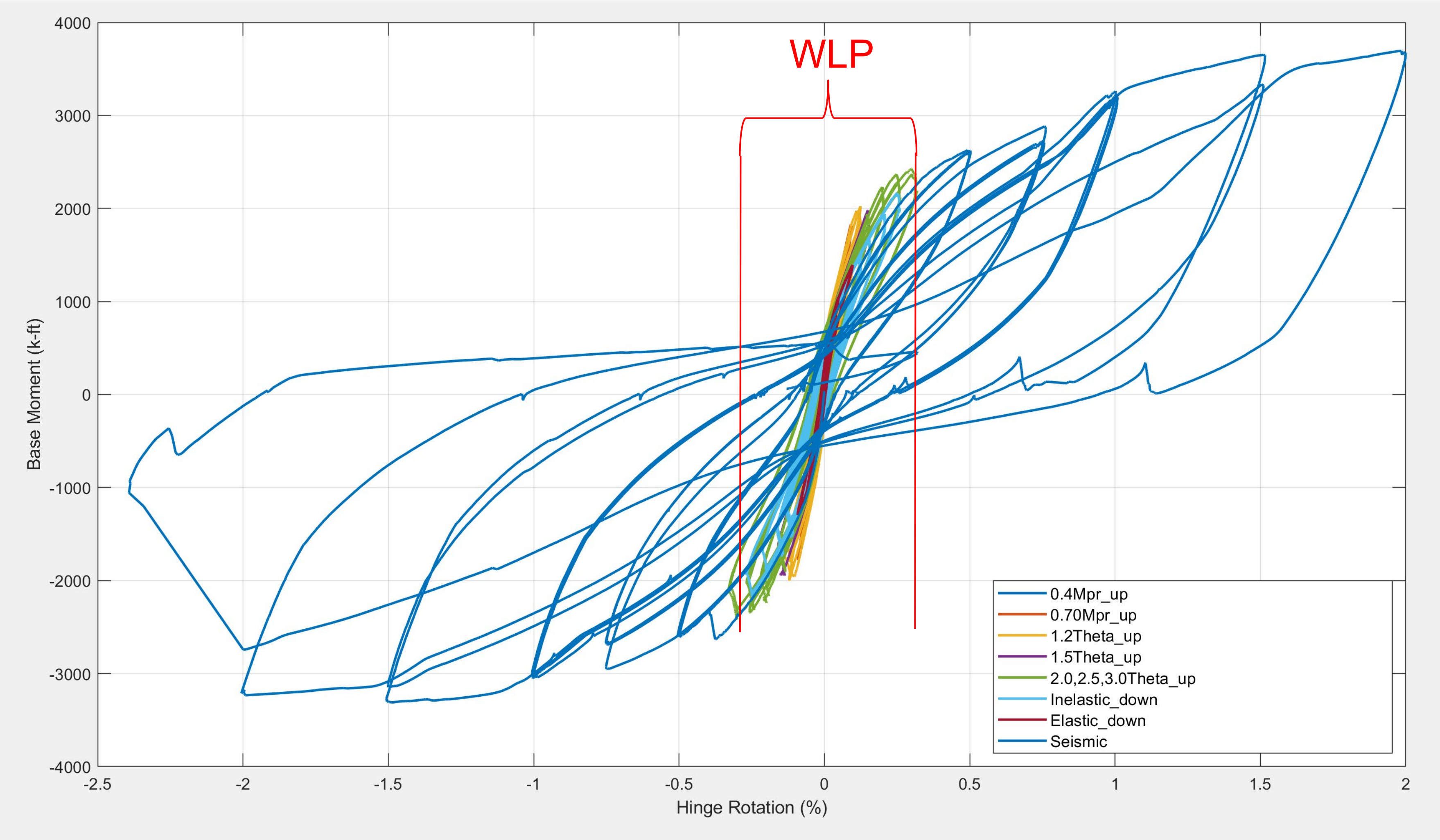
Performance of Ordinary Structural Walls Subjected to Wind and Seismic Loading Protocols

Wall 1 Test Results

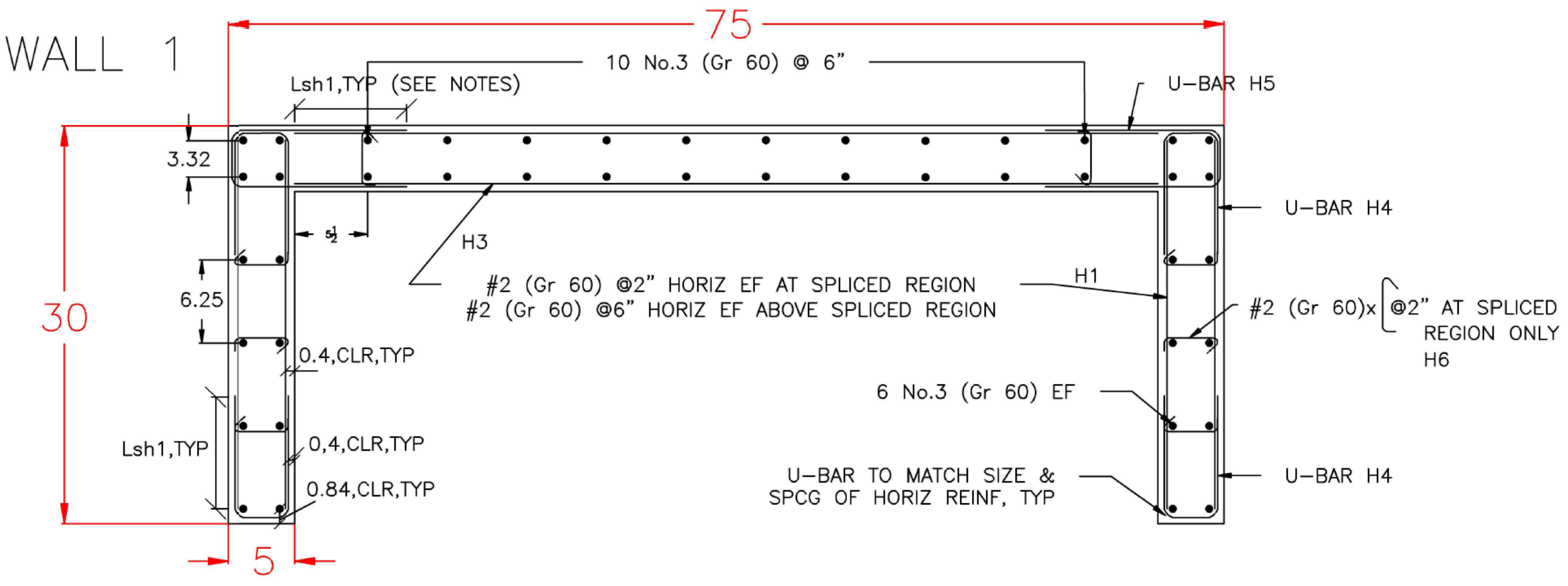
06.27.2023

Base Moment – Hinge Rotation (WLP+SLP)



Design Properties

- Geometry
  - C-shaped wall (~ 1/4 to 1/3-scale)
  - Wall panel (88” ≈ 2 story)
  - 5” thick flanges and web
  - 75” long web with 30” long flanges ($l_w/t_w = 15$)
- Material properties
  - $f'_c \approx 8$ ksi (Local aggregate)
  - Grade 60 steel
- Longitudinal reinforcement
  - $\rho_l = 0.75\%$
  - #3 bars
  - Uniform distribution
  - Ordinary Detailing
  - Lap-splices at the base
- Shear stress
  - $v_{in\text{-}plane} = 2.6\sqrt{f'c}$
- Axial load
  - P=0.1Agf’c



Design Properties

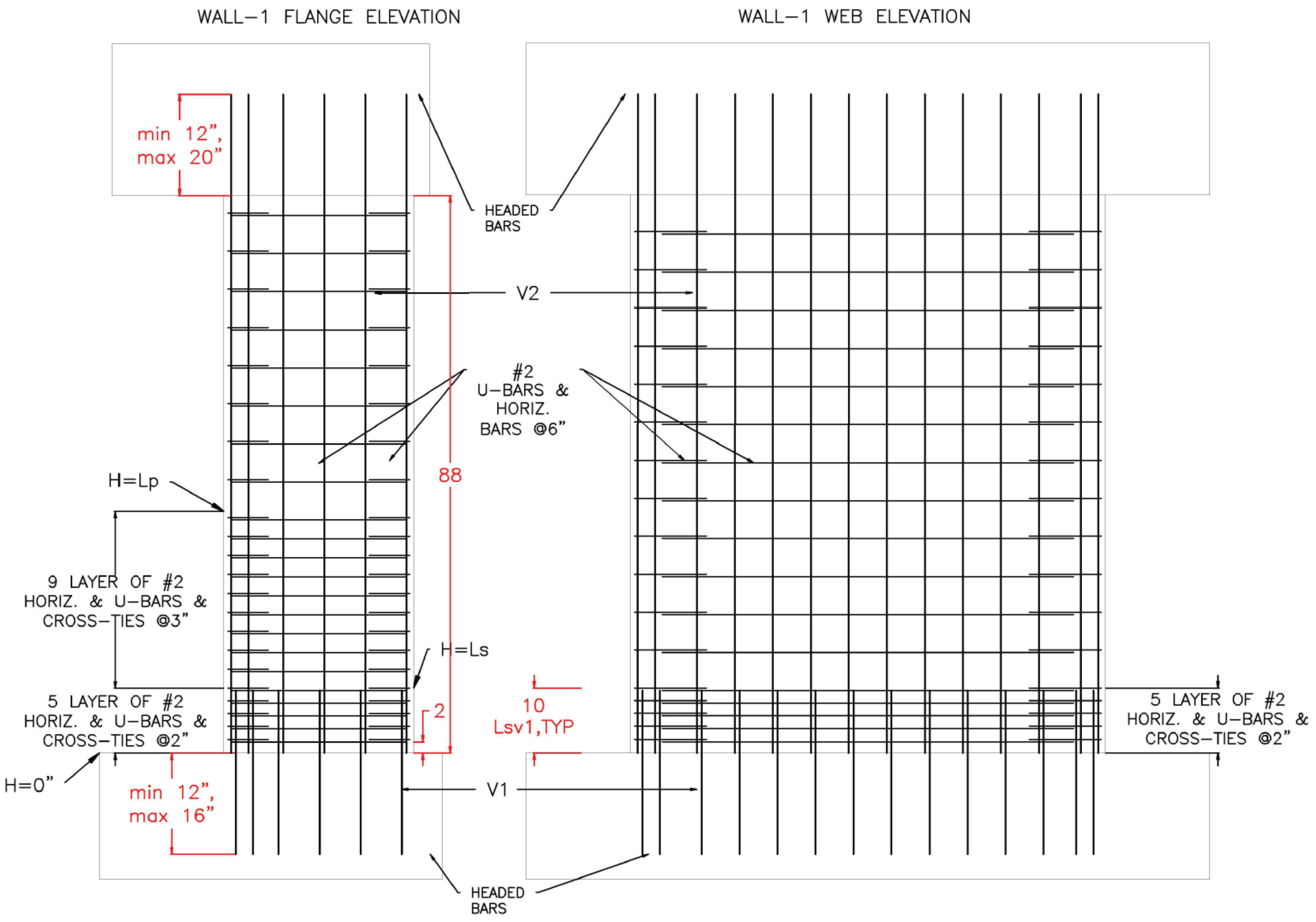
Flanges

Spliced Regions (s=2”)
- Cross-ties
- U-bars
- Transverse reinf.

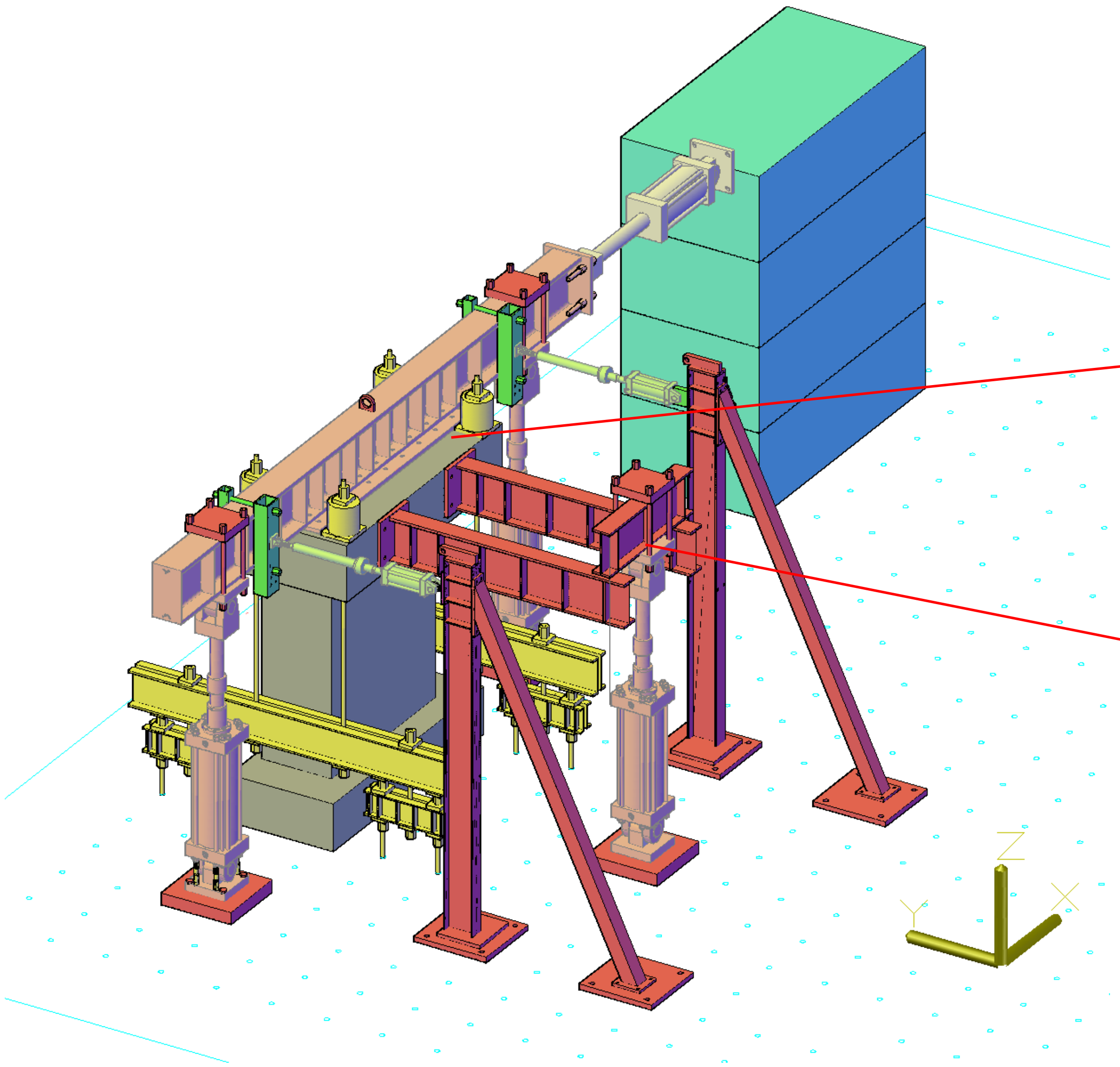
Above Spliced Regions (s=3”)
- Cross-ties
- U-bars
- Transverse reinf.

Above Plastic Hinge Region (s=6”)
- U-bars
- Transverse reinf.

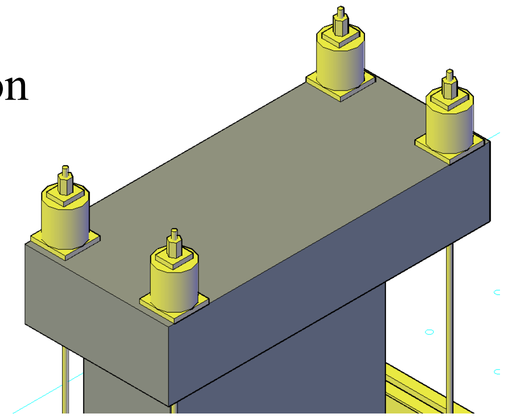
- #3 (Gr.60) longitudinal bars
- #2 (Gr.60) transverse bars



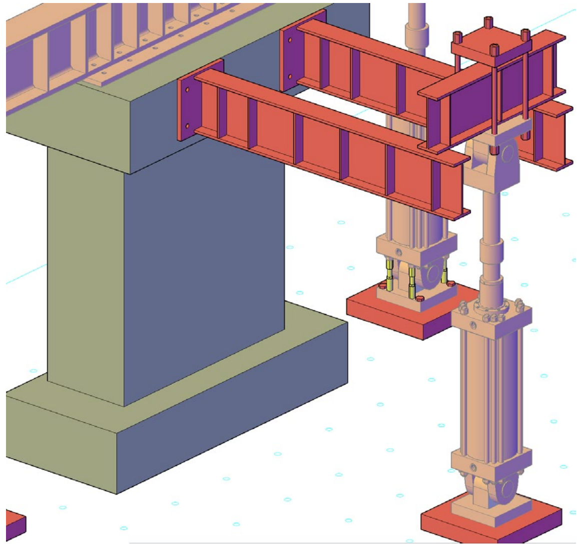
Test Setup



Axial Load Application
(0.1Agf'c)

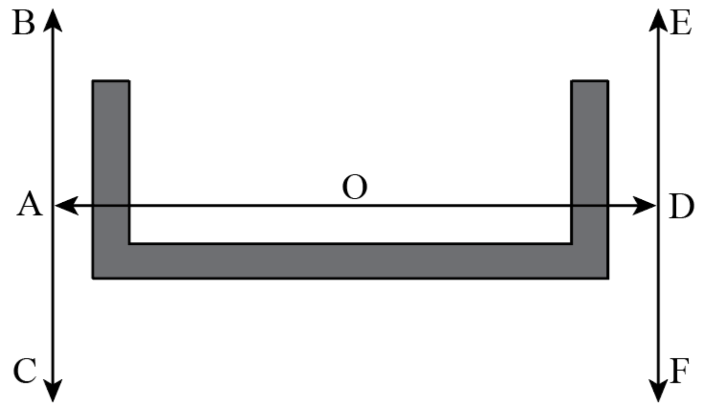


Out-of-plane Load Application

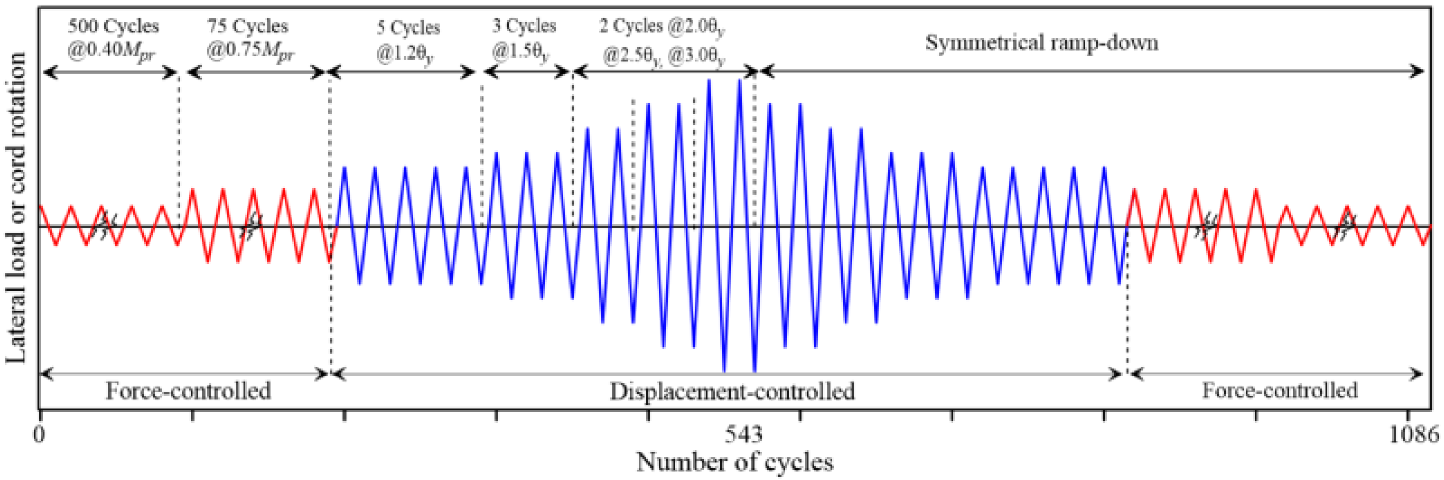


Wind Loading Protocol

- Biaxial Loading
  - Max ductility demand of 3.0ϴy
  - 26 inelastic cycles
  - Apply full protocol in IP and, OOP during nonlinear cycles
  - H-shaped
  - $M_{pr,IP} + 0.5M_{pr,OOP}$

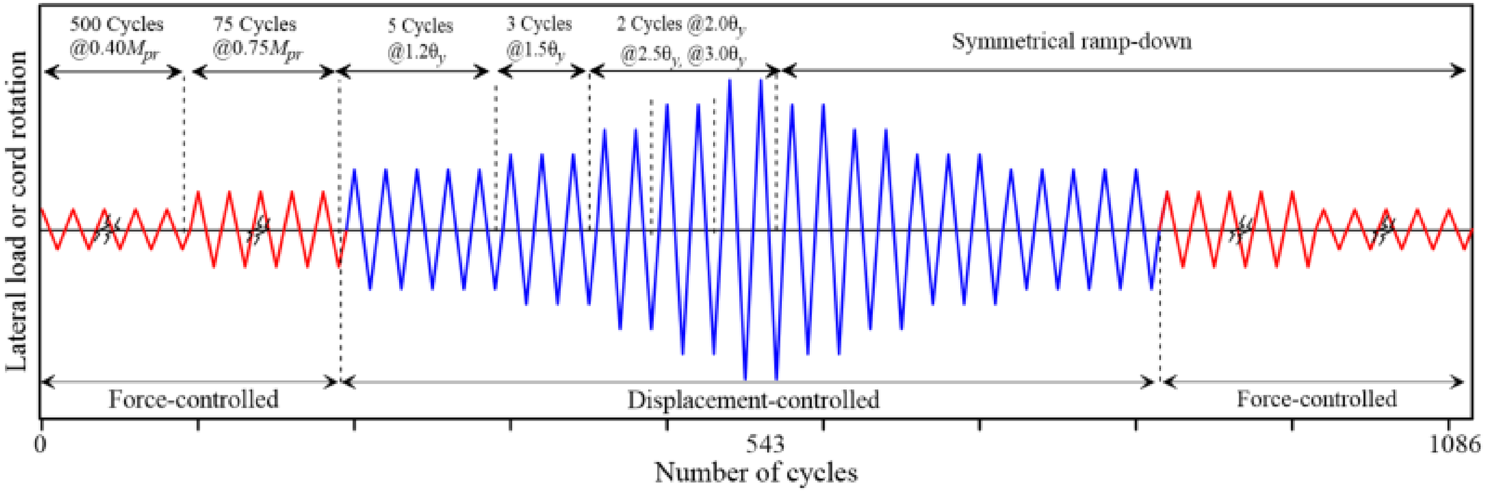


O-A-B-C-A-D-E-F-D-O

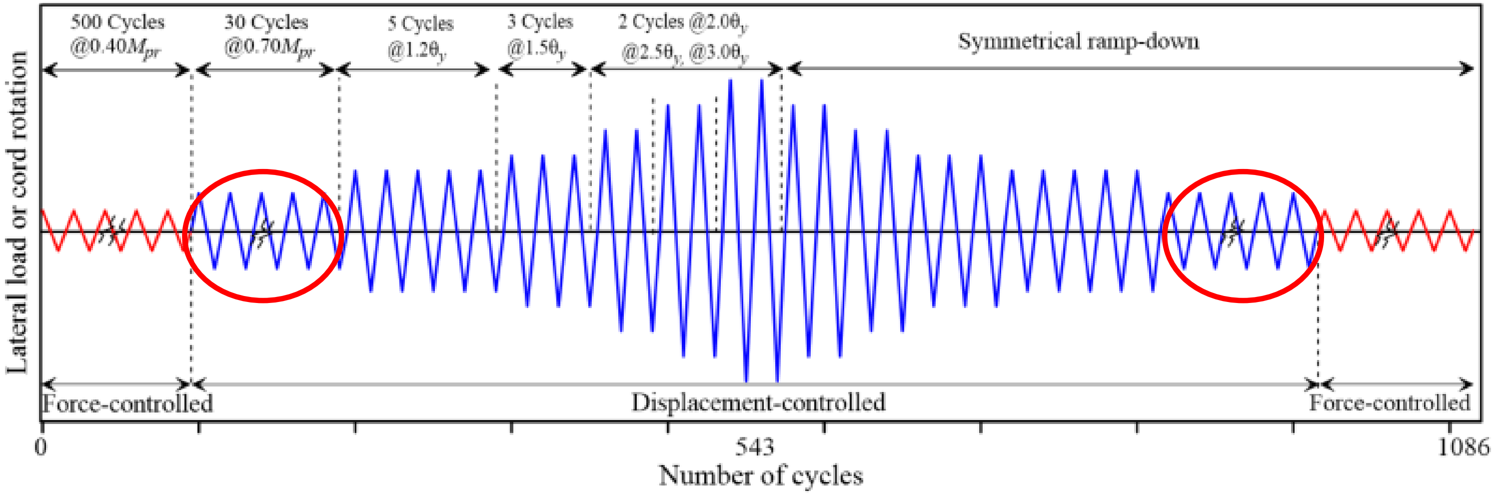


Original wind loading protocol for the Wall-Wind Project

Wind Loading Protocol – Changes during testing

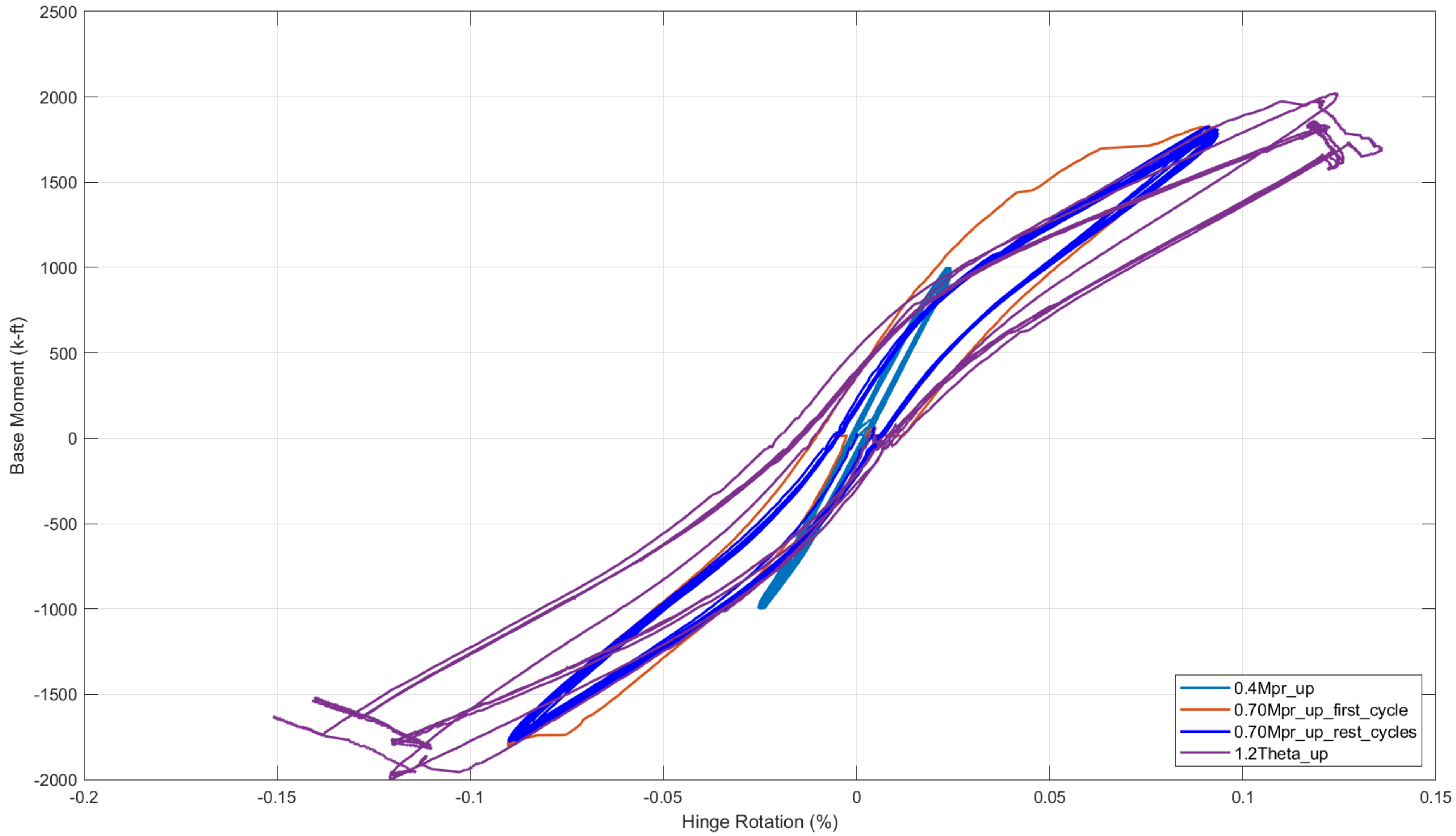


Original wind loading protocol for the Wall-Wind Project



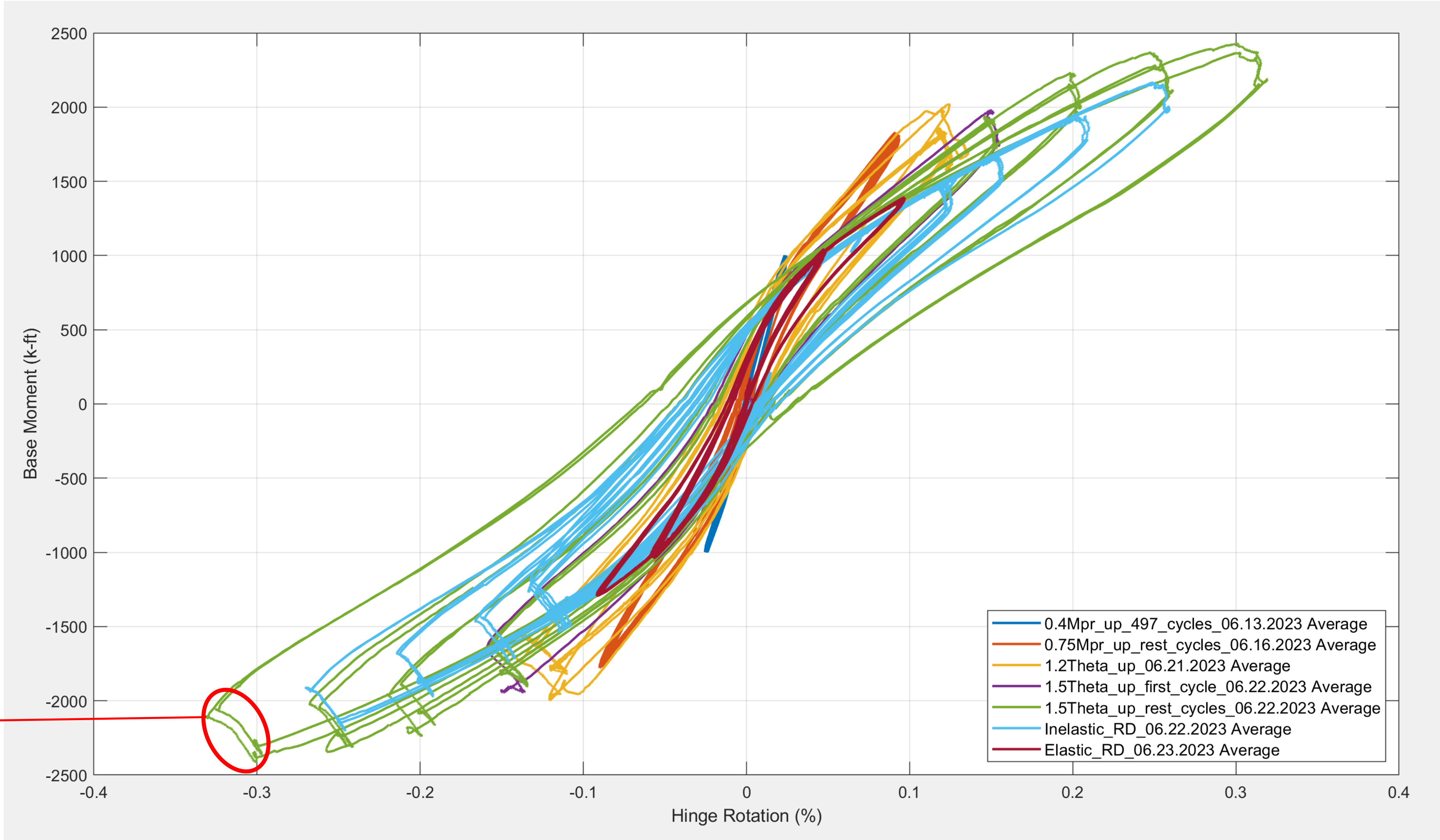
- Due to inelasticity observed at around 0.6M_{pr} (see next slide);
  - Wall was loaded up to 0.7M_{pr} instead of 0.75M_{pr}
    - $\Theta_{@0.7Mpr}$ = 0.09% ($\Theta_{y,estimated}$)
    - $\Theta_{y,test}$= 0.1%
  - Loading was done as displacement controlled
  - The number of cycles were decreased to 30 from 75

Wind Loading Protocol – Changes during testing



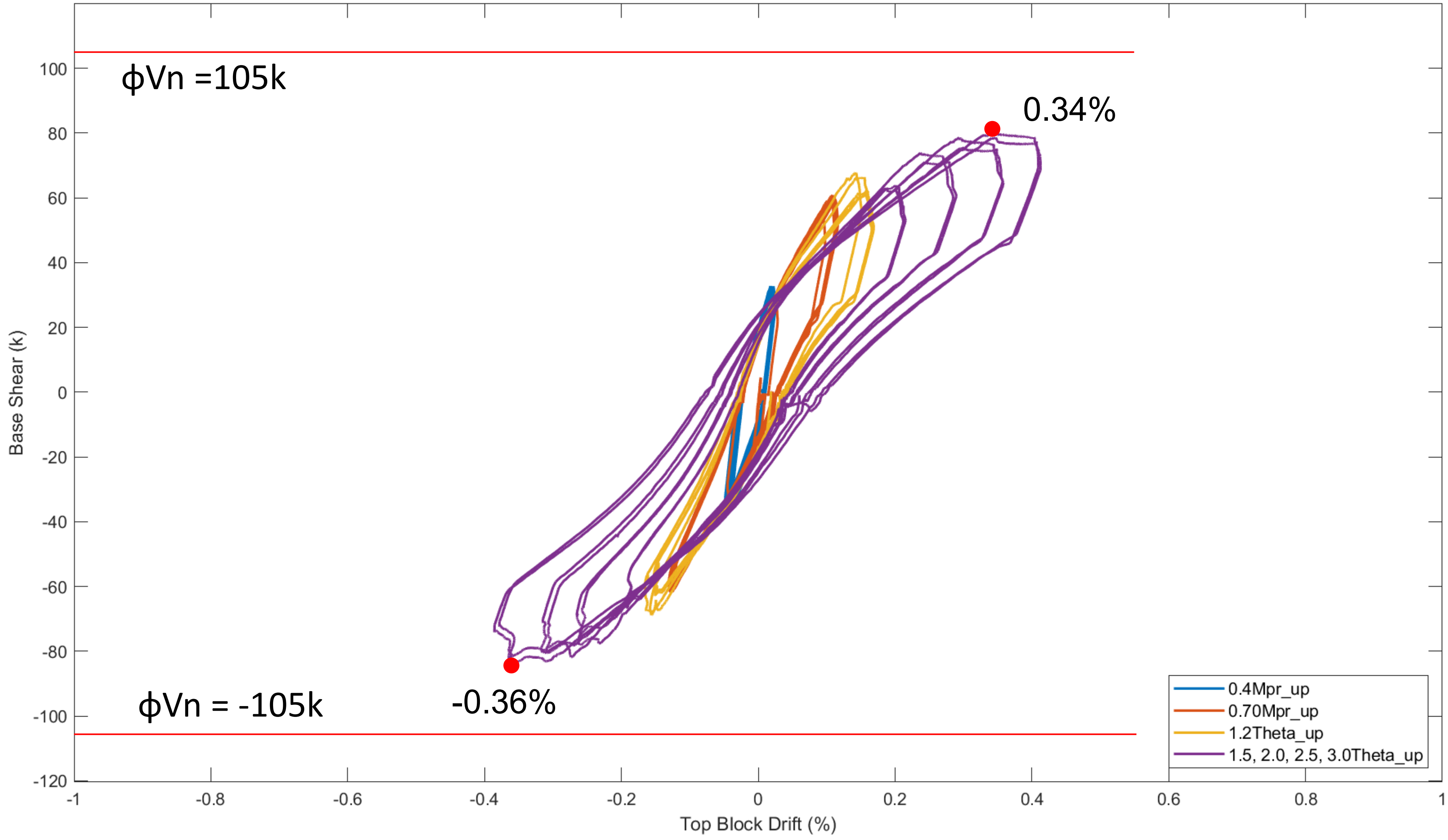
Wind Loading Protocol Results (M-Rot)

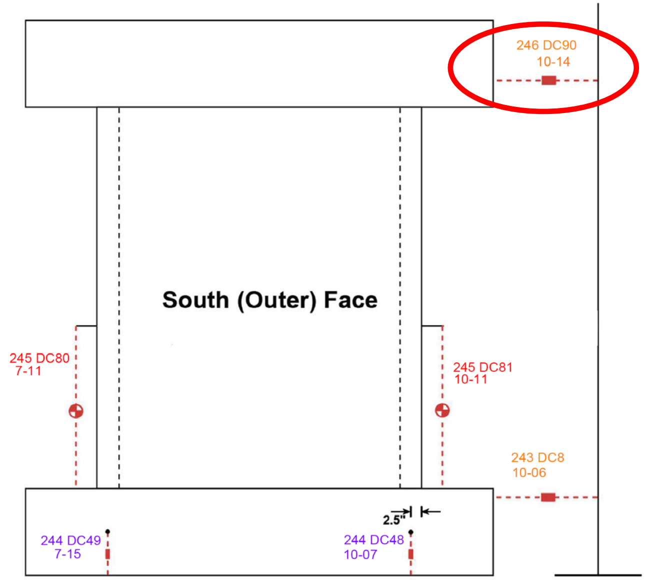
- No damage was observed during the WLP.



OOP Load application

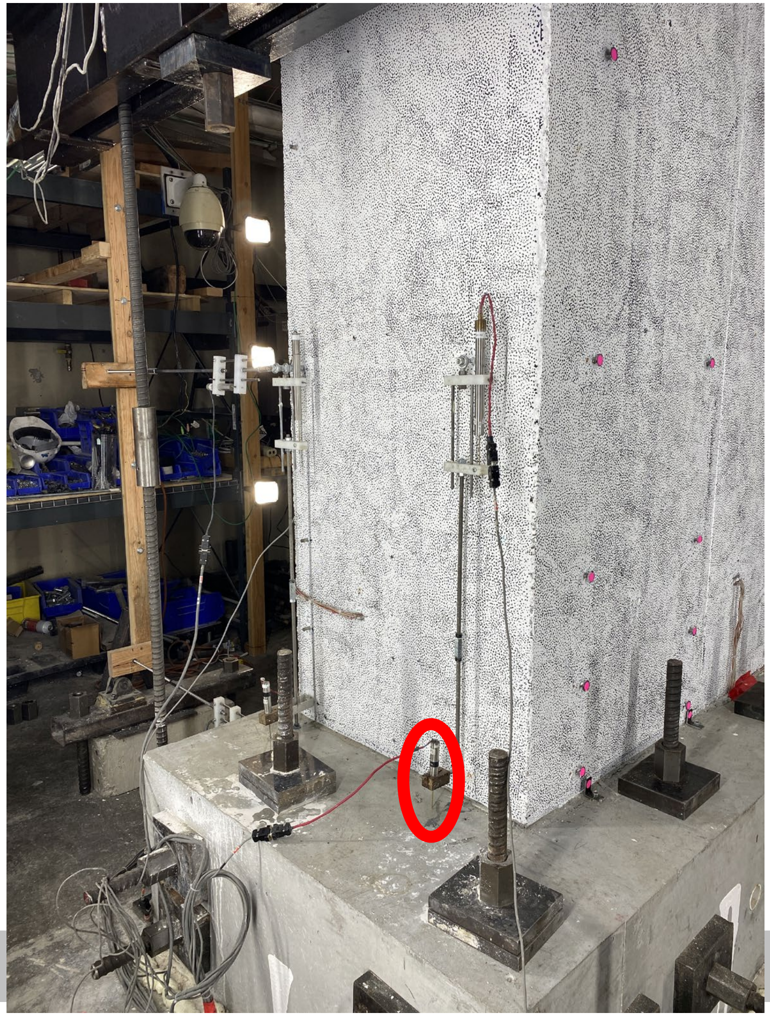
Wind Loading Protocol Results (Base shear-Top Drift)

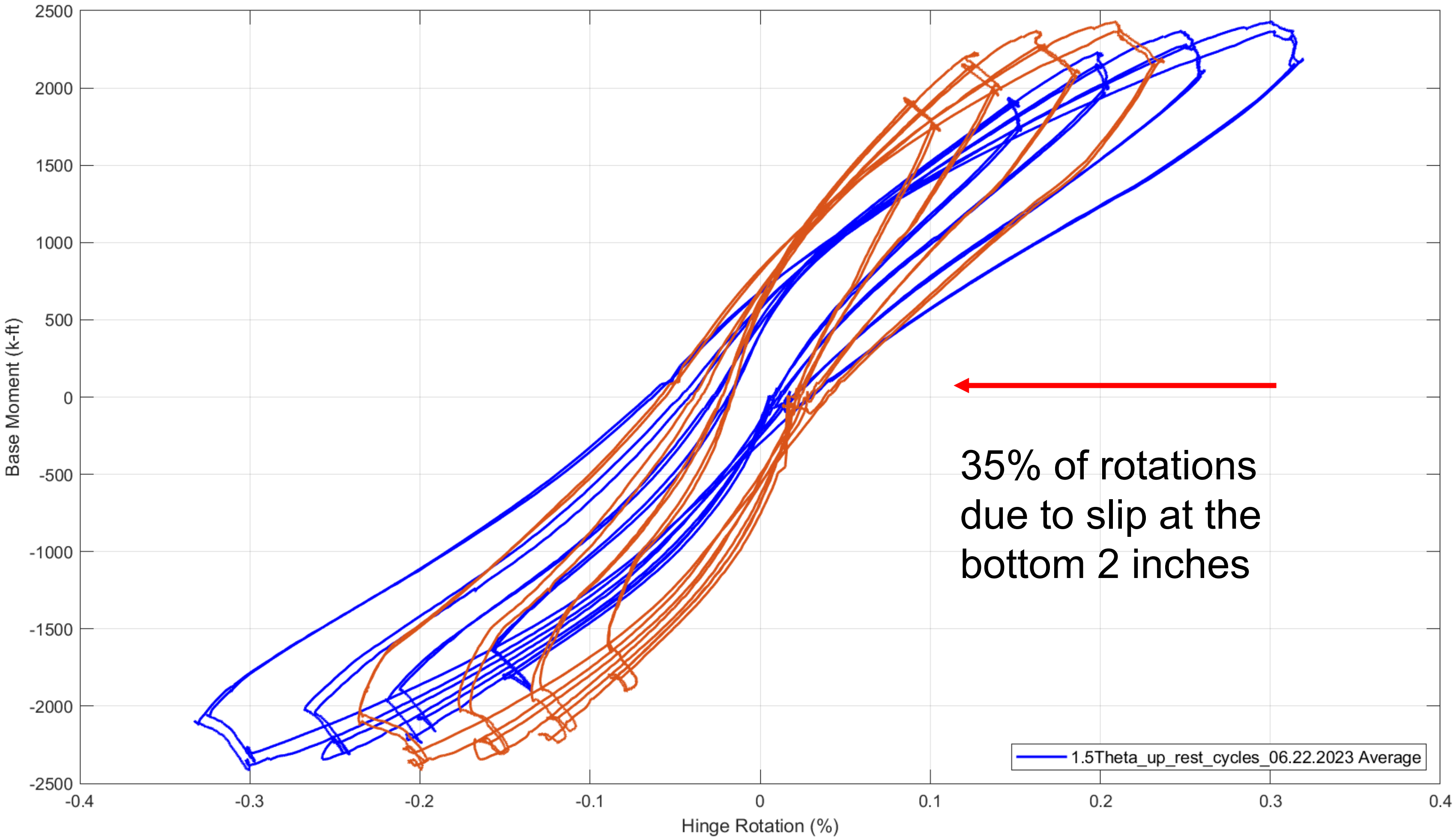




Wind Loading Protocol Results

- Red Curve (total hinge rotation)
- Blue Curve (hinge rotation without slip)



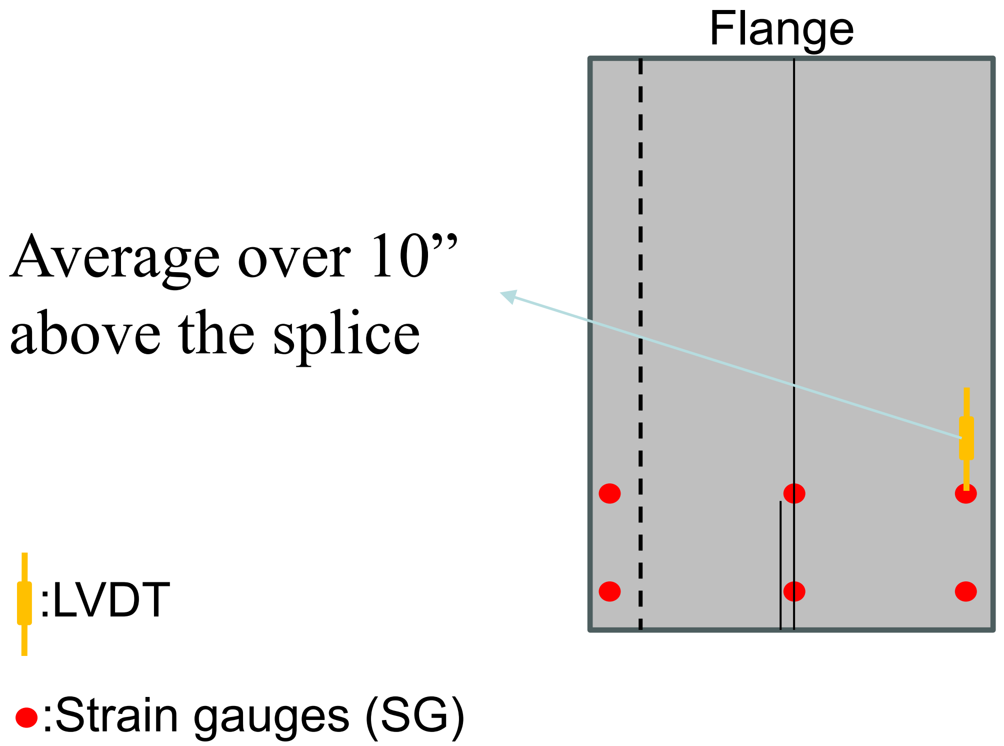


Wind Loading Protocol Results – Rebar Strains

East Flange (above splice)	SG Flange Edge	SG Flange Center	SG Corner	LVDT Flange Edge
1.2ϴy	0.65%	0.8%	0.53%	0.4%
1.5ϴy	0.9%	0.75%	0.5%	0.4%
2.0ϴy	1.2%	0.86-1.1%	0.6-0.73%	0.45%
2.5ϴy	2.0%	1.7%	1%	0.55%
3.0ϴy	2.0%	1.9-1.7%	1.3%	0.65%

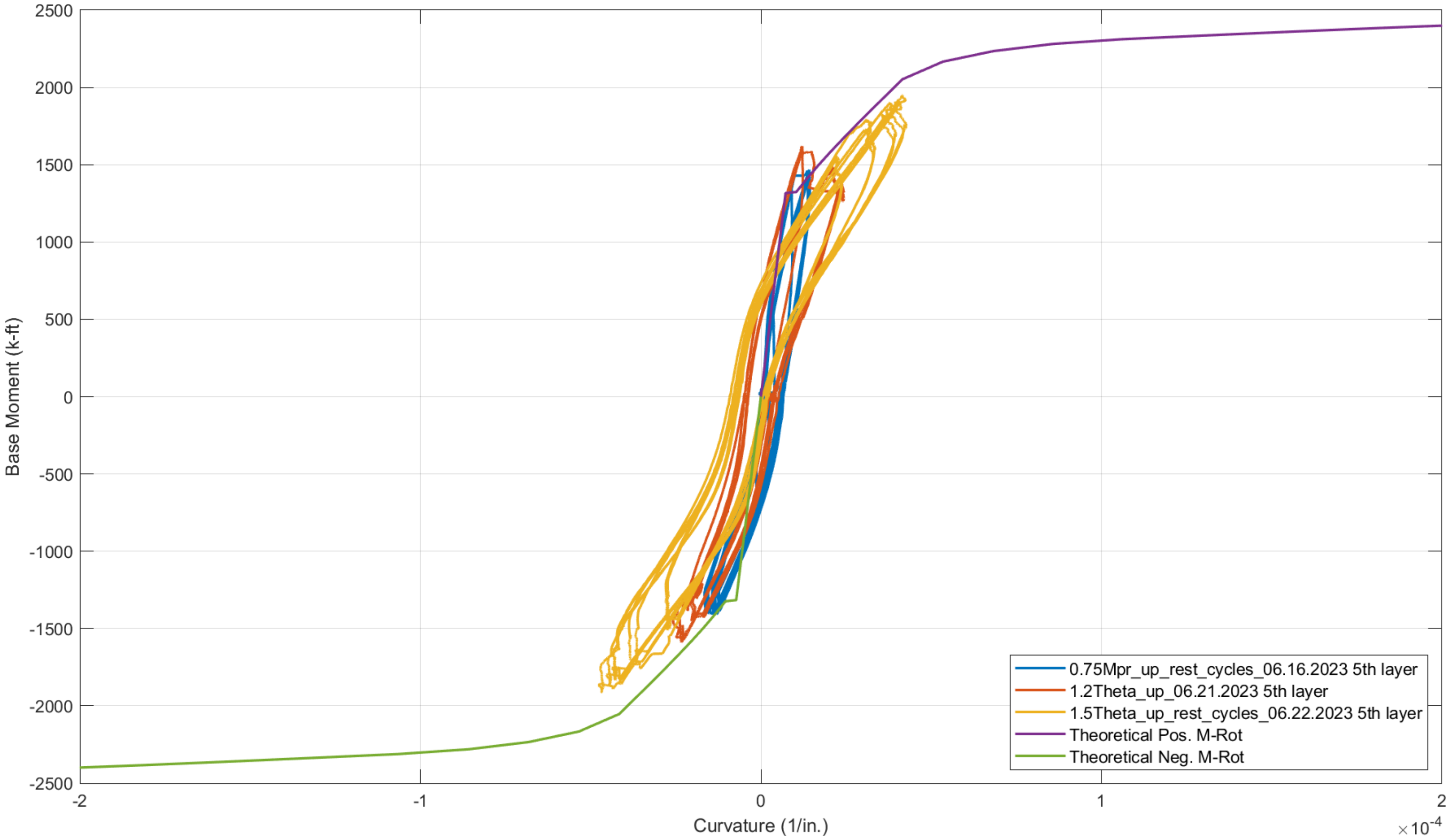
West Flange (above splice)	SG Flange Edge	SG Flange Center	SG Corner	LVDT Flange Edge
1.2ϴy	0.91%	-	0.77%	0.18%
1.5ϴy	0.87%	-	0.77%	0.16%
2.0ϴy	1.0%	-	0.83%	0.20%
2.5ϴy	2.2%	-	0.94%	0.43%
3.0ϴy	2.6%	-	1.6%	0.62%

At max in-plane rotations (before OOP rotations applied)



Wind Loading Protocol Results M-Cur

Curvature is calculated using the LVDTSs at the flanges only



- Average curvature at spliced region

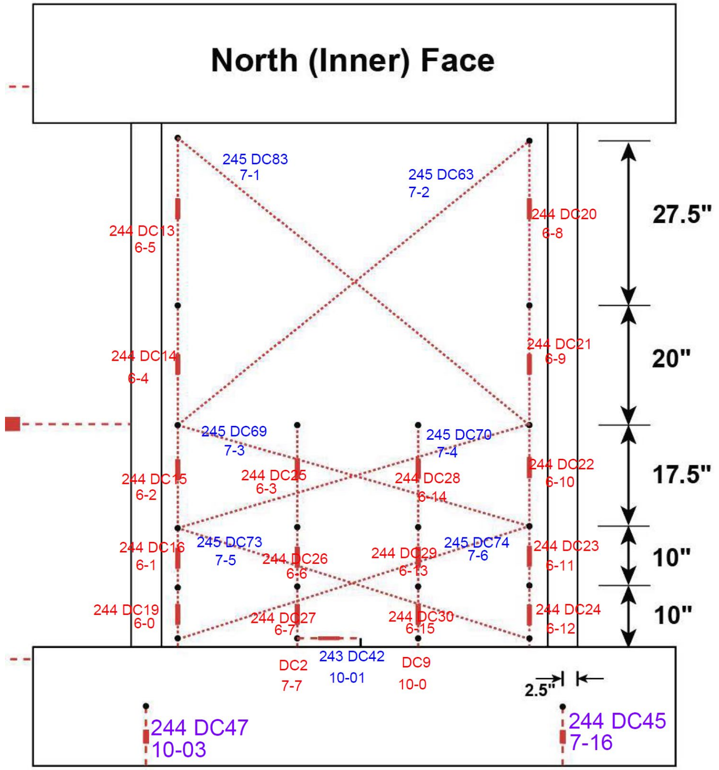
$\Phi_{3\Theta y}= 1.1*10^{-4}$ 1/in.

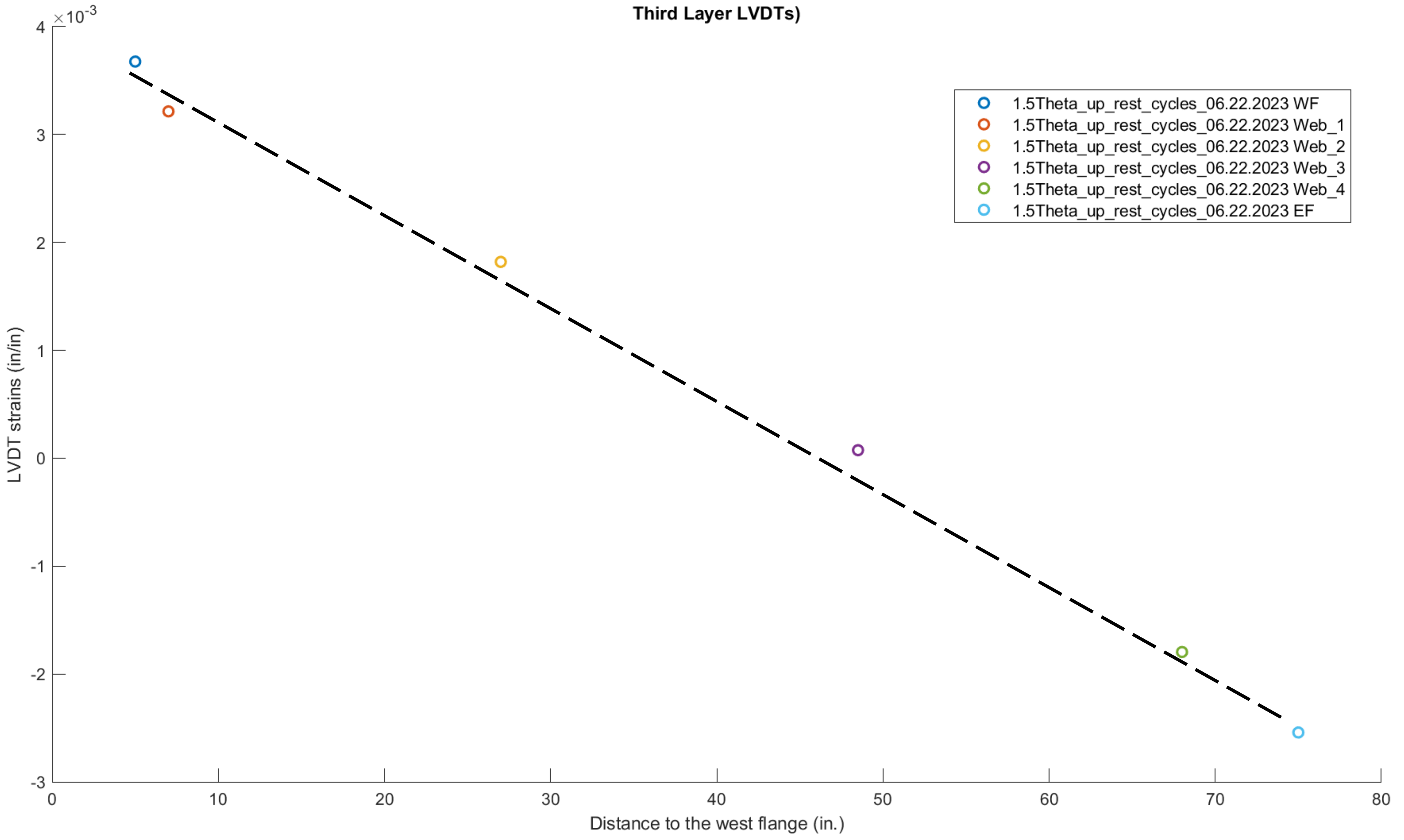
- Average curvature 10” above the spliced region

$\Phi_{3\Theta y}= 0.85*10^{-4}$ 1/in.

Wind Loading Protocol Results M-Cur

- Curvature values are also calculated using all the LDVTs (flanges + web)





Wind Loading Protocol Results Effective Stiffness

P/Agf'c = 10%

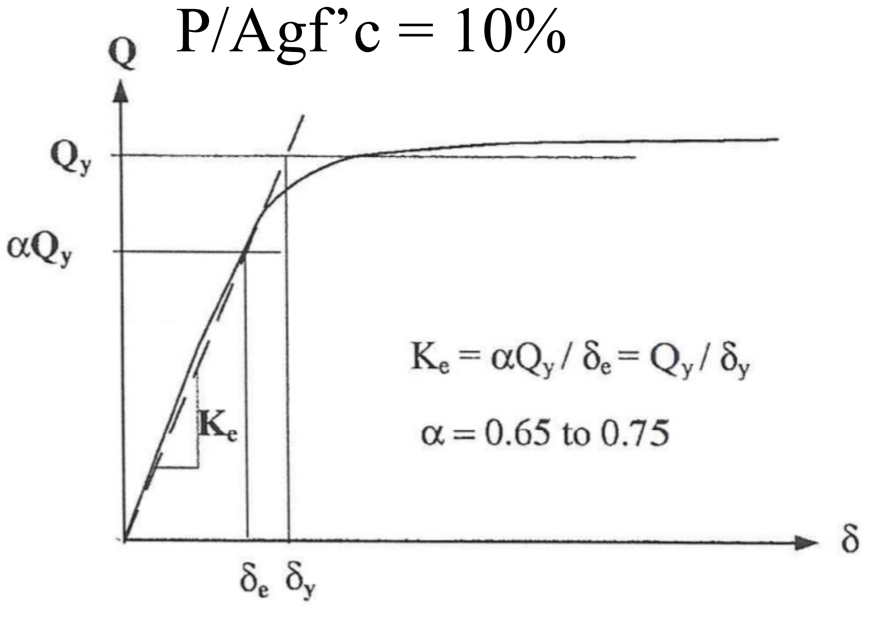


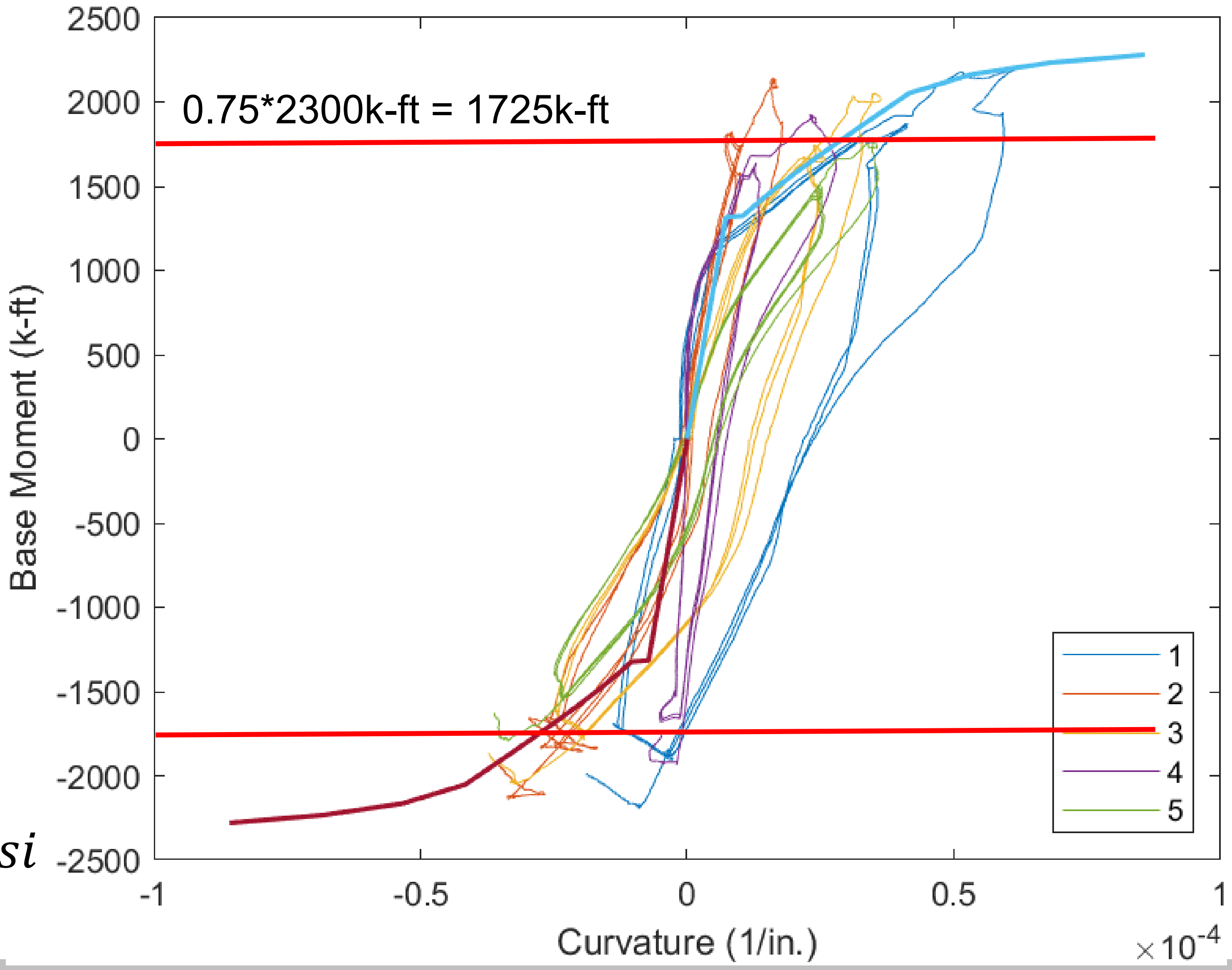
Fig. 4.7.1—Determination of yield values Q_y and δ_y.

Ranging from 0.25EcIg to 0.45EcIg

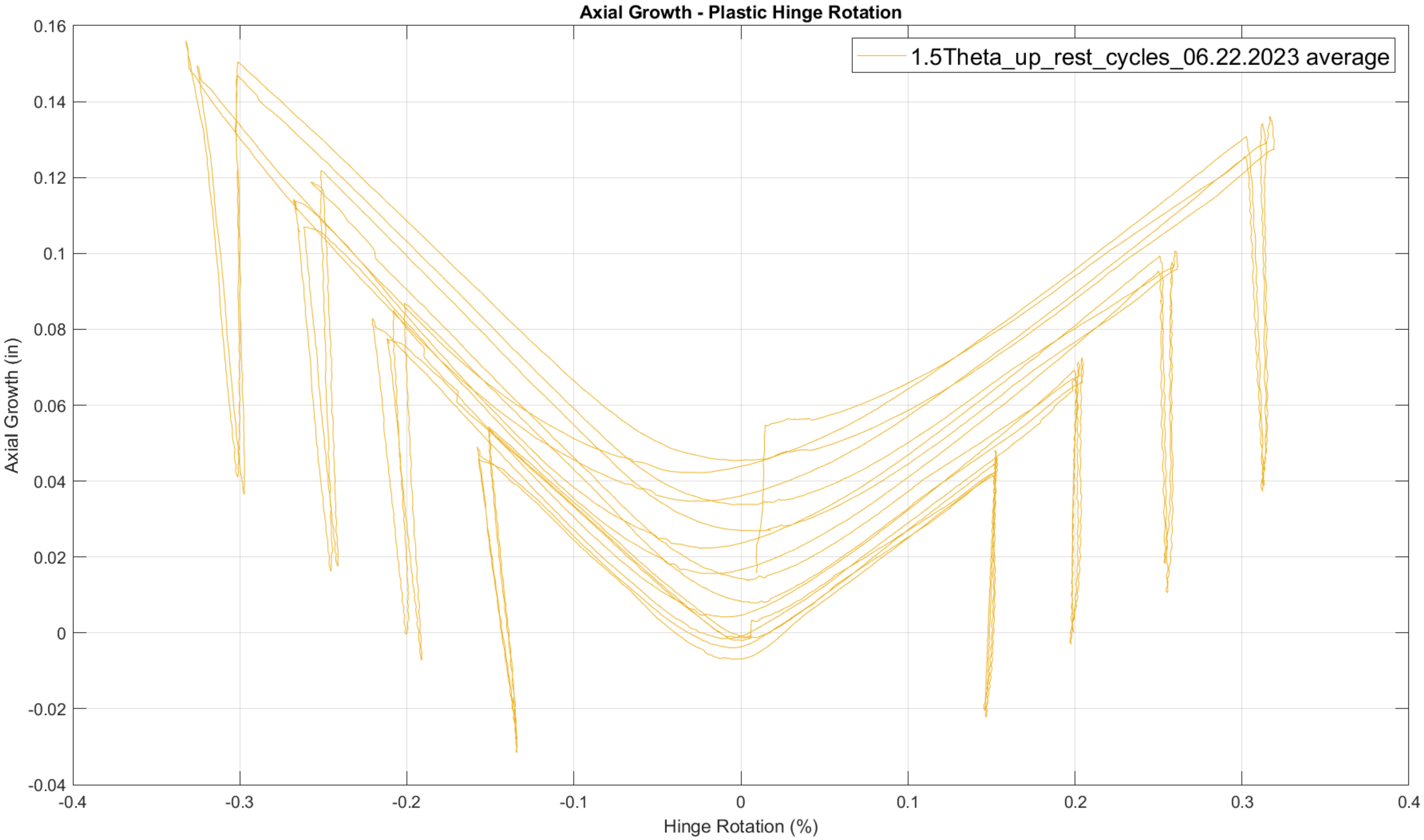
On average 0.34EcIg (loading in both dir.)

$$Ec = 40000\sqrt{fc'psi} + 10^6 = 4577ksi$$

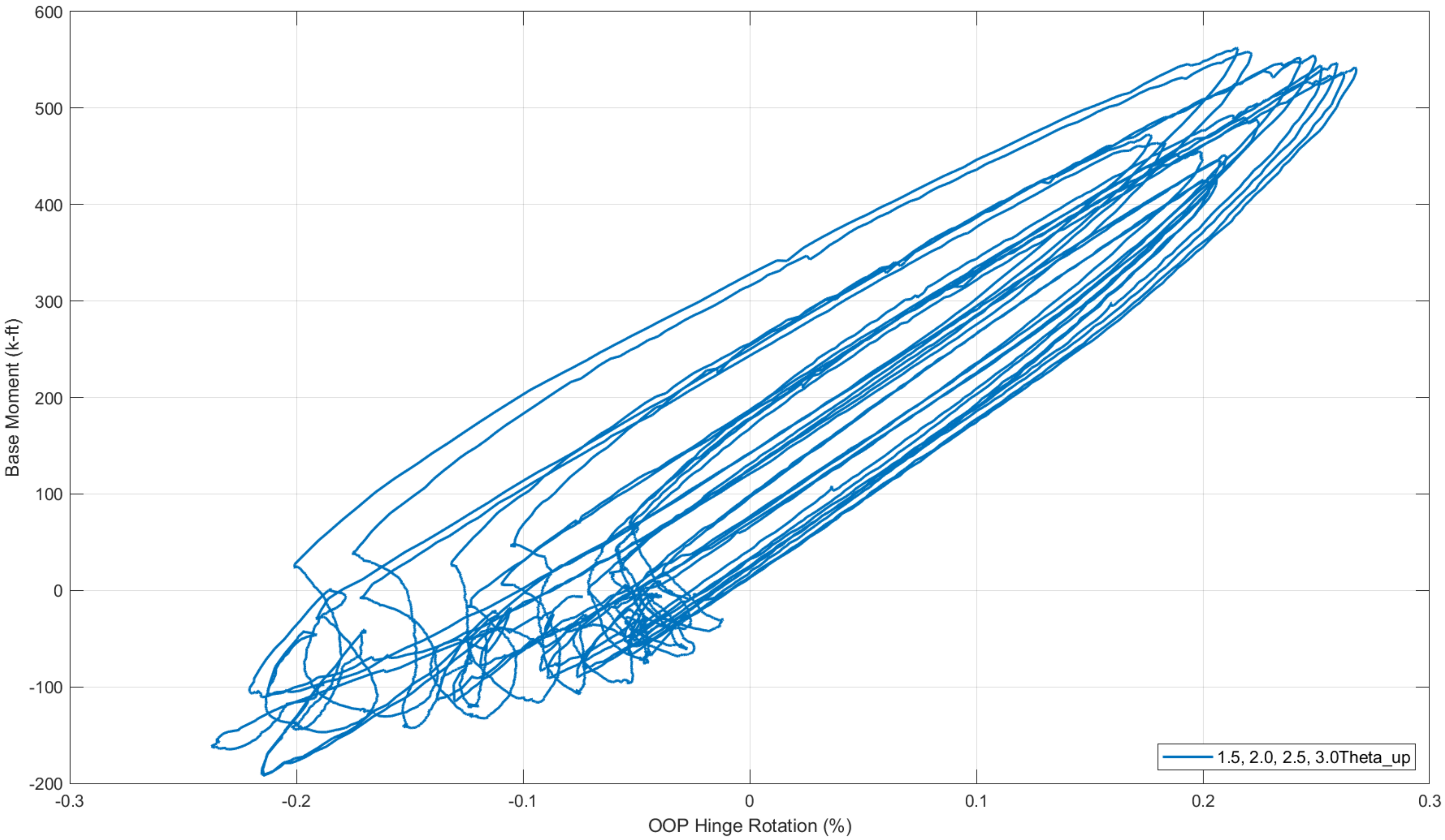
$$Ec, test = 3610ksi$$



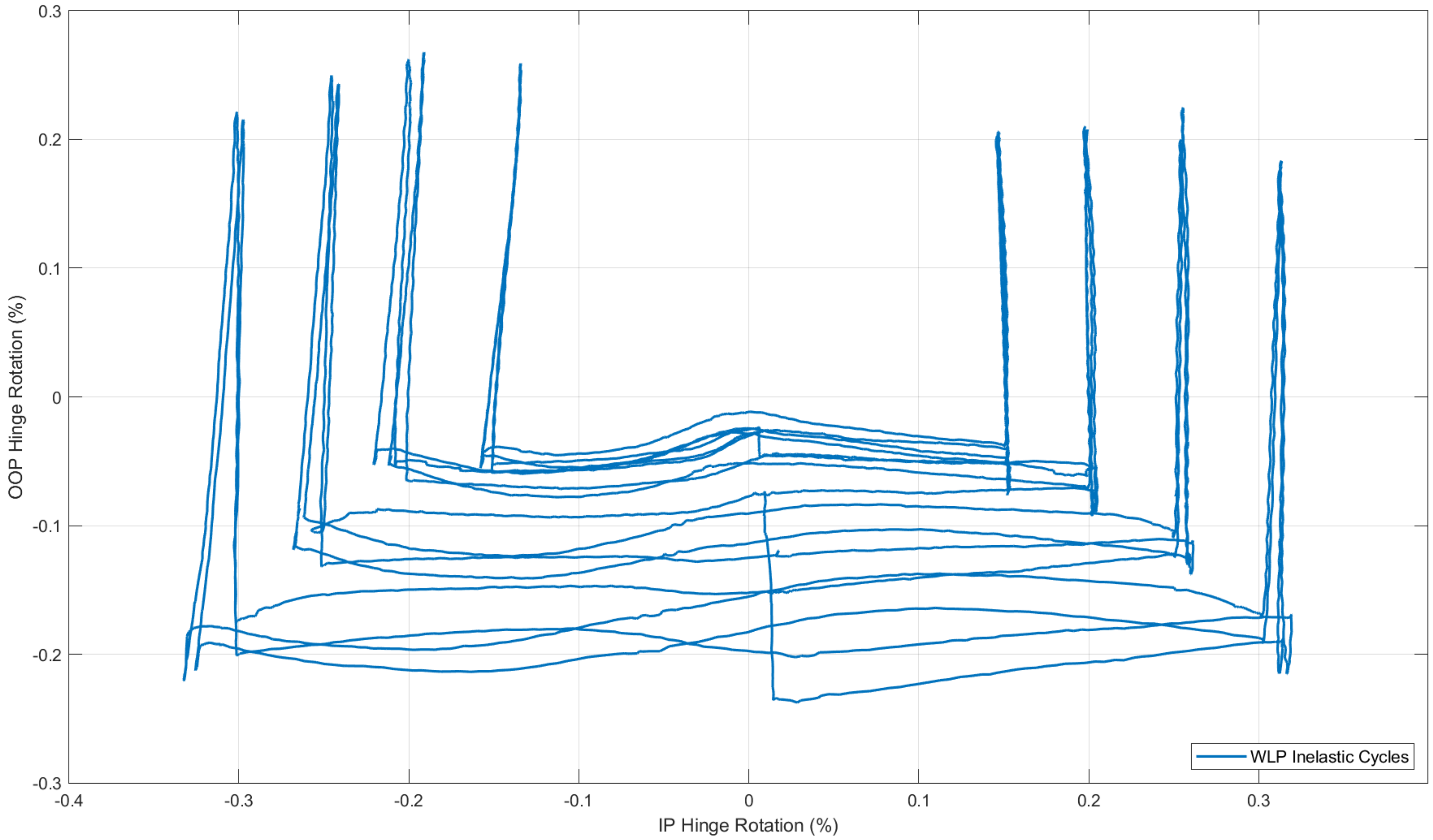
Axial Growth During Inelastic cycles

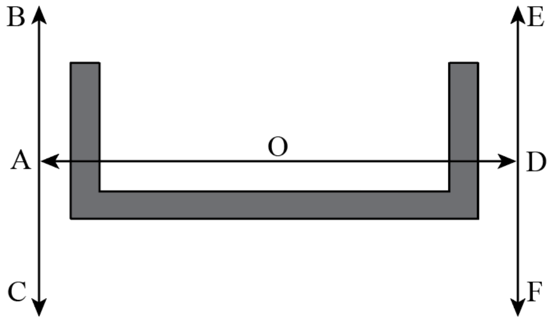


Wind Loading Protocol – OOP Bending



Wind Loading Protocol – Biaxial Loading

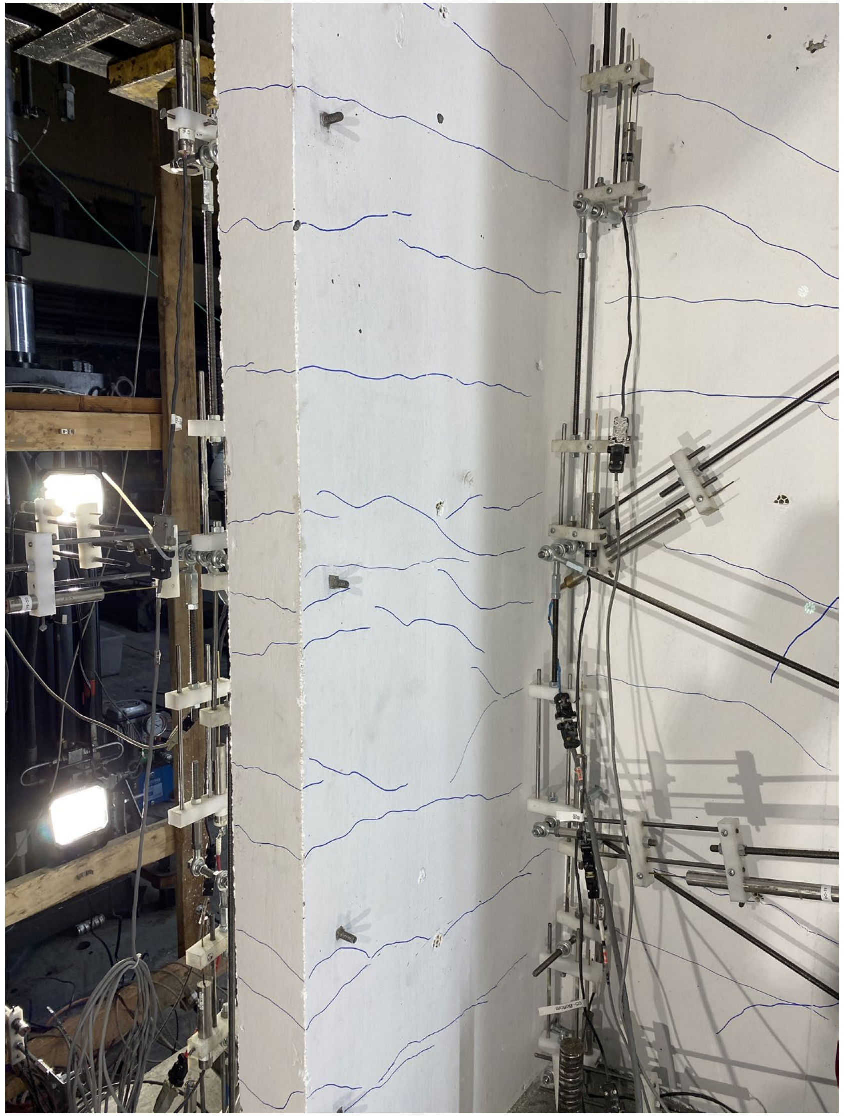


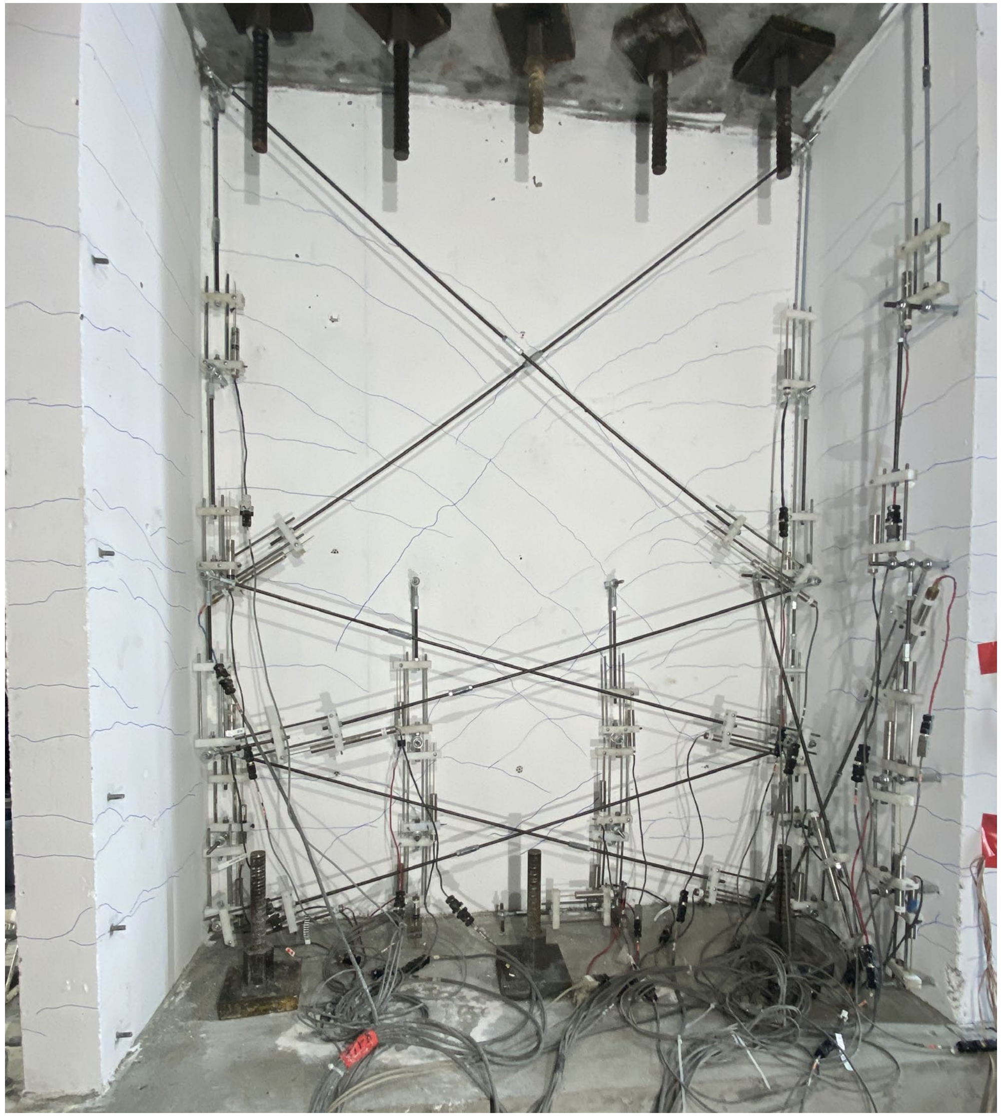


O-A-B-C-A-D-E-F-D-O

Wind Loading Protocol Results

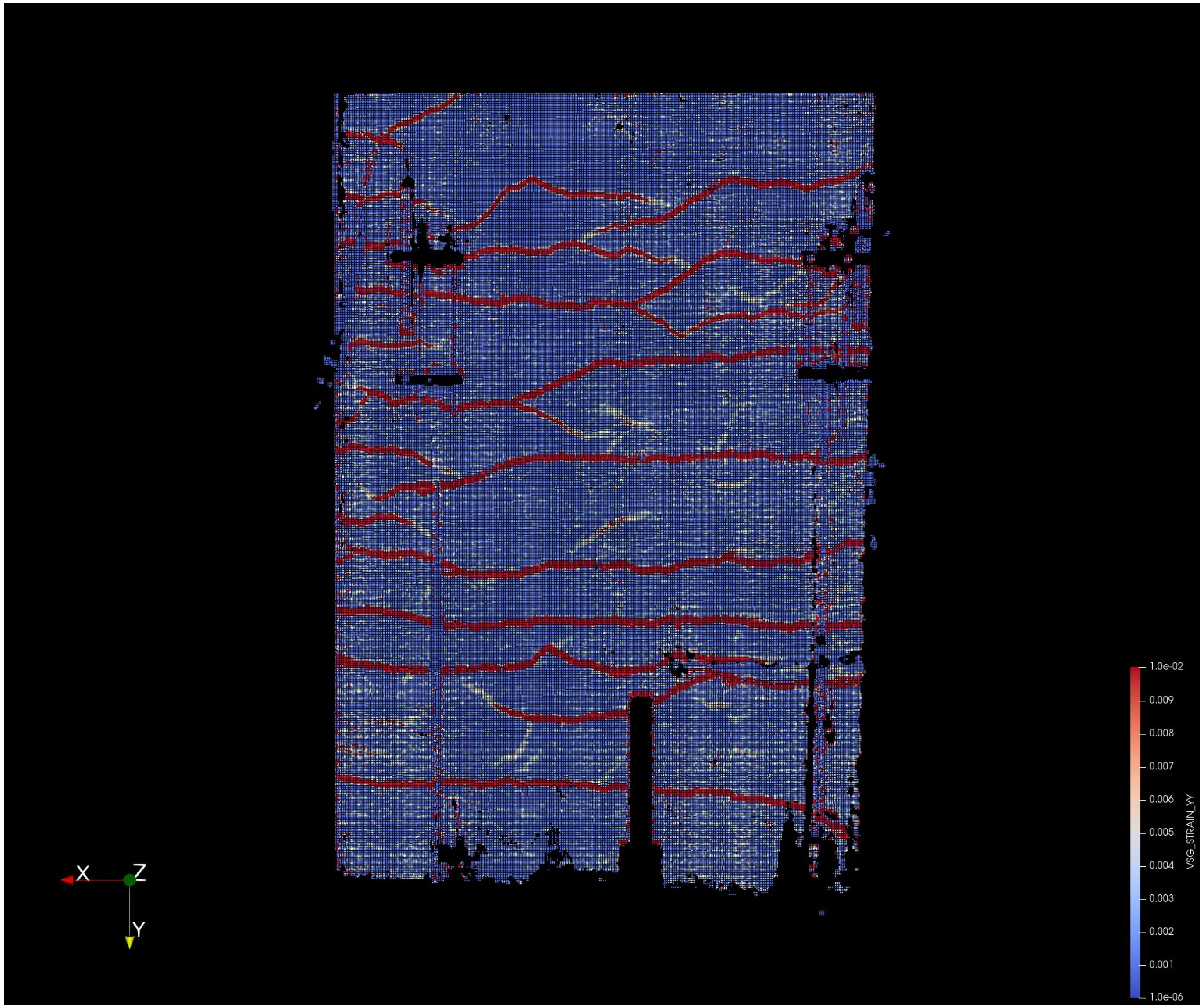
Cracking pattern after WLP





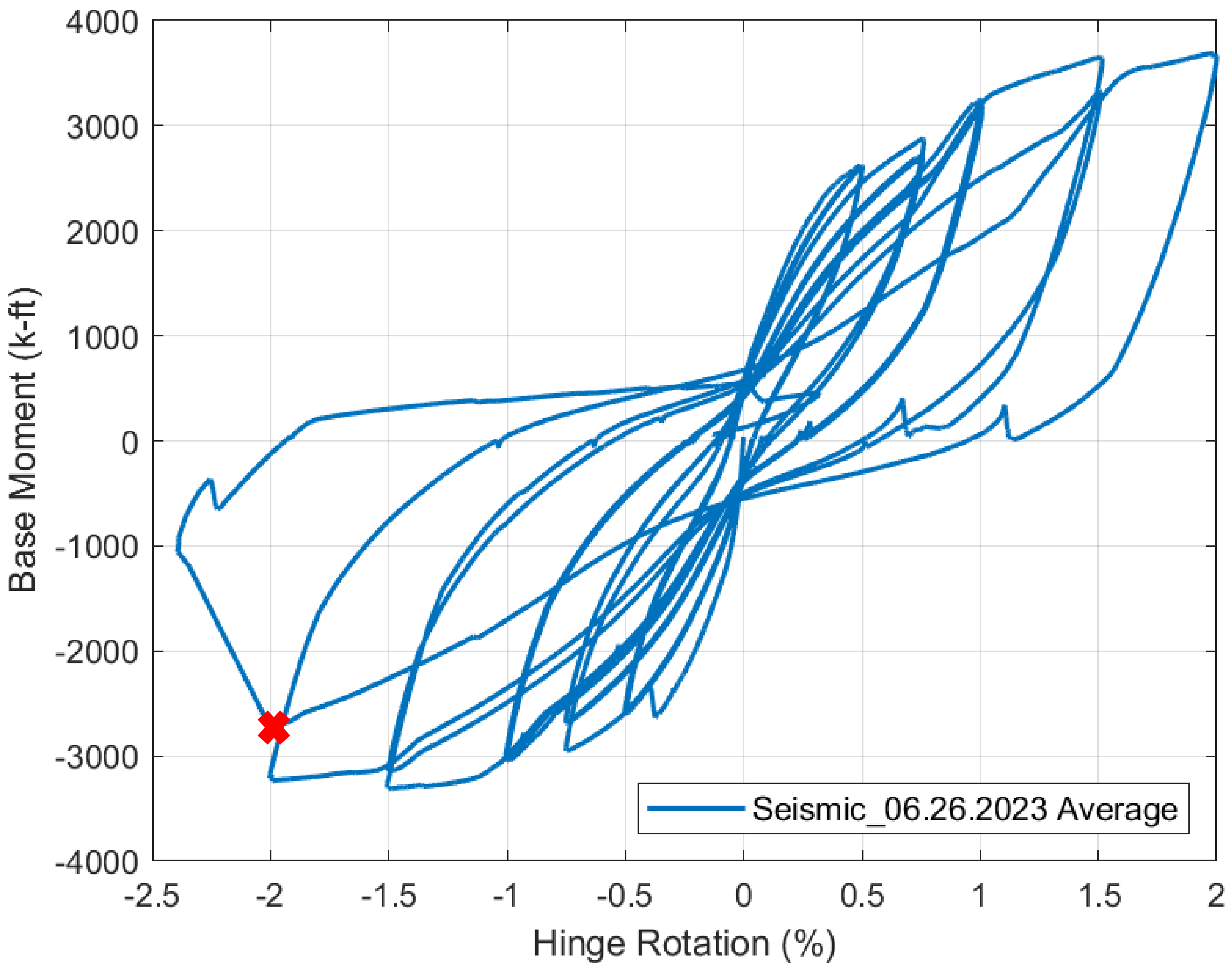
Wind Loading Protocol Results

Cracking pattern after WLP using the DIC images

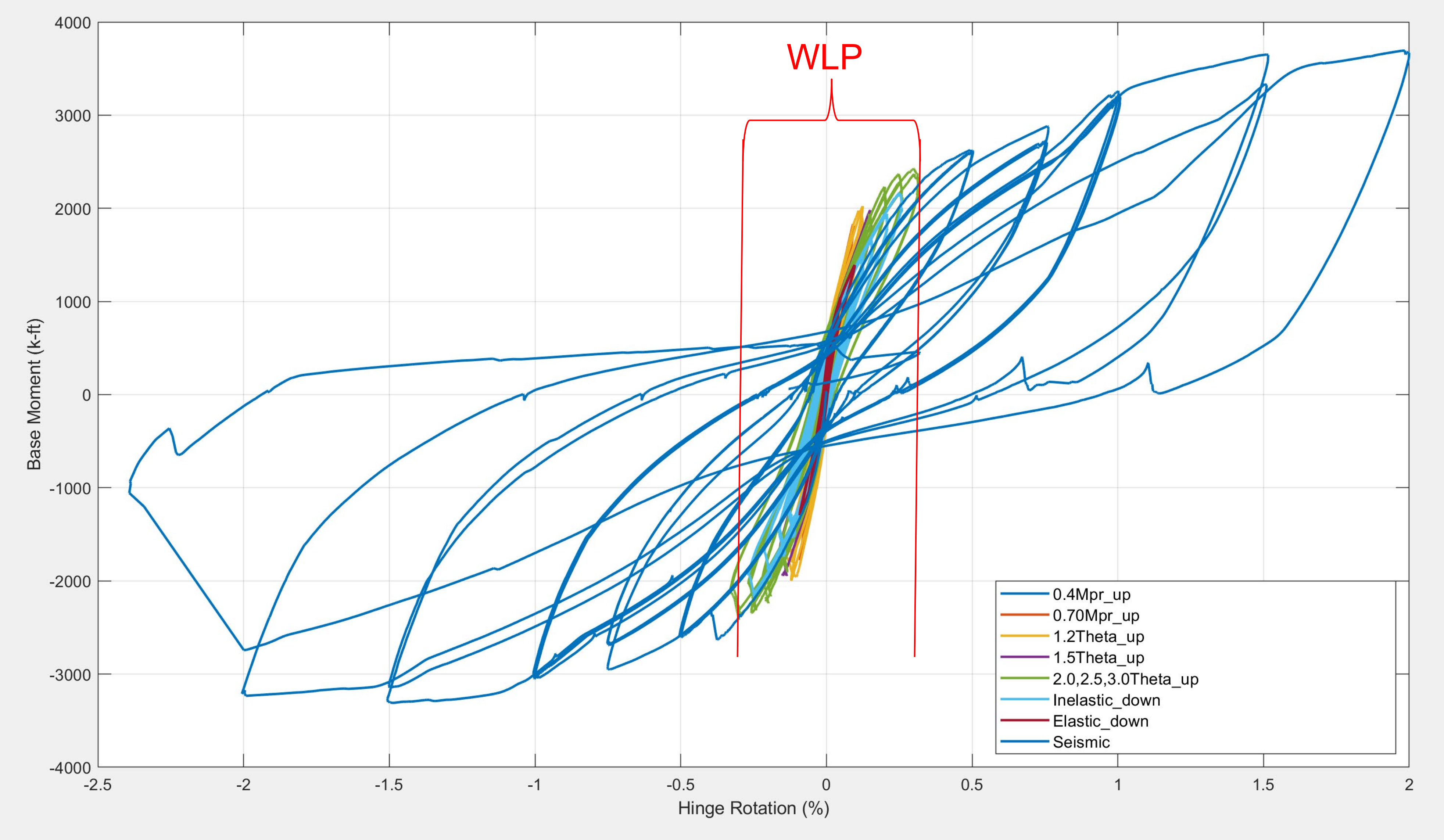


Seismic Loading Protocol Results

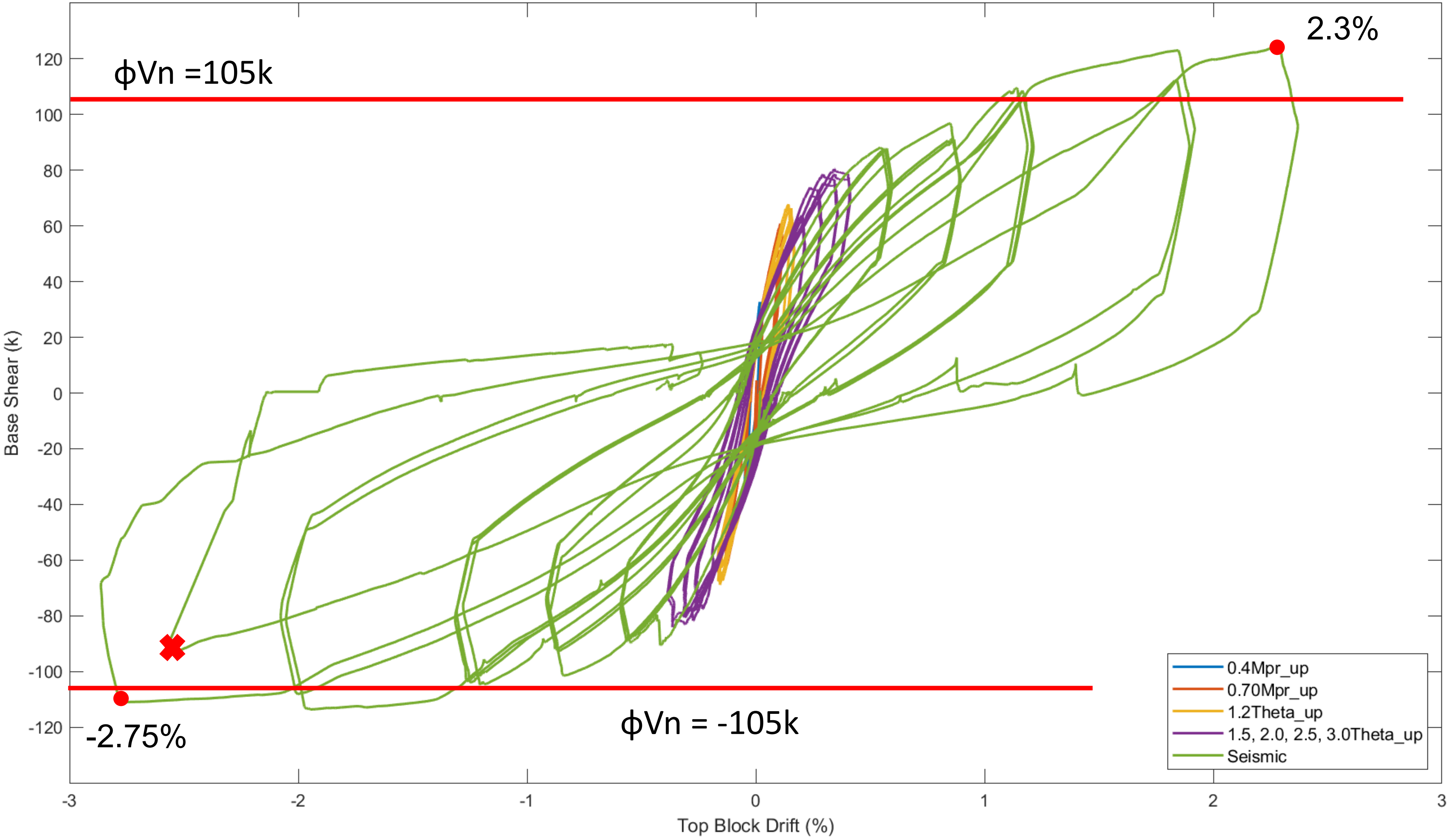
	Rotation demand (%)	xϴy	# of cycles (including ramp down)
WLP	0.12%	1.2	10
	0.15%	1.5	6
	0.2%	2	4
	0.25%	2.5	4
	0.3%	3	2
SLP	0.5%	5	3
	0.75%	7.5	3
	1%	10	3
	1.5%	15	2
	2%	20	2



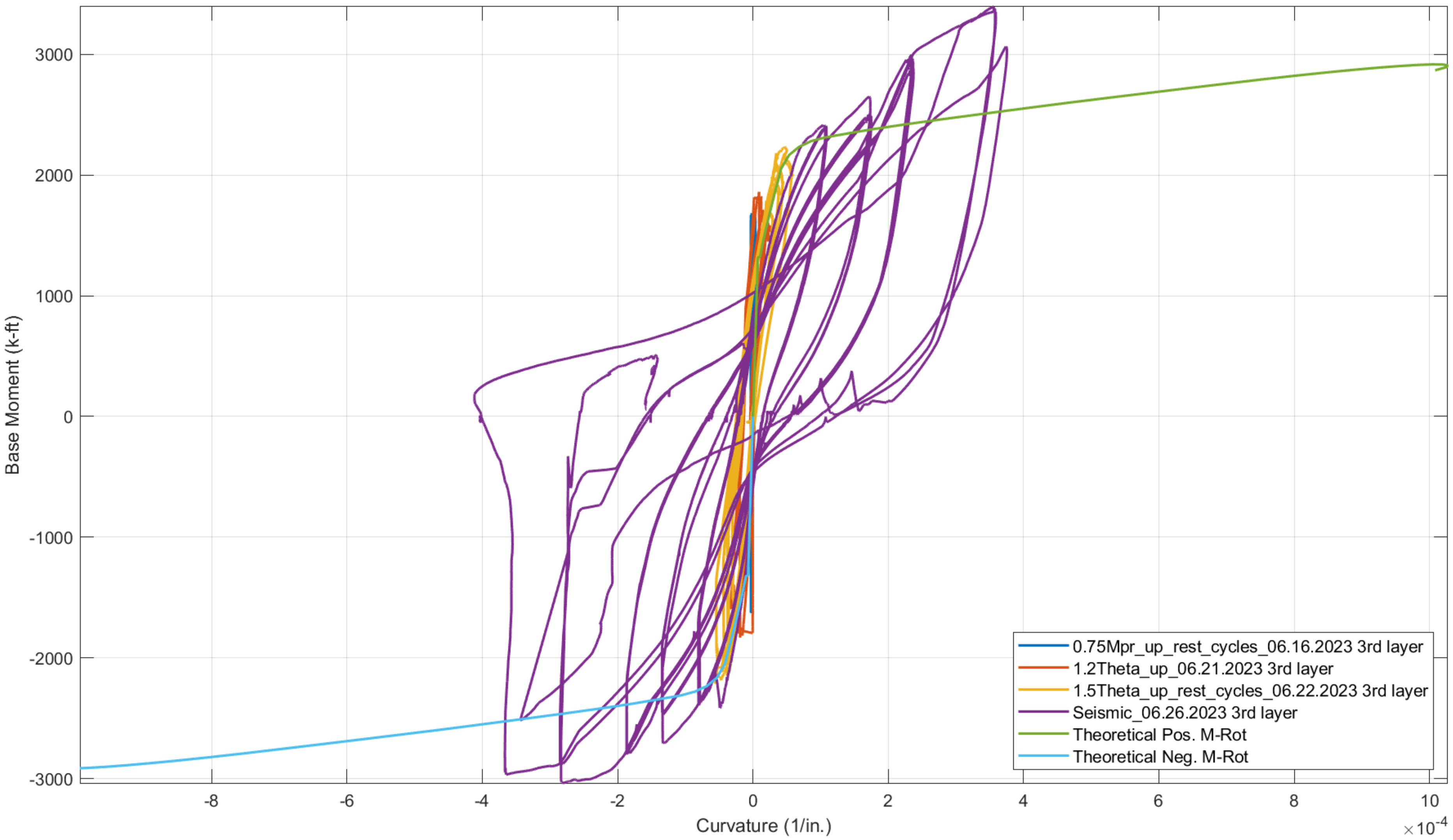
Test Results (WLP+SLP)



Seismic Loading Protocol Results (V-Δ)

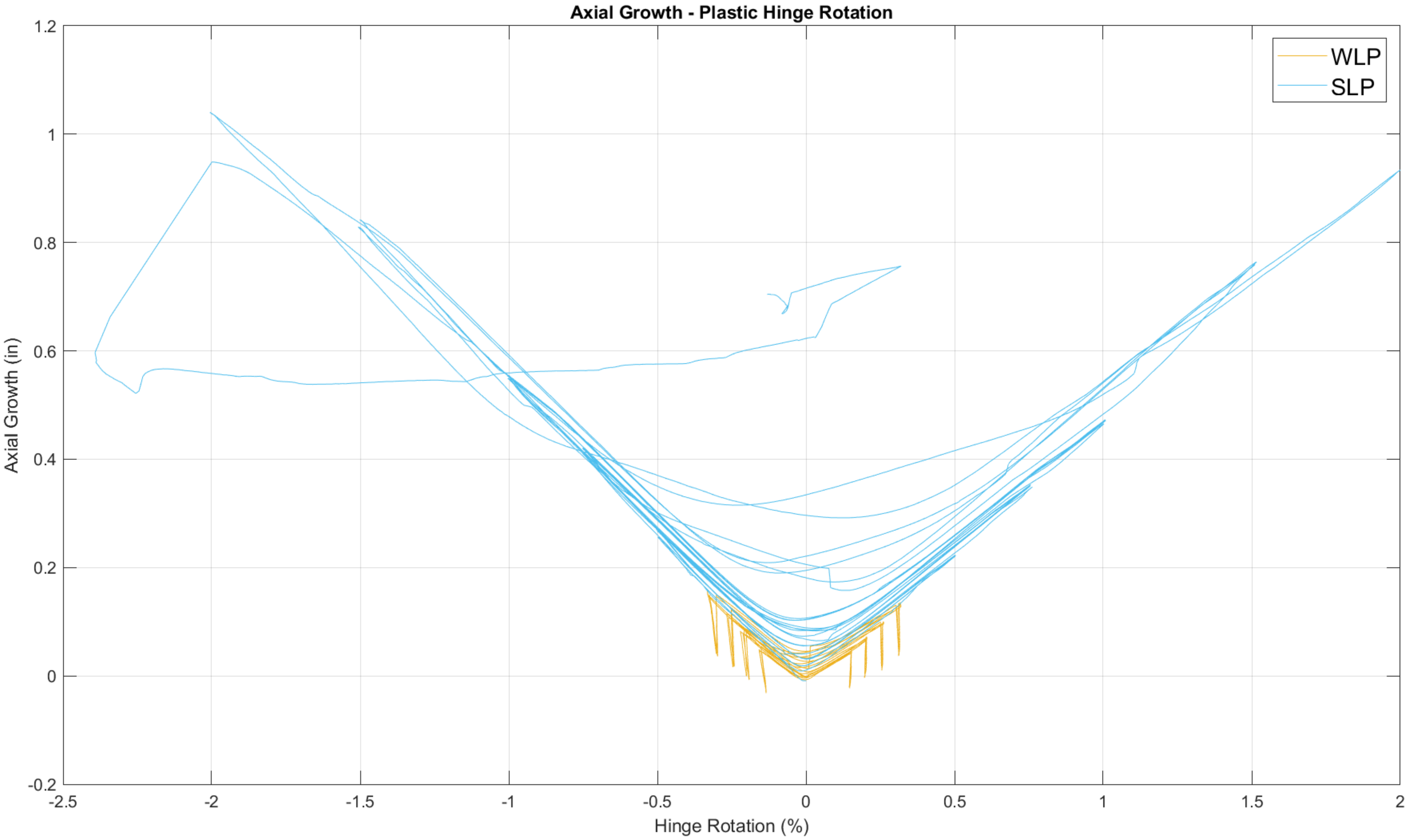


M-Cur



3000
2000
1000
0
-1000
-2000
-3000
Base Moment (k-ft)
-8
-6
-4
-2
0
2
4
6
8
10
Curvature (1/in.)
$\times 10^{-4}$
0.75Mpr_up_rest_cycles_06.16.2023 3rd layer
1.2Theta_up_06.21.2023 3rd layer
1.5Theta_up_rest_cycles_06.22.2023 3rd layer
Seismic_06.26.2023 3rd layer
Theoretical Pos. M-Rot
Theoretical Neg. M-Rot

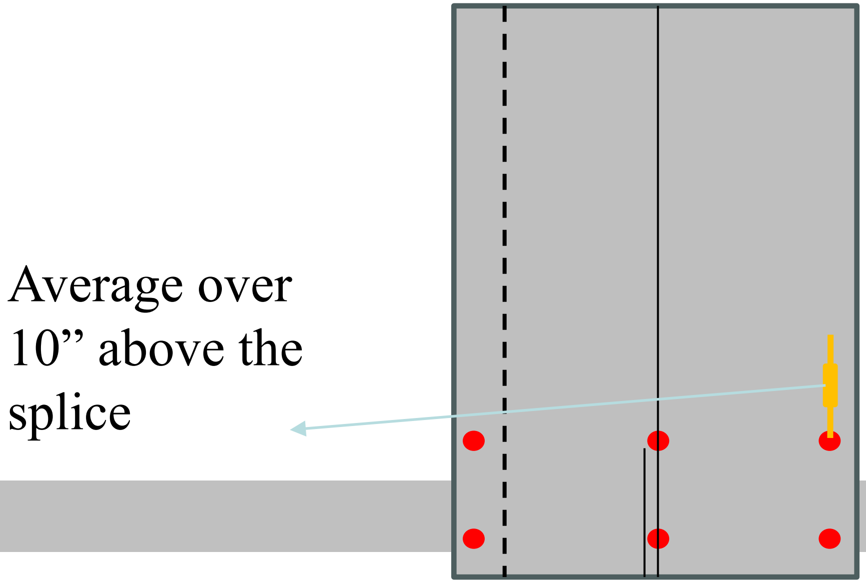
Axial Growth (average of the two flanges)



Seismic Loading Protocol Results Strains

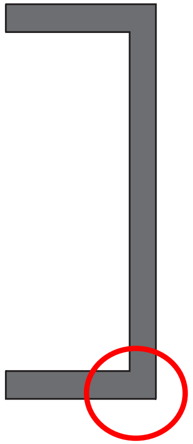
East Flange (above splice)	SG Flange Edge	SG Flange Center	SG Corner	LVDT Flange Edge
0.5%	2.3%	2.0%	1.75%	0.8%
0.75%	2.8%	-	-	1.2%
1%	-	-	-	1.5%
1.5%	-	-	-	2.2%
2.0%	-	-	-	2.8%

West Flange (above splice)	SG Flange Edge	SG Flange Center	SG Corner	LVDT Flange Edge
0.5%	2.9%	-	2.0%	0.85%
0.75%	3.3%	-	2.4%	1.5%
1%	4%	-	2.6%	1.8%
1.5%	-	-	2.5%	2.5%
2.0%	-	-	-	4%



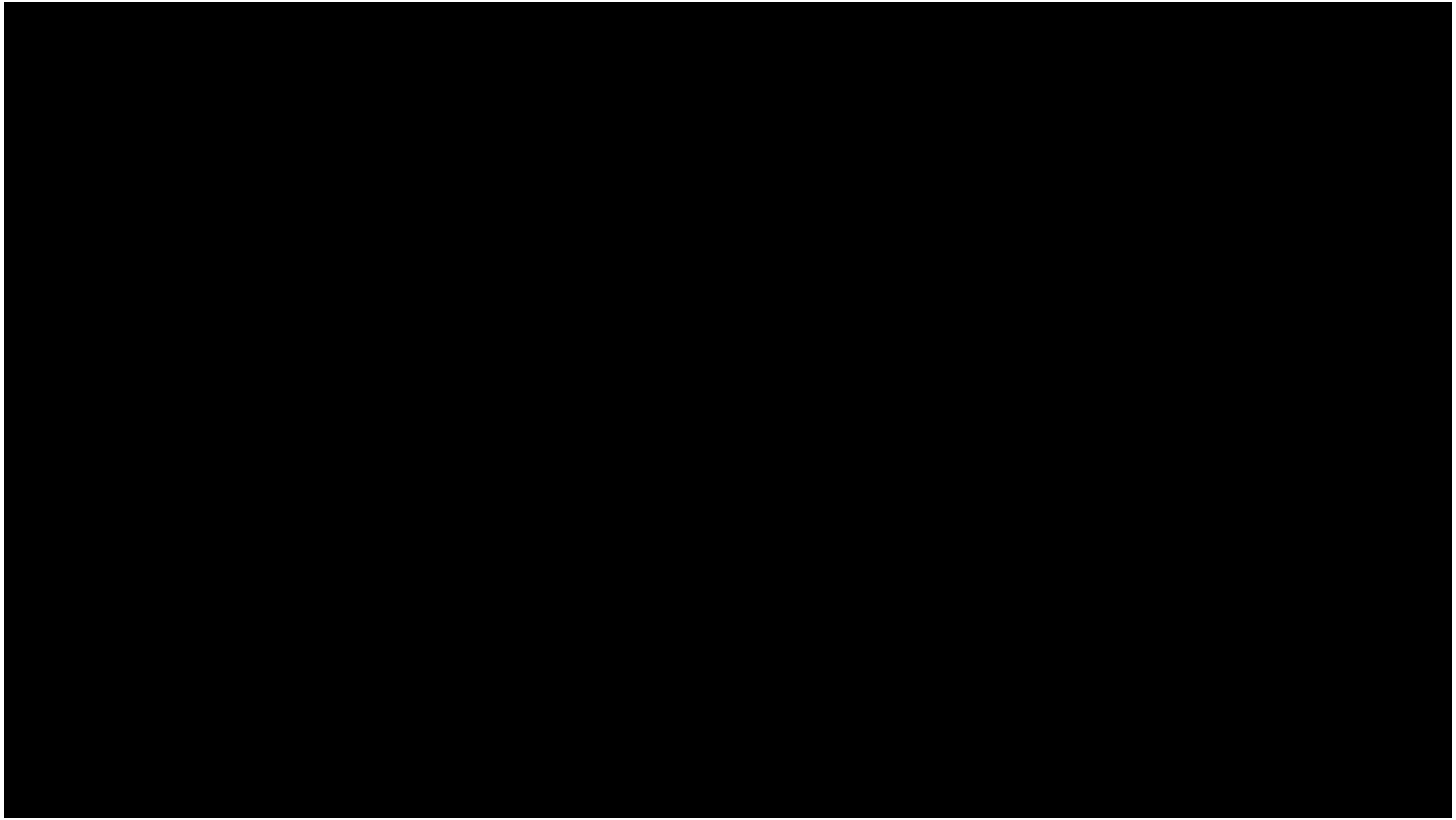
Seismic Loading Results

- Initiation of bar buckling at the corner (above the spliced region) bars at 1.3% hinge rotation

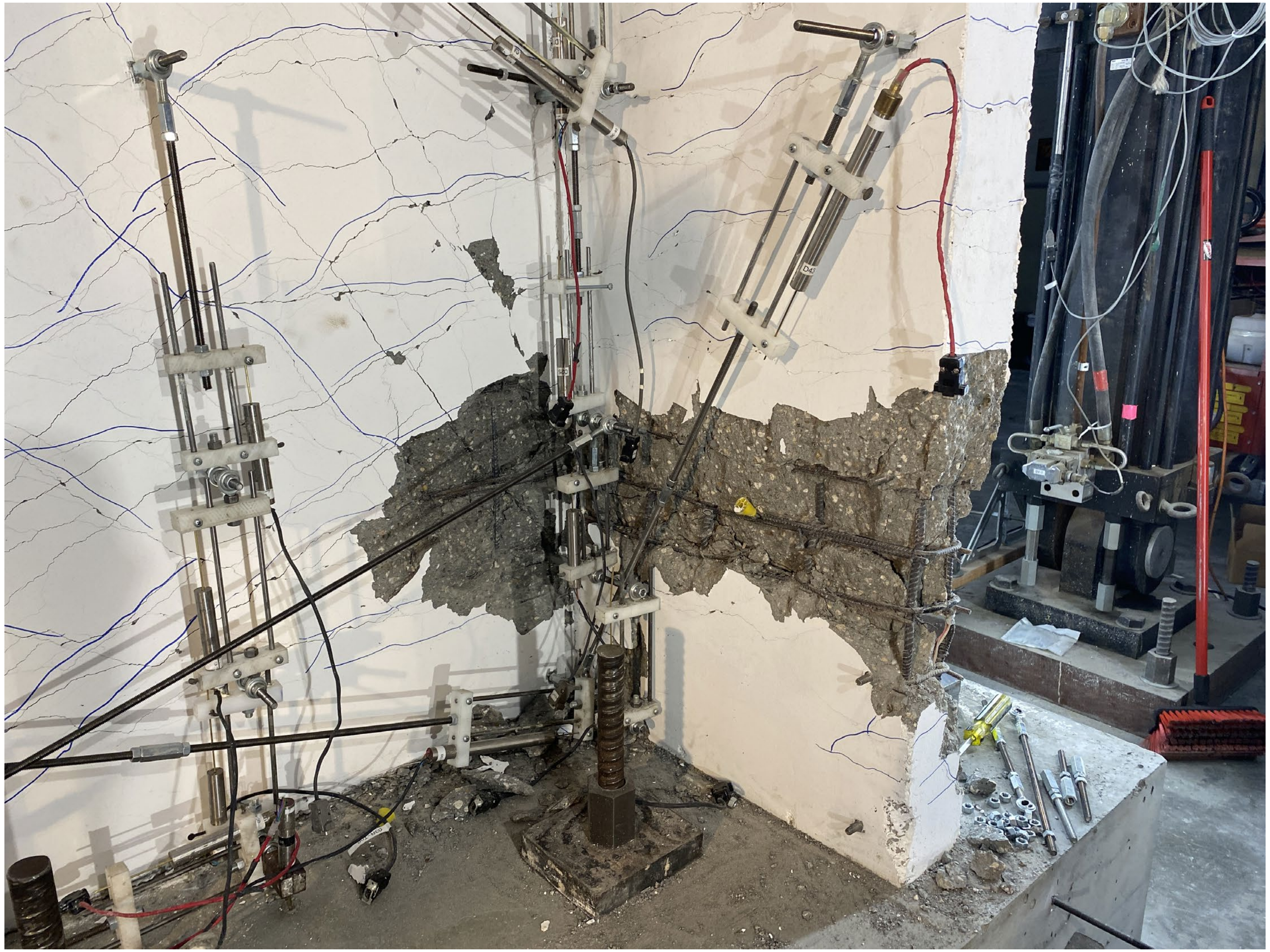


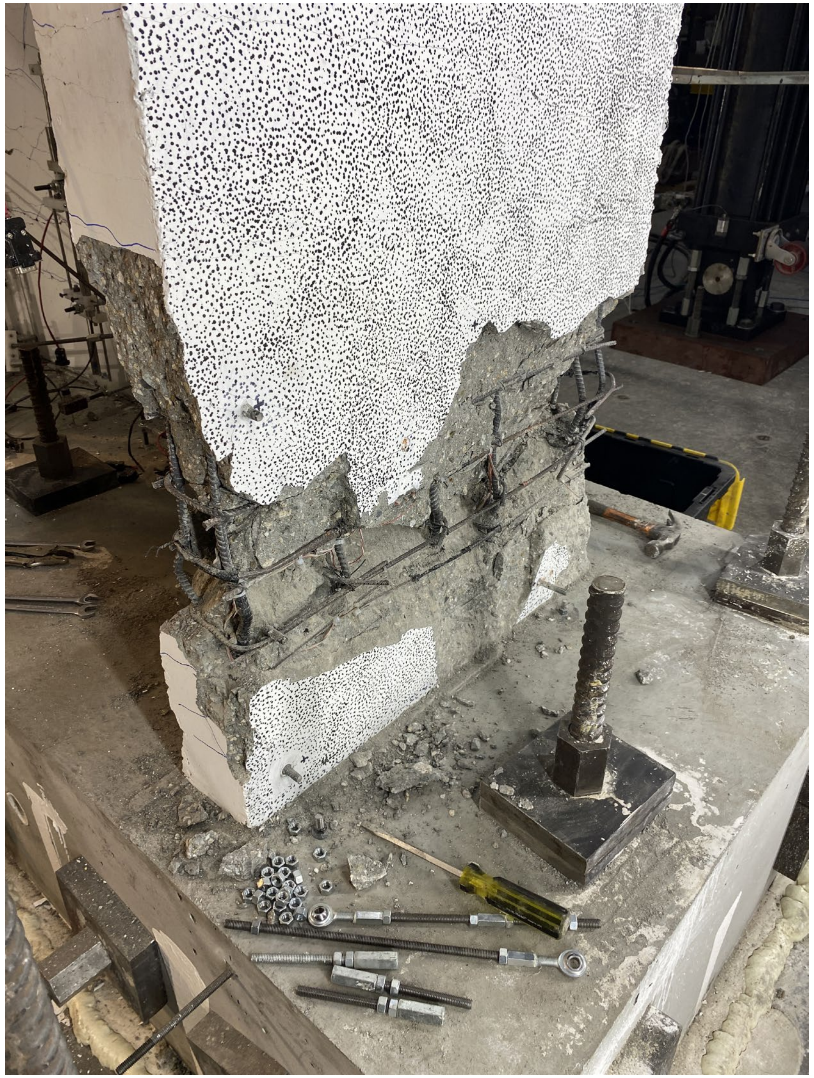
Seismic Loading Results

- Failure of west flange at the second 2% rotation cycle due to bar buckling/rupture

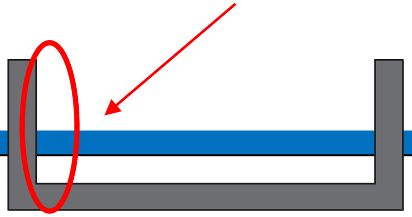


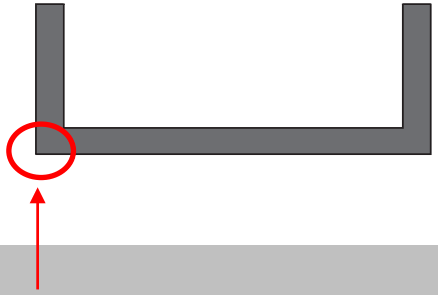
Seismic Loading Results (West flange)

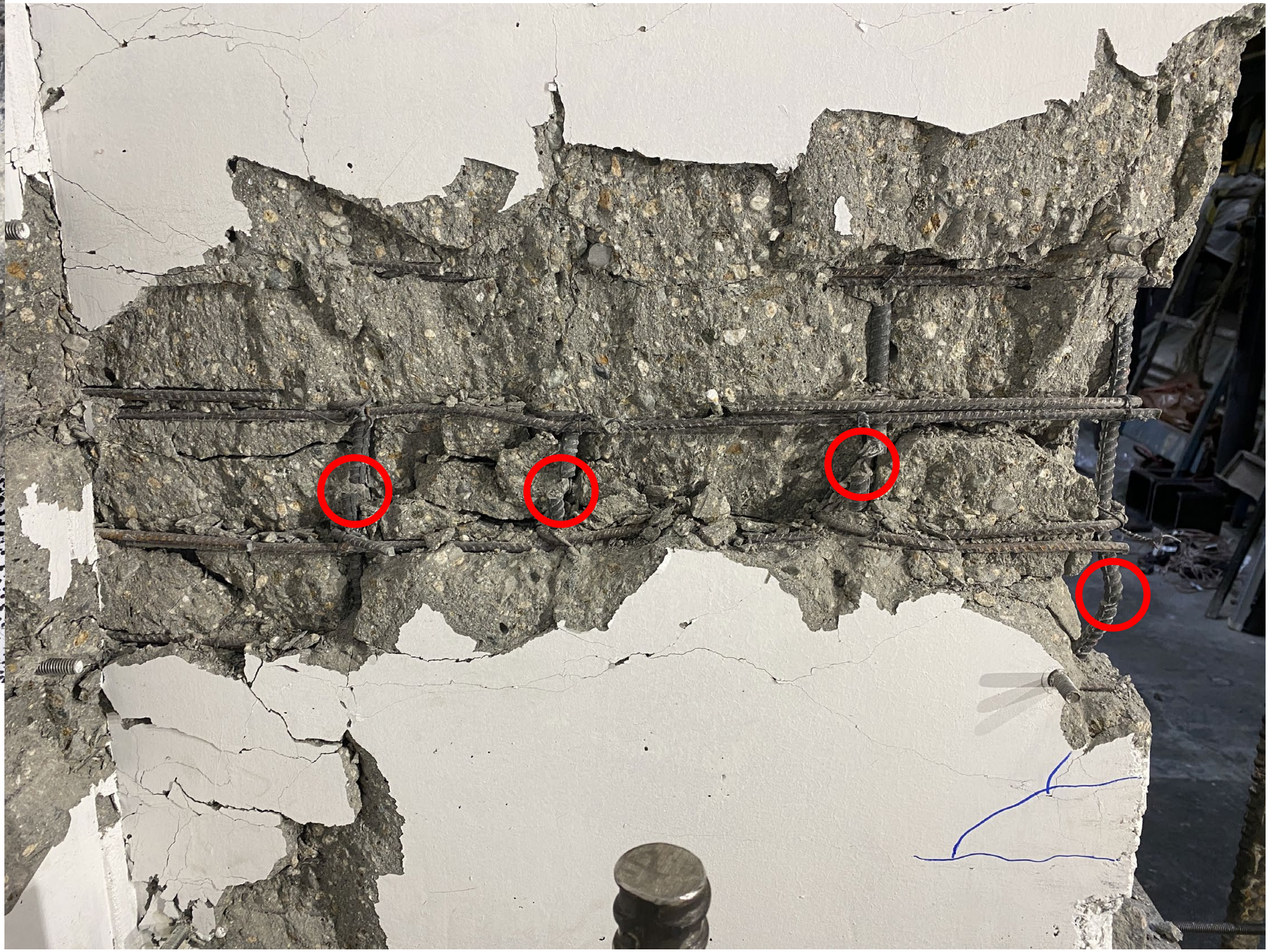




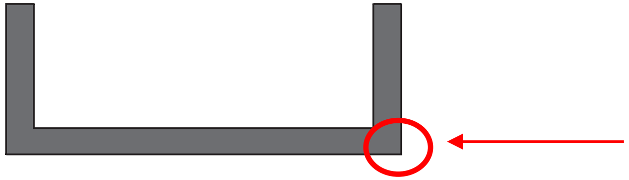
Seismic Loading Results (West flange)

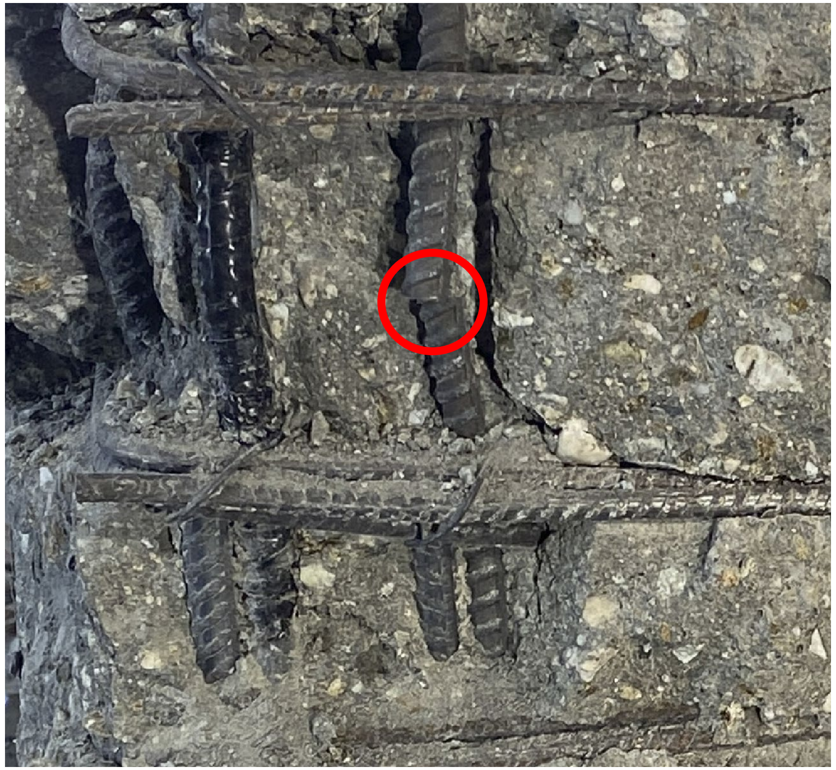


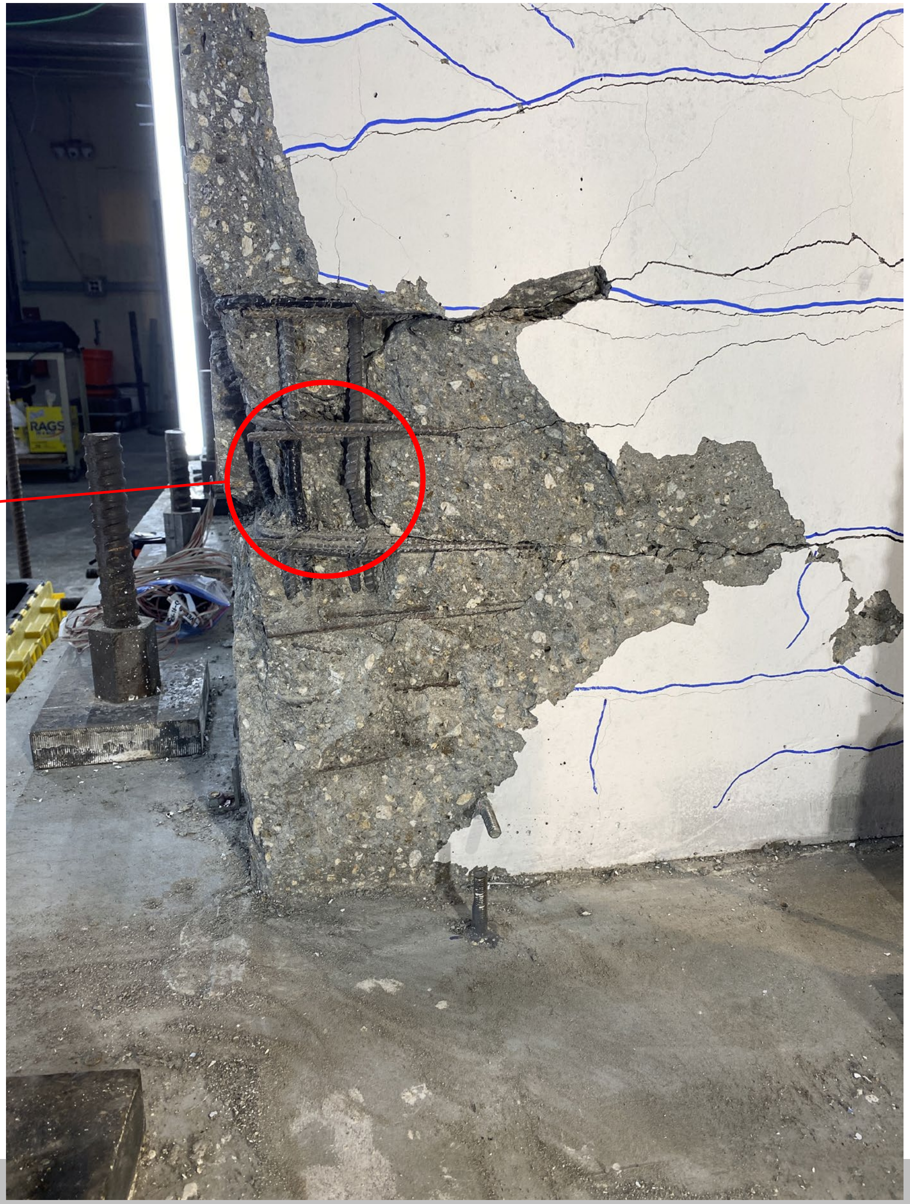




Seismic Loading Results (East flange)

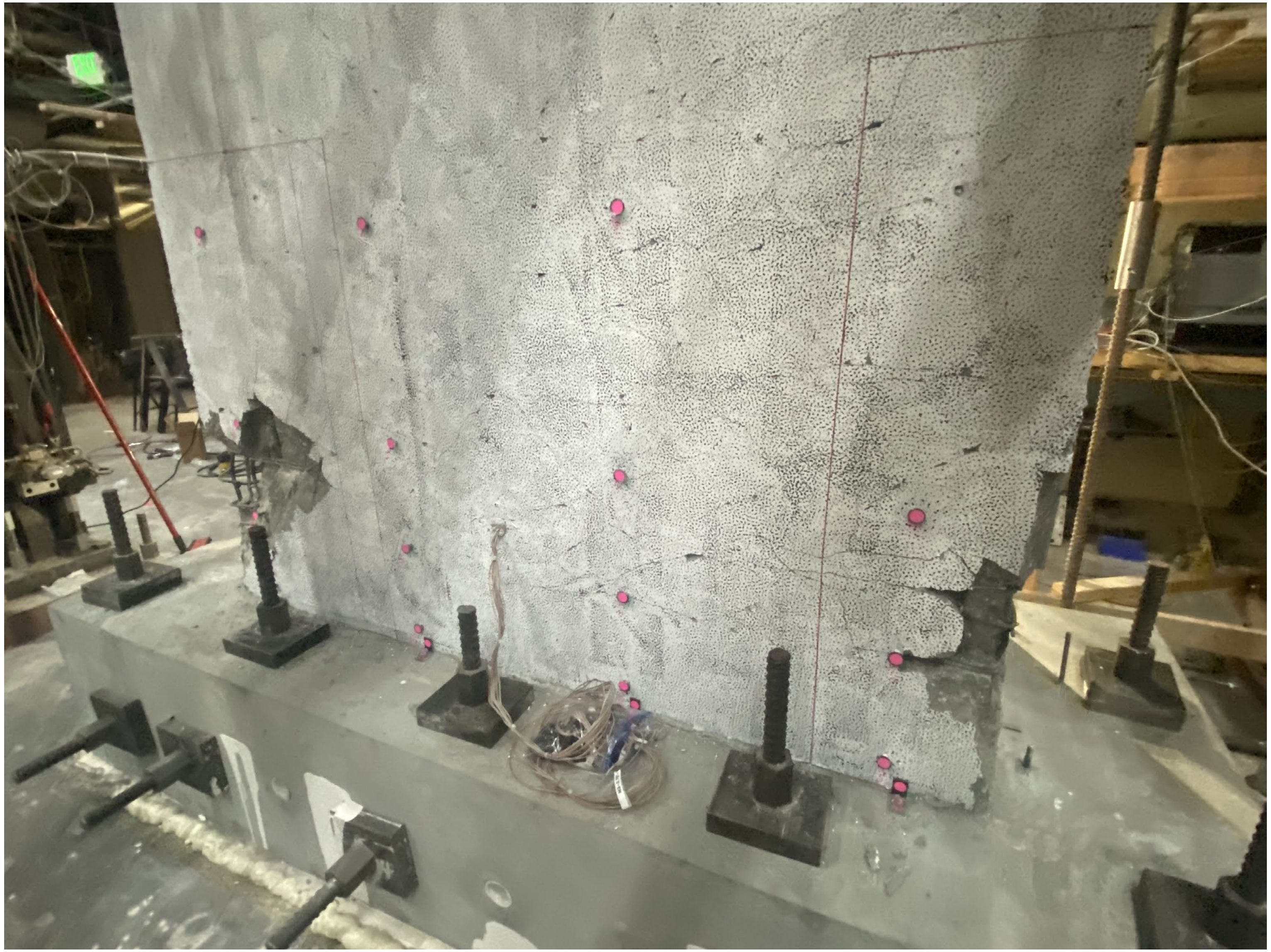


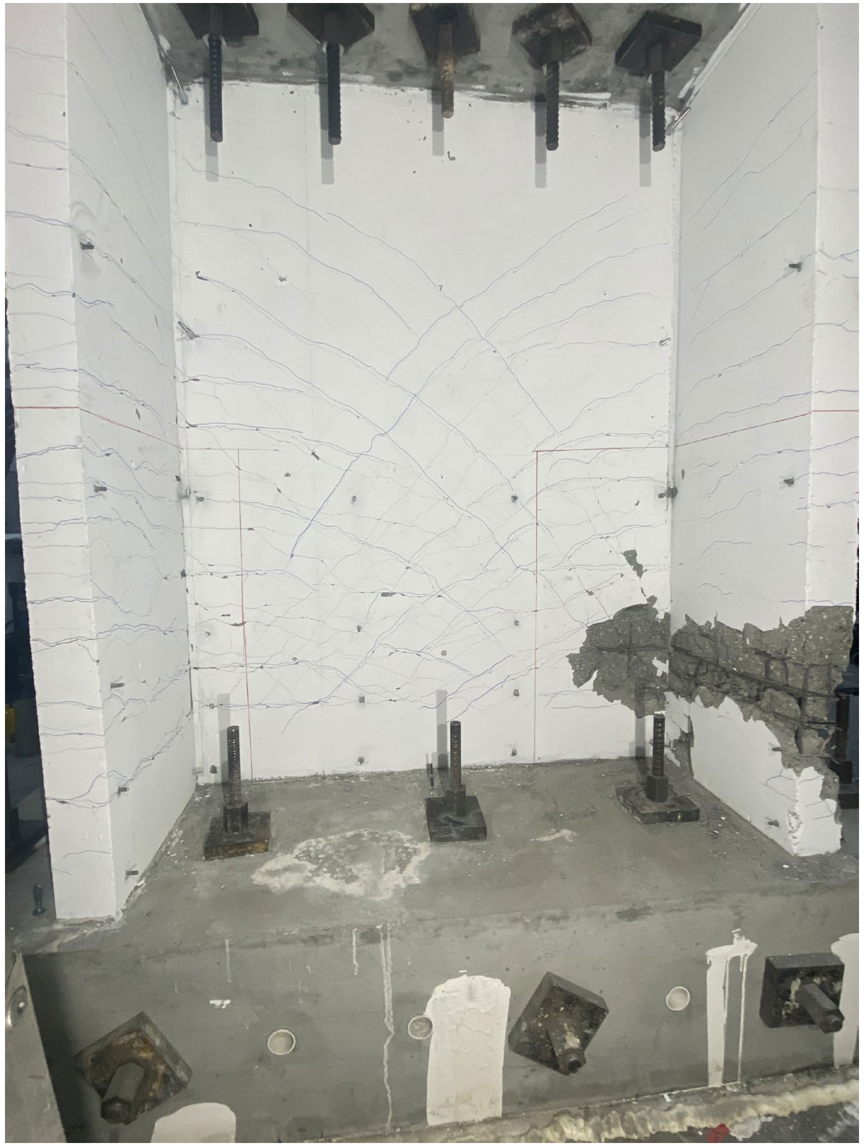




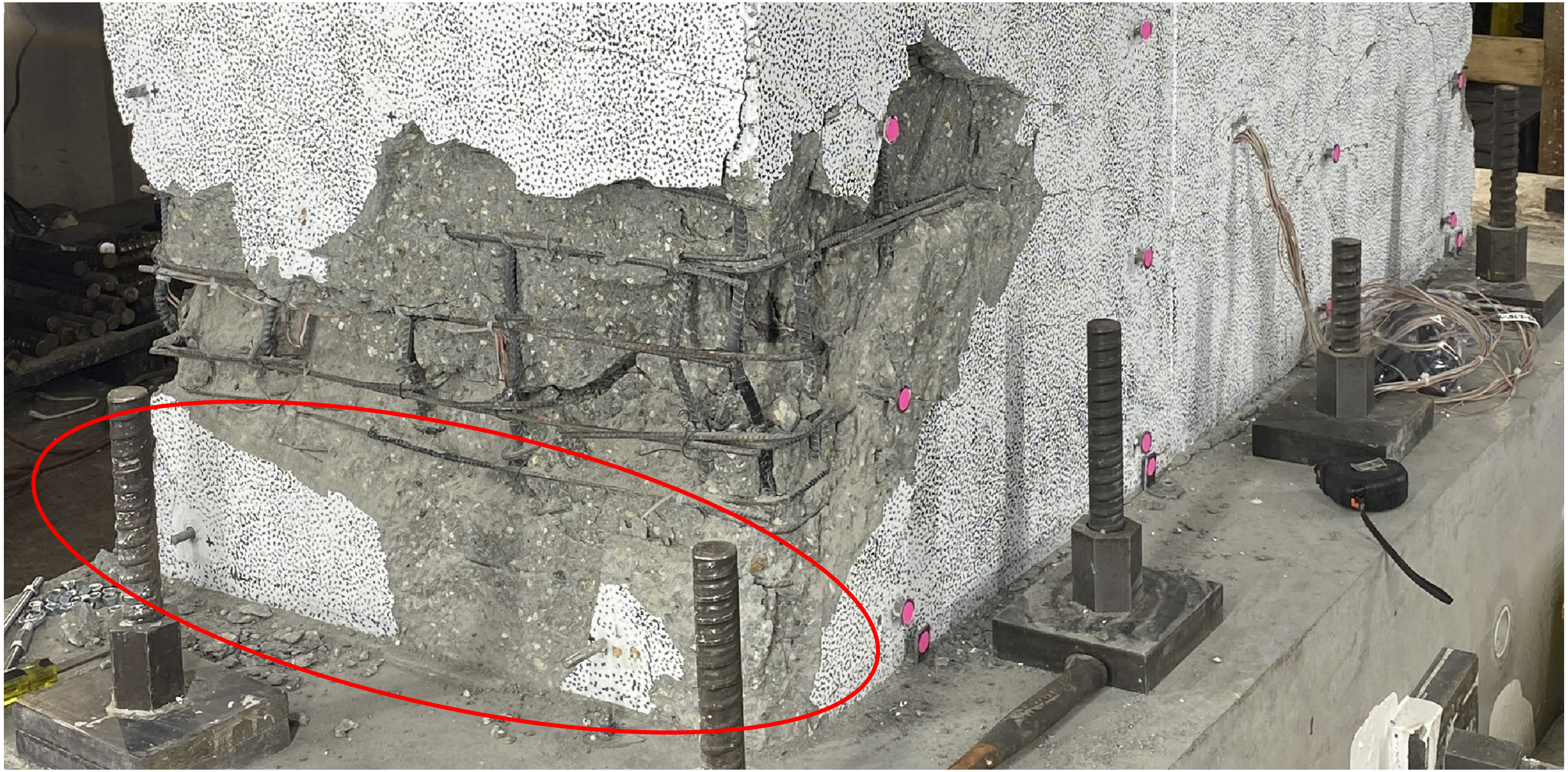
- Bar buckling/rupture of corner bars

Seismic Loading Results (Web)





Seismic Loading Results Spliced Regions

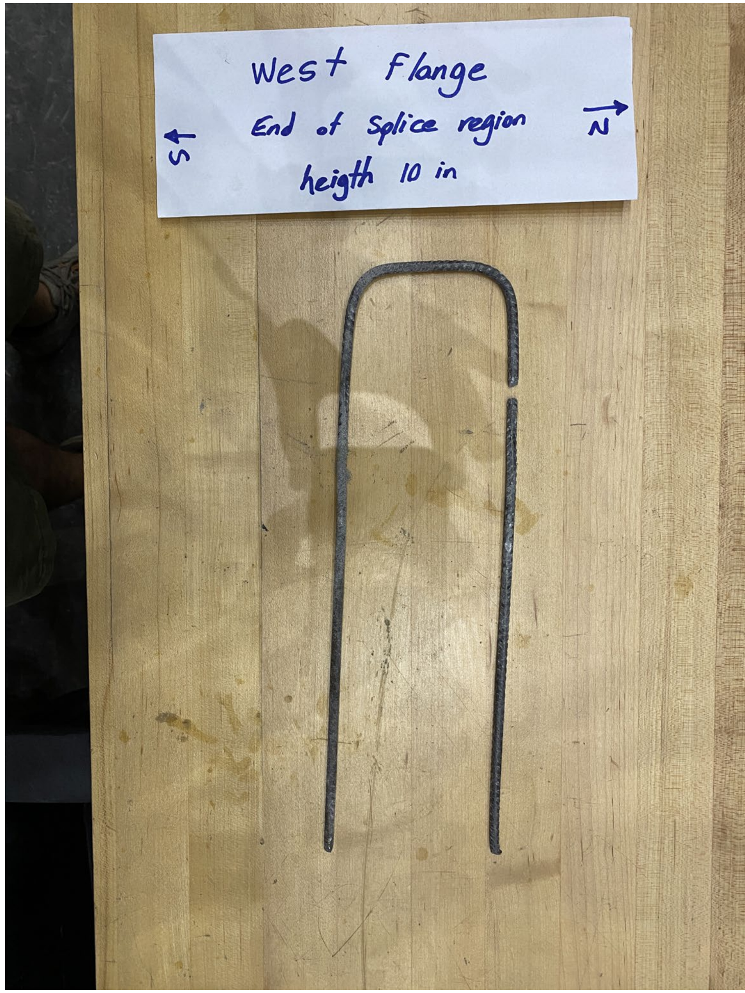


- Concrete crushing of the spliced zones at outside surfaces of the flanges

Seismic Loading Results

West flange @ 13” (first layer above spliced region)

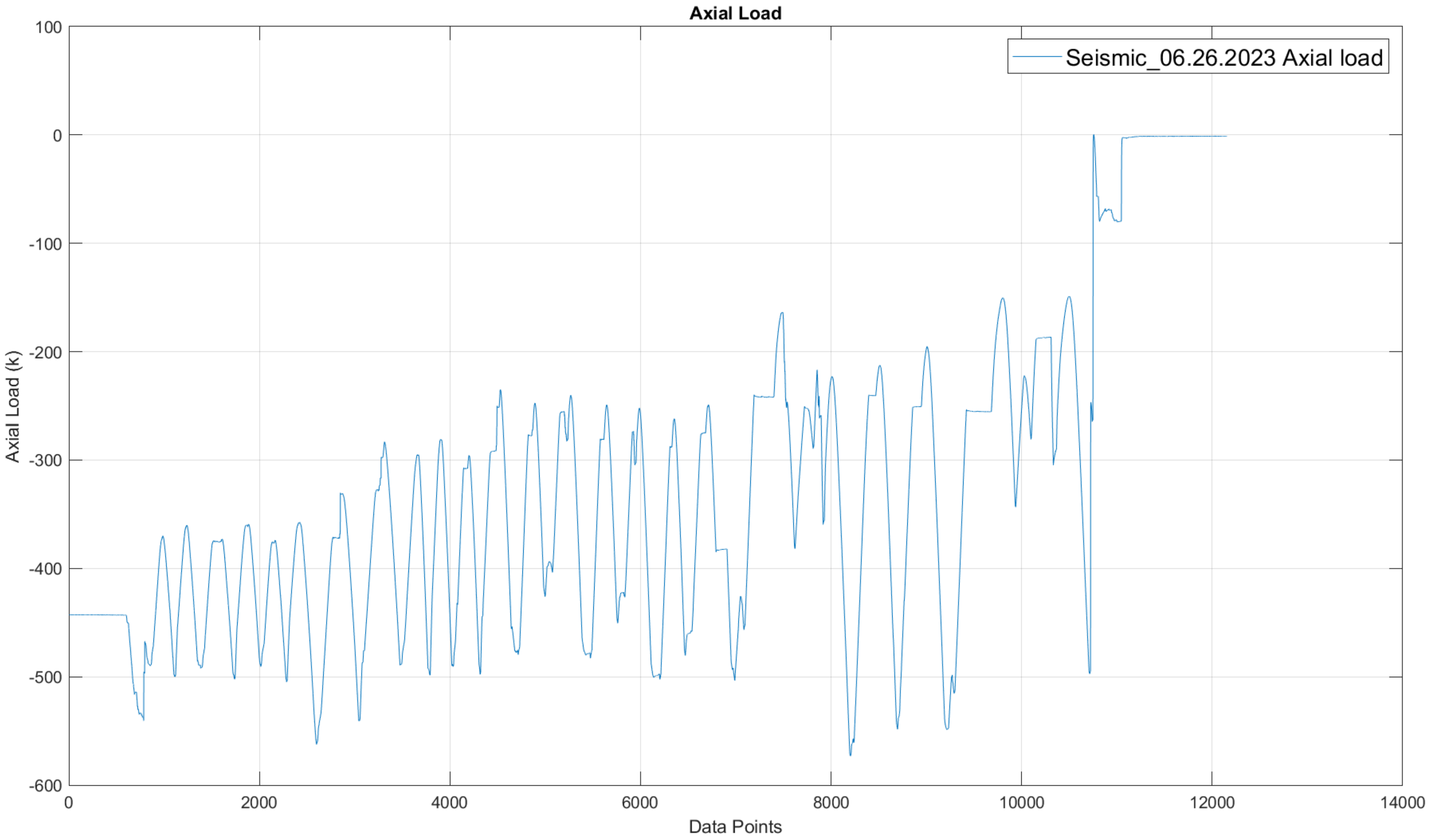
90-degree corners opened up

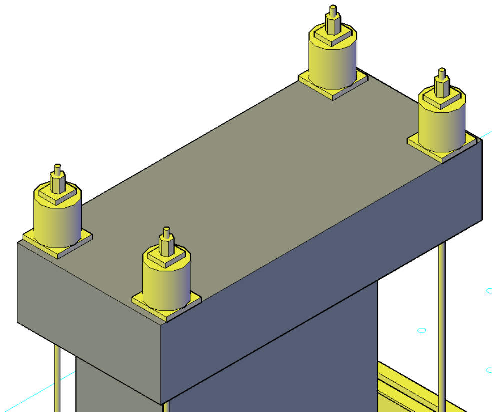


West flange @ 10” (U-bar at the web corner)

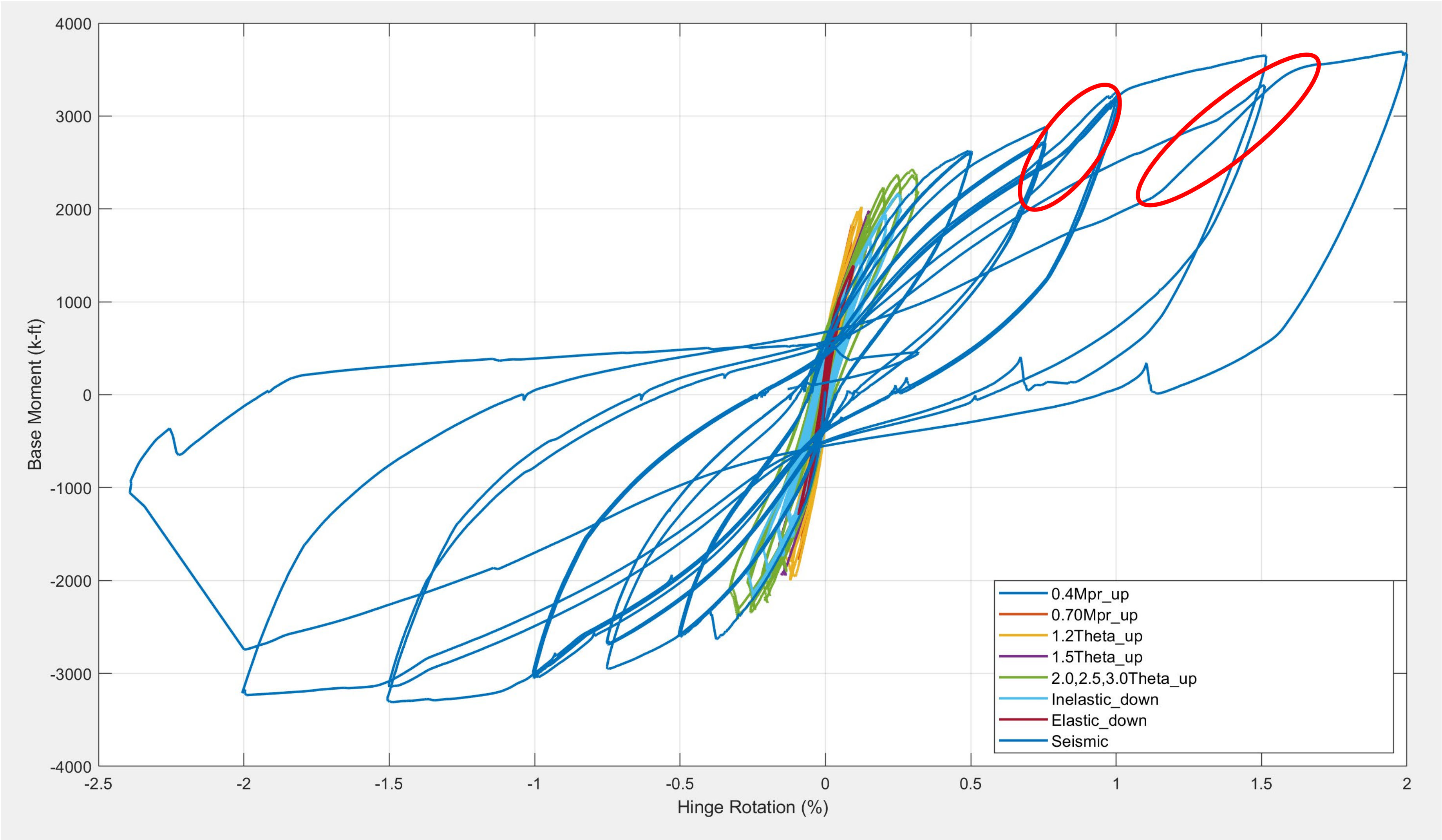
SOME CHALLENGES

Variation in Axial Load





Increase in stiffness in wall

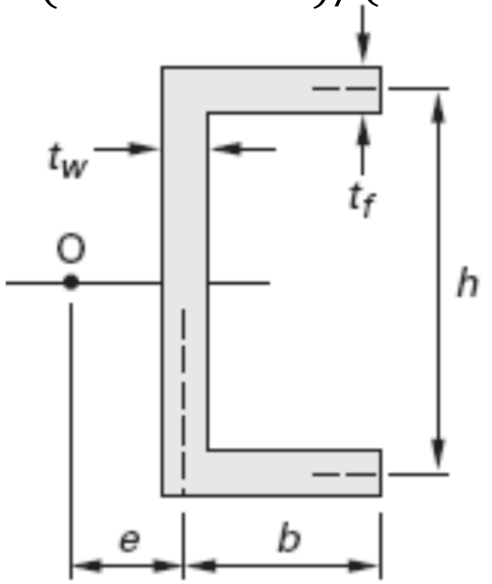


Increase in stiffness in wall

Fully retracted (due to axial growth) at the point where stiffness starts to increase

Torsion

$$e = (3 * 5 * 27.5^2)/(70 * 5 + 6 * 27.5 * 5) = 9.5''$$

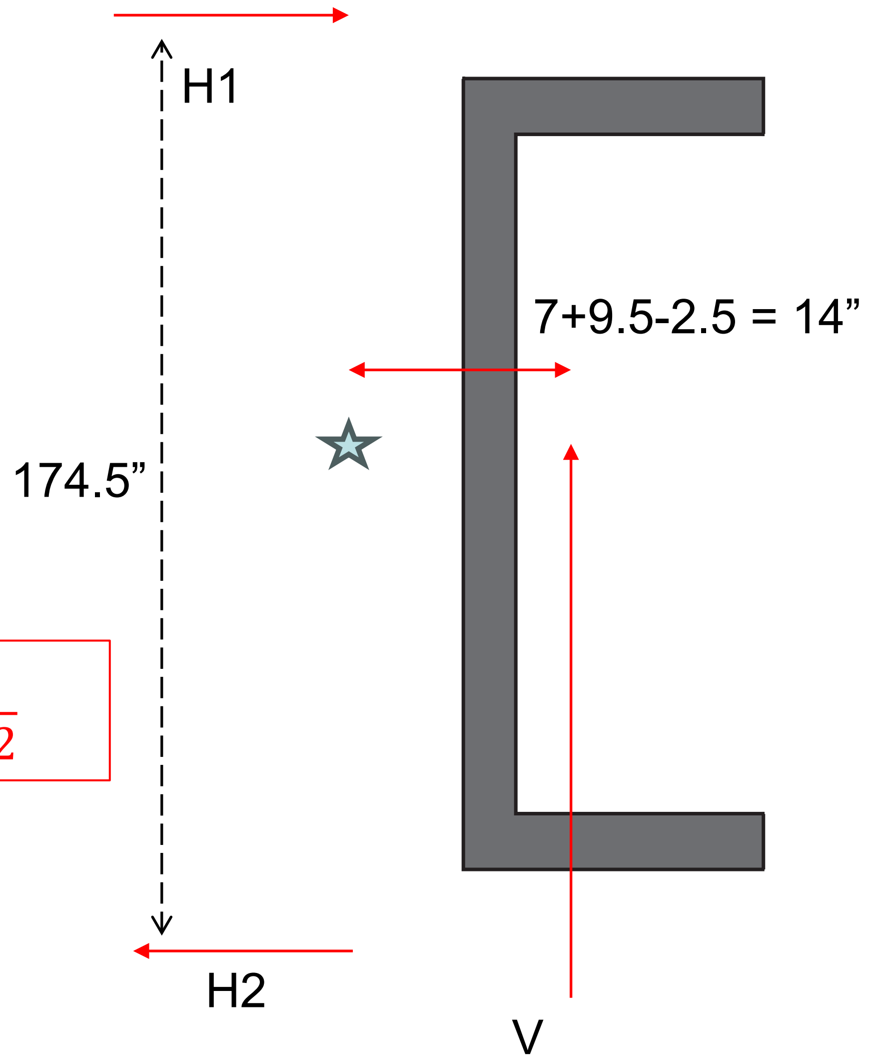


Eq. 1

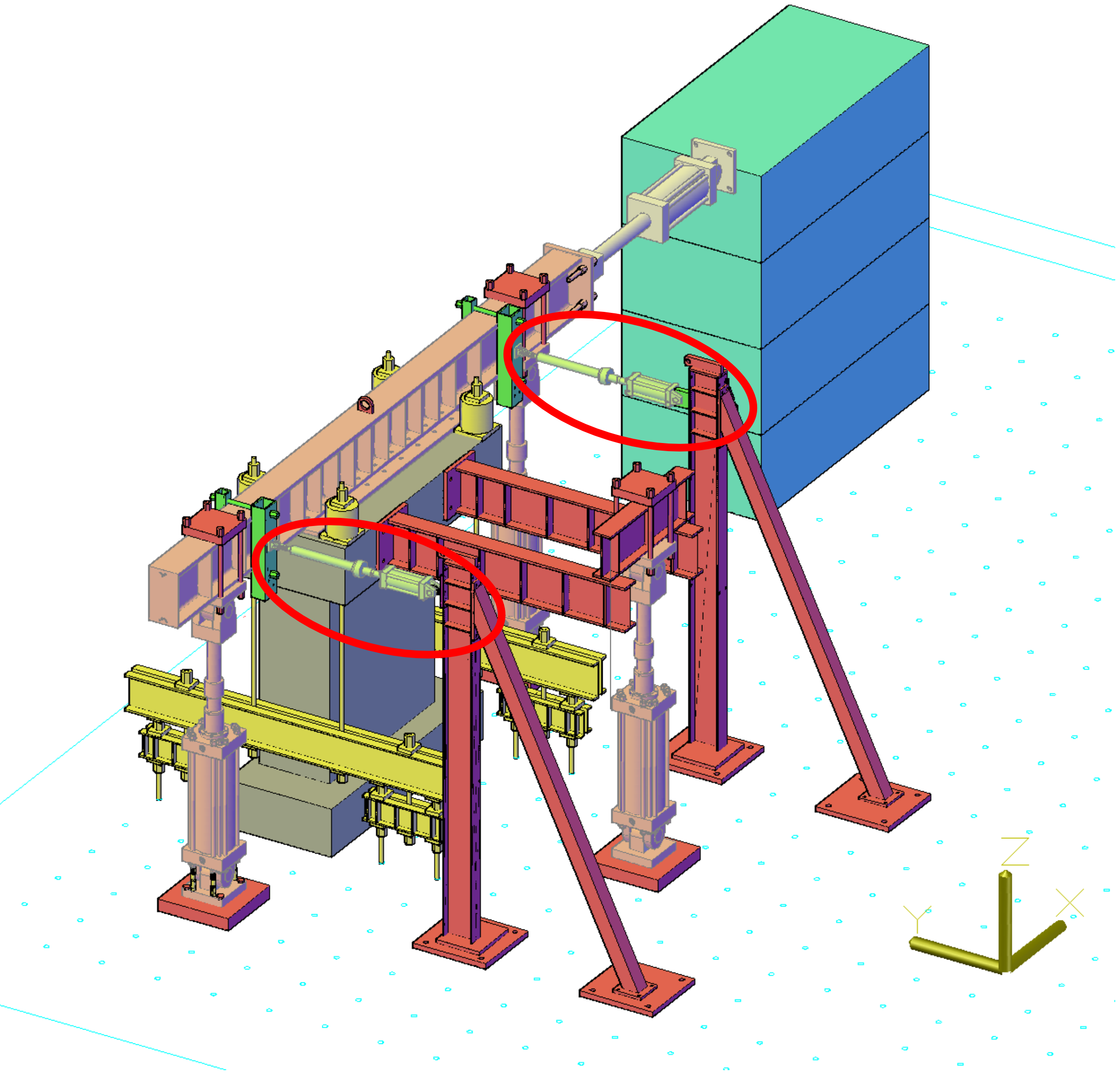
$$e = (3 \cdot t_f \cdot b^2)/(h \cdot t_w + 6 \cdot b \cdot t_f)$$

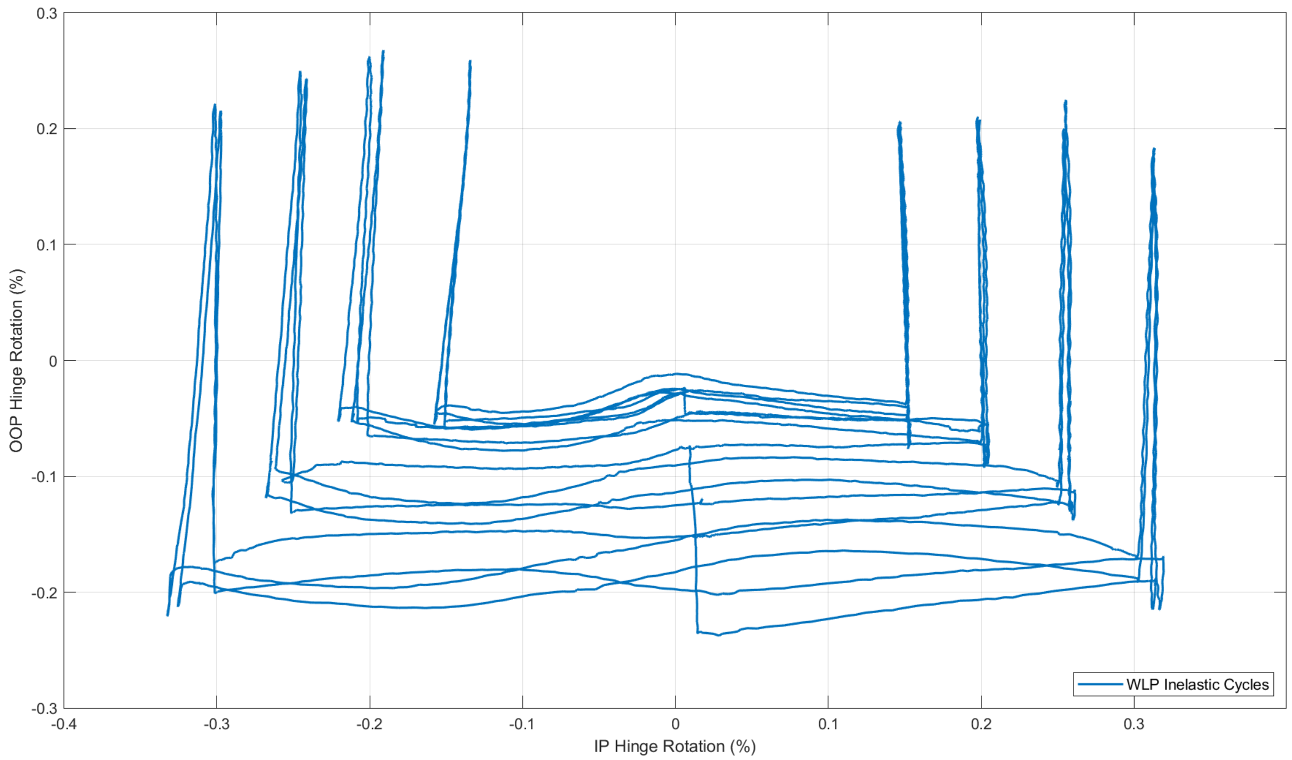
Shear center of C − wall

$$\boxed{H1 - H2 = \frac{V * 14''}{174.5''/2}}$$

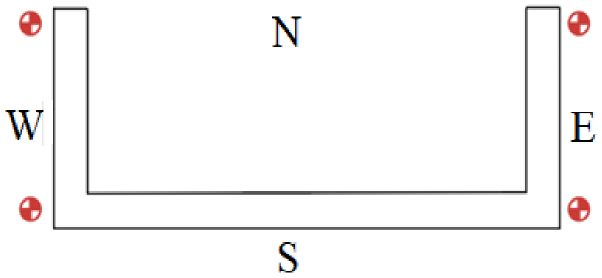


Torsion


Z
Y
X

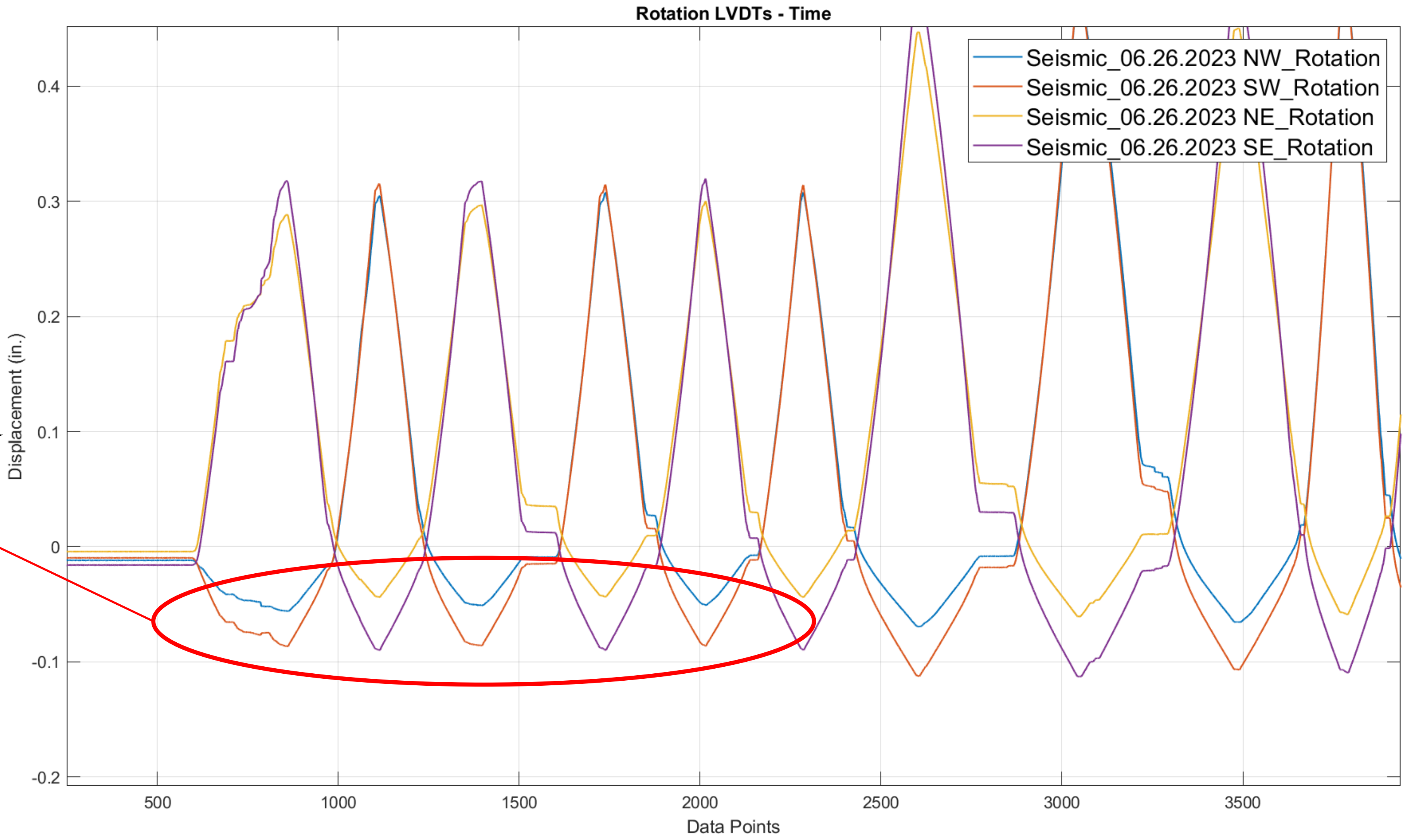

0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
OOP Hinge Rotation (%)
IP Hinge Rotation (%)
WLP Inelastic Cycles

Effect of Torsion

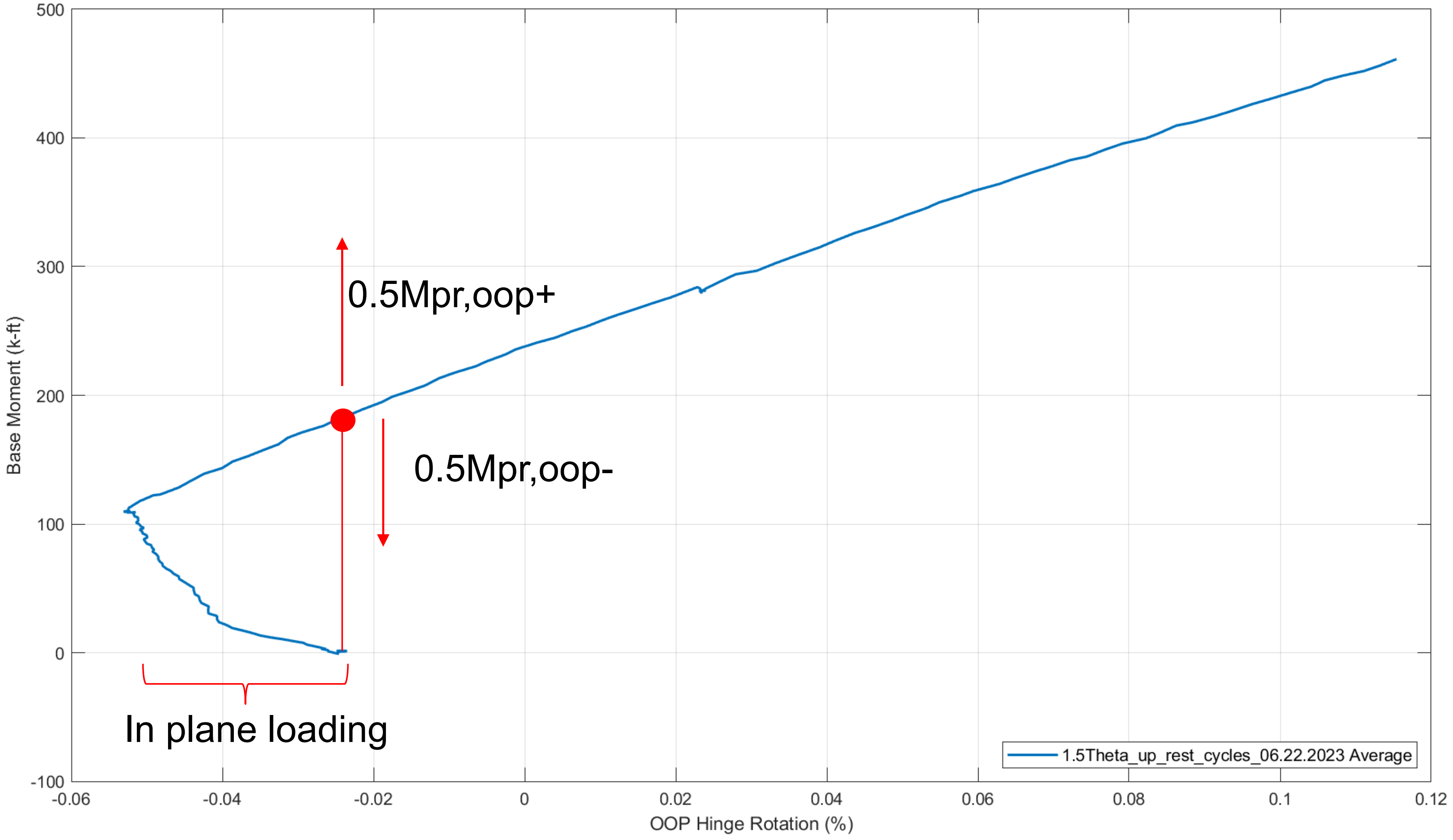


- Web corners have almost double the compressive strains compared to flange edges

Initiation of bar buckling for corner bars first



OOP Bending



0.5Mpr,oop+
0.5Mpr,oop-
In plane loading
Base Moment (k-ft)
OOP Hinge Rotation (%)
1.5Theta_up_rest_cycles_06.22.2023 Average
500
400
300
200
100
0
-100
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
0.12

REPAIR & RETROFIT

Repair

Cold swaged couplers

Repair