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:

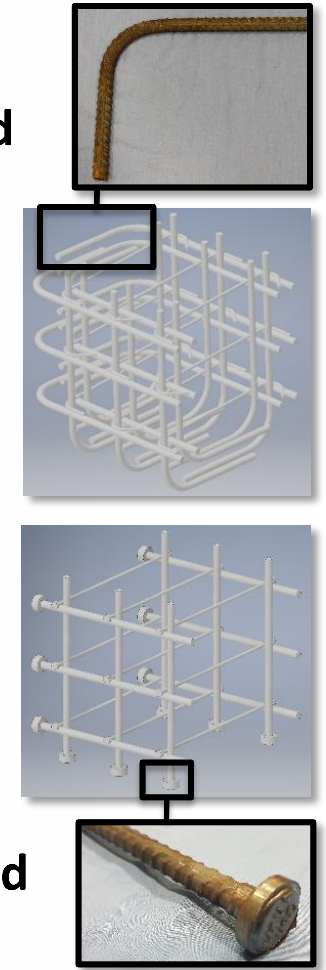
1) High-strength reinforcing steel bars (rebar) up to Grade 120 (versus current Grade 60)
2) Headed (versus current hooked) anchorages
3) Prefabricated rebar assemblies
4) High-strength concrete up to 20 ksi (versus current 5 ksi)

Most Congested (current)

Multiple layers of hooked Grade 60 bars

Fewer layers of headed high-strength bars

Least Congested (envisioned)



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HIGH STRENGTH MATERIALS PREFABRICATION

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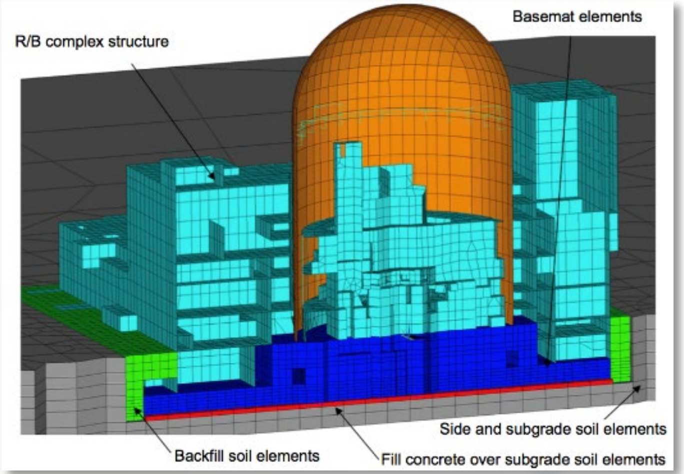
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

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. Evaluation of Prefabricated Rebar
   - Industry Survey
   - Experimental Evaluation of Prefabricated Rebar
2. Experimental Testing of High-Strength Materials
   - Deep Beam (Wall Slice) Specimens
   - Shear Wall Specimens
3. Detailed Numerical Modeling
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Prefabricated Rebar Assemblies

Evaluating prefab rebar assemblies for:

- labor hours, costs, advantages, disadvantages, and methods
- transportability and liftability in terms of rebar spacing changes

through:

- industry survey
- full-scale laboratory experimentation

retrieved from http://www.siteright.net/prefabricated-reinforcement-p-38.html

retrieved from http://www.sellwoodbridge.org/?e=517

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

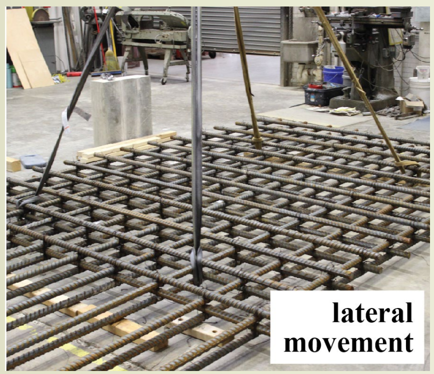
[2]includes worker-hours for tasks common to both in-place and prefabricated construction

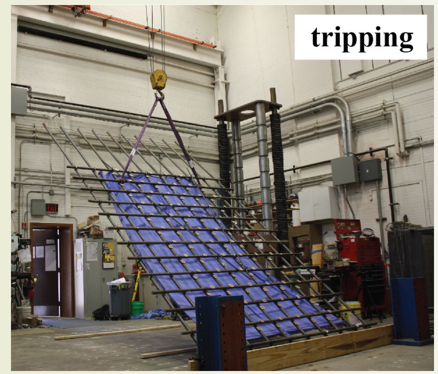
Advantages and Disadvantages of Prefabrication

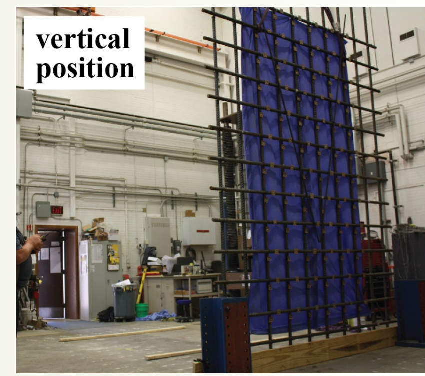
- Situations where prefabrication is beneficial:
  1. to save on-site construction time (i.e., improved construction schedule, which is a primary project objective)
  2. to improve safety and/or quality control
  3. for areas with heavy rebar congestion
  4. for structures with significant repetition in rebar layout/configuration
- Most commonly reported disadvantages of prefabrication:
  1. more logistical planning
  2. increased capacity of lifting equipment
  3. more field adjustments
  4. difficulties interfacing prefabricated rebar assemblies with existing components

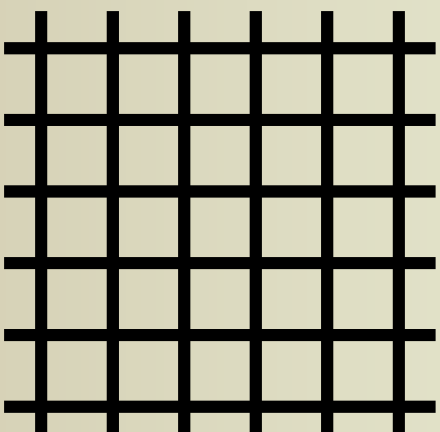
Testing of Prefabricated Rebar

- Full-scale experimental evaluation to determine effect of tripping prefabricated 2D rebar mats and 3D cages on rebar spacing



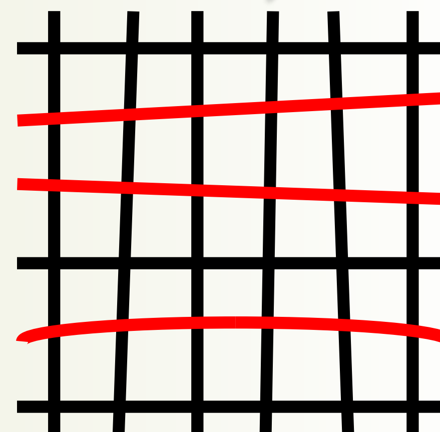






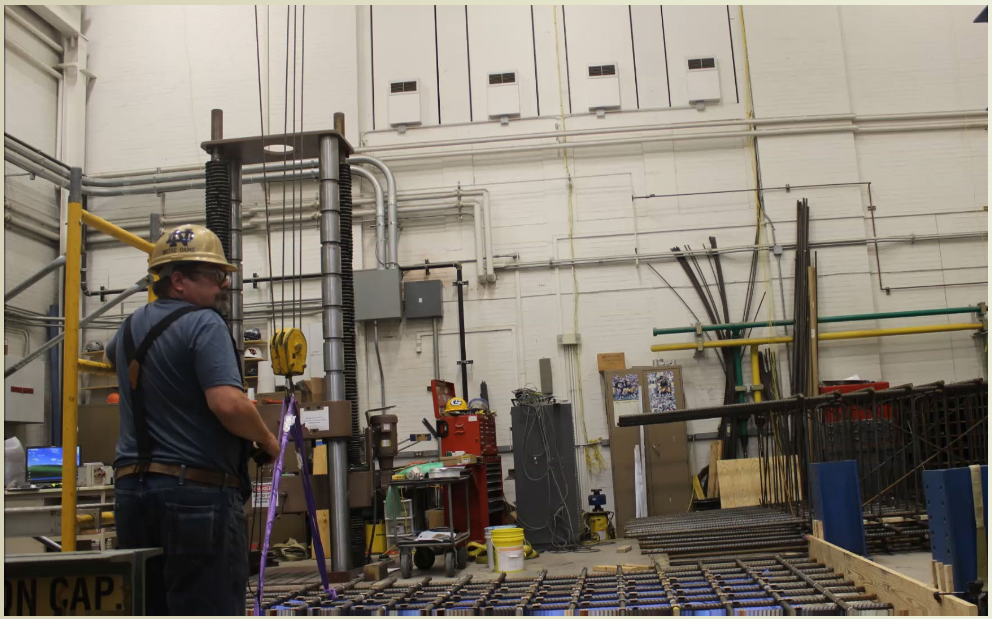
before cage/mat tripping

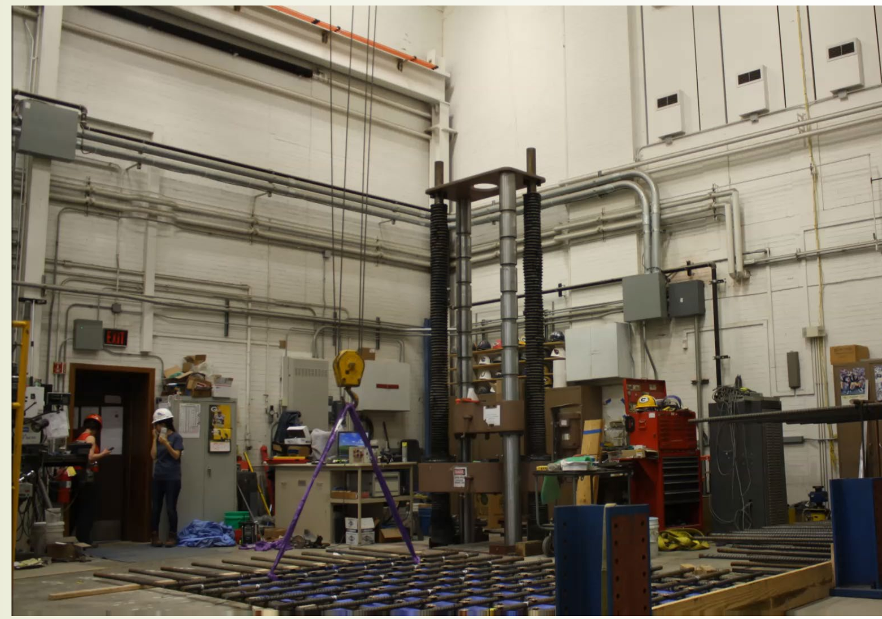
after cage/mat tripping



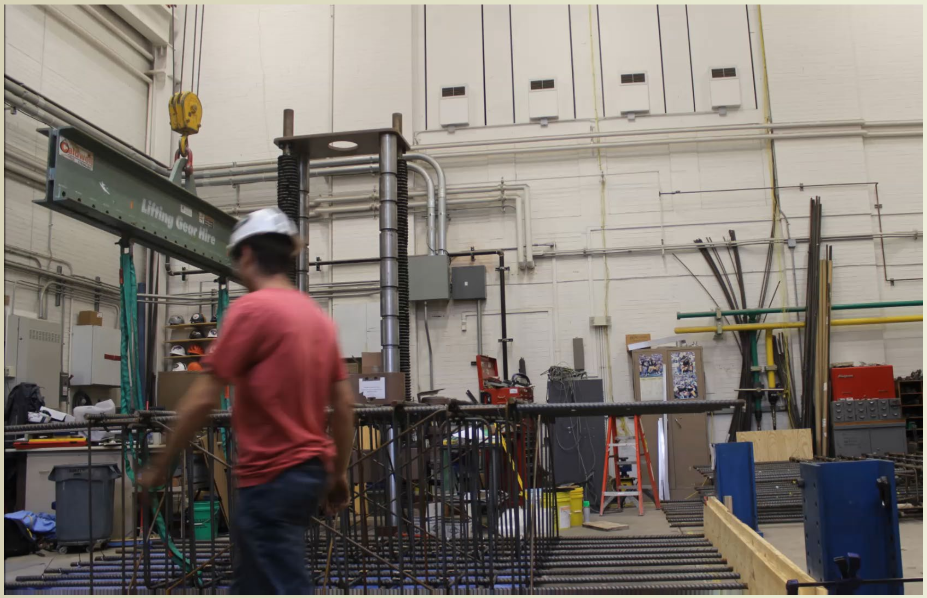
Assembly of a 3D Cage

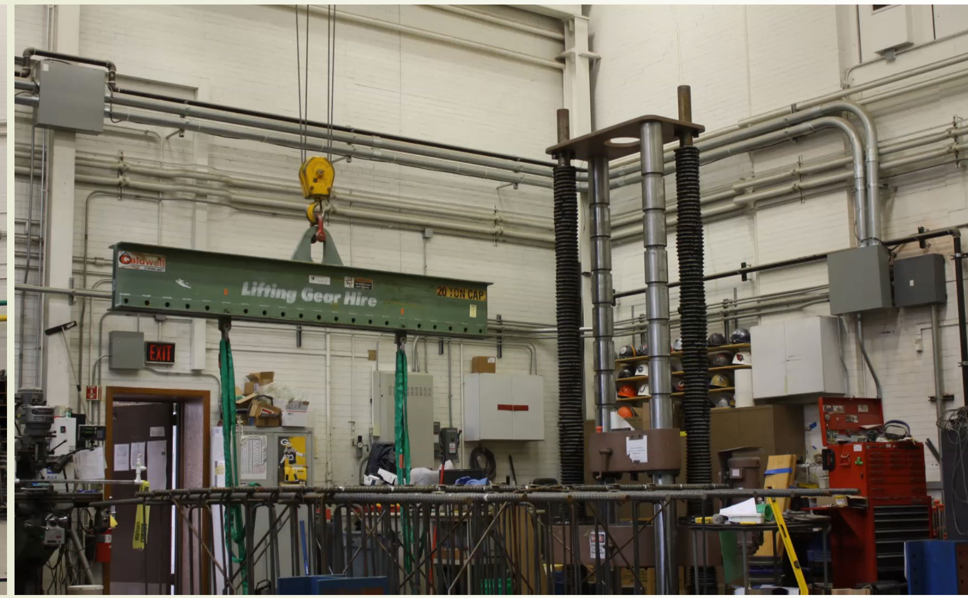
Tripping of a 2D Mat





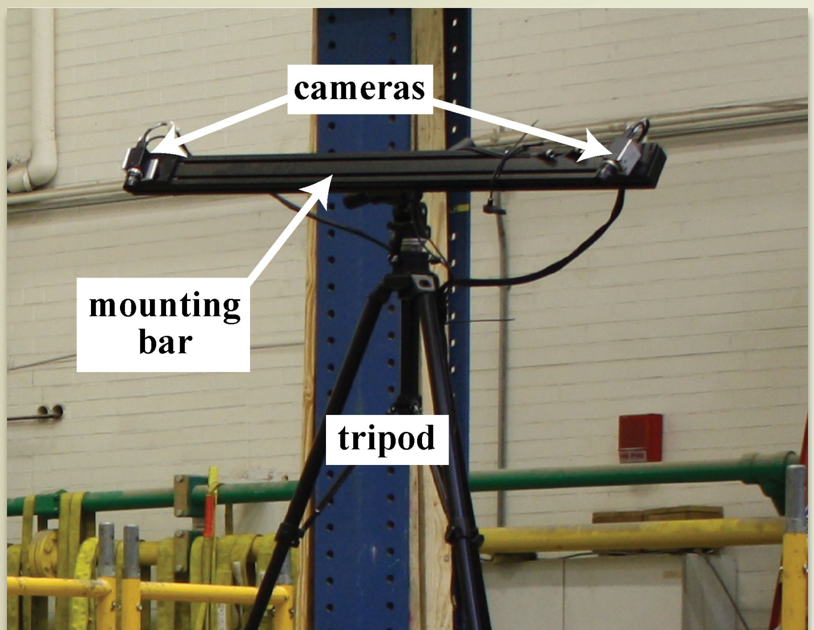
Tripping of a 3D Cage

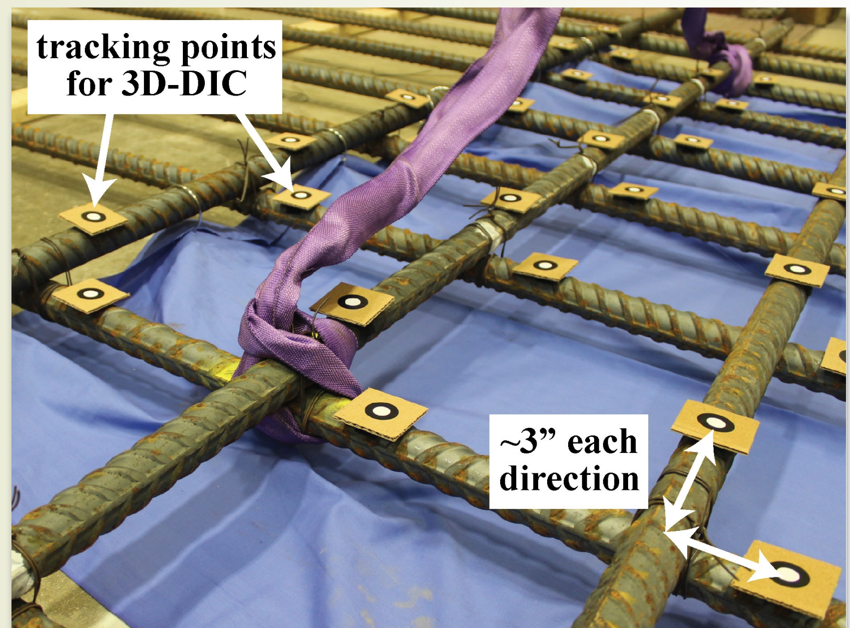




Measurement of Rebar Spacing Changes

- Use Digital Image Correlation (DIC) to track points on individual rebar
- Compare relative movement between rebar to code-required tolerances for rebar placement





Summary of Prefab Rebar Tests

- Largest prefabricated rebar spacing changes were for the horizontal bars involved in tripping/movement
- Spacing changes between all bars not directly involved in the tripping/moving of the specimens were typically small
- The following parameters did not have a significant effect on bar spacing changes:
  - Number of rebar layers in mats or cages
  - Type of transverse reinforcement (headed vs hooked) in cages
  - Thickness of cage (nuclear vs building thickness)

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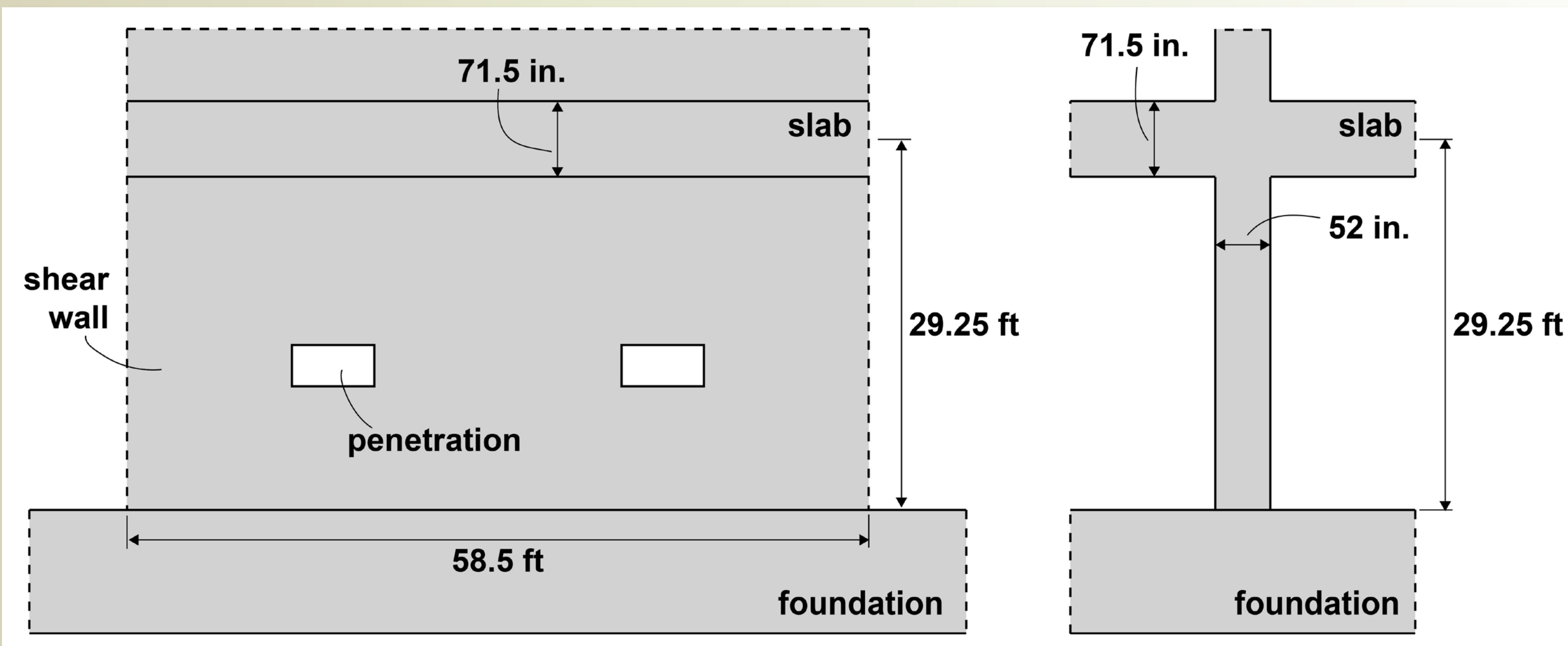
Department of Energy United States of America

Testing of High-Strength Materials

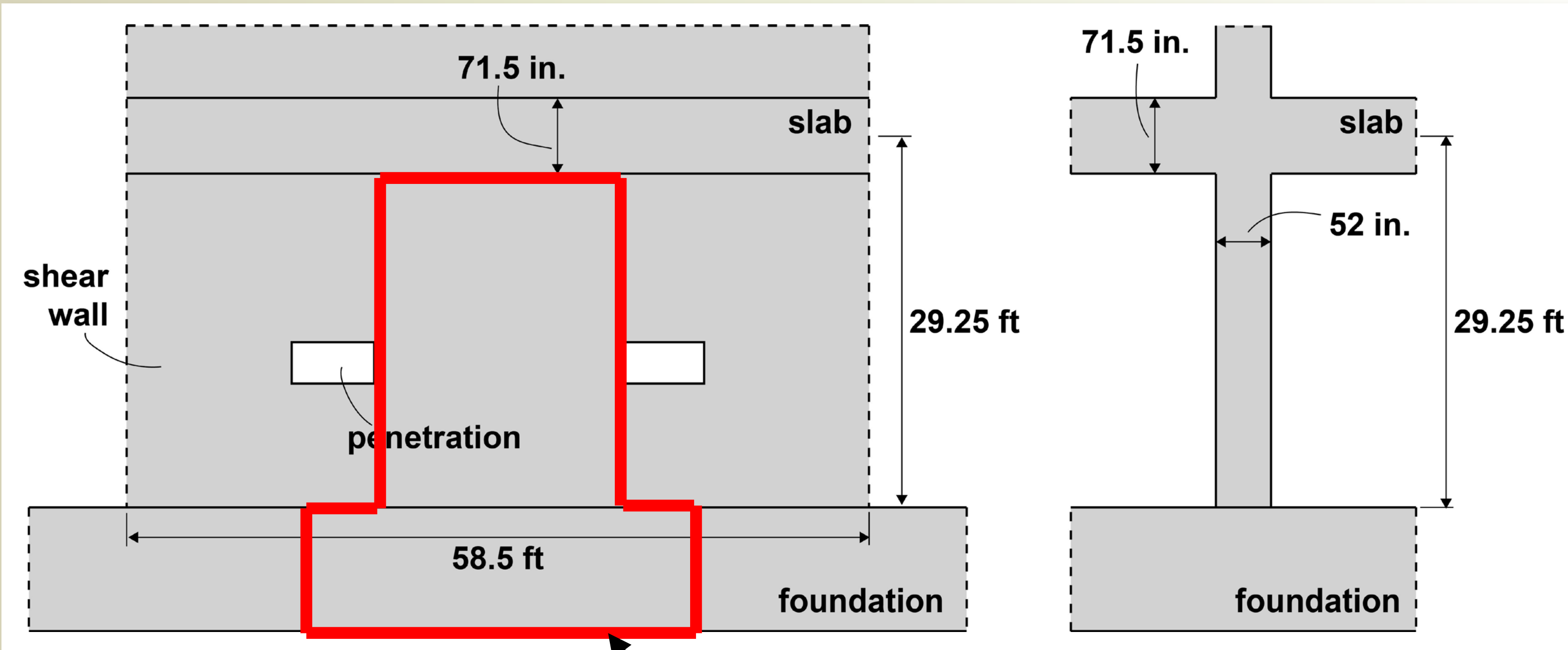
- "Generic full-scale wall" dimensions determined using publicly-available design control documents
- Provided basis for deep beam and shear wall tests conducted at 1:6.5 scale



Primary Goals

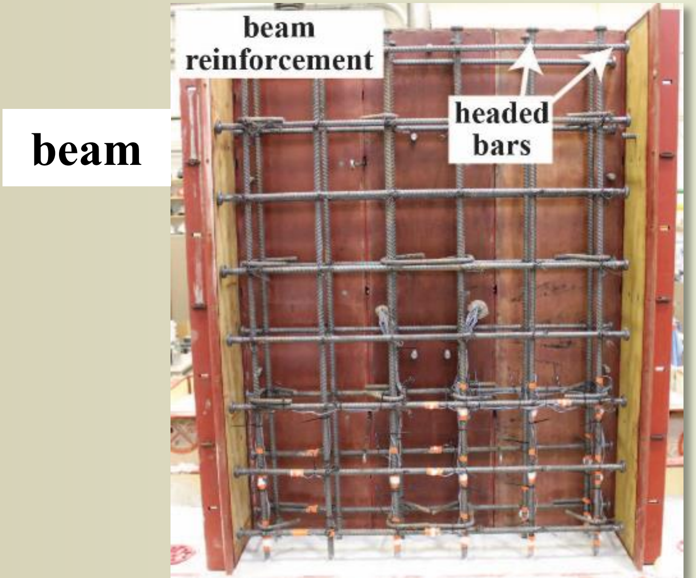
1) Demonstrate performance of proposed system in comparison with state-of-practice walls
2) Validate:
   - Closed-form design methods including ACI and ASCE code equations
   - Simplified finite element models using VecTor2
   - Simplified finite element models using ATENA
   - Detailed finite element models using SIERRA (Sandia National Lab partner)

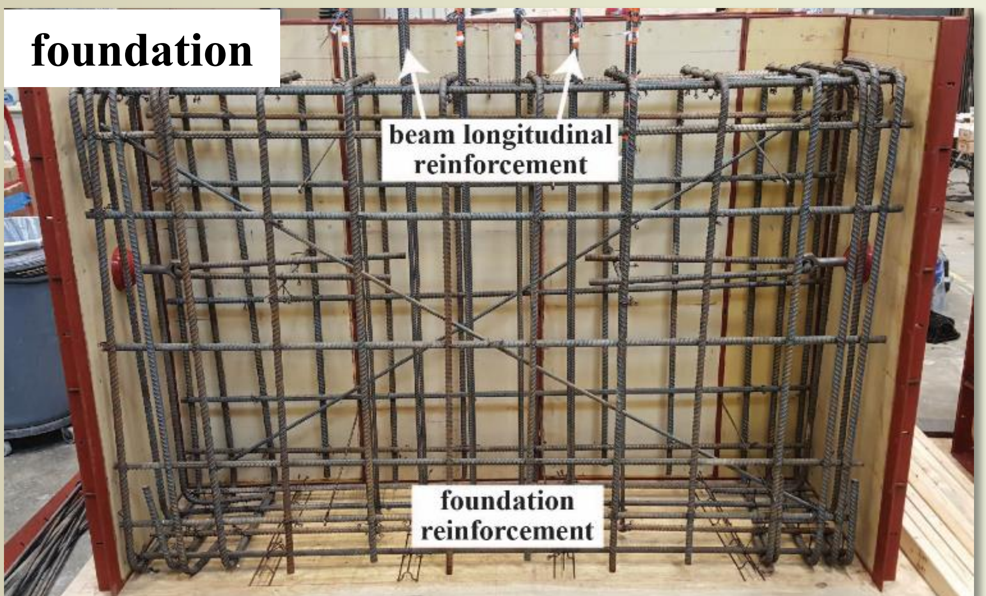
Deep Beam Tests

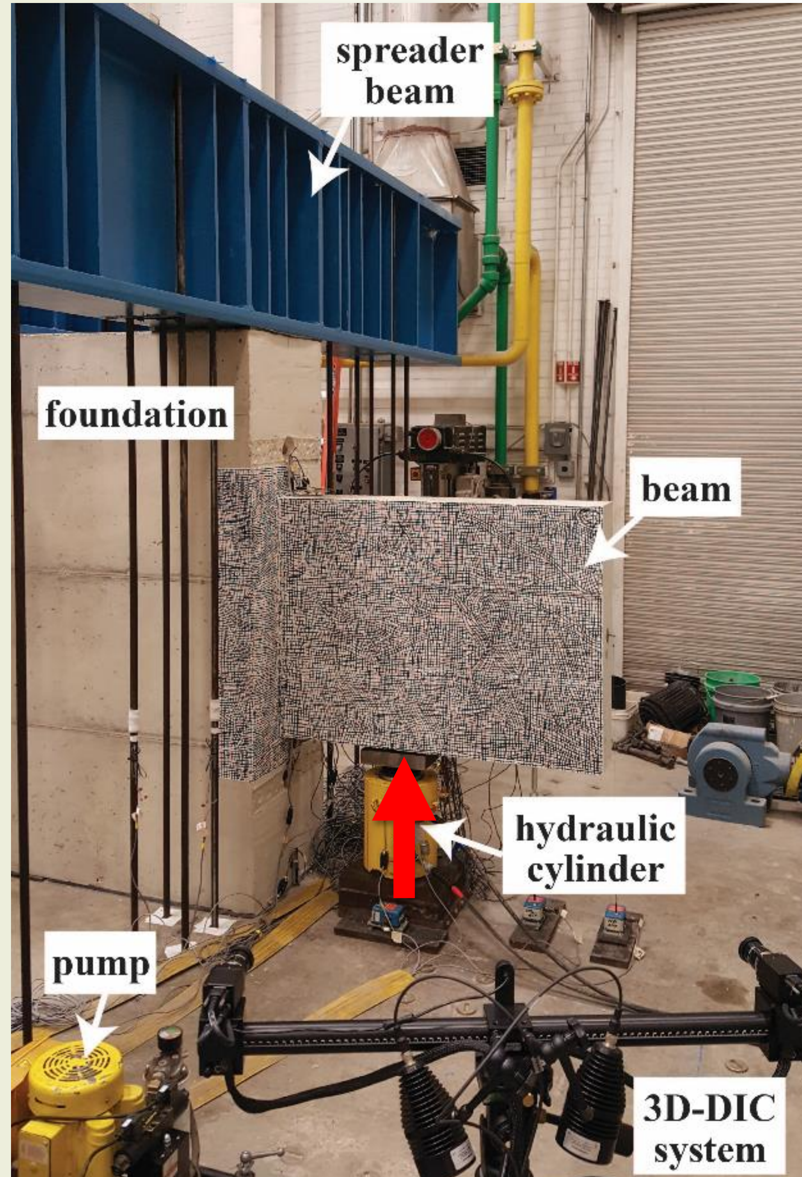


representative slice of generic wall for deep beam tests (@ 1:6.5 scale)

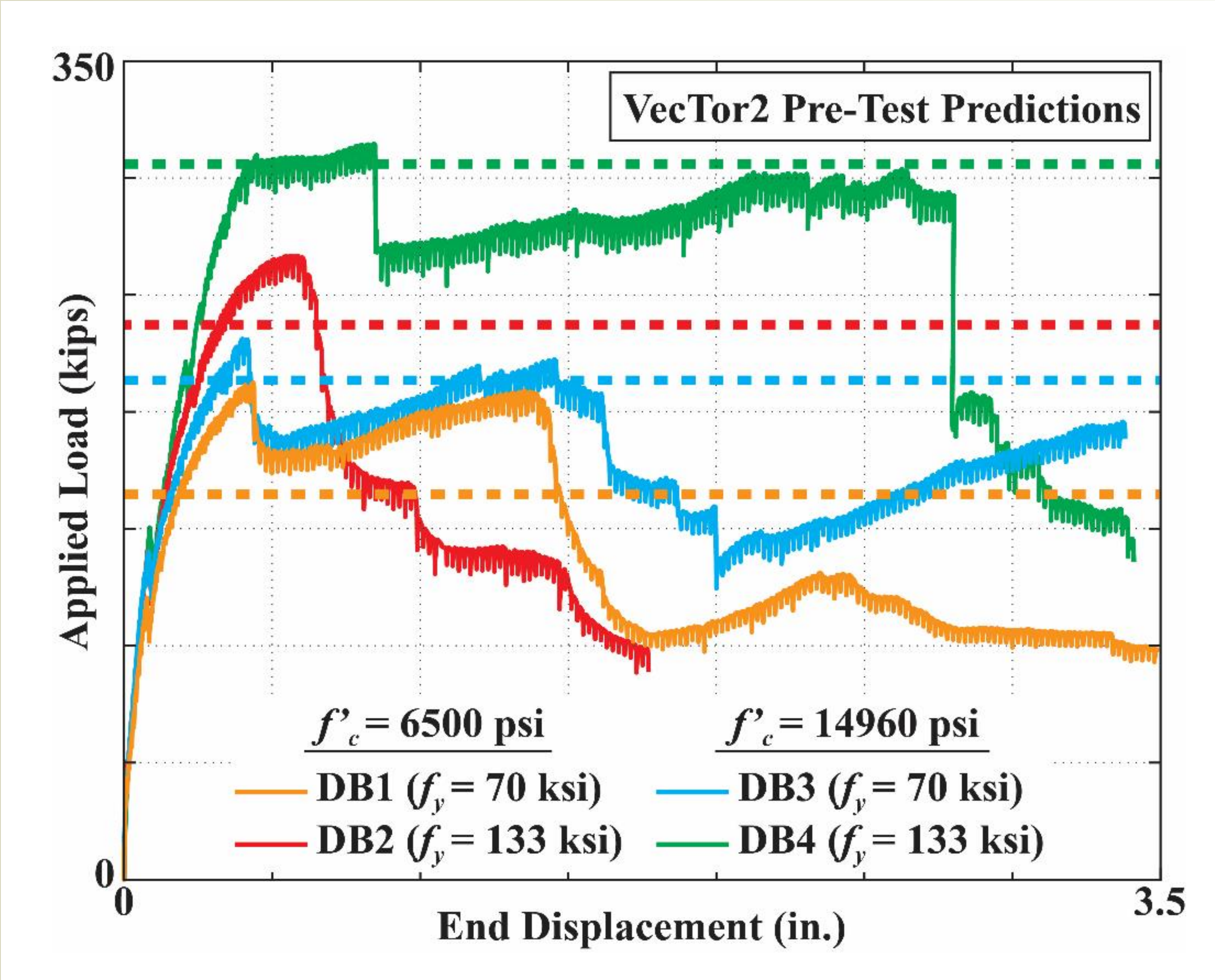
Construction and Test Setup







Deep Beam Specimen Response



DB4 ($f'_c = 14960$ psi, $f_y = 133$ ksi)

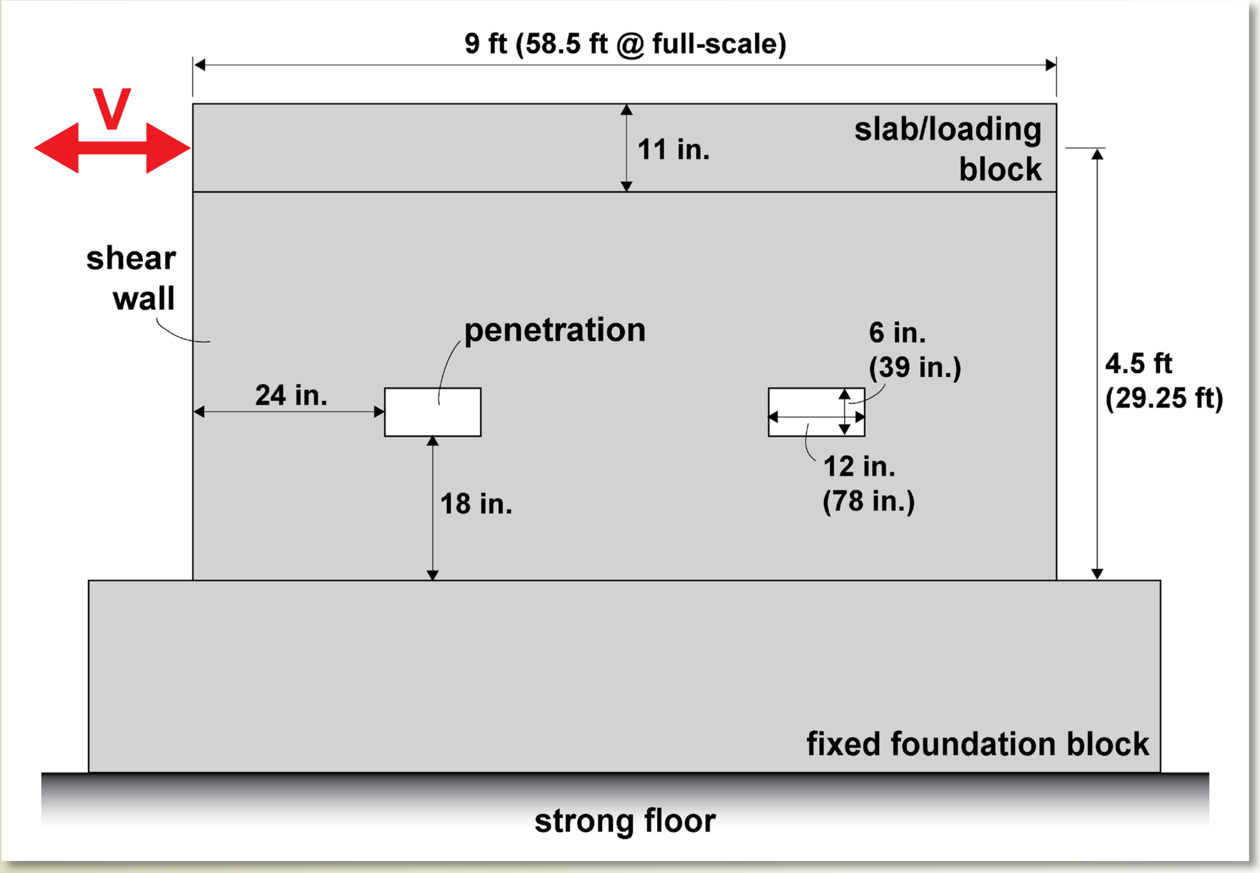
Maximum principal (tension) strains on concrete surface

Summary of Deep Beam Tests

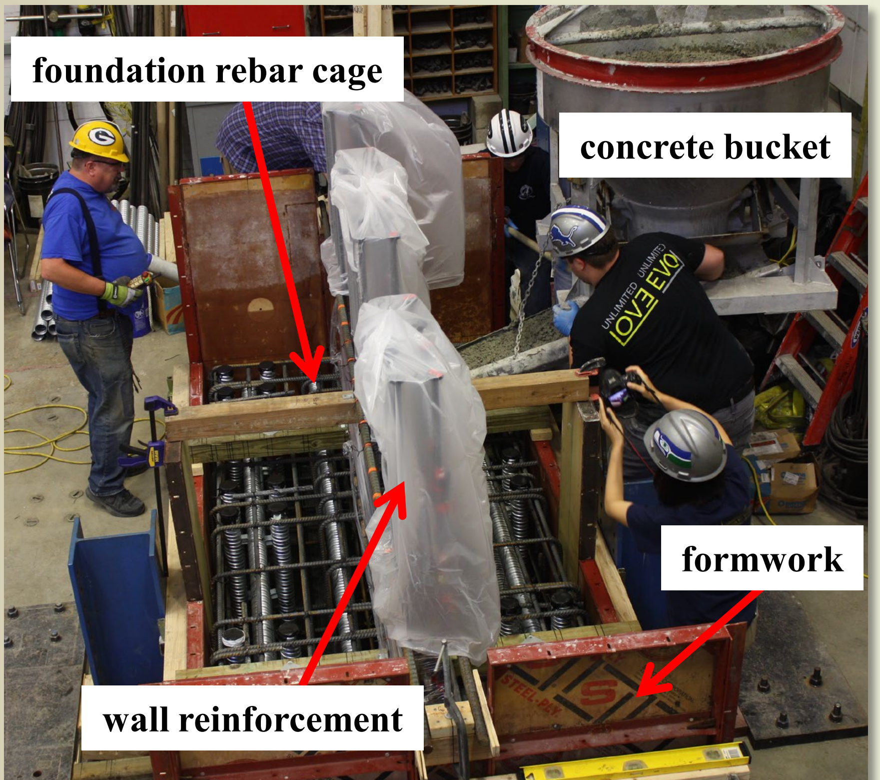
- Increasing the rebar strength had a greater effect on lateral strength (26% increase) than increasing the concrete compression strength (9% increase)
- Increase in lateral strength (48% increase) was greatest when using high-strength materials together
- Combination of high-strength materials also resulted in greatest deformation capacity
- Pre-test numerical models provided reasonable and conservative predictions for all specimens
- Design code equations provided gross overestimations of measured specimen stiffness, with mixed results for lateral strength

Shear Wall Tests

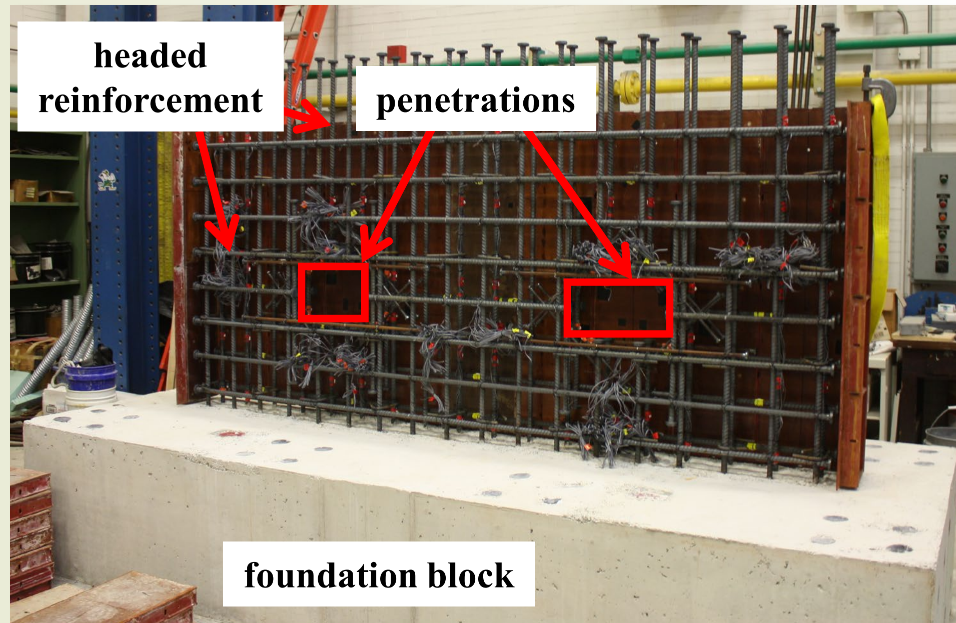
- 1:6.5 scale of “generic wall”
- Tested under cyclic lateral loads



Wall Construction

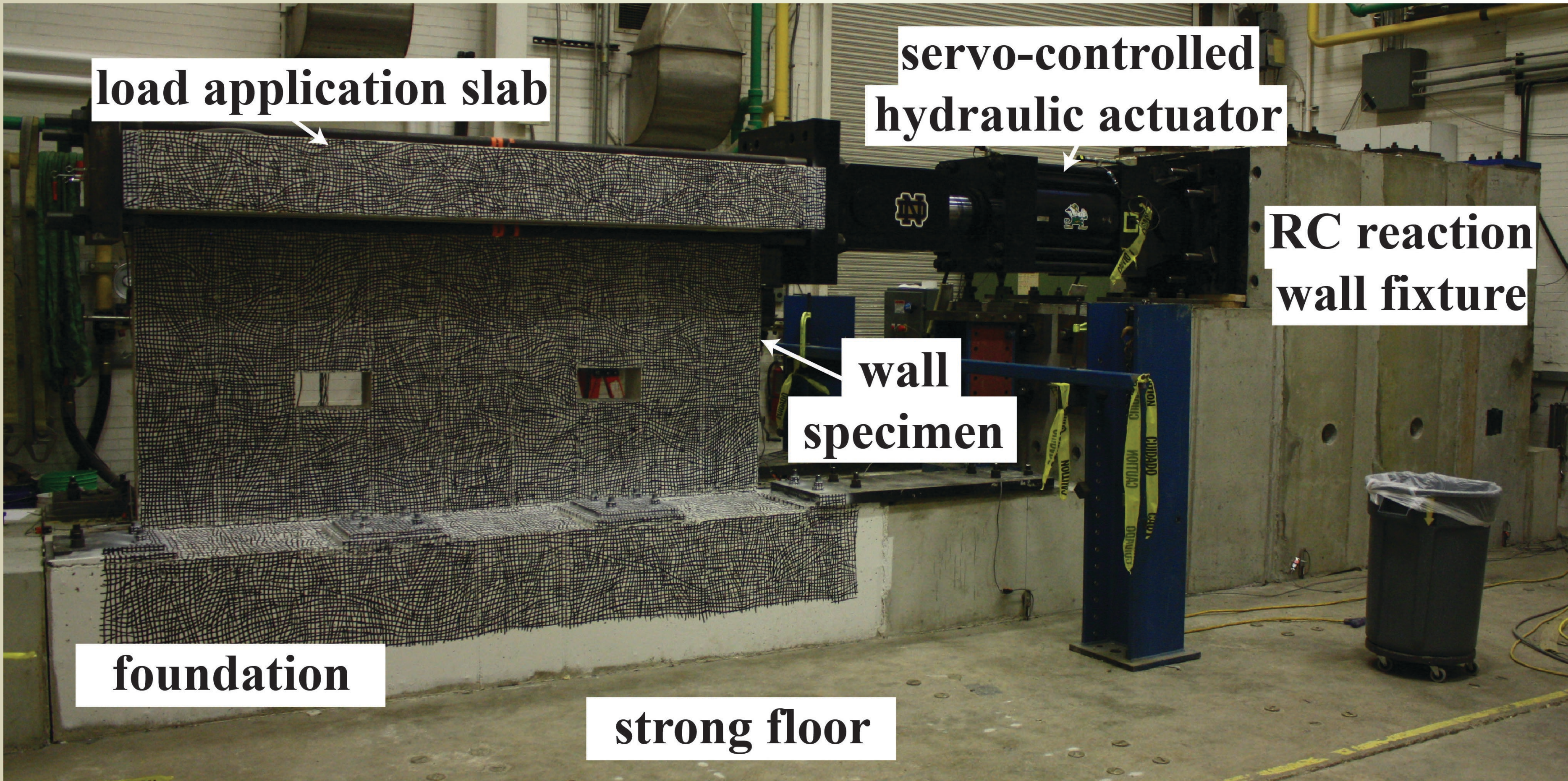


Concrete Placement in Wall Foundation Block

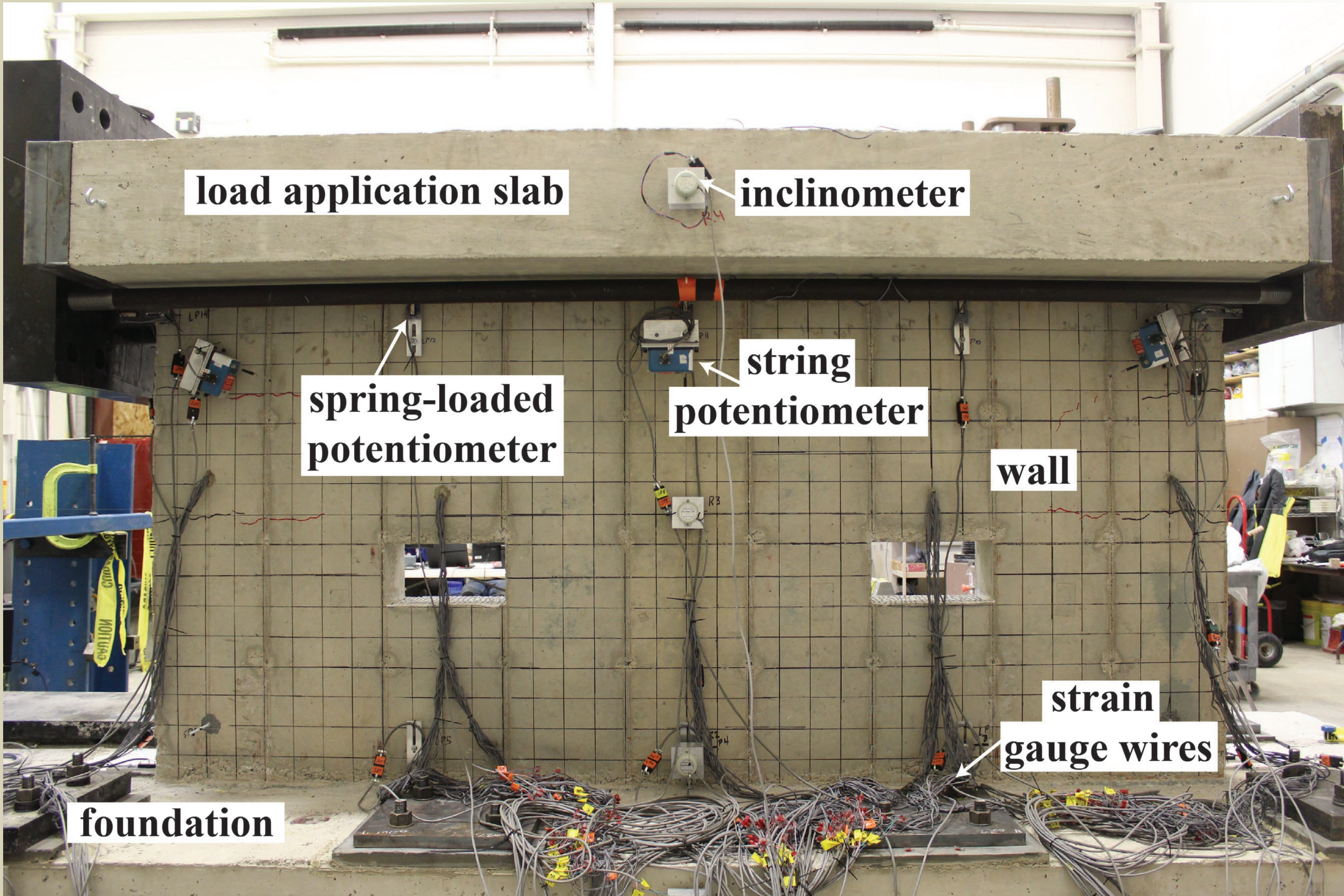


Shear Wall Reinforcement Prior to Concrete Placement

Wall Test Setup



Wall Instrumentation

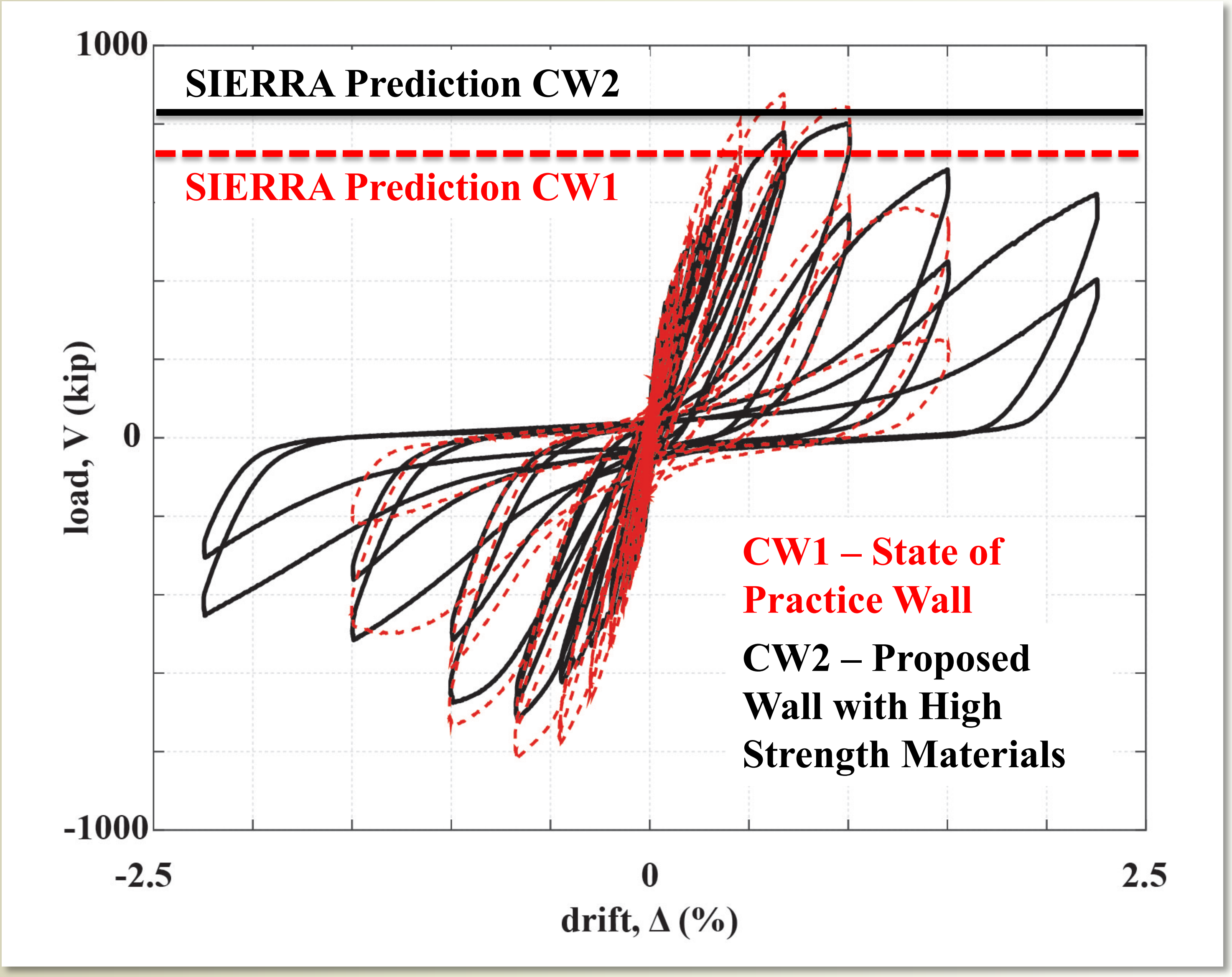


Wall Test Parameters

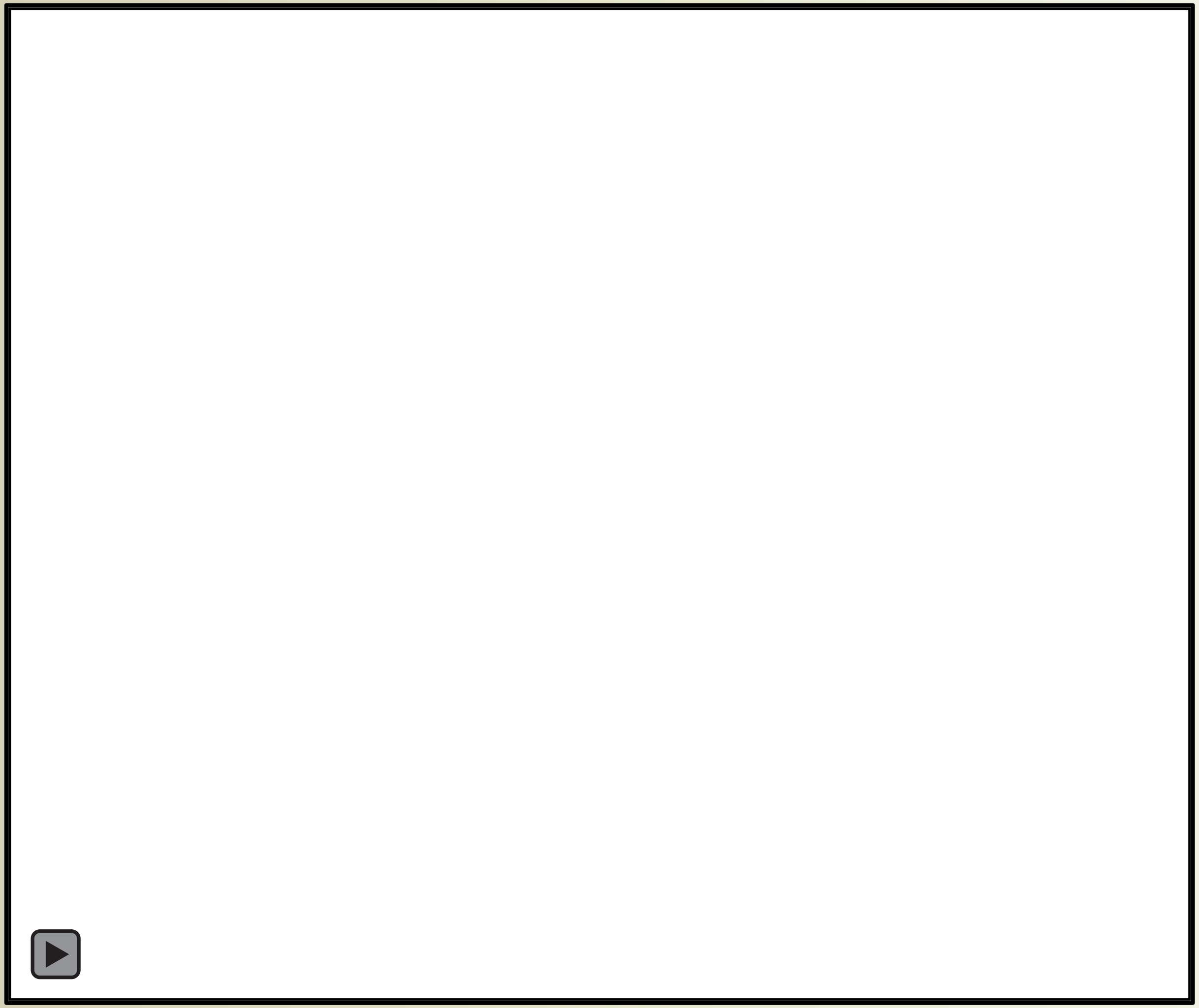
Specimen	f'_c (psi)	f_y (ksi)	ρ_{sw} (%)	$M/(Vl_w)$	ρ_{sf} (%)
CW1	6950	72.5	1.833	0.5	no flange
CW2	14760	123	0.833	0.5	no flange
CW3	14390	123	0.833	0.75	no flange
CW4	14010	124	0.833	0.75	0.833

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

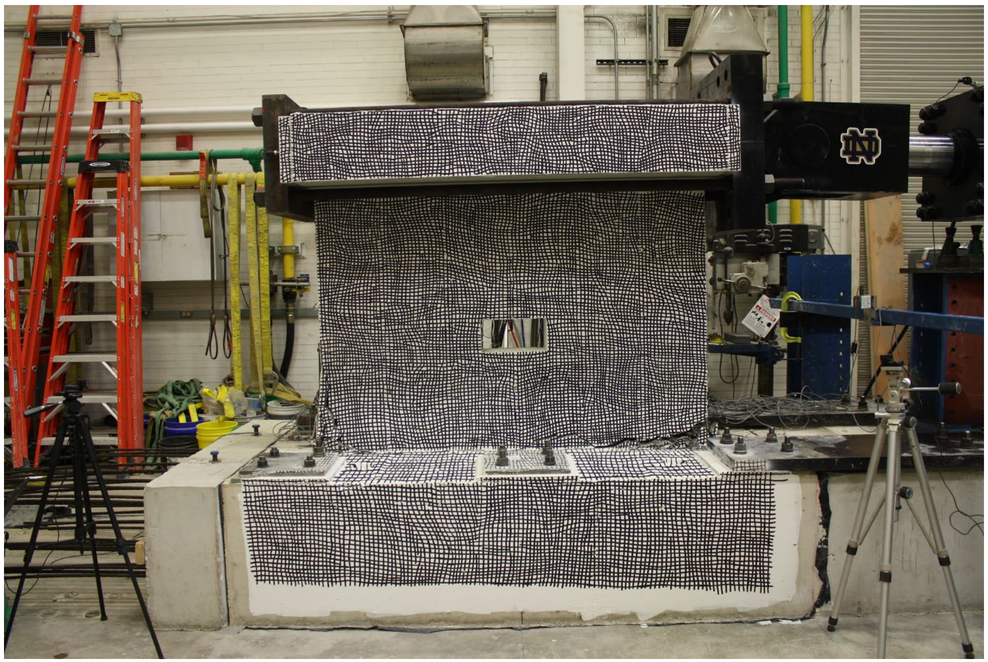
CW1 versus CW2 Behaviors

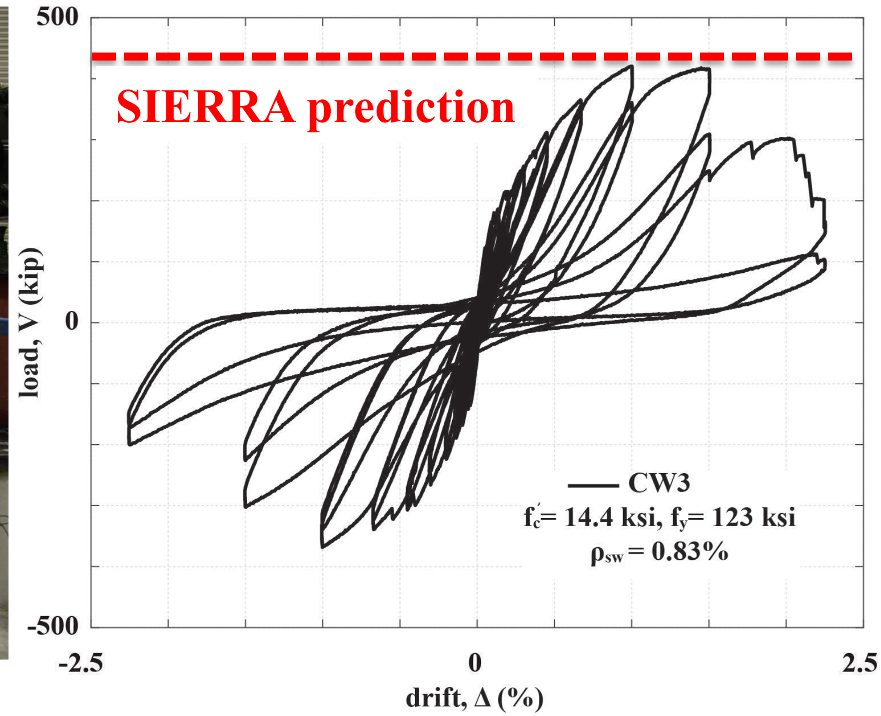


CW2 (f'_c = 14760 psi, f_y = 123 ksi)
(wall with high-strength materials)

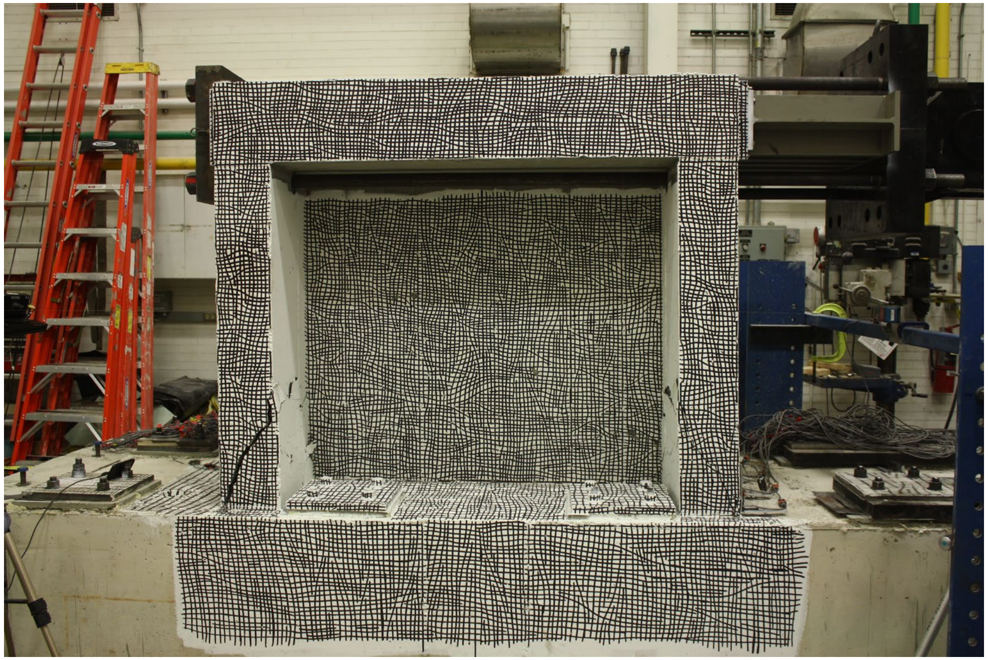


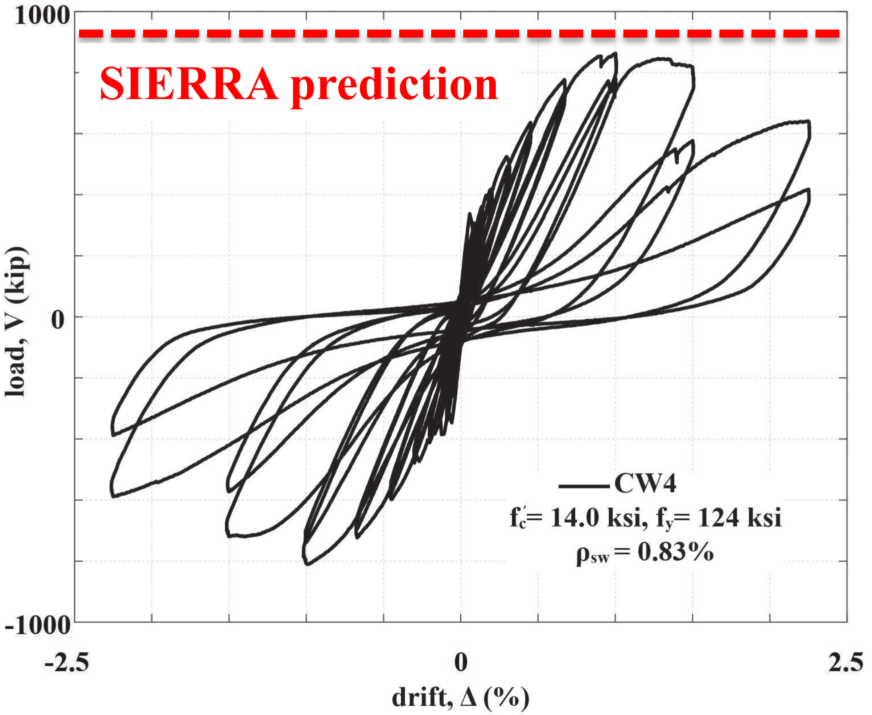
CW3 ($f'_c = 14390$ psi, $f_y = 123$ ksi)
(increased $M/(Vl_w)$)





CW4 ($f'_c = 14010$ psi, $f_y = 124$ ksi)
(flanged wall)





Summary of Shear Wall Tests

- Proposed wall with 45% rebar weight achieved 91% of the peak lateral strength of state-of-practice wall
- The initial stiffness was slightly increased, while the stiffness after diagonal cracking was reduced
- Headed rebar was effective, including trim reinforcement around penetrations
- Numerical finite element models provided better estimates of behavior than closed form design equations

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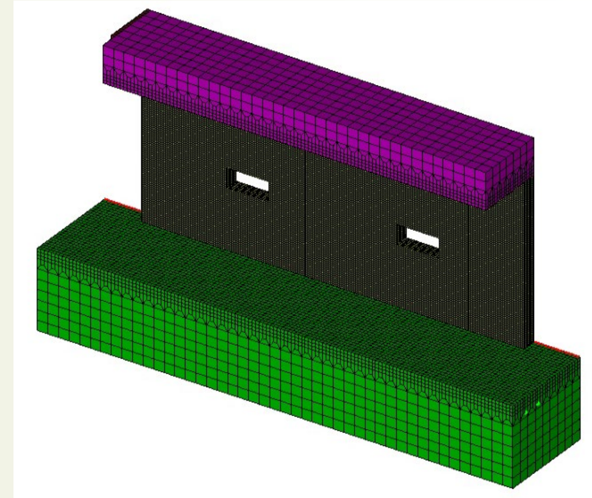
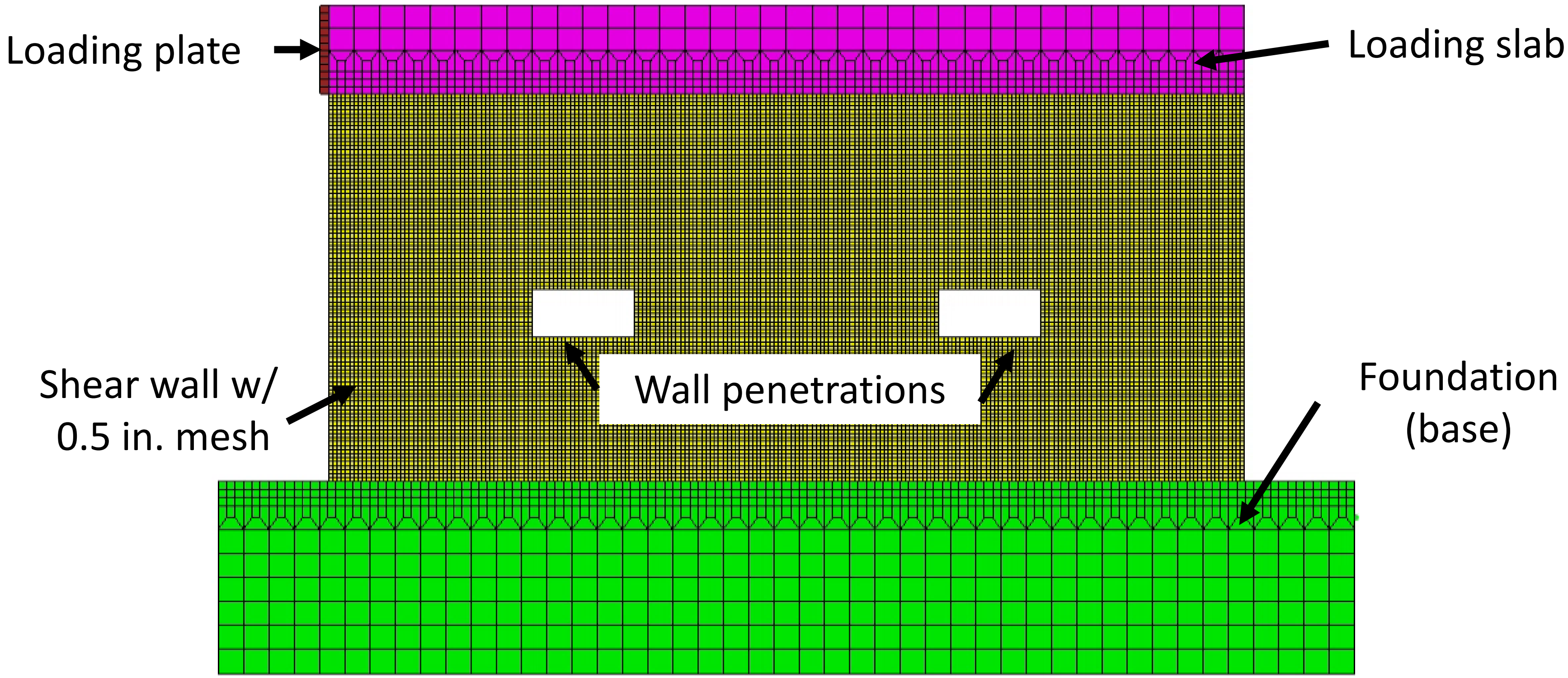
FEA Modeling

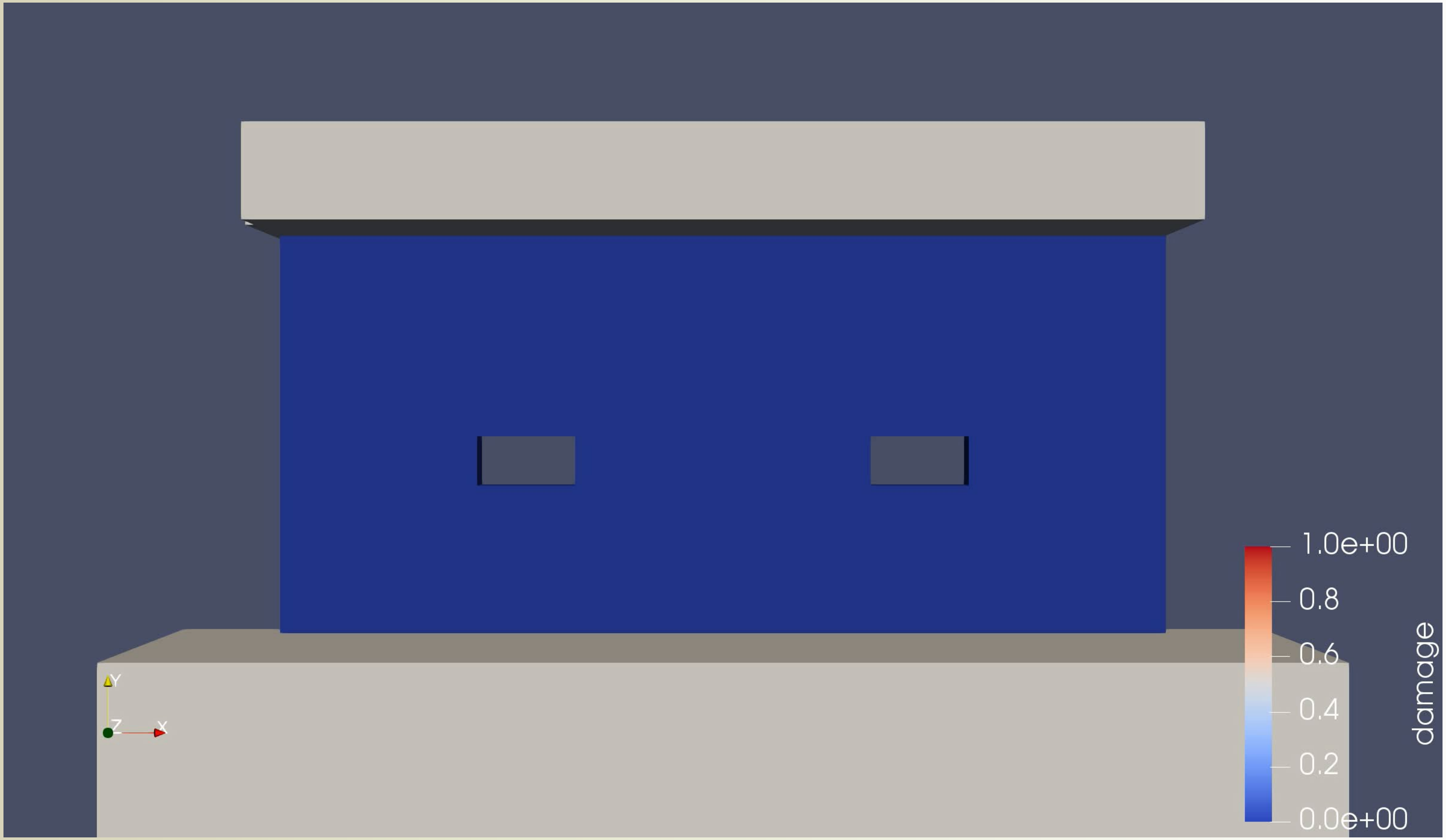


- Developed at Sandia National Labs using SIERRA
- Half-symmetry simulation
- Loading slab and foundation modeled as elastic, while the shear wall could accrue damage
- Concrete modeled with eight-noded hexahedral elements
- Rebar modeled with fully-embedded two-noded discrete beam elements
- 0.5 in. concrete and rebar mesh size on shear wall

FEA Geometry and Mesh

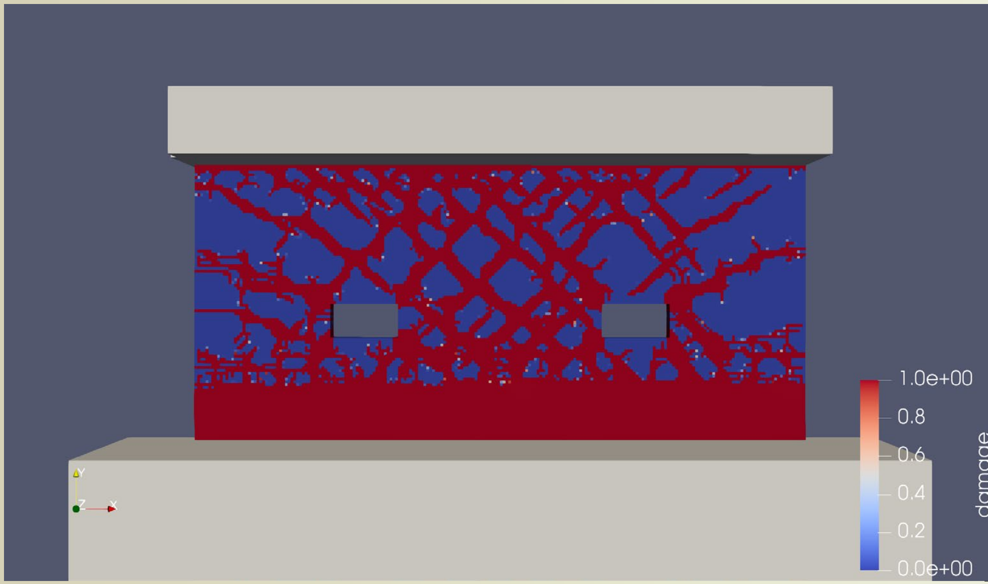


Specimen CW1 (State-of-Practice)

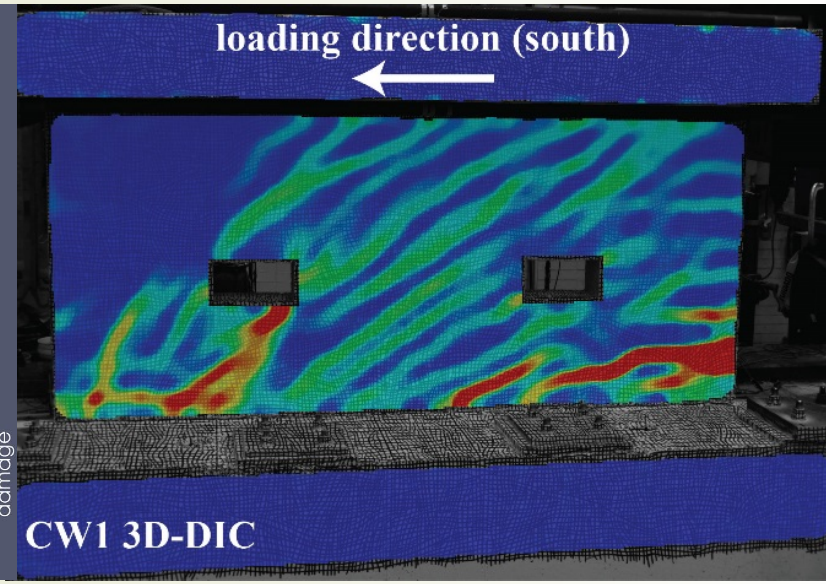


CW1 Cracking and DIC Comparison

FEA Damage



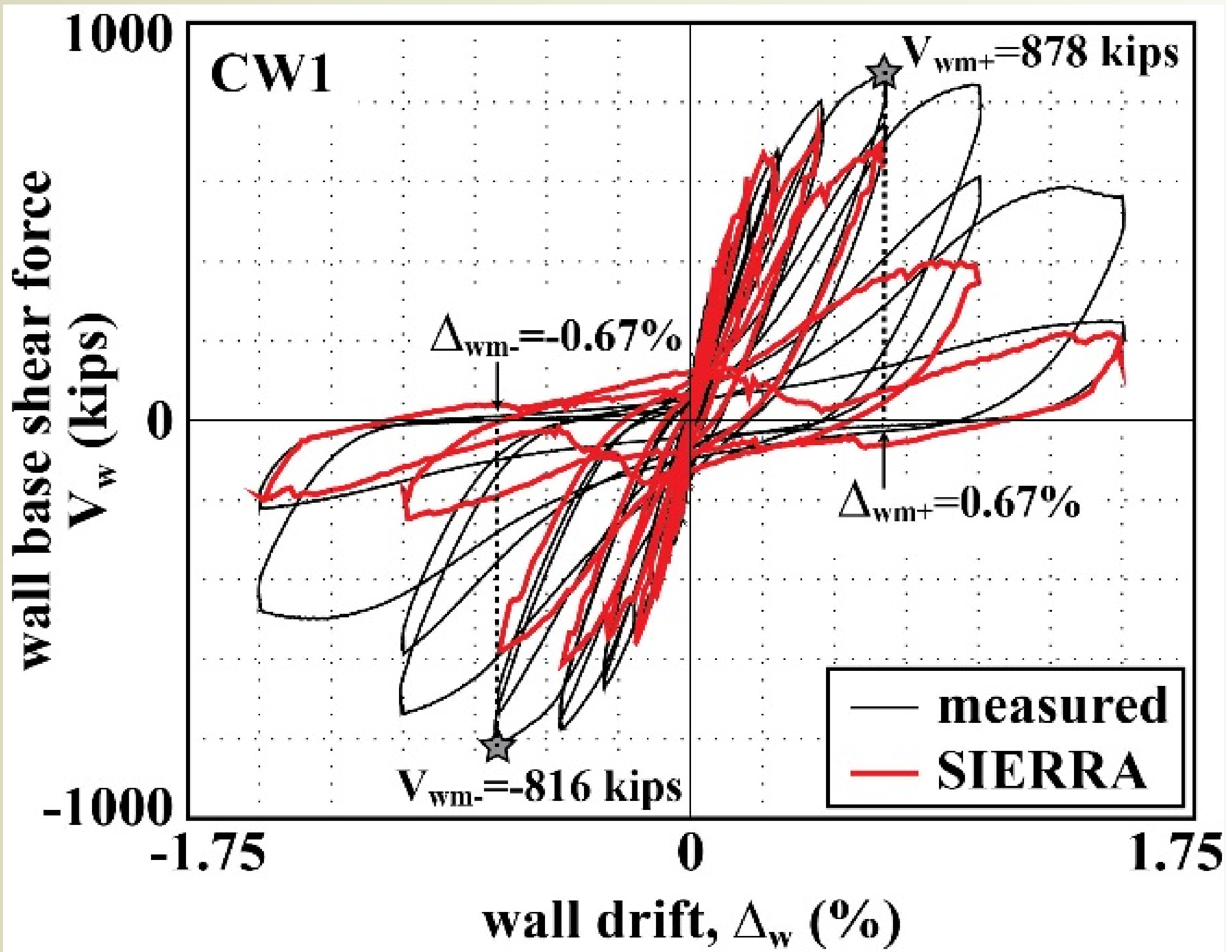
3D DIC



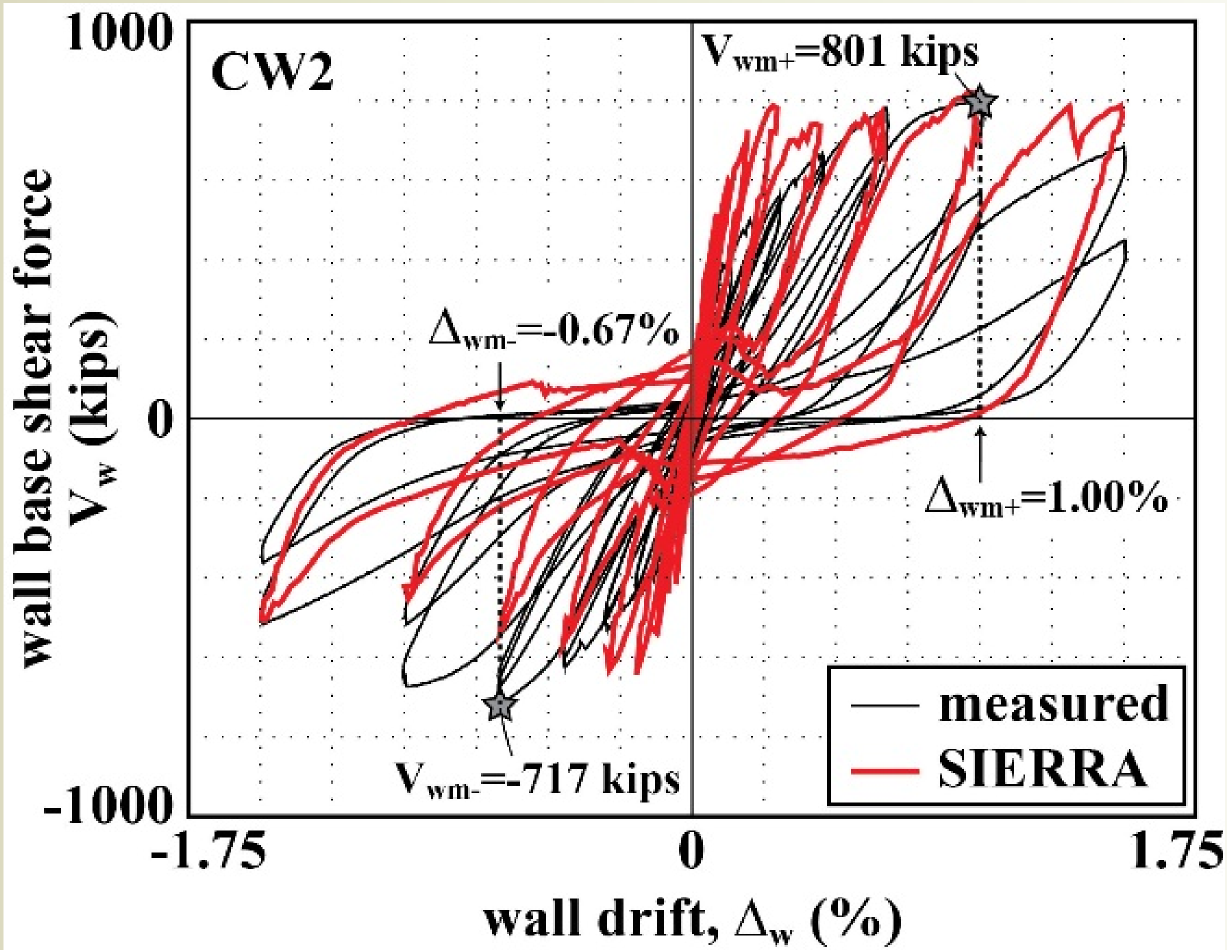
Accumulated total damage in concrete and rebar under cyclic loading

Maximum principal strains on concrete surface in south loading direction

CW1 Lateral Load-Deflection
(State-of-Practice Wall)



CW2 Lateral Load-Deflection
(Proposed Wall with High-Strength Rebar & Concrete)



Summary of Detailed Modeling

- Models able to capture wall behavior including
  - initial stiffness
  - damage propagation and cracking
  - lateral strength and failure mechanism
  - hysteretic behavior

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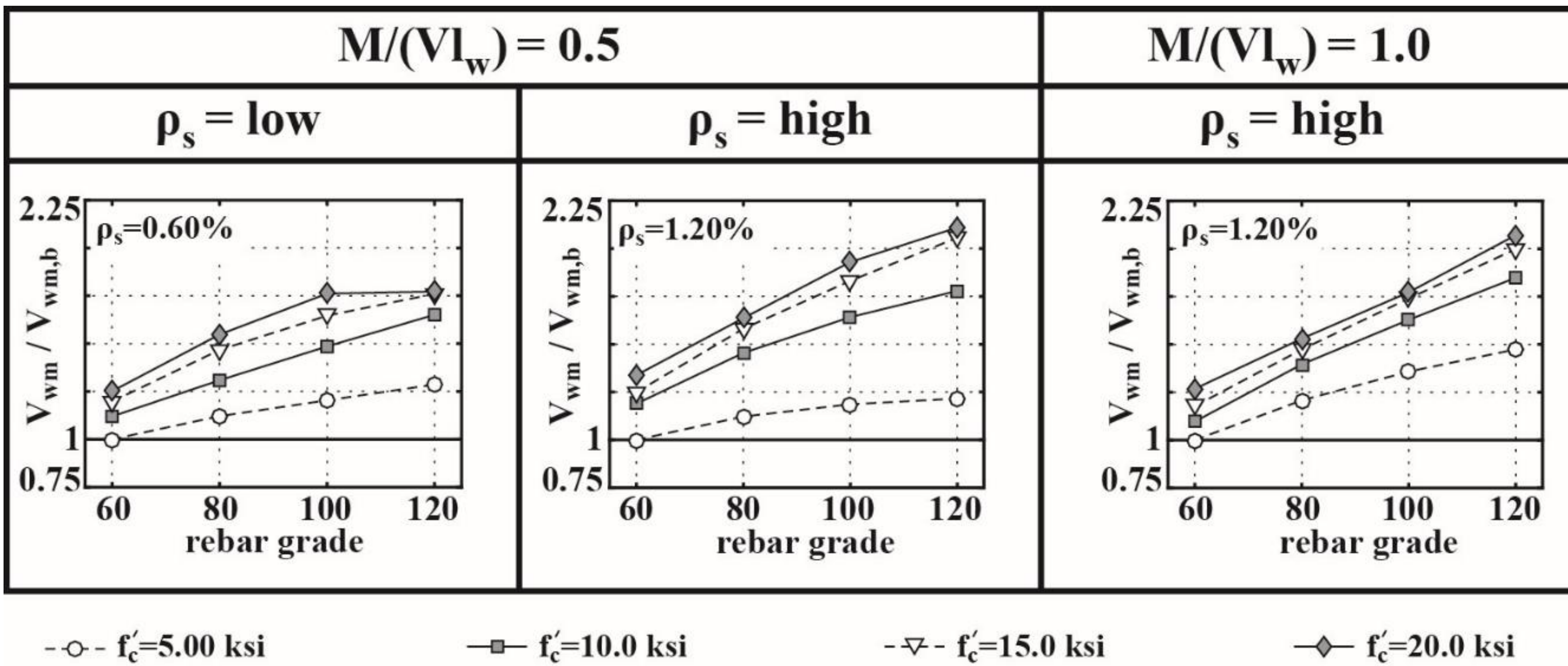
Limit-Benefit Analysis

- Goal to establish effects of high-strength rebar and high-strength concrete on peak wall lateral strength (192 parametric walls)
- Scenario 1 represents building construction, while Scenarios 2 and 3 represent nuclear construction

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.)	15	45	45
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 (%)	0.25, **0.50**	0.60, **1.20**	0.60, **1.20**

Increase in Peak Lateral Strength

Scenario 2 (60 ft long, 120 ft tall, 45 in. thick walls):



V_{wm} = Predicted peak lateral strength

$V_{wm,b}$ = Predicted peak lateral strength of "benchmark" with normal strength materials

Limit-Benefit Summary

- Combination of high-strength rebar with high-strength concrete results in a higher-performing structure than with either high-strength material on its own
- Significant benefits by using concrete strength of f'_c =10 ksi, with diminishing returns for higher strengths
- Greatest benefits of high-strength materials for walls with large rebar ratios, ρ_s

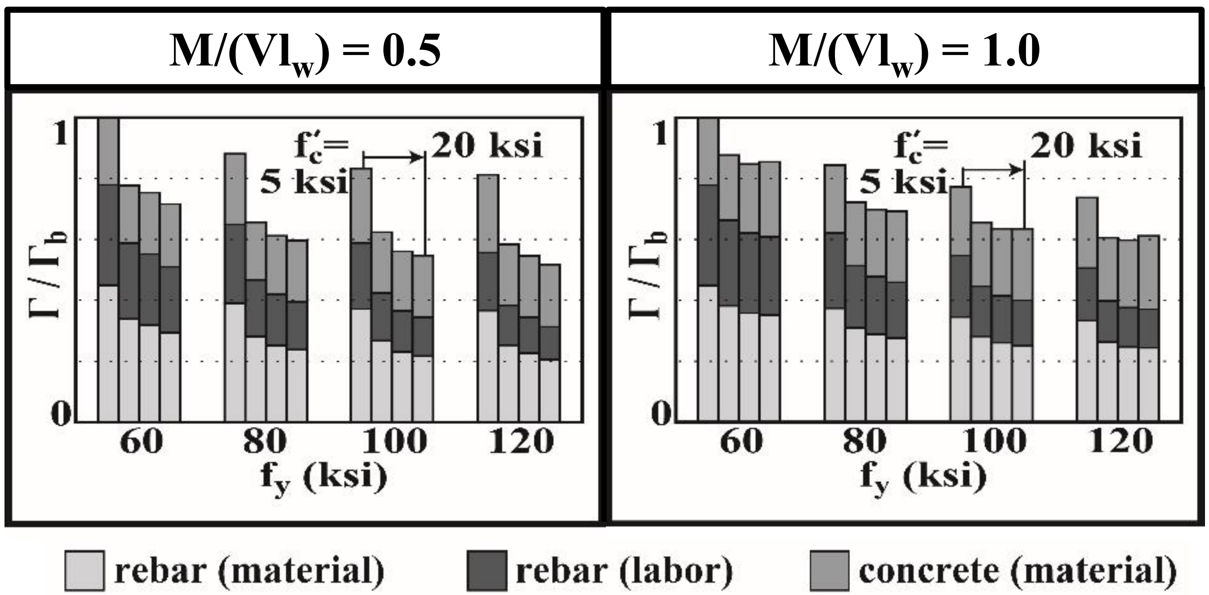
Cost-Benefit Analysis

- 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 $T = T_w/V_{wm}$
- 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 high	low to high	low to high

Construction Cost Metric

Scenario 2 (60 ft long, 120 ft tall, 45 in. thick), ρ_l = very high:



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

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

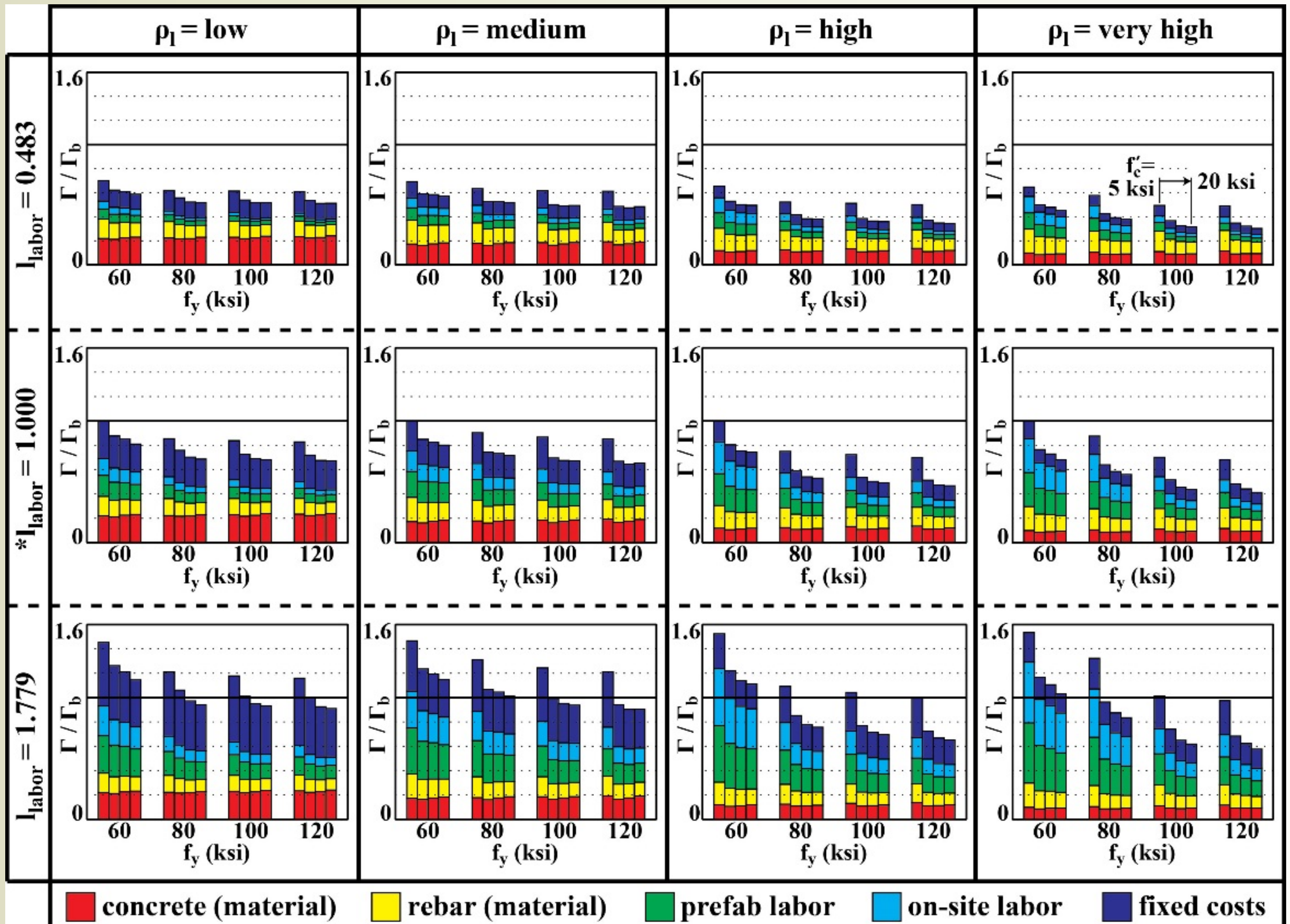
Adjustment for Local Labor Costs
(including prefabrication)

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

Low

National average

High

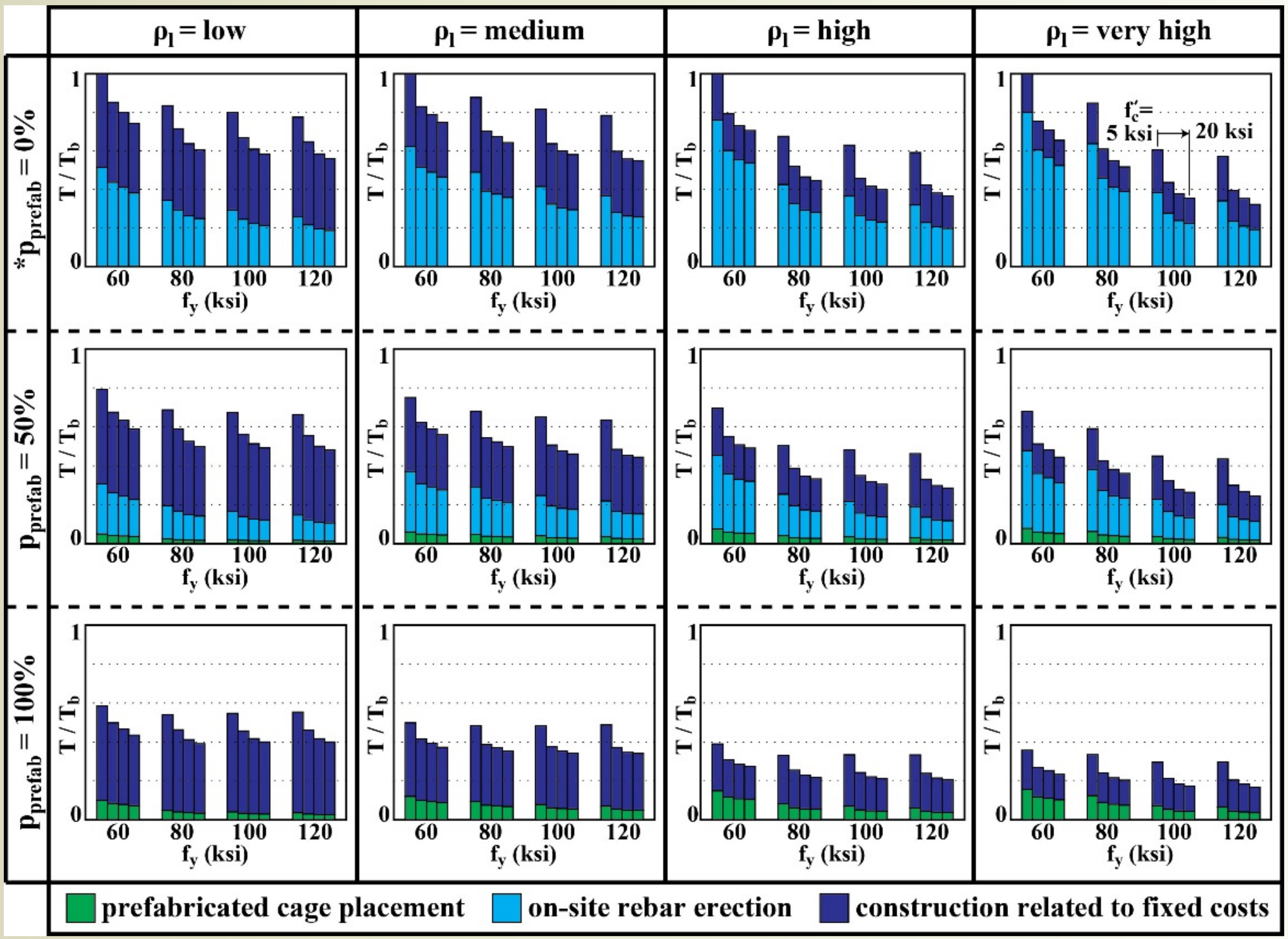


Construction Cost Summary

- 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), $M/(Vl_w)=0.5$:



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 ~80%

Presentation Outline

1. Evaluation of Prefabricated Rebar
   - Industry Survey
   - Experimental Evaluation of Prefabricated Rebar
2. Experimental Testing of High-Strength Materials
   - Deep Beam (Wall Slice) Specimens
   - Shear Wall Specimens
3. Detailed Numerical Modeling
4. Parametric Limit-Benefit and Cost-Benefit Evaluation
5. Conclusions

Summary and Conclusions

- Performance demonstrated through large-scale testing of 4 deep beam and 4 shear wall specimens
- High-strength steel more effective when combined with high-strength concrete, resulting in greatest increase in lateral strength (up to ~60% saving in construction cost to achieve specified wall design strength)
- Results validate simplified and detailed numerical models as well as identify limitations in code design equations
- Prefabricated rebar assemblies can improve construction schedules (up to ~80% reduction in on-site time)
- Reduced rebar amounts also improve quality control and concrete placement

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
- Presentations:
  - American Concrete Institute Convention, Fall 2015, Fall 2016, Spring 2017, Spring 2018, Fall 2018
  - Center for Sustainable Energy Luncheon, U. Notre Dame, IN, Fall 2016
  - American Nuclear Society Winter Meeting and Nuclear Tech. Expo, 2016
  - Concrete Sustainability Symposium, New Mexico State U., 2016
  - Sustainability Research Expo, U. Notre Dame, 2016
  - Energy Week, Center for Sustainable Energy, U. Notre Dame, IN, 2015

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