Cost-Benefit Analysis of High-Strength Materials for Safety-Related Nuclear Reinforced Concrete Shear Walls

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DOE-NE NEET-1 Program Goals

- Nuclear Energy Enabling Technologies Program-Advanced Methods for Manufacturing (NEET-1)
- "Accelerate innovations that reduce the cost and schedule of constructing new nuclear plants and make fabrication of nuclear power plant components faster, cheaper, and more reliable."
- "Develop new/revised nuclear industry codes and standards that enable the utilization of newly developed technologies."

Project Objective

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

1) High-strength rebar
2) Prefabricated rebar assemblies, including headed anchorages
3) High-strength concrete

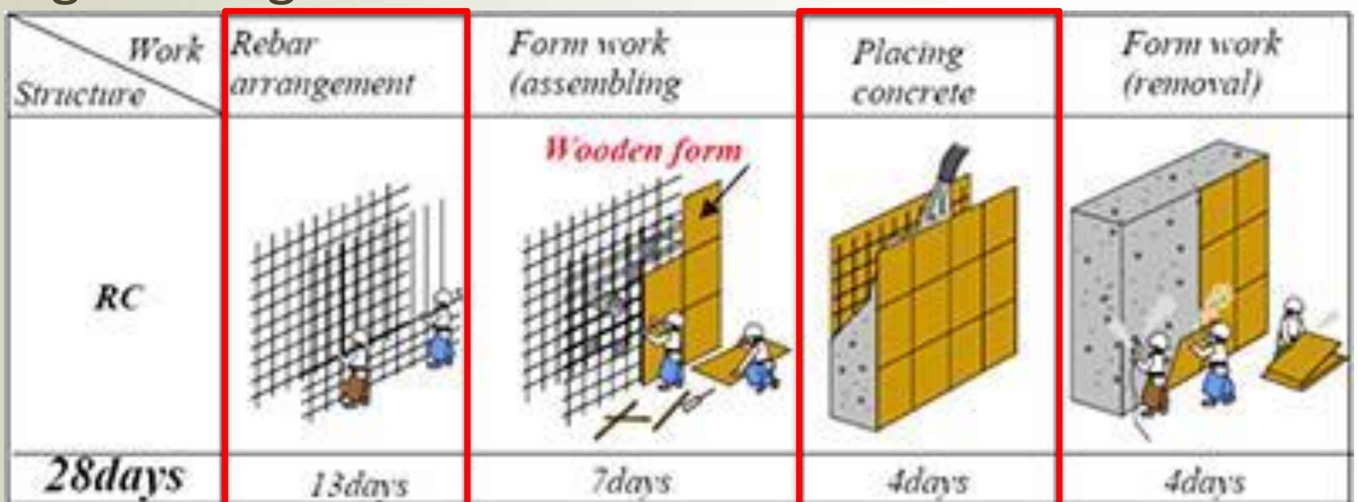
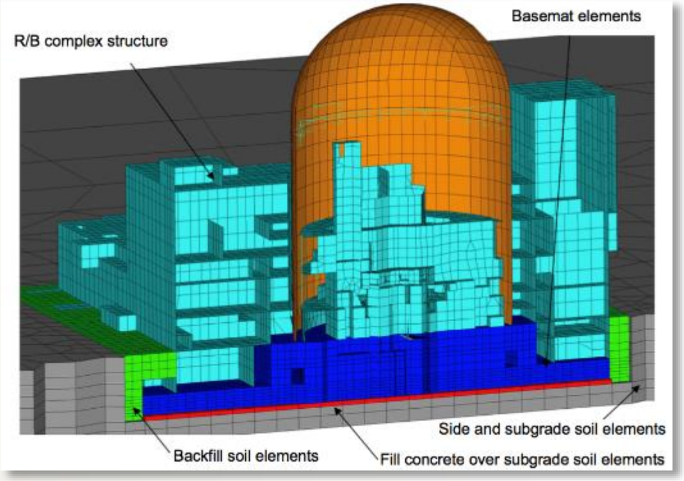


Figure From: MPR-2610 Rev 2 Sept. 2004

Project Scope

- Explore effectiveness, code conformity, and viability of existing high-strength materials
- Focus on stocky shear walls – predominant load resisting members in nuclear structures (pressure vessels not in scope)
- Aim to reduce complexities in rebar to improve construction quality and ease of inspection



US-APWR Design Control Doc.

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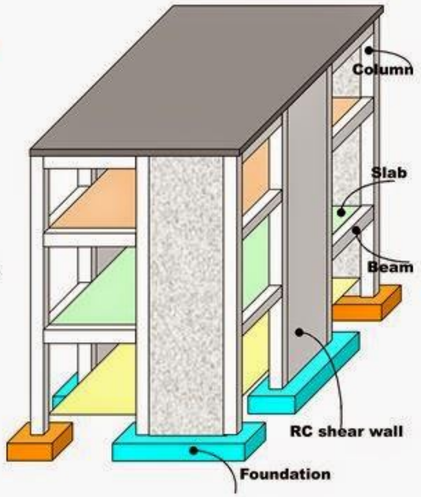
RC shear walls carry earthquake loads down to the foundation. They provide large strength and stiffness to buildings in the direction of their orientation.



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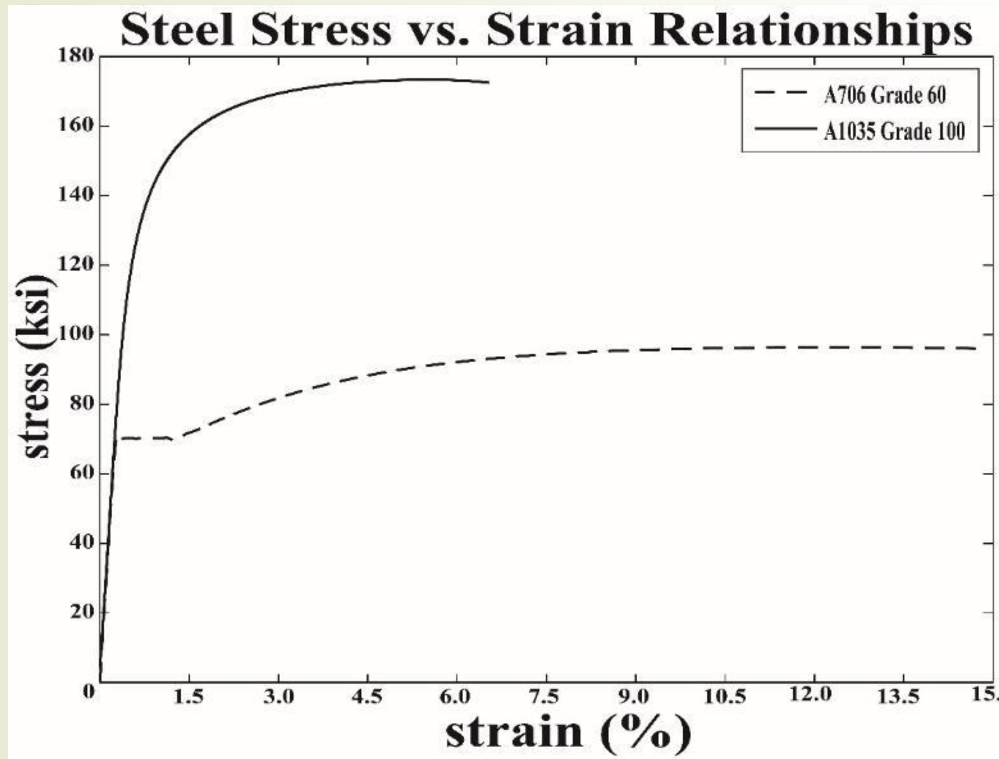
High-Strength Materials

- High-strength rebar (up to Grade 120) with high-strength concrete (up to 20,000 psi compressive strength)
- ACI 349 limits headed bars and shear reinforcement to Grade 60
- Concrete strength of 5,000 psi typical in current practice



Potential Benefits

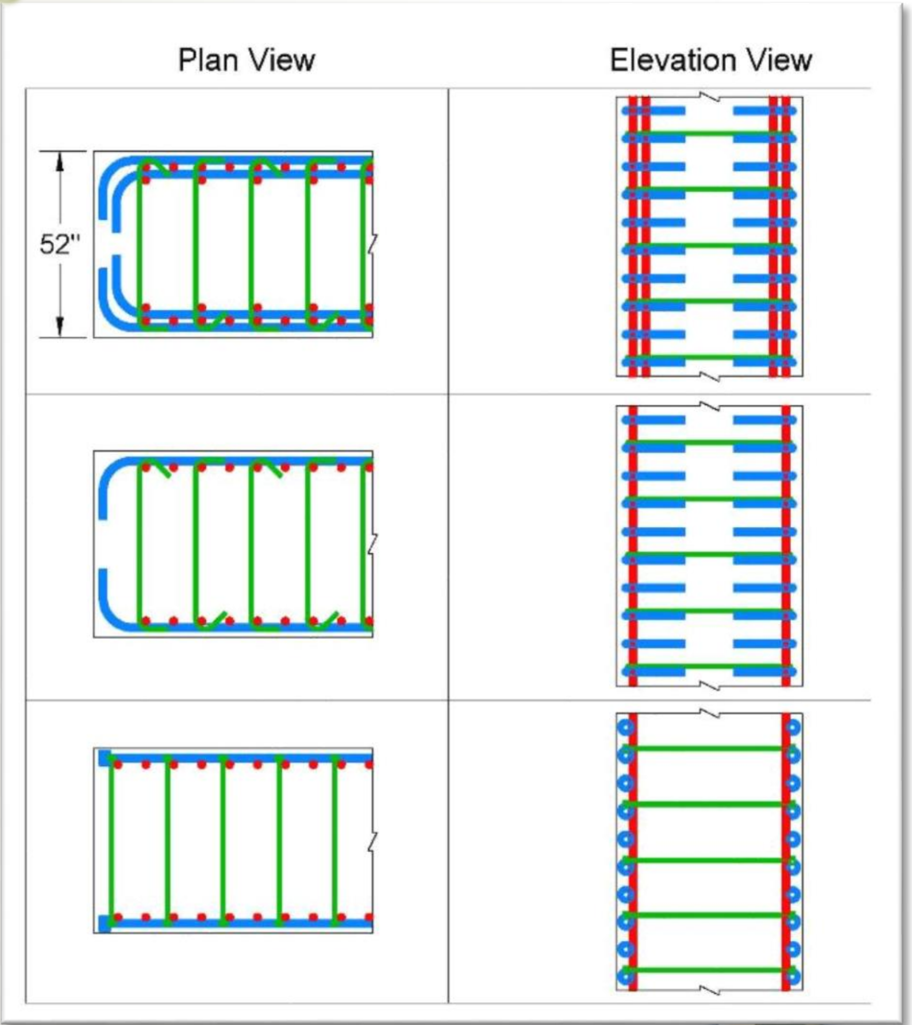
Most Congested (current)

Multiple layers of hooked Grade 60 bars

Fewer layers of hooked high-strength bars

Least Congested (envisioned)

Fewer layers of headed high-strength bars



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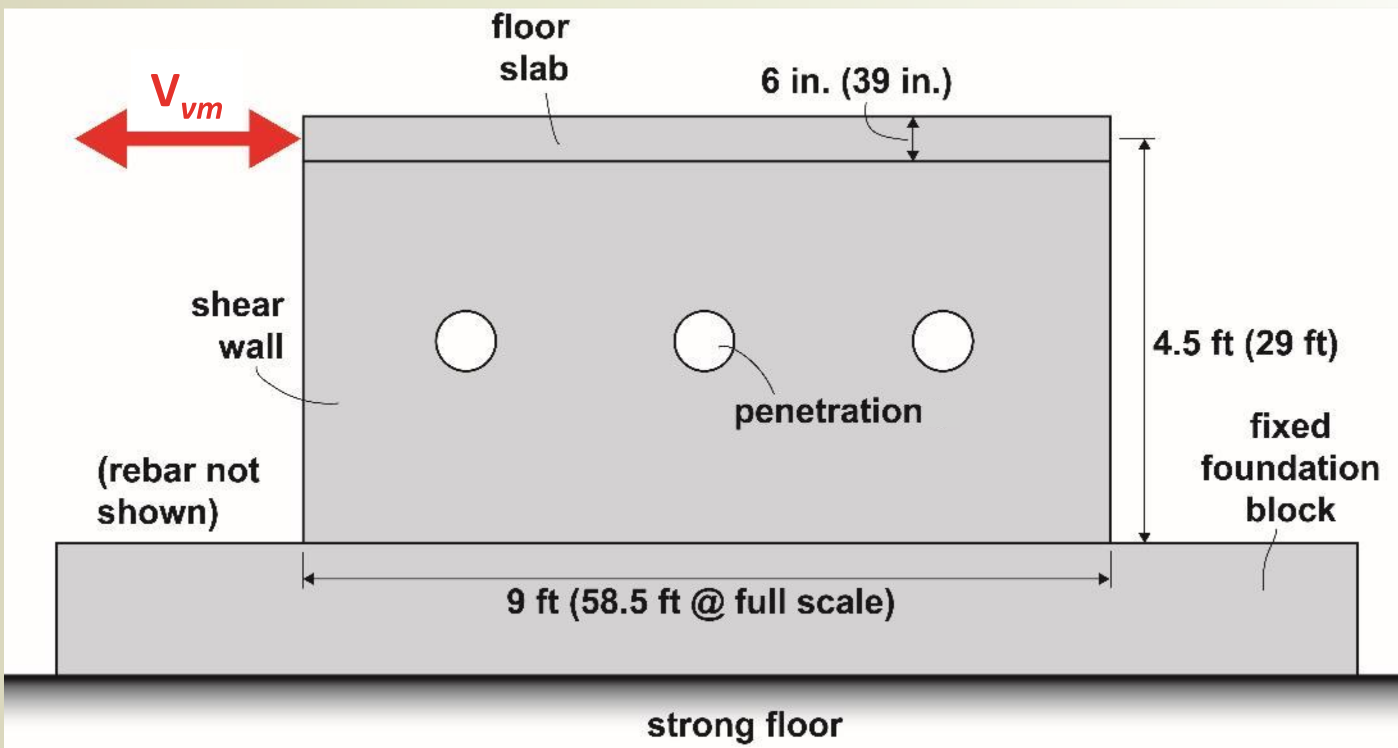
Outline

1. Numerical Modeling
2. Limit-Benefit Analysis
3. Cost-Benefit Analysis
4. Experimental Testing

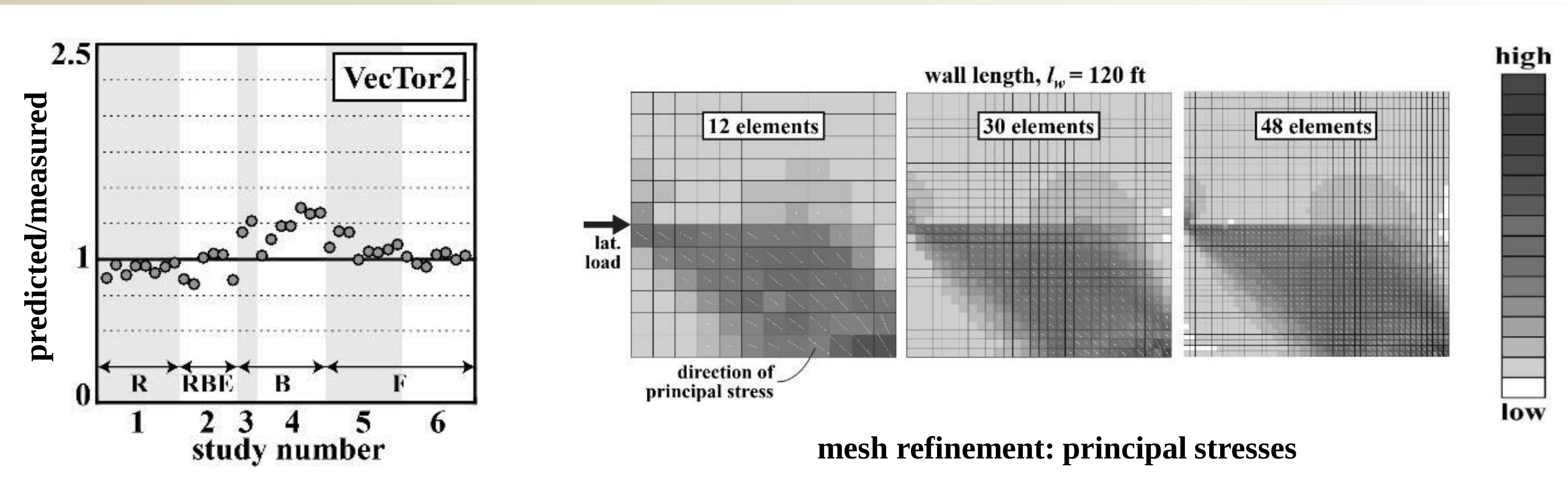
1. Modeling Approach

- Evaluated methods for predicting peak lateral strength (V_{vm}) of stocky shear walls:
  1) Closed-form Design Methods
  2) Finite Element Modeling Predictions



1. VecTor2 Finite Element Model

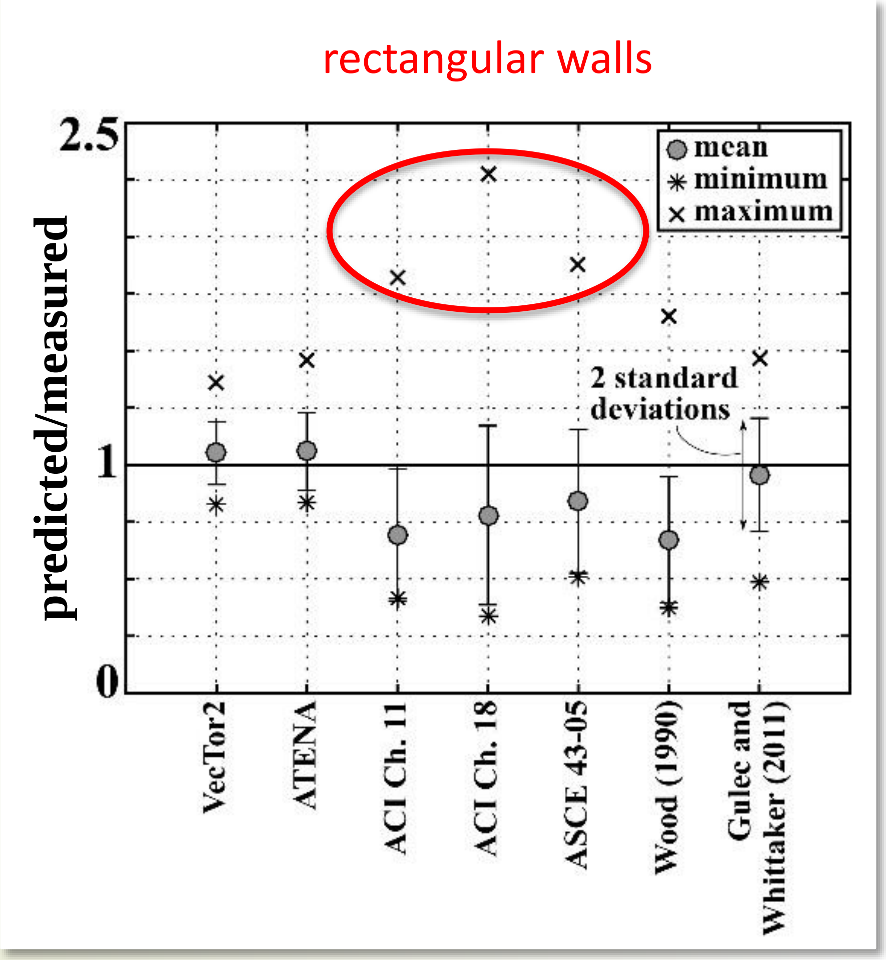
- Reliably captures the peak strength for rectangular walls with a wide range of material properties and base moment-to-shear ratios



mesh refinement: principal stresses

1. Comparison of Predictions

- Design equations should be revisited, although mean predictions are conservative, there are unconservative outliers for typical nuclear wall geometries.
- VecTor2 and ATENA are reliable for predicting peak strength; ABAQUS will also be used.



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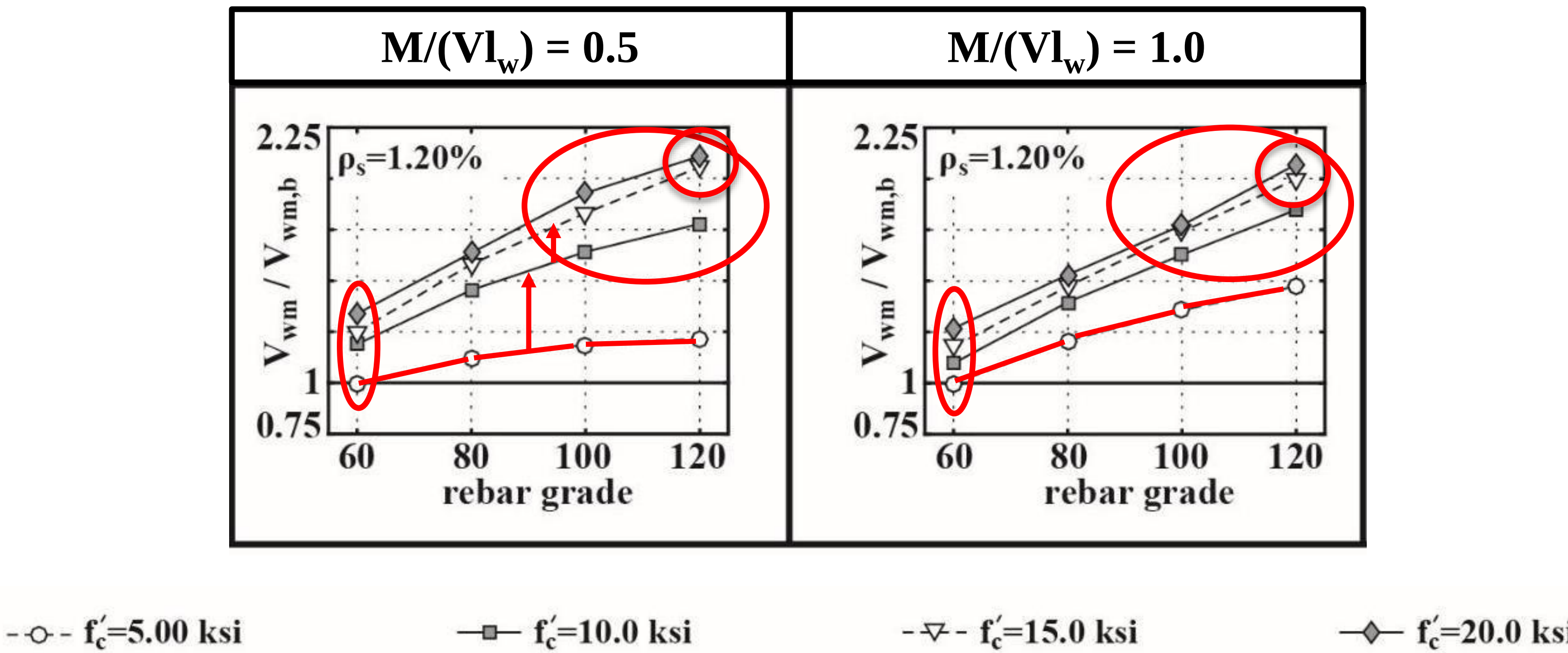
2. Limit-Benefit Analysis

- Numerical limit-benefit study to establish effects of high-strength materials on peak lateral strength of stocky shear walls:
  - Parametric numerical investigation of 192 walls
  - Peak strength predicted via VecTor2 finite element model

Parameter	Wall 1	Wall 2	Wall 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**

2. Representative Limit-Benefit Results

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



V_{wm} = Predicted peak lateral strength

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

2. Limit-Benefit Summary

- Combination of high-strength rebar with high-strength concrete resulted in a higher-performing structure than with either high-strength material on its own
- Higher-strength concrete contributed more effectively for lower base moment to shear ratio walls; rebar yield strength becomes more significant as base moment to shear ratio increases
- Significant benefits are seen by using concrete compressive strength of 10 ksi, with diminishing returns for higher strengths
- Greatest benefits of high-strength materials for walls with large rebar amounts

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3. Cost-Benefit Analysis

- Numerical cost-benefit study of economic effectiveness of high-strength materials for stocky shear walls:
  - Parametric numerical investigation of 2304 walls

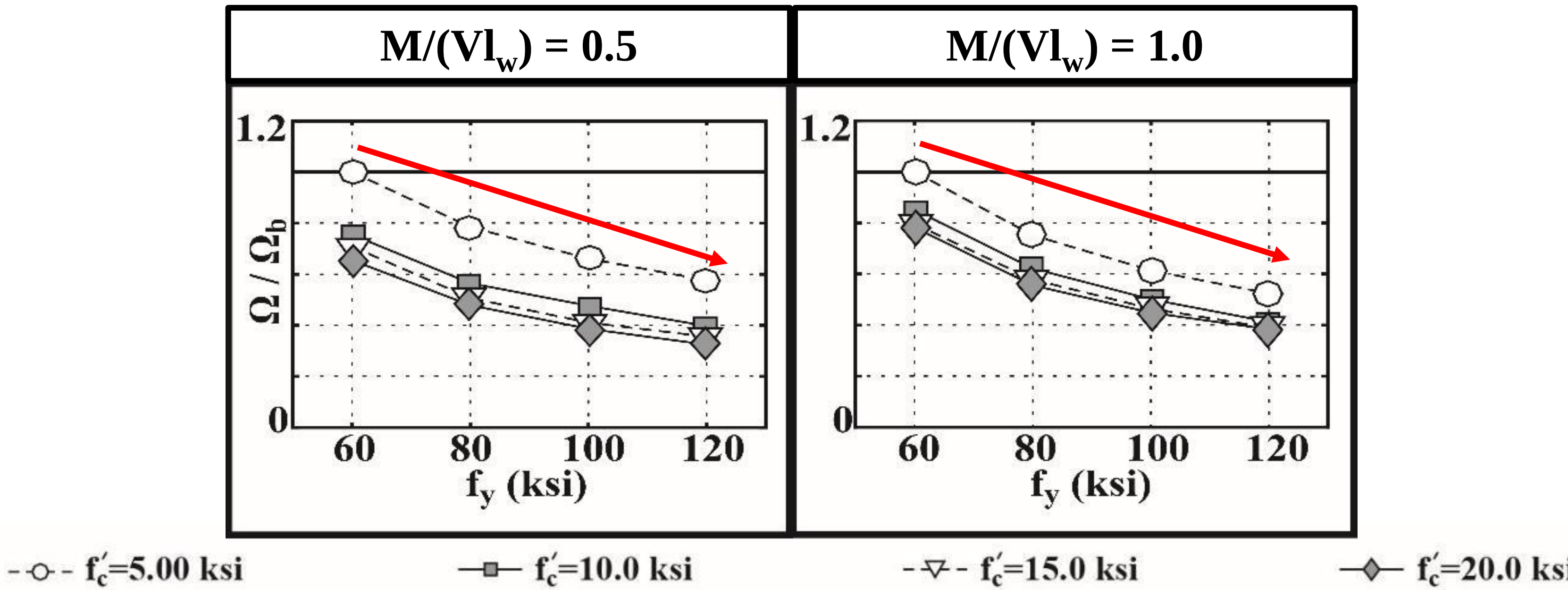
Parameter	Wall 1	Wall 2	Wall 3
length, l_w (ft)	20	60	120
height, h_w (ft)	40	120	120
thickness, t_w (in.)	10, **15**, 20	30, **45**, 60	30, **45**, 60
moment to shear ratio, $M/(Vl_w)$	**0.5**, 1.0	**0.5**, 1.0	**0.5**, 1.0
concrete strength, f'_c (ksi)	**5**, 10, 15, 20	**5**, 10, 15, 20	**5**, 10, 15, 20
rebar strength, f_y (ksi)	**60**, 80, 100, 120	**60**, 80, 100, 120	**60**, 80, 100, 120
reinforcement ratio, ρ_l (%)	low to high	low to high	low to high
ratio of reinforcement, ρ_t/ρ_l	0.80, **1.00**	0.80, **1.00**	0.80, **1.00**

3. Cost-Benefit Metrics

- Rebar weight factor (Ω) captures the total weight of rebar (w_r) normalized by peak strength (V_{wm}): $\Omega = \frac{w_r}{V_{wm}}$
- Construction cost metric (Γ) includes rebar material cost, rebar labor cost, and concrete material cost (C_w), normalized by peak strength (V_{wm}): $\Gamma = \frac{C_w}{V_{wm}}$
- Both metrics are then normalized by "benchmark" metrics (e.g. Ω_b, Γ_b) for walls with normal-strength materials

3. Rebar Weight Factor Results

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



$$\Omega = \frac{w_r}{V_{wm}}$$

Ω = Rebar weight factor

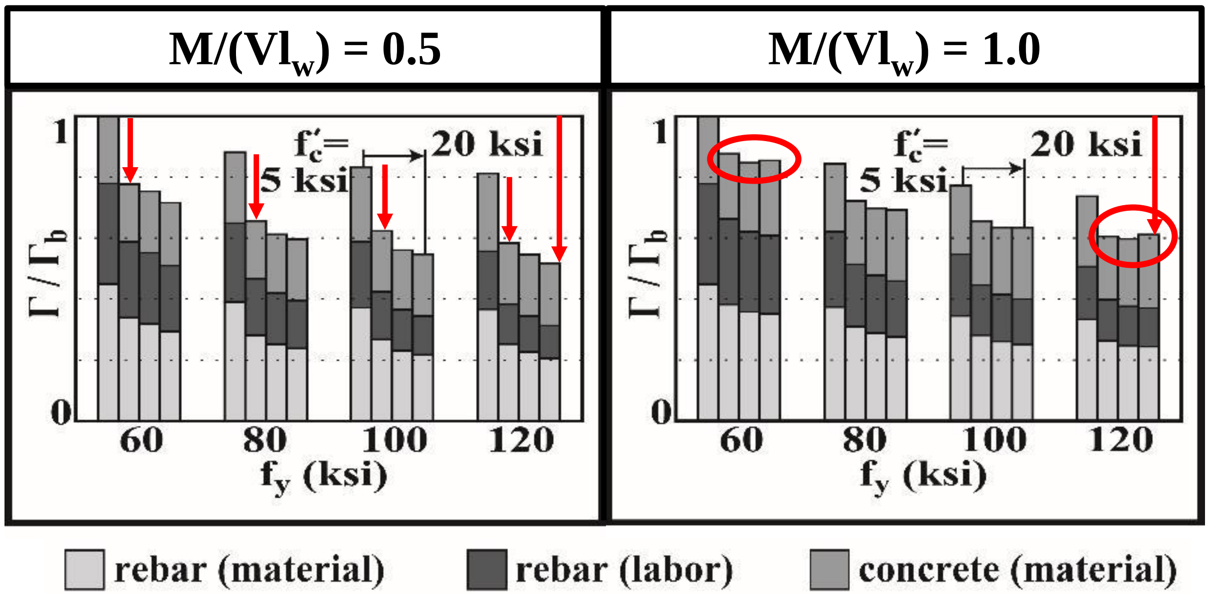
Ω_b = Rebar weight factor of "benchmark" with normal-strength materials

w_r = Total weight of longitudinal and transverse rebar

V_{wm} = Predicted peak lateral strength

3. Construction Cost Metric Results

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



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

Γ = Construction cost metric

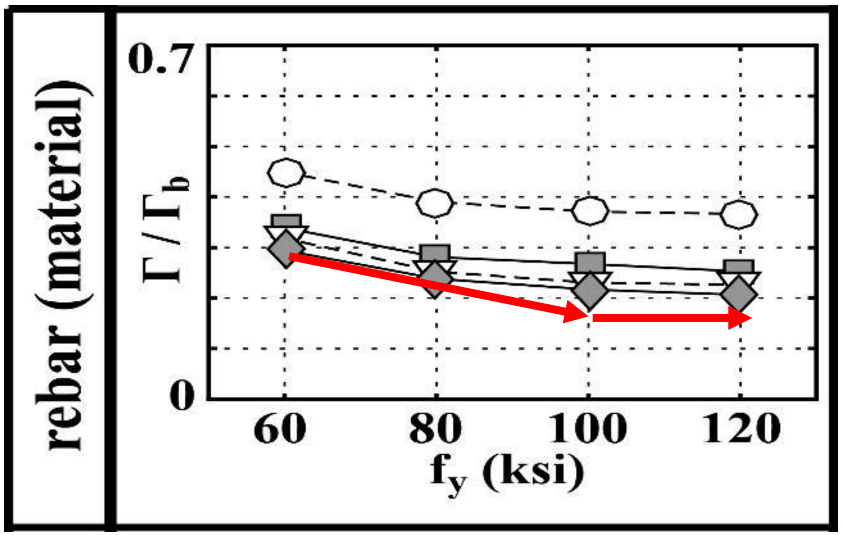
Γ_b = Construction cost metric of "benchmark" with normal-strength materials

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

V_{wm} = Predicted peak lateral strength

3. Rebar Cost Results

Wall 2 (60 ft long, 120 ft tall, 45 in. thick) with $M/(Vl_w)$=0.5, ρ_l = very high :



f'_c=5.00 ksi f'_c=10.0 ksi f'_c=15.0 ksi f'_c=20.0 ksi

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

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

3. Cost-Benefit Summary

- For all walls, increasing the material strength of both concrete and rebar resulted in lower Rebar Weight Factors
- Combination of high-strength rebar with high-strength concrete resulted in greatest economic benefits
- A concrete compressive strength of 10 ksi showed the largest incremental reduction in construction cost; higher concrete strengths can increase normalized cost metric
- Rebar grades greater than 100 can lead to negligible economic benefits due to the increased unit cost

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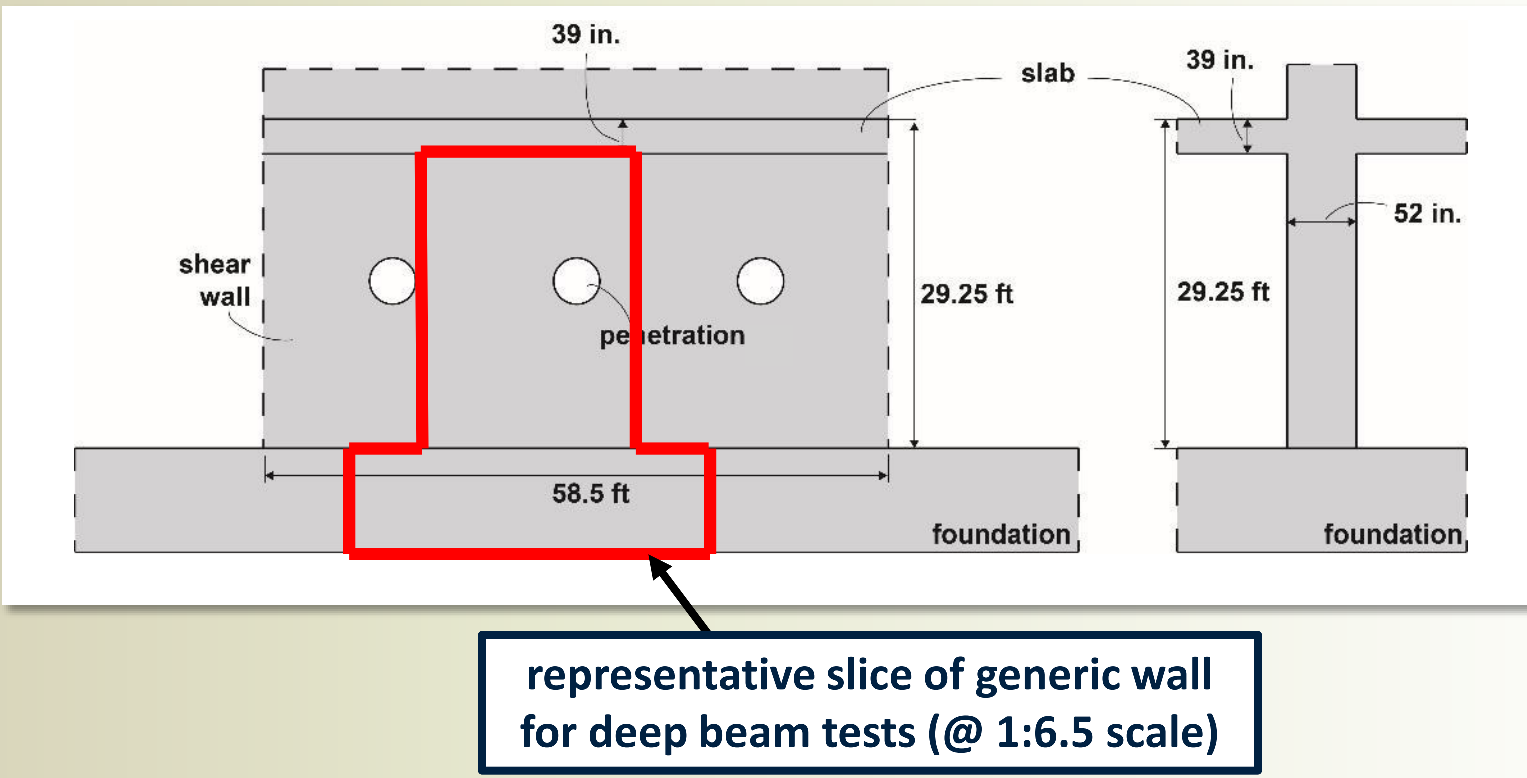
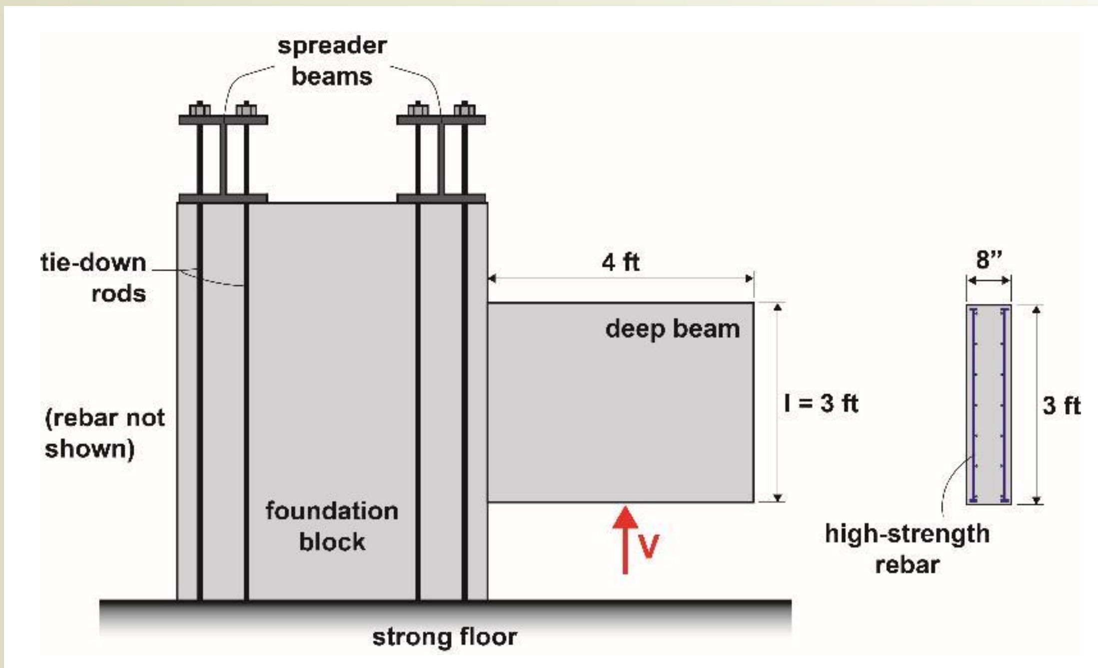
4. Experimental Testing

- "Generic wall" dimensions determined using publicly-available design control documents

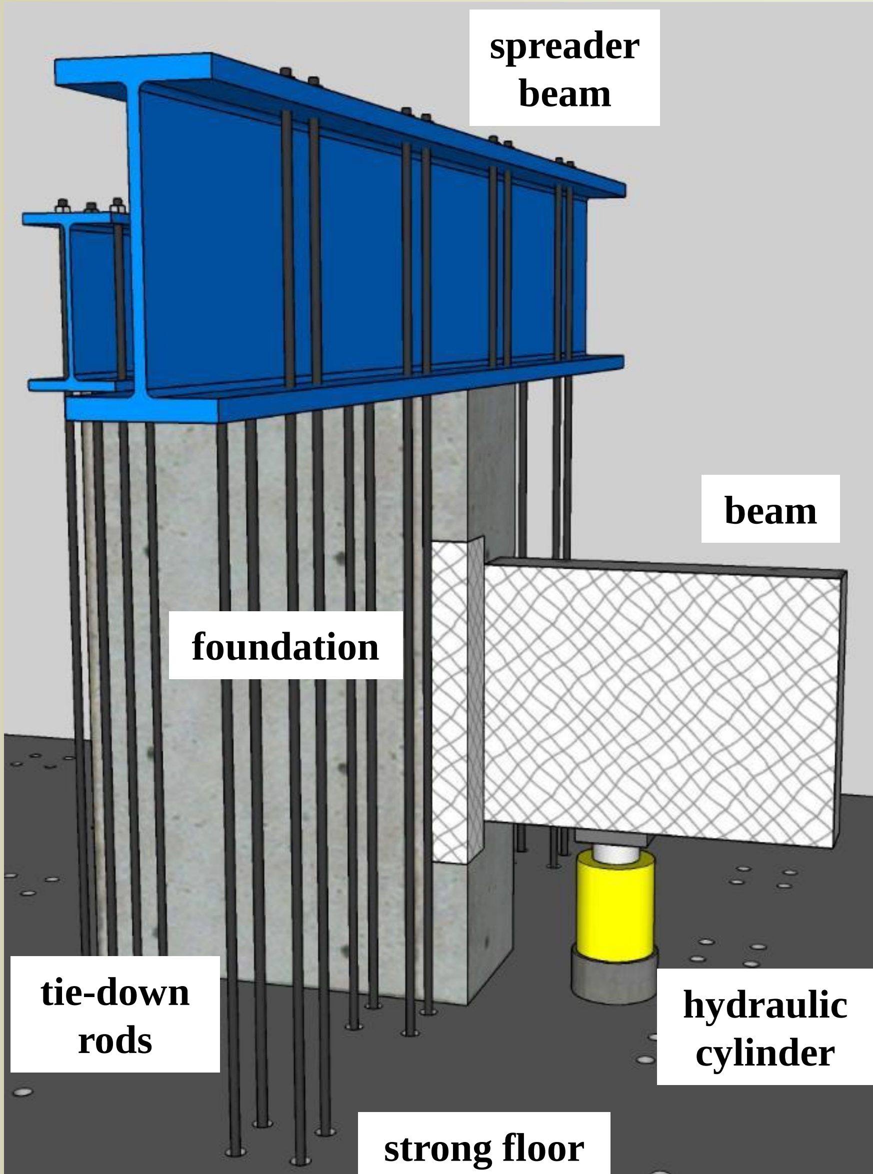


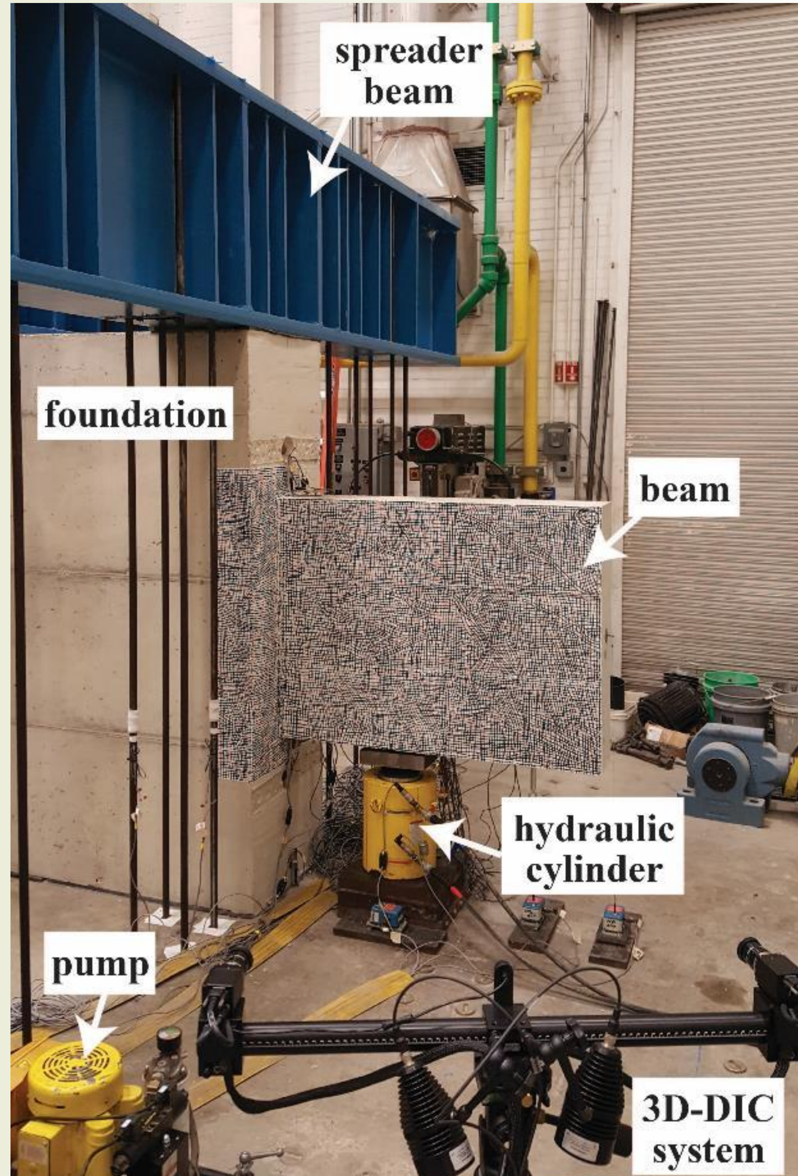
4. Experimental Testing

- “Generic wall” dimensions determined using publicly-available design control documents

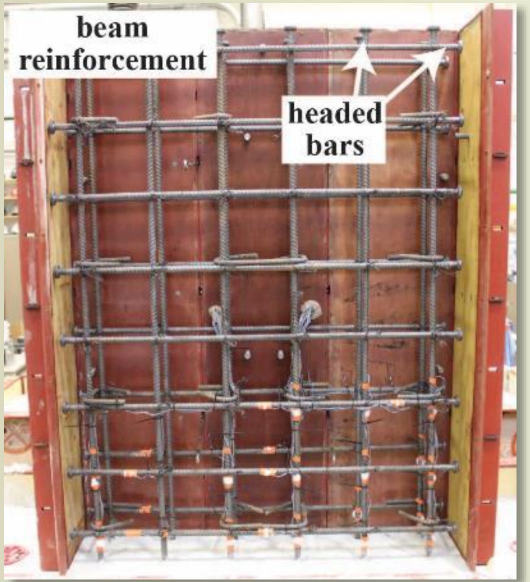


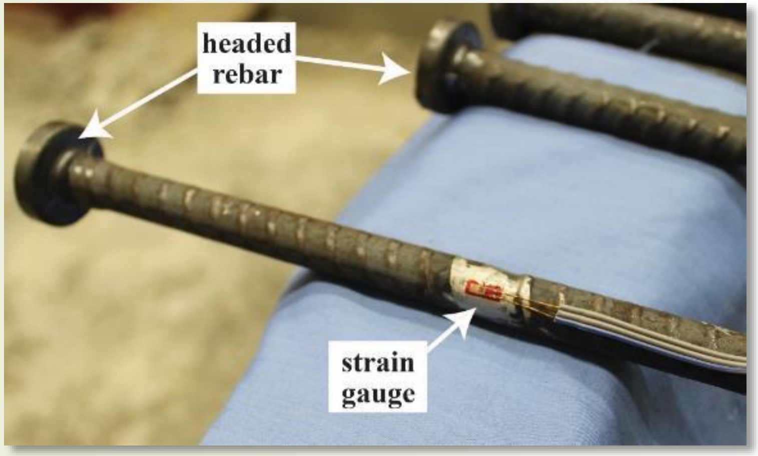
4. Test Setup

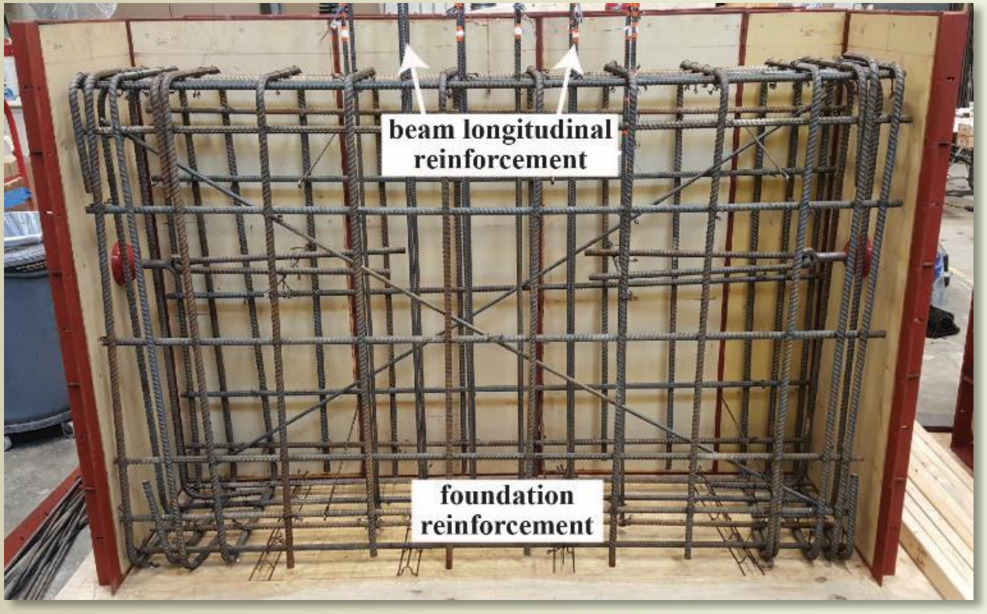

spreader beam
beam
foundation
tie-down rods
hydraulic cylinder
strong floor

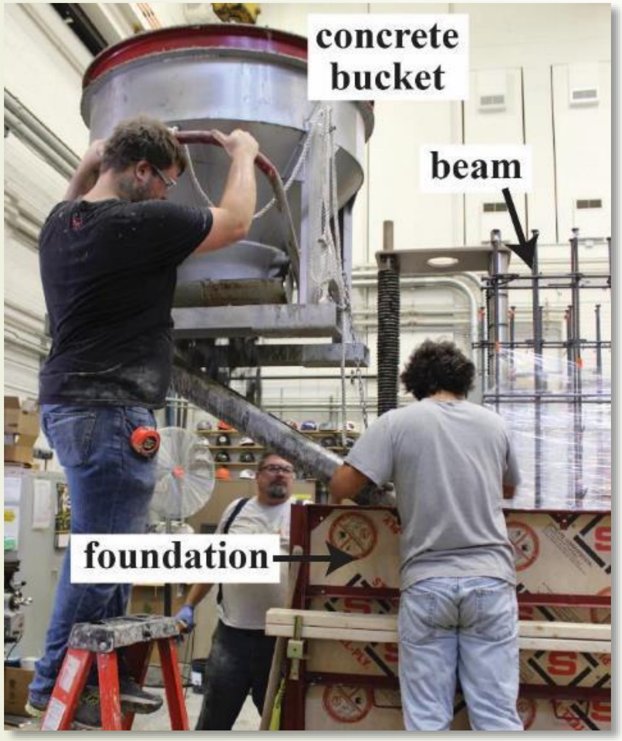

spreader beam
foundation
beam
hydraulic cylinder
pump
3D-DIC system

4. Specimen Construction







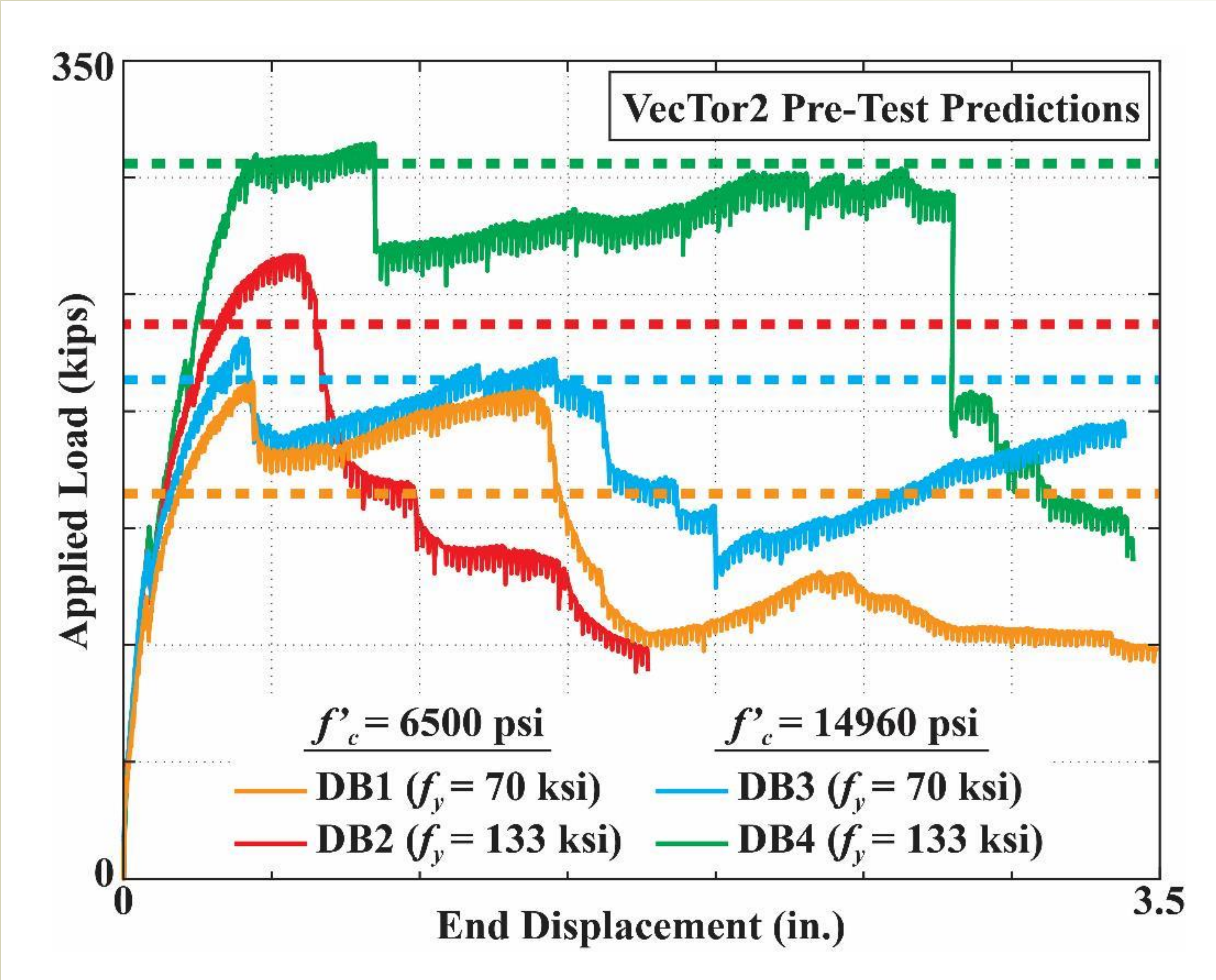


4. Test Parameters

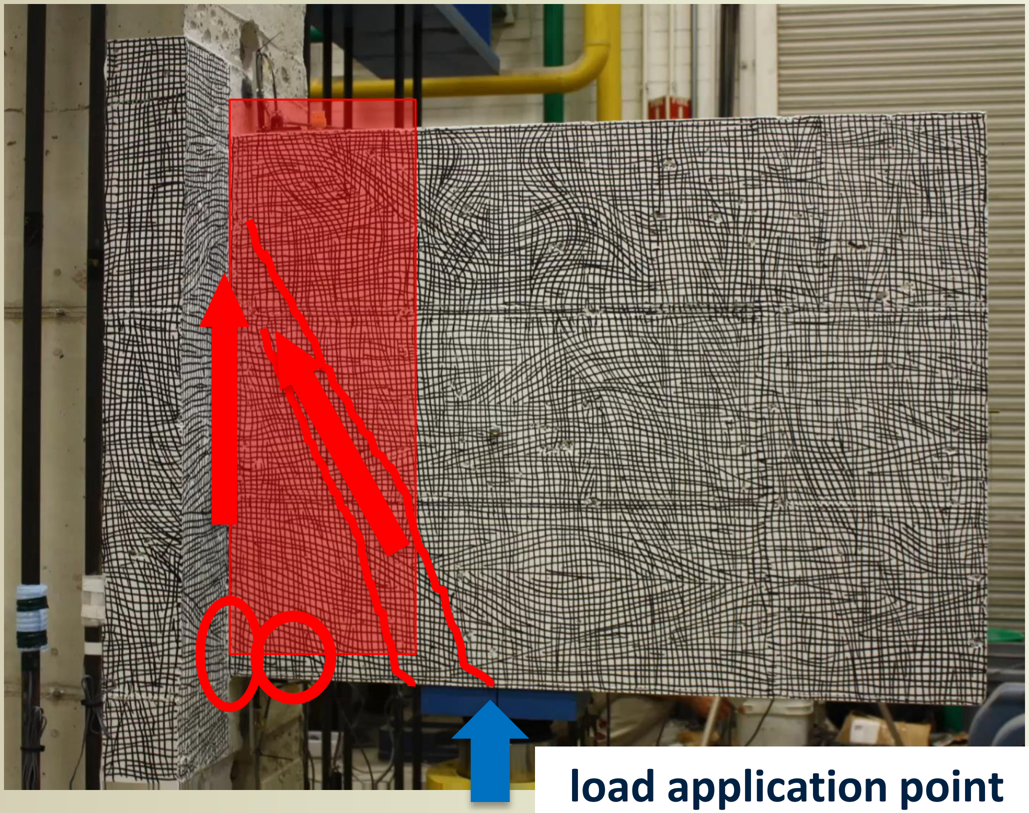
Specimen	f'_c (psi)	f_y (ksi)	ρ_s (%)	$M/(Vl_w)$
DB1	6500	70	0.833	0.5
DB2	6500	133	0.833	0.5
DB3	14960	70	0.833	0.5
DB4	14960	133	0.833	0.5

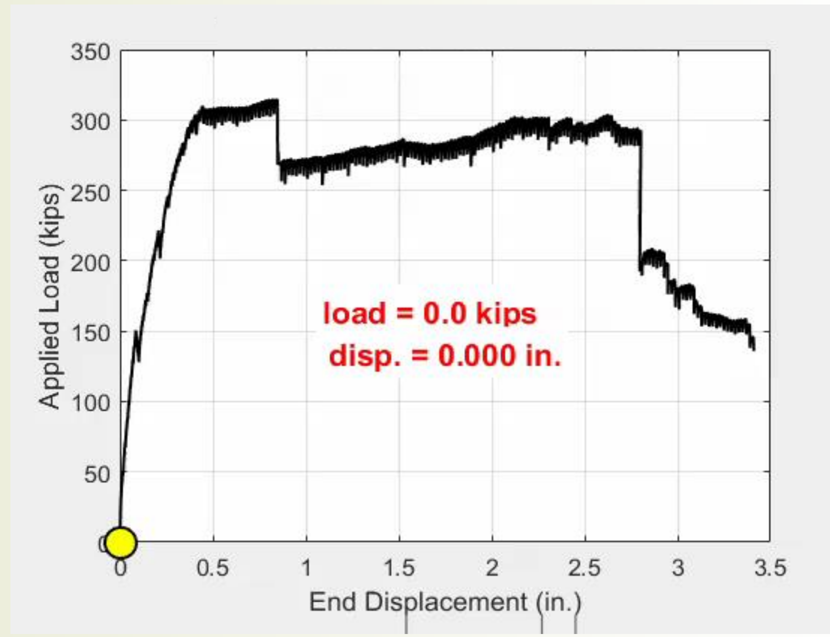
Definitions: f'_c – concrete 28 day compressive strength
f_y – rebar yield strength, determined by tensile tests and 0.2% offset method
ρ_s – reinforcement ratio, symmetric for longitudinal and transverse rebar

4. Specimen Response



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





VIDEO, contact ykurama@nd.edu or athrall@nd.edu for more information

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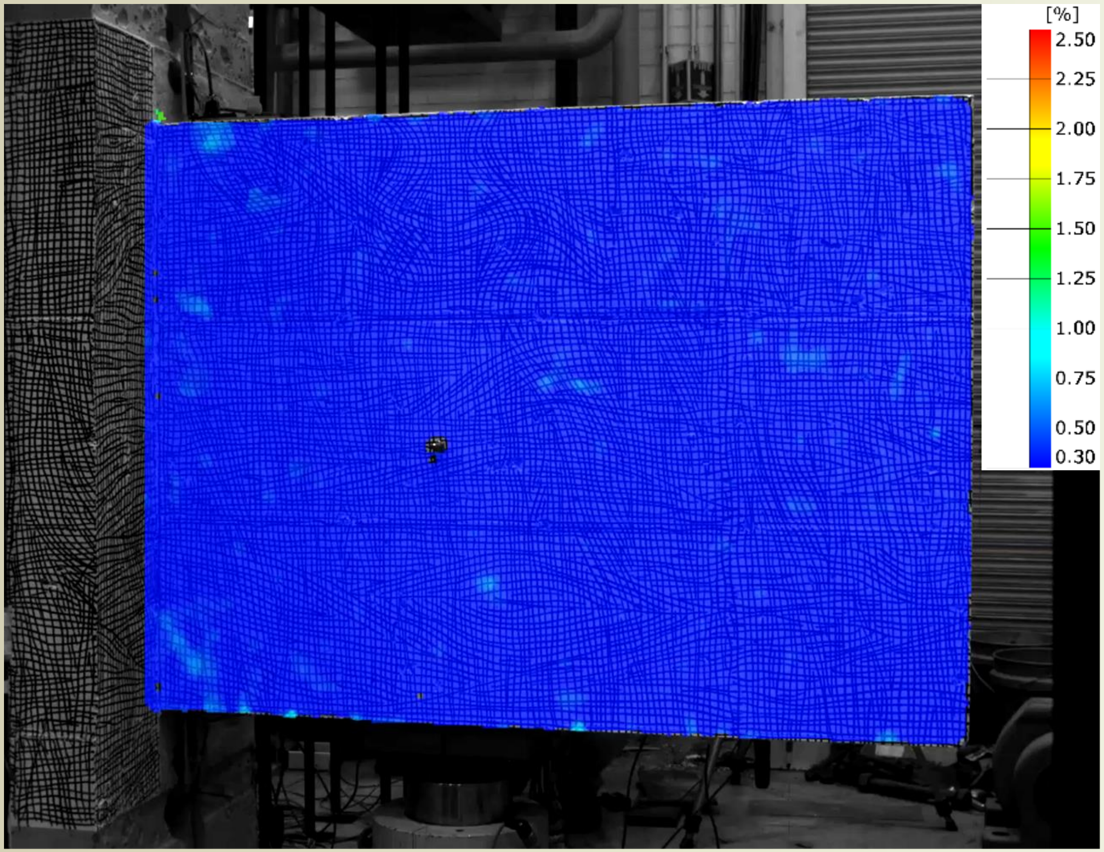

VIDEO, contact ykurama@nd.edu or athrall@nd.edu for more information

4. Summary of Tests

- Most significant strength increase and most ductile failure for deep beams was when high-strength materials were used together (DB4)
- Isolated increase in rebar yield strength (DB2) resulted in higher increase in deep beam strength than isolated increase of concrete compressive strength (DB3)
- Pre-test analyses provided reasonable and conservative predictions for all specimens

Conclusions

- High-strength steel more effective when combined with high-strength concrete
  - Numerically demonstrated (economics and peak strength)
  - Measured experimentally
- Greatest benefit for walls with low base moment to shear ratios and large reinforcement amounts; typical of nuclear concrete shear walls
- Largest economic and structural benefits when using Grade 100 rebar together with 10 ksi compressive strength concrete

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Questions?

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