Use of High-Strength Concrete in Low-Rise RC Shear Walls

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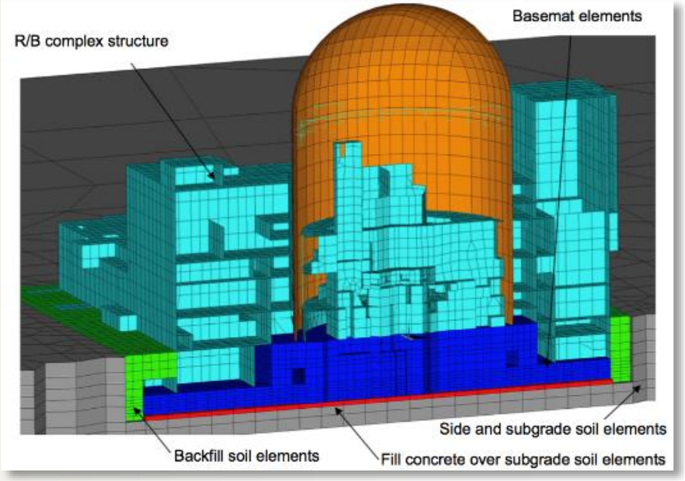
Project Objective

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

Project Scope

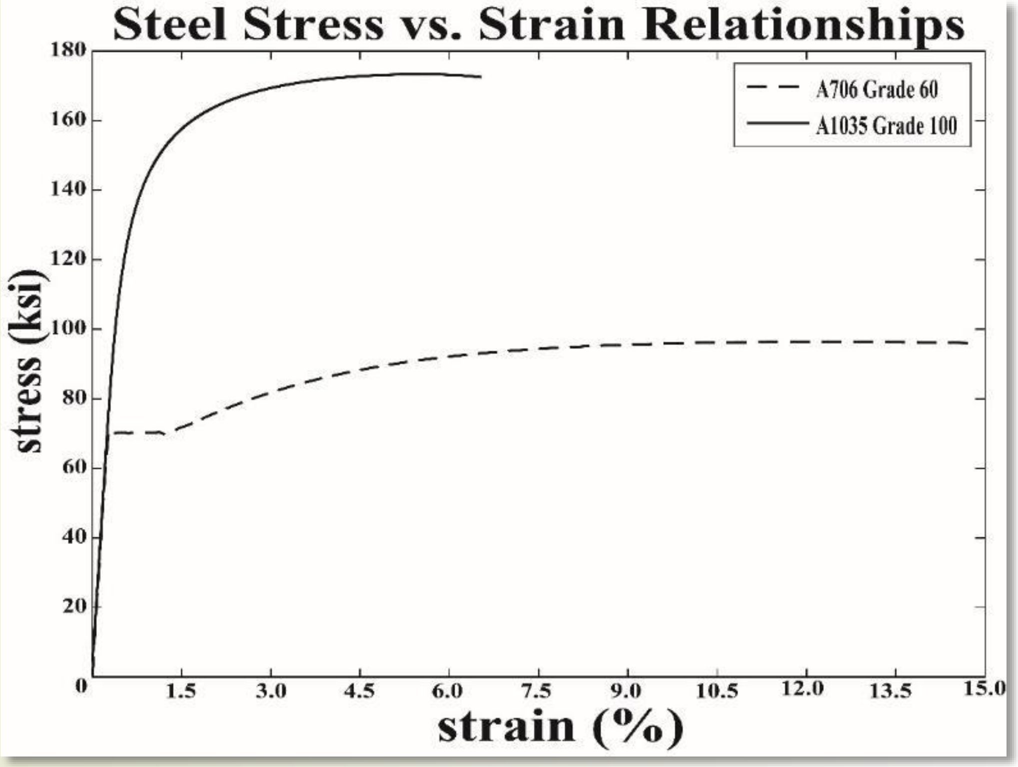
- Explore effectiveness, code conformity, and viability of existing high-strength materials
- Focus on stocky shear walls – most common lateral load resisting members in nuclear structures (pressure vessels not in scope)
- Aim to reduce complexities in rebar to improve construction quality and ease of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



US-APWR Design Control Doc.

High-Strength Materials

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



Potential Benefits

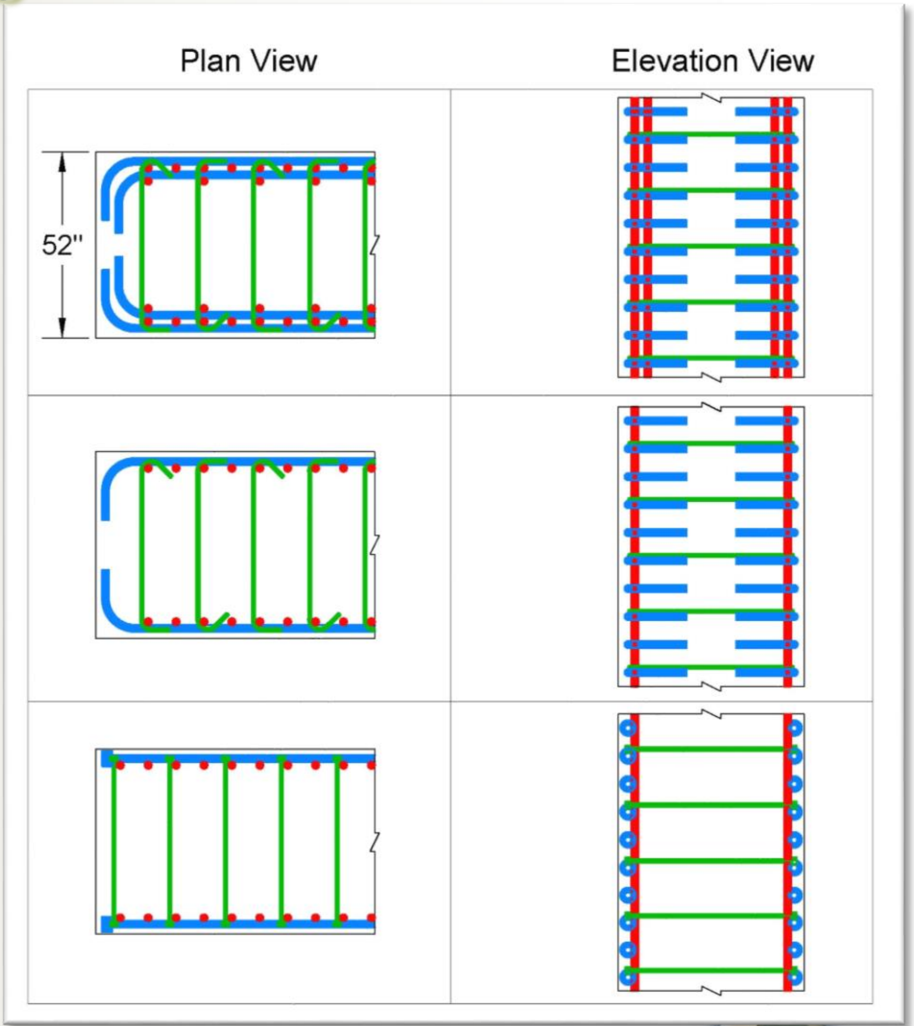
Most Congested (current)

Multiple layers of hooked Grade 60 bars

Fewer layers of hooked high-strength bars

Least Congested (envisioned)

Fewer layers of headed high-strength bars



Outline

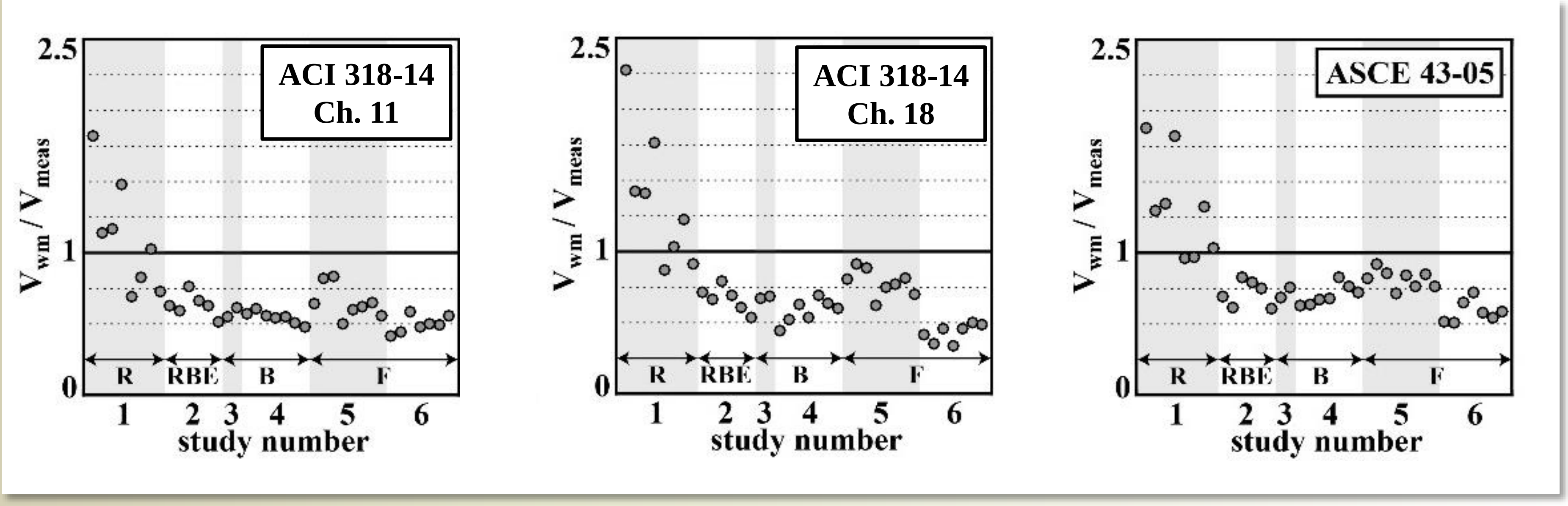
1. Numerical Modeling
2. Limit-Benefit Analysis
3. Cost-Benefit Analysis
4. Experimental Testing

1. Modeling Approach

- Evaluated methods for predicting peak lateral strength of low-aspect-ratio shear walls:
  1) Closed-form Methods
  2) Finite Element Modeling using VecTor2
  3) Finite Element Modeling using ATENA
- Compared predictions with measured strengths of 38 walls from 6 different experimental studies:
  - Study 1: normal-strength benchmark study
  - Study 2-6: high-strength materials utilized
  - Parameter range: $M/(Vl_w)$ = 0.33 - 1.36, f'_c = 3.50 - 19.9 ksi, f_y = 50.3 - 205.9 ksi

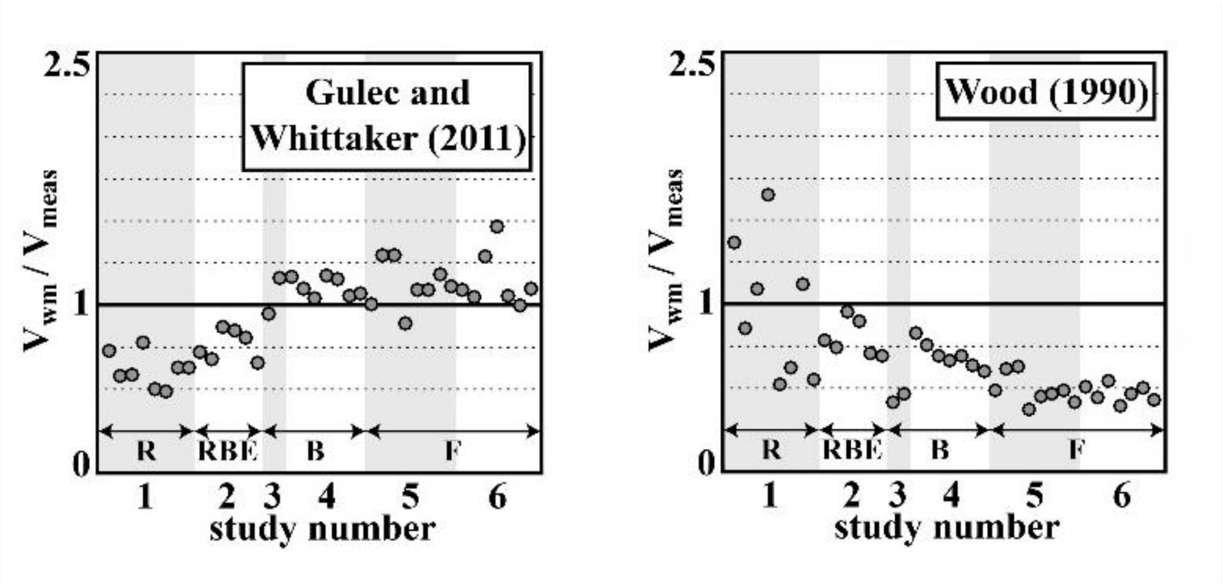
1. ACI and ASCE Code Equations

- Overestimate strength of rectangular walls without boundary regions (Study 1), indicating un-conservatism
- Underestimated strength of walls with boundary regions, barbells, or flanges (Studies 2-6), indicating over-conservatism



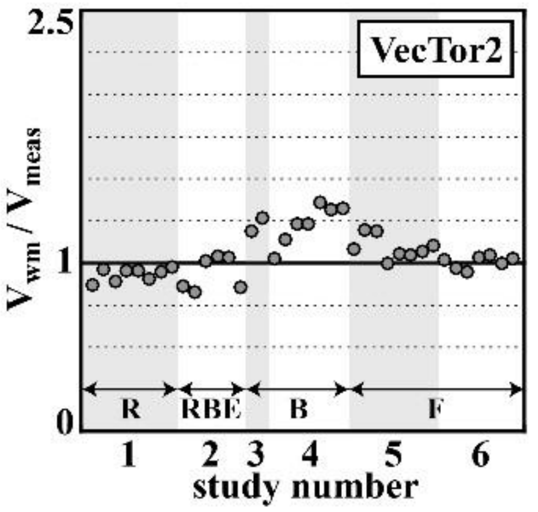
1. Other Closed-Form Equations

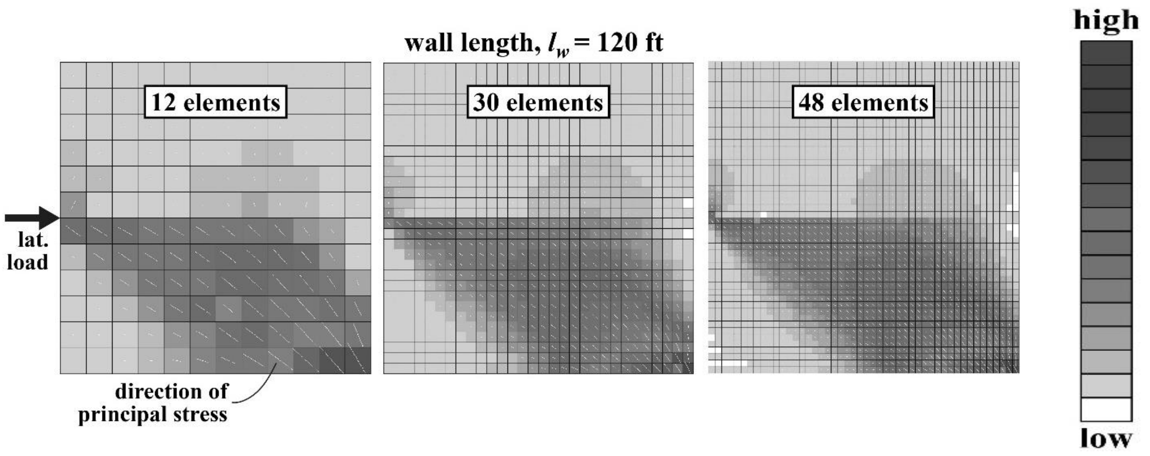
- Gulec and Whittaker (2011) provided best predictions, underestimating the strength of rectangular walls while slightly overestimating the strength of walls with boundary regions/members



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
- Best predictor of walls with boundary regions, barbells, and flanges

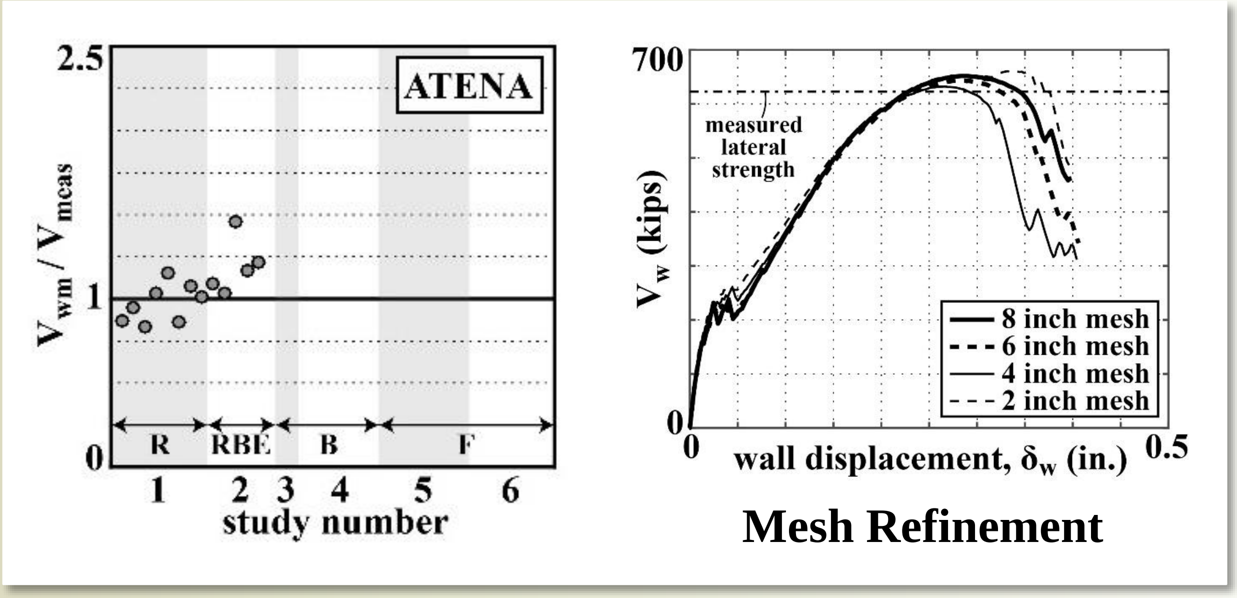




Mesh Refinement: Principal Stresses

1. ATENA Finite Element Model

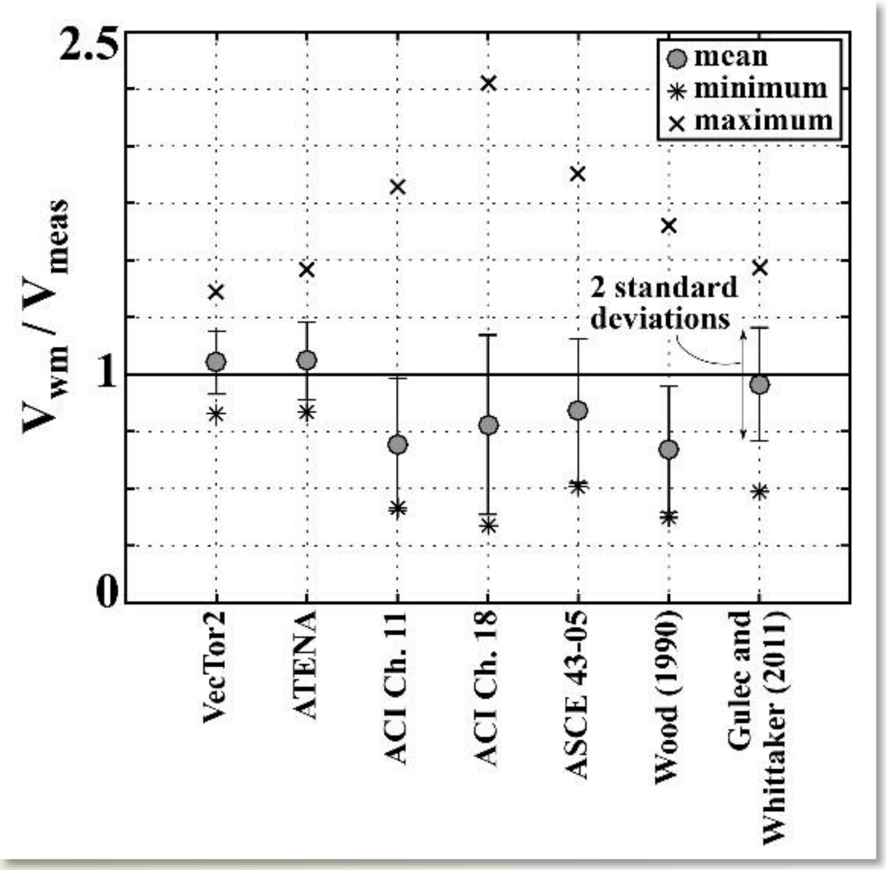
- Also reliably predicts the peak strength of rectangular walls



Mesh Refinement

1. Comparison of Predictions

- Design equations should be revisited for high-strength materials
- VecTor2 and ATENA are reliable for predicting peak strength; ABAQUS will also be used.



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2. Limit-Benefit Analysis

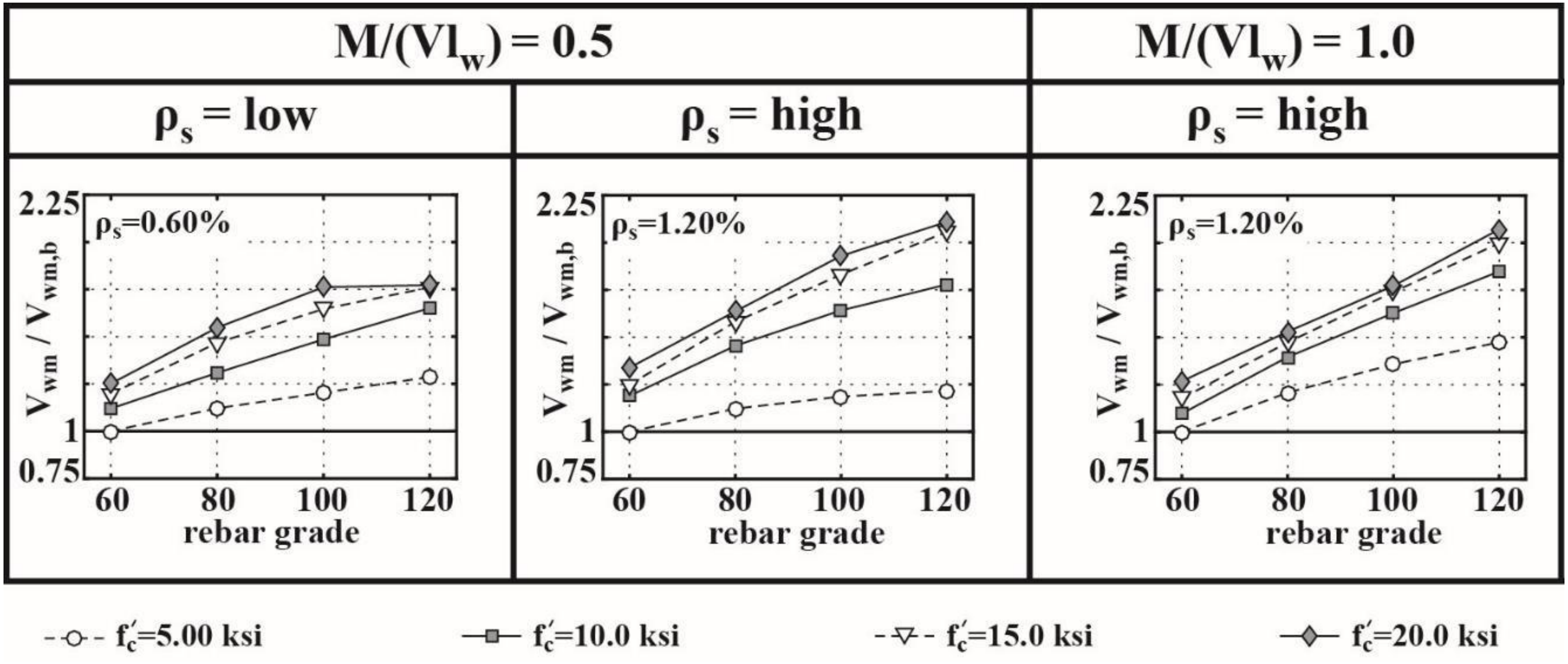
Numerical limit-benefit study to establish effects of high-strength materials on peak lateral strength of low-aspect-ratio shear walls:

- 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 Results

Wall 2 (60 ft x 120 ft x 45 in.):



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 at lower $M/(Vl_w)$ ratios; wall response was more dependent on rebar for larger $M/(Vl_w)$ ratios
- 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

Outline

1. Numerical Modeling
2. Limit-Benefit Analysis
3. Cost-Benefit Analysis
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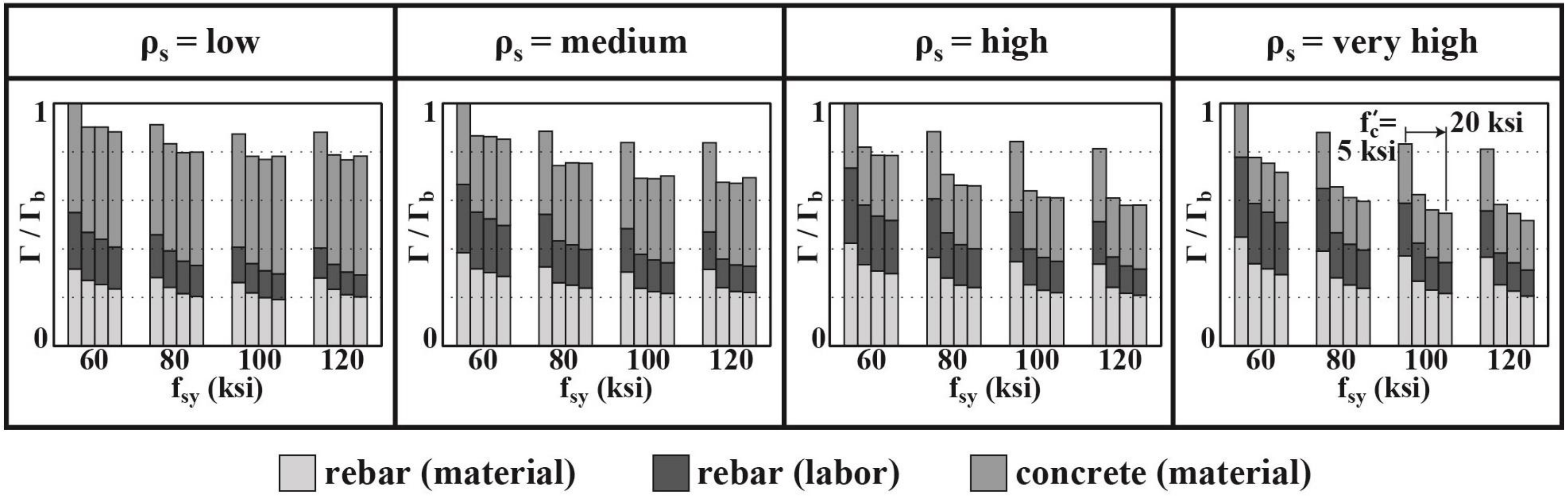
3. Cost-Benefit Analysis

- Numerical cost-benefit study of economic effectiveness of high-strength materials for low-rise shear walls:
  - Parametric numerical investigation of 2304 walls
  - Construction cost metric (Γ) includes rebar material cost, rebar labor cost, and concrete material cost (C_w), normalized by peak strength (V_{wm}): $\Gamma = \frac{C_w}{V_{wm}}$

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_s (%)	low to high	low to high	low to high

3. Representative Results

Wall 2 (60 ft x 120 ft x 45 in.) with $M/(Vl_w)$=0.5:



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

Γ = Construction cost metric

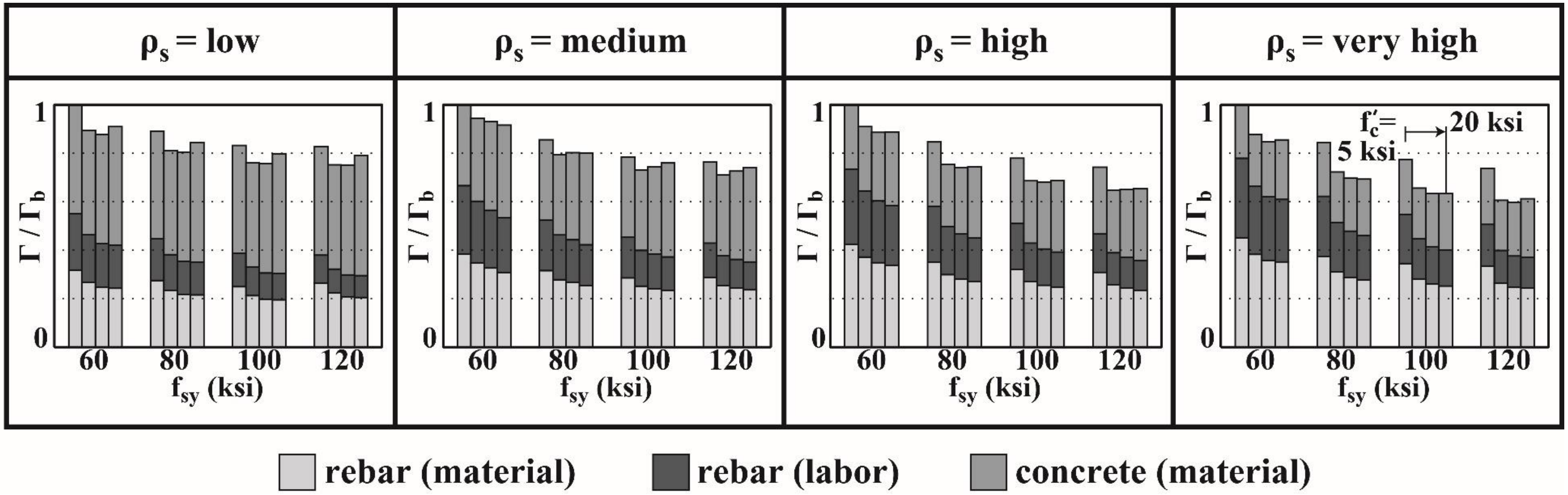
Γ_b = Construction cost metric of "benchmark" with normal-strength materials

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

V_{wm} = Predicted peak lateral strength

3. Representative Results

Wall 2 (60 ft x 120 ft x 45 in.) with $M/(Vl_w)$=1.0:



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

Γ = Construction cost metric

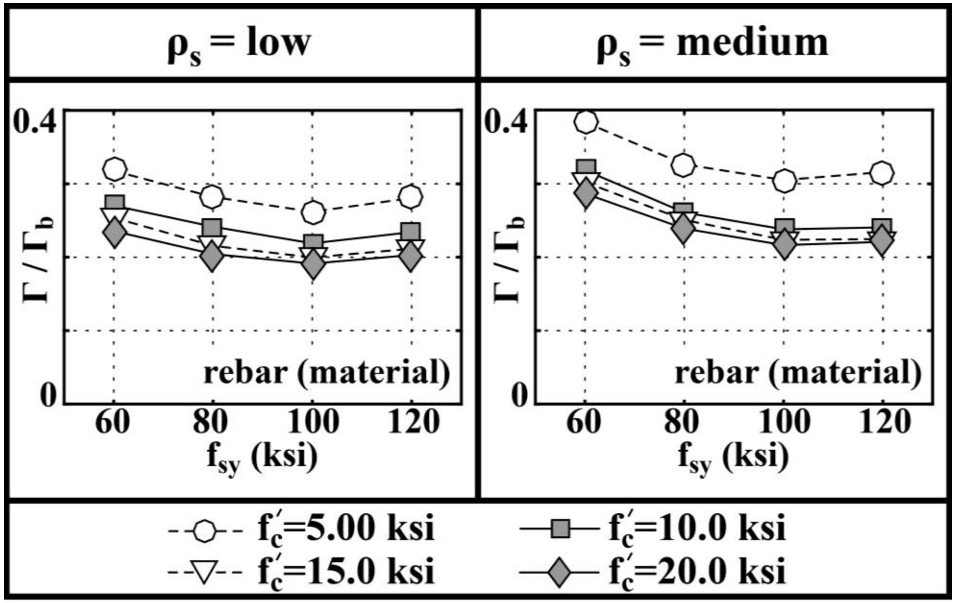
Γ_b = Construction cost metric of “benchmark” with normal-strength materials

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

V_{wm} = Predicted peak lateral strength

3. Representative Results

Wall 2 (60 ft x 120 ft x 45 in.) with $M/(Vl_w)$=0.5, rebar material costs:



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

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

- Combination of high-strength rebar with high-strength concrete resulted in greatest economic benefits for walls with lower $M/(Vl_w)$ ratios and large reinforcement ratios, ρ_s
- A concrete strength of f'_c=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 decreased economic benefits due to the increased unit cost

Outline

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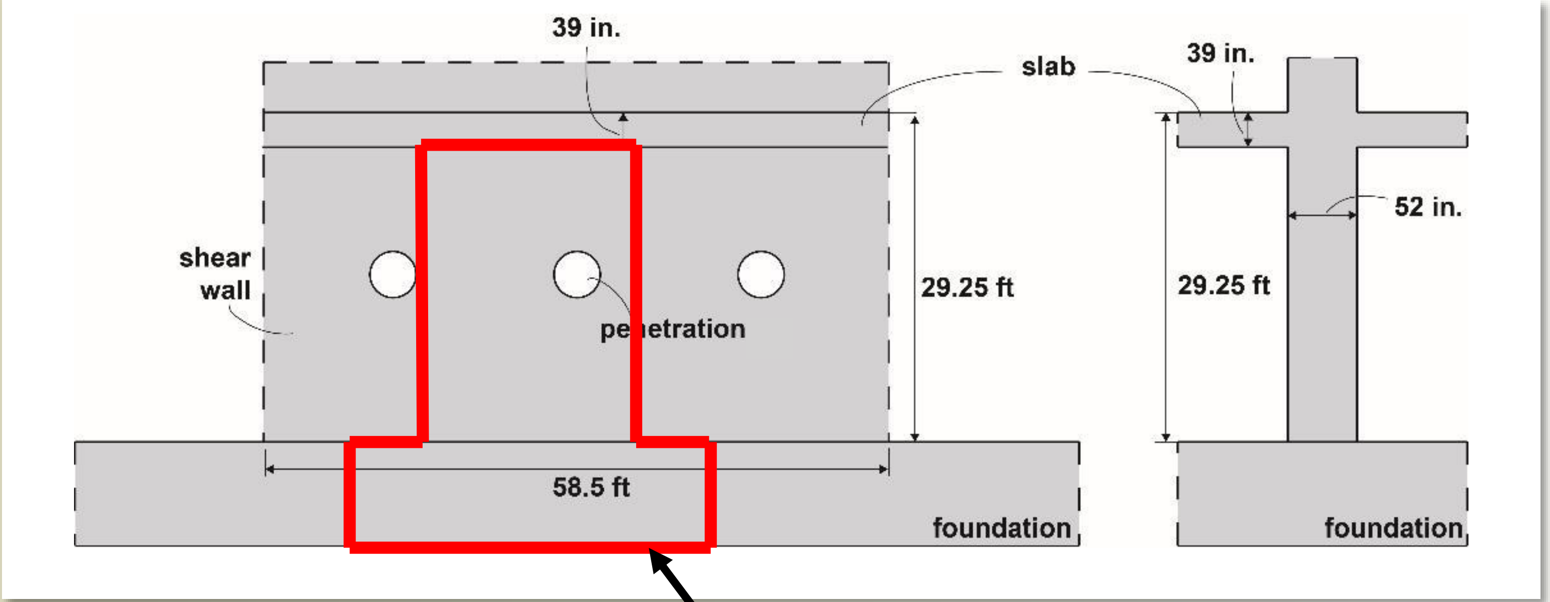
4. Experimental Testing

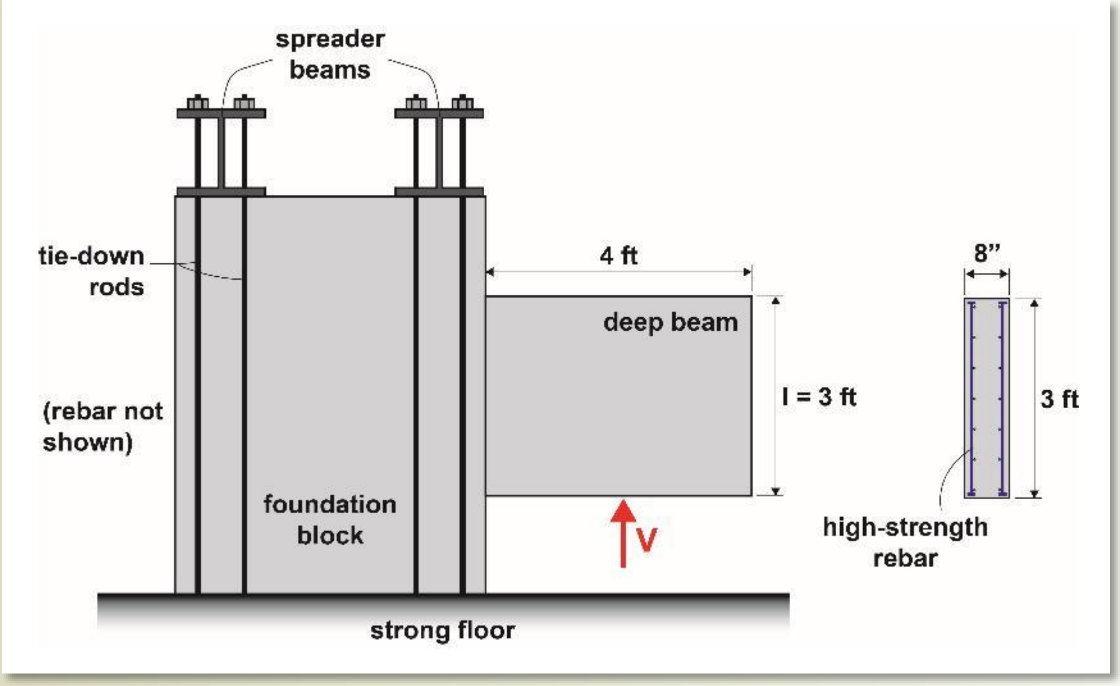
- “Generic wall” dimensions determined using publicly-available design control documents



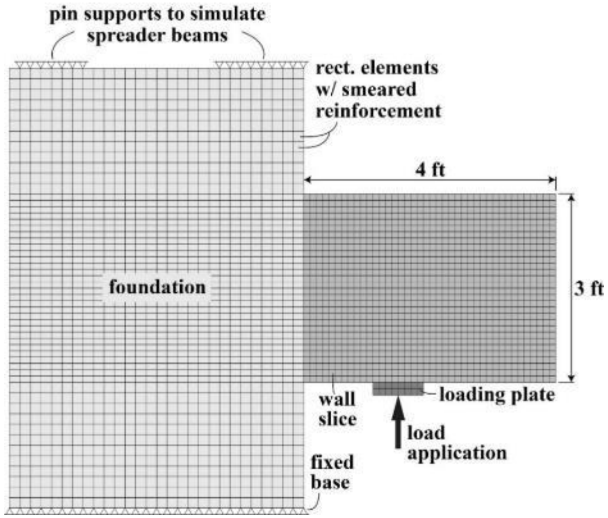
representative slice of generic wall for deep beam tests (@ 1:6.5 scale)

4. Experimental Testing

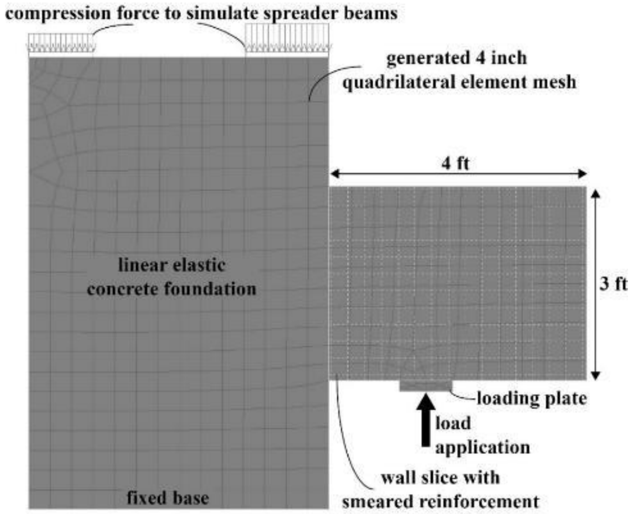
- “Generic wall” dimensions determined using publicly-available design control documents



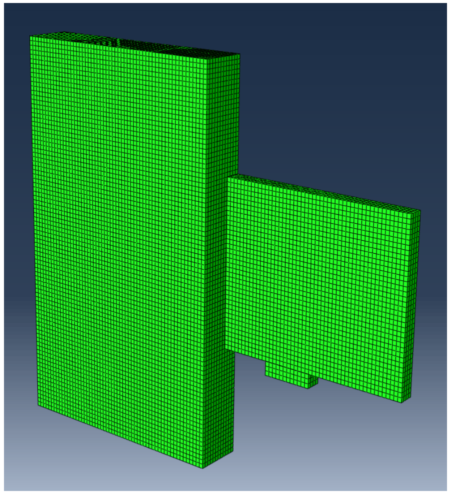
4. Pre-test Analyses



VecTor2

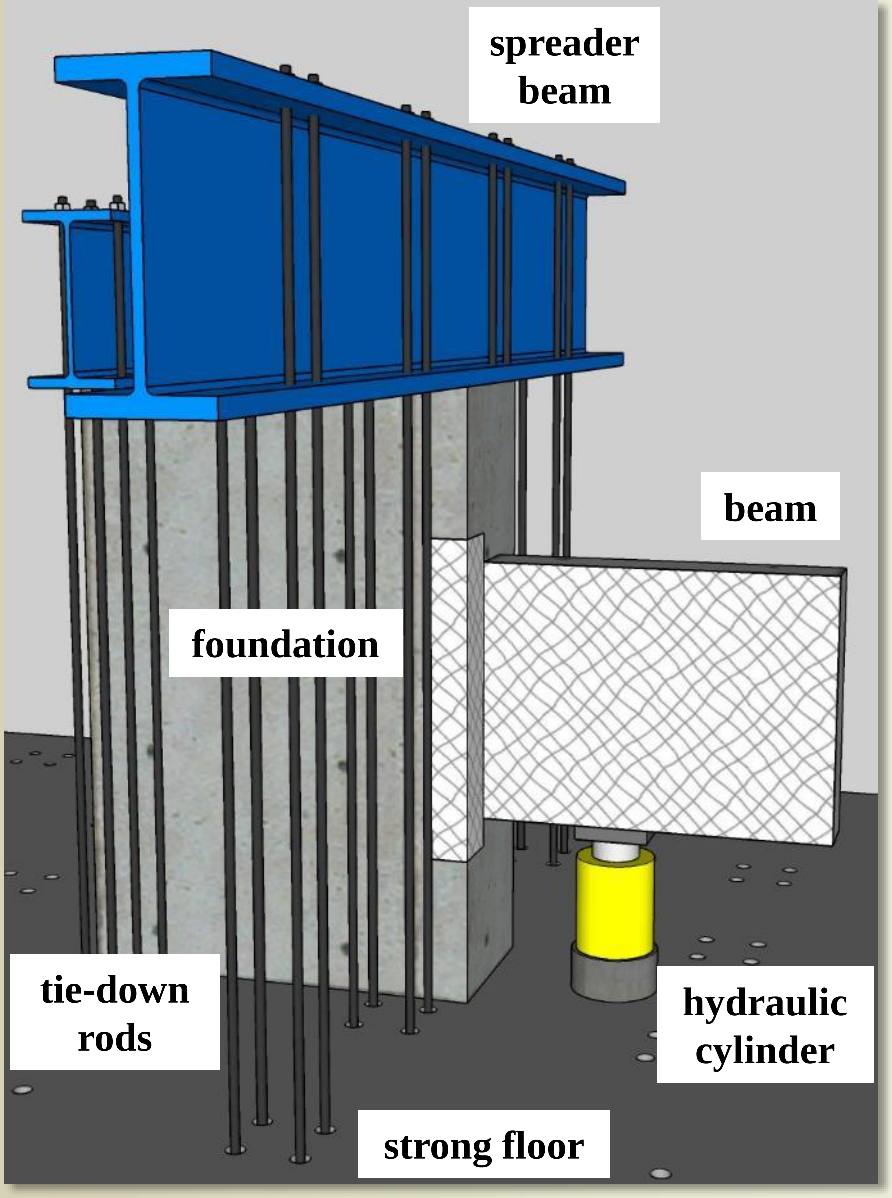


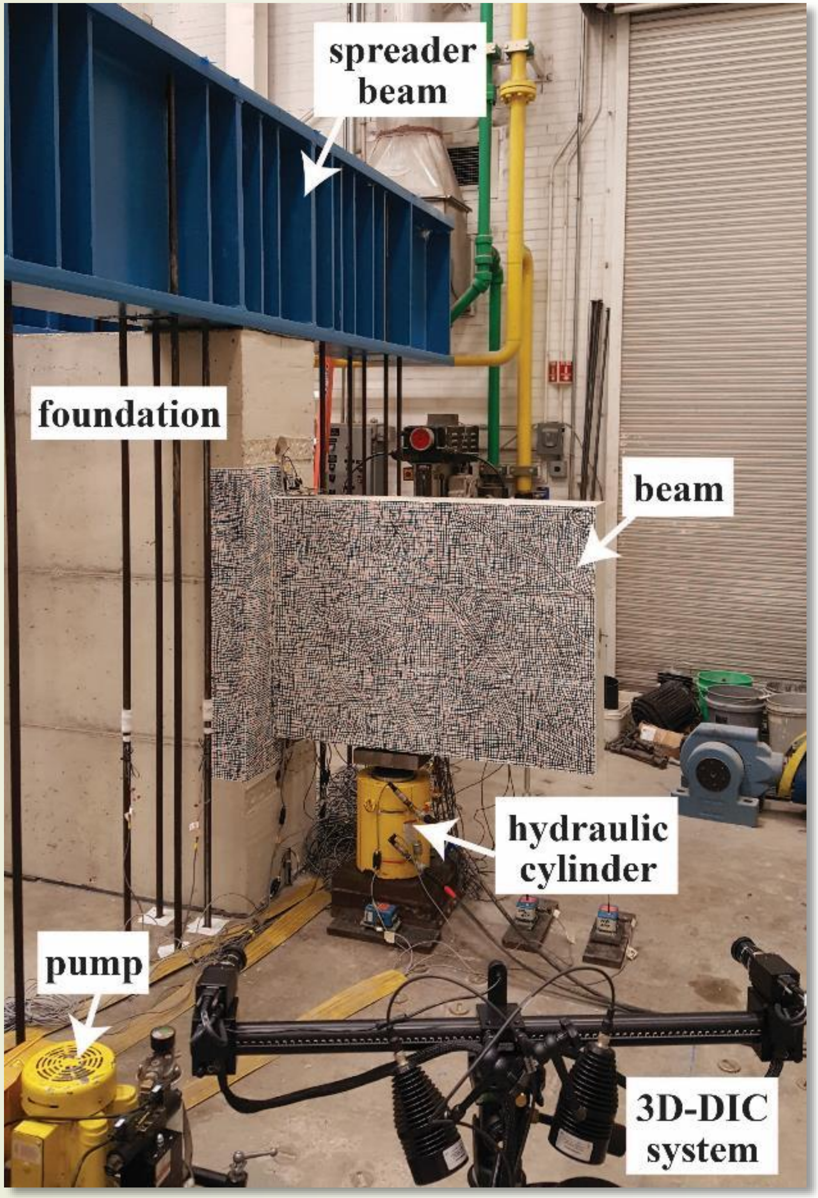
ATENA



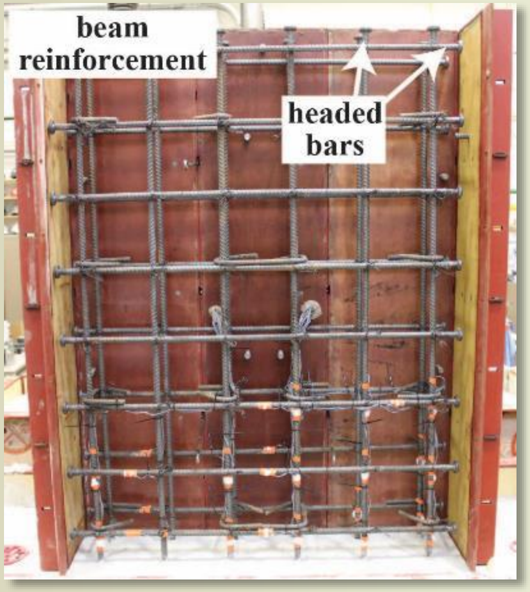
ABAQUS

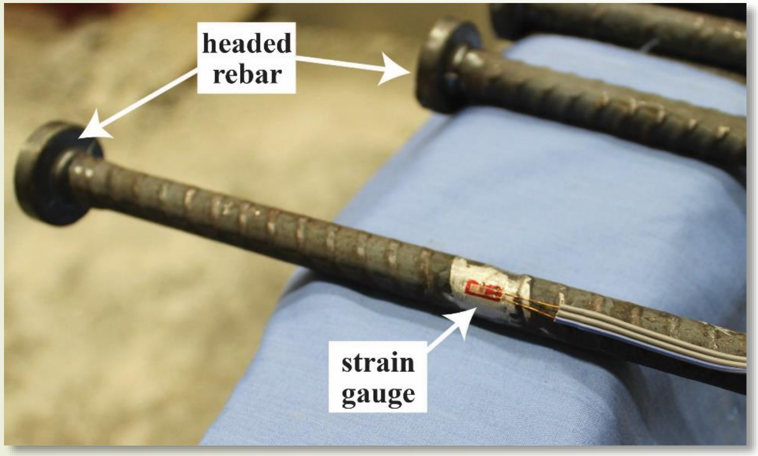
4. Test Setup

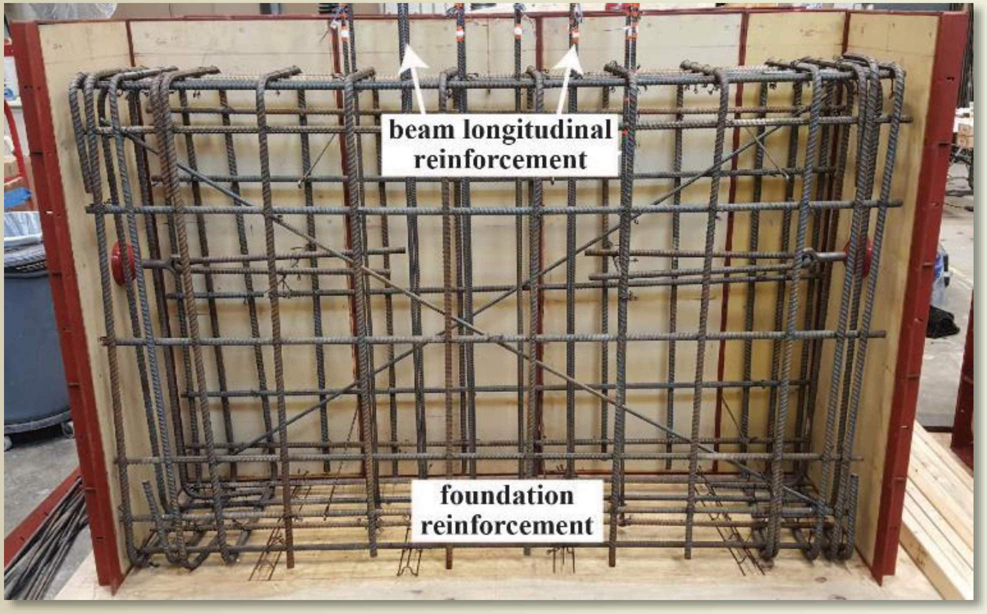

spreader beam
beam
foundation
tie-down rods
hydraulic cylinder
strong floor

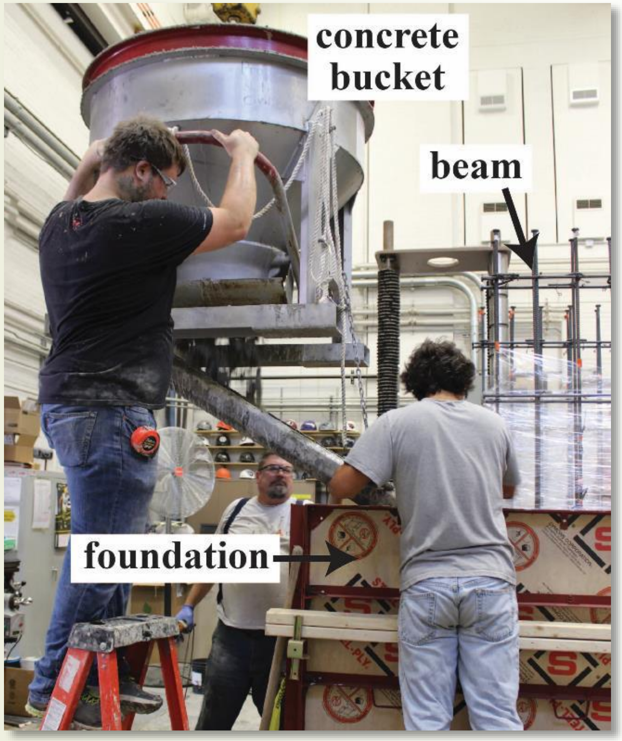

spreader beam
foundation
beam
hydraulic cylinder
pump
3D-DIC system

4. Specimen Construction









4. Concrete Mix Design

Constituents	Normal-Strength Concrete	High-Strength Concrete
Portland Cement Type I/II (lb/yd^3)	182	400
Ground granulated blast-furnace slag (lb/yd^3)	437	350
Silica Fume (lb/yd^3)	0	50
Crushed Limestone (lb/yd^3)[a]	1745	1615
Fine Aggregate (lb/yd^3)[a]	1346	1353
Water (lb/yd^3)[a]	250	220
HRWR (fl. oz./cwt)	2.0	6.75
Water/Binder Ratio	0.41	0.28
Air Content	2.6%	1.5%
Slump (in)	8	8.75
Measured 28-day f'_c (psi)	**6500**	**14960**
Predicted Temp. Rise (°F)	85	110

[a] Weights of aggregates and water reported as saturated surfaced dry weight and weight of water above SSD respectively.

4. Concrete Mix Design

Normal-Strength Concrete

f'_c = 6500 psi

slump = 8 in.

High-Strength Concrete

f'_c = 14960 psi

slump = 8.75 in.

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

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Definitions: f'_c – concrete 28 day compressive strength

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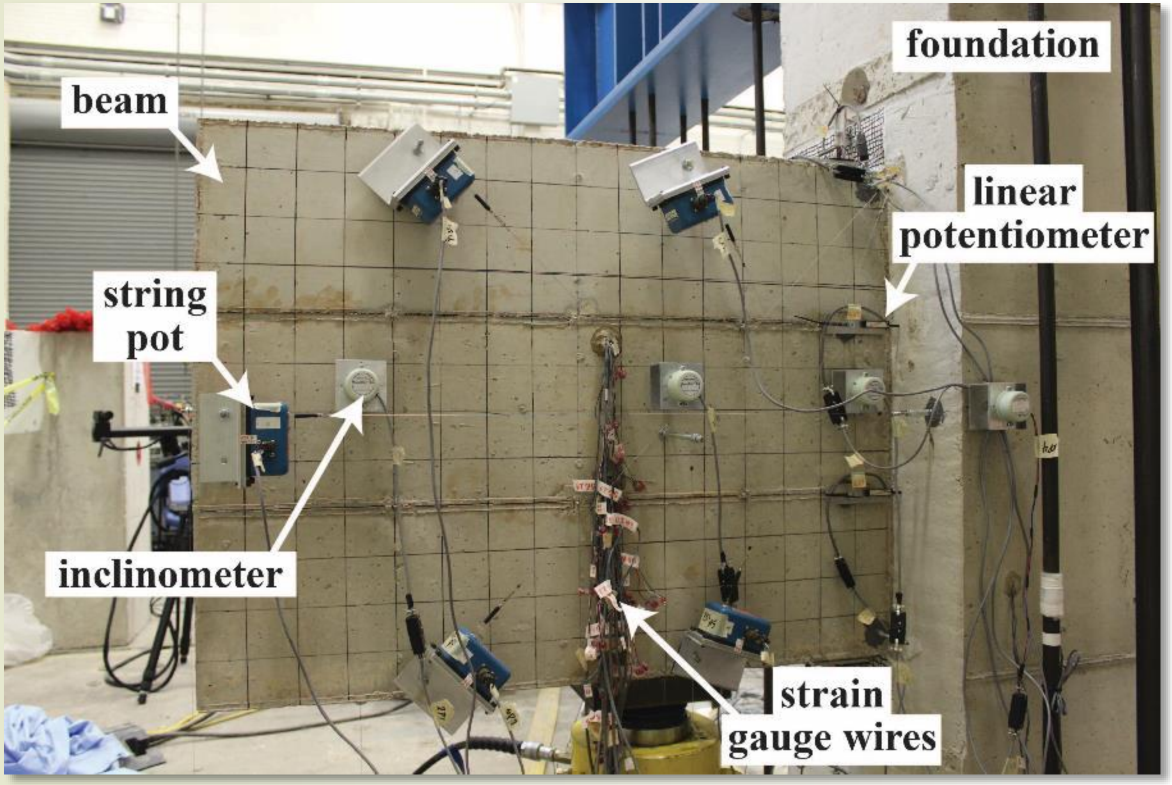
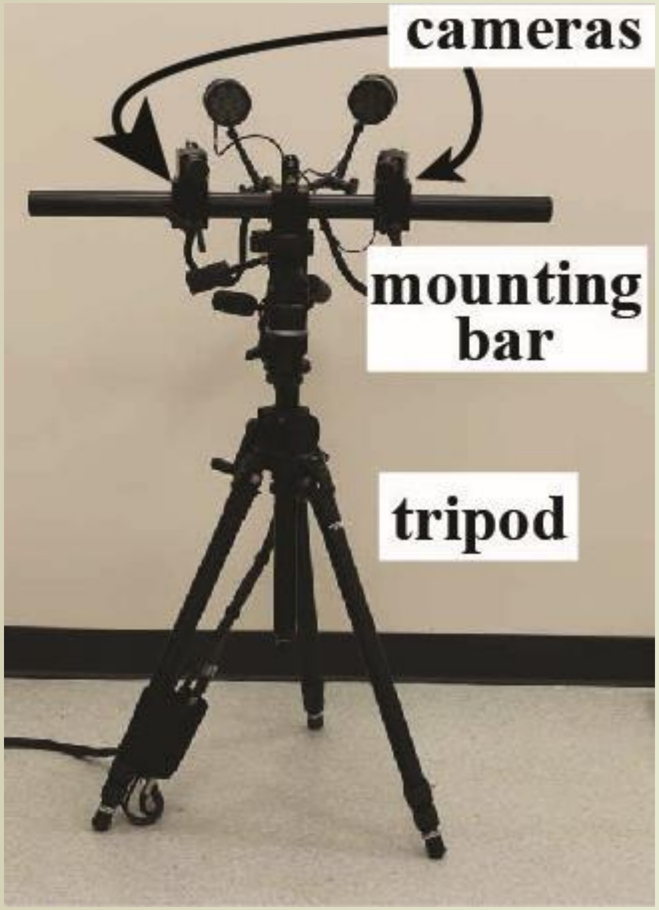
ρ_s – reinforcement ratio, symmetric for longitudinal and transverse rebar

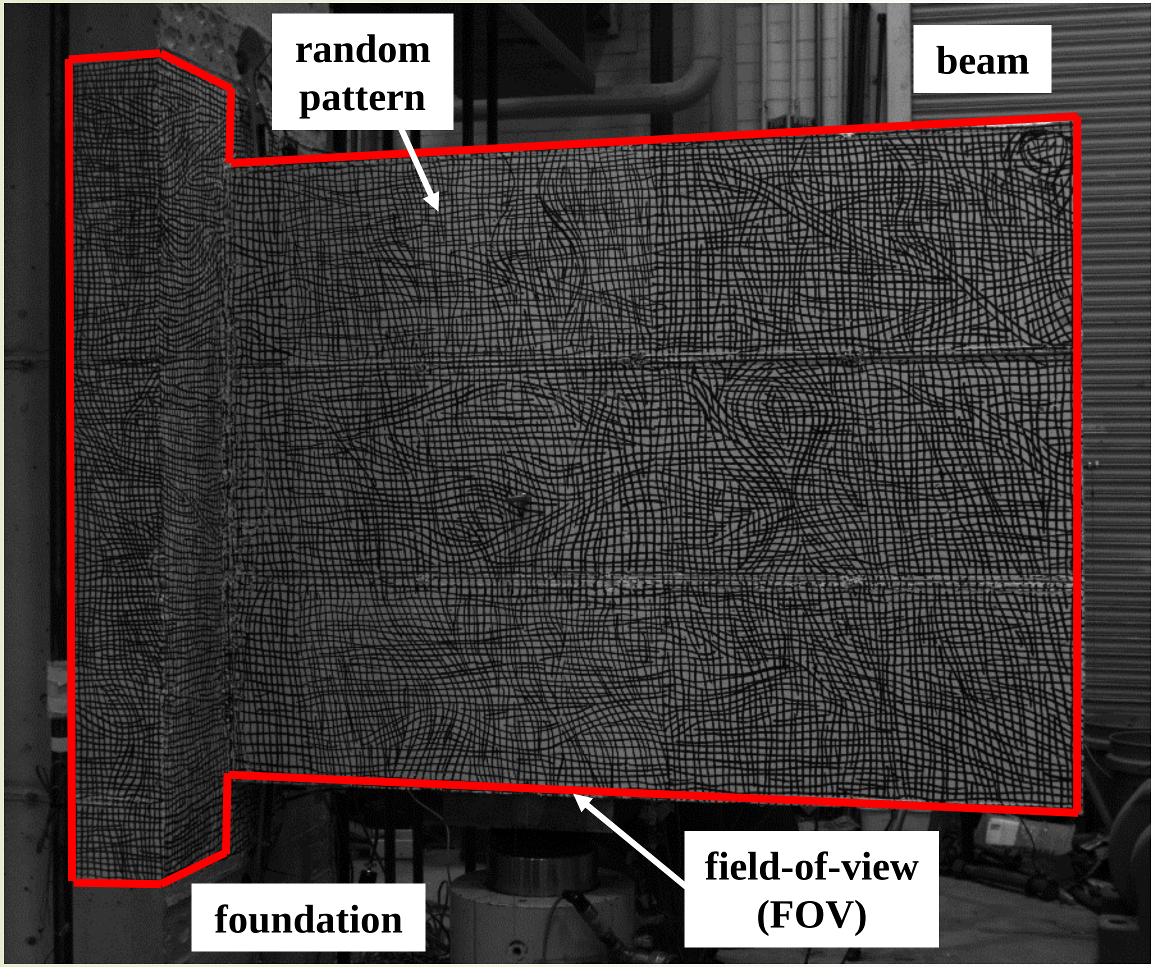
4. Conventional Instrumentation

Type	Number
pressure transducer	2
string potentiometer	9
linear potentiometer	8
inclinometer	4
strain gauge	42
TOTAL	**65**



4. 3D Digital Image Correlation





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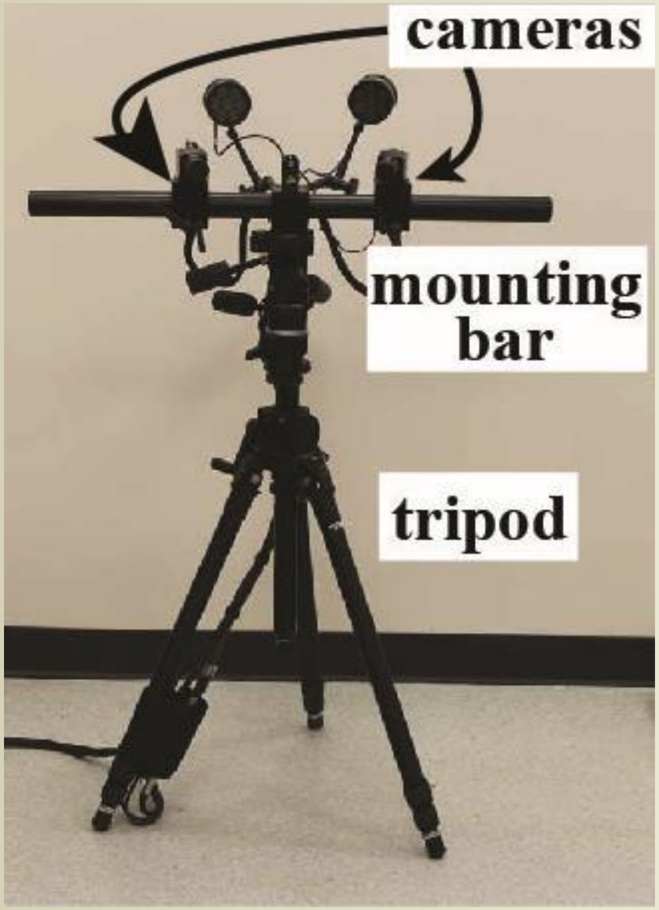
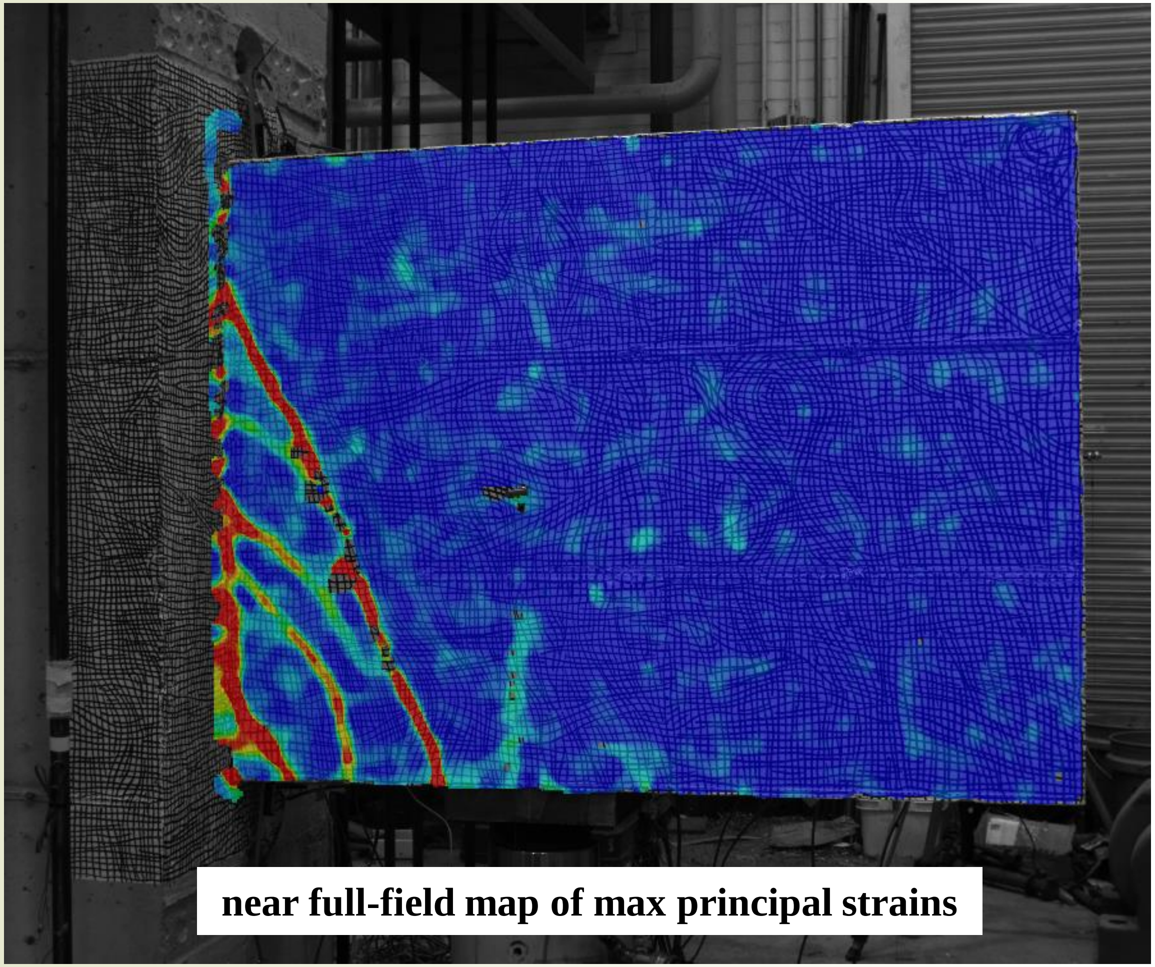
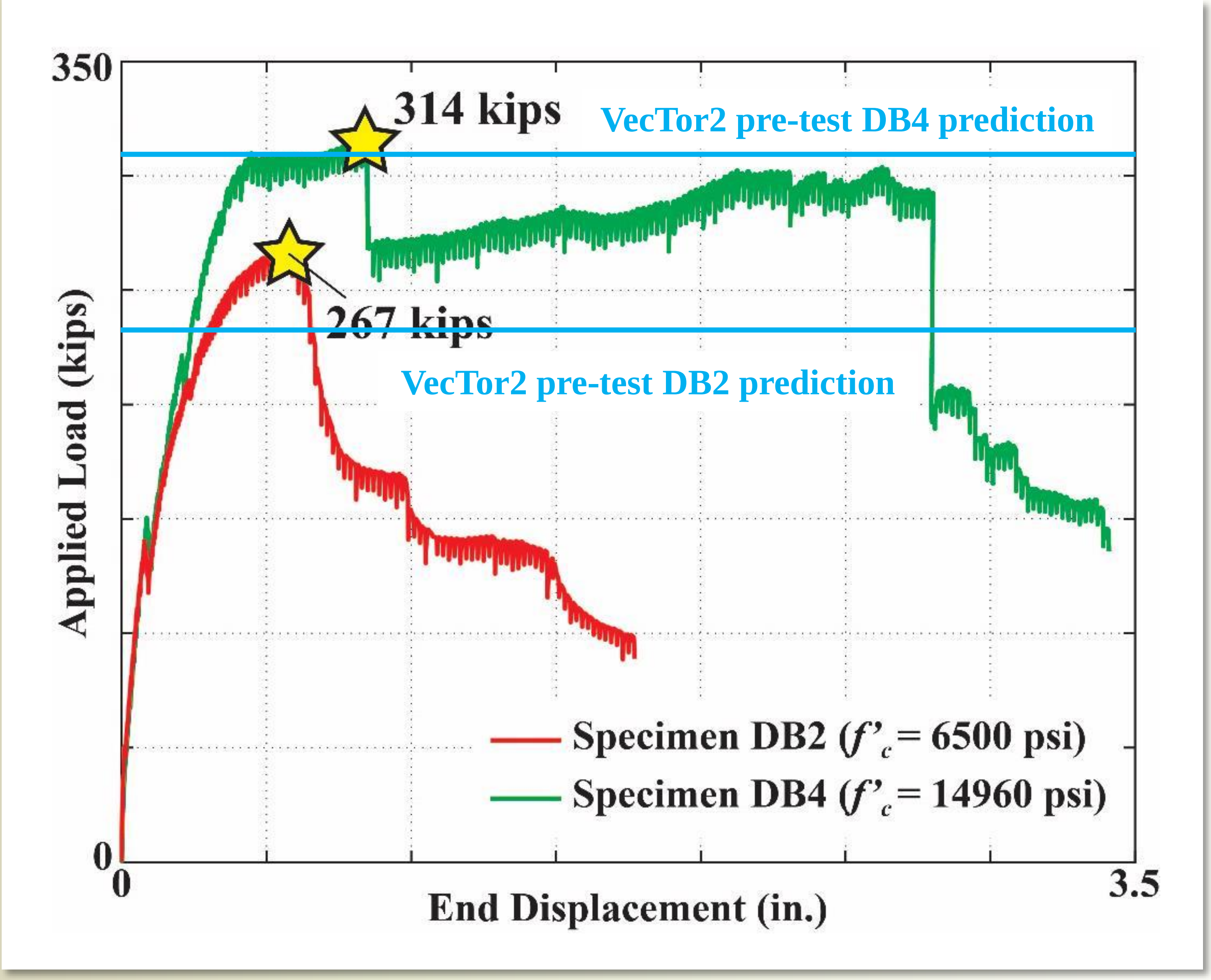


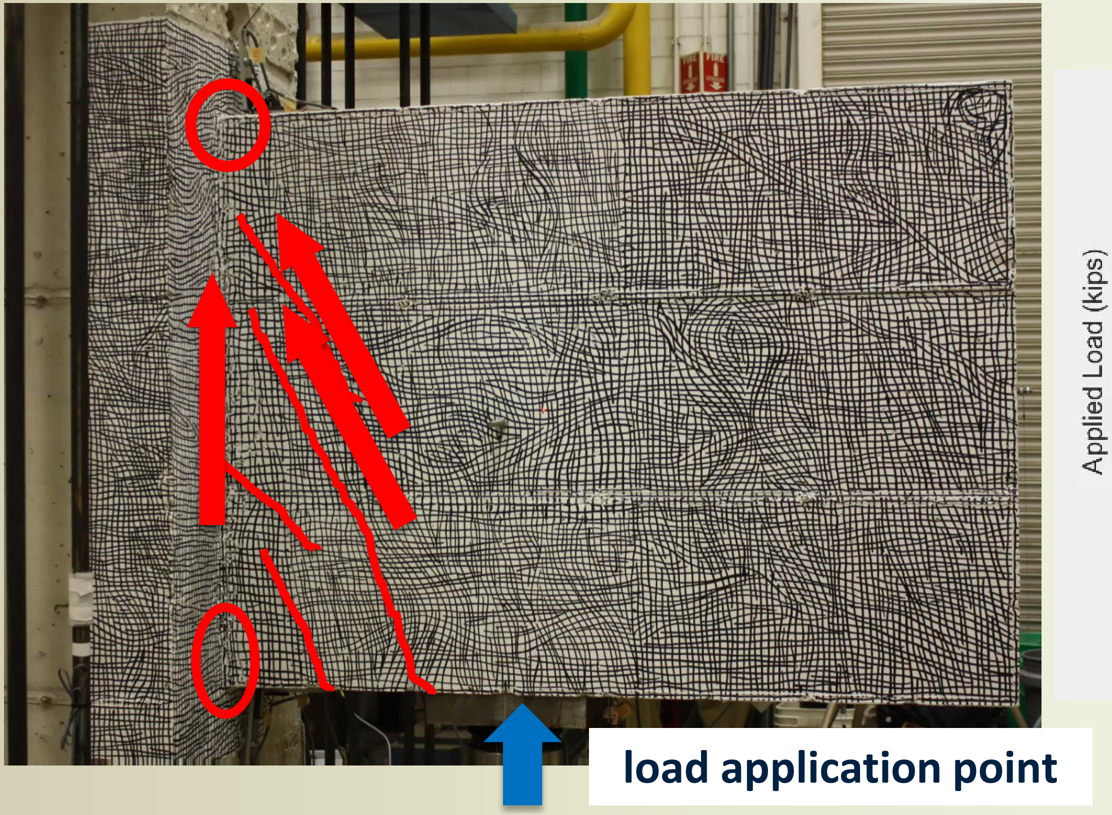


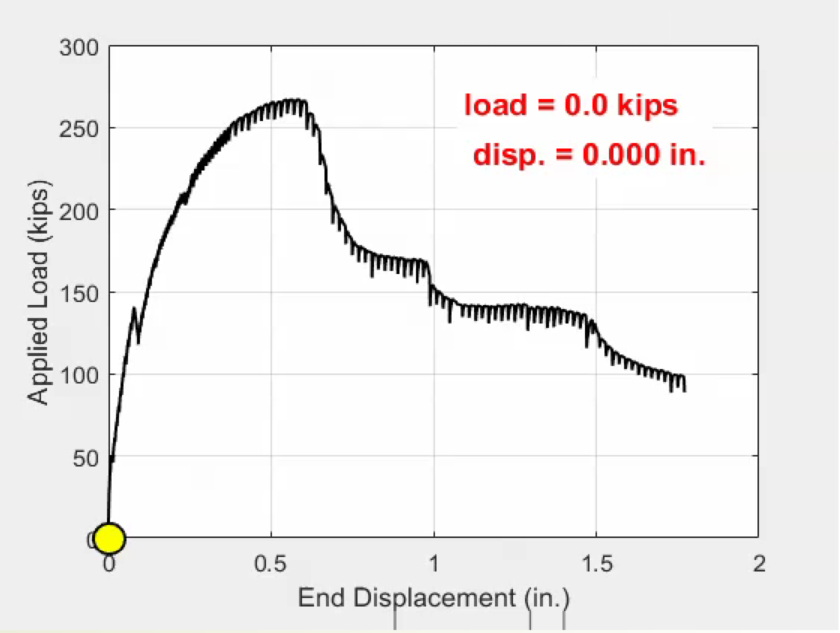
near full-field map of max principal strains

4. Specimen Response



4. DB2 (f'_c = 6500 psi, f_y = 133 ksi)





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

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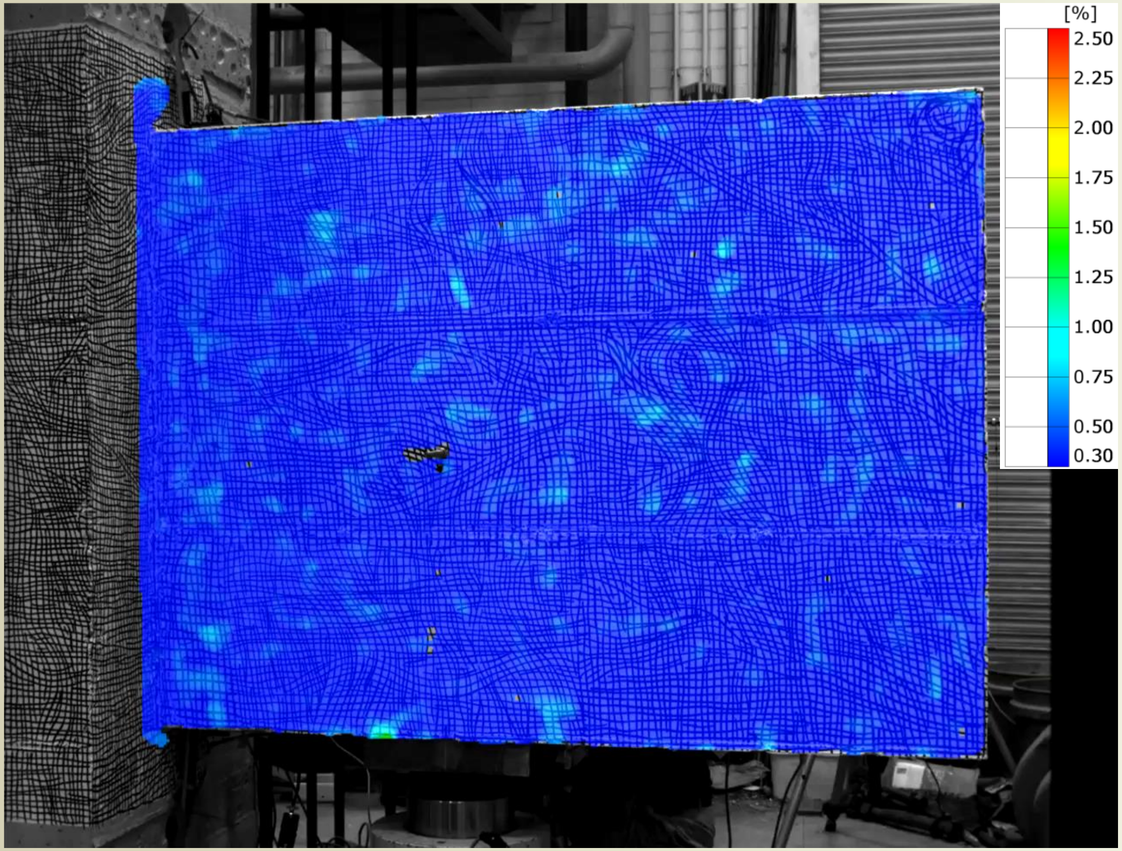

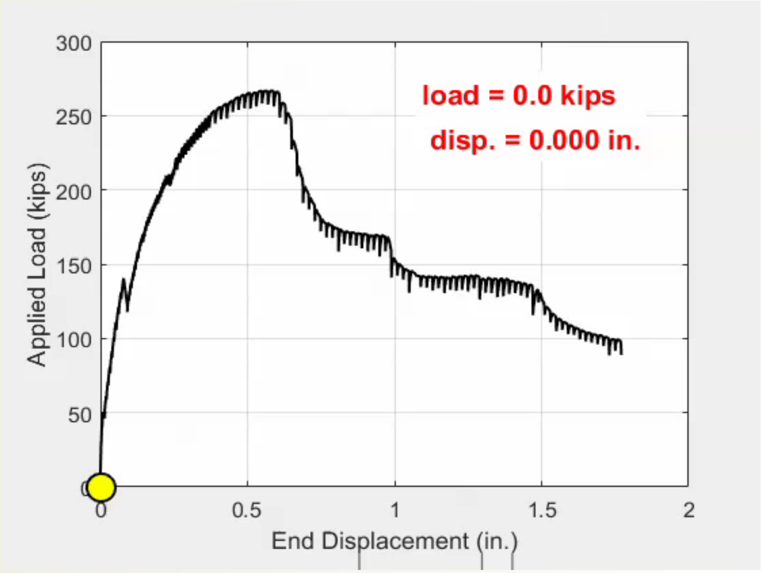

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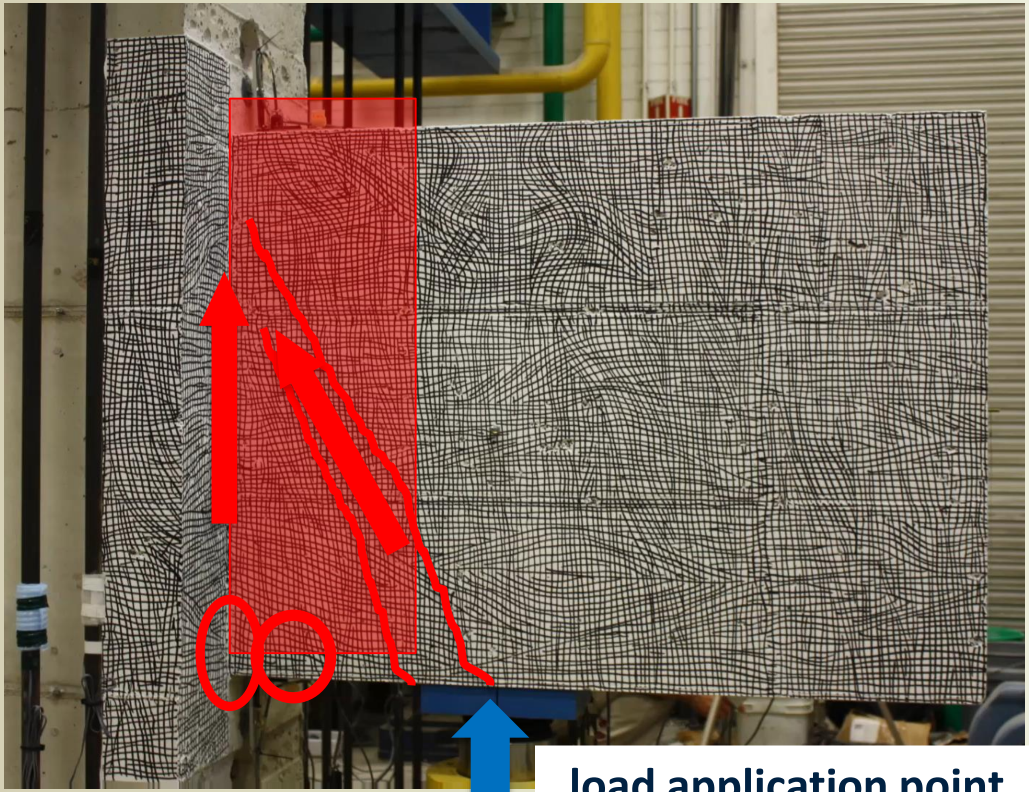
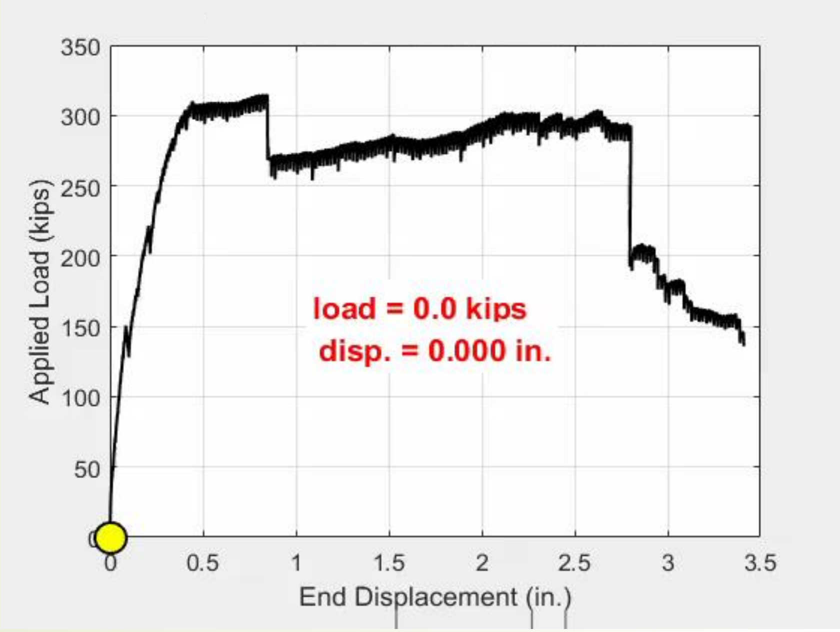
4. DB4 ($f'_c = 14960$ psi, $f_y = 133$ ksi)



load application point



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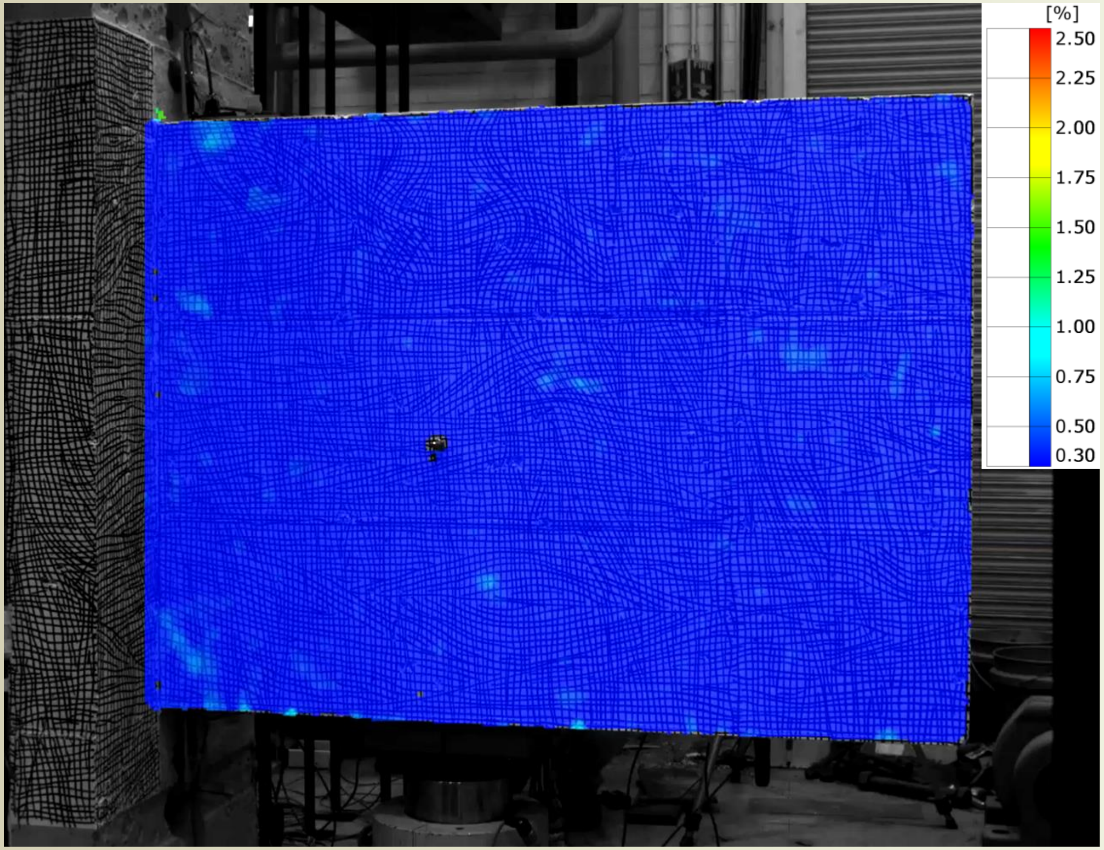

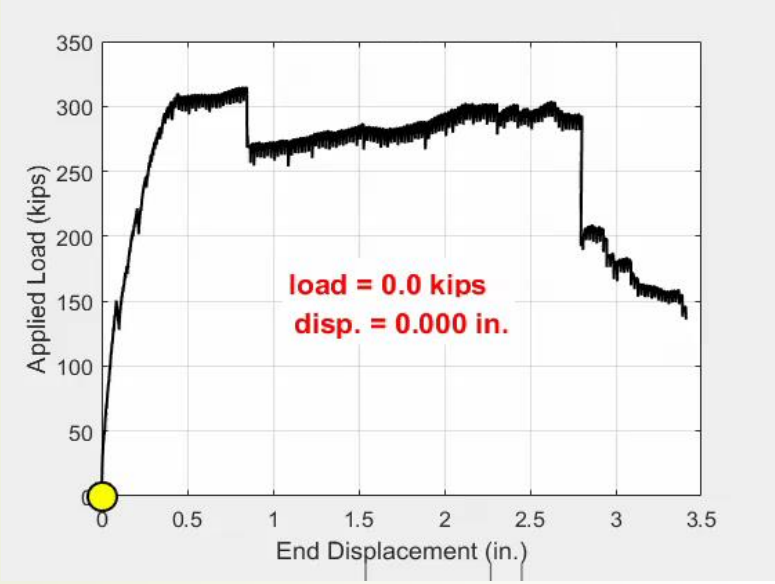

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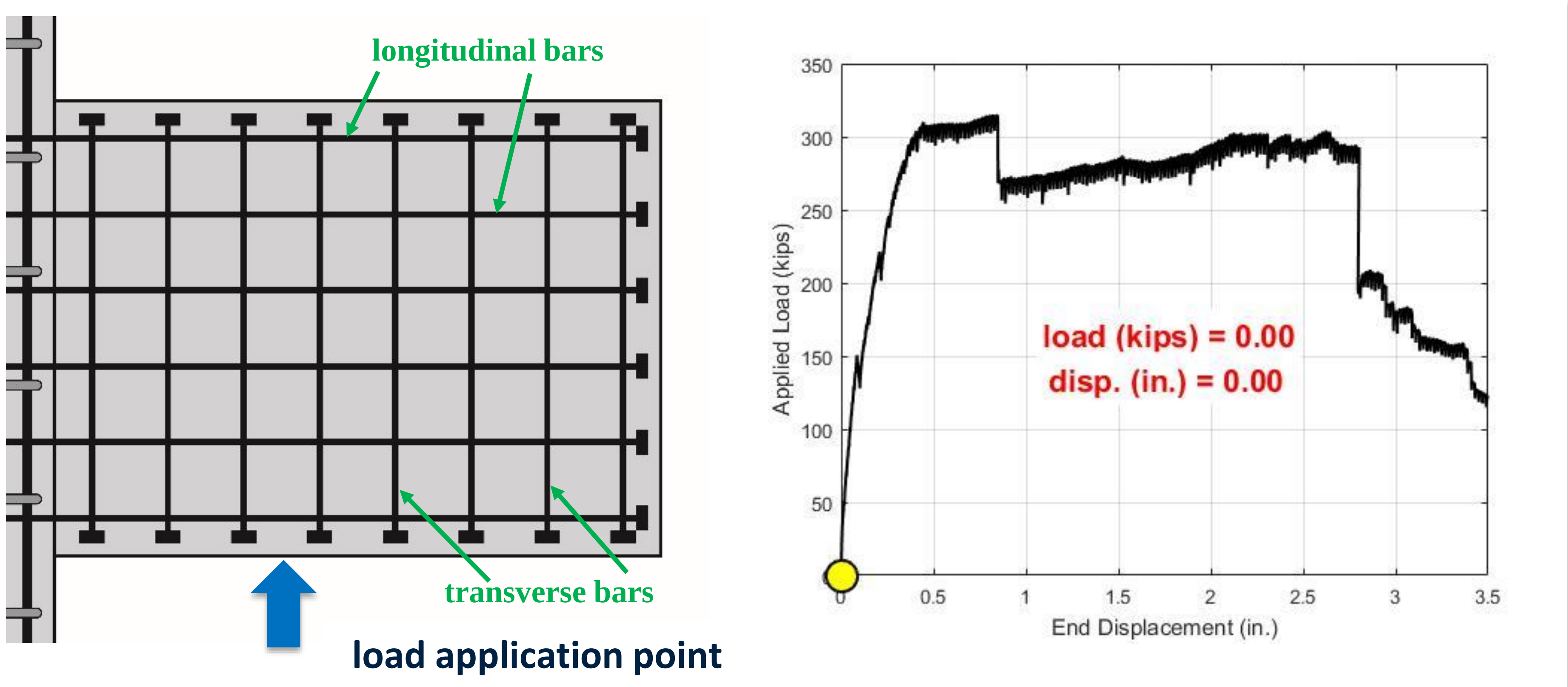
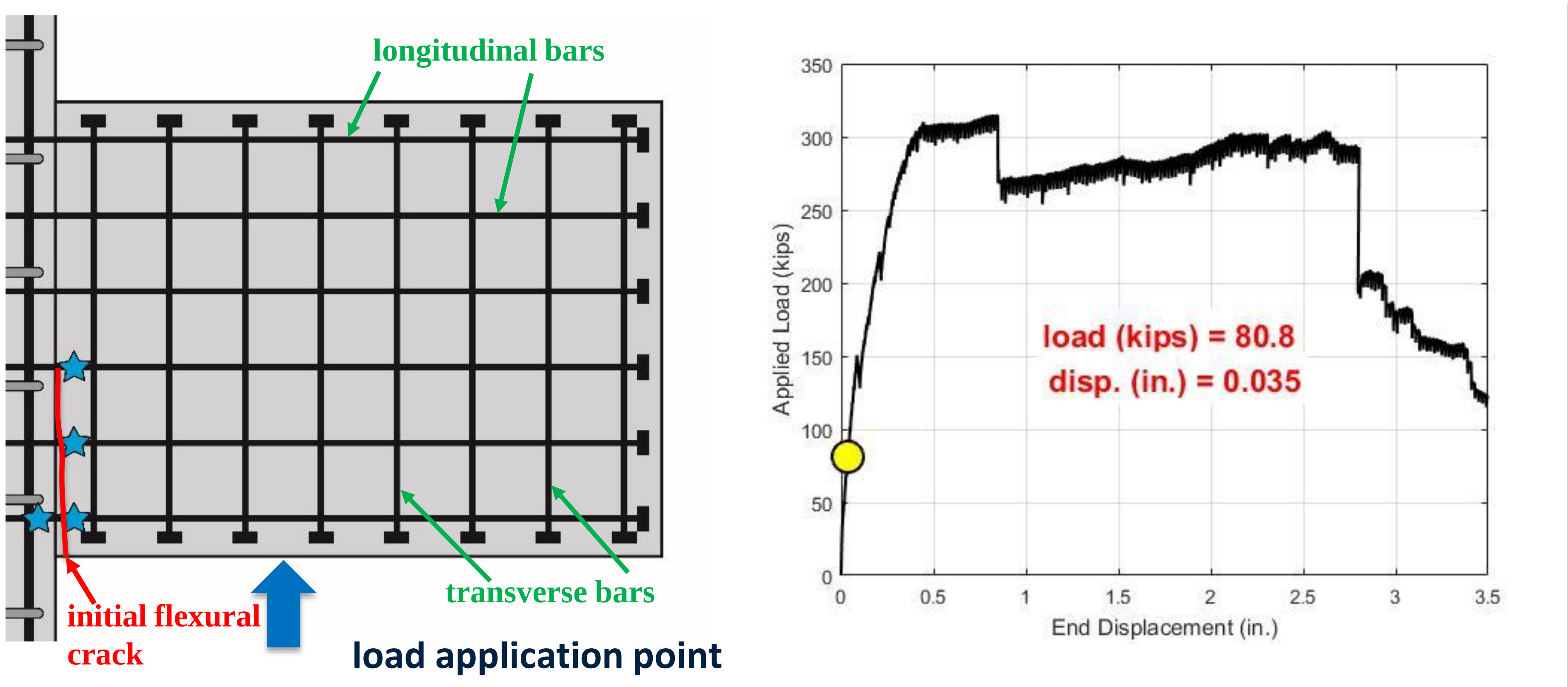


★ active tension strain

☆ tension yield (6.85 mε)

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

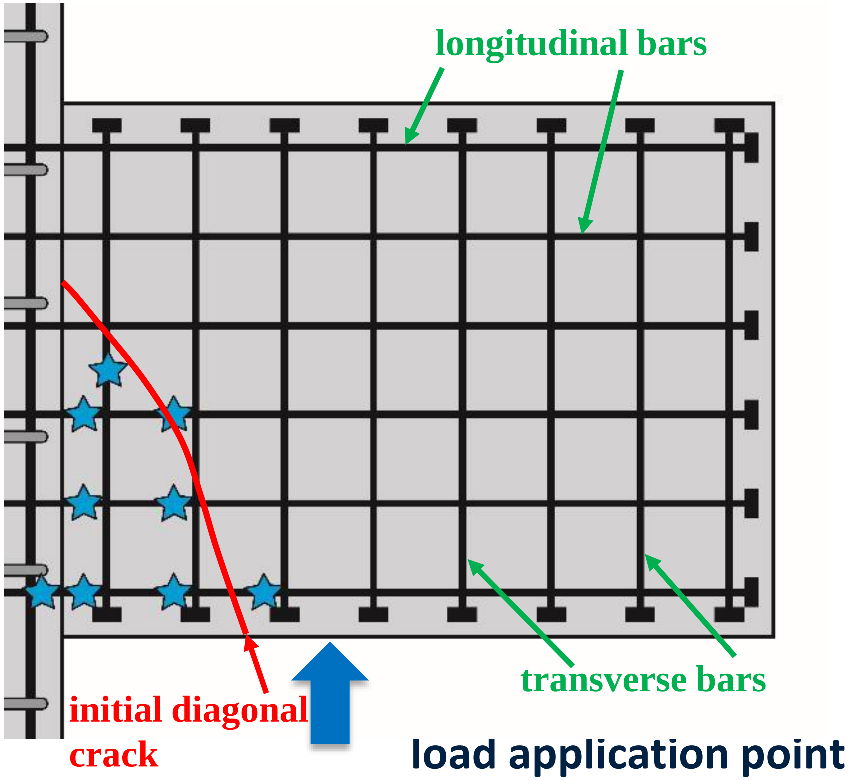


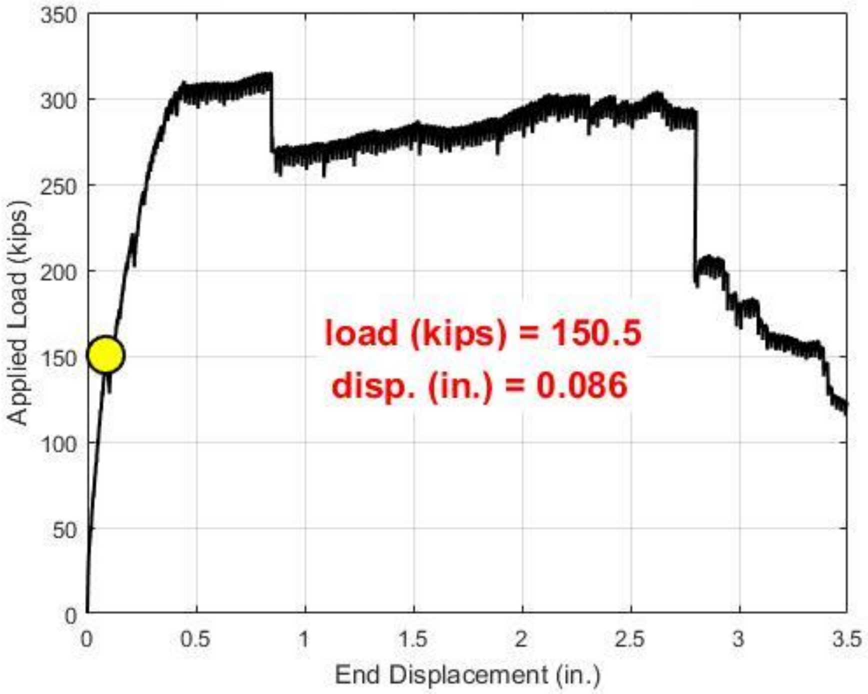
★ active tension strain

☆ tension yield (6.85 mε)

Initial flexural cracking, bottom three longitudinal layers active in tension

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



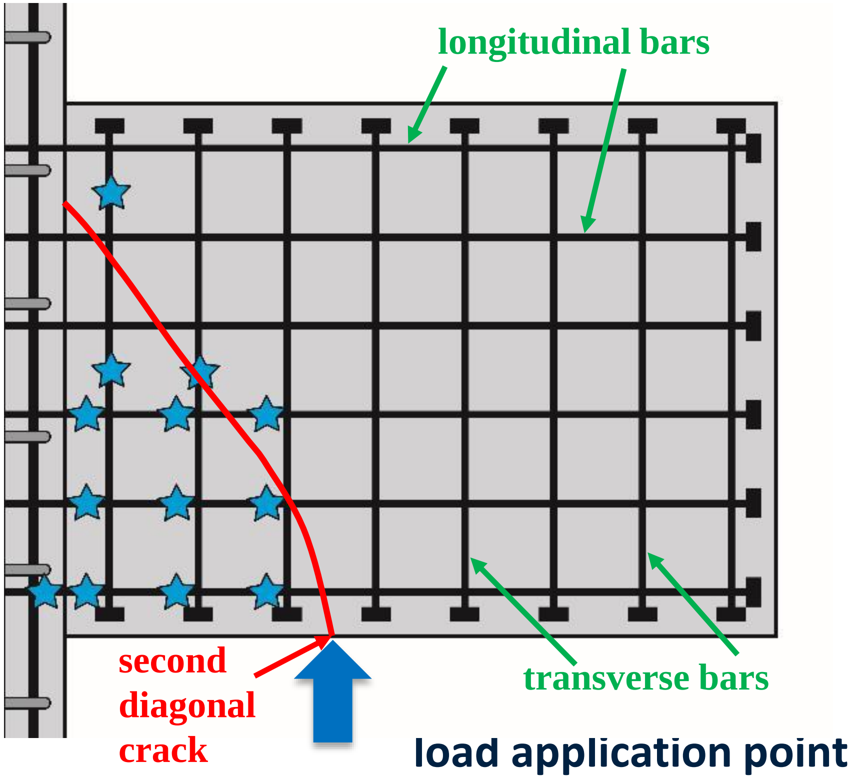


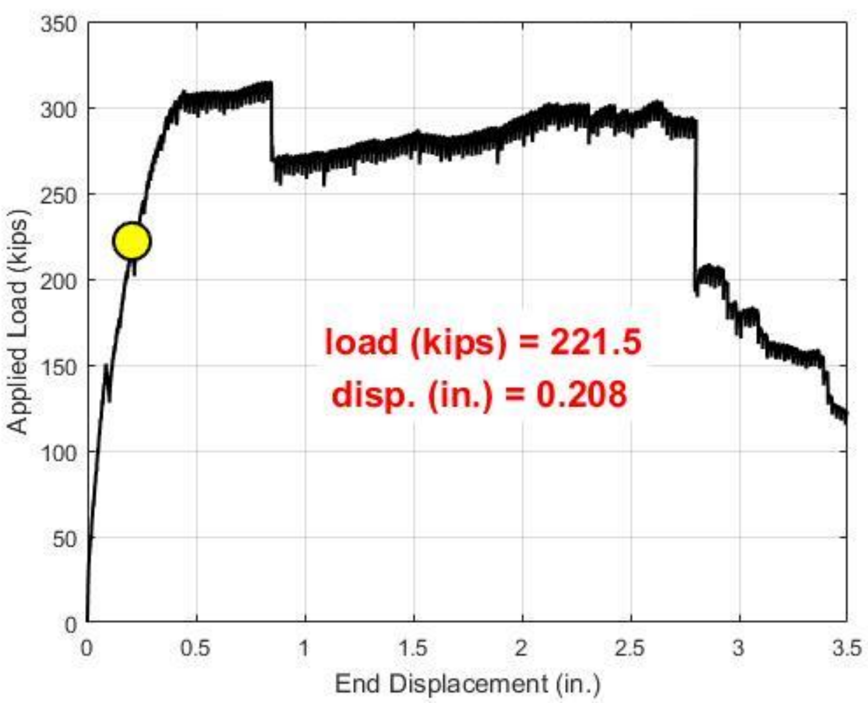
★ active tension strain

☆ tension yield (6.85 mε)

Bottom three longitudinal layers and closest transverse layer to foundation strain to arrest diagonal crack

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



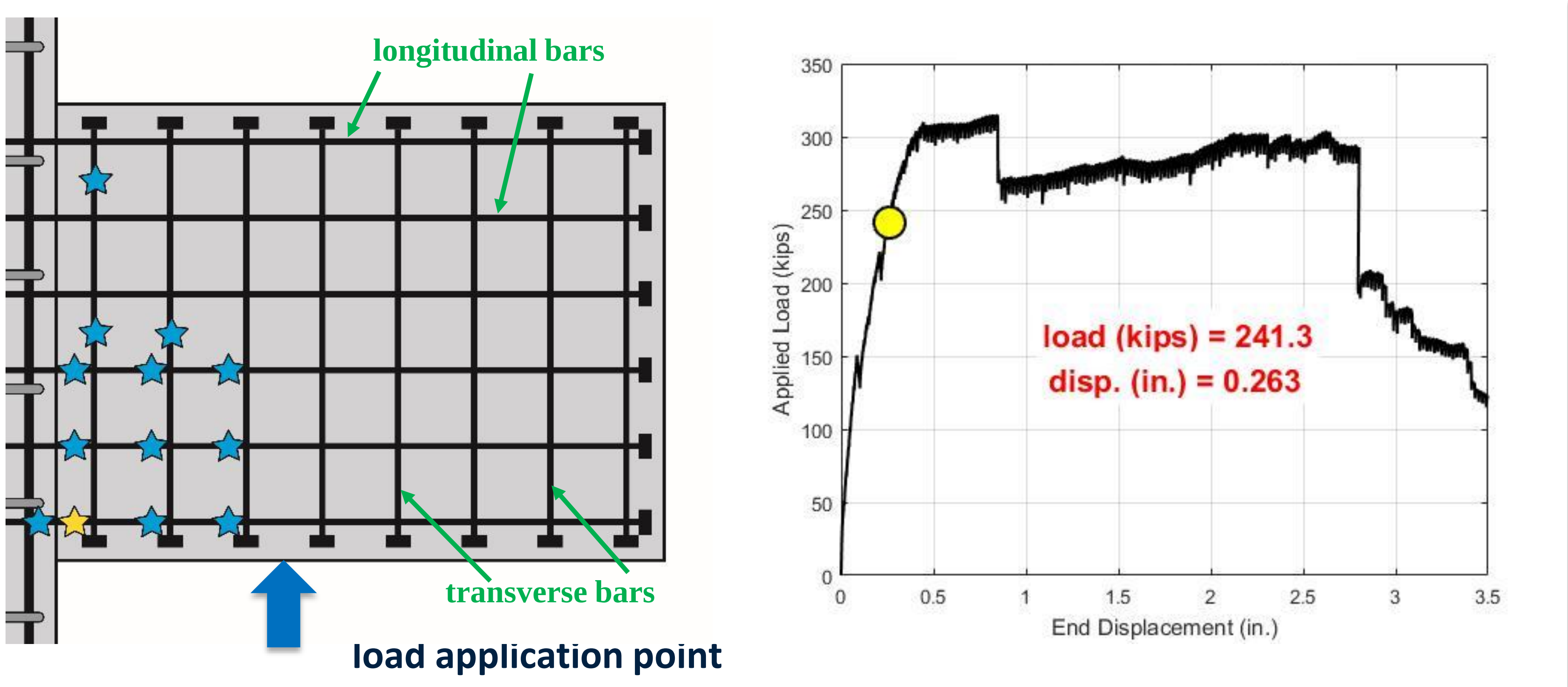


★ active tension strain

☆ tension yield (6.85 mε)

Two transverse bar layers and two longitudinal bar layers above the bottom experience strain increase

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

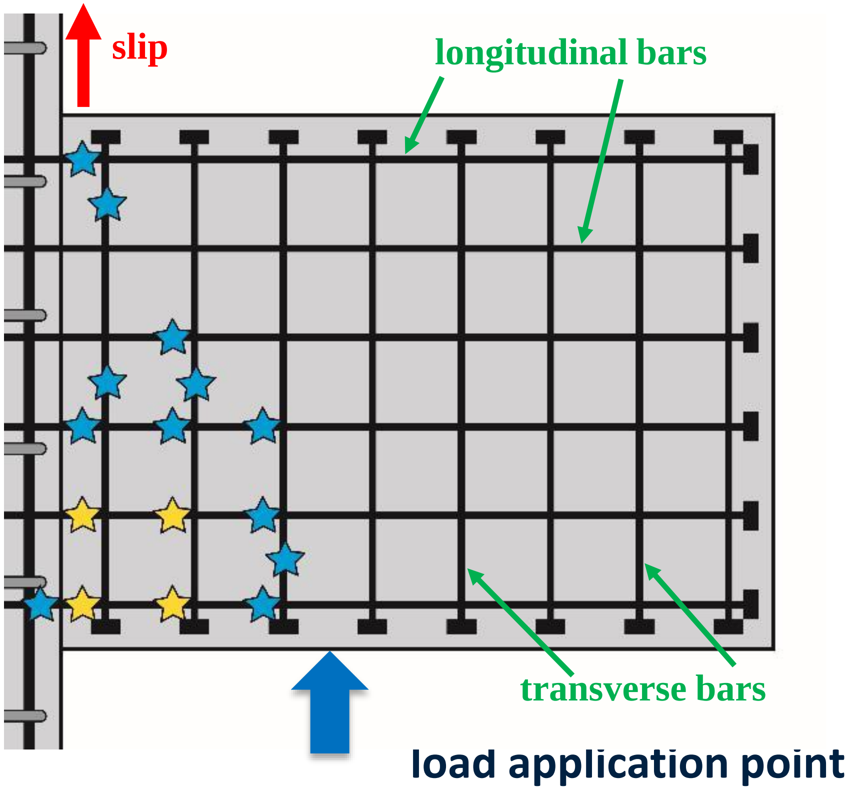


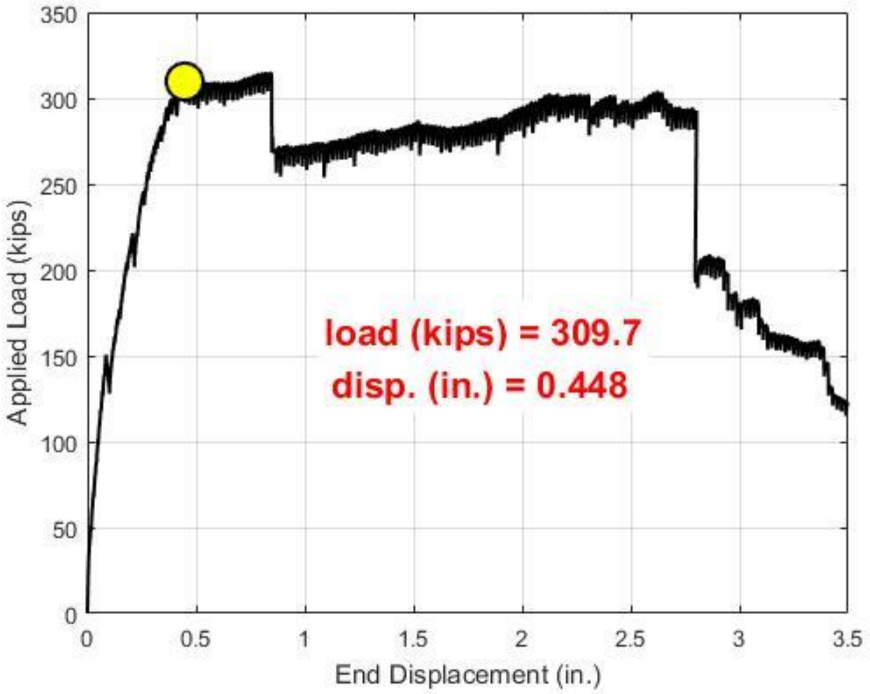
★ active tension strain

☆ tension yield (6.85 mε)

Initiation of longitudinal reinforcement yielding

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





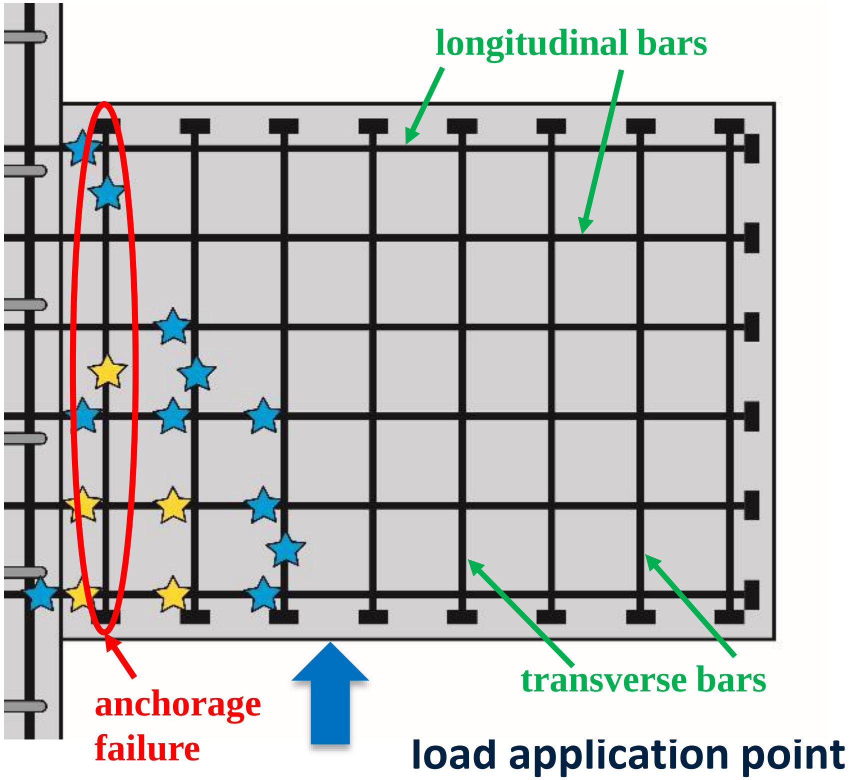
★ active tension strain

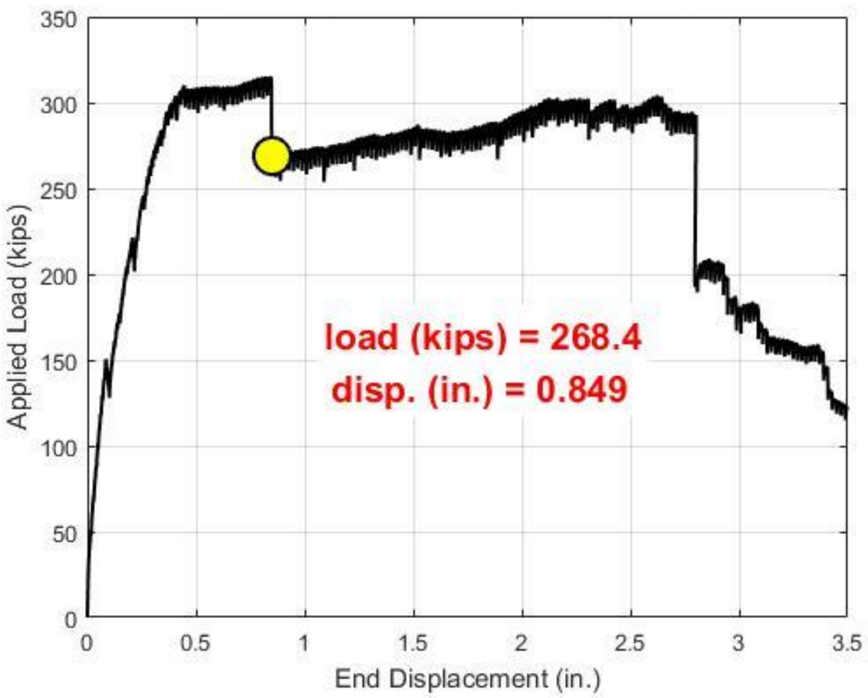
☆ tension yield (6.85 mε)

Slip at foundation interface

Extensive yielding of longitudinal reinforcement

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



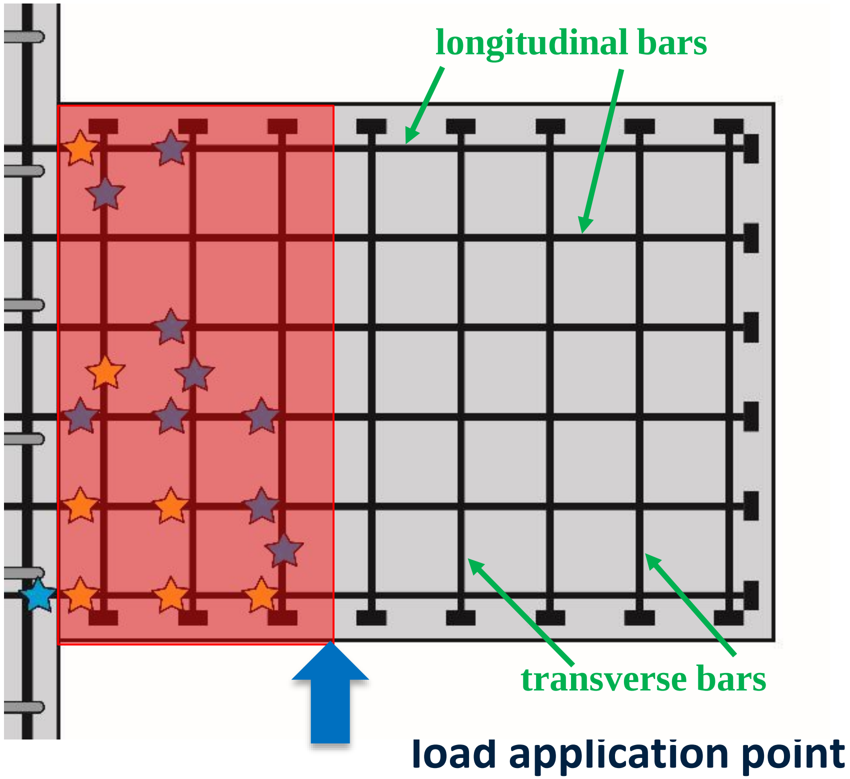


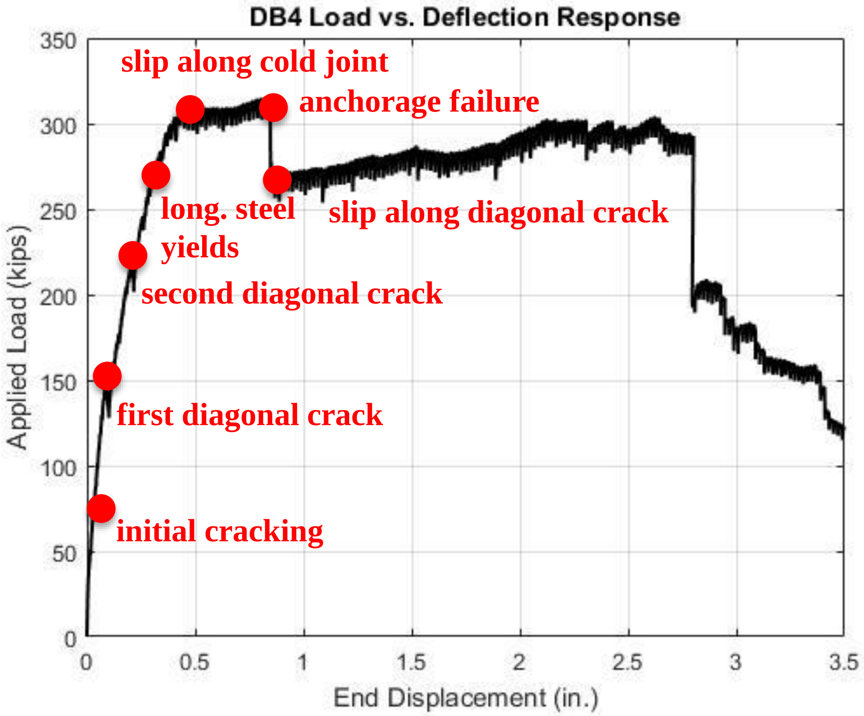
★ active tension strain

☆ tension yield (6.85 mε)

Anchorage failure of first transverse bar after yielding to arrest diagonal cracks

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



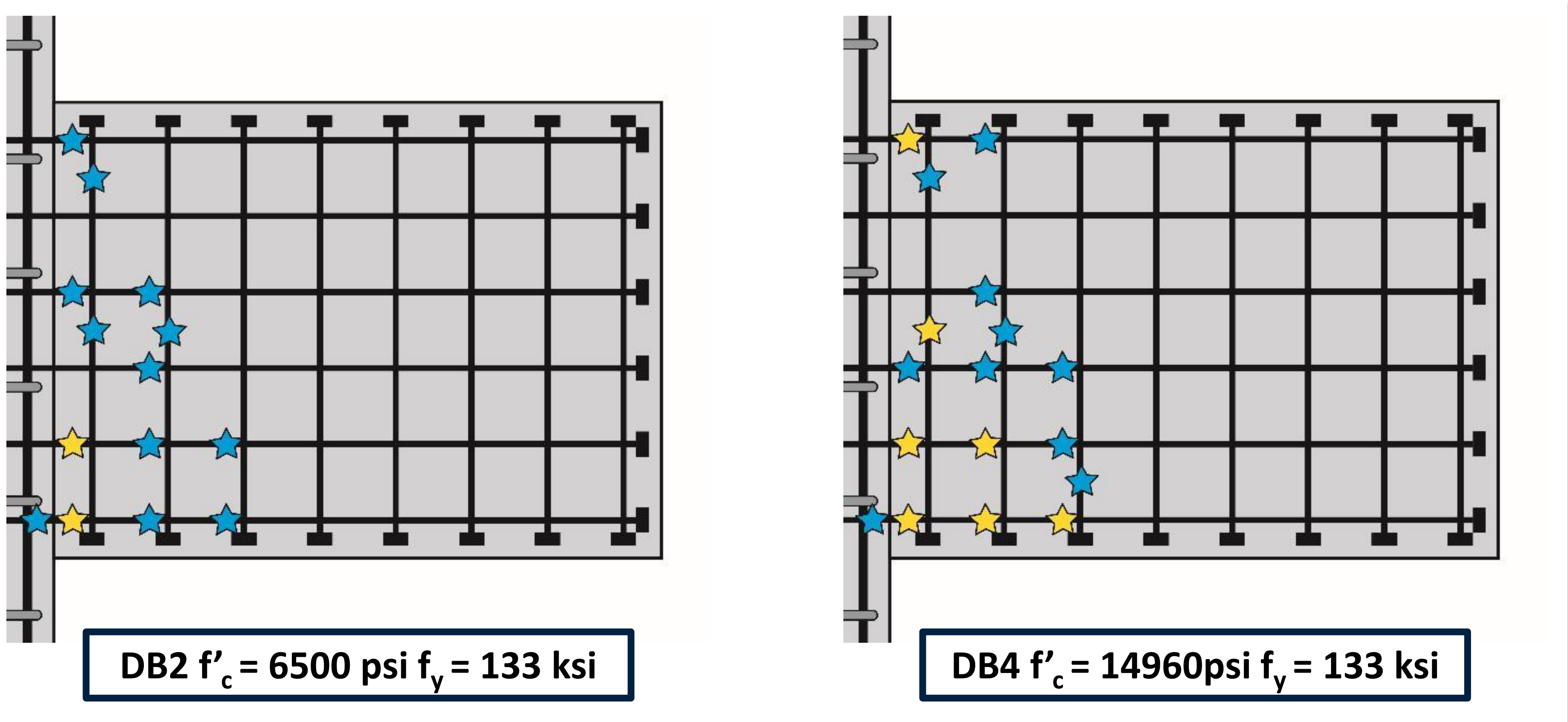


★ active tension strain

★ tension yield (6.85 mε)

Extensive concrete degradation

4. Strain Comparisons



DB2 f'_c = 6500 psi f_y = 133 ksi

DB4 f'_c = 14960psi f_y = 133 ksi

★ active tension strain

☆ tension yield (6.85 mε)

High-strength concrete able to better take advantage of higher yield strengths of reinforcement

4. Summary of Tests

- 17.6% increase in peak shear strength when increasing f'_c from 6500 psi to 14960 psi
- Significant increase in ductility due to increase in f'_c
- Pre-test analyses provided reasonable predictions for peak strength

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 moment-to-shear ratios and large reinforcement ratios; typical of nuclear concrete shear walls
- Largest economic and structural benefits when using Grade 100 rebar together with 10 ksi concrete

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  - Dayton Superior Corp.
  - HRC, Inc.
  - Sika Corp. U.S.

Questions?

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High Strength Materials Prefabrication

Sandia National Laboratories

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