Prefabricated High-Strength Rebar Systems with High-Performance Concrete for Accelerated Construction of Nuclear Concrete Structures

NEUP
Nuclear Energy University Programs

UNIVERSITY OF NOTRE DAME

HIGH STRENGTH MATERIALS PREFABRICATION

Sandia National Laboratories

AECOM

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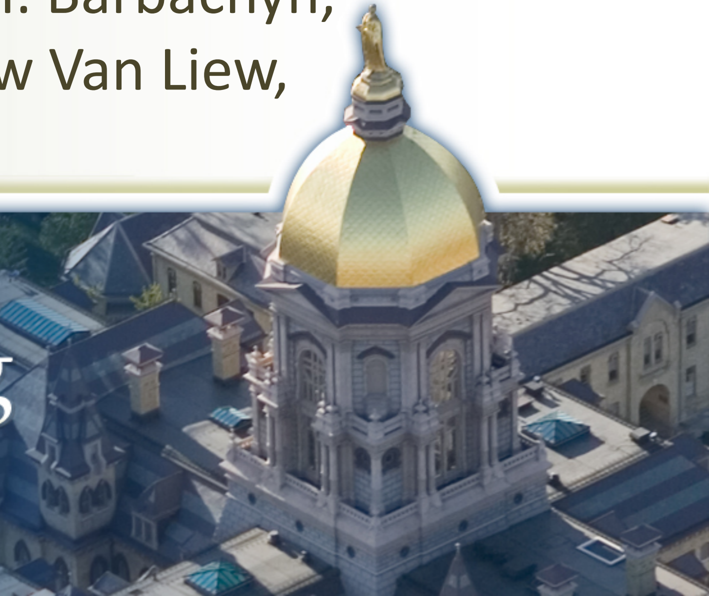
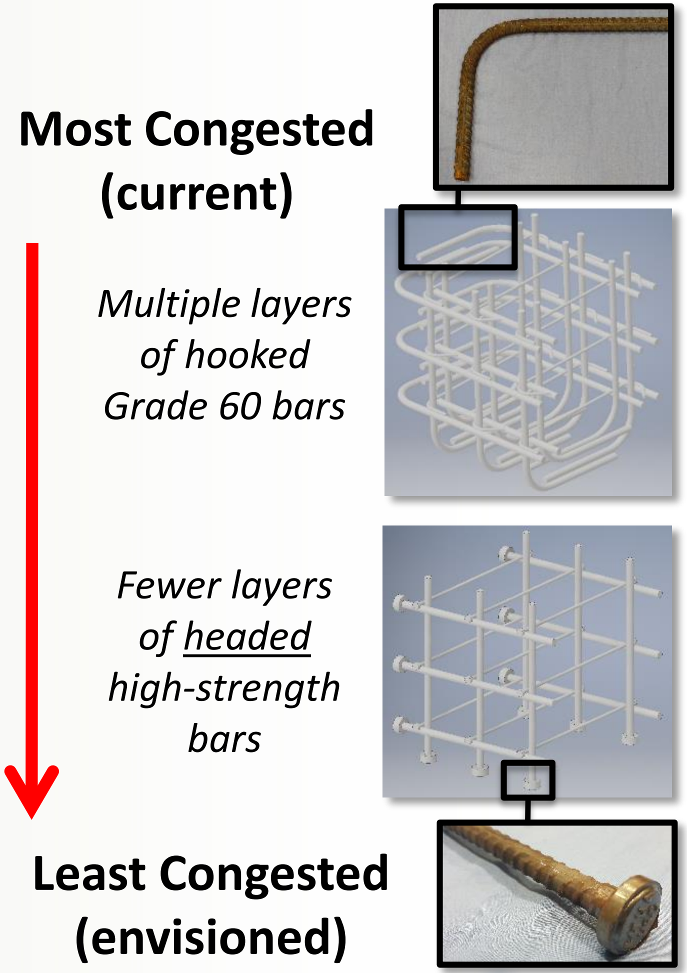


Primary Objective

Reduce field construction times and fabrication costs of reinforced concrete nuclear structures through:

1) High-strength rebar (HSR) up to Grade 120
2) High-strength concrete (HSC) up to 20 ksi (versus current 5 ksi)
3) Headed (versus hooked) anchorages
4) Prefabricated rebar assemblies



Most Congested (current)

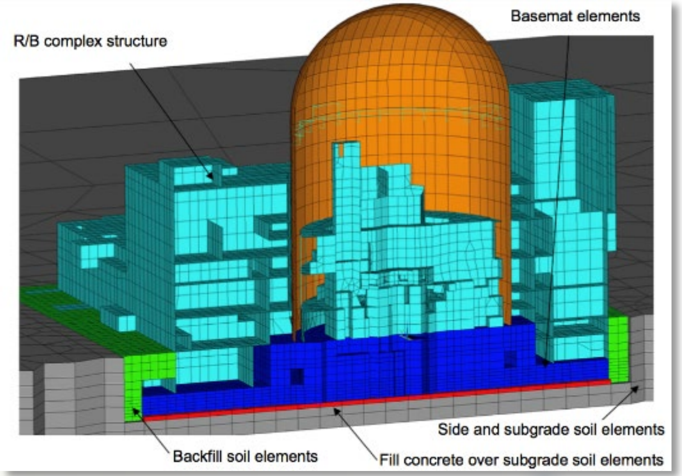
Multiple layers of hooked Grade 60 bars

Fewer layers of headed high-strength bars

Least Congested (envisioned)

Scope and Focus

- Explore effectiveness, code conformity, and viability of existing high-strength materials
- Focus on stocky shear walls – most common lateral load resisting members in nuclear structures (pressure vessels not in scope)
- Aim to reduce complexities in rebar (reduction of wall thickness is not a goal)



US-APWR Design Control Doc.

Presentation Outline

1. Experimental Testing of High-Strength Materials
    - Deep Beam (Wall Slice) Specimens
    - Shear Wall Specimens
2. Predictive Strength Evaluation
3. Cost-Benefit Evaluation
4. Conclusions

Presentation Outline

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    - Shear Wall Specimens
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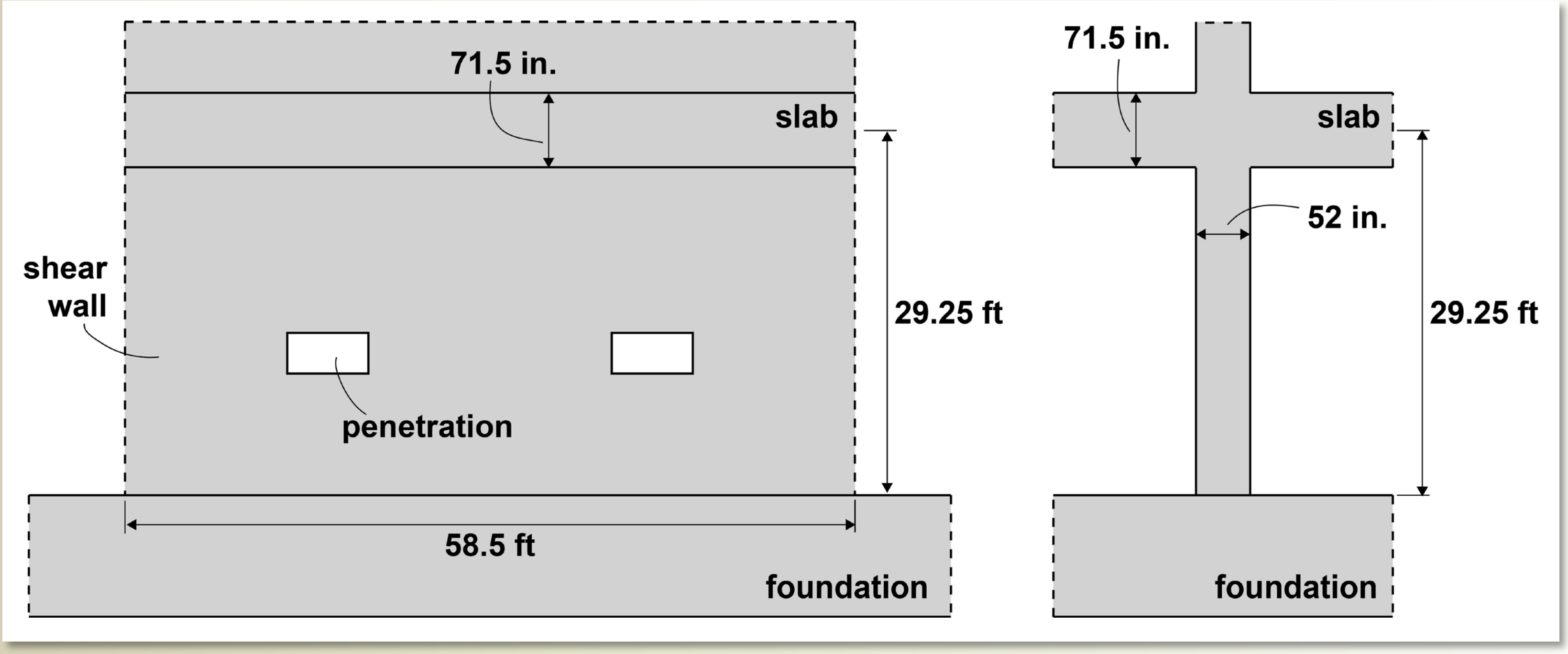
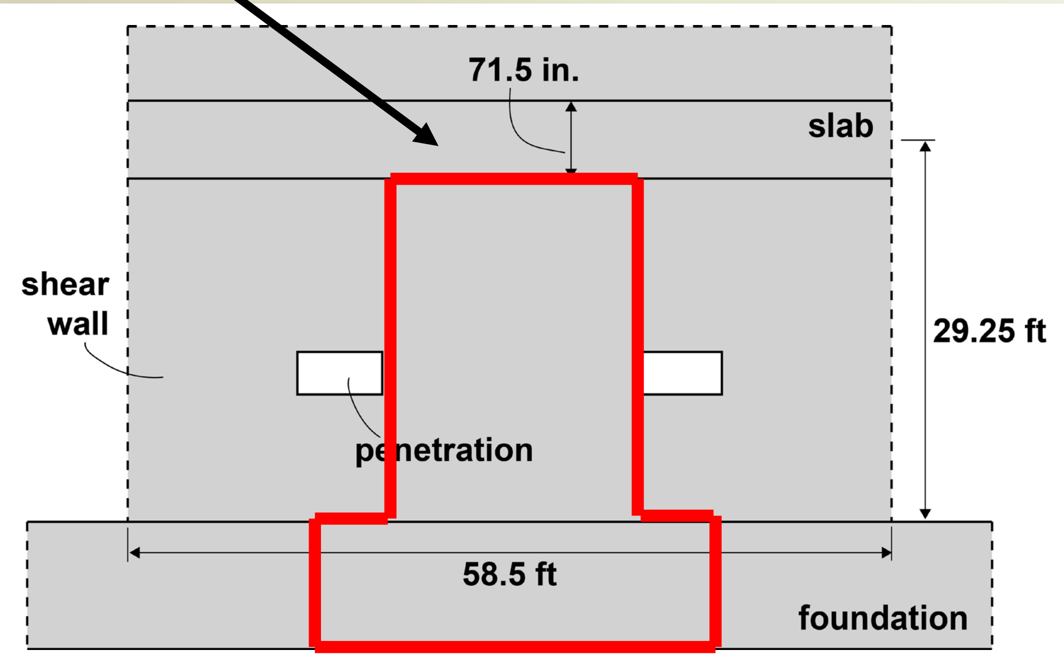
Testing of High-Strength Materials

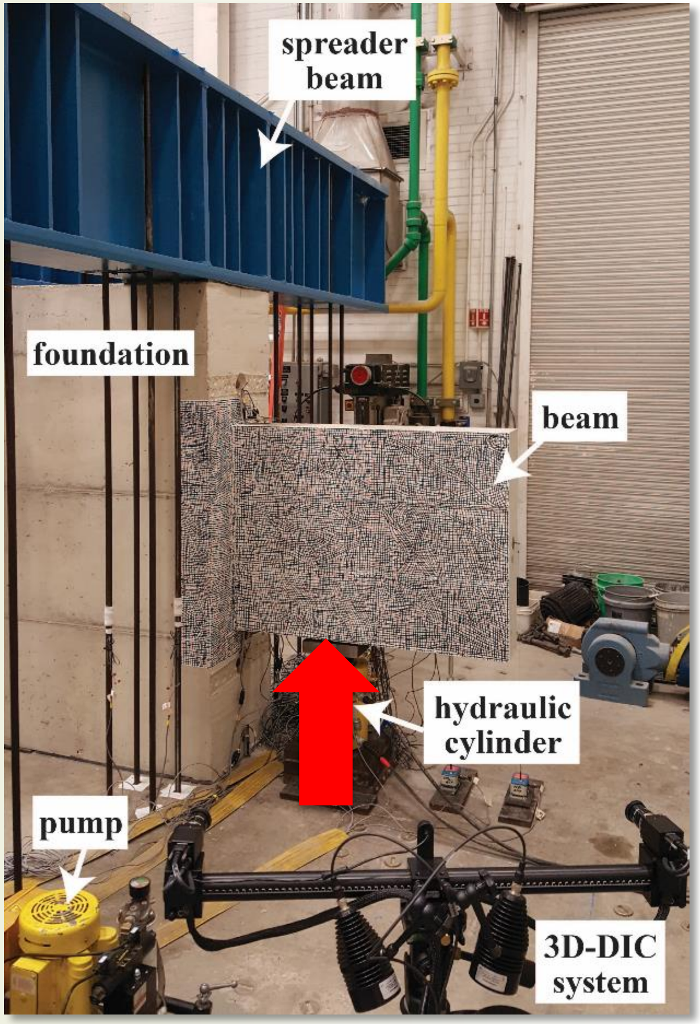
- “Generic full-scale wall” dimensions determined using publicly-available design control documents
- Provided basis for deep beam and shear wall tests conducted at 1:6.5 scale



Deep Beam Tests

representative slice of generic wall for deep beam tests (@ 1:6.5 scale)





Deep Beam Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$
DB1	7280	69.0	0.833	0.5
DB2	6910	132	0.833	0.5
DB3	14640	69.0	0.833	0.5
DB4	15300	132	0.833	0.5

f'_c – concrete compressive strength, test day
f_y – rebar yield strength
ρ_{sw} – web reinforcement ratio (vertical and horizontal rebar)

reinforcement layout and loading kept constant

Deep Beam Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$
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f'_c – concrete compressive strength, test day
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state-of-practice normal-strength rebar (NSR) and normal-strength concrete (NSC)

Deep Beam Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$
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isolated HSC and HSR

Deep Beam Test Parameters

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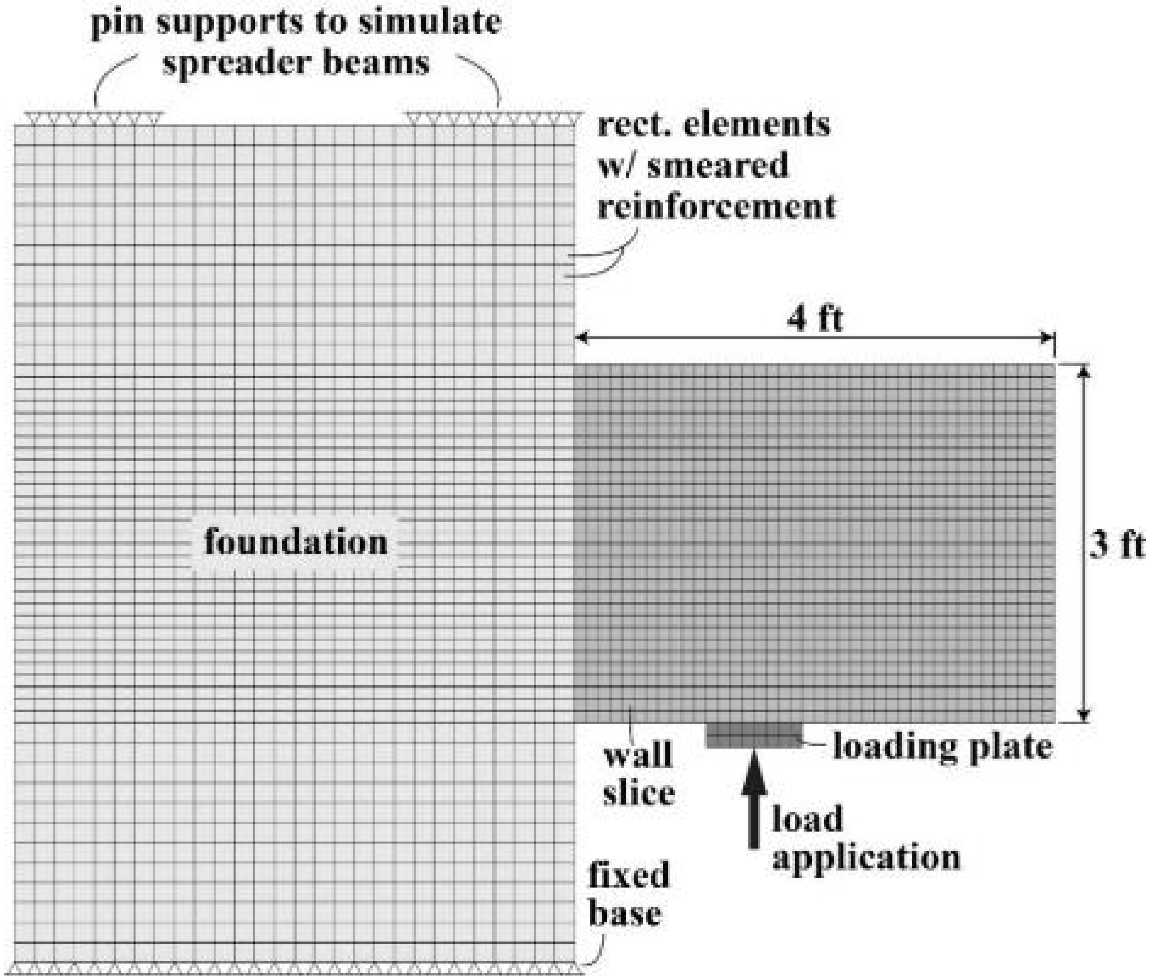
f'_c – concrete compressive strength, test day
f_y – rebar yield strength
ρ_{sw} – web reinforcement ratio (vertical and horizontal rebar)

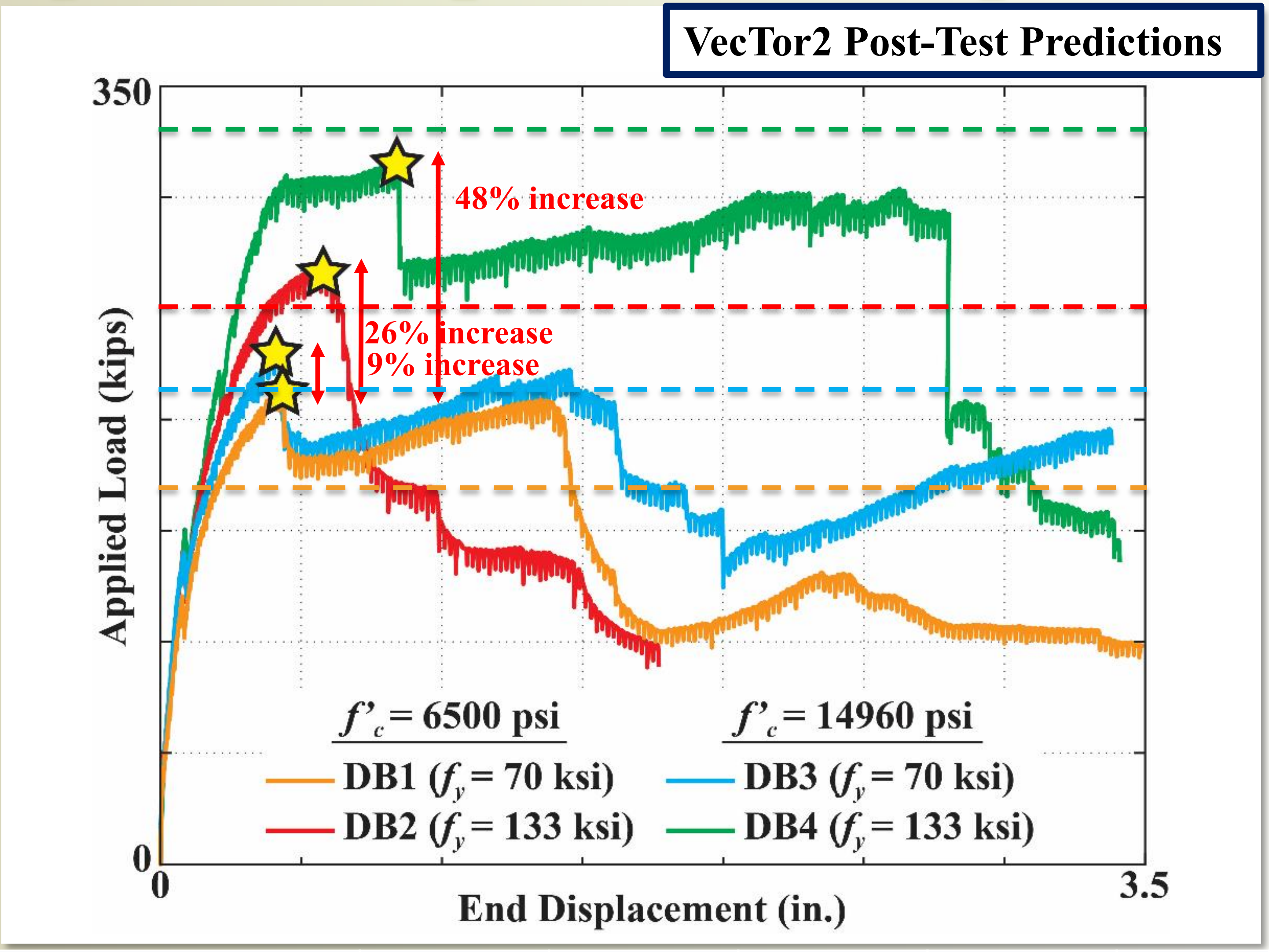
combined HSR and HSC

VecTor2 Finite Element Model



VecTor2 2D representation

Deep Beam Specimen Response



VecTor2 Post-Test Predictions

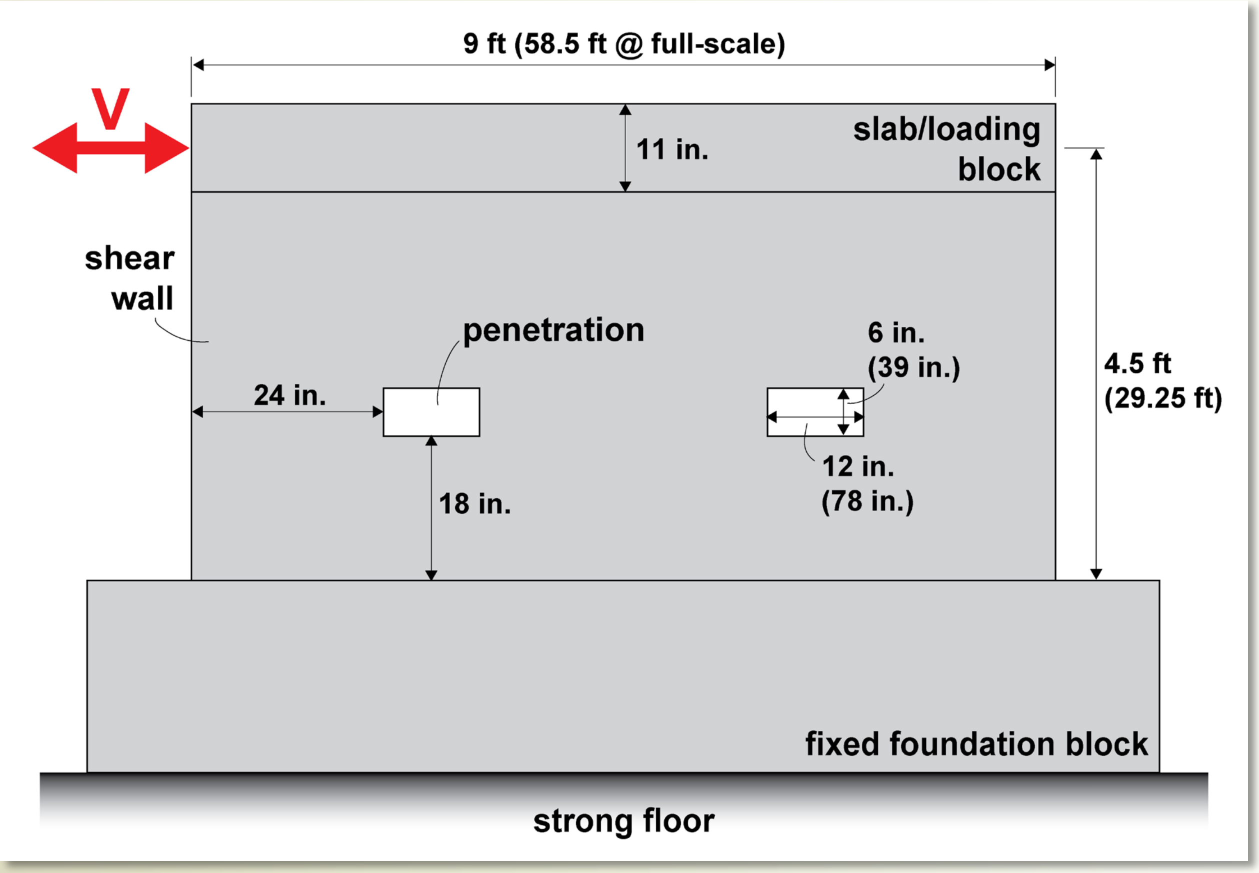
	DB1	DB2	DB3	DB4	Mean	STD
V_{pm}/V_{pp}	1.25	1.07	1.08	0.95	1.09	0.12

Summary of Deep Beam Tests

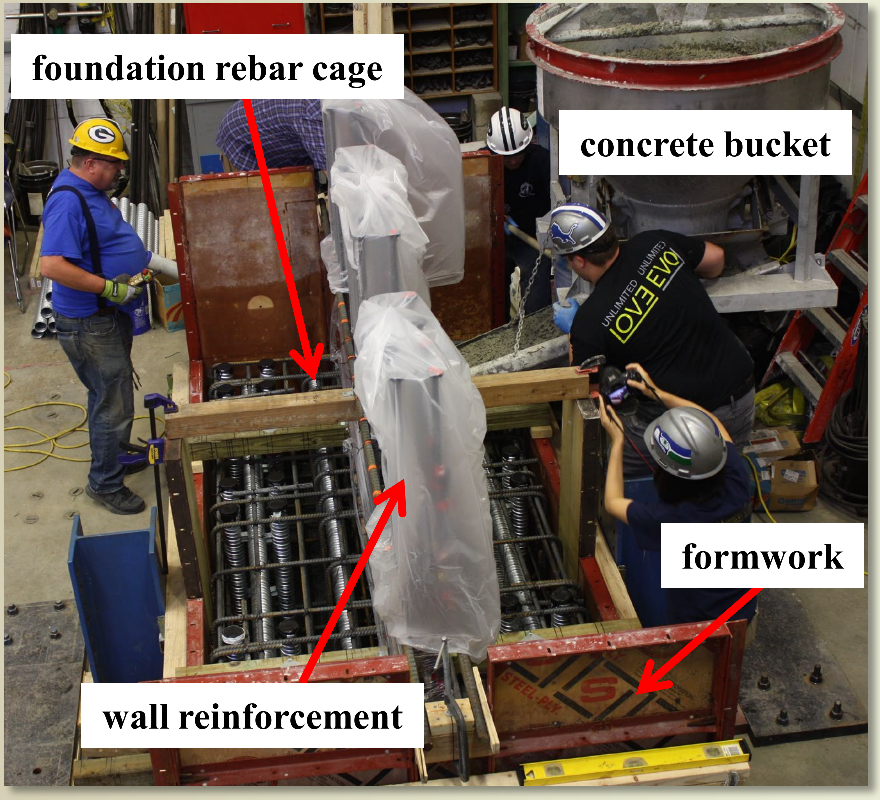
- Increasing the rebar strength had a greater effect on lateral strength (26% increase) than increasing the concrete compression strength (9% increase)
- Increase in lateral strength (48% increase) was greatest when using high-strength materials together
- Combination of high-strength materials also resulted in greatest deformation capacity
- Numerical models provided reasonable predictions for all specimens

Shear Wall Tests

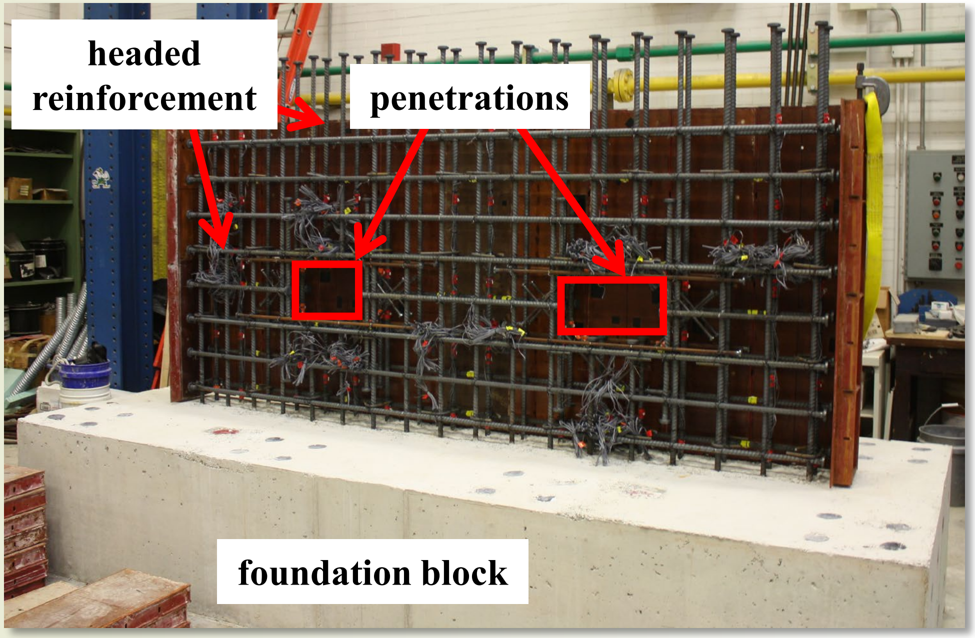
- 1:6.5 scale of "generic wall"
- Tested under cyclic lateral loads



Wall Construction

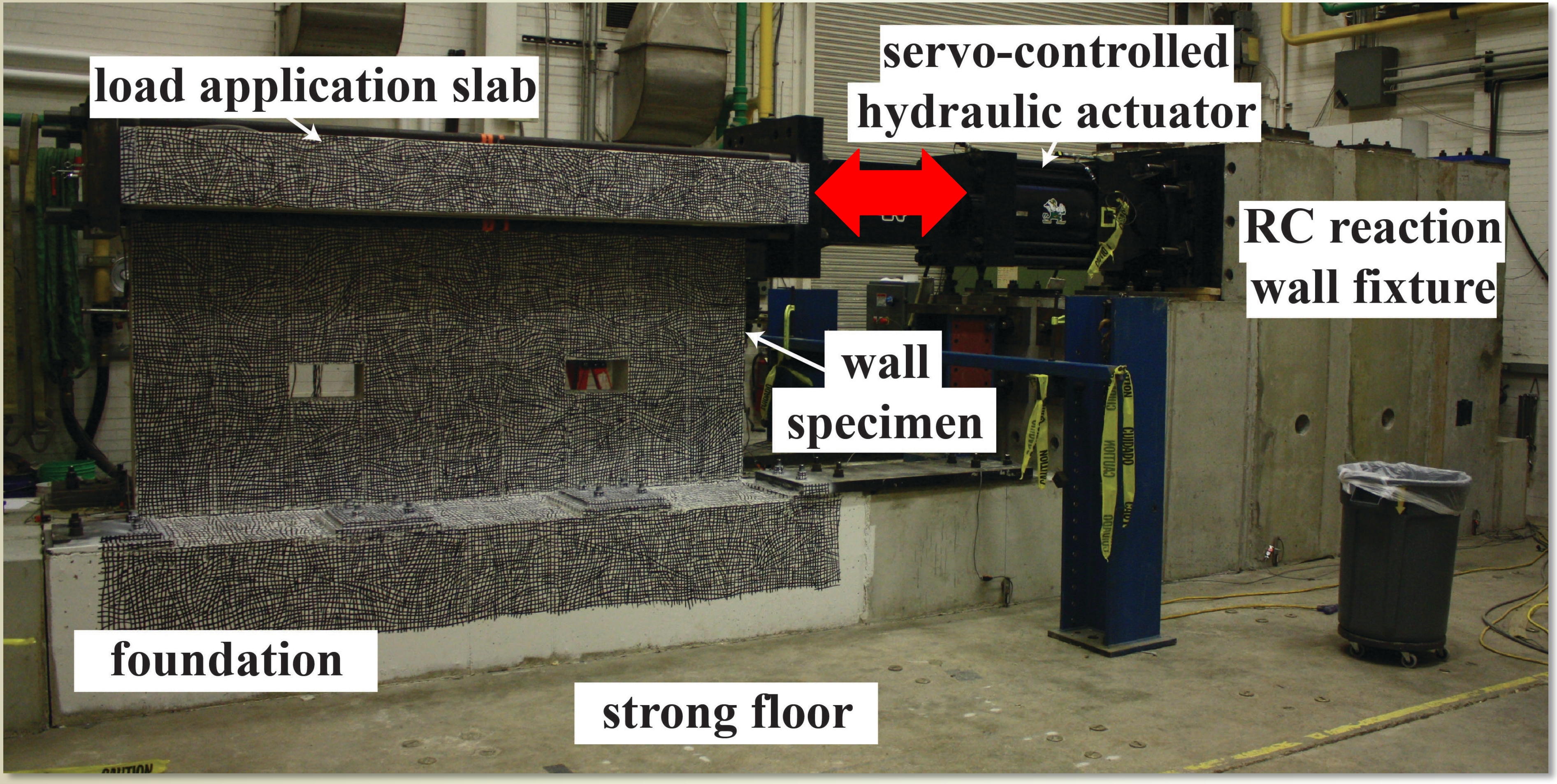


Concrete Placement in Wall Foundation Block



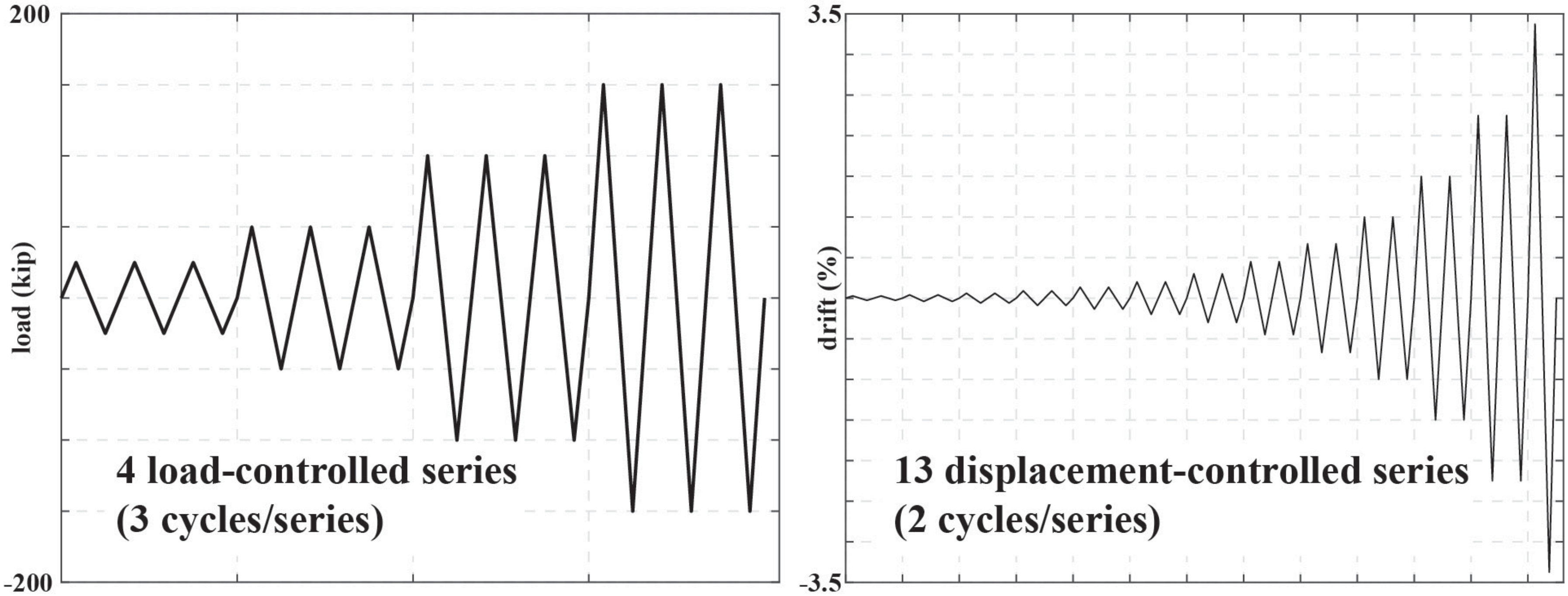
Shear Wall Reinforcement Prior to Concrete Placement

Wall Test Setup

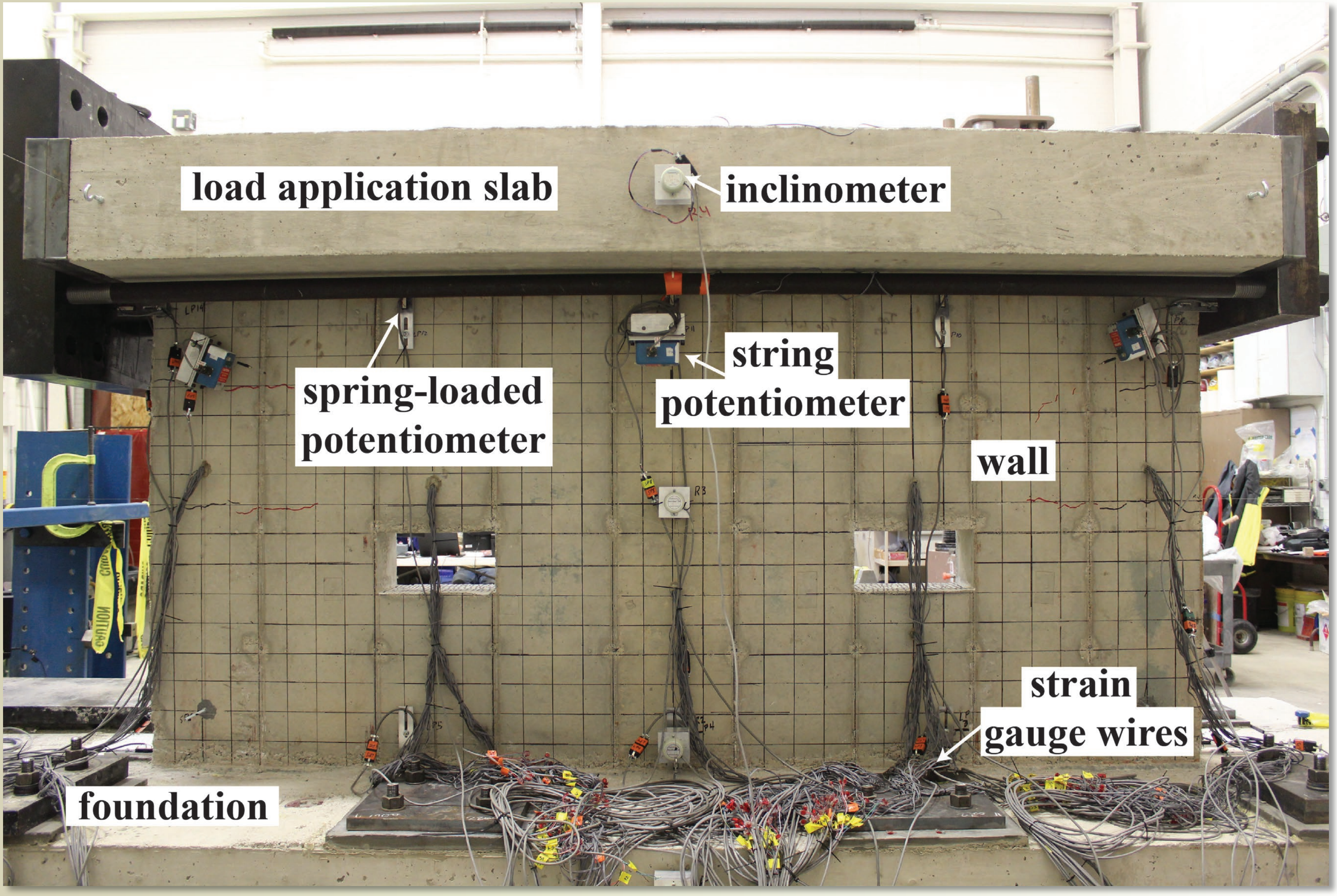


Shear Wall Loading Protocol

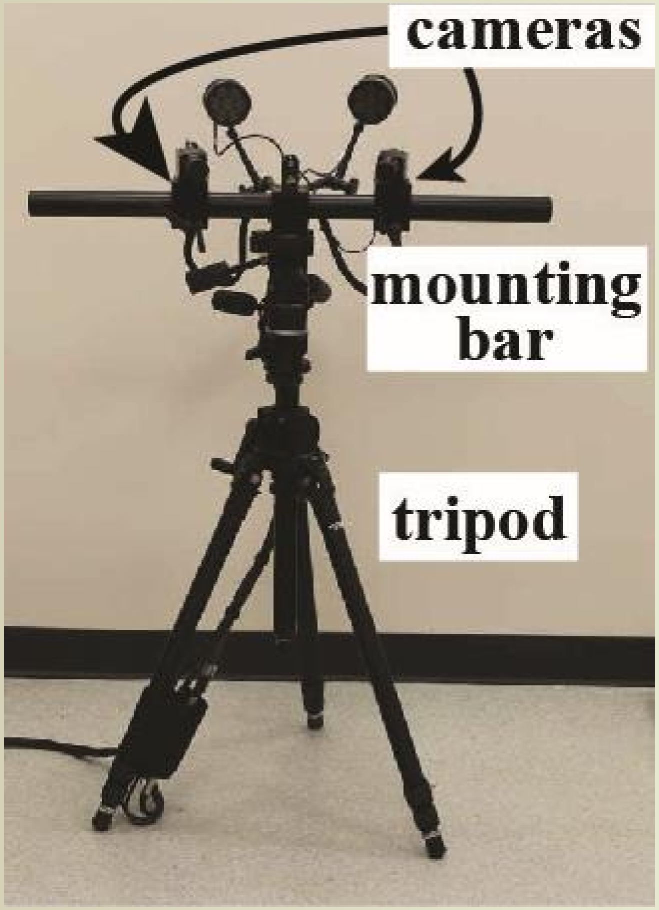
Example Loading Protocol; Modified from ACI ITG 5.1

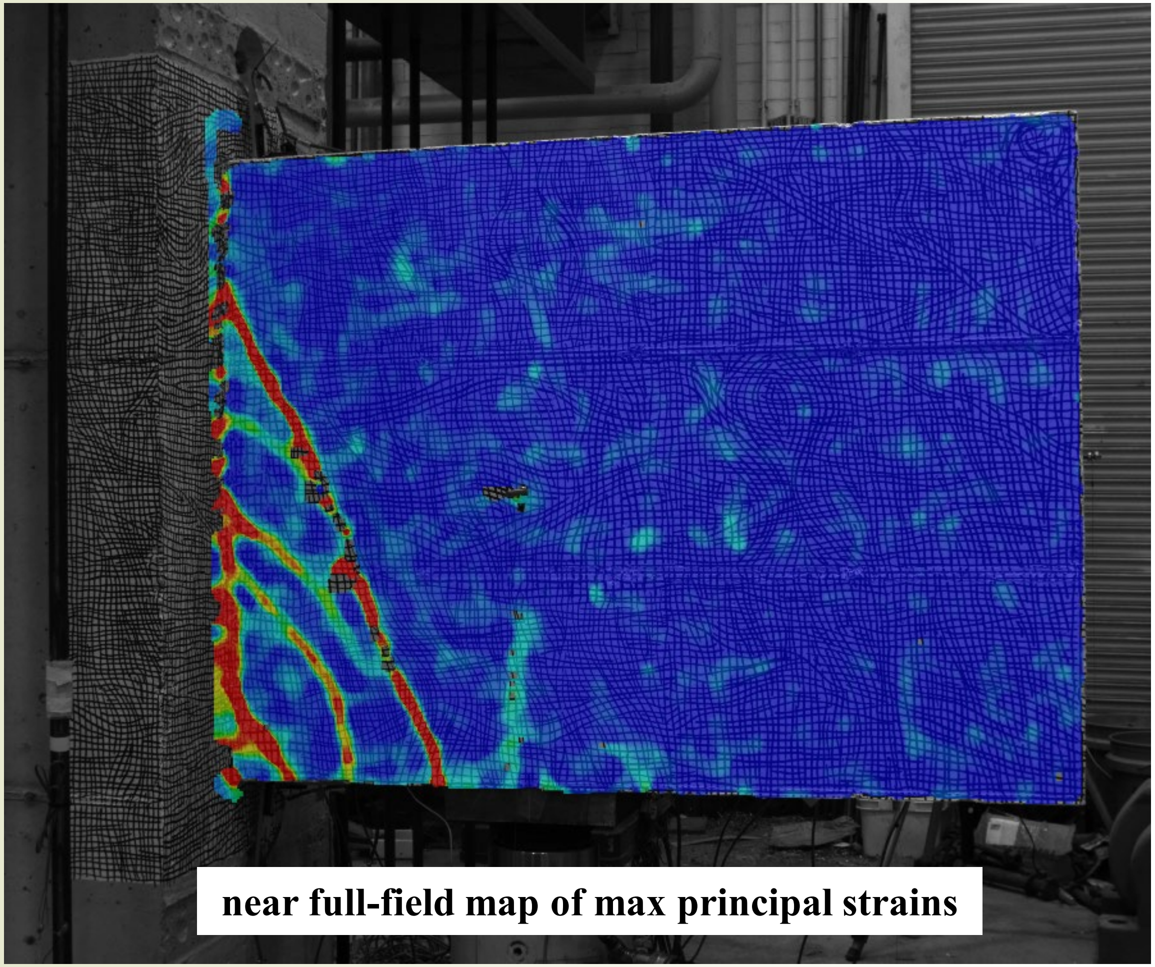


Wall Instrumentation



3D Digital Image Correlation





Wall Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$	ρ_{sf} (%)
CW1	6950	72.5	1.833	0.5	no flange
CW2	14760	122	0.833	0.5	no flange
CW3	14240	122	0.833	0.75	no flange
CW4	14010	125	0.833	0.75	0.833

f'_c – concrete compressive strength
f_y – rebar yield strength
ρ_{sw} – web reinforcement ratio
ρ_{sf} – flange reinforcement ratio

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

Wall Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$	ρ_{sf} (%)
CW1	6950	72.5	1.833	0.5	no flange
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f'_c – concrete compressive strength
f_y – rebar yield strength
ρ_{sw} – web reinforcement ratio
ρ_{sf} – flange reinforcement ratio

increased base moment-to-shear ratio (less than 2.0)

Wall Test Parameters

Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$	ρ_{sf} (%)
CW1	6950	72.5	1.833	0.5	no flange
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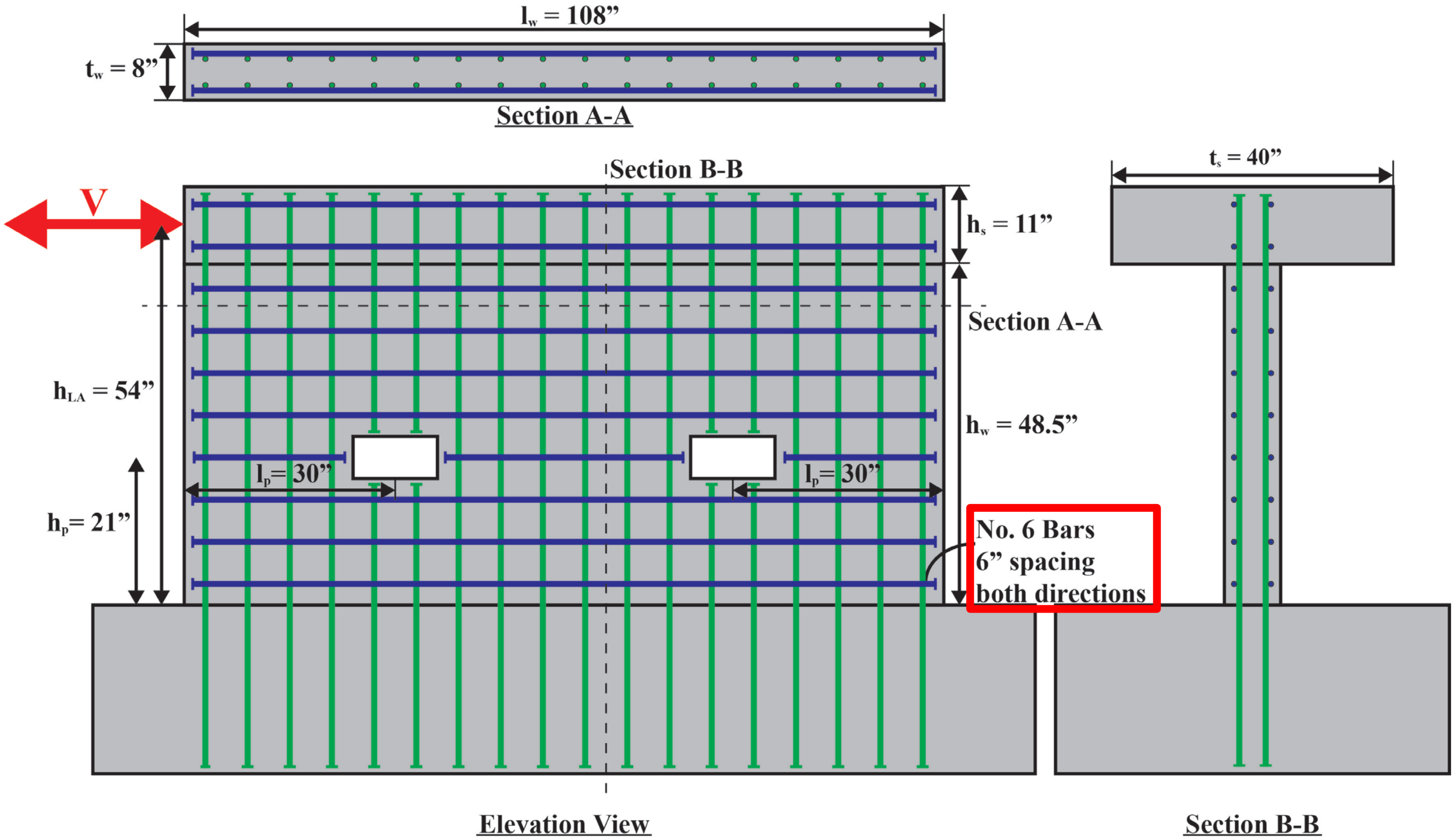
f'_c – concrete compressive strength
f_y – rebar yield strength
ρ_{sw} – web reinforcement ratio
ρ_{sf} – flange reinforcement ratio

intersecting walls effectiveness as boundary flanges

Wall Layouts

CW1

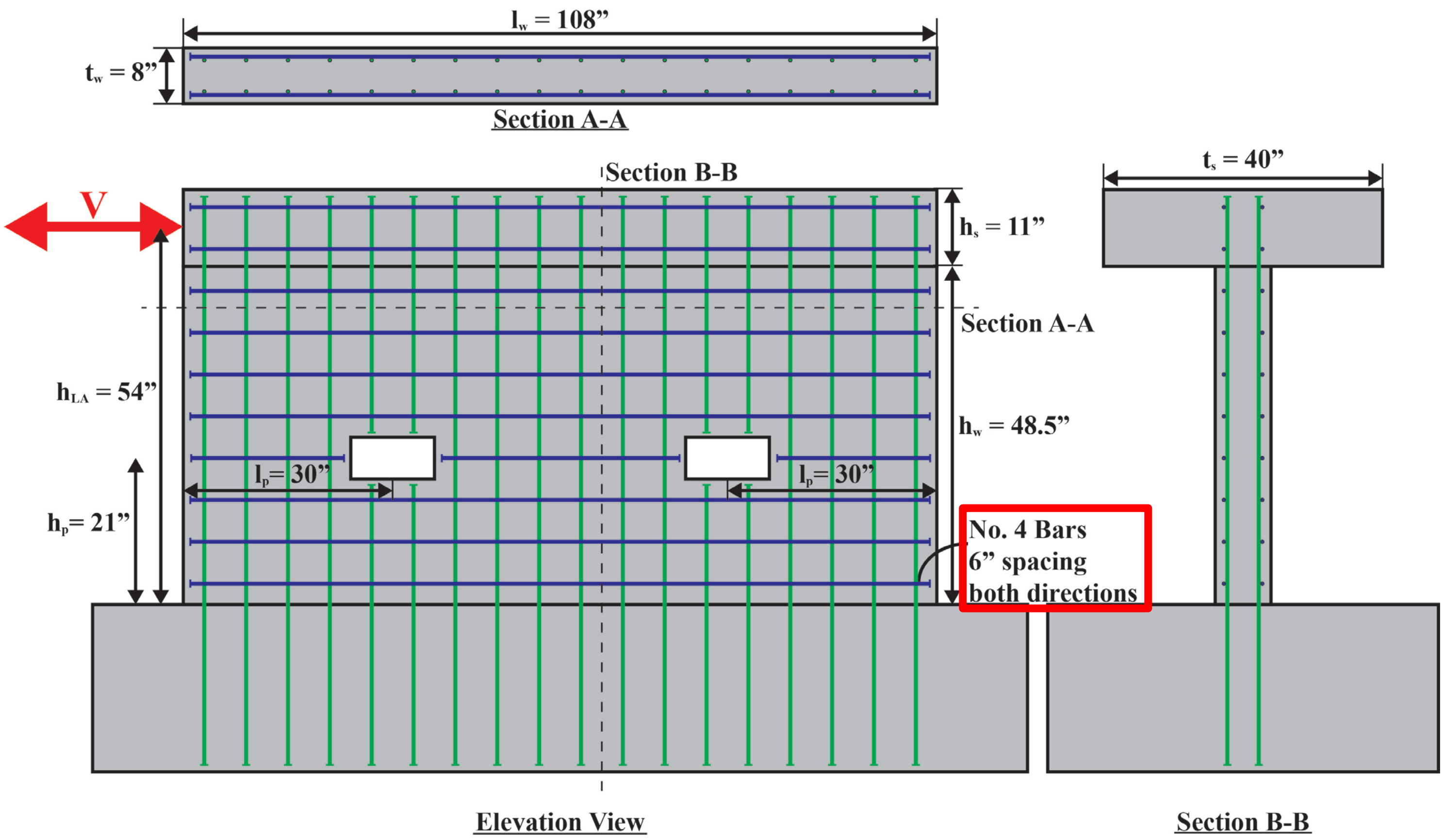


No. 6 Bars
6” spacing
both directions

cross-ties @ 12” on center not shown

Wall Layouts

CW2

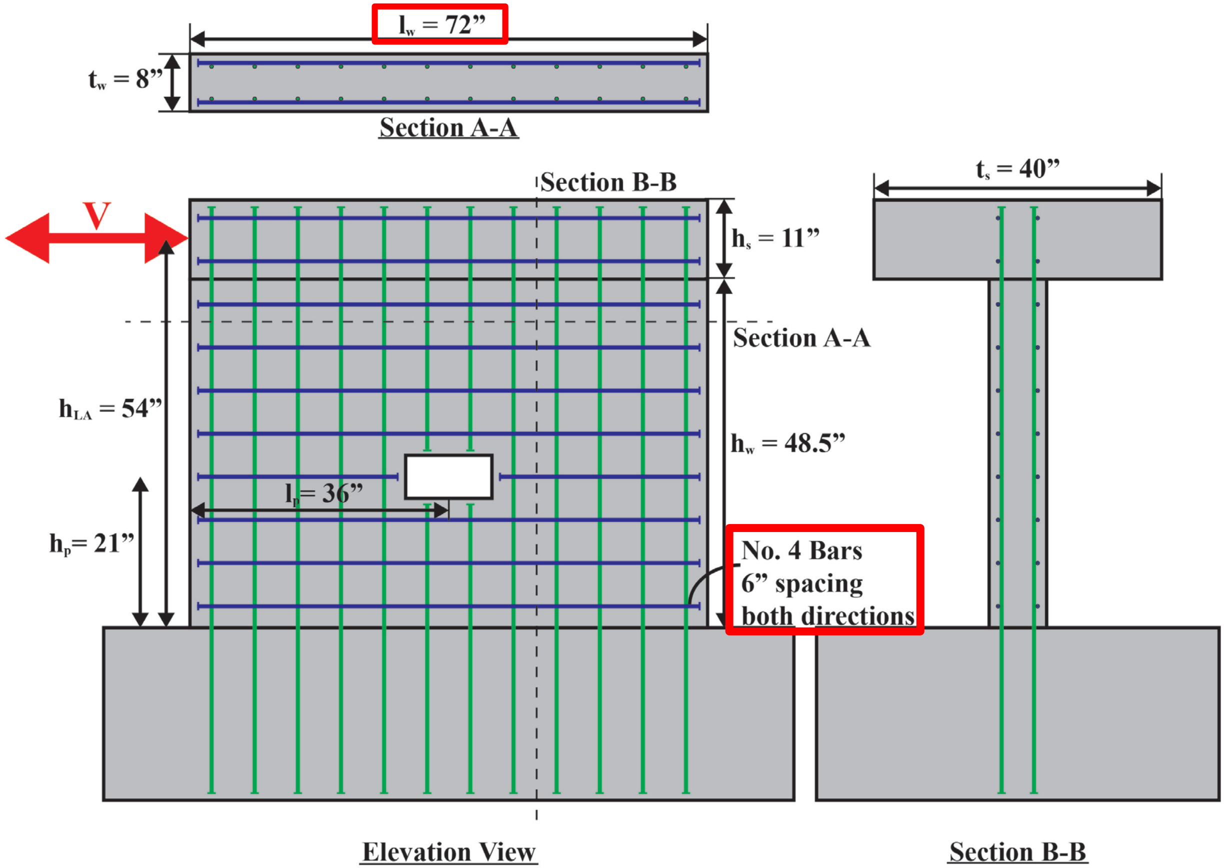


No. 4 Bars
6” spacing
both directions

cross-ties @ 12” on center not shown

Wall Layouts

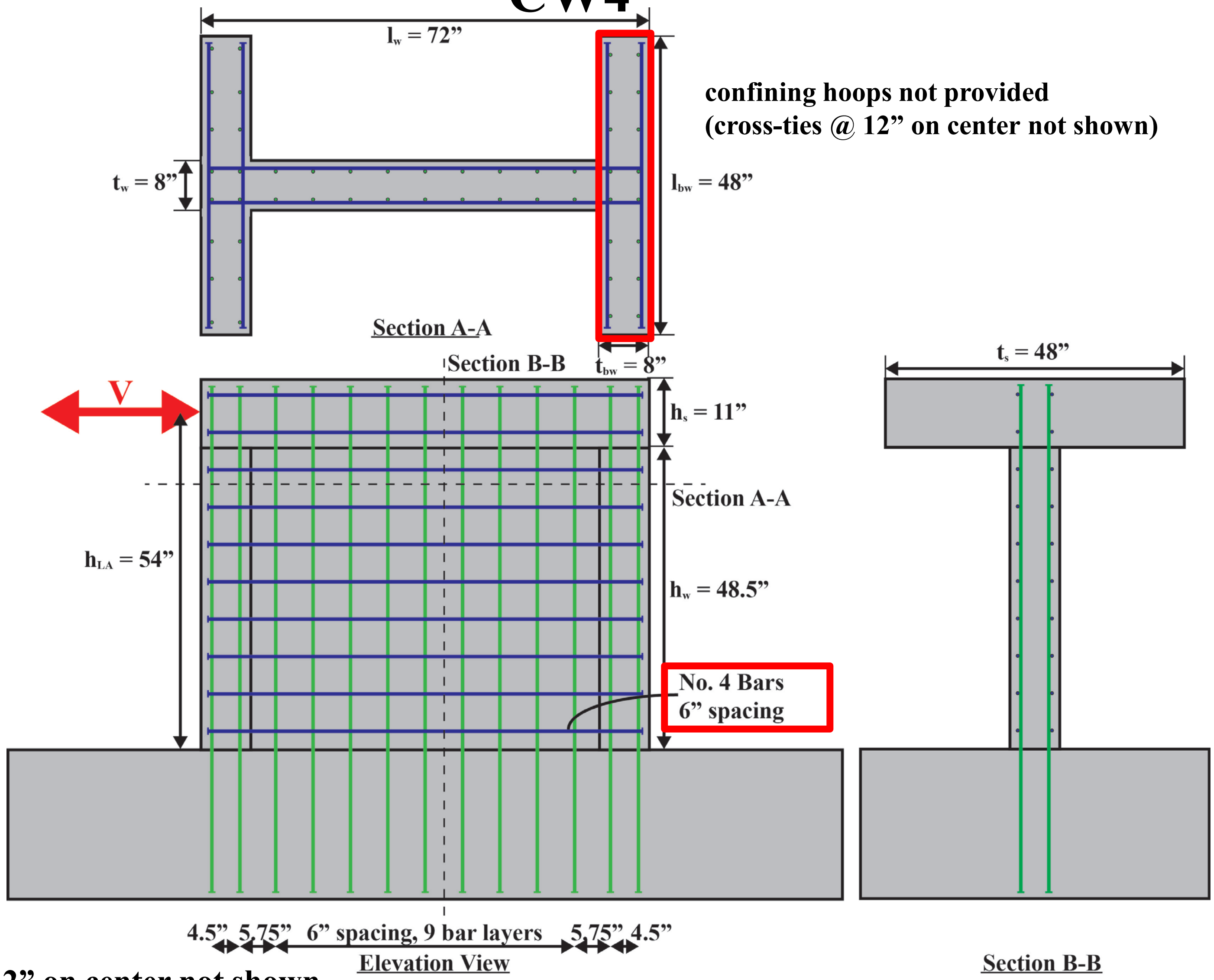
CW3



cross-ties @ 12” on center not shown

Wall Layouts

CW4

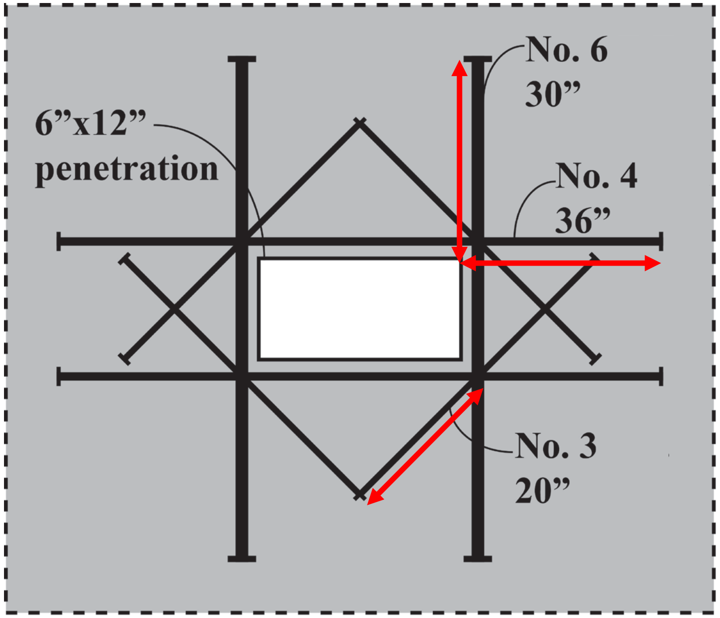


confining hoops not provided
(cross-ties @ 12” on center not shown)

No. 4 Bars
6” spacing

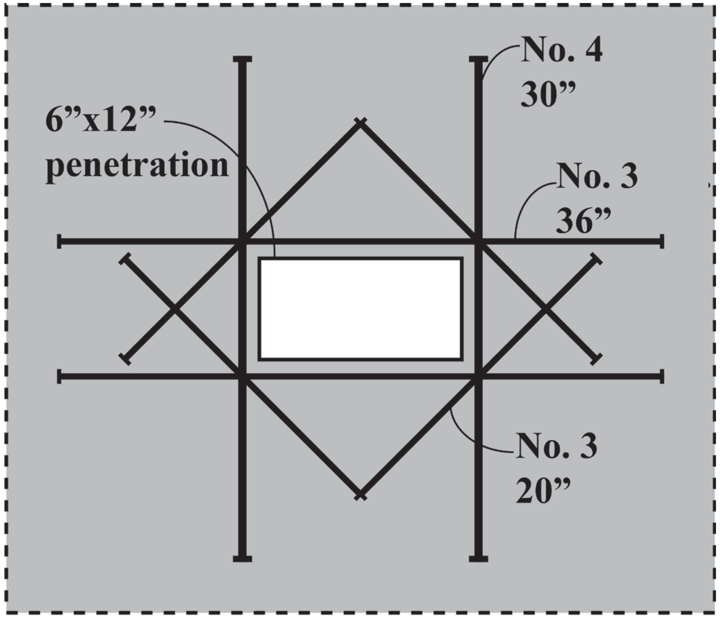
cross-ties @ 12” on center not shown

Penetration Rebar



Normal-Strength Trim Reinforcement

CW1



High-Strength Trim Reinforcement

CW2 and CW3

development length provided at least headed development length*, less than straight development length, testing headed anchorages

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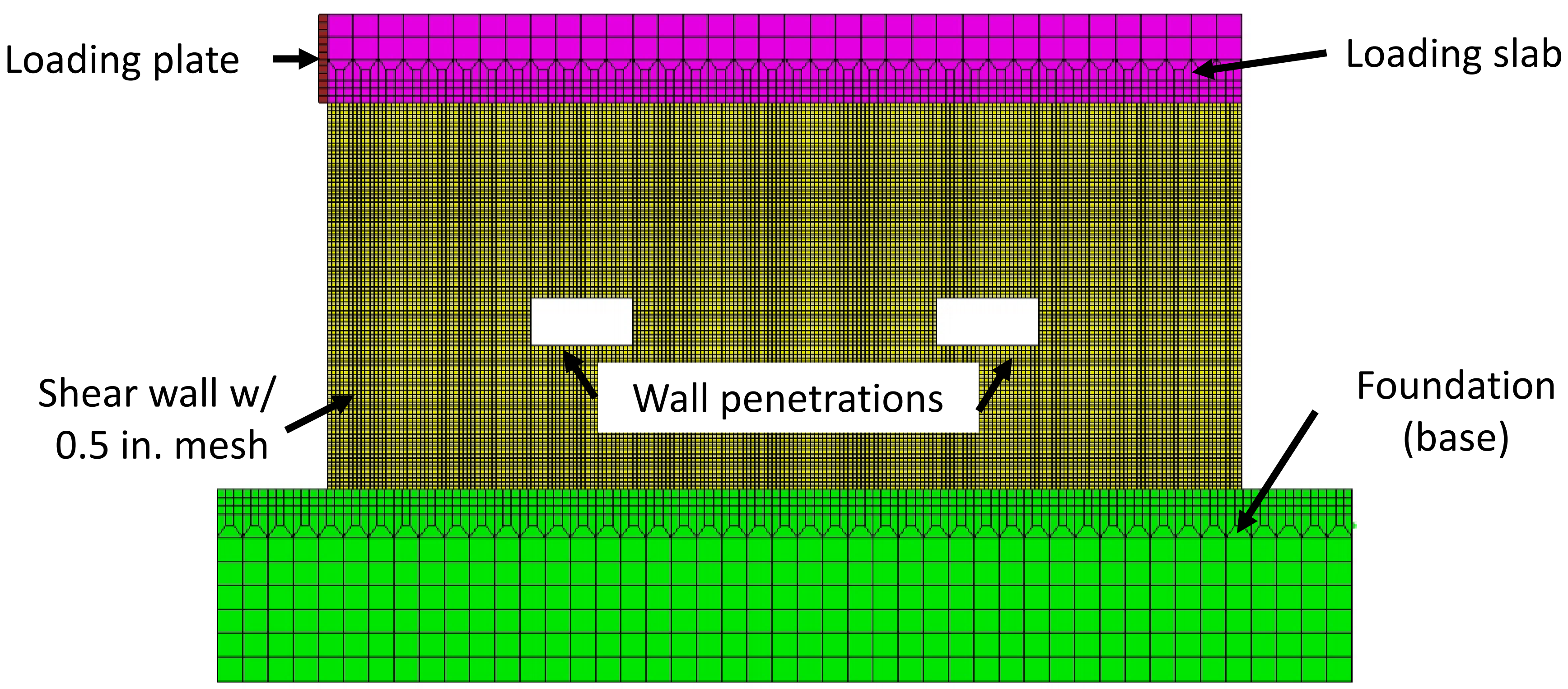
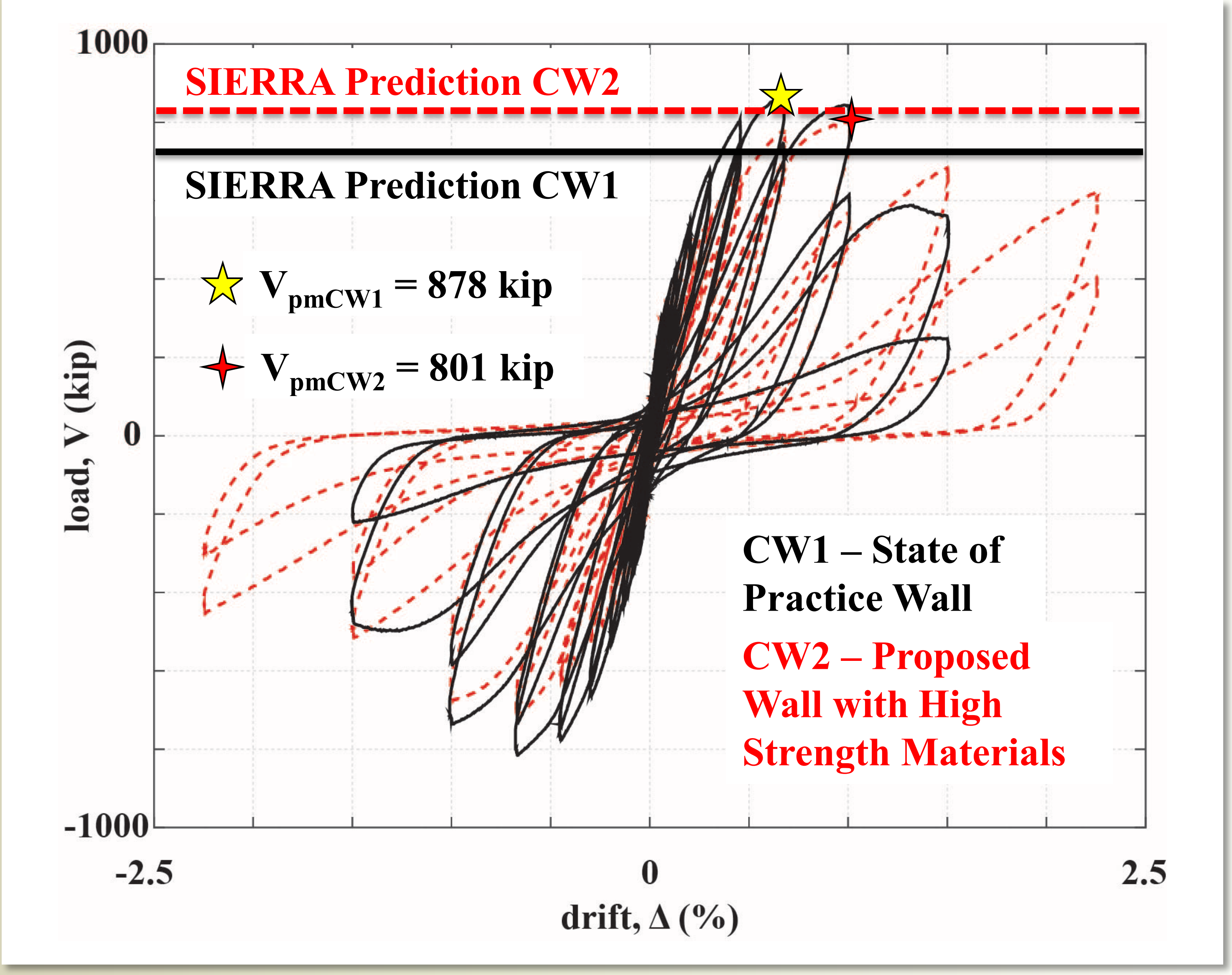
[1] for HSR/HSC, determined by Shao, Y., Darwin, D., O’Reilly, M., Lequesne, R., Ghimire, K., and Hano, M., “Anchorage of Conventional and High-Strength Headed Reinforcing Bars,” *The University of Kansas Center for Research, Inc.*, SM Report No. 117, 2016, 234 pp.

Finite Element Modeling

- Detailed Finite Element Models developed at Sandia National Labs using in house software SIERRA

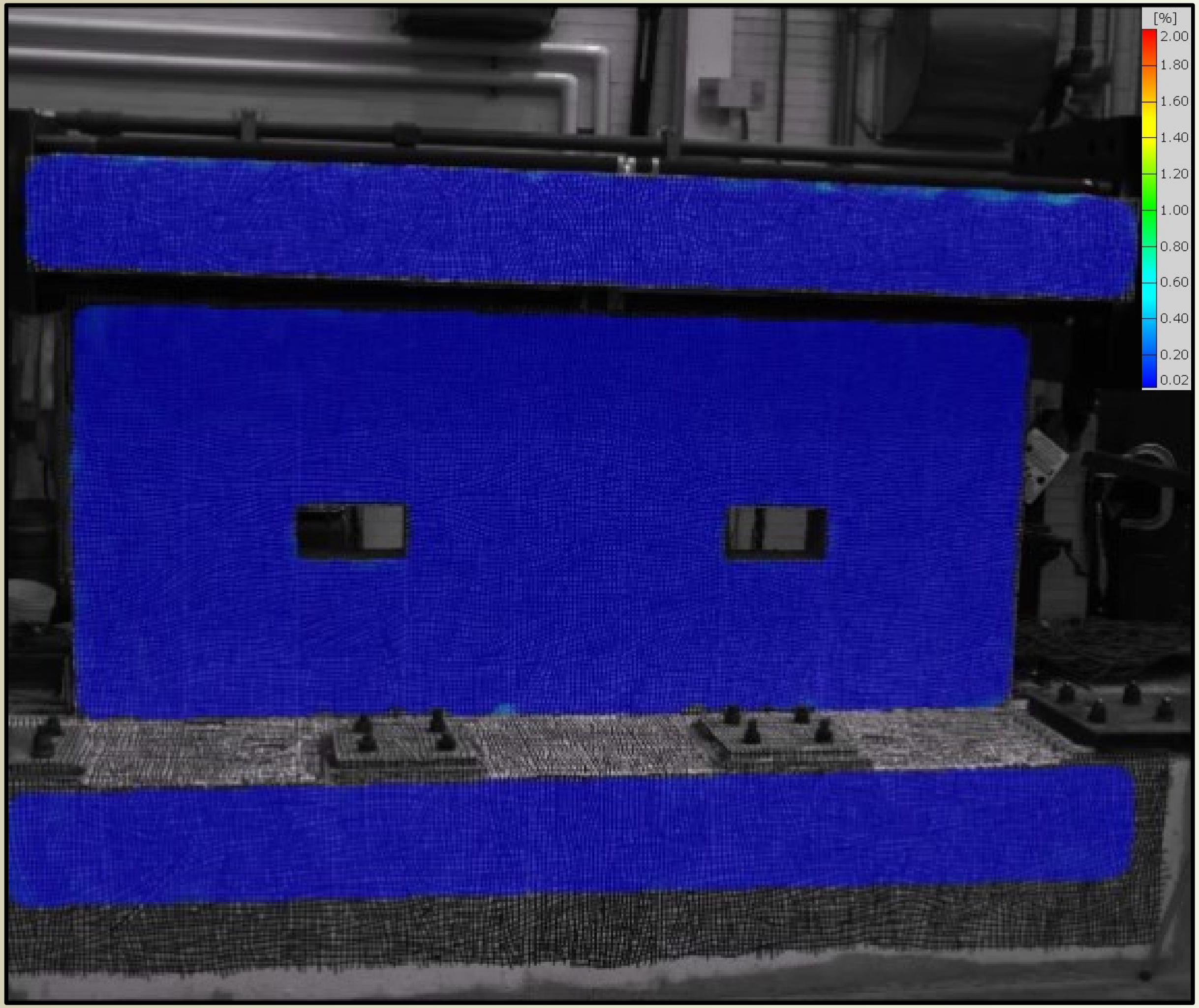


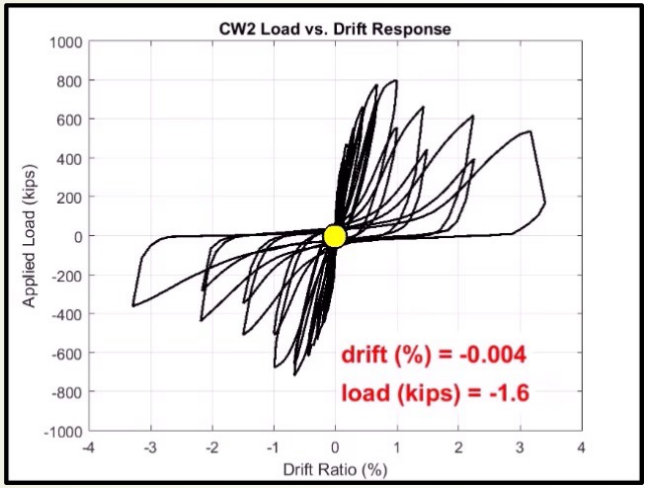
CW1 versus CW2 Behaviors



CW2 ($f'_c = 14760$ psi, $f_y = 122$ ksi)

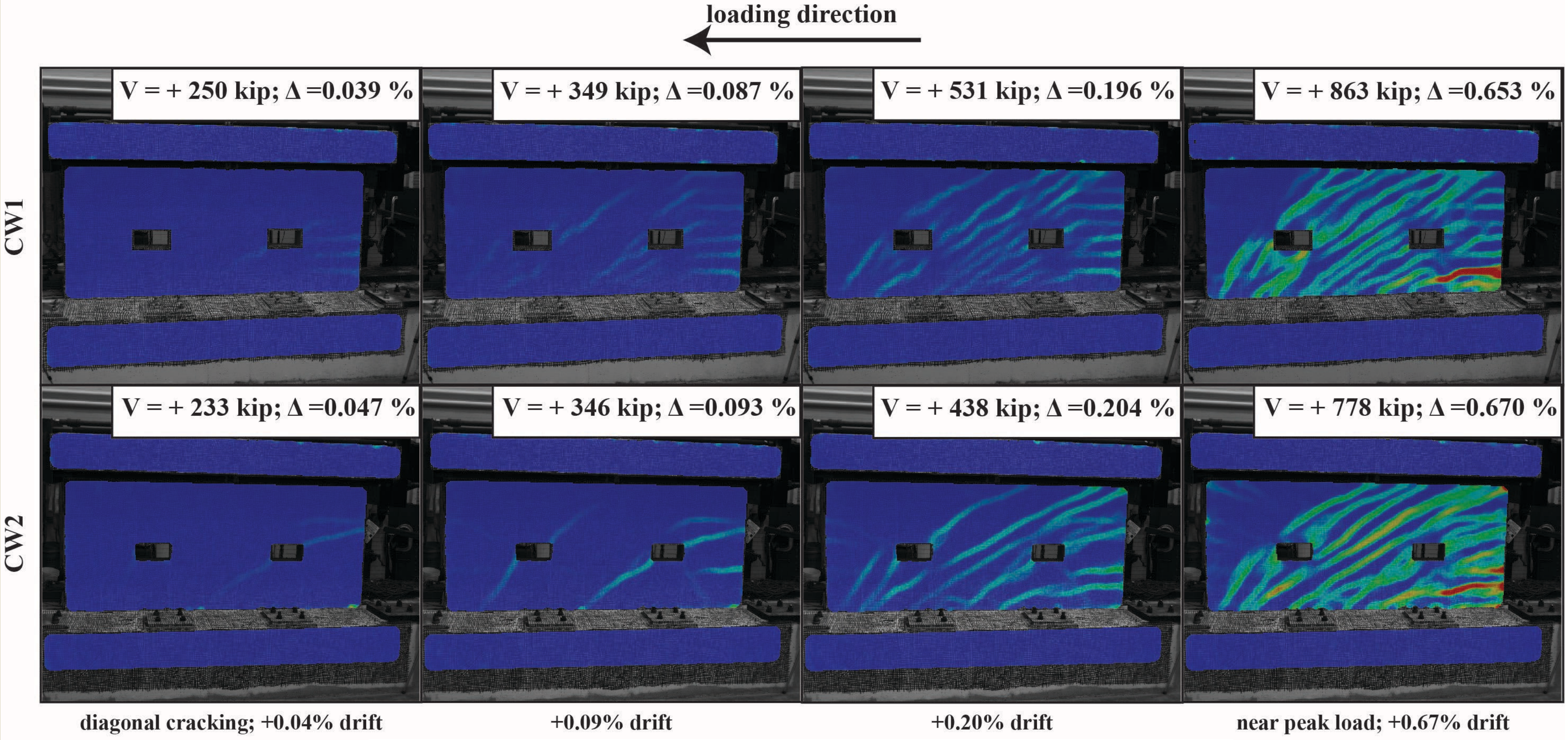
(wall with high-strength materials)





video not available on website version, please contact if interested

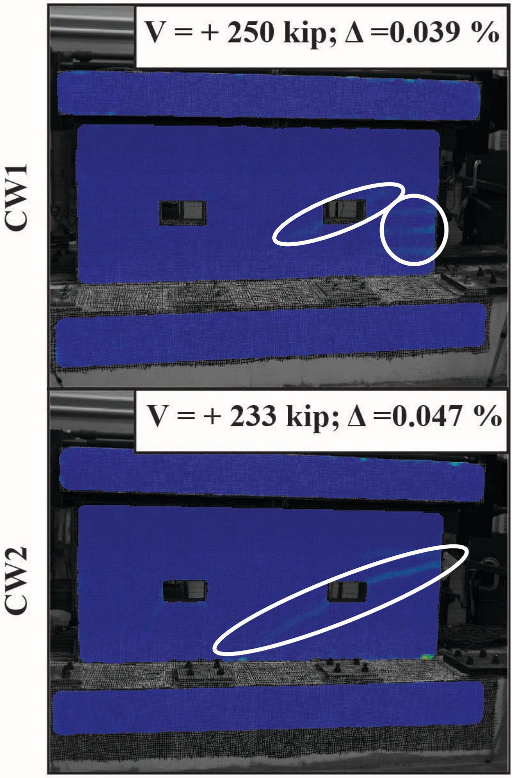
CW1 & CW2 Cracking Behaviors



maximum principal surface strains

CW1 & CW2 Cracking Behaviors

loading direction ←



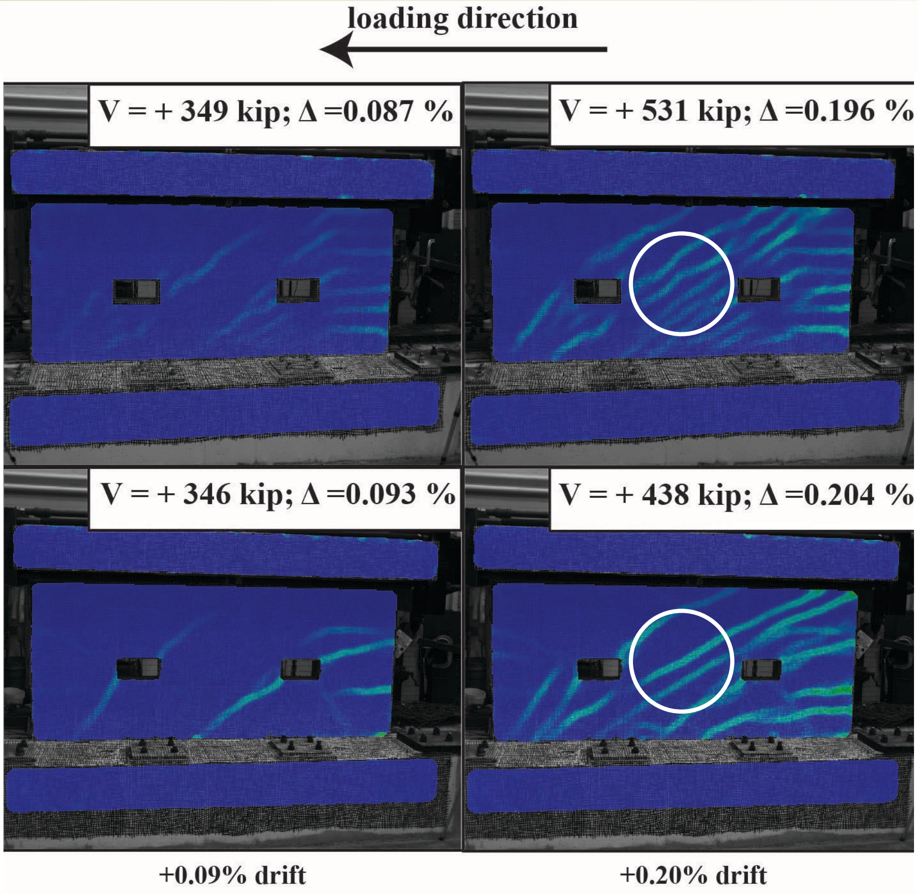
diagonal cracking; +0.04% drift

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

isolated diagonal crack
initial diagonal crack – 252 kips

maximum principal surface strains

CW1 & CW2 Cracking Behaviors



more distributed cracking

cracking away from
penetrations &
yielding of trim rebar

fewer cracks

strains similar as a
proportion of yield
strain

larger measured
reinforcement
strains, therefore
wider cracks

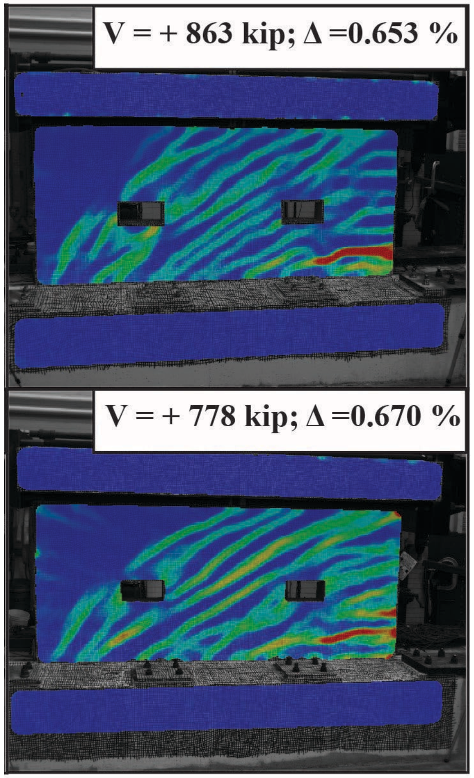
maximum principal surface strains

CW1 & CW2 Cracking Behaviors

loading direction ←

CW1

CW2



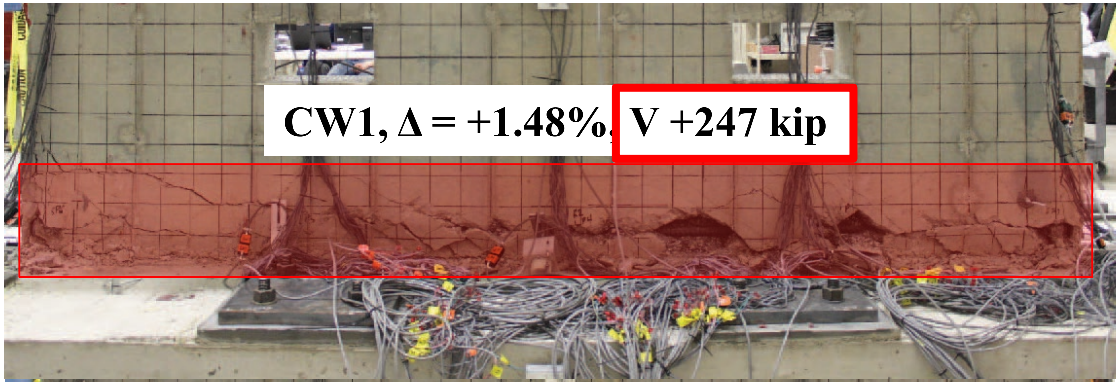
near peak load; +0.67% drift

similar cracking pattern

maximum principal surface strains

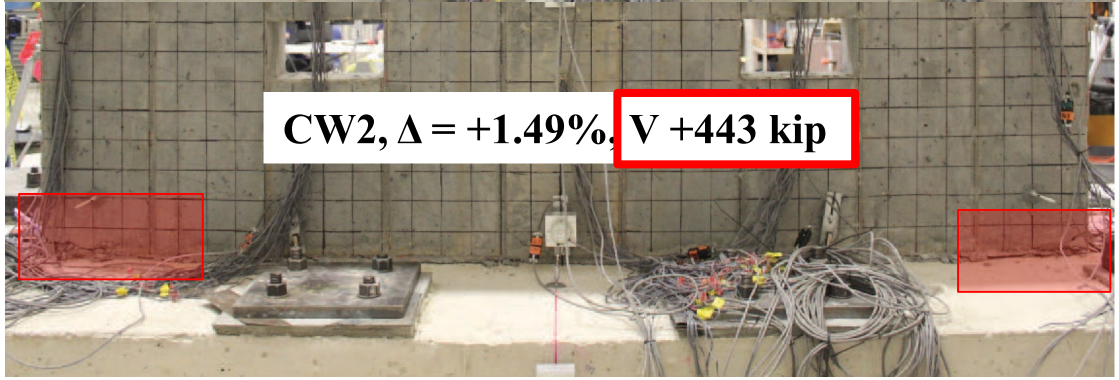
CW1 & CW2 Post Peak Behavior

loading direction →



CW1, Δ = +1.48%, V +247 kip

extensive concrete spalling
exposed reinforcement

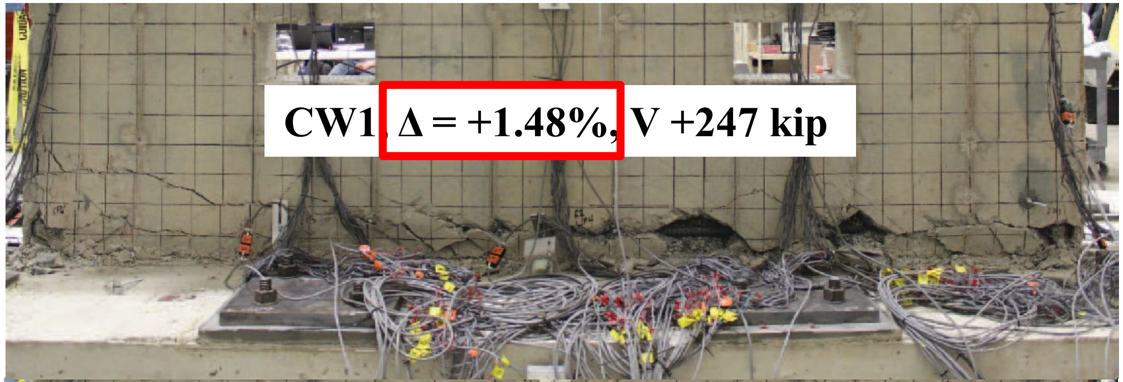


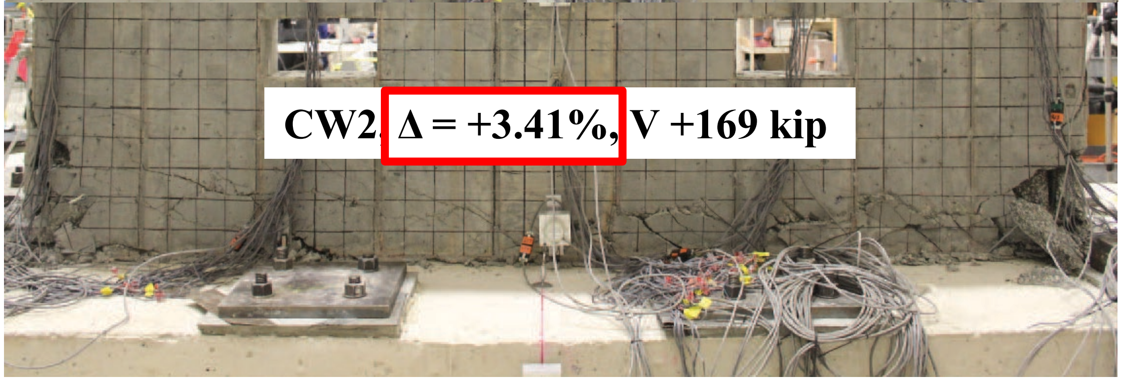
CW2, Δ = +1.49%, V +443 kip

minimal concrete damage
no exposed reinforcement

CW1 & CW2 Post Peak Behavior

loading direction →


CW1, Δ = +1.48%, V +247 kip

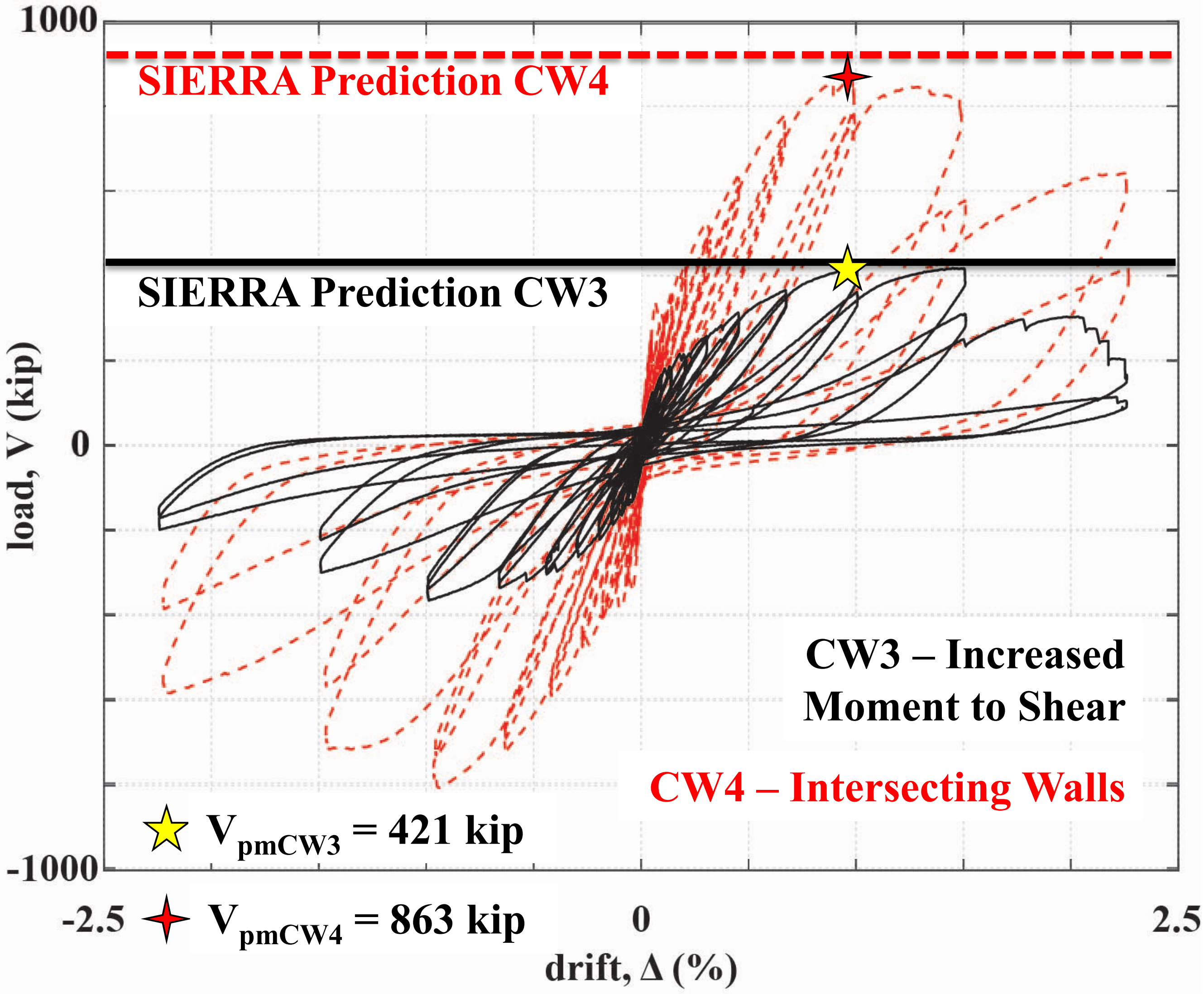

CW2, Δ = +3.41%, V +169 kip

similar final damage state
both failures due to slip

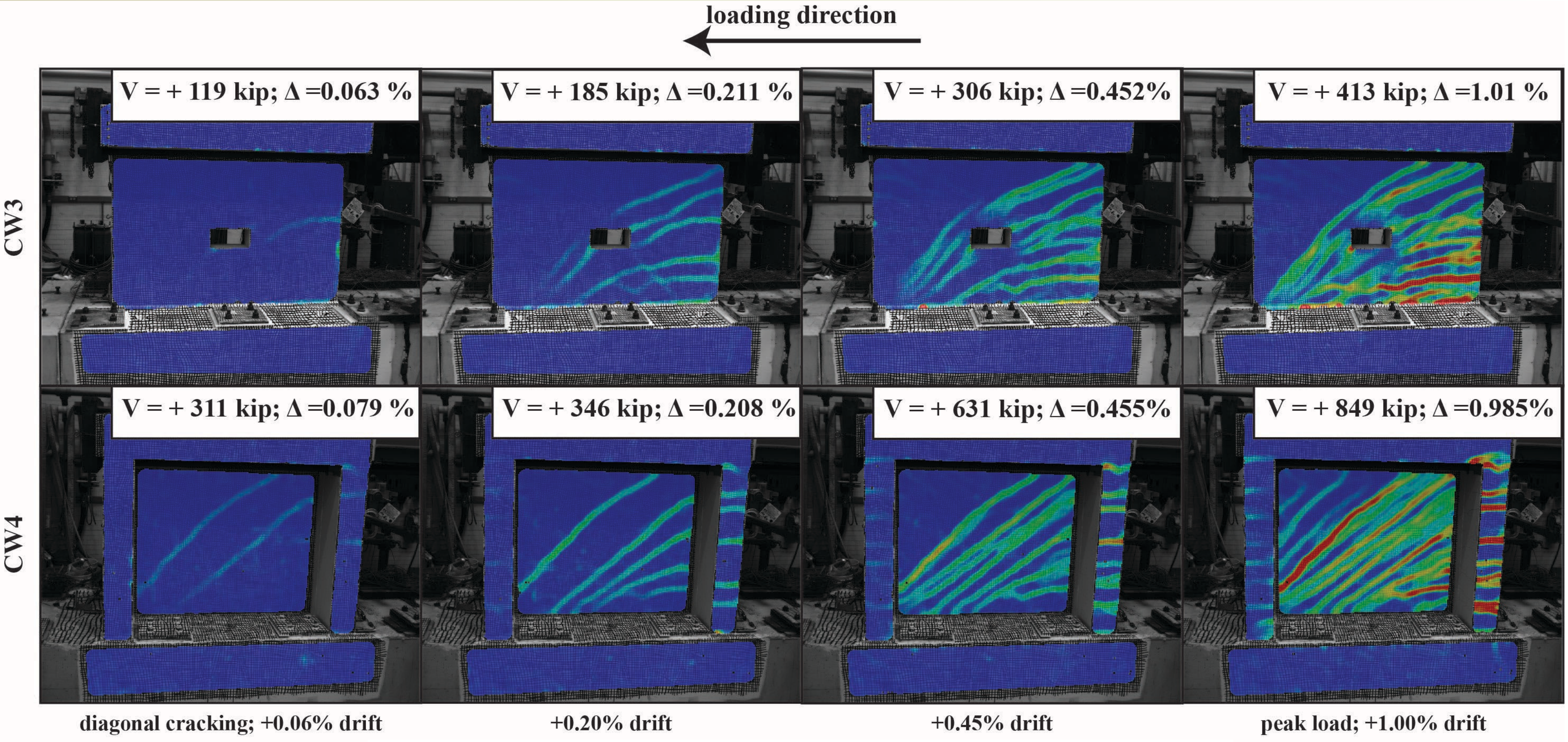
Summary of CW1 & CW2

- Proposed high-strength wall with 55% reduction in rebar area achieved 91% of the peak lateral strength of state-of-practice wall
- Incorporation of HSR and HSC resulted in:
  - Different cracking patterns during early and mid-level loading cycles changed
  - Similar by cracking patterns by peak load
  - Reinforcement strains were increased by the incorporation of HSC/HSR, but similar as a proportion of the reinforcement specified yield strain
  - The initial stiffness was slightly increased by HSC
  - Cracked stiffness reduced due to reduced rebar area
  - Post-peak behavior was improved

CW3 versus CW4 Behaviors



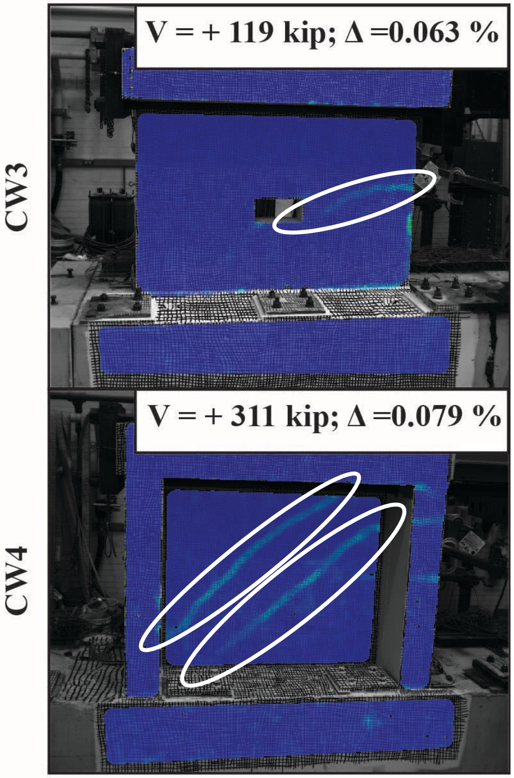
CW3 & CW4 Cracking Behaviors



maximum principal surface strains

CW3 & CW4 Cracking Behaviors

loading direction ←



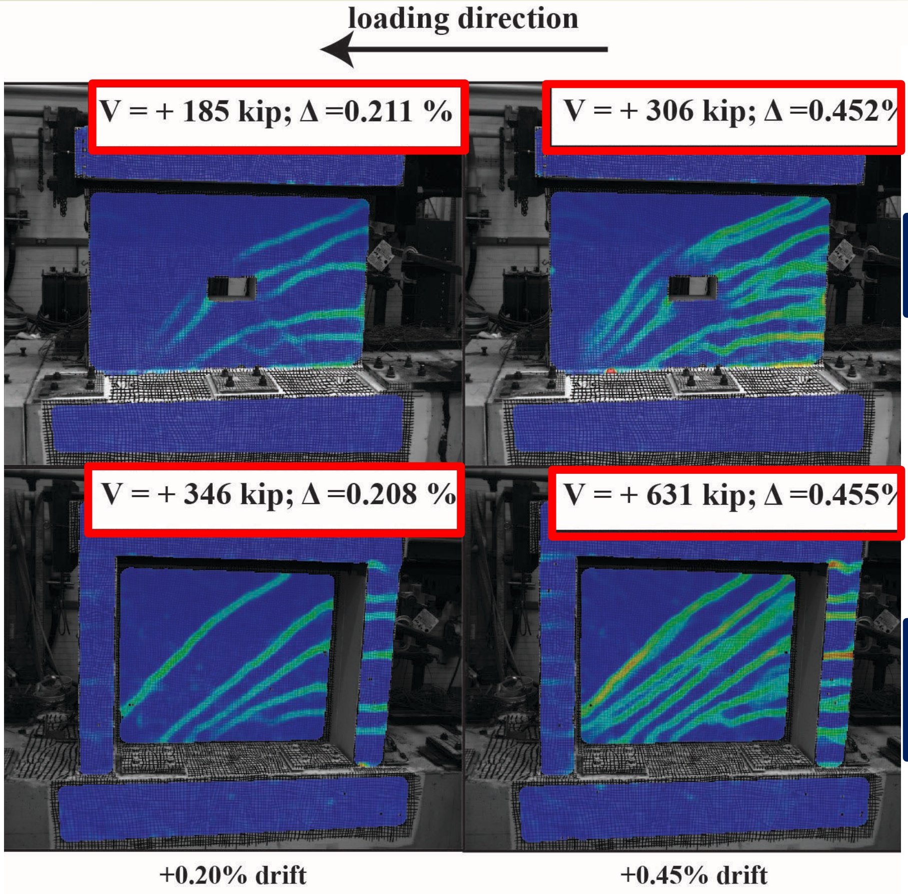
diagonal cracking; +0.06% drift

single crack, smaller

large load increase to initiate diagonal cracking, larger cracks

maximum principal surface strains

CW3 & CW4 Cracking Behaviors



~2x greater stiffness provided by flanges

well distributed away from penetration with increasing drift

well distributed cracking in web region, horizontal cracks in flange walls

maximum principal surface strains

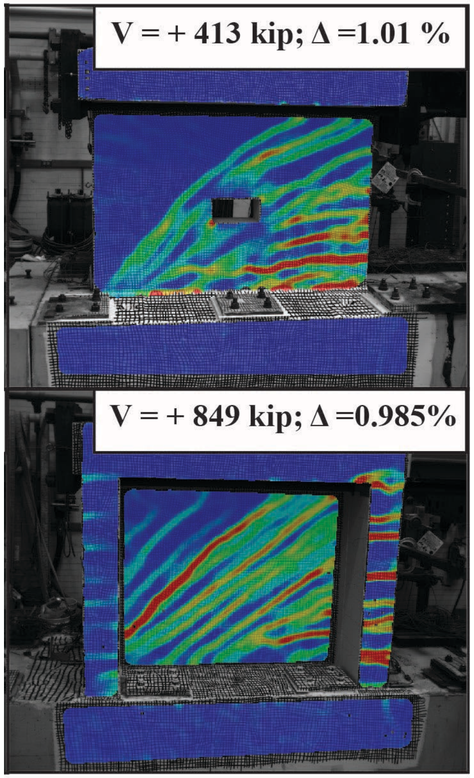
CW3 & CW4 Cracking Behaviors

loading direction

CW3

CW4

similar cracking pattern
same drift at peak load



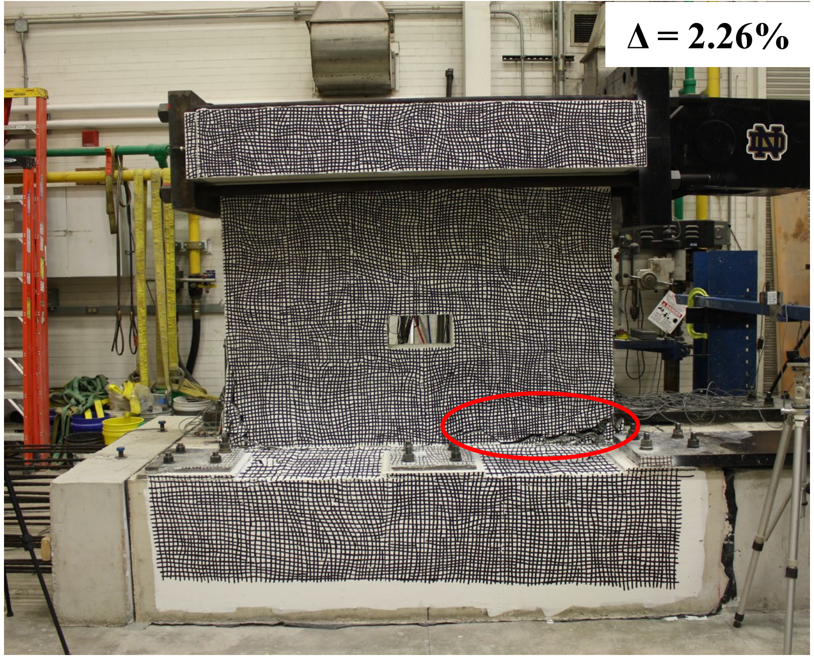
peak load; +1.00% drift

maximum principal surface strains

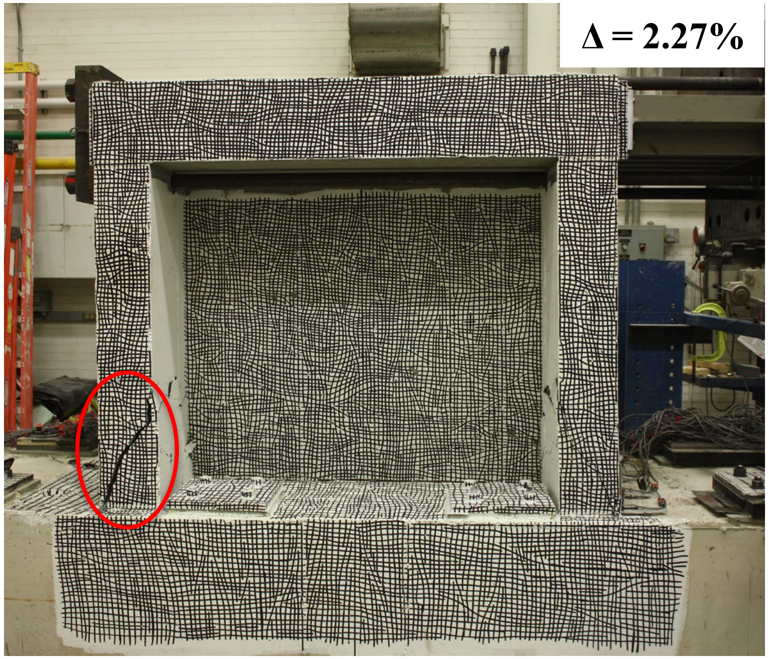
CW3 & CW4 Failure Modes

final peak drift; Δ = +2.25%

loading direction ←



rebar fractures



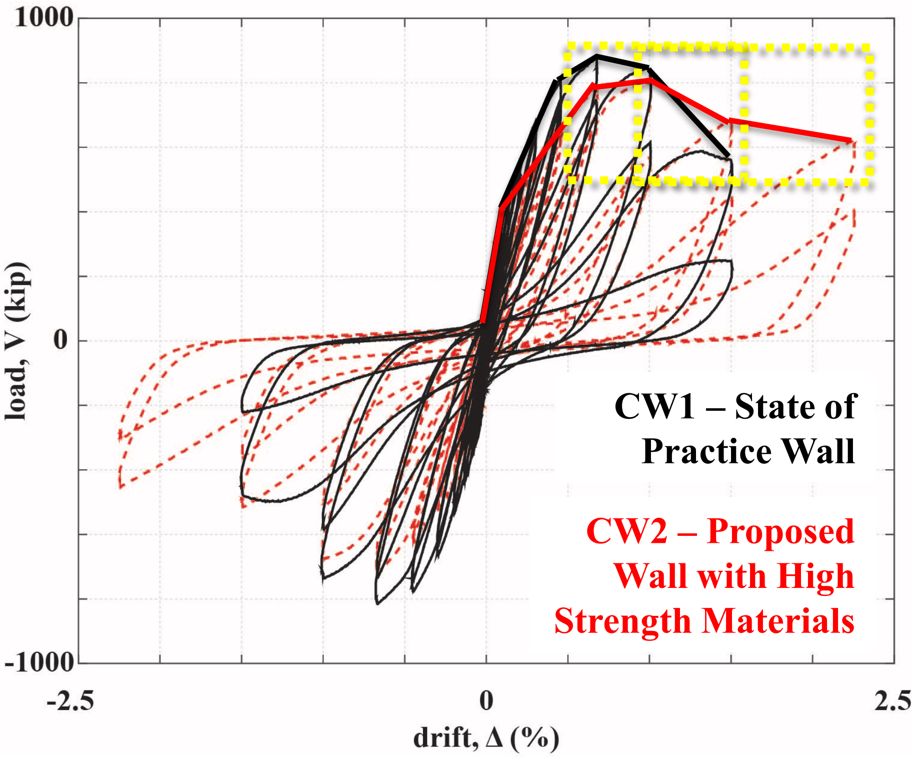
shear crack through flange

Summary of CW3 and CW4

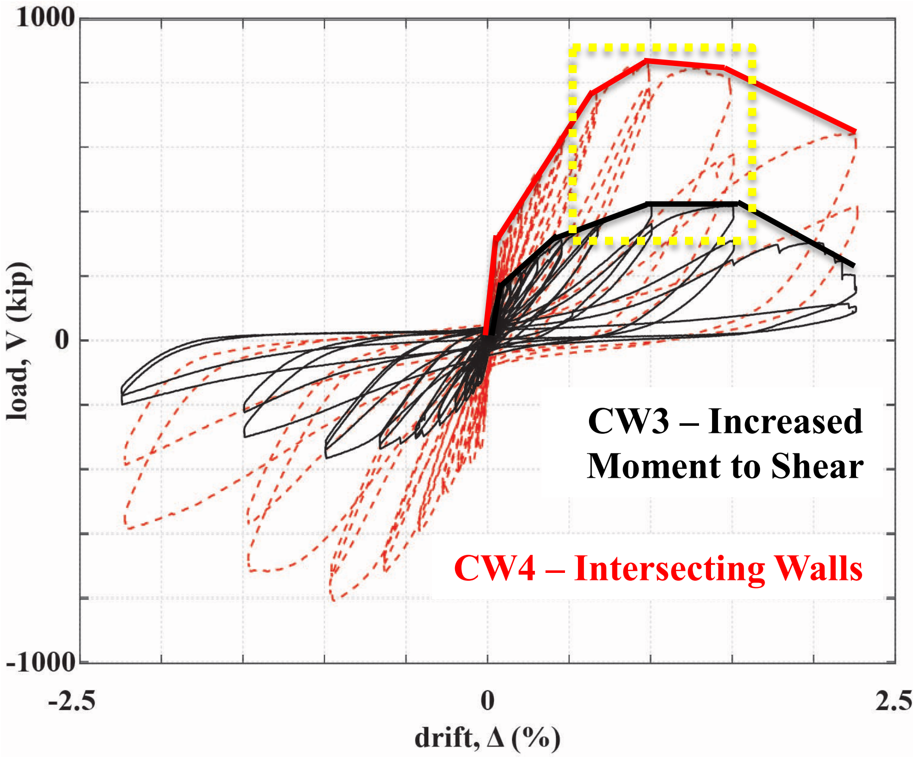
- Boundary flanges more than doubled the peak load of specimen with same web area and base moment-to-shear ratio
- Diagonal cracking occurred during the same drift cycle, yet boundary flanges increased the diagonal cracking load significantly
- The incorporation of intersecting walls as boundary flanges increased the cracked stiffness of the specimen
- Flexural failure observed even in a stocky shear wall, base moment-to-shear ratio of 0.75

All Wall Behaviors

$M/Vl_w = 0.5$



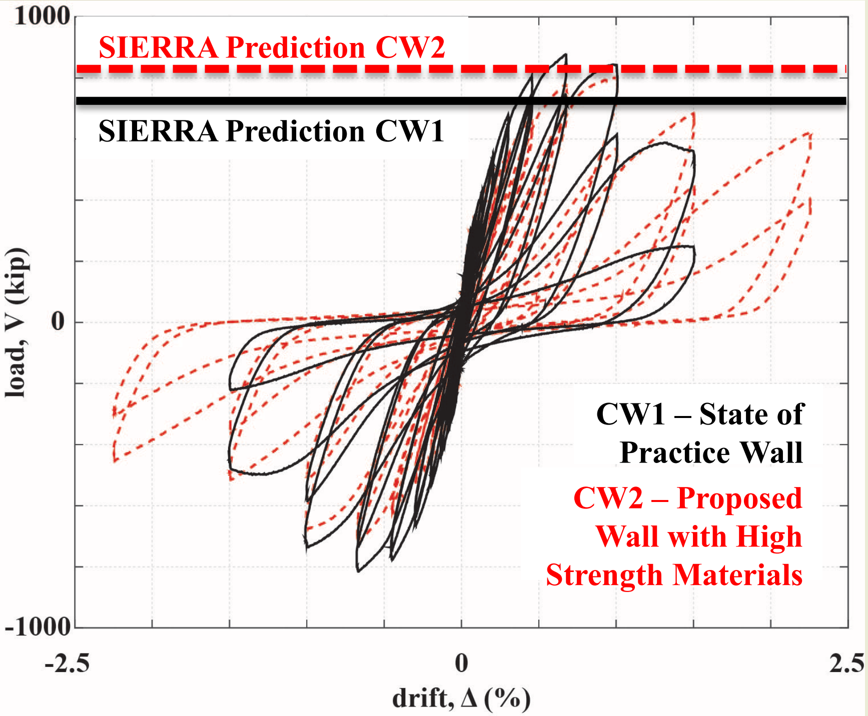
$M/Vl_w = 0.75$

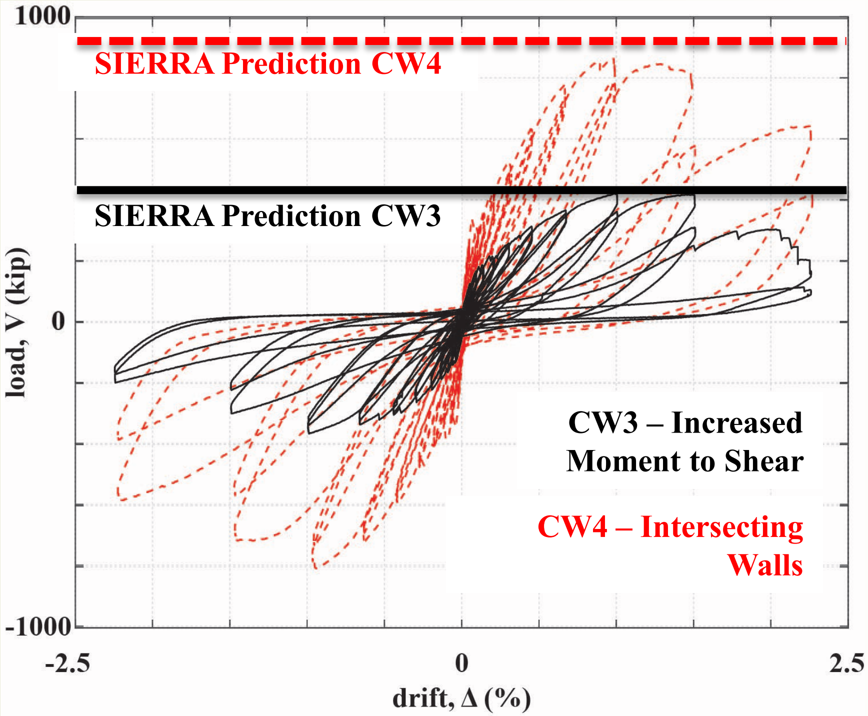


improved post-peak residual load from HSC/HSR

peak load at increased drift series due to increased M/Vl_w

Strength Predictions (V_{pm}/V_{pp})





	CW1	CW2	CW3	CW4	Mean	STD
V_{pm}/V_{pp}	1.21	0.96	0.96	0.93	1.01	0.13

SIERRA provided a conservative prediction for state-of-practice walls and close predictions of three high-strength material walls

Wall Test Experimental Results

Result		CW1	CW2	CW3	CW4
Description		state-of-practice	high-strength materials	Increased M/Vl_w	flanged
Positive Loading	[1] V_{pm} (kip)	878	801	421	863
	[2] $V_{pm}/(A_w\sqrt{f_c'})$	12.2	7.63	6.12	12.7

[1] Peak applied load.

[2] Normalized shear stress factor at peak applied load, where A_w = gross cross-sectional area of wall web and f_c' is in psi units.

With 55% reduction in reinforcement area with HSC and HSR, CW2 achieved 91% V_{pm} of CW1 (NSC and NSR)

Wall Test Experimental Results

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Boundary flanges more than doubled the peak load of Specimen CW4 with same web area and base moment-to-shear ratio as CW3

Wall Test Experimental Results

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Description		state-of-practice	high-strength materials	Increased M/Vl$_w$	flanged
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[1] Peak applied load.

[2] Normalized shear stress factor at peak applied load, where A_w = gross cross-sectional area of wall web and f_c' is in psi units.

Specimens CW1 and CW4 demonstrate that both NSC and HSC can exceed the current ACI shear stress limit of $10\sqrt{f_c'}$

Wall Test Experimental Results

Result		CW1	CW2	CW3	CW4
Description		state-of-practice	high-strength materials	Increased M/Vl_w	flanged
Positive Loading	[1]V_{pm} (kip)	878	801	421	863
	[2] $V_{pm}/(A_w\sqrt{f_c'})$	12.2	7.63	6.12	12.7

[1] Peak applied load.

[2] Normalized shear stress factor at peak applied load, where A_w = gross cross-sectional area of wall web and f_c' is in psi units.

Specimens CW2 and CW3 demonstrate that rectangular walls with HSC and HSR without boundary regions may fail prior to the ACI shear stress limit of $10\sqrt{f_c'}$

Summary from All Walls

- Increased base moment-to-shear ratio resulted in increased deformation capacity
- The lateral strength of rectangular shear walls with HSR and HSC did not reach the current ACI limit for peak shear stress, $10\sqrt{f_c'}$, which could result in unconservative overpredictions of strength
- The incorporation of intersecting walls as boundary flanges resulted in a specimen with HSC shear stresses above the ACI maximum limit of $10\sqrt{f_c'}$, due to the increase in moment capacity
- Numerical finite element models provided good estimates of all walls peak lateral strength

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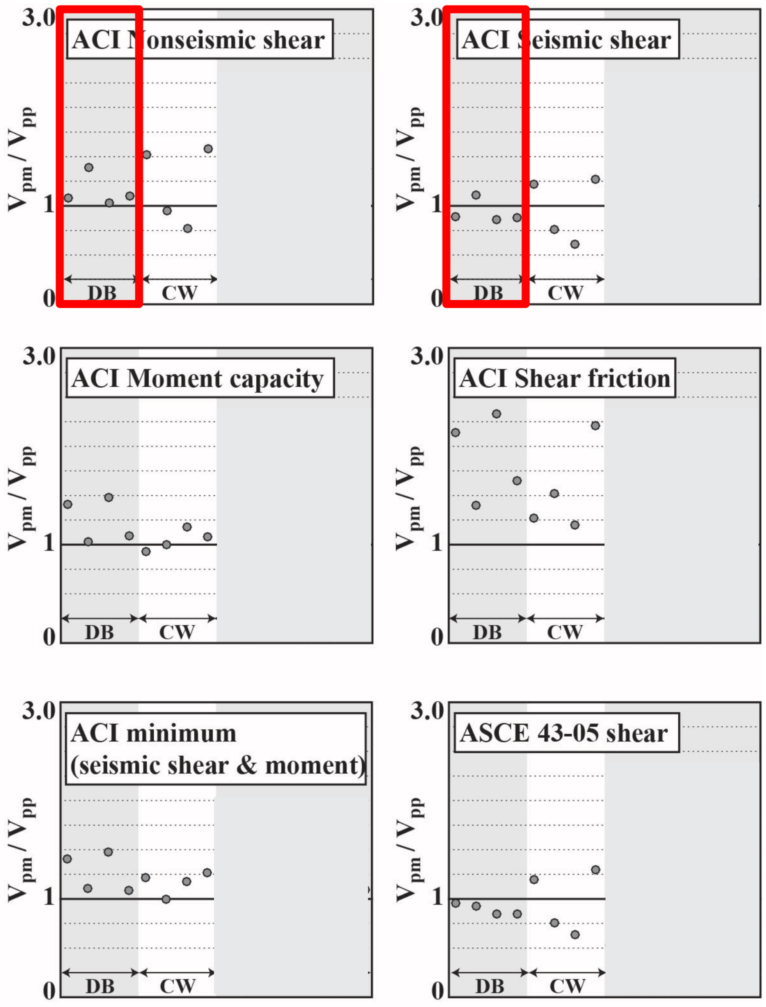
Peak Strength Predictive Methods

Equation	Description
ACI 318-14 Chp. 11 (ACI 349-13 Chp. 11)	Non-seismic Shear
ACI 318-14 Chp. 18 (ACI 349-13 Chp. 21)	Seismic Shear
ACI 318-14 Chp. 22.2-3 (ACI 349-13 Chp. 10.2-3)	Flexural Capacity reinforcement assumed elastic-perfectly-plastic
ACI 318-14 Chp. 22.9 (ACI 349-13 Chp. 11.6)	Shear Friction
ASCE 43-05 Section 4.0	Seismic Shear Nuclear Facilities

measured material properties used to investigate current equations' viability with high-strength materials

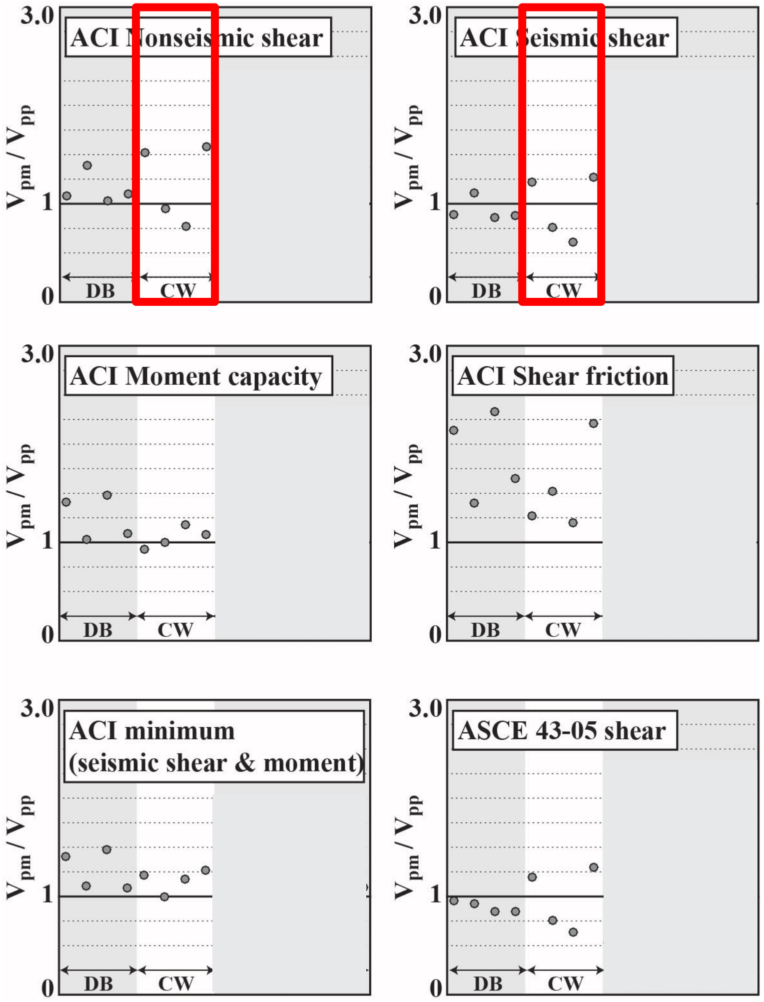
Strength Predictions (V_{pm}/V_{pp})



ACI nonseismic shear - conservative for all deep beams
(effective depth d = 0.8*l_w)
ACI seismic shear - unconservative for three of four specimens
(no effective depth requirement)

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

Strength Predictions (V_{pm}/V_{pp})



Both ACI shear equations conservative for walls with large shear stresses

- **CW1 - NSC/NSR, high rebar ratio**
- **CW4 – intersecting walls**

Both ACI shear equations unconservative for rectangular walls with HSC/HSR

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

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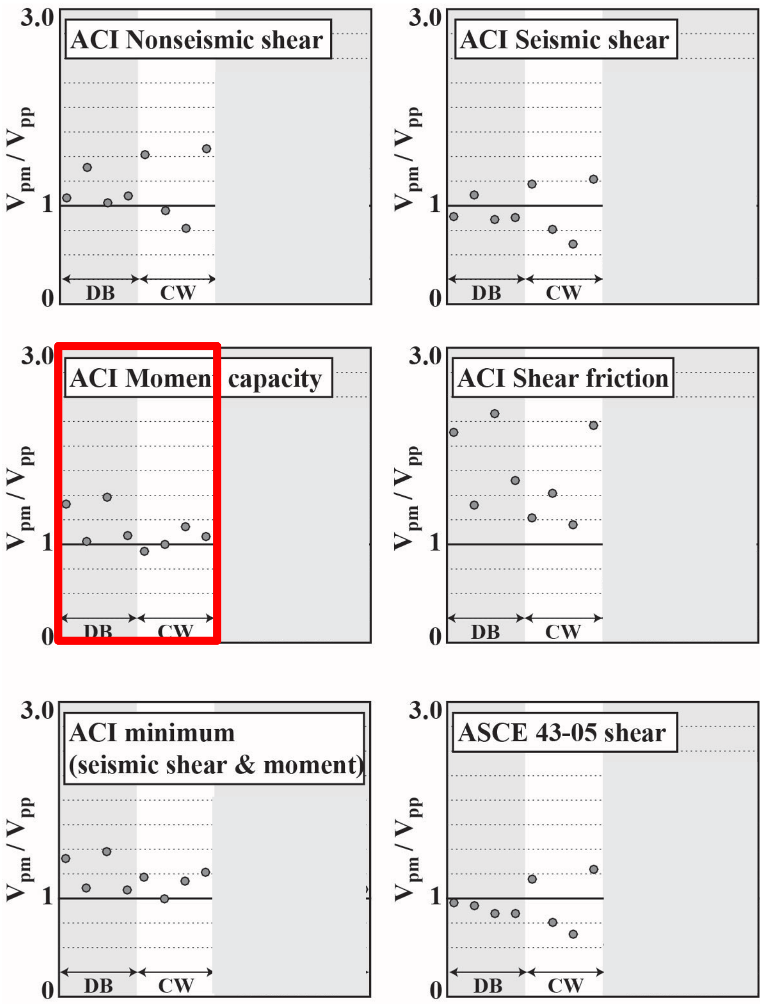

ACI moment capacity provides conservative predictions for 7/8 specimens
Highly conservative for DB1 and DB3, lightly reinforced with NSR

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

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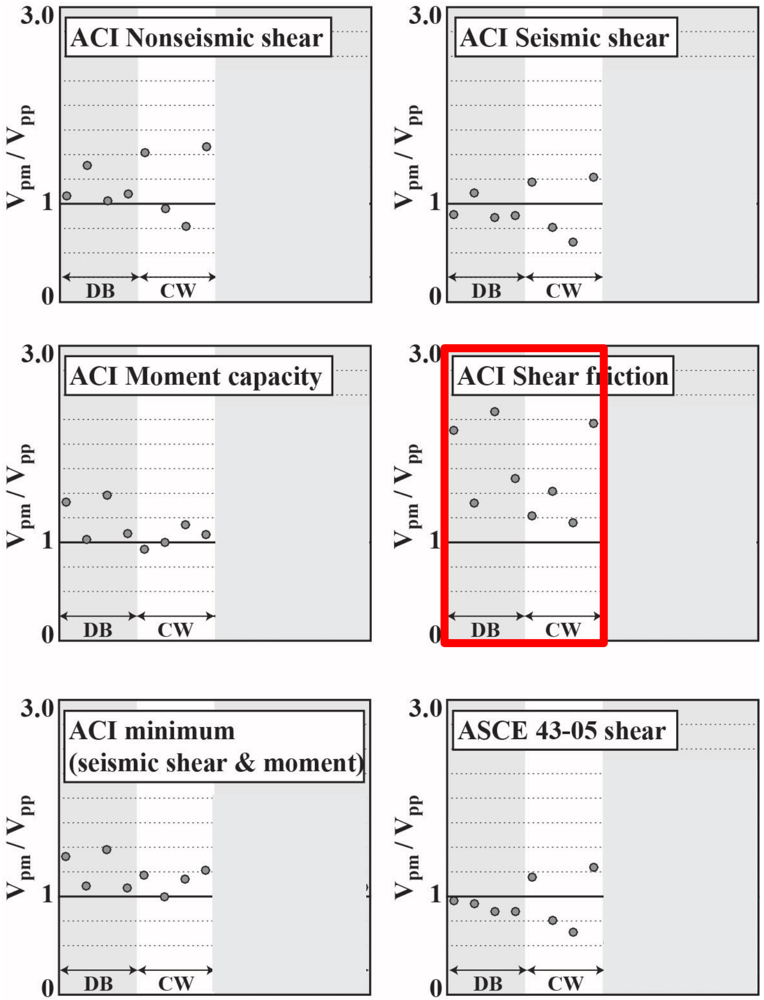

Shear friction very conservative for all deep beam and wall specimens

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

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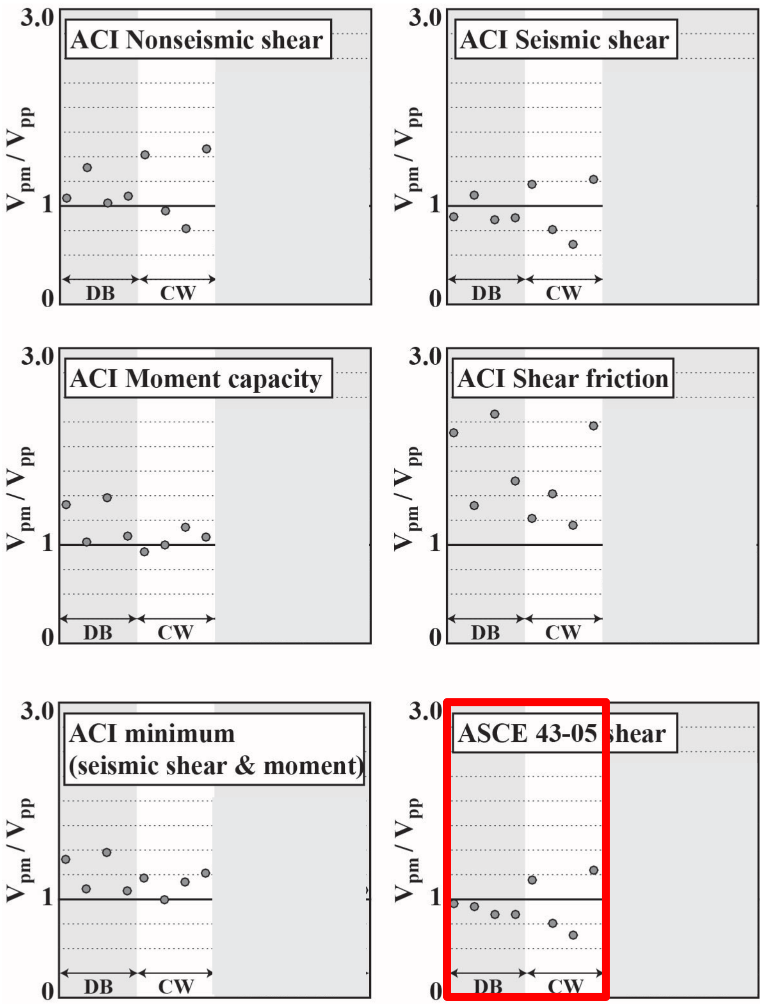

Unconservative for all specimens except two with high shear stresses

- **CW1 - NSC/NSR, high rebar ratio**
- **CW4 – intersecting walls**

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

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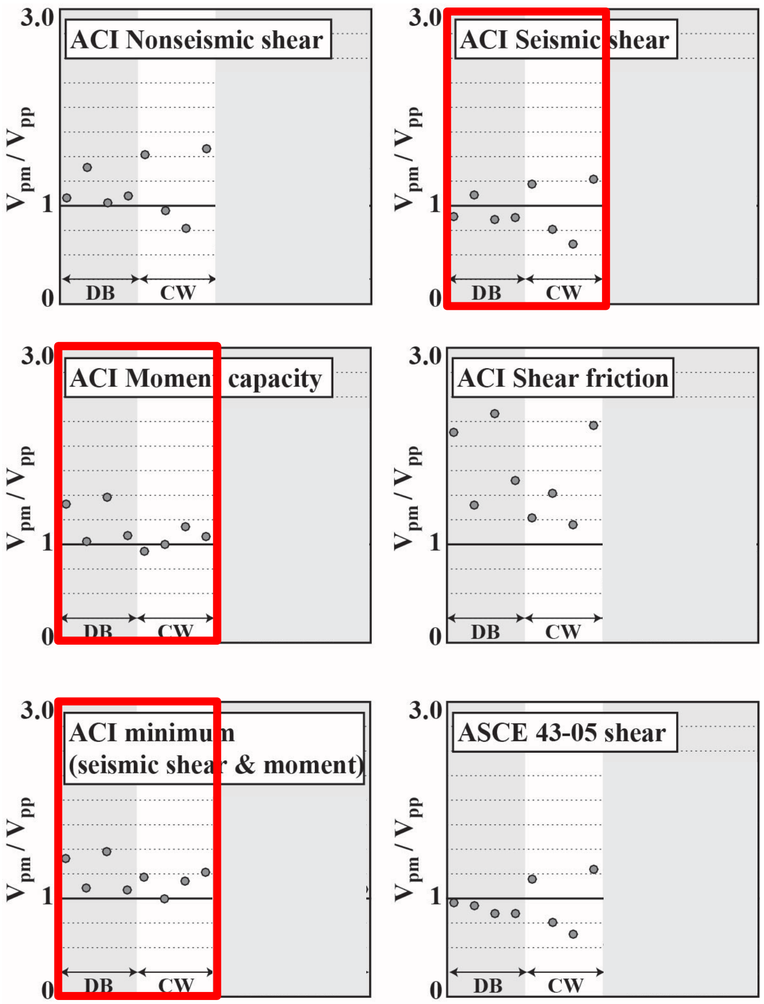

Combination of ACI seismic shear and ACI moment capacity results in conversative predictions of all specimens, including HSC/HSR

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., "Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *ACI Structural J.*, 112(5), 2015, 593-604.

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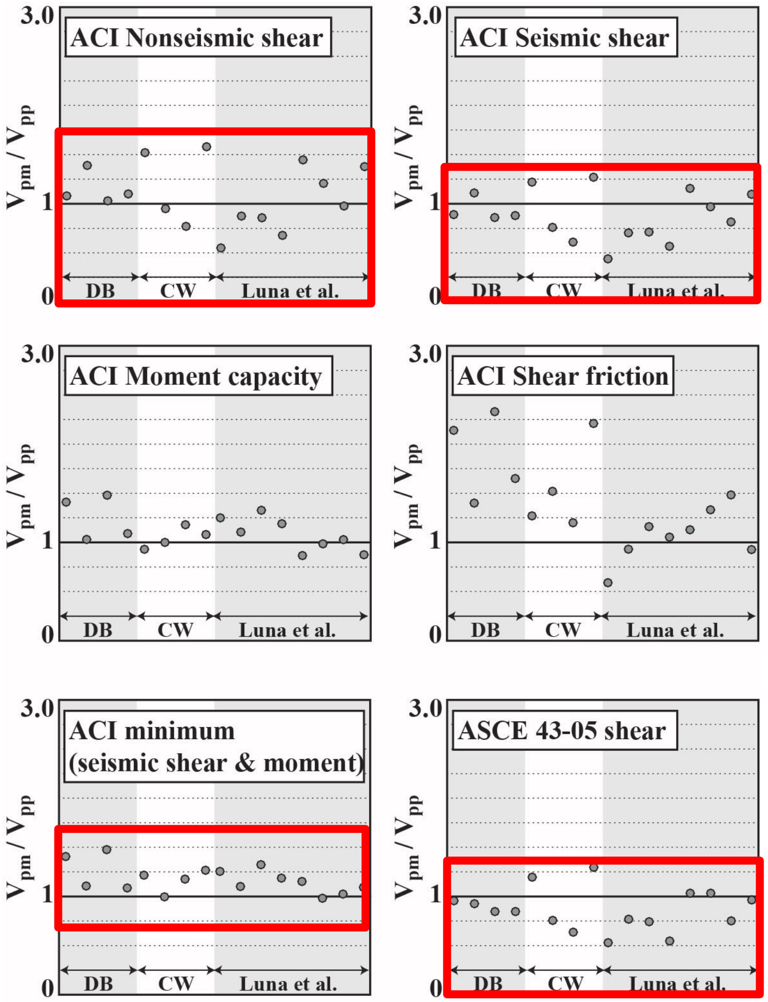

Similar issues for rectangular walls without boundary regions with NSR/NSC
Reinforcement ratio – 0.33 to 1.5%
Moment-to-shear – 0.33 to 0.94

[1] Luna, B. N., Rivera, J. P., and Whittaker, A. S., “Seismic Behavior of Low-Aspect-Ratio Reinforced Concrete Shear Walls,” *ACI Structural J.*, 112(5), 2015, 593-604.

Summary

- Current ACI predictive shear equations have significant scatter and produce unconservative predictions of peak lateral strength for rectangular walls, regardless of material strength
- If the moment capacity of a stocky wall is significantly higher than the shear capacity, the current ACI limit for peak shear stress, $10\sqrt{f_c'}$, may be conservative, regardless of material strength
- The current ACI limit for peak shear stress, $10\sqrt{f_c'}$,may be unconservative for rectangular walls without boundary regions
- Current moment capacity predictions in combination with ACI seismic shear predictions provided conservative predictions for all specimens with high-strength materials
- The moment capacity of stocky shear walls must be considered for design, especially in rectangular walls without boundary regions

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Cost-Benefit Analysis

- Numerical evaluation (2304 walls) for effectiveness of high-strength materials and prefabrication on :
  - construction cost, using cost metric $\Gamma = C_w / V_{wm}$
  - on-site construction time, using time metric $T = T_w / V_{wm}$
- Scenario 1 represents building construction, while Scenarios 2 and 3 represent nuclear construction
- Data from Industry Survey and "RSMeans Building Construction Cost Data – 75th Annual Edition." The Gordian Group, 2016, 932 pp."

Parameter	Scenario 1	Scenario 2	Scenario 3
length, l_w (ft)	20	60	120
height, h_w (ft)	40	120	120
thickness, t_w (in.)	10, **15**, 20	30, **45**, 60	30, **45**, 60
moment to shear ratio, $M/(Vl_w)$	**0.5**, 1.0	**0.5**, 1.0	**0.5**, 1.0
concrete strength, f'_c (ksi)	**5**, 10, 15, 20	**5**, 10, 15, 20	**5**, 10, 15, 20
rebar strength, f_y (ksi)	**60**, 80, 100, 120	**60**, 80, 100, 120	**60**, 80, 100, 120
reinforcement ratio, ρ_s (%)	low to very high	low to very high	low to very high

Effect of Prefabrication on Total Worker-Hours per Ton of Rebar

Construction Type	Construction Task	Worker-Hours per Ton of Rebar		
		[1]< 200 lb/yd^3	[1]200-400 lb/yd^3	[1]> 400 lb/yd^3
Common to In-Place and Prefabricated	Cut, tag, bundle	1.98	2.20	3.42
	Unload and handle	3.26	4.97	9.08
	Other	0.05	0.07	0.09
	TOTAL	**5.29**	**7.24**	**12.59**
In-Place	Rebar tying	13.80	15.40	20.00
	Other	0.80	0.70	0.80
	[2]TOTAL	**19.89**	**23.34**	**33.39**
Prefabricated	Rebar tying	9.20	11.20	14.60
	Set and secure in-place	2.50	4.00	5.70
	Other	0.05	0.10	0.20
	[2]TOTAL	**17.04**	**22.54**	**33.09**

[1] rebar density in RC wall (i.e., degree of congestion), in pounds of rebar per cubic yard of concrete

[2] includes worker-hours for tasks common to both in-place and prefabricated construction

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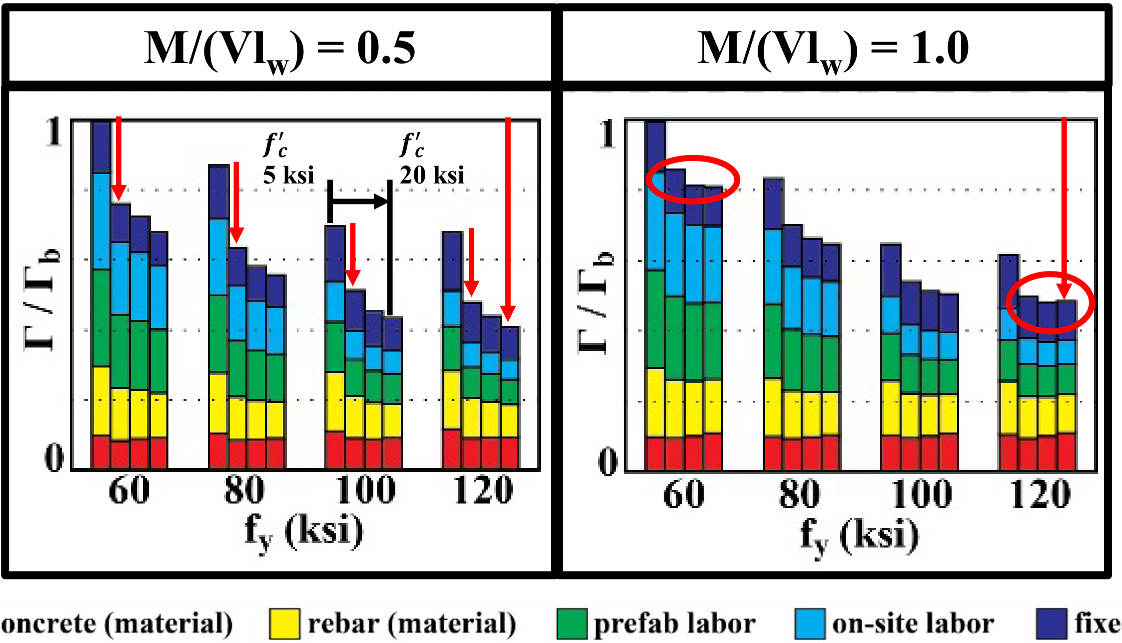
Construction Cost Metric

Scenario 2 (60 ft long, 120 ft tall, 45 in. thick), $M/(Vl_w)=0.5$, 100% prefabrication:



$$\Gamma = \frac{C_w}{V_{wm}}$$

Γ = Construction cost metric

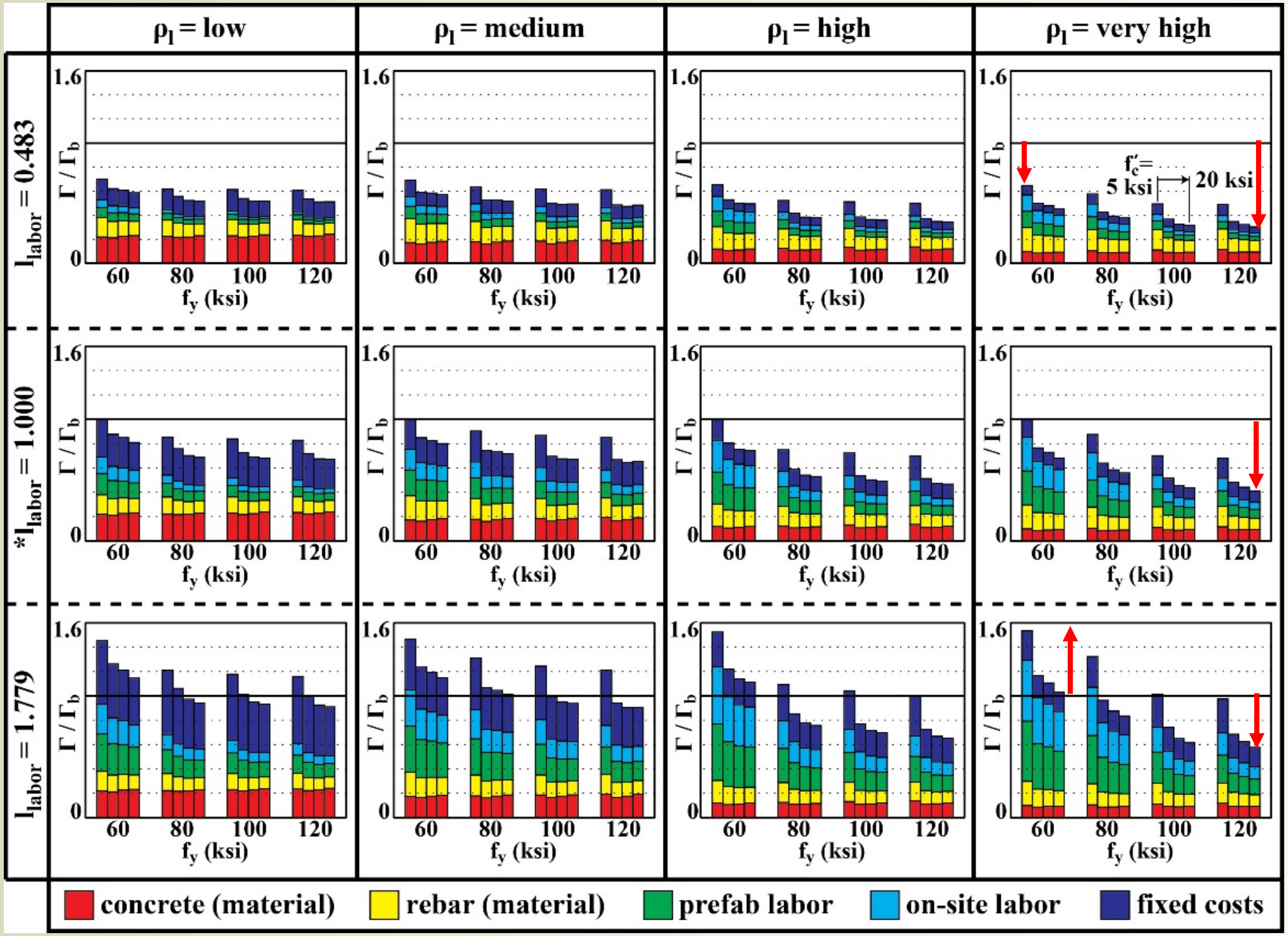
Γ_b = Construction cost metric of "benchmark" with normal-strength materials

C_w = Total cost of rebar material, rebar labor, and concrete material

V_{wm} = Predicted peak lateral strength

Adjustment for Local Labor Costs

Scenario 2 (60 ft long, 120 ft tall, 45 in. thick), $M/(Vl_w)=0.5$, 100% prefabrication:



Low

National average

High

HSR/HSC increase savings

~60% reduction

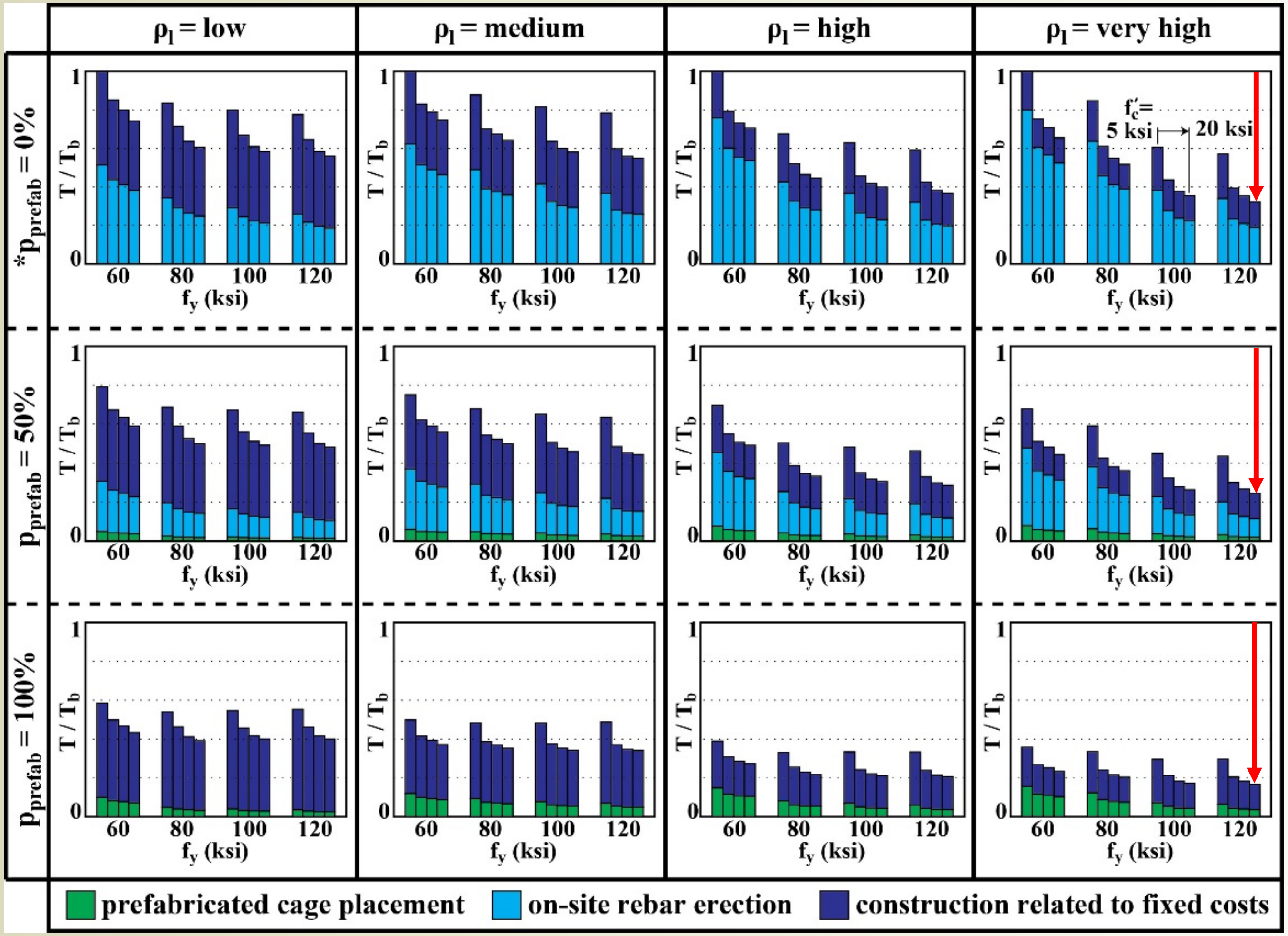
HSR/HSC can offset increased labor and material costs

Construction Cost Summary

- Combination of high-strength rebar with high-strength concrete resulted in greatest cost benefits
- Combination of high-strength materials and prefabrication for walls with large thickness, large ρ_s, low $M/(Vl_w)$ resulted in largest reductions in wall construction cost (up to ~60%)
- Savings can compensate for construction in regions of U.S. with higher than average material and labor costs

On-Site Construction Time Metric

Scenario 2 (60 ft long, 120 ft tall, 45 in. thick), $M/(Vl_w)=0.5$:



68% reduction

75% reduction

83% reduction

T = On-site construction time metric

T_b = On-site construction time metric of "benchmark" with normal-strength materials

On-Site Construction Time Summary

- Overall, combination of prefabrication with high-strength materials resulted in significant on-site construction time reductions
- Largest benefits were for walls with large thickness, large ρ_s, and low $M/(Vl_w)$, with reductions in on-site construction time up to ~83%
- While 100% prefabrication may not be logistically possible, 50% prefabrication can also result in significant savings, up to ~76%

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Summary and Conclusions

- Performance of HSR/HSC demonstrated through large-scale testing of deep beam and shear wall specimens
- High-strength steel more effective when combined with high-strength concrete, resulting in greatest increase in lateral strength
- Proposed high-strength wall with 55% reduction in rebar area achieved 91% of the peak lateral strength of state-of-practice wall
- Results validate simplified and detailed numerical models as well as identify limitations in code design equations
- Up to ~60% saving in construction cost to achieve specified wall design strength using HSR/HSC
- Prefabricated rebar assemblies can improve construction schedules (up to ~80% reduction in on-site time)

Research Products

- Journal Papers (published):
  - “Effect of Tripping Prefabricated Rebar Assemblies on Bar Spacing,” *ASCE J. of Construction Engineering and Management*, 2018
  - “Experimental Evaluation of Deep Beams with High-Strength Concrete and High-Strength Rebar,” *ACI Structural J.*, 2018
  - “Effect of High-Strength Materials on Lateral Strength of Stocky Reinforced Concrete Walls,” *ACI Structural Journal*, 2017
  - “Economic Evaluation of High-Strength Materials in Stocky Reinforced Concrete Shear Walls,” *ASCE J. of Construction Engineering and Management*, 2017

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  - Essve Tech, Inc.
  - Harris Rebar
  - HRC, Inc.
  - MMFX Steel
  - Nucor Corporation
  - Sika Corporation U.S.

Questions?

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http://phsrc-nuclearwalls.nd.edu