Structural Performance of High-Strength Concrete and High-Strength Rebar in Nuclear Shear Walls

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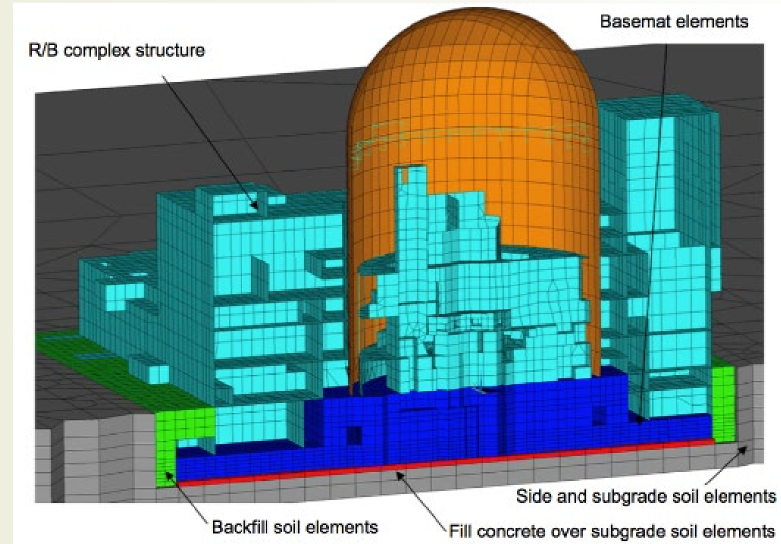
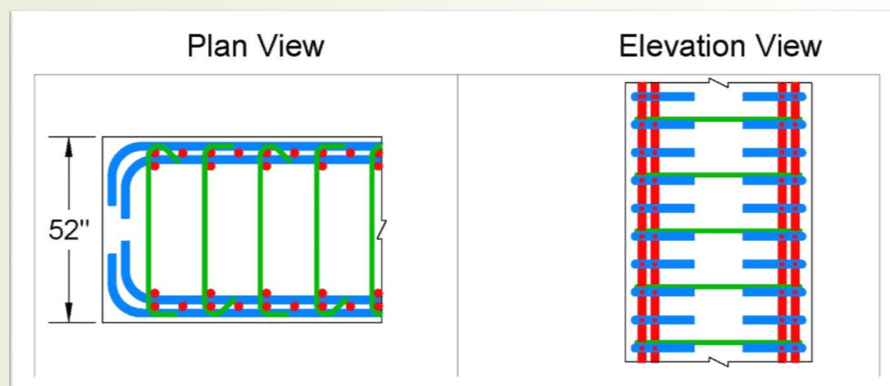
Research Objectives

Demonstrate behavior of high-strength rebar (HSR) and high-strength concrete (HSC) in shear walls typical of RC nuclear structures.

- thickness > 40”
- squat ($h_w/l_w < 2.0$)
- large reinforcement volumes (ρ_{sw} > 1.5% with normal-strength materials)
- boundary elements not required
- intersecting walls
- expected to be shear critical, limited by $10\sqrt{f_c'}A_{cv}$ (ACI 349)
- “essentially elastic” during design basis earthquake (ASCE/SEI 43-05)



US-APWR Design Control Doc.



High-Strength Materials

Constituents	Normal-Strength Concrete	High-Strength Concrete
PC Type I/II (lb/yd^3)	182	400
Slag (lb/yd^3)	437	350
Silica Fume (lb/yd^3)	-	50
Crushed Limestone (lb/yd^3)	1745	1675
Fine Aggregate (lb/yd^3)	1346	1403
Water (lb/yd^3)	250	220
Superplasticizer (fl. oz./cwt)	2-4	7.5-9.0
Water/binder Ratio	0.40	0.28
Slump (in)	7.5	8.5-9.25
28-day Properties		
f'_c (ksi)	5.6-6.9	13.4-14.6
f_t (psi)	680-850	1000-1130
E_c (ksi)	5570-6070	6580-6770

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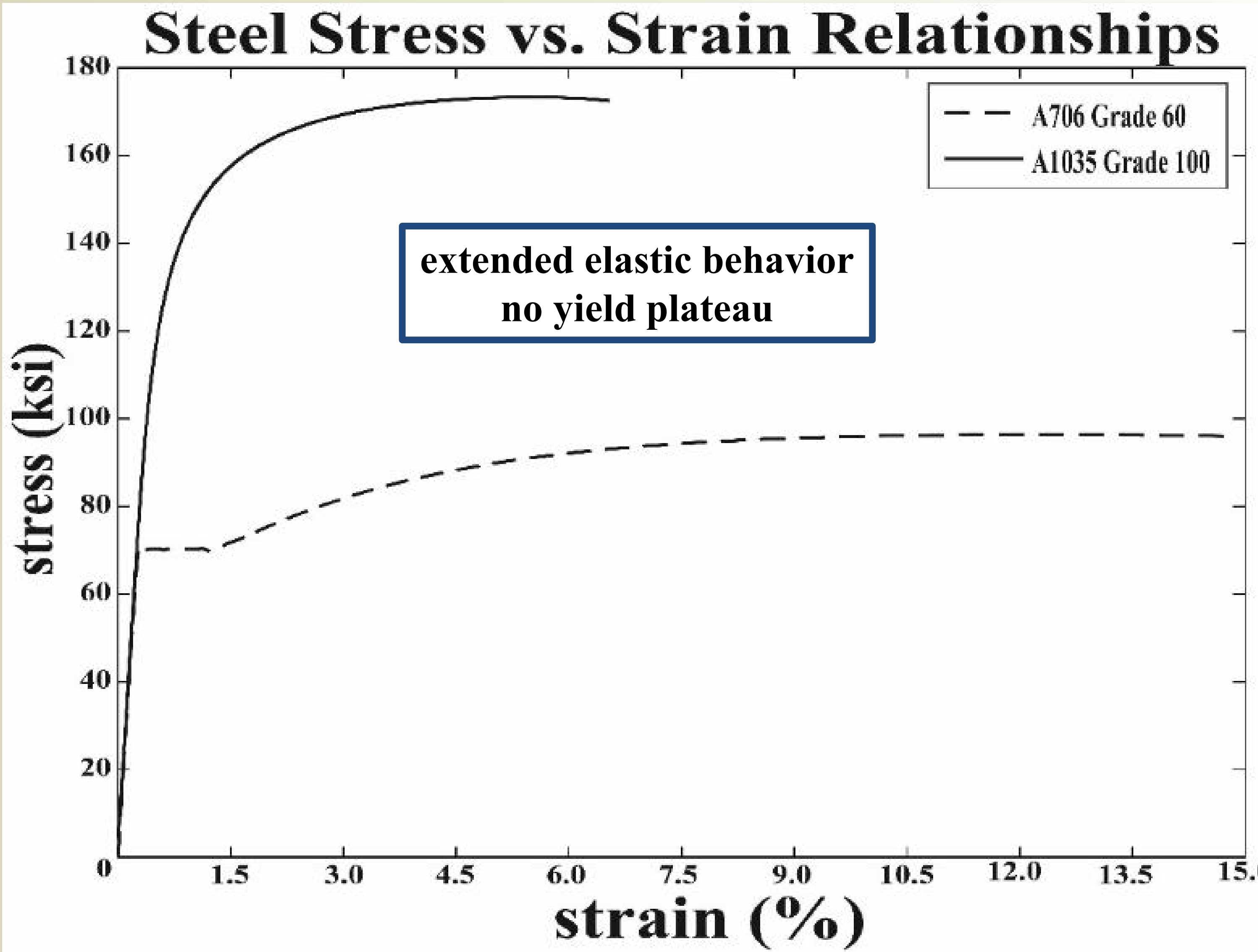
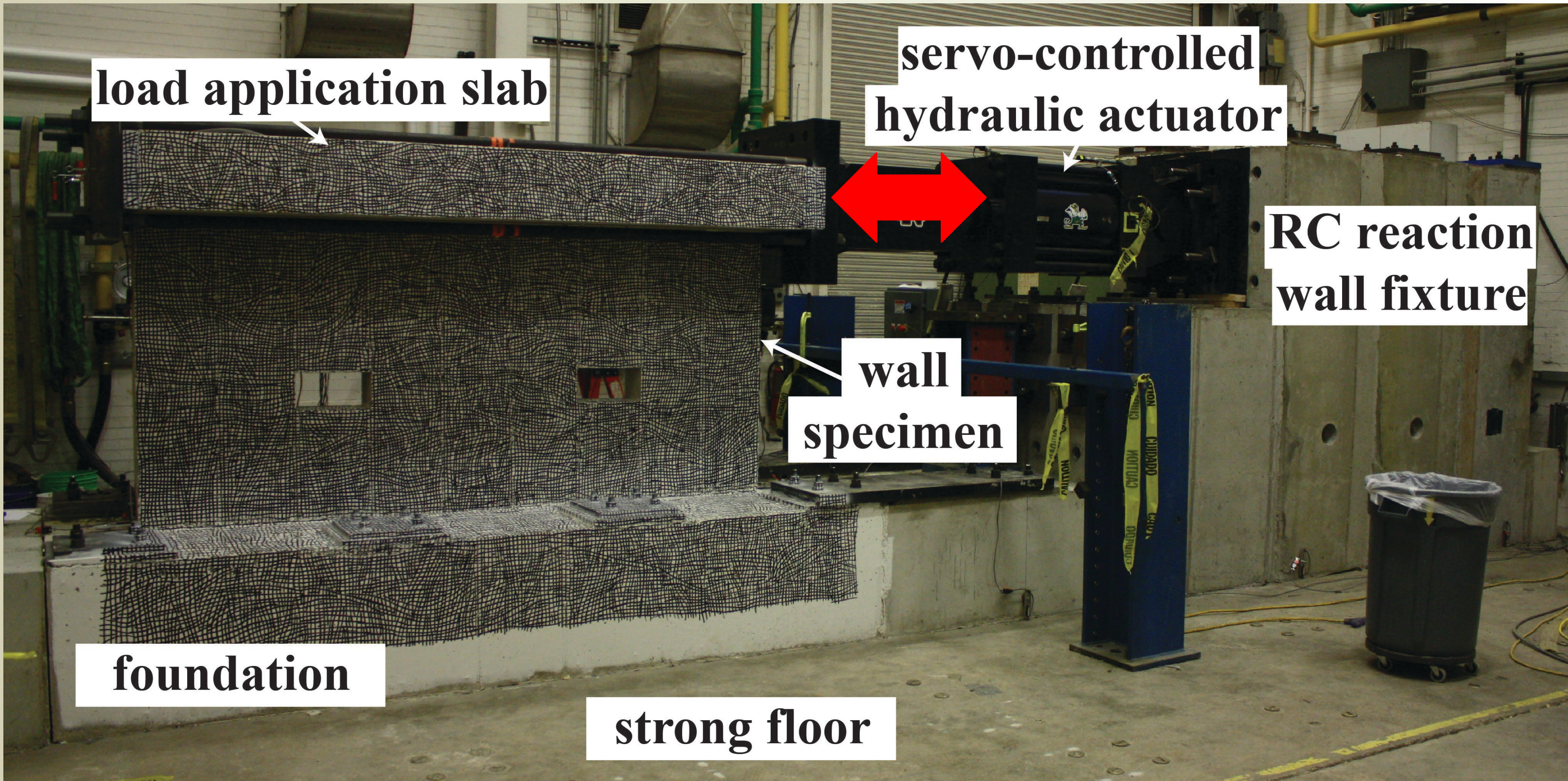


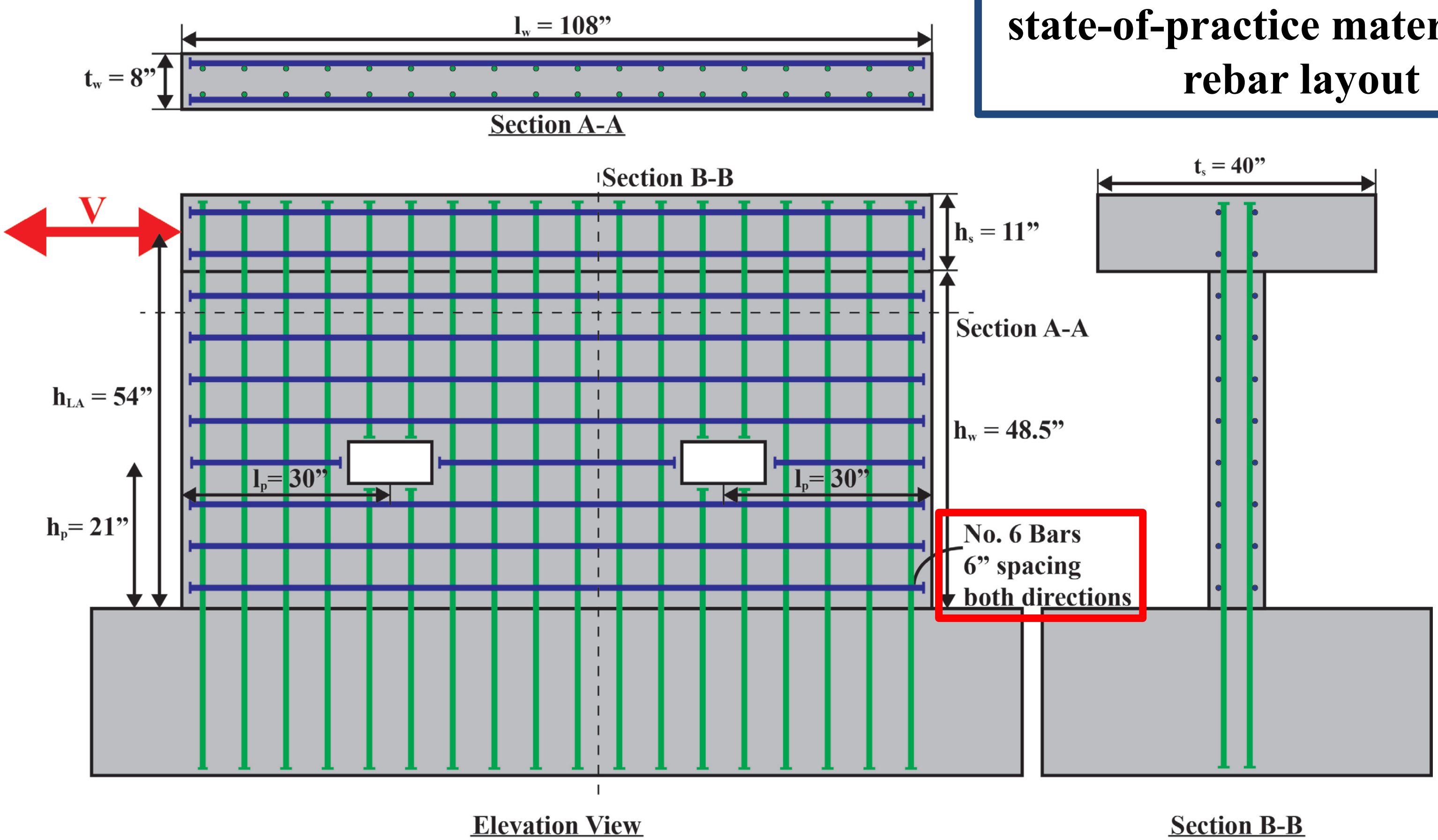
Wall Test Setup



Wall Layouts – W1 (1:6.5 Scale)

Specimen	f'_c (ksi)	f_y (ksi)	ρ_{sw} (%)	h_{LA}/l_w	ρ_{sf} (%)
W1	6.95	72.5	1.833	0.5	no flange

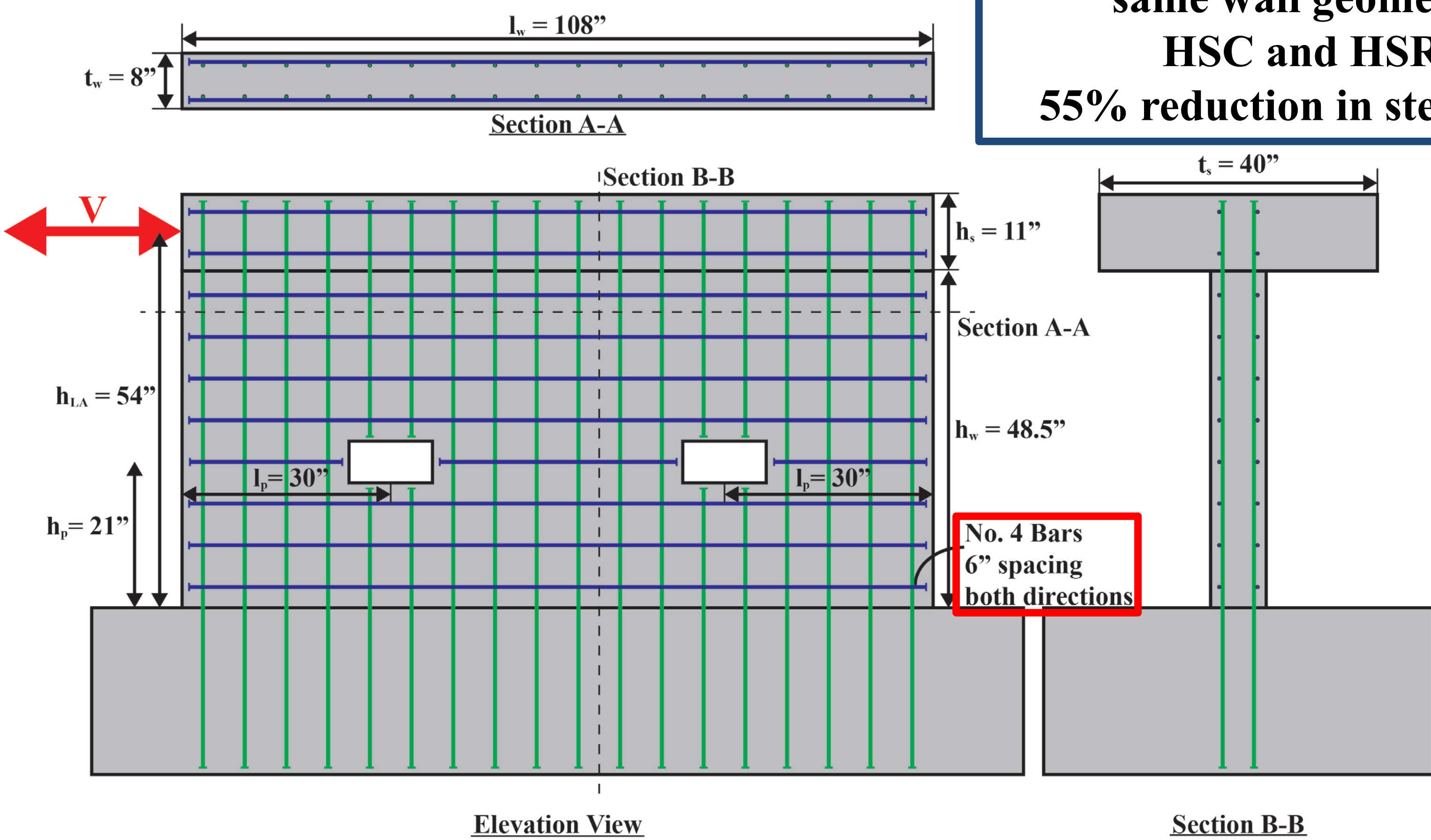
state-of-practice materials and rebar layout



Wall Layouts – W2 (1:6.5 Scale)

Specimen	f'_c (ksi)	f_y (ksi)	ρ_{sw} (%)	h_{LA}/l_w	ρ_{sf} (%)
W2	**14.8**	**122**	**0.833**	0.5	no flange

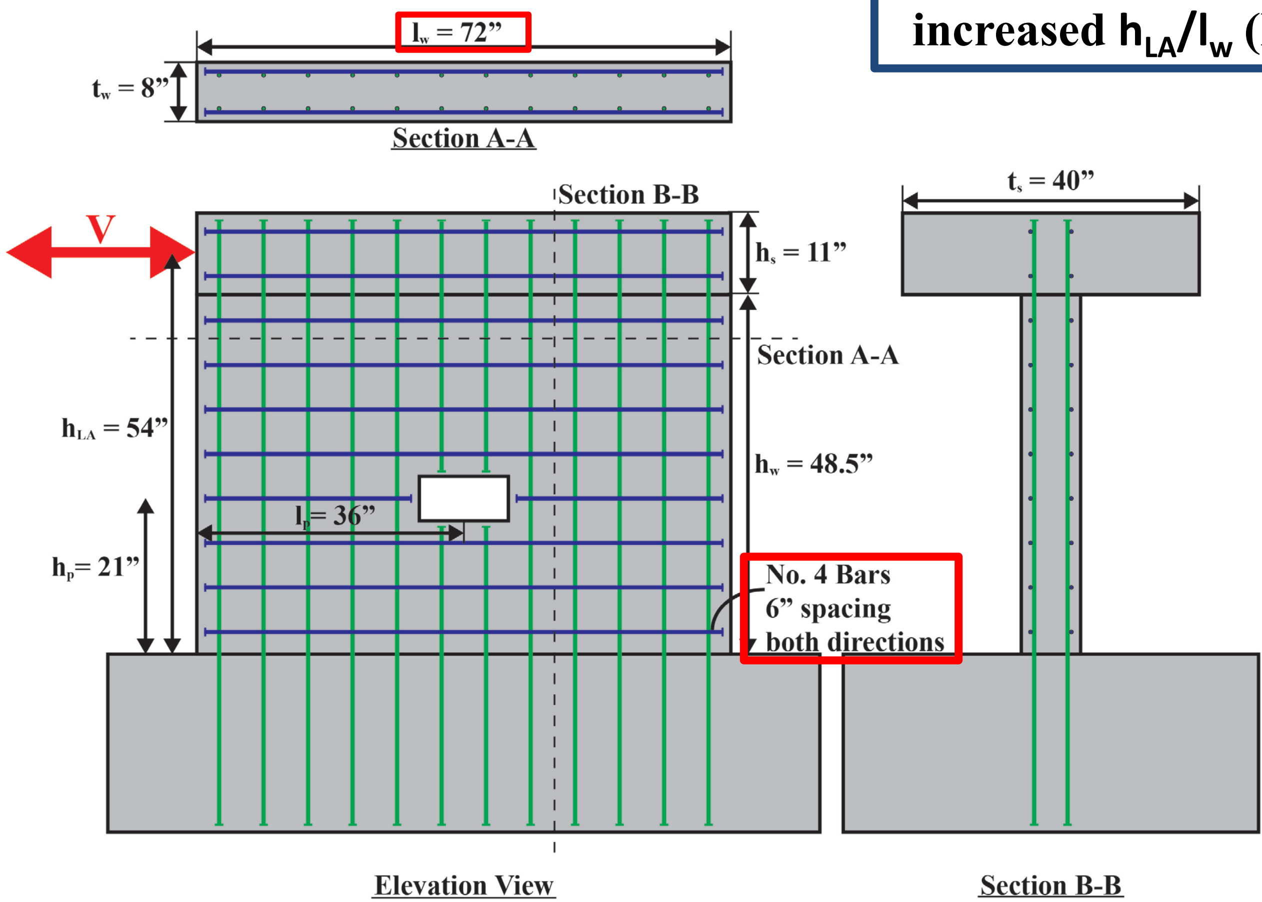
same wall geometry
HSC and HSR
55% reduction in steel area



Wall Layouts – W3 (1:6.5 Scale)

Specimen	f'_c (ksi)	f_y (ksi)	ρ_{sw} (%)	h_{LA}/l_w	ρ_{sf} (%)
W3	14.2	122	0.833	**0.75**	no flange

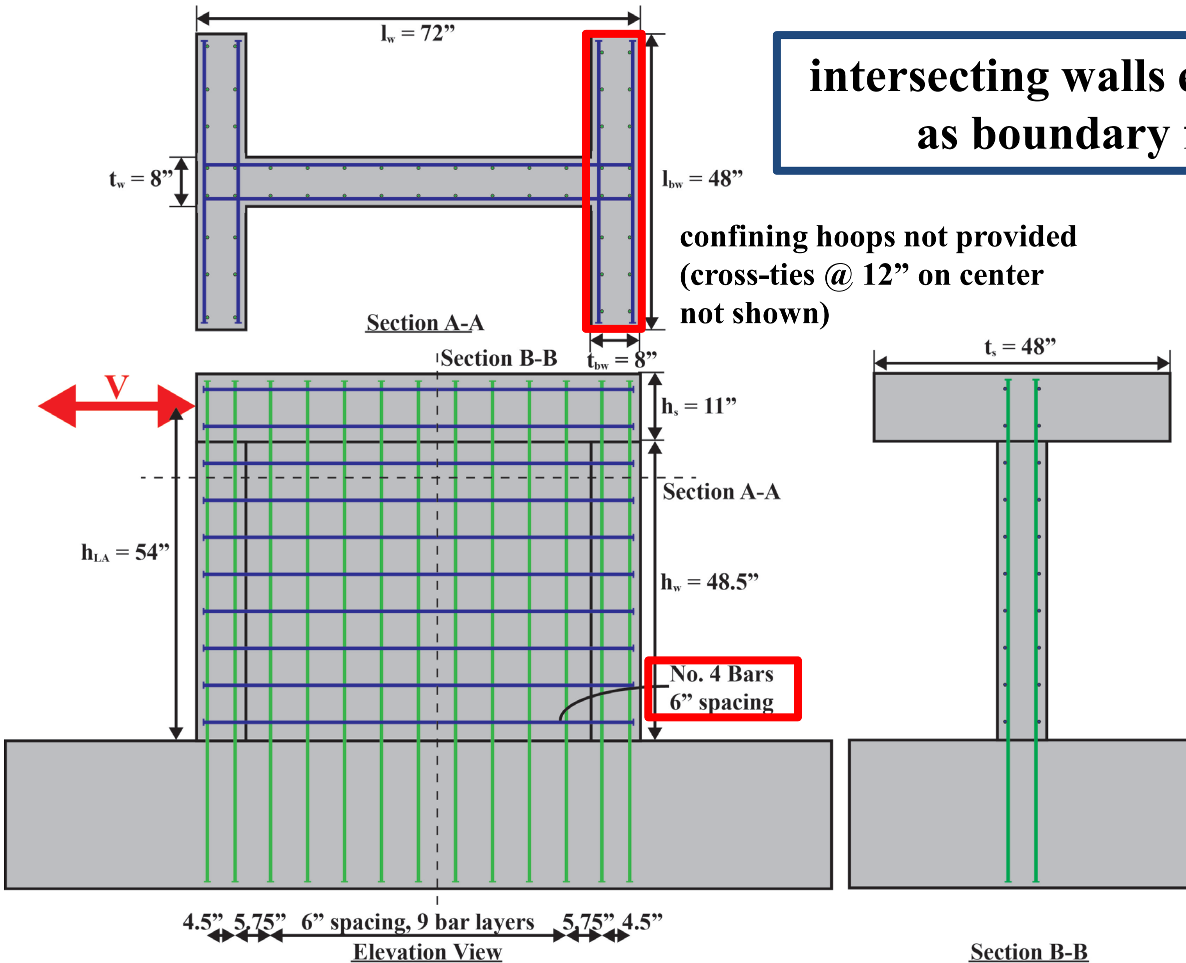
increased h_{LA}/l_w (less than 2.0)



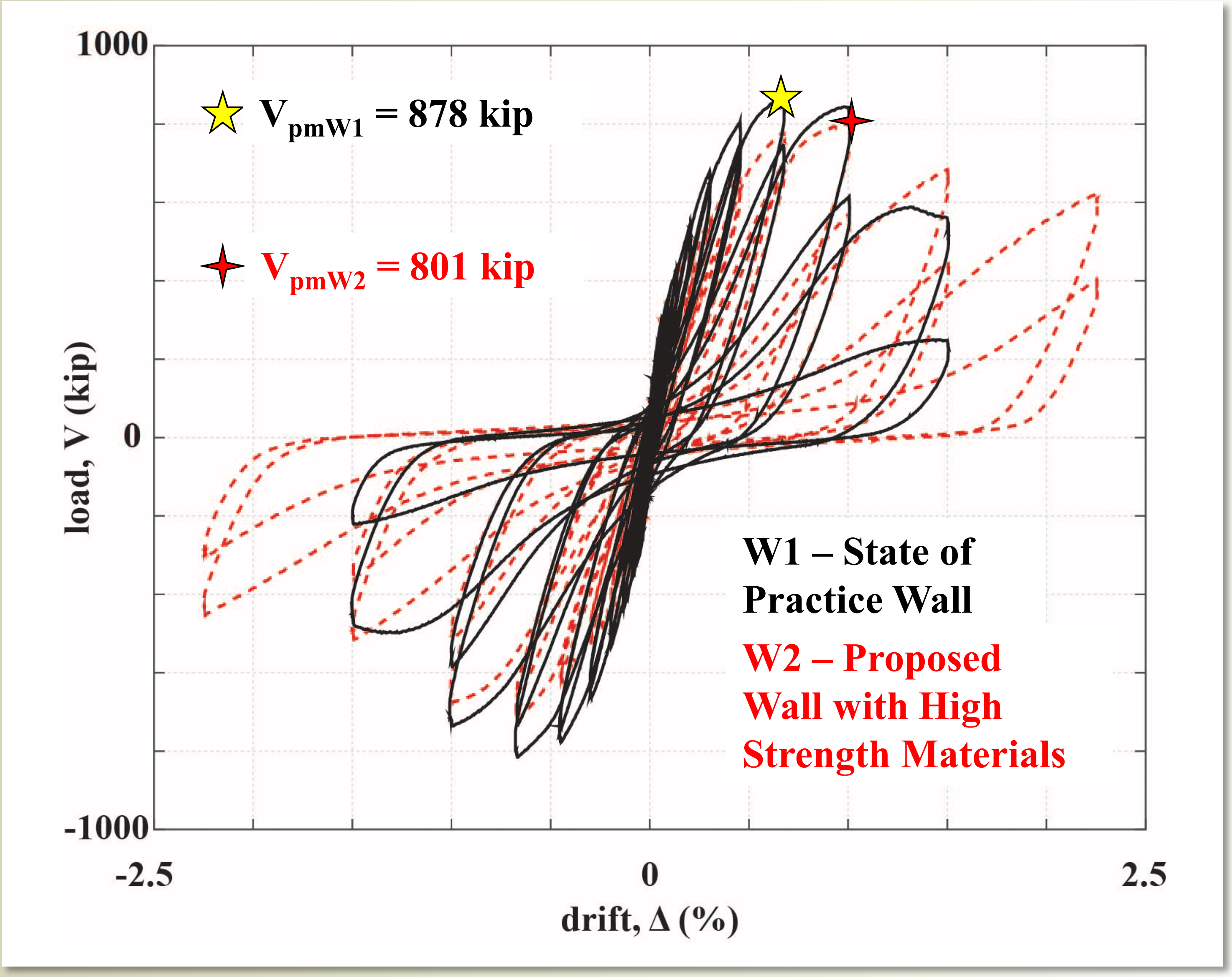
Wall Layouts – W4 (1:6.5 Scale)

Specimen	f'_c (ksi)	f_y (ksi)	ρ_{sw} (%)	h_{LA}/l_w	ρ_{sf} (%)
W4	14.0	125	0.833	0.75	**0.833**

intersecting walls effectiveness as boundary flanges



W1 versus W2 Behaviors



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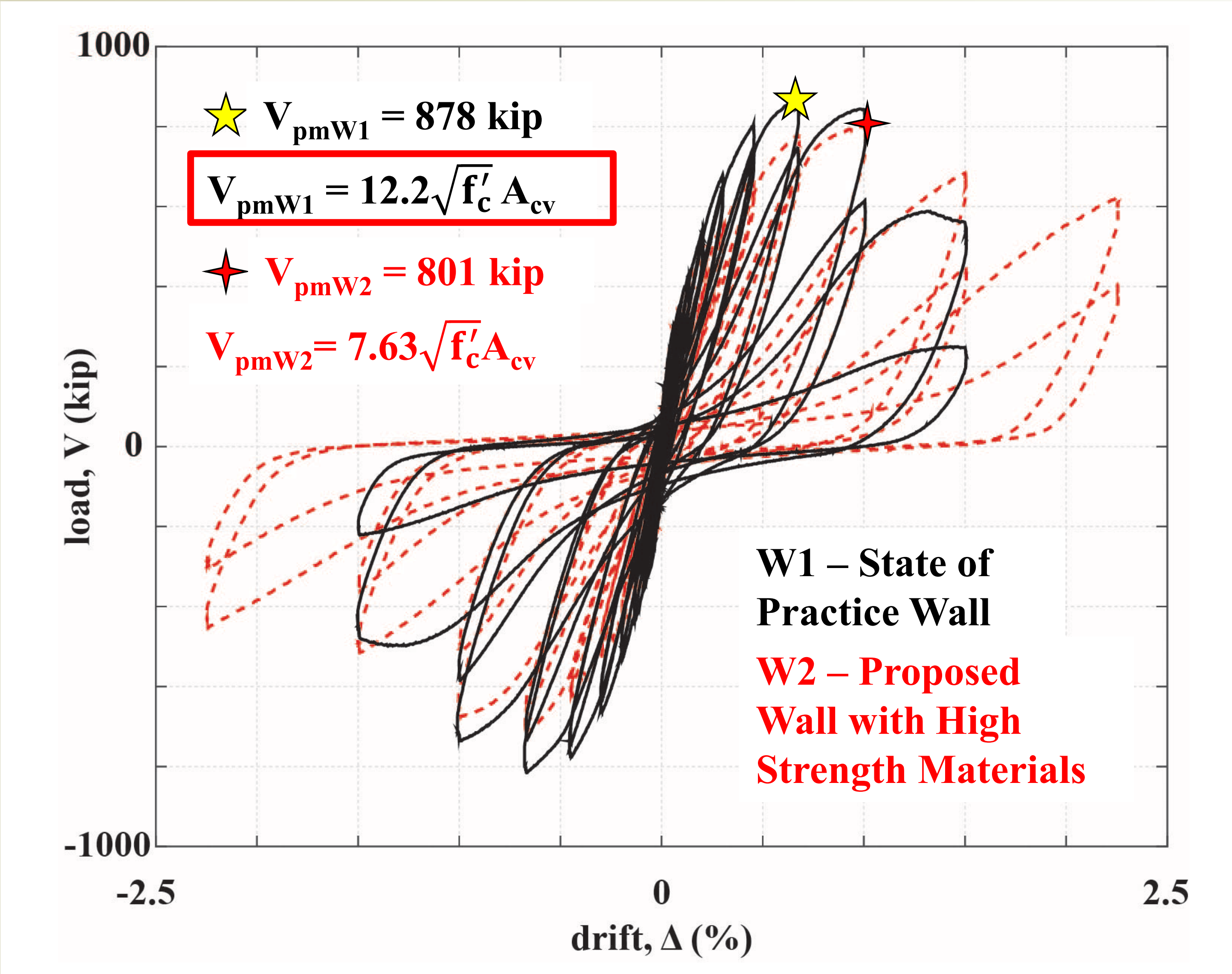

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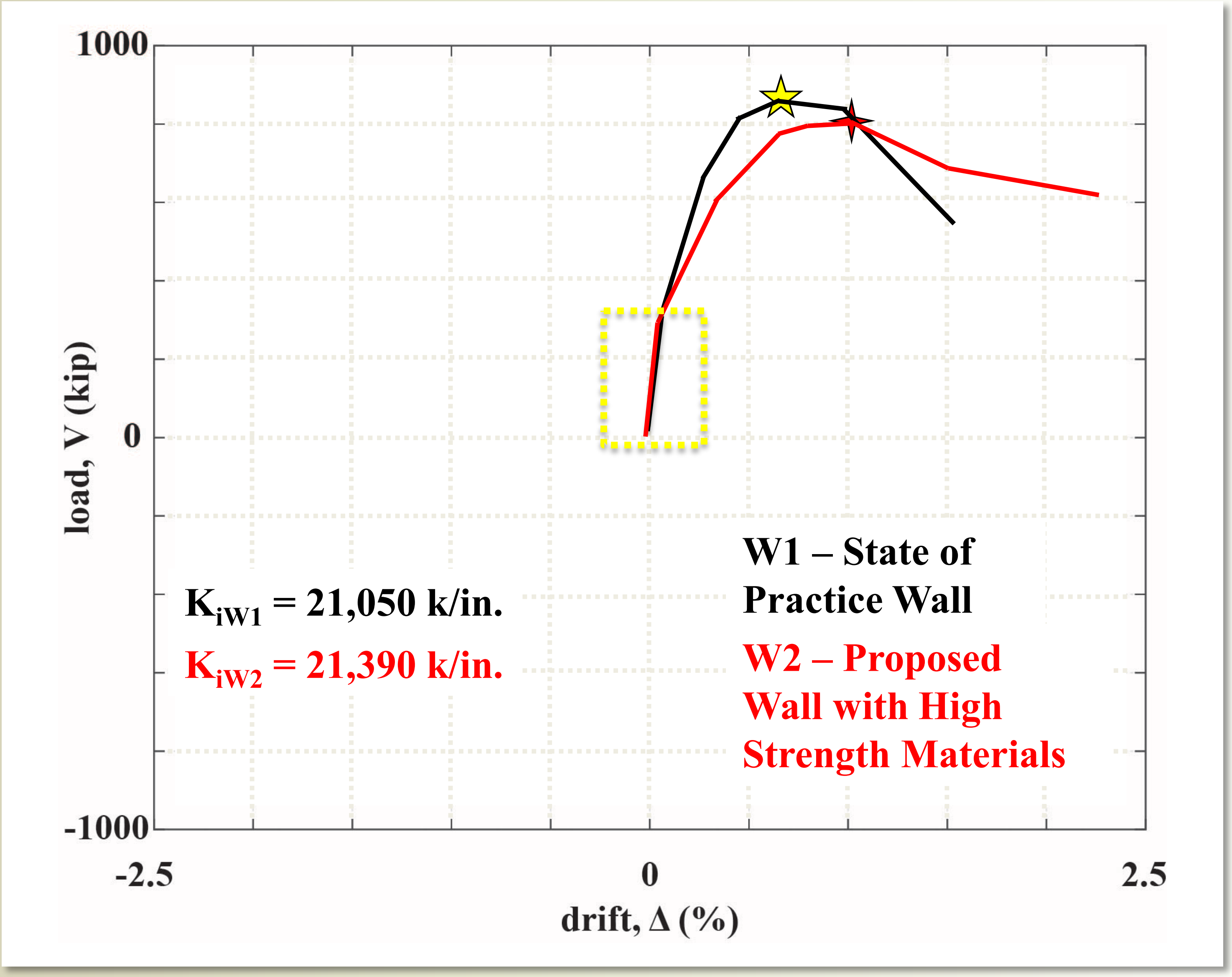

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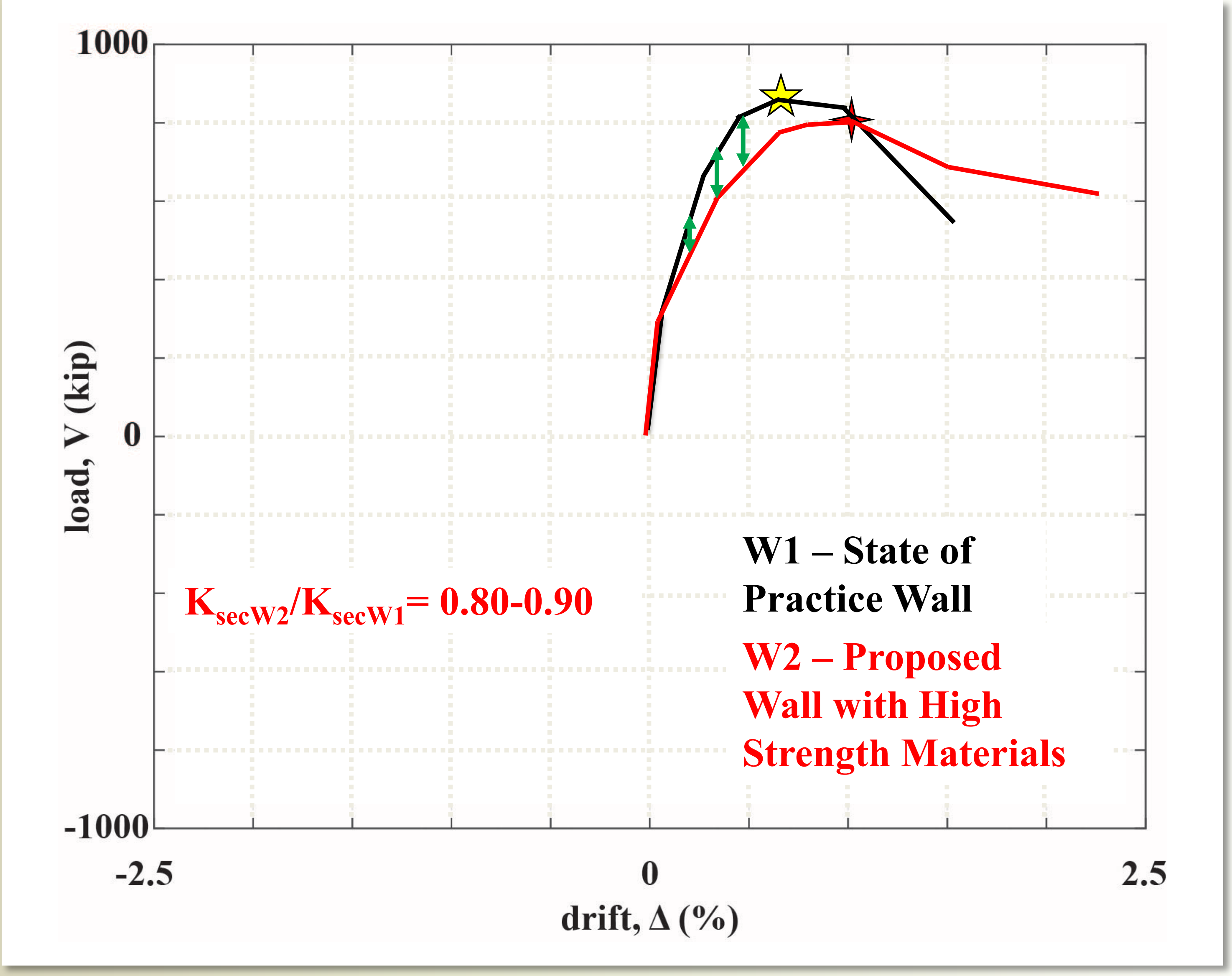

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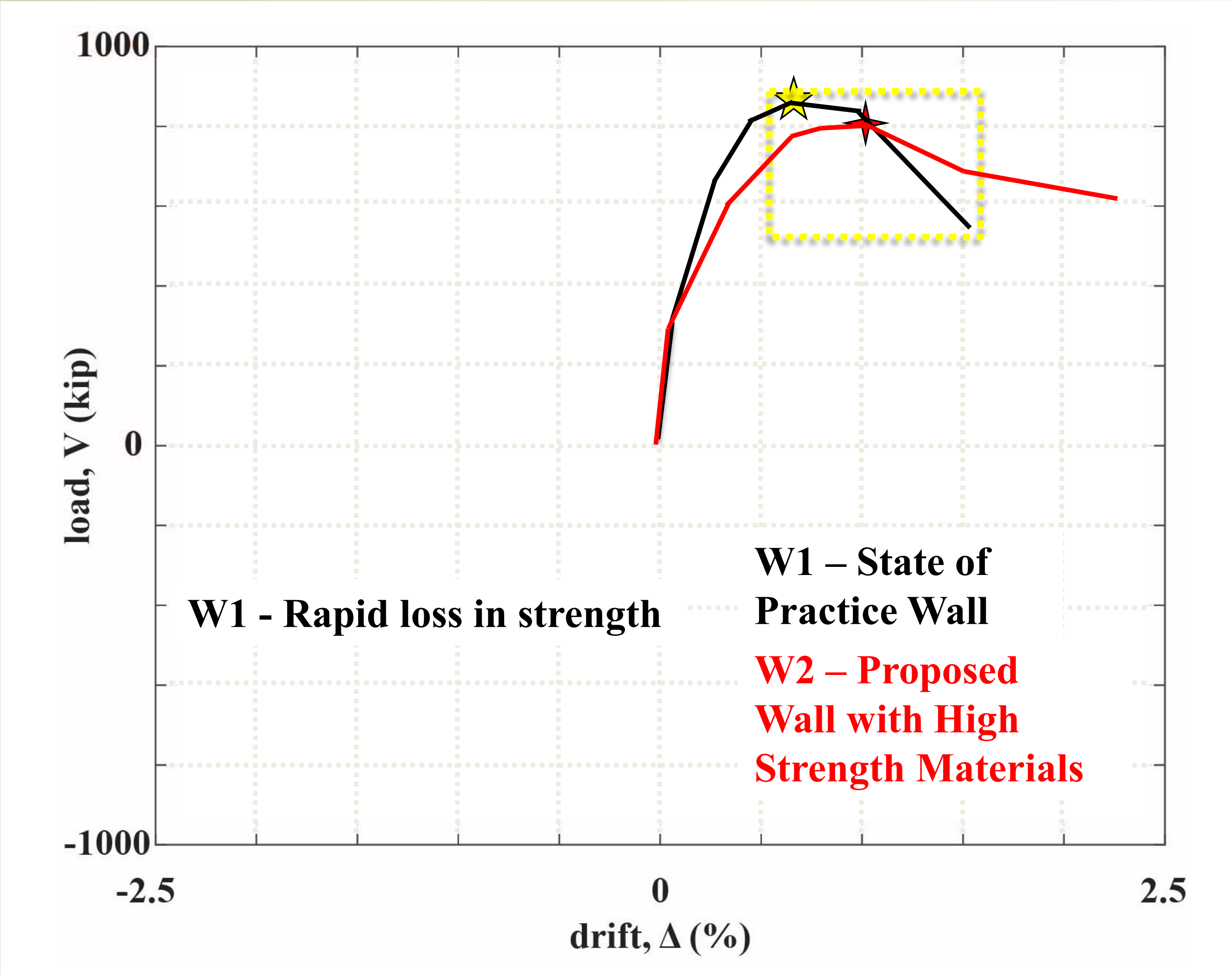
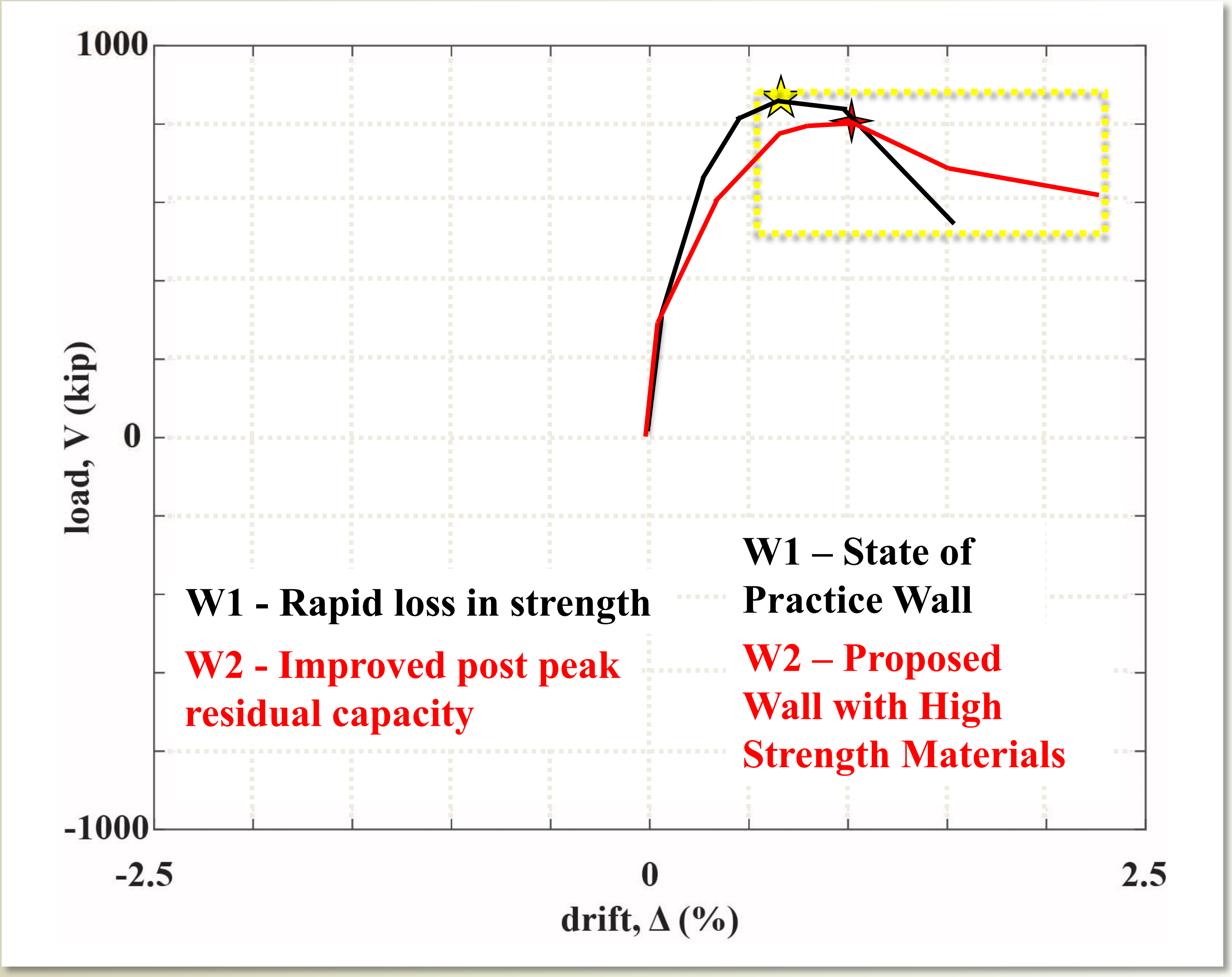
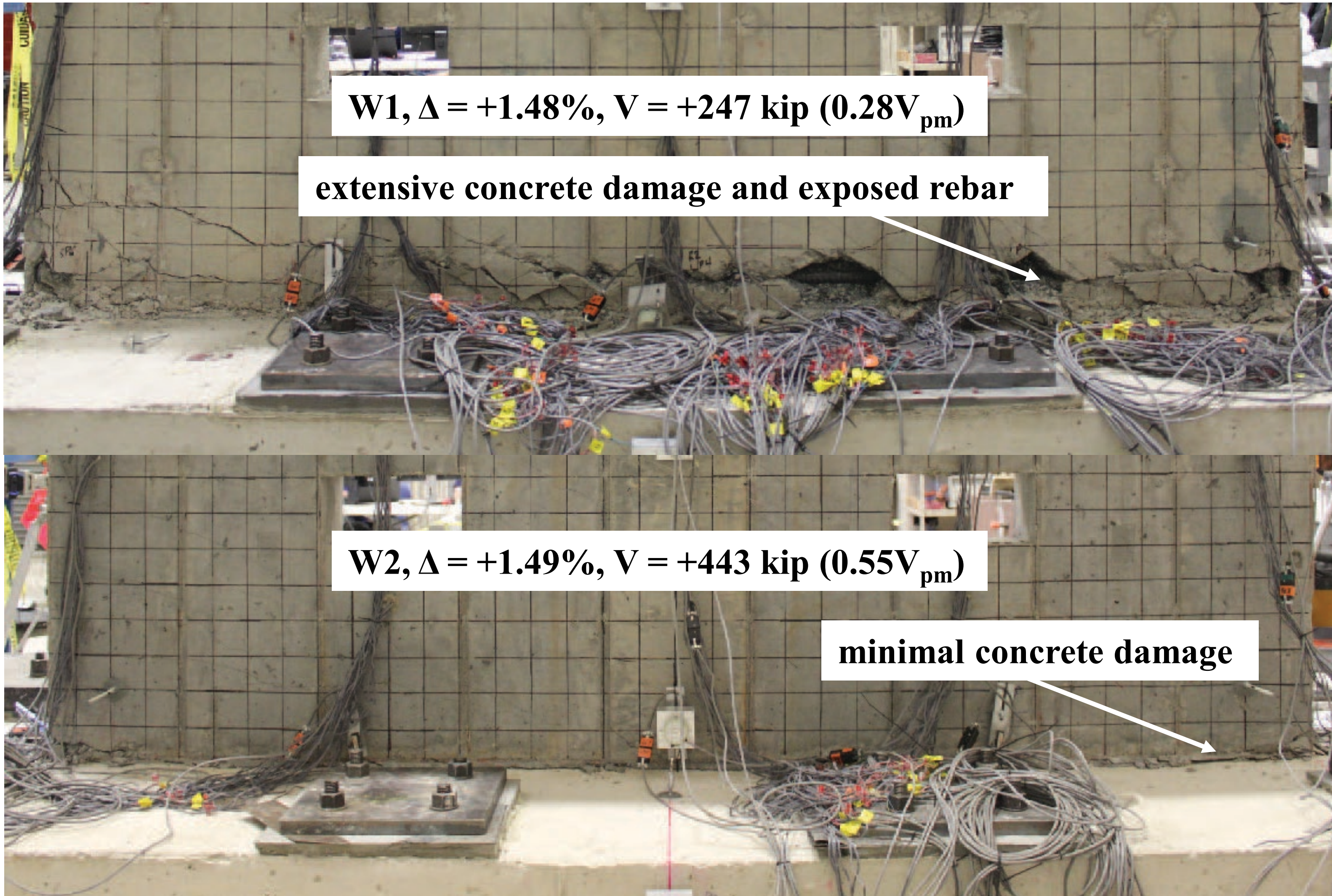


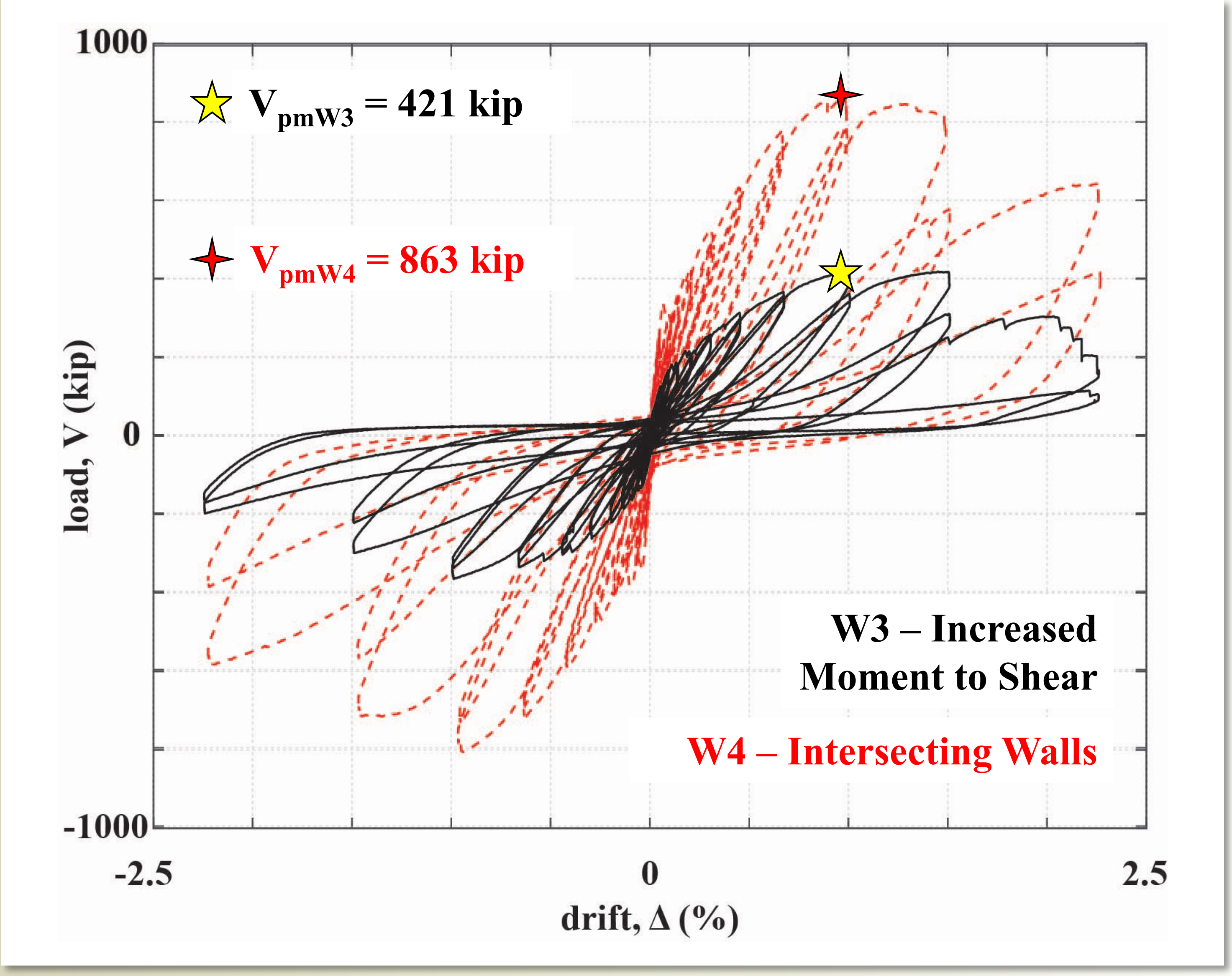
W1 versus W2 Behaviors



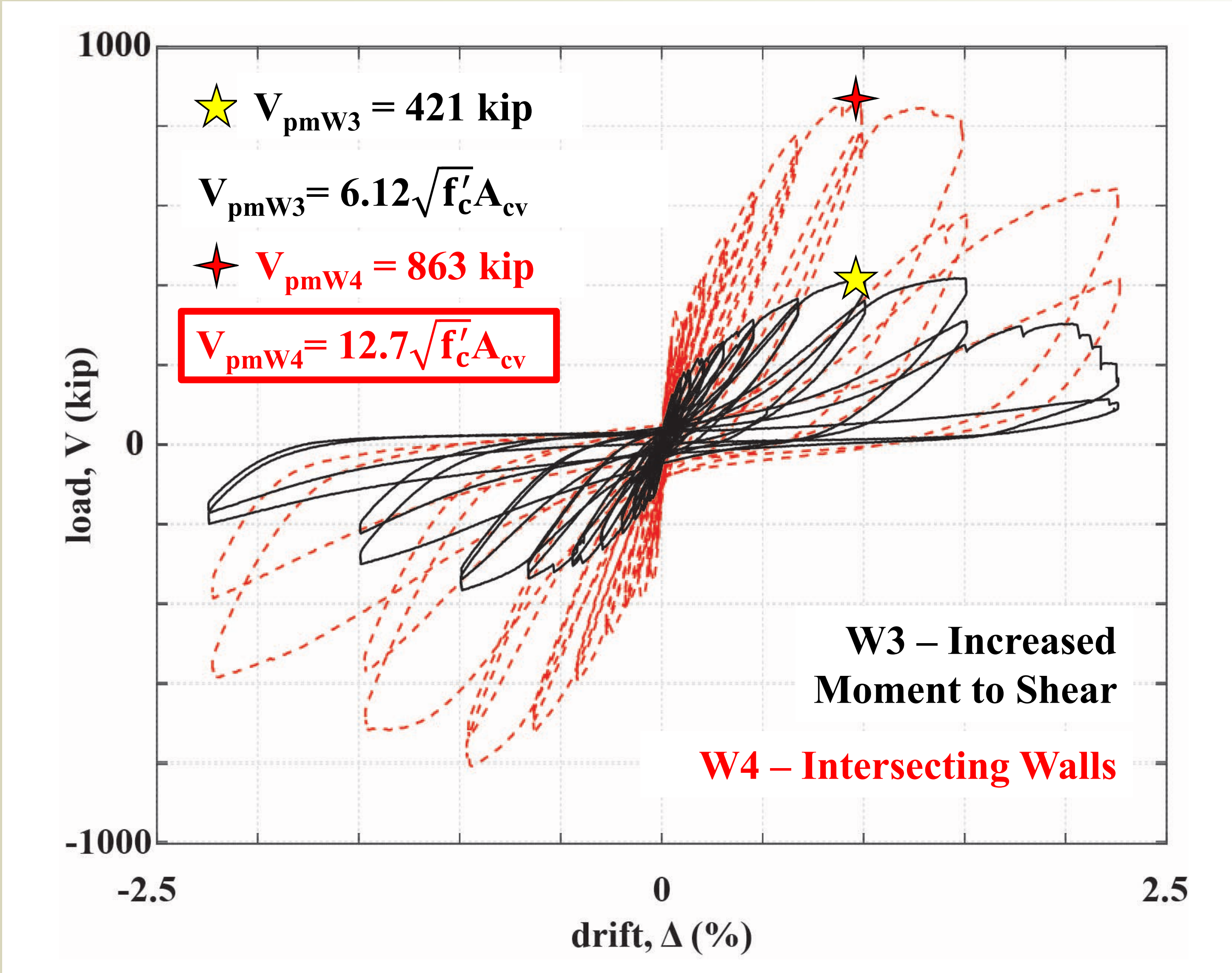
W1 & W2 Post Peak Behavior



W3 versus W4 Behaviors



W3 versus W4 Behaviors



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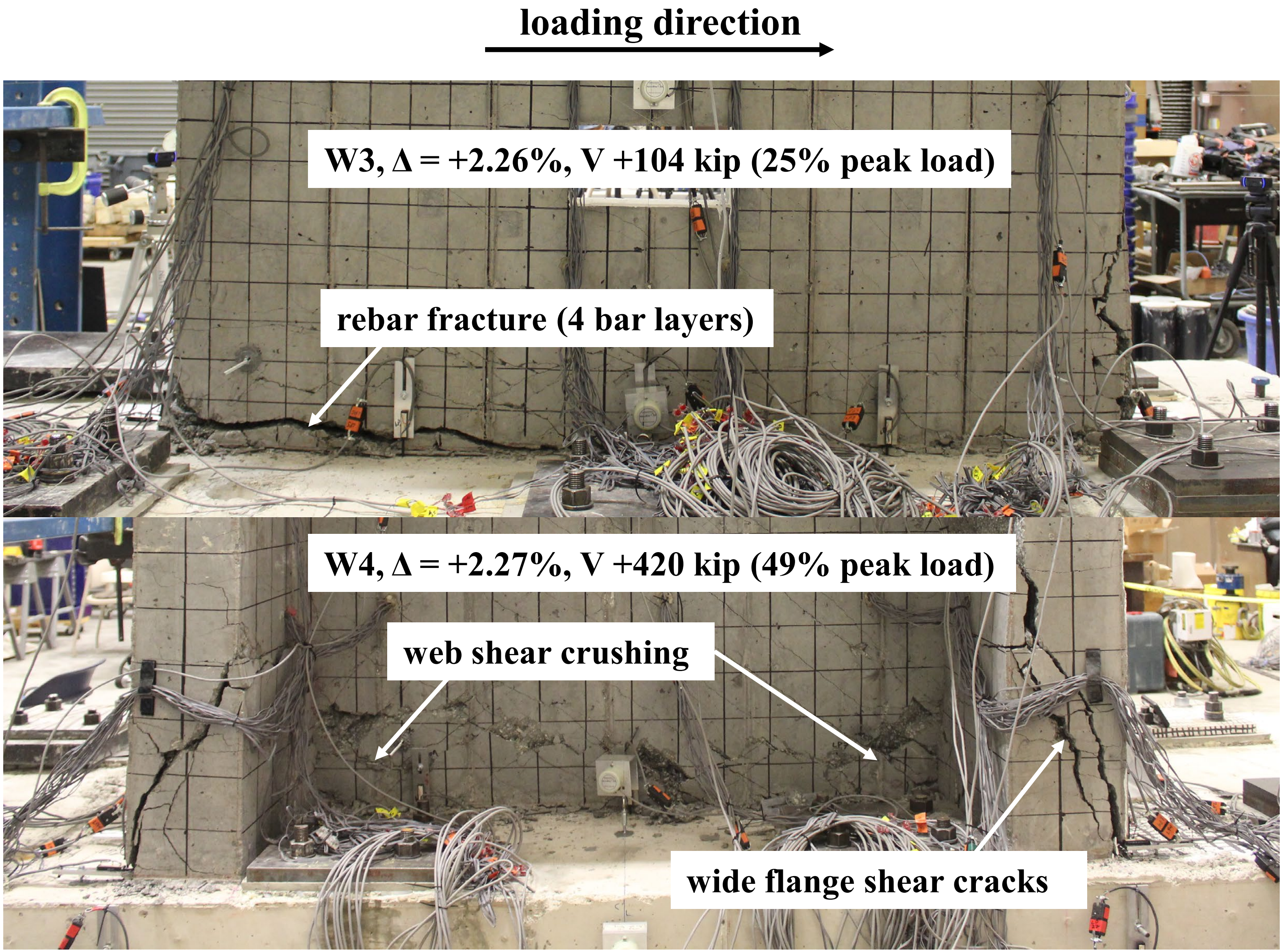
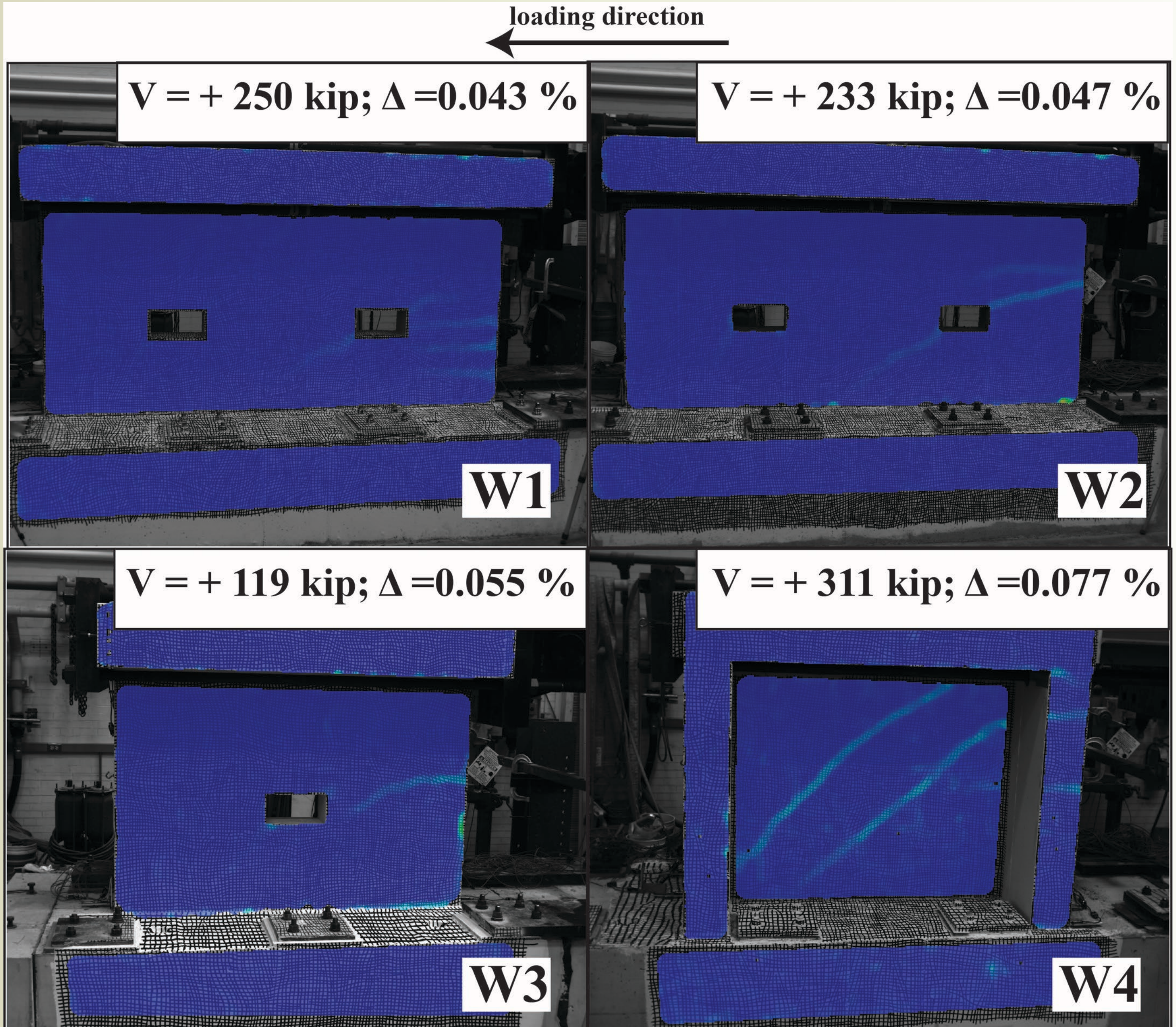


Initial Cracking Behaviors



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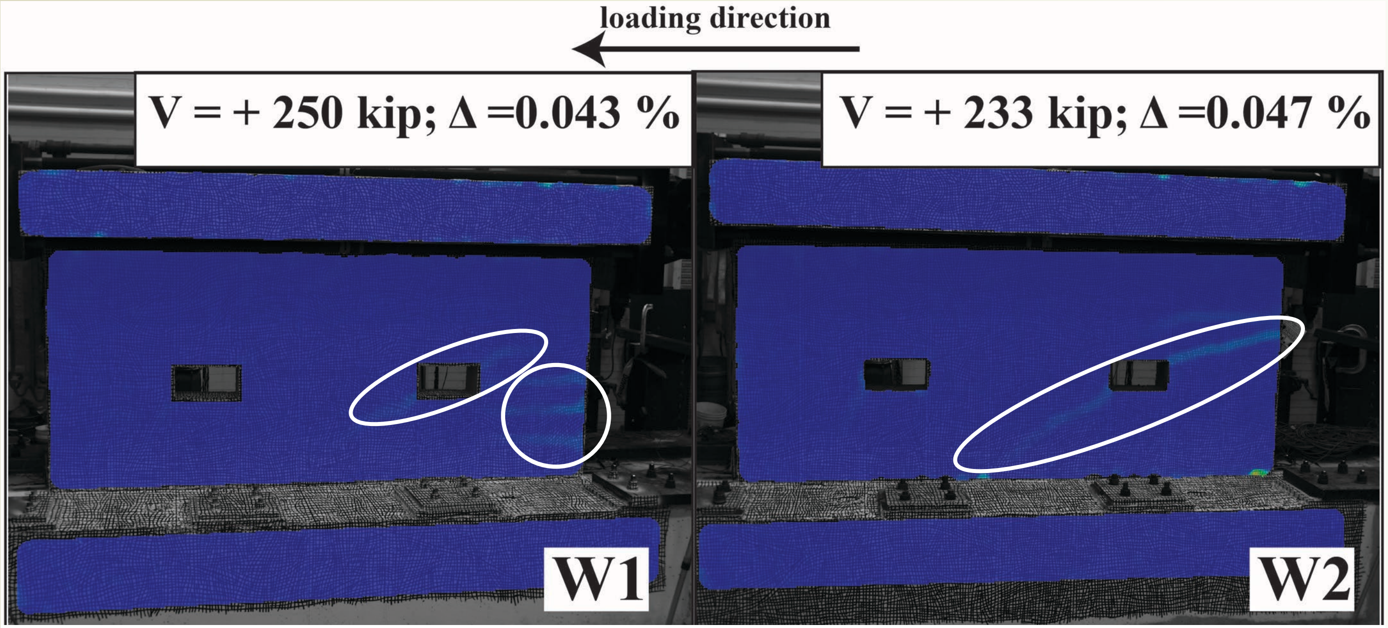
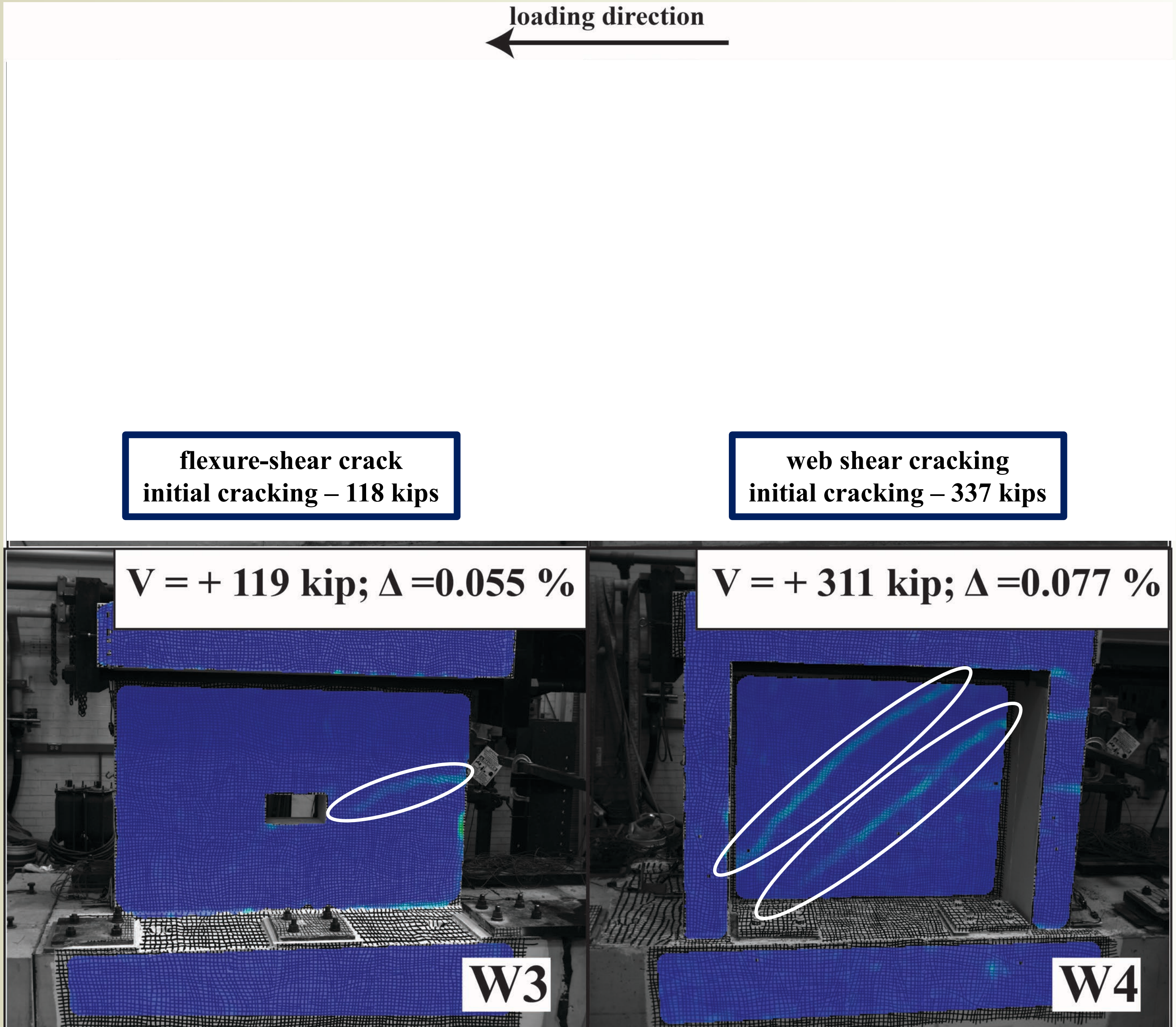


horizontal and diagonal cracks
initial cracking – 89 kips
initial diagonal crack – 226 kips

isolated diagonal crack
initial crack – 252 kips

Initial Cracking Behaviors



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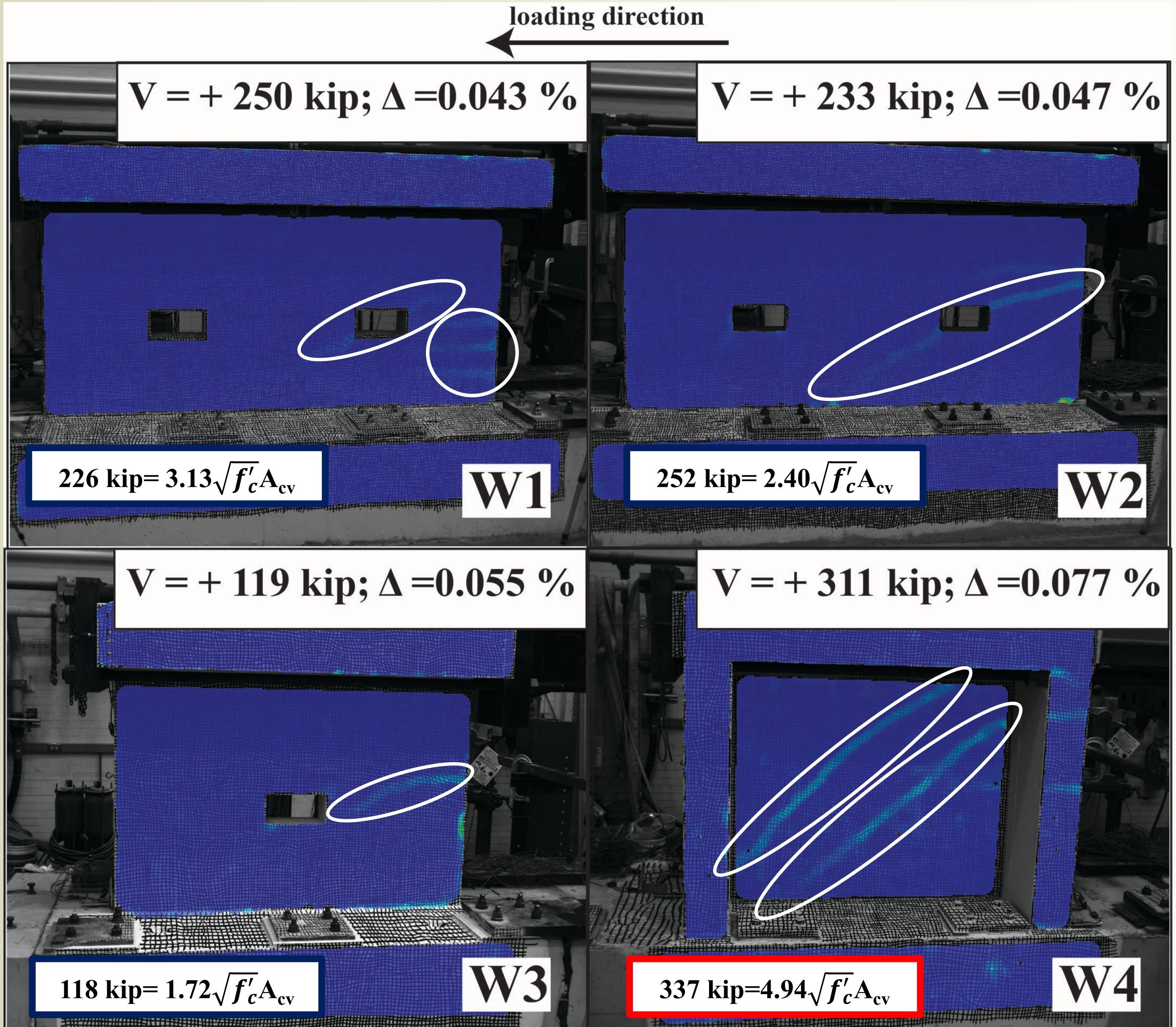
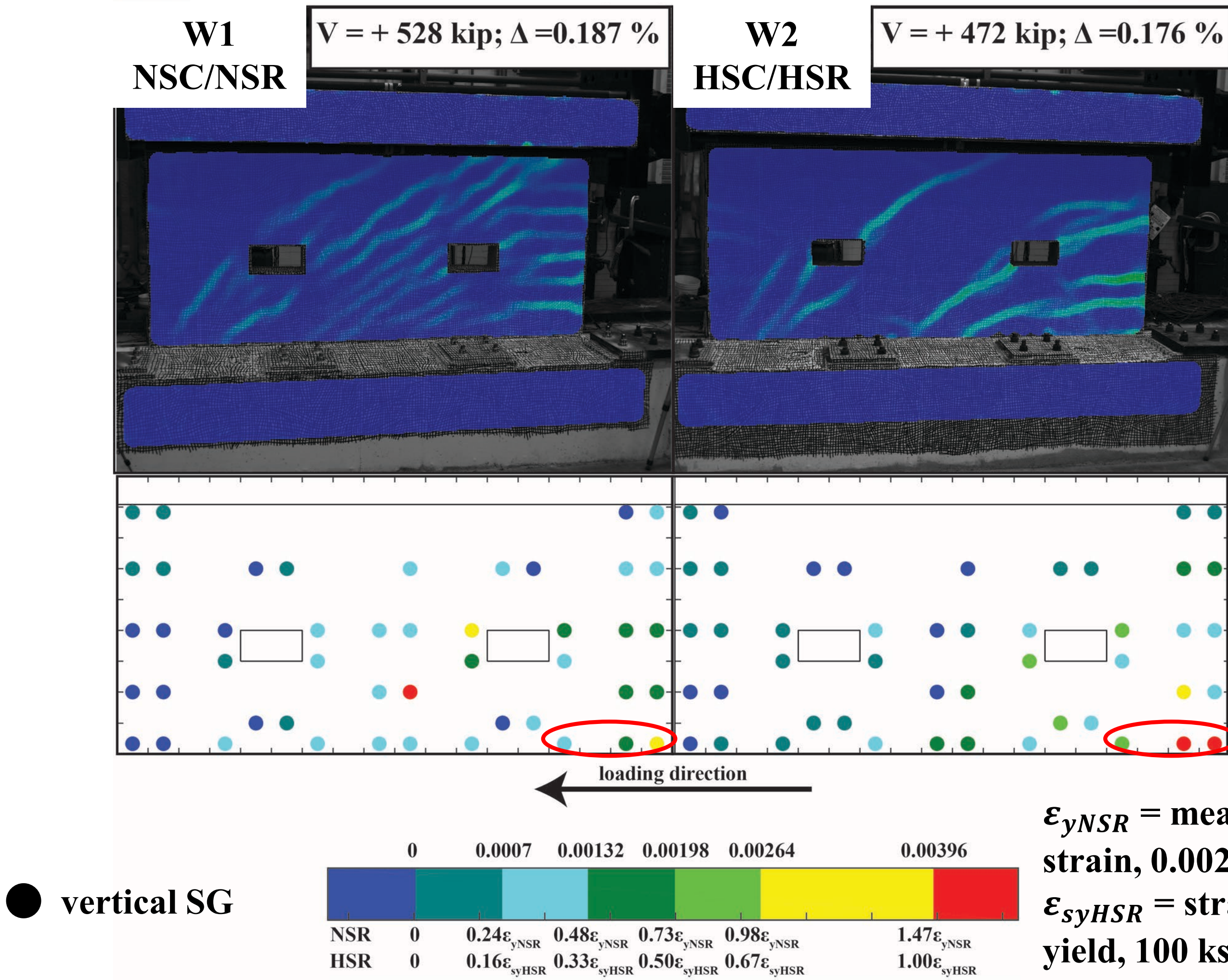


W1 & W2 Reinforcement Strains

rebar yielding immediately above cold joint



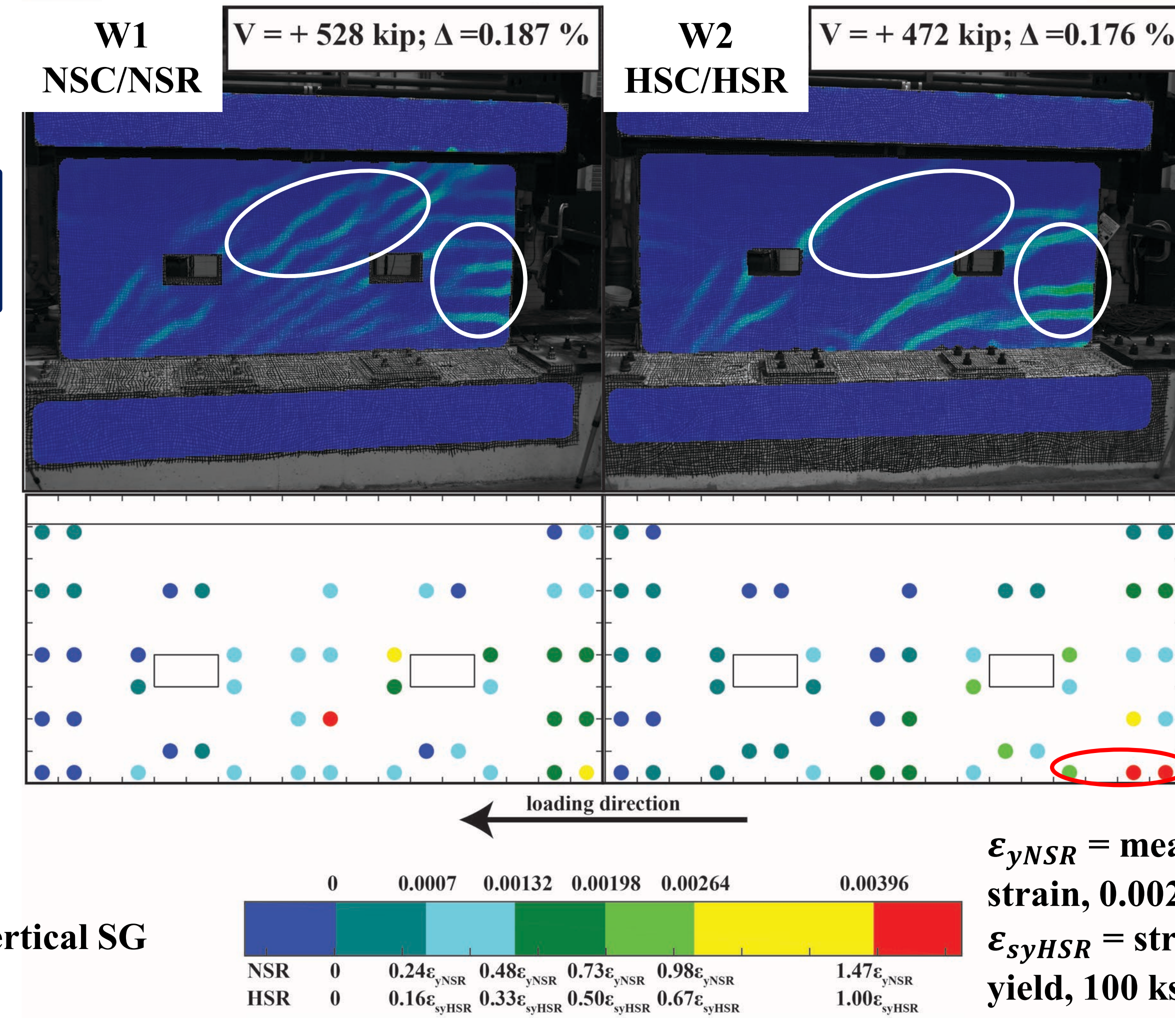
ε_{yNSR} = measured yield strain, 0.00270

ε_{syHSR} = strain at specified yield, 100 ksi, 0.00396

W1 & W2 Reinforcement Strains

rebar yielding immediately above cold joint

more distributed cracking



fewer cracks

● vertical SG

ε_{yNSR} = measured yield strain, 0.00270

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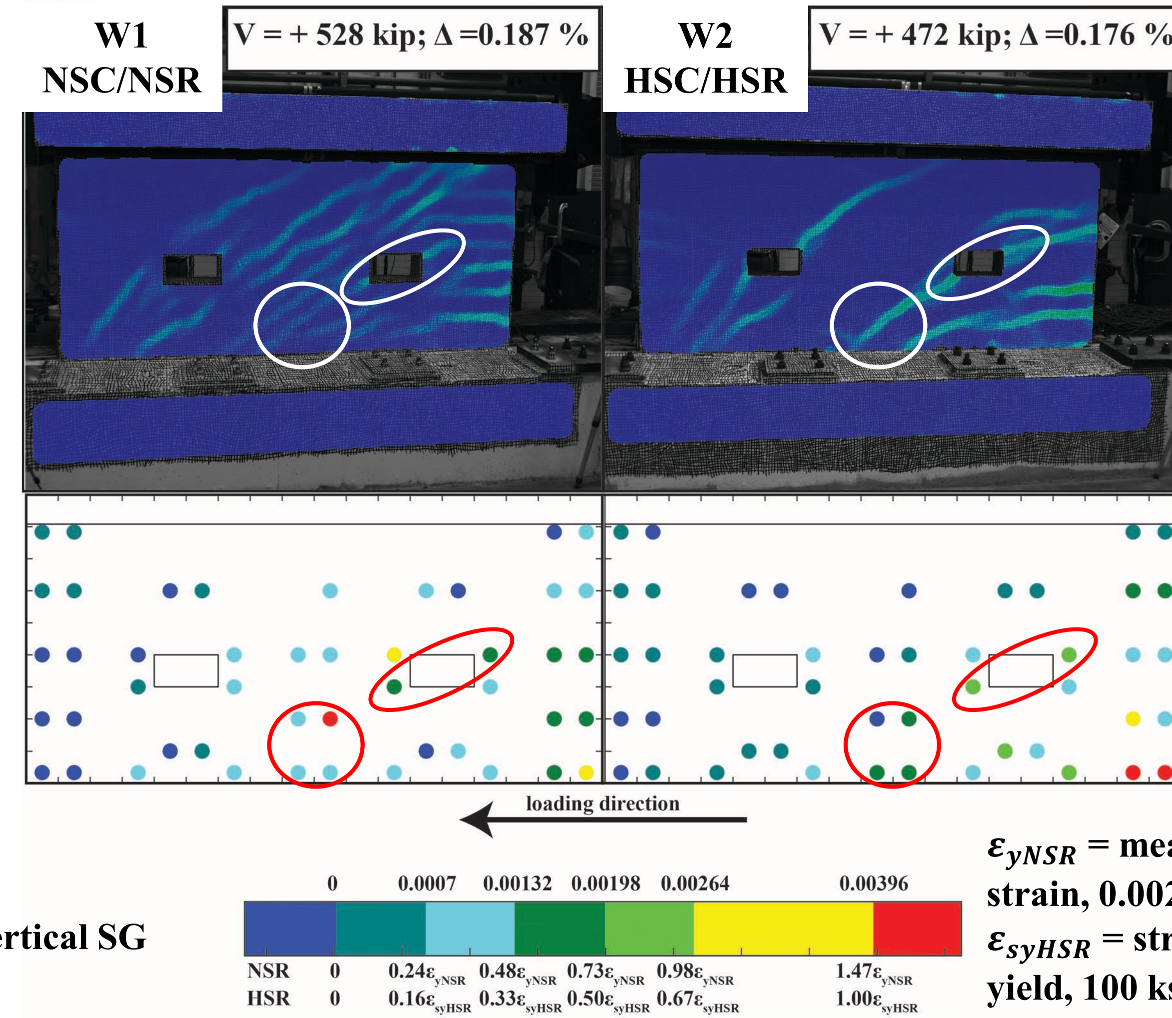
W1 & W2 Reinforcement Strains

rebar yielding immediately above cold joint



larger strains, but proportionally to ε_y

● vertical SG

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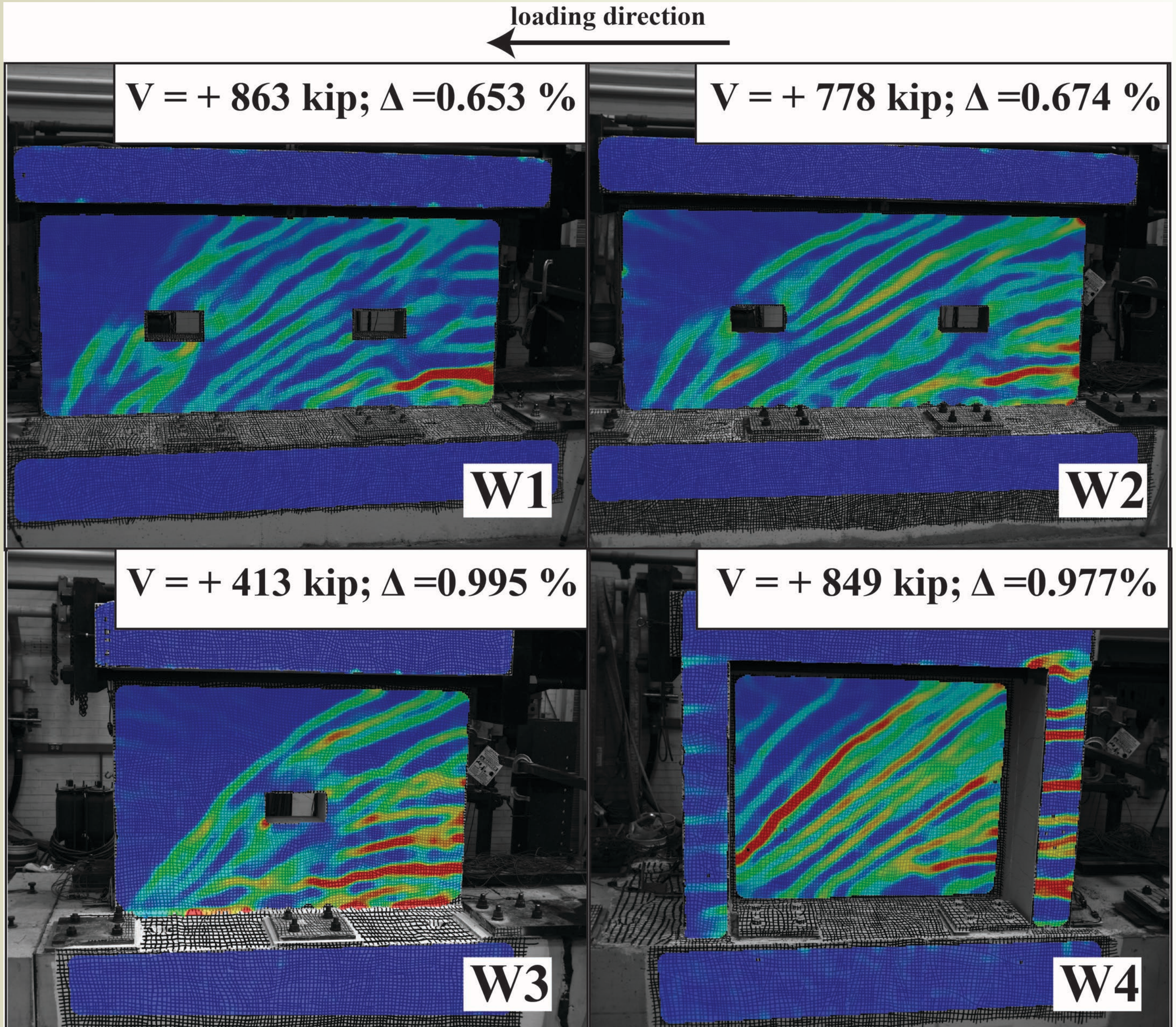
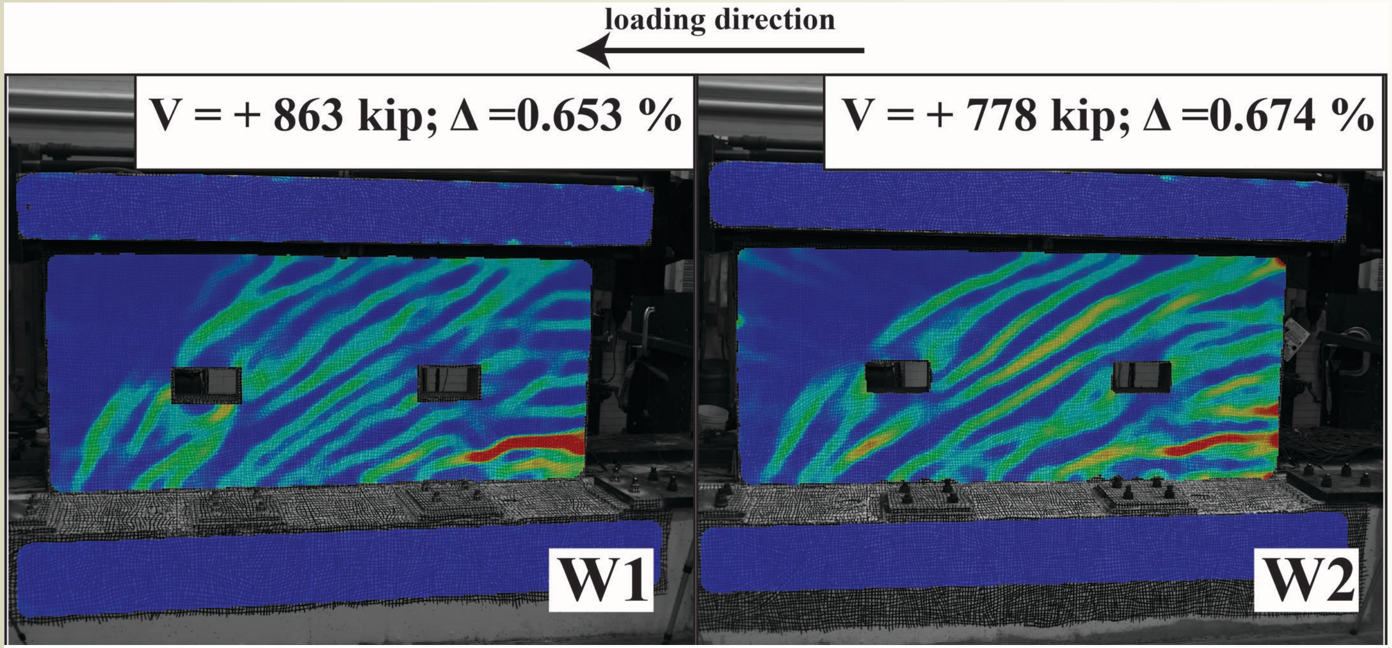
Peak Load Cracking Behaviors



Peak Load Cracking Behaviors

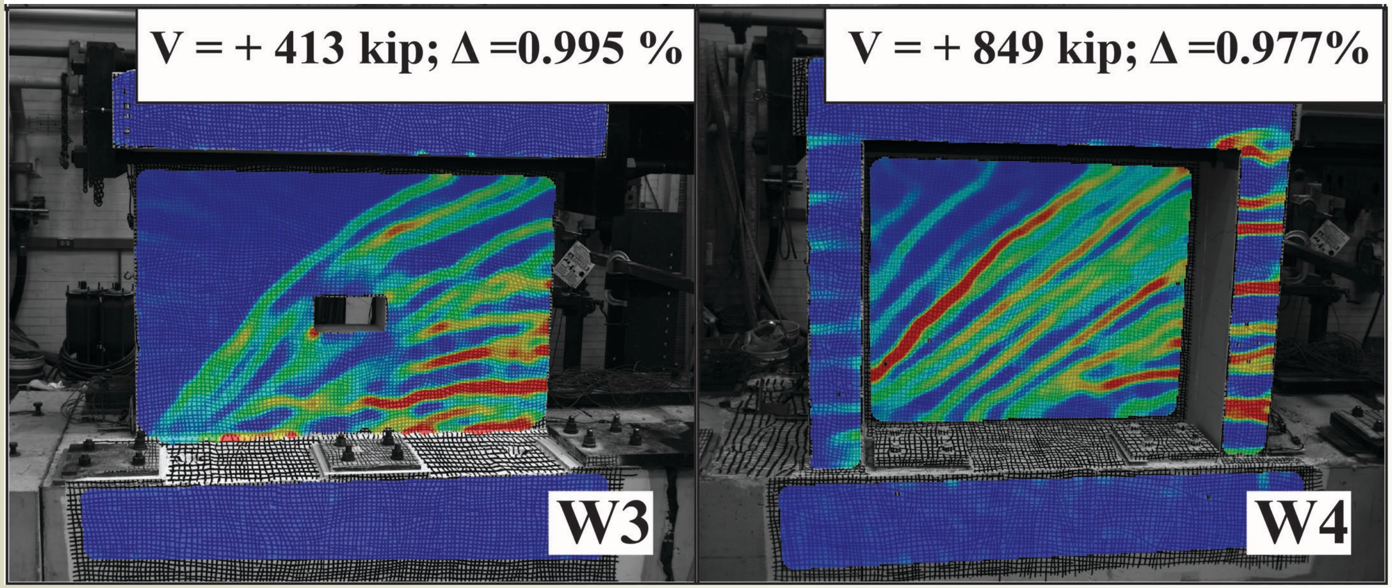


similar cracking pattern

Peak Load Cracking Behaviors

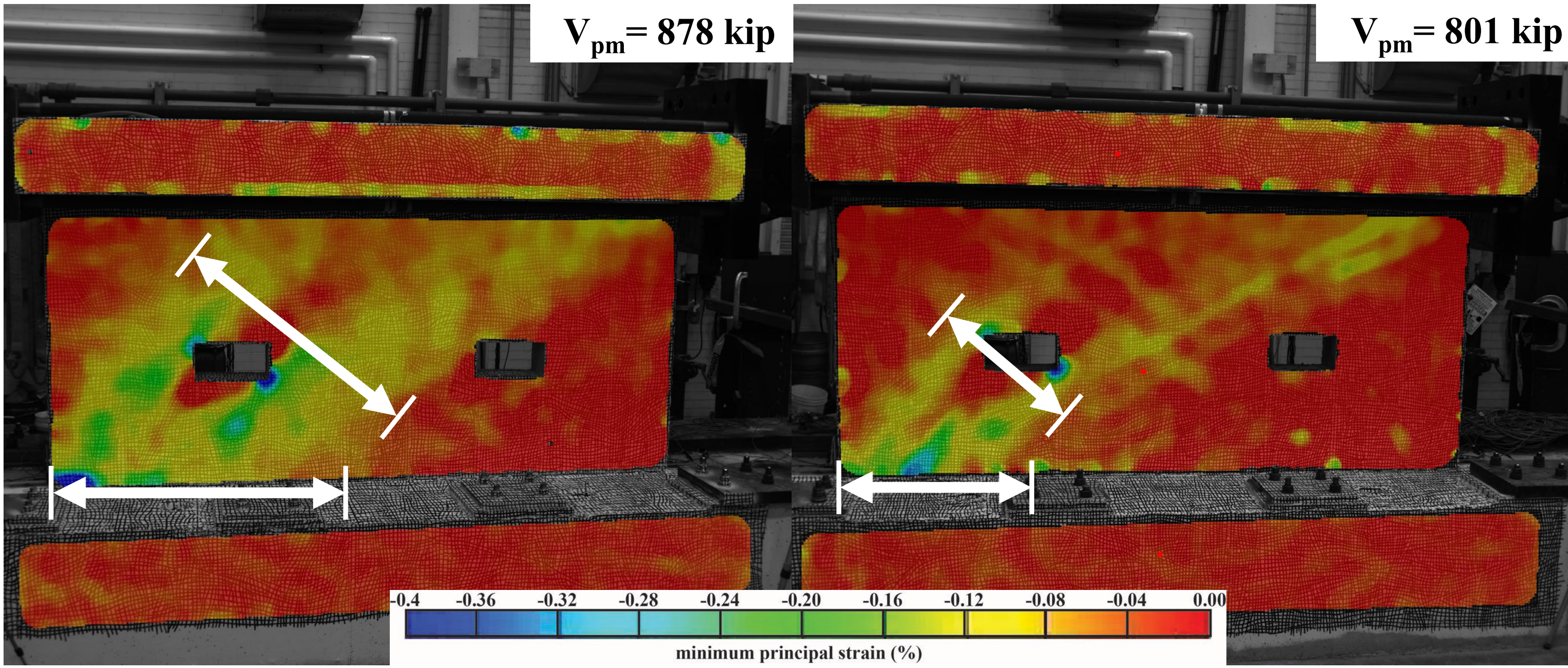
loading direction

W3 – more flexure-shear cracks
W4 – horizontal in flange, diagonal in web



W1 & W2 Compression Strut

loading direction

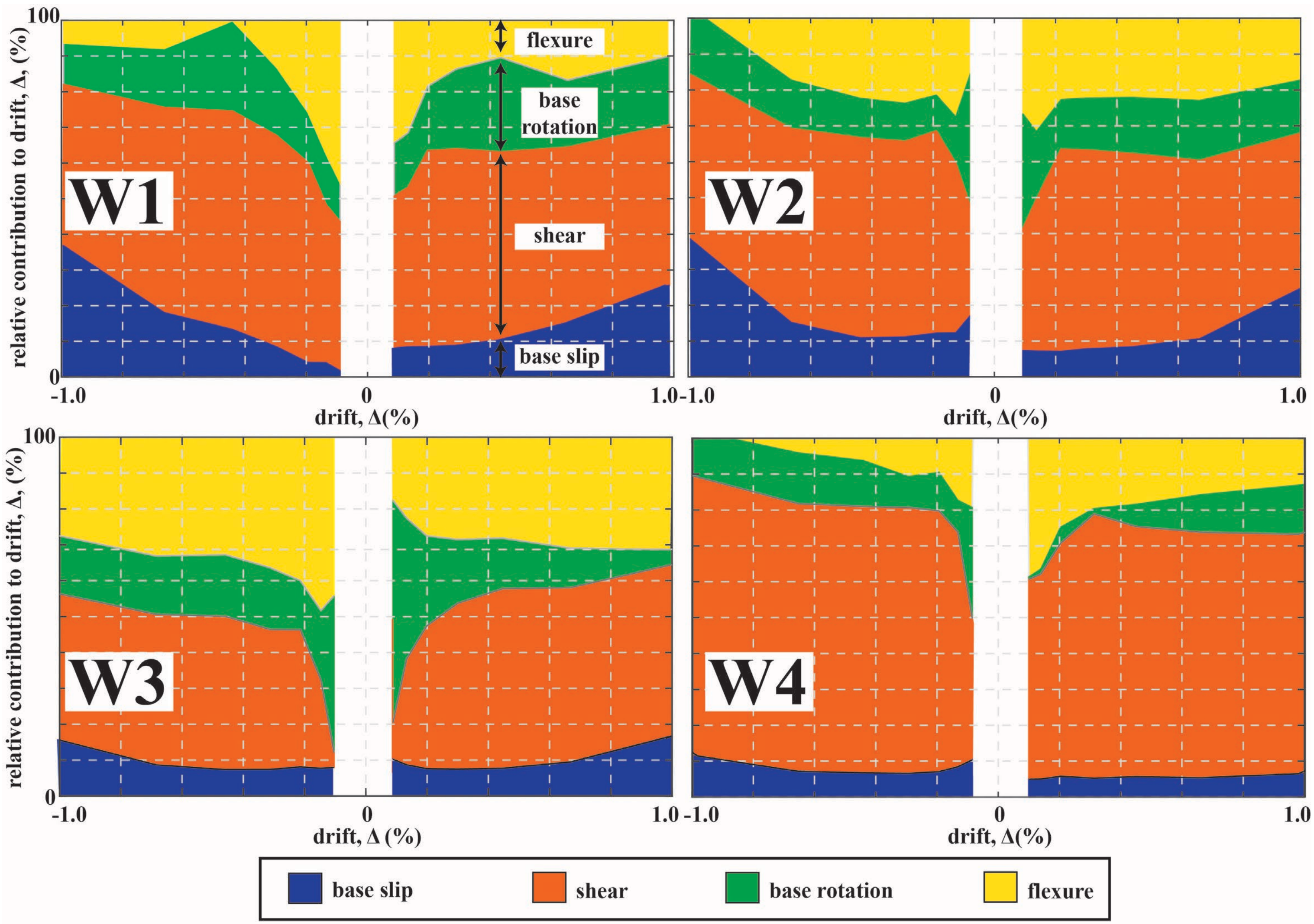


W1 – NSC/NSR

W2 – HSC/HSR

reduced compression region and diagonal strut width when using HSC

Deformation Mechanisms



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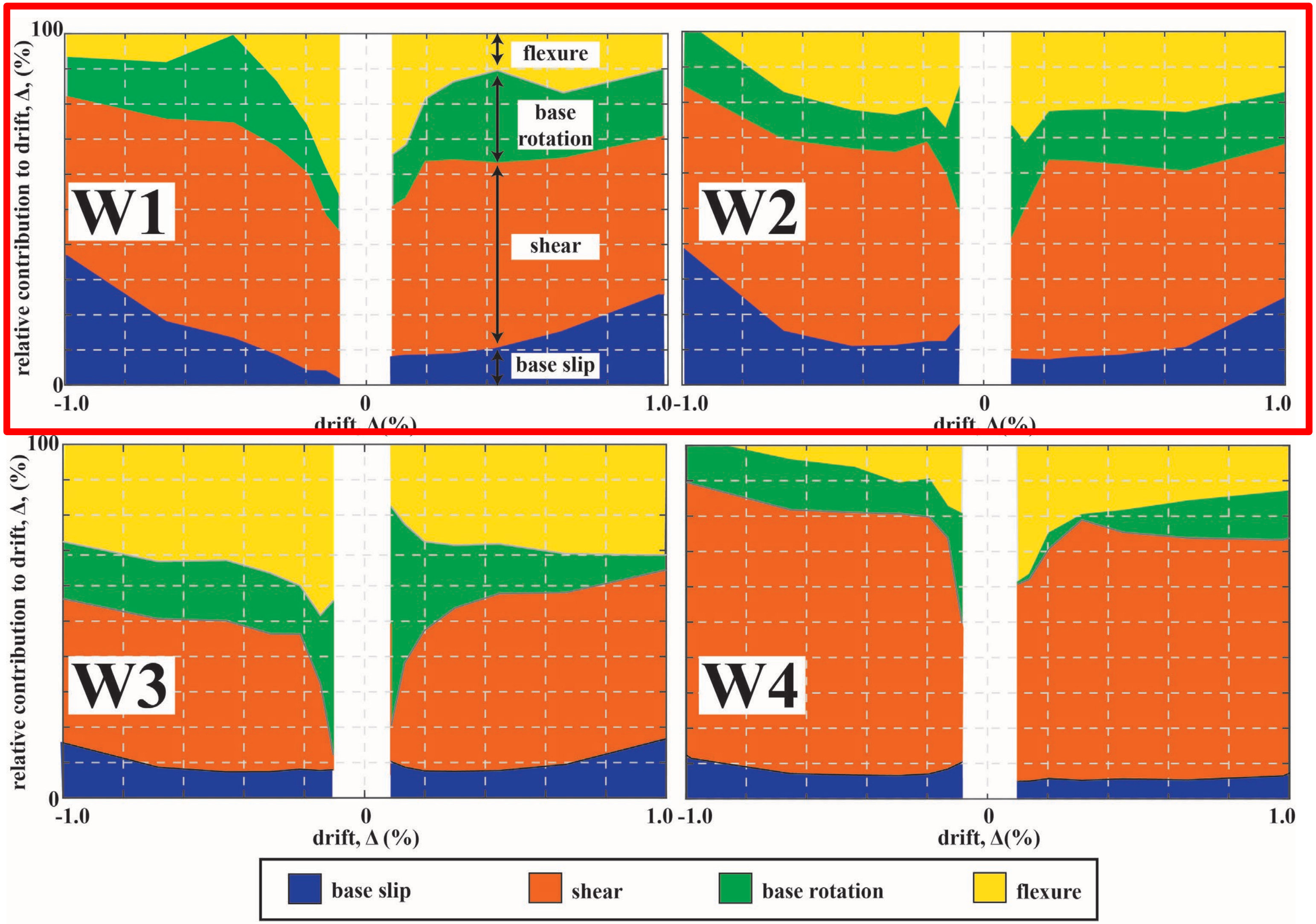
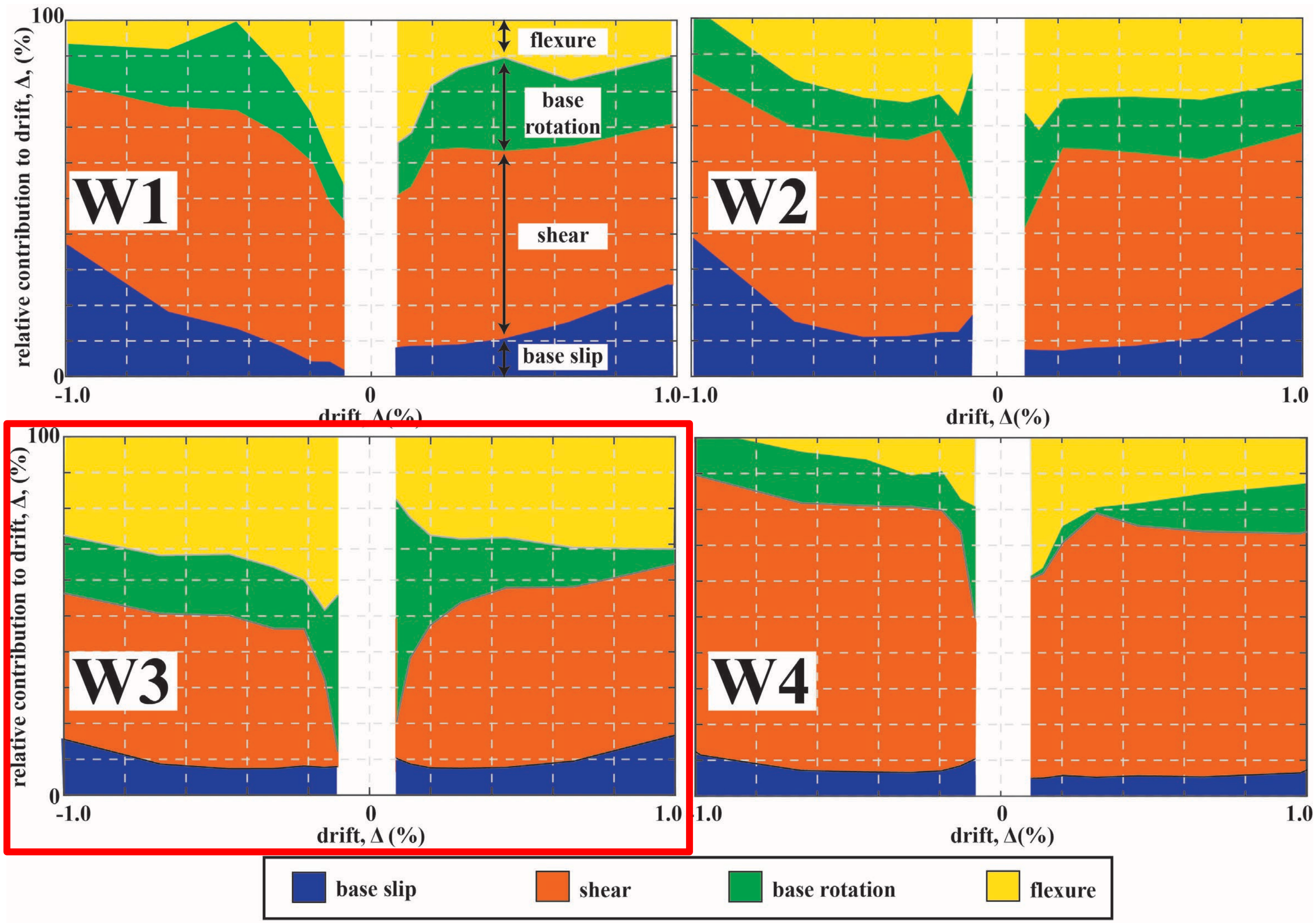


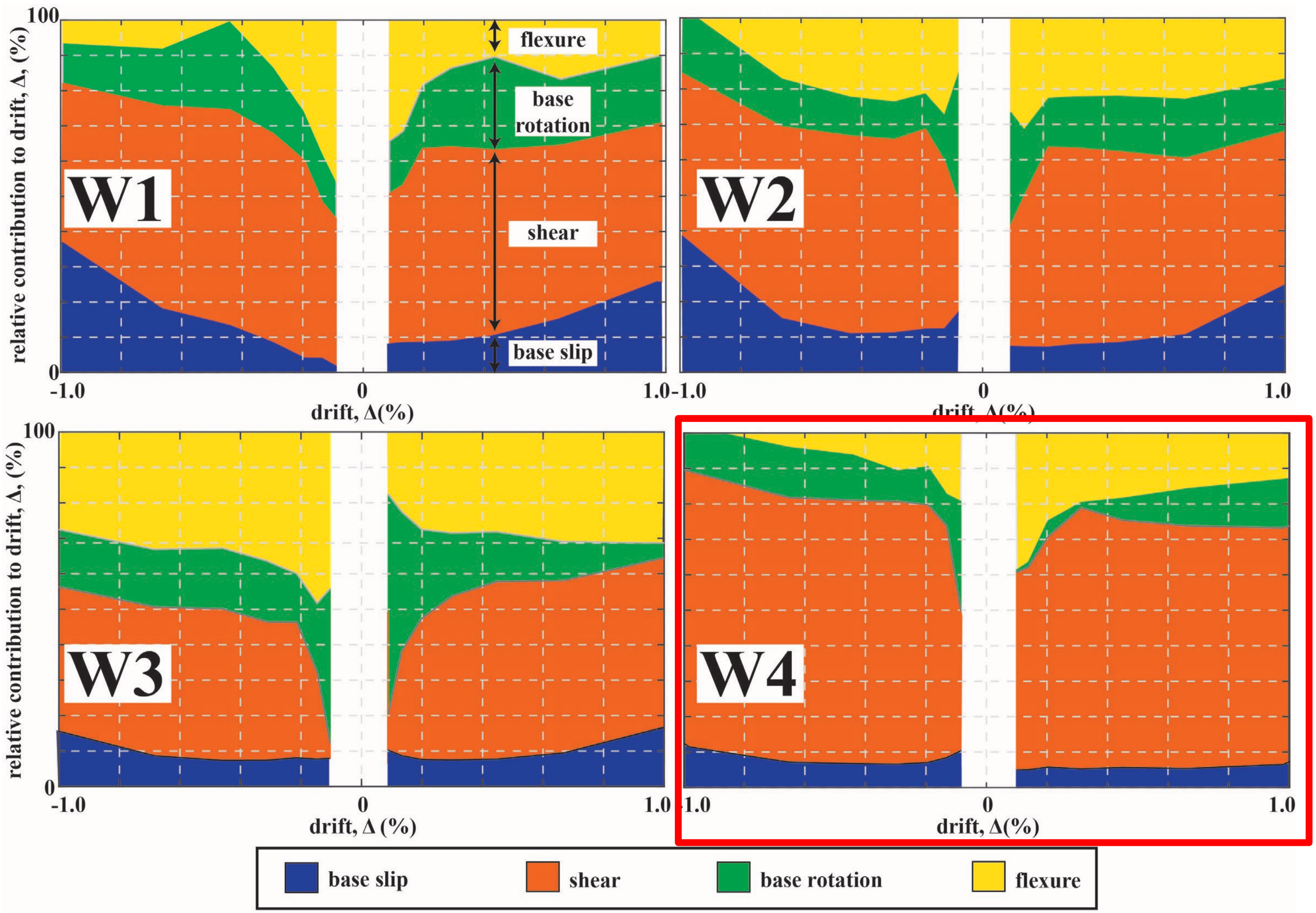
similar deformations between W1 and W2 (inclusion of HSC/HSR)

Deformation Mechanisms



increased flexural deformations in W3 (increased h_{LA}/l_w)

Deformation Mechanisms



increased shear deformations in W4 (flange walls)

HSC/HSR Peak Strength Predictions

Specimen	W2	W3	W4
Failure Mode	shear	flexure	shear
***Measured peak load* (kips)**	**801**	**421**	**863**
Flexure ACI 318 (349) (kip)	672	297	645
Flexure ACI 439.6R (kip)	926	408	950
Seismic shear ACI 318 (349) (kip)	979	653	653
Shear friction ACI 318 (349) (kip)	259	173	187

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Current ACI 318 shear strength predictions may be unconservative for rectangular walls with HSC

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Typical squat wall which was predicted to and did fail in flexure, contrary to current ACI 349 and ASCE/SEI 43 commentary

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Flange walls increased shear strength above ACI prediction

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ACI 439.6R nonlinear steel flexural prediction methods provided an excellent prediction of the peak lateral strength

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ACI 318-19 flexural prediction methods (f_y=100 ksi, elastic perfectly plastic steel) provide very conservative predictions

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Overly conservative predictions of flexural capacity could result in underestimates of the necessary reinforcement to resist the resulting shear demands.

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All specimens, shear friction (μ=0.6 and f_y=60 ksi) is overly conservative

Experimental Conclusions

- HSR, HSC, and 55% reduction in rebar area:
  - Slightly increased initial stiffness
  - Significantly increased initial cracking load
  - Similar deformation mechanisms
  - Similar peak lateral strength
  - Improved post-peak behavior
  - Reduced compression region depth and diagonal strut width at peak load
  - Reduced cracked stiffness due to reduced rebar area
  - Increased crack widths and reinforcement strains (similar proportion to ε_{sy})

Experimental Conclusions

- Increased aspect ratio
  - Flexural failure observed in a typical nuclear rectangular squat shear wall
  - Increased flexural deformations
- Boundary flanges
  - Increased the imposed shear stress at initial cracking and peak load
  - Increased shear deformations

Peak Strength Design Conclusions

- The current ACI seismic shear equations:
  - May be unconservative for rectangular squat walls without boundary regions
  - Overly conservative for walls with flanges
- ACI 349-13 and ASCE/SEI 43-05 commentaries should recognize the potential of flexural failure (rather than unlikely) squat rectangular walls without boundary regions
- Nonlinear HSR stress strain behavior (ACI 439.6R-19) provided the best prediction of the flexural capacity of the specimen which failed in flexure
- Shear friction predictions were overly conservative for all walls with HSC and HSR

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Essve Tech, Inc.
Harris Rebar
HRC, Inc.
MMFX Steel, a Commercial Metals Company
Nucor Corporation
Sika Corporation U.S.

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High Strength Materials Prefabrication
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