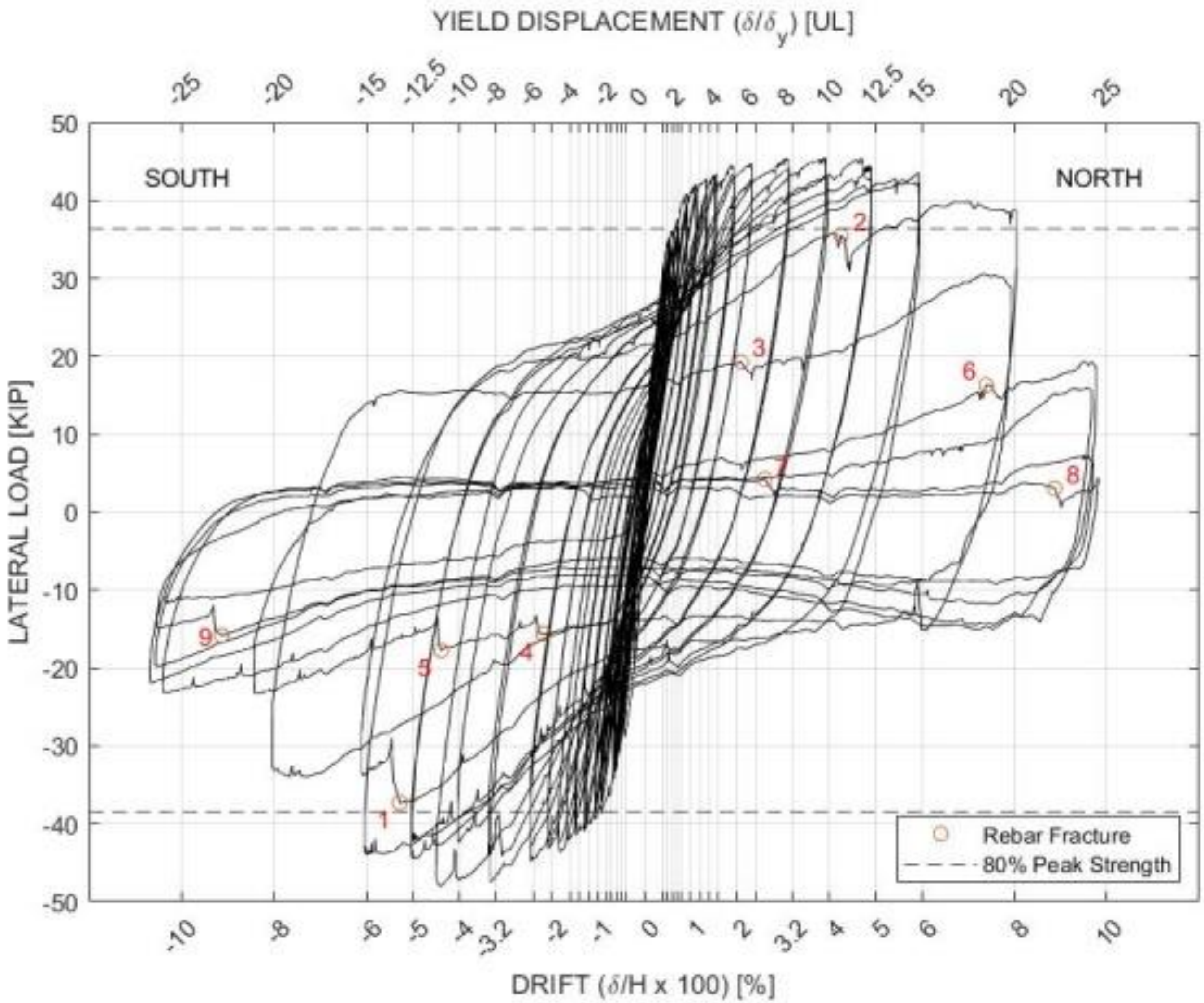


Loading Protocol

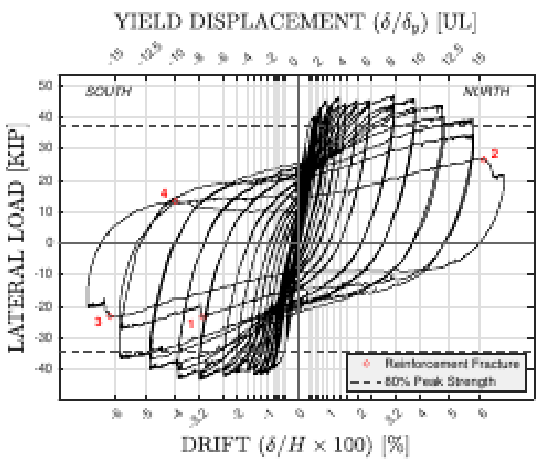


Test Video

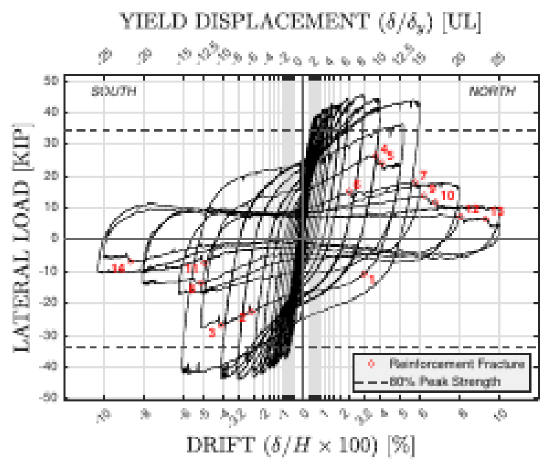
Test Results: Load-Deformation



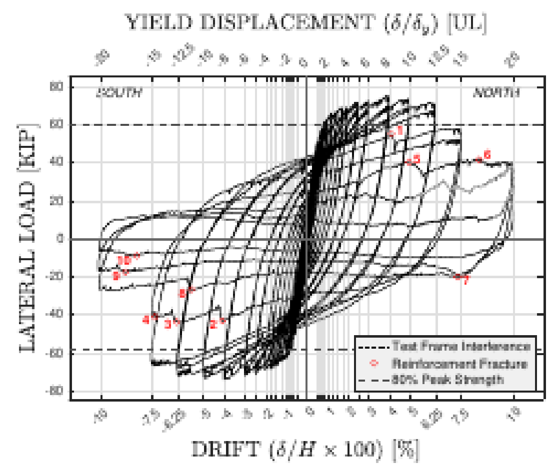
Test Results: Load-Deformation - Steel



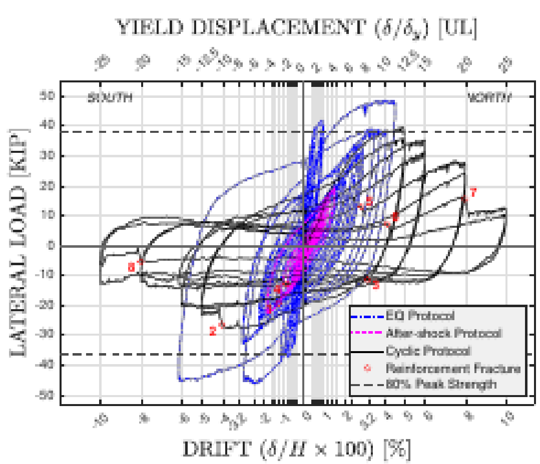
(a) C(S)-4.0-#7(1.3)-0.05



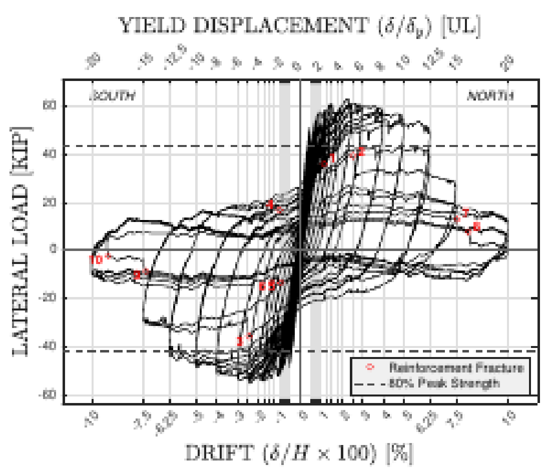
(b) C(S)-4.0-#5(1.4)-0.05



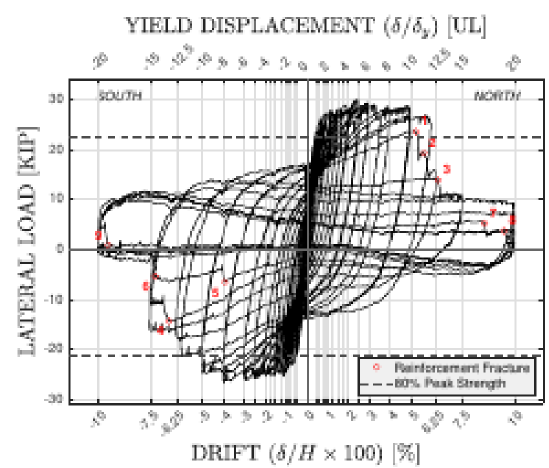
(c) C(S)-4.0-#7(2.7)-0.05



(d) C(S)-4.0-#7(1.3)-0.05-EQ



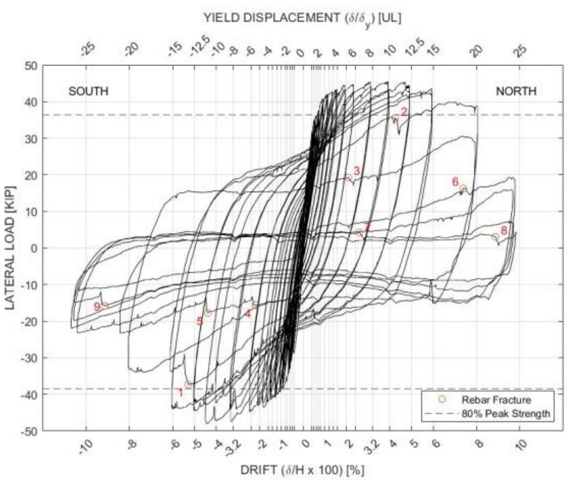
(e) C(S)-4.0-#7(1.3)-0.15



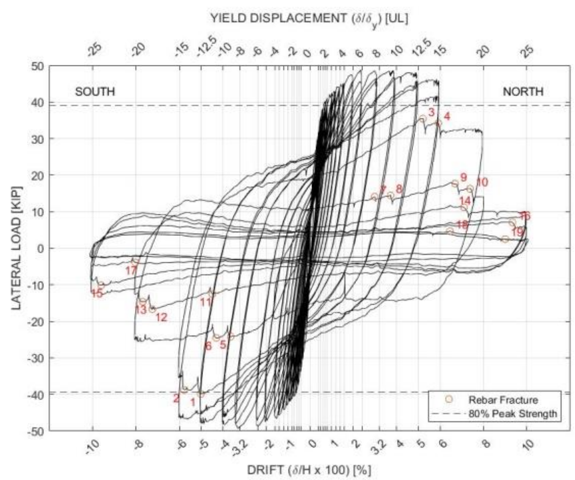
(f) C(S)-6.0-#7(1.3)-0.05

Test Results: Load-Deformation - FRP

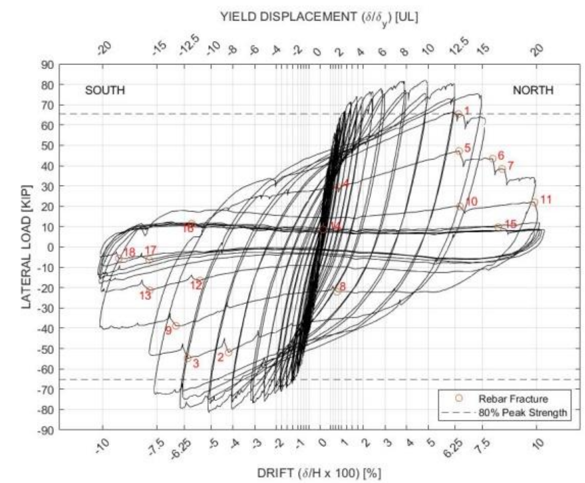
C(CFRP)-#7(1.3)-0.05



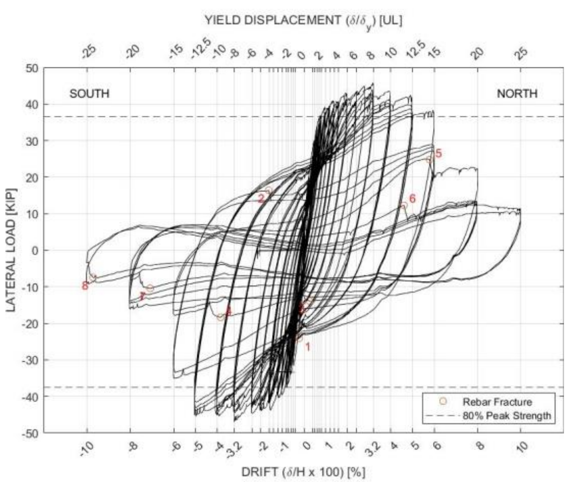
C(CFRP)-#5(1.4)-0.05



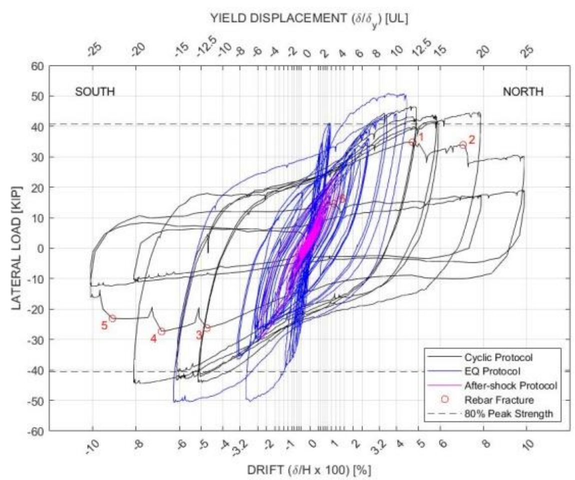
C(CFRP)-#7(2.7)-0.05



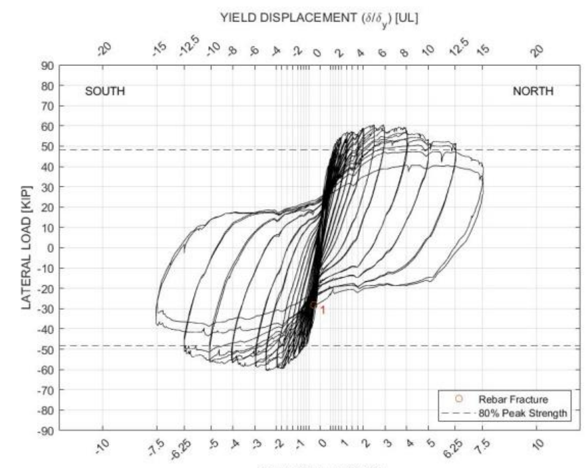
C(CFRP)-#7(1.3)-0.05-2X



C(CFRP)-#7(1.3)-0.05-EQ



C(CFRP)-#7(1.3)-0.15



Test Results: Deformation Capacity

Steel Jacket Retrofitted:

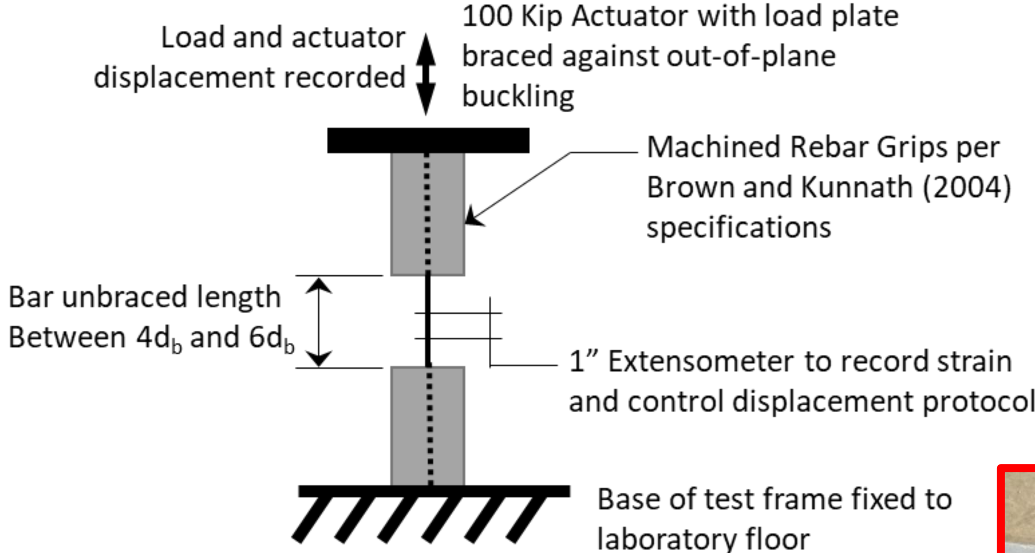
Column I.D.	Lateral Failure				Axial Failure	
	$\frac{\delta}{\delta_y}$ (Cycle Number)		Drift [%]		$\frac{\delta}{\delta_y}$ (Cycle Number)	Drift [%]
	(+)	(−)	(+)	(−)		
C(S)-4.0-#7(1.3)-0.05	15.0 (1)+	15.0 (1)−	6.0	6.0	N.A.	N.A.
C(S)-4.0-#5(1.4)-0.05	12.5 (1)+	15.0 (1)−	5.0	6.0	N.A.	N.A.
C(S)-4.0-#7(2.7)-0.05	12.5 (2)+	15.0 (1)−	6.25	7.5	N.A.	N.A.
C(S)-4.0-#7(1.3)-0.05-EQ	12.5 (1)+	15.4 (1)−	5.0	6.1	N.A.	N.A.
C(S)-4.0-#7(1.3)-0.15	12.5 (1)+	12.5 (2)−	6.25	6.25	20.0 (5)−	10.0−
C(S)-6.0-#7(1.3)-0.05	12.5 (1)+	12.5 (1)−	6.25	6.25	20.0 (1)−	10.0−

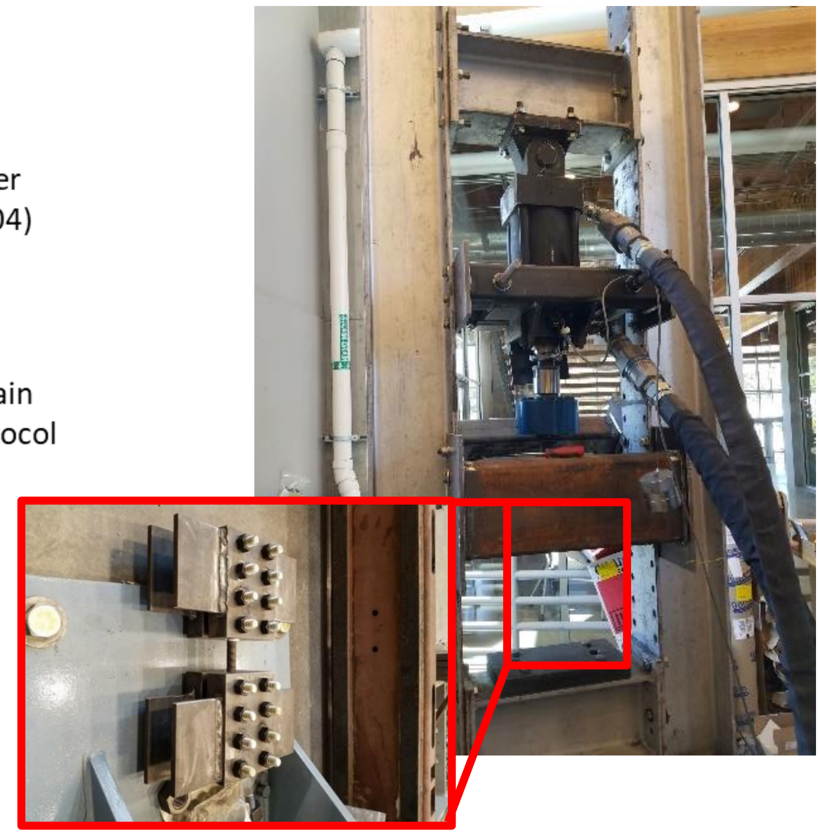
FRP Jacket Retrofitted:

Column I.D.	Lateral Failure			
	$\frac{\delta}{\delta_y}$ (Cycle Number)		Drift [%]	
	(+)	(−)	(+)	(−)
C(CFRP)- #7(1.3)-0.05	20.0 (1) +	15.0 (1) −	8.0	6.0
C(CFRP)-#5(1.4)-0.05	15.0 (2) +	15.0 (1) −	6.0	6.0
C(CFRP)-#7(2.7)-0.05	15.0 (1) +	15.0 (1) −	7.5	7.5
C(CFRP)-#7(1.3)-0.05-EQ	20.0 (1) +	20.0 (1) −	8.0	8.0
C(CFRP)-#7(1.3)-0.05-2X	15.0 (1) +	12.5 (4) −	6.0	5.0
C(CFRP)-#7(1.3)-0.15	12.5 (2) +	12.5 (2) −	6.25	6.25

Reinforcement Fatigue

Bar Testing Setup

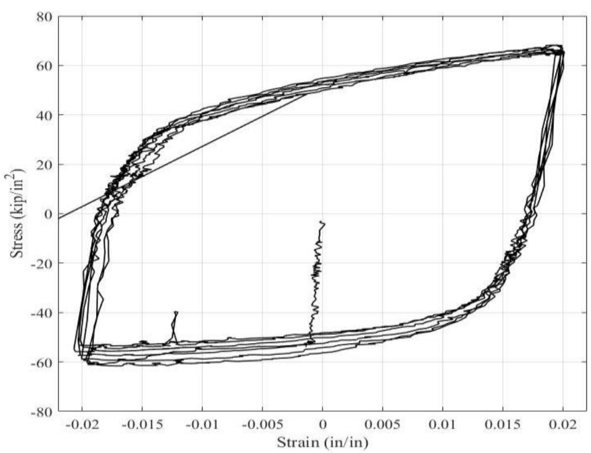


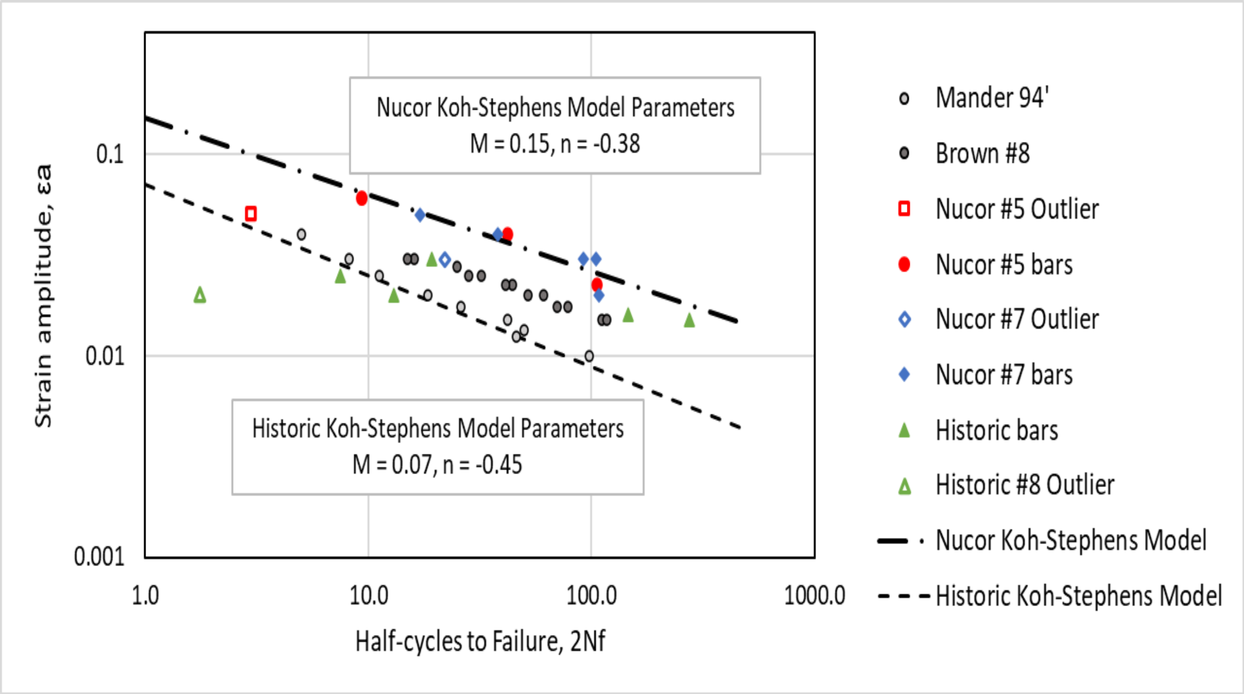


Constant Amplitude Testing

Koh-Stephens
(total-strain amplitude)

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = M(2N_f)^m$$

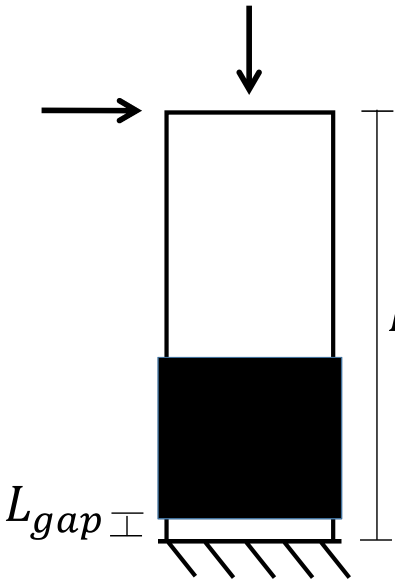




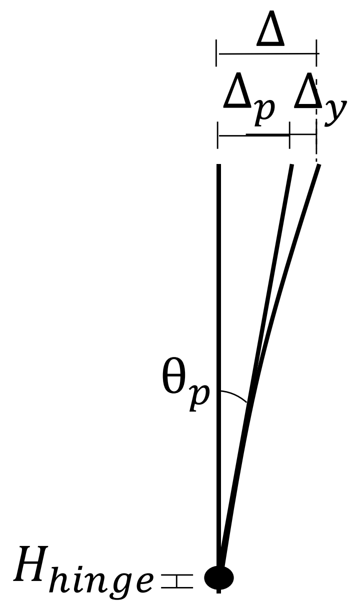
Column Modeling

Deformation Capacity Model

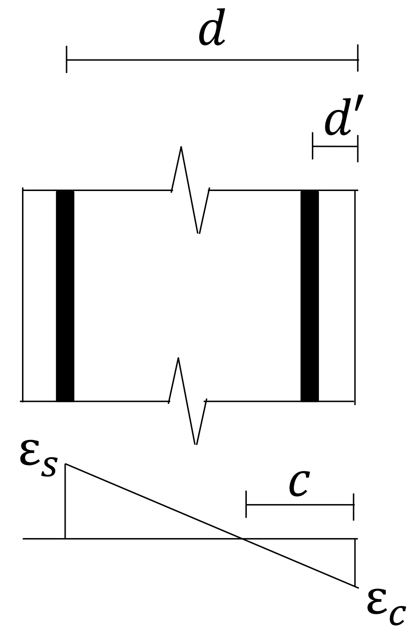
Steel Jacket Retrofitted Column:



Hinge Rotation Model:



Plane-Strain Behavior:



$$\varepsilon_{p,t} = \phi_p(d - c) = \frac{\theta_p}{L_p}(d - c) = \frac{\Delta_p}{\left(H - \frac{L_{gap}}{2}\right) L_p}(d - c)$$

$$\varepsilon_{p,c} = \phi_p(c - d') = \frac{\theta_p}{L_p}(c - d') = \frac{\Delta_p}{\left(H - \frac{L_{gap}}{2}\right) L_p}(c - d')$$

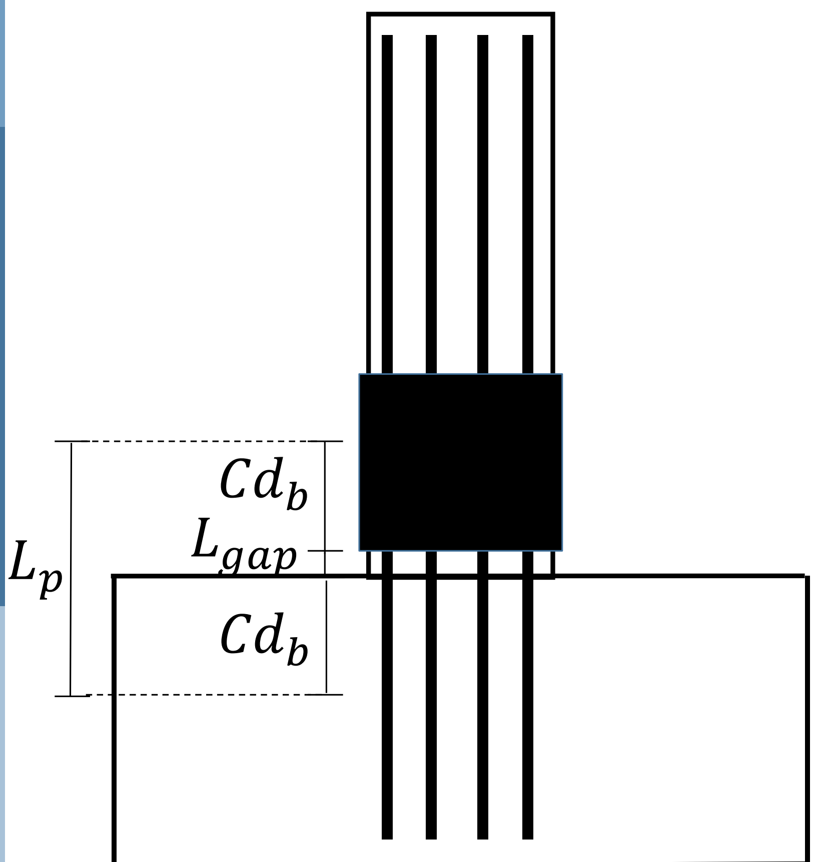
OpenSees Model

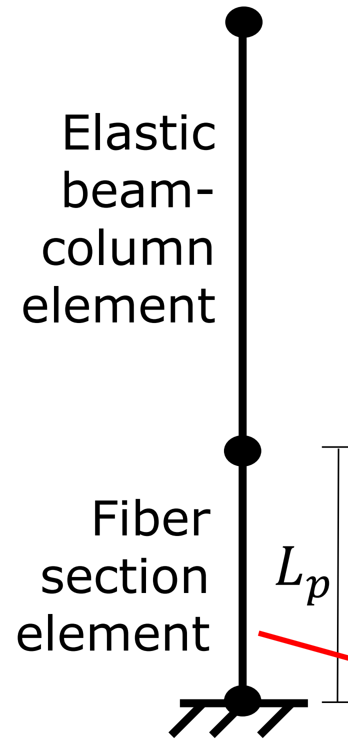
$$L_p = L_{gap} + Cd_b$$

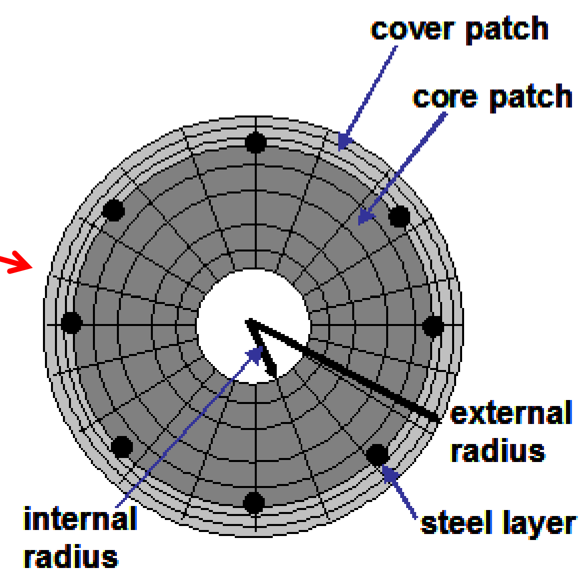
where C^*d_b accounts for strain penetration

C = 12 recommended for Grade 40

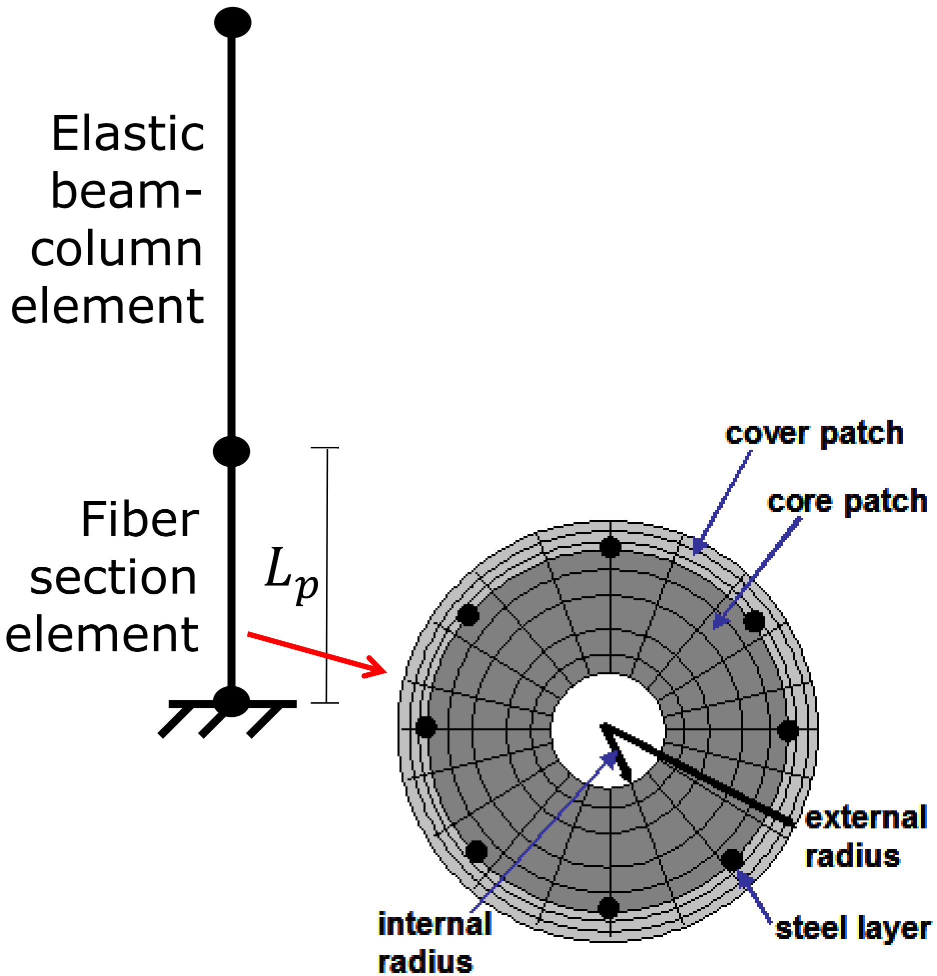
C = 18 recommended for Grade 60



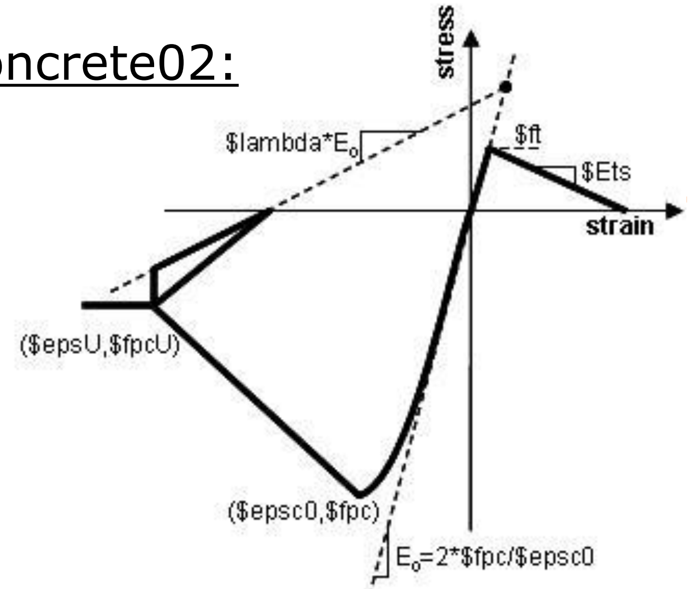




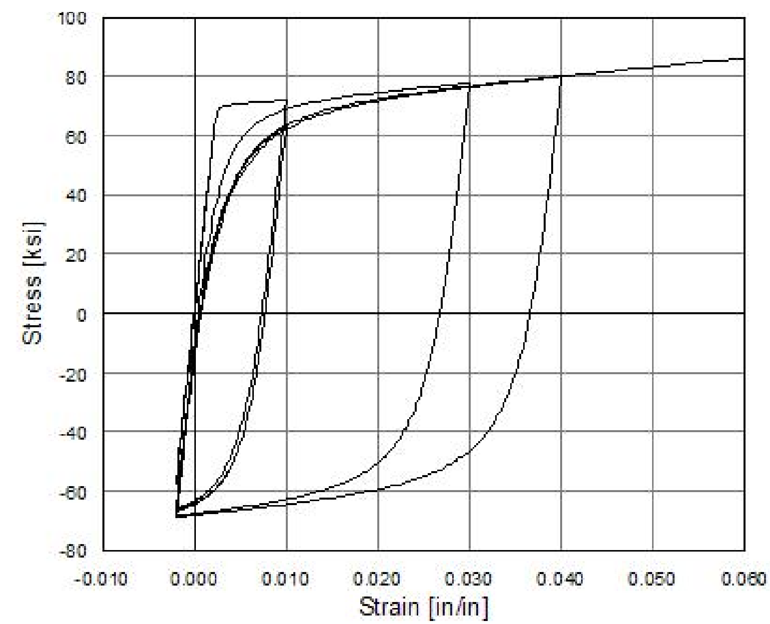
OpenSees Model



Concrete02:



Steel02:



Plastic Hinge Length

- Alsiwat and Saatcioglu (1992):

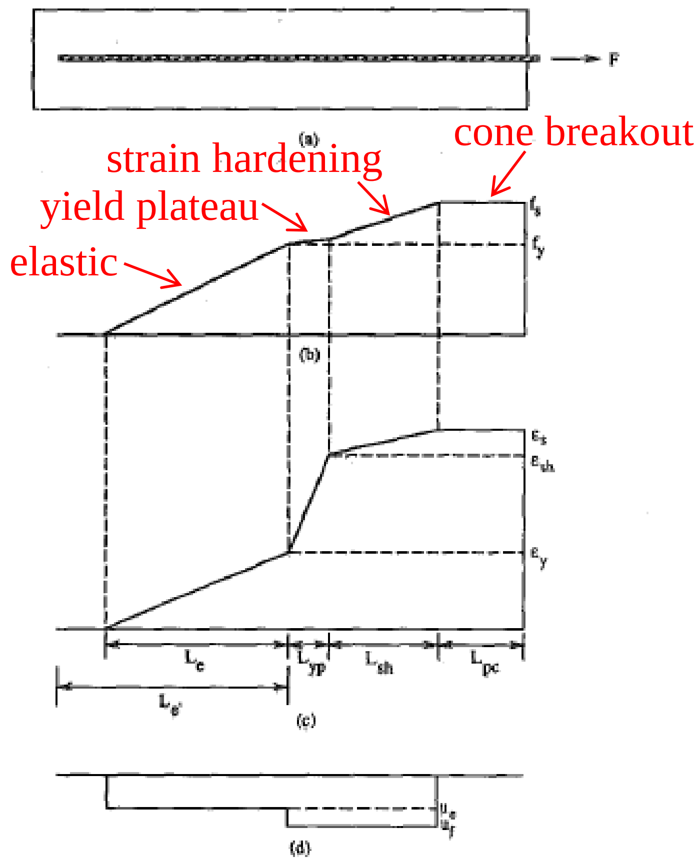


FIG. 1. (*a*) Reinforcing Bar Embedded in Concrete; (*b*) Stress Distribution; (*c*) Strain Distribution; (*d*) Bond Stress between Concrete and Steel

Extension:

$$\delta_{ext} = \varepsilon_s L_{pc} + 0.5(\varepsilon_s + \varepsilon_{sh}) L_{sh} + 0.5(\varepsilon_{sh} + \varepsilon_y) L_{yp} + 0.5(\varepsilon_y) L_e$$

Slip:

$$\delta_s = \delta_{s1} \left(\frac{u'_e}{u_u} \right)^{2.5}$$

$$\delta_{s1} = \sqrt{\frac{30}{f'_c}}$$

$$u_u = \left(20 - \frac{d_b}{4} \right) \sqrt{\frac{f'_c}{30}}$$

$$u'_e = 0 \qquad \text{if } L'_e > L_e$$

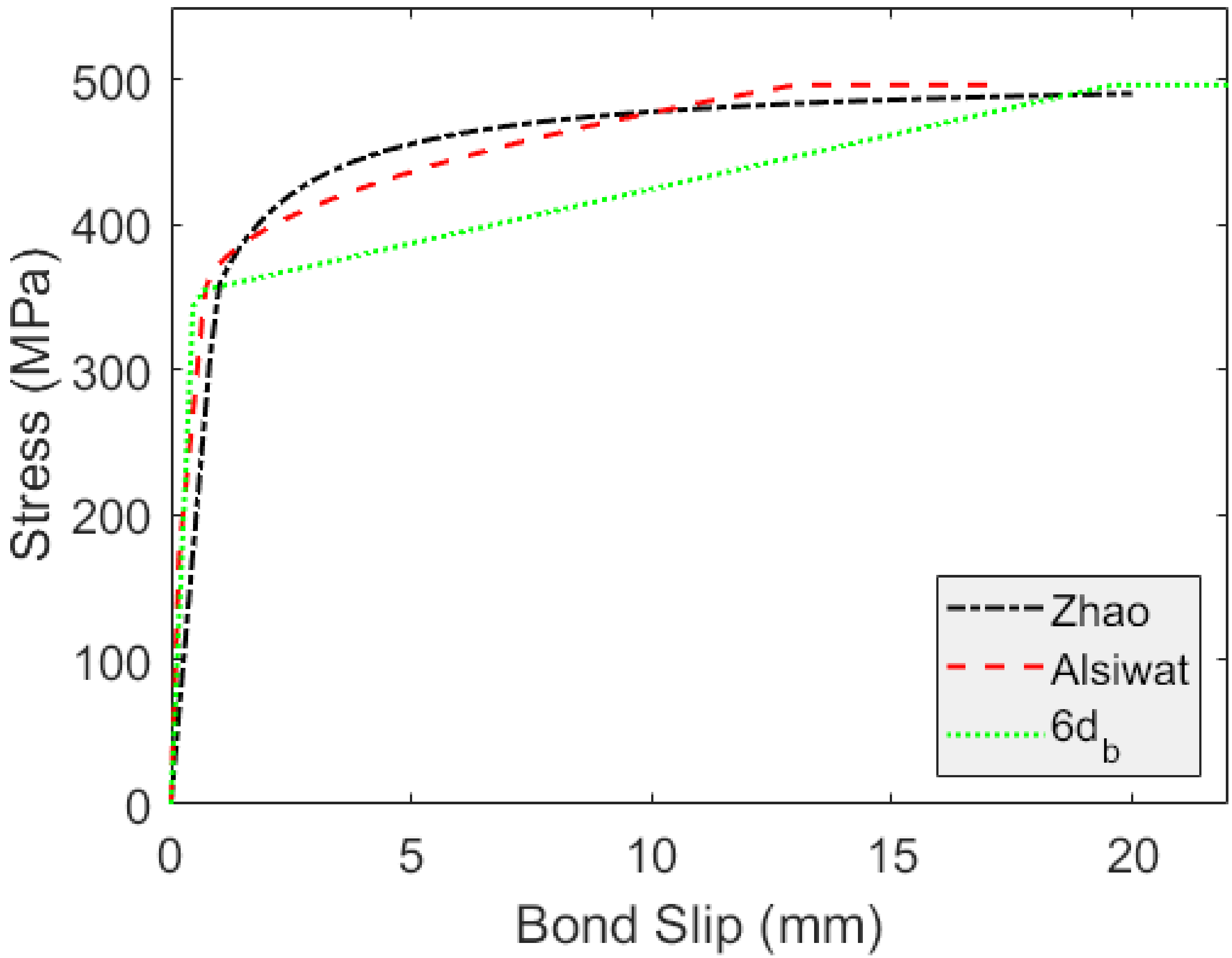
$$u'_e = \frac{f_s d_b}{4 L'_e} \qquad \text{if } L'_e \le L_e$$

Total:

$$\delta_{total} = \delta_{ext} + \delta_s$$

typically small

Bond Slip Model



Effective Stiffness

- Elwood and Eberhard (2009) procedure for reinforced concrete columns:

$$\Delta = \Delta_{flexure} + \Delta_{slip} + \Delta_{shear}$$

$$\Delta_{flexure} = \frac{H^2 \phi_y}{3}$$

$$\Delta_{slip} = \frac{H d_b f_y \phi_y}{8u} = \frac{H d_b f_y \phi_y}{8\left(9.6\sqrt{f_c'}\right)}$$

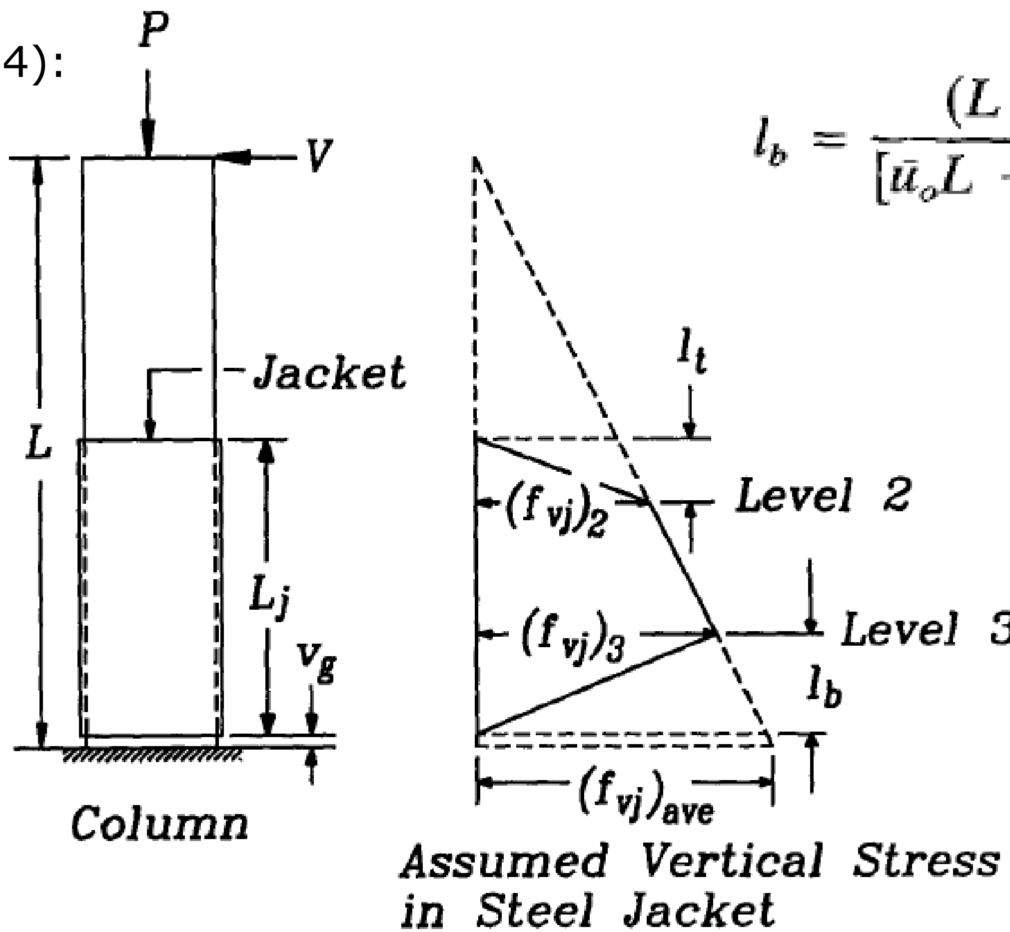
$$\Delta_{shear} = \frac{M_y}{A_v G_{eff}} = \frac{M_y}{(0.85D)(0.2E_c)}$$

Effective Stiffness

- Chai et al (1994) procedure for steel jacketed reinforced concrete columns:

Chai et al (1994):

$$l_b = \frac{(L - v_g)t_j}{[\bar{u}_o L + (f_{vj})_{ave} t_j]} (f_{vj})_{ave}$$



Deformation Capacity Model - Fatigue

Coffin (1954 and 1971) and Manson (1965) formulation:

$$\varepsilon_p = \varepsilon_0 \left(2N_f\right)^{-m}$$

$$2N_f = 10^{(-m)^{-1} \log\left(\frac{\varepsilon_p}{\varepsilon_0}\right)}$$

Brown and Kunnath (2000, 2004):

$$\varepsilon_0 = 0.12$$

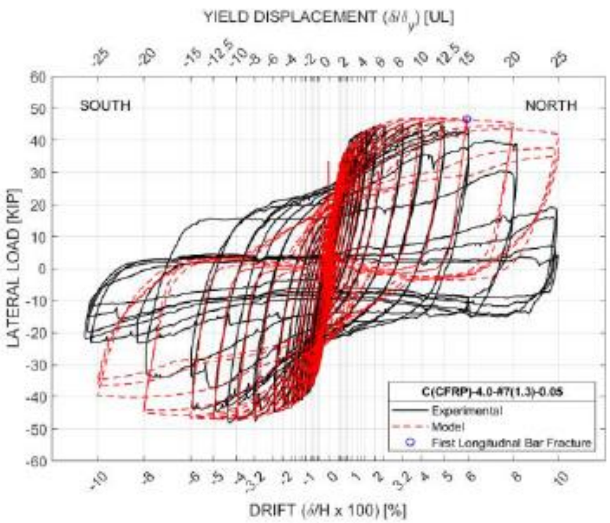
$$m = 0.44$$

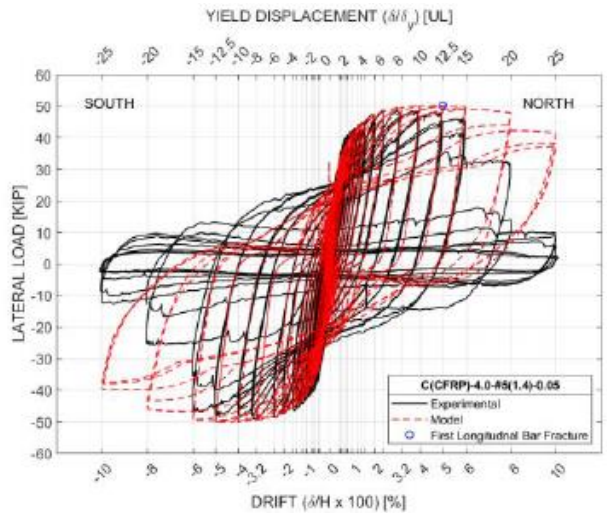
Minor's rule:

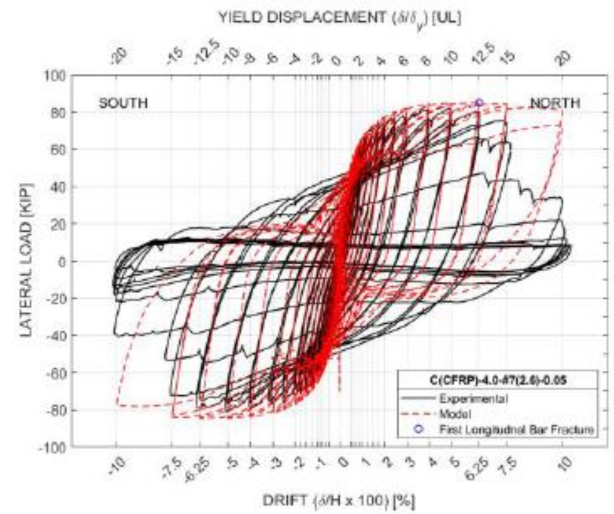
$$DI = \sum \frac{2n_i}{2N_f}$$

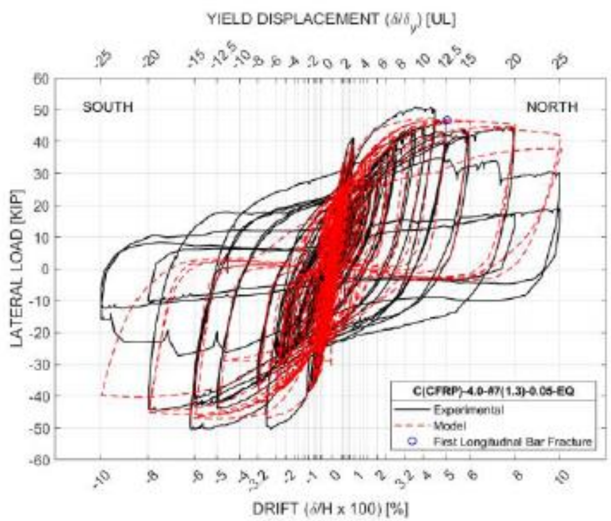
$DI > 1.0 \rightarrow$ Failure

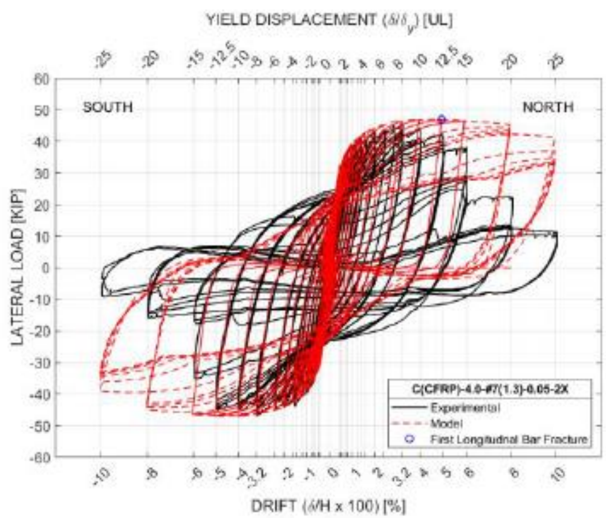
Model Validation – FRP Jacket

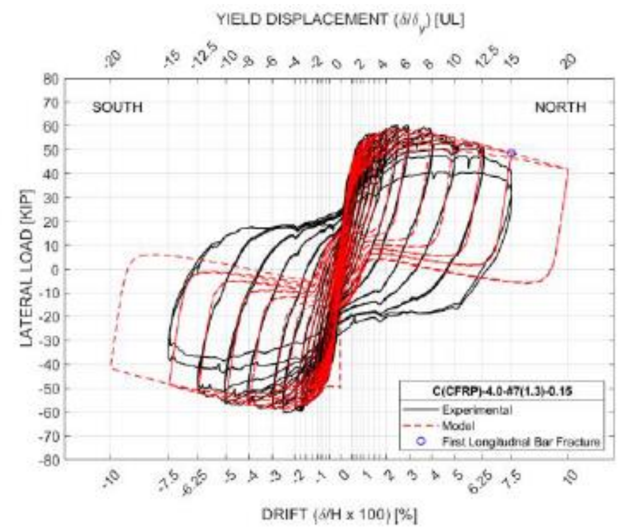




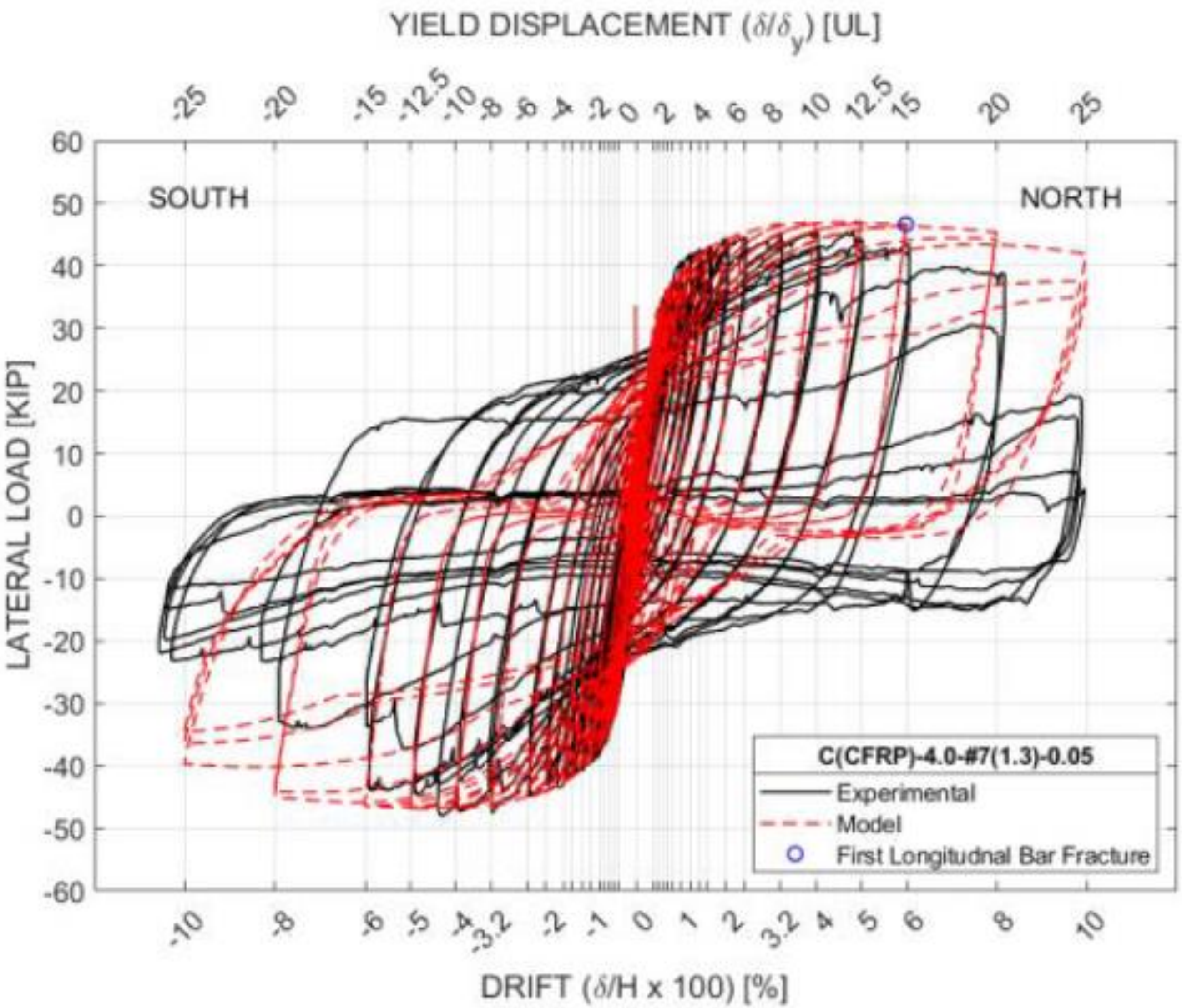






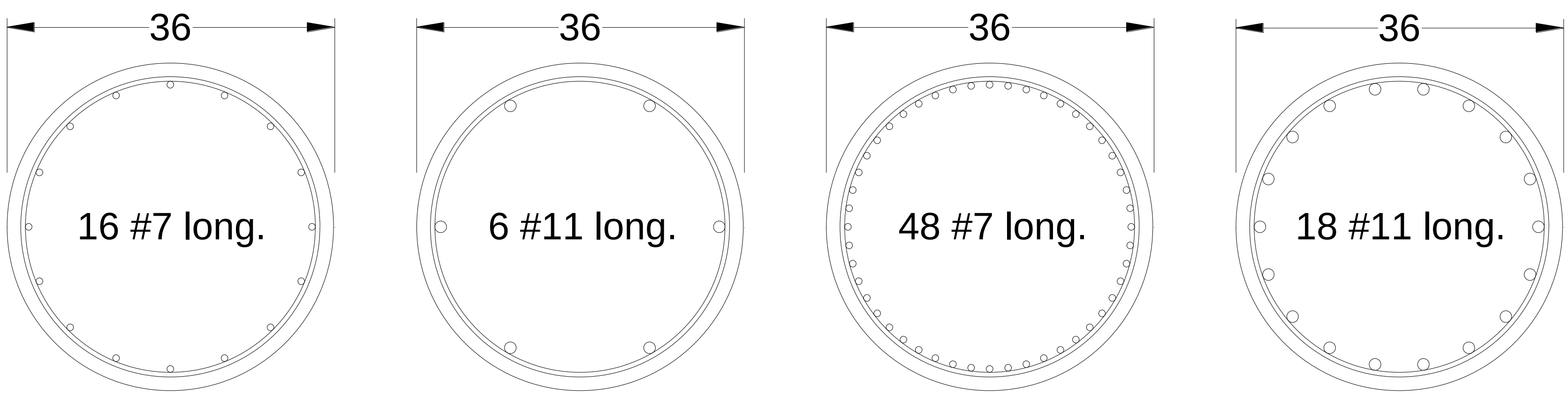


Model Validation – FRP Jacket



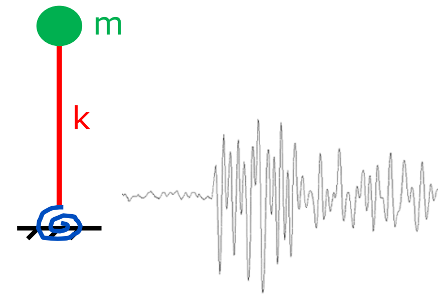
Column Fragility

Column Sections Considered



Column Name	Column Shape	Jacket Type	Long. Bar Size	# Long. Bars	As/Ag	P/(Agf'c)
C(S)-#7(0.9)-0.05	Circular	Steel	#7	16	0.0094	0.05
C(S)-#11(0.9)-0.05	Circular	Steel	#11	6	0.0092	0.05
C(S)-#7(2.8)-0.05	Circular	Steel	#7	48	0.0283	0.05
C(S)-#11(2.8)-0.05	Circular	Steel	#11	18	0.0276	0.05
C(S)-#7(0.9)-0.15	Circular	Steel	#7	16	0.0094	0.15
C(S)-#11(0.9)-0.15	Circular	Steel	#11	6	0.0092	0.15
C(S)-#7(2.8)-0.15	Circular	Steel	#7	48	0.0283	0.15
C(S)-#11(2.8)-0.15	Circular	Steel	#11	18	0.0276	0.15

SDOF Nonlinear Time History Analyses



- Site locations of Seattle and Forks, site class C
- SaW/Fy of 3, 4, and 5 used to determine mass

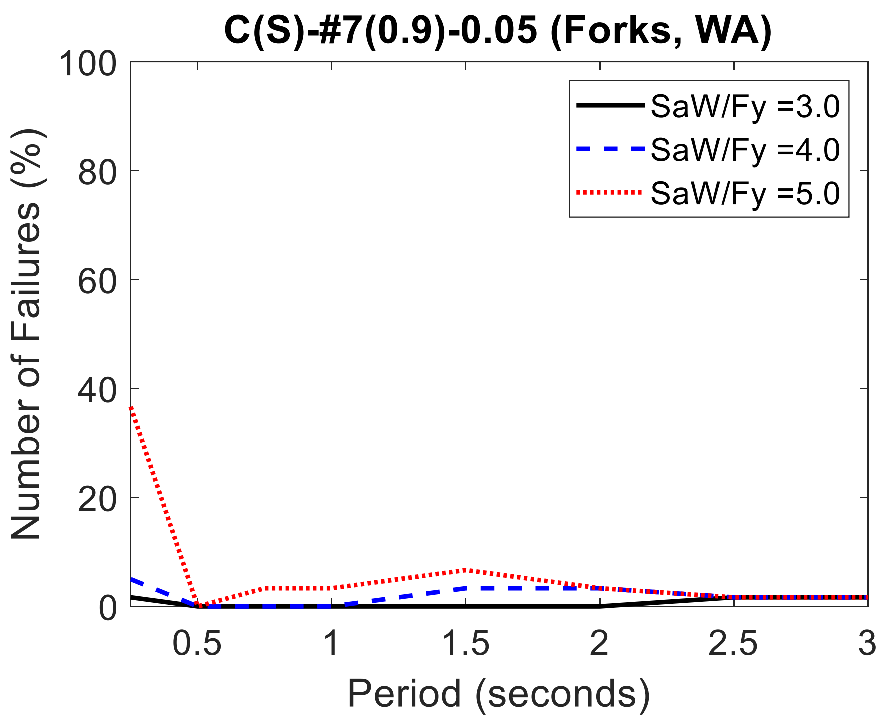
$$\frac{S_a W}{F_y} = \frac{S_a m g}{F_y}$$

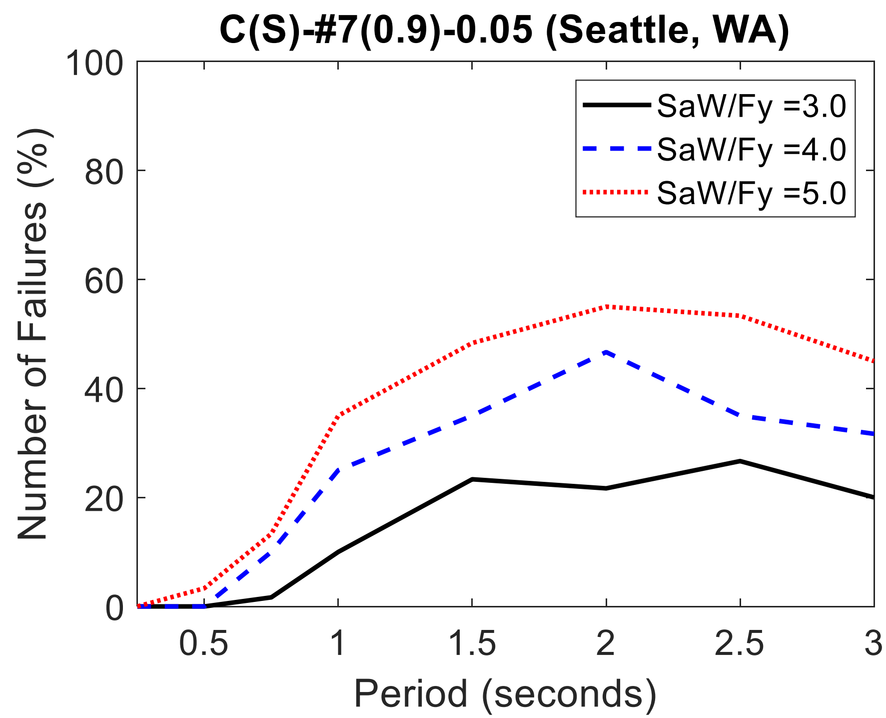
- Structural periods of 0.25s, 0.5s, 0.75s, 1.0s, 1.5s, 2.0s, and 3.0s used to determine stiffness (i.e., height of column)
- Model columns, each with axial load of 0.05Agf'c and 0.15Agf'c
- Site-specific M9 ground motion suits provided by UW/USGS (Cervantes, 2019):

Table 3.1. Station ID, Coordinates, and $R_{cd,avg}$ Used to Represent Washington Cities

City Location			Nearest Station Location			
City Name	Latitude	Longitude	Station ID	Latitude	Longitude	$R_{cd,avg}$ (km)
Forks	47.9504	-124.3855	Z0FORK	47.9456	-124.5662	25.92
Ocean Shores	46.9737	-124.1563	Z0XOCS	46.9778	-124.1544	23.94
Port Angeles	48.1181	-123.4307	Z0XANG	48.1191	-123.4309	57.61
Olympia	47.0379	-122.9007	Z00CPW	46.9717	-123.1376	75.53
Port Townsend	48.1170	-122.7604	Z0XTWN	48.1146	-122.7561	95.73
Vancouver	45.6272	-122.6727	Z0HUBA	45.6287	-122.6526	109.49
Tacoma	47.2529	-122.4443	Z0TBPA	47.2559	-122.3682	105.61
Seattle	47.6062	-122.3321	Z0XWLK	47.6120	-122.3375	114.56
Graham	47.0529	-122.2943	Z00GHW	47.0395	-122.2737	117.40
Everett	47.9790	-122.2021	Z0EVCC	48.0056	-122.2043	128.53

Column Fragility – Lateral Failures





Summary and Conclusions

- Loading protocol formulated for CSZ demands
  - Cyclic content found to impact column deformation capacity
- Concrete damage limited to gap and footing cover concrete
- Strength degradation due to fatigue fracture
  - 20% strength loss (lateral failure) at first fracture
- Lateral failure at 12.5 to 15.0 δ_y (5% to 6.25% drift)
- Axial failure at fatigue fracture of all longitudinal bars
  - 10% drift at axial failure in test columns
- Fatigue life lower for historic reinforcement
- OpenSees + fatigue model to predict column behavior
  - Used for nonlinear time history analysis
- Lateral failure probability higher for short period bridges near coast and for periods of ~0.75-s and higher in sedimentary basin

Questions?

- Acknowledgements:

Washington State Department of Transportation

Pacific NW Transportation Consortium
PACTRANS
Region 10

TriDurLE
National Center for Transportation Infrastructure Durability & Life-Extension

NUCOR®

Metals Fabrication Company