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

The College of Engineering at the University of Notre Dame

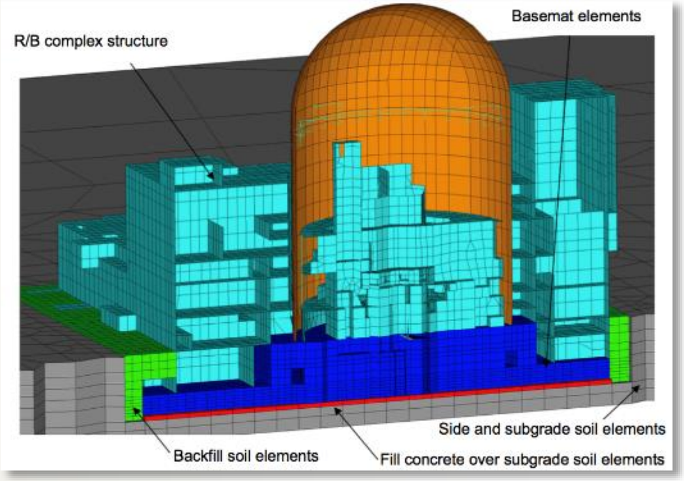
Primary Objective

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

1) High-strength reinforcing steel bars (rebar)
2) Prefabricated rebar assemblies, including headed anchorages
3) High-strength concrete

Scope

- Explore effectiveness, code conformity, and viability of existing high-strength materials
- Focus on 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.

Collaboration

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Molly Phillips

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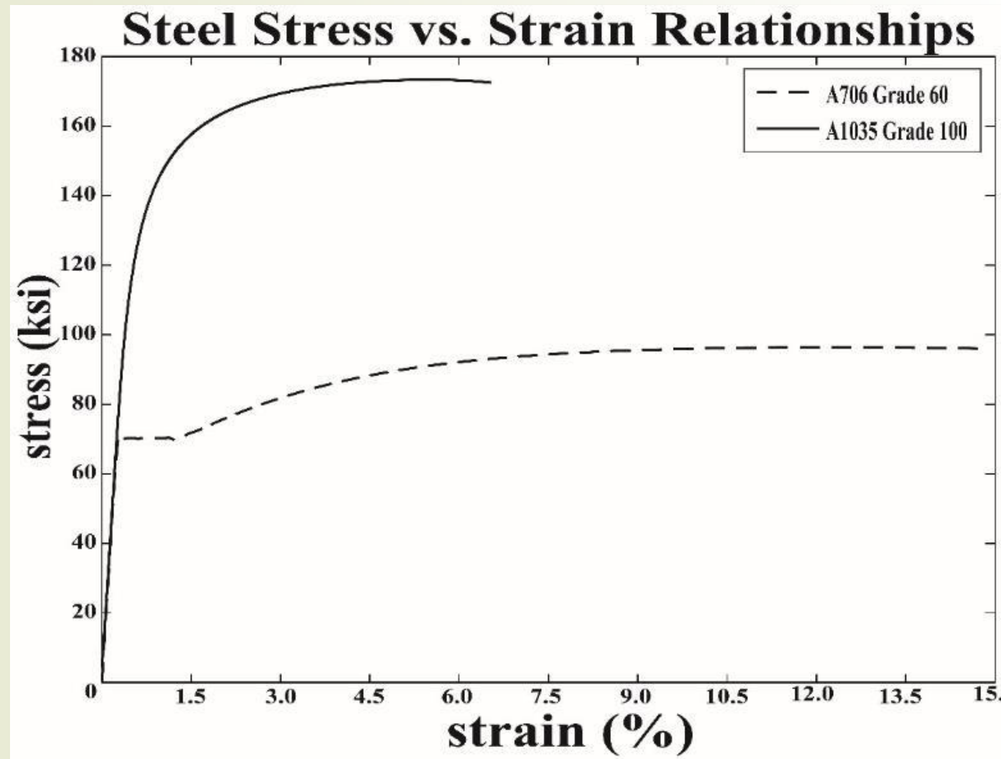
Project Tasks

1. Evaluation of High-Strength Materials
   - Limit-benefit Analysis
   - Cost-benefit Analysis
2. Evaluation of Prefabricated Rebar Cages
3. Optimization, Modeling, and Design
   - Pre-test Analyses
4. Experimental Testing
   - Deep Beam (Wall Slice) Specimens
   - Shear Wall Specimens
5. Design/Modeling/Construction Recommendations

1. High-Strength Materials: Scope

- High-strength rebar (up to Grade 120) with high-strength concrete (up to 15 ksi compressive strength)
- Concrete strength of 5 ksi typical in current practice
- ACI 349 limits headed bars and shear reinforcement to Grade 60



1. High-Strength Materials

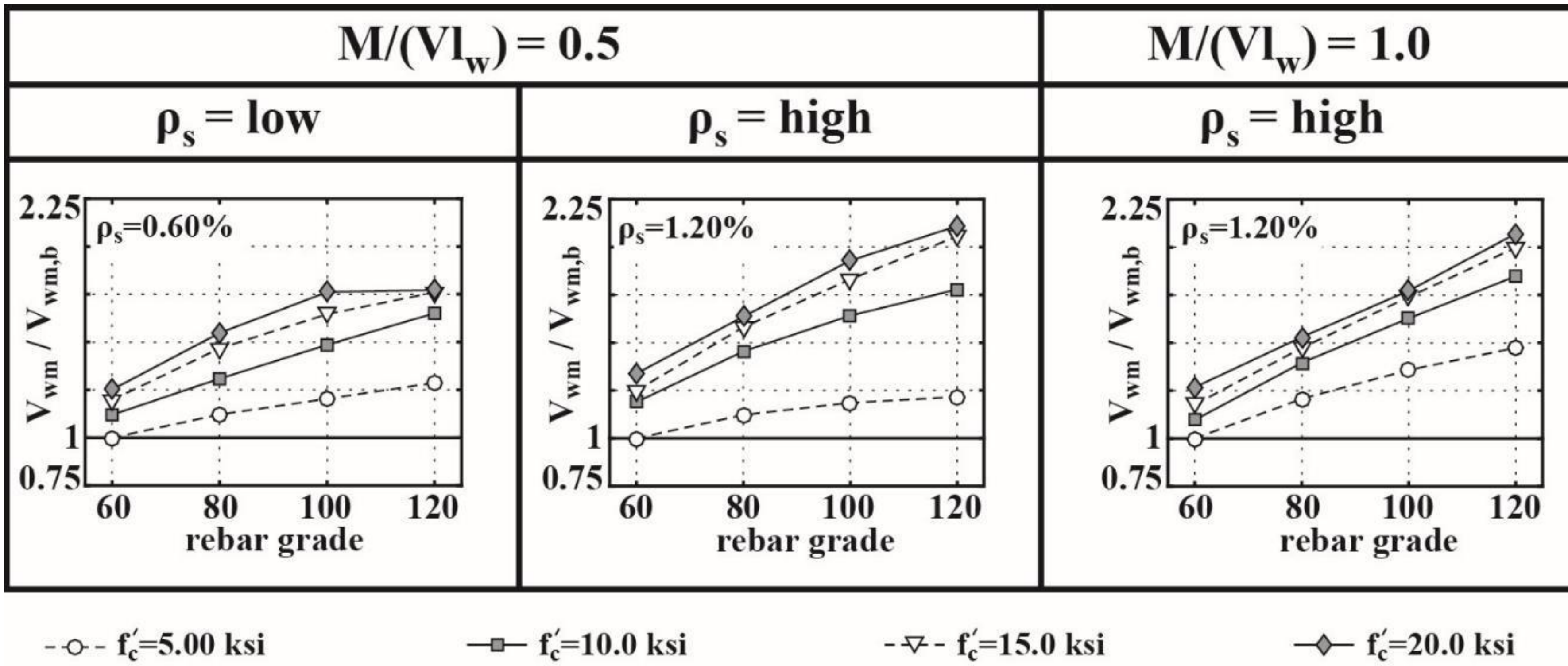
Numerical limit-benefit study to establish effects of high-strength materials on peak lateral strength of low-aspect-ratio shear walls:

- Parametric numerical investigation of 192 walls
- Peak strength predicted via 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**

1. High-Strength Materials

Results for 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

1. High-Strength Materials

Summary of results of limit-benefit analysis

- Combination of high-strength rebar with high-strength concrete resulted 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

Barbachyn, SM, Devine, RD, Thrall, AP, and Kurama, YC "Effect of High-Strength Materials on Lateral Strength of Shear-Critical Reinforced Concrete Walls." *ACI Structural Journal*, Submitted May 2016

1. High-Strength Materials

Numerical cost-benefit study of economic effectiveness of high-strength materials for low-aspect-ratio 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

1. High-Strength Materials

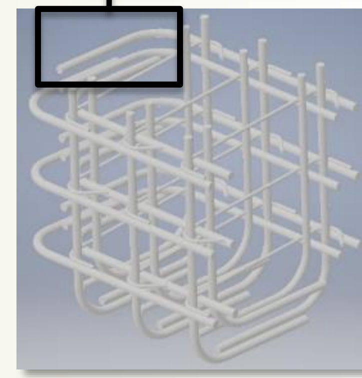
Summary of results of <u>cost-benefit</u> analysis:

- 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
- Rebar grades greater than 100 can lead to decreased economic benefits due to the increased unit cost

2. Prefabricated Rebar

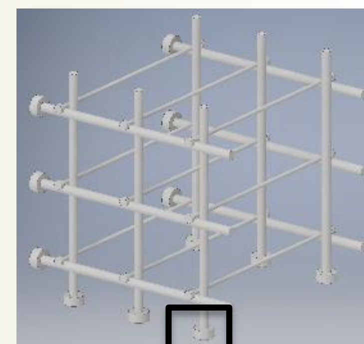
- Evaluating prefab rebar cages for:
  - transportability
  - liftability
  - modularity
- Using mini-scale rapid prototyping

Most Congested (current)



Multiple layers of hooked Grade 60 bars

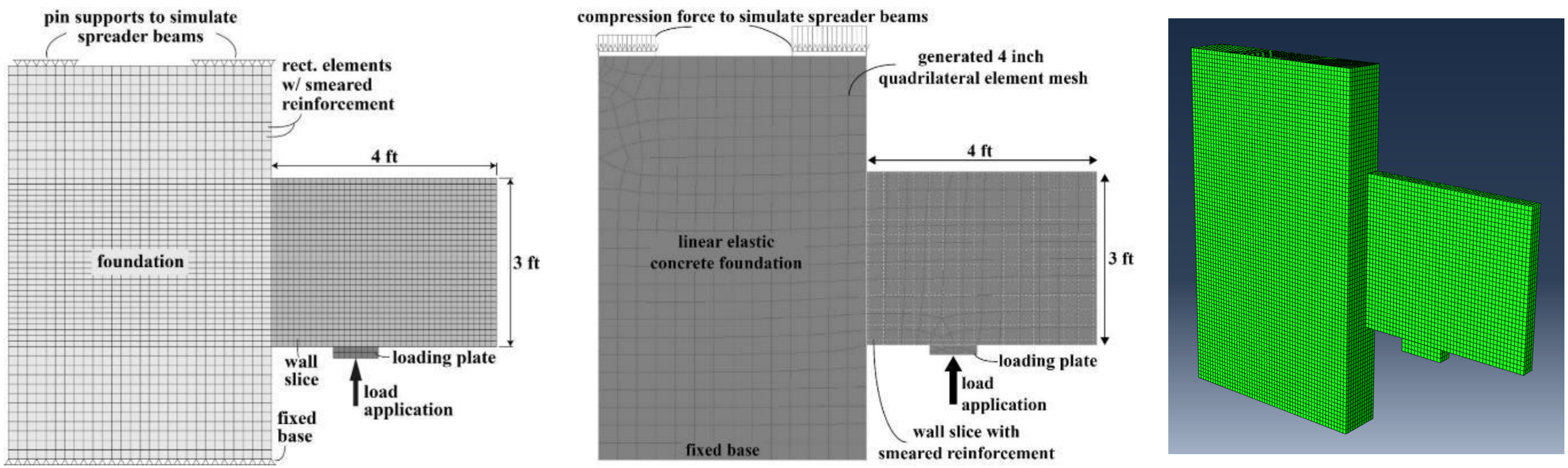
Fewer layers of <u>headed</u> high-strength bars



Least Congested (envisioned)

3. Optimization, Modeling and Design

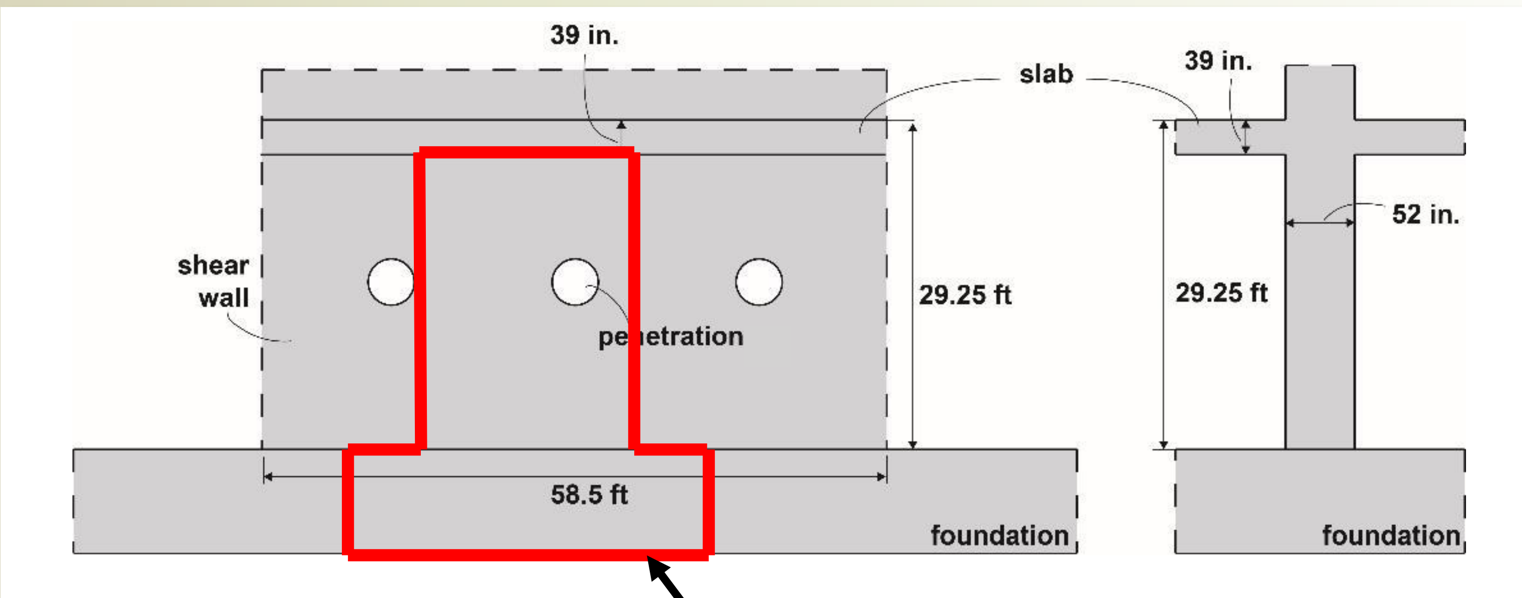
Pre-test Analyses of Deep Beam (Wall Slice) and Shear Wall Specimens in Vector2, ATENA, and ABAQUS



Vector2 ATENA ABAQUS

4. Experimental Testing

- “Generic wall” dimensions determined using publicly-available design control documents
- Provides basis for future deep beam and shear wall tests



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

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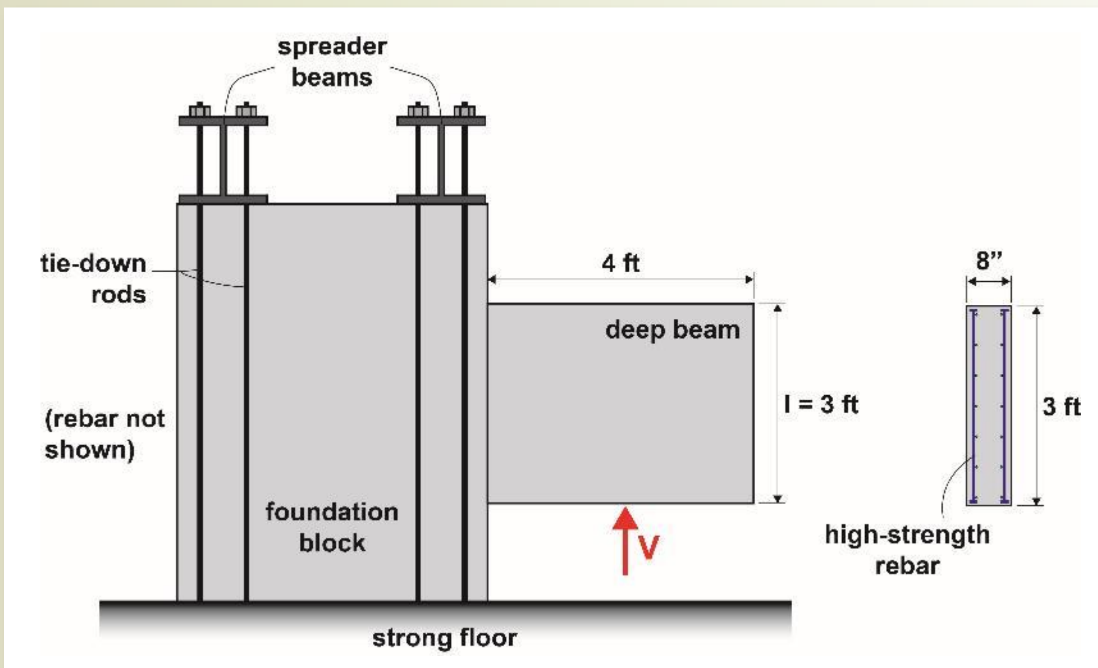
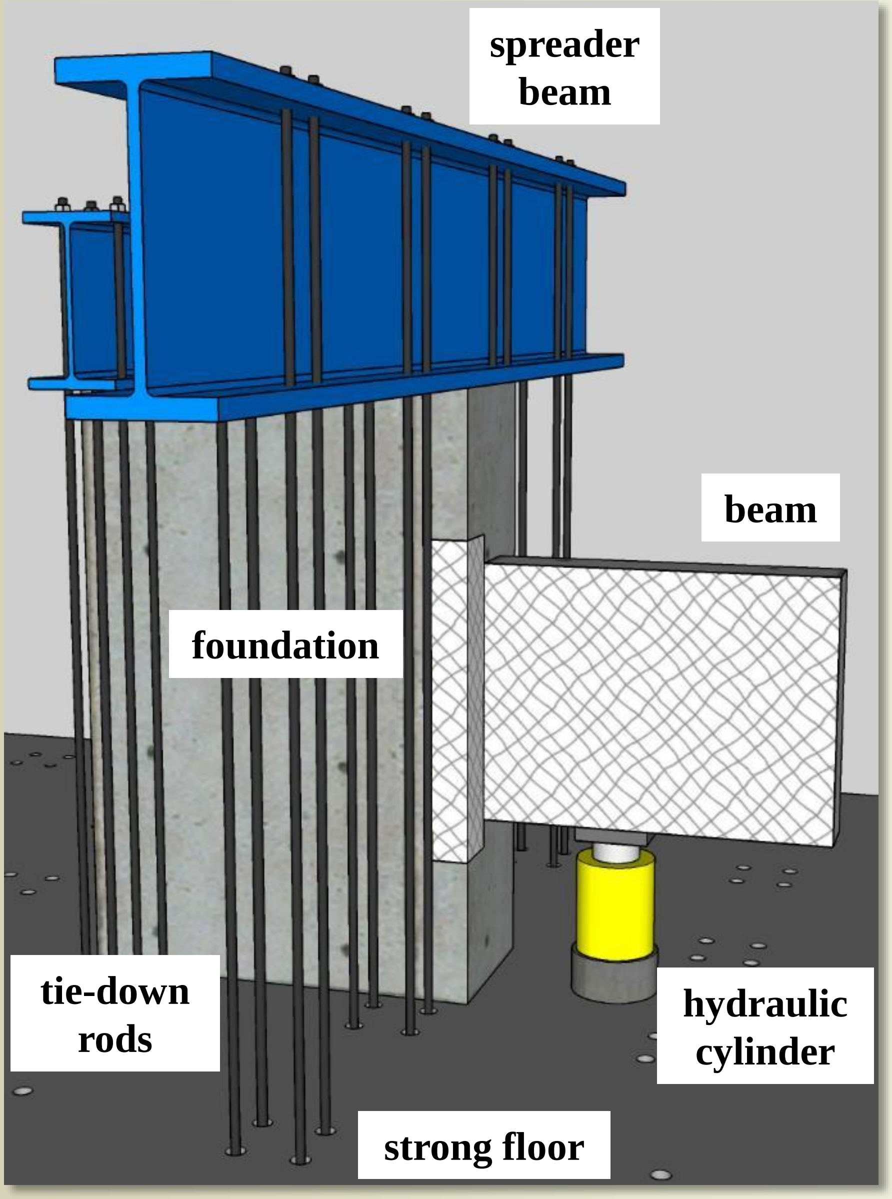
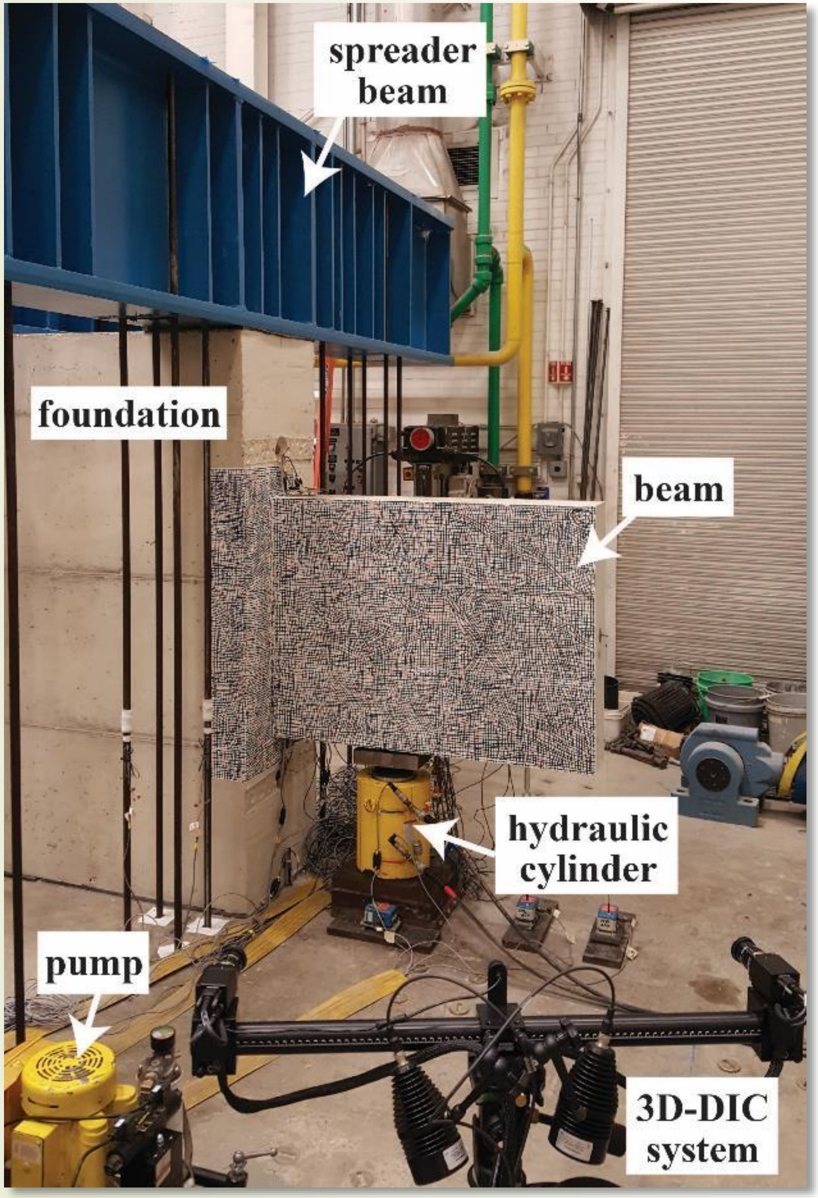
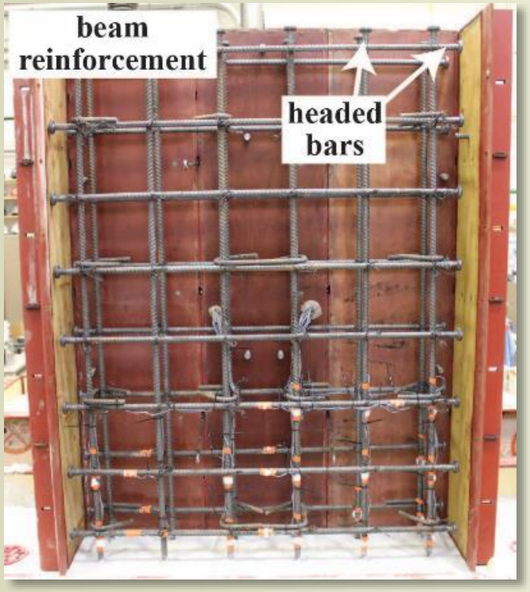


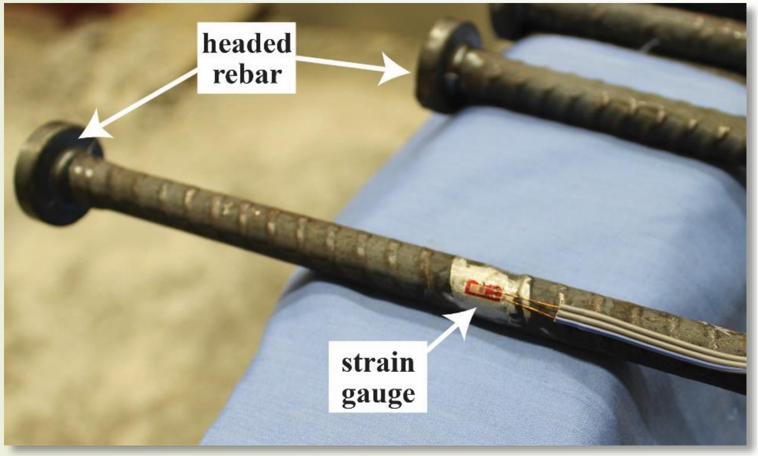
Deep Beam Test Setup

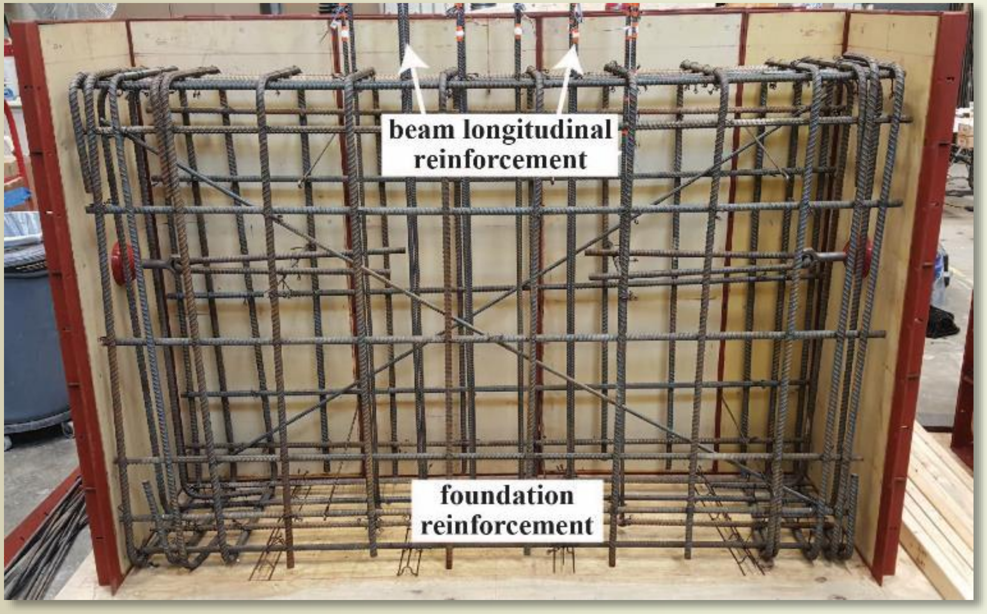


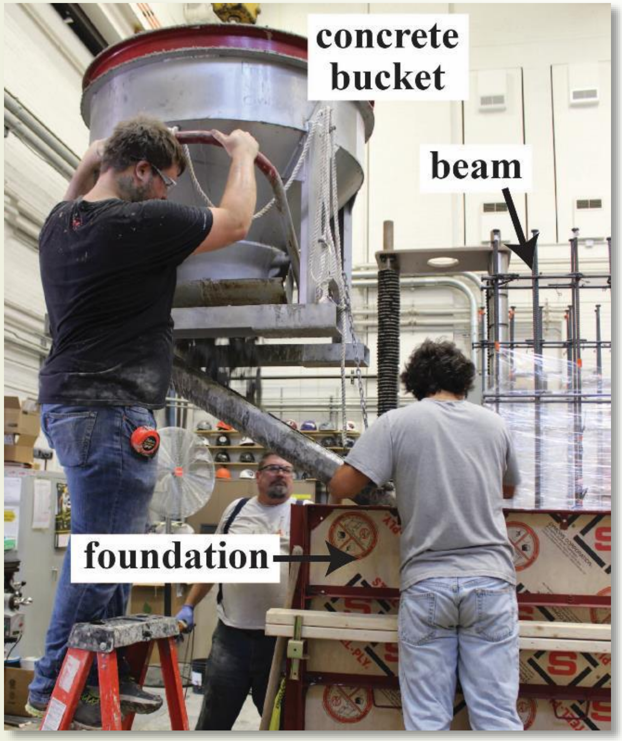


Deep Beam Construction









Deep Beam Construction

Normal-Strength Concrete

f'_c = 6500 psi

slump = 8 in.

High-Strength Concrete

f'_c = 14690 psi

slump = 8.75 in.

Deep Beam 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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<u>Definitions:</u> f'_c – concrete 28 day compressive strength
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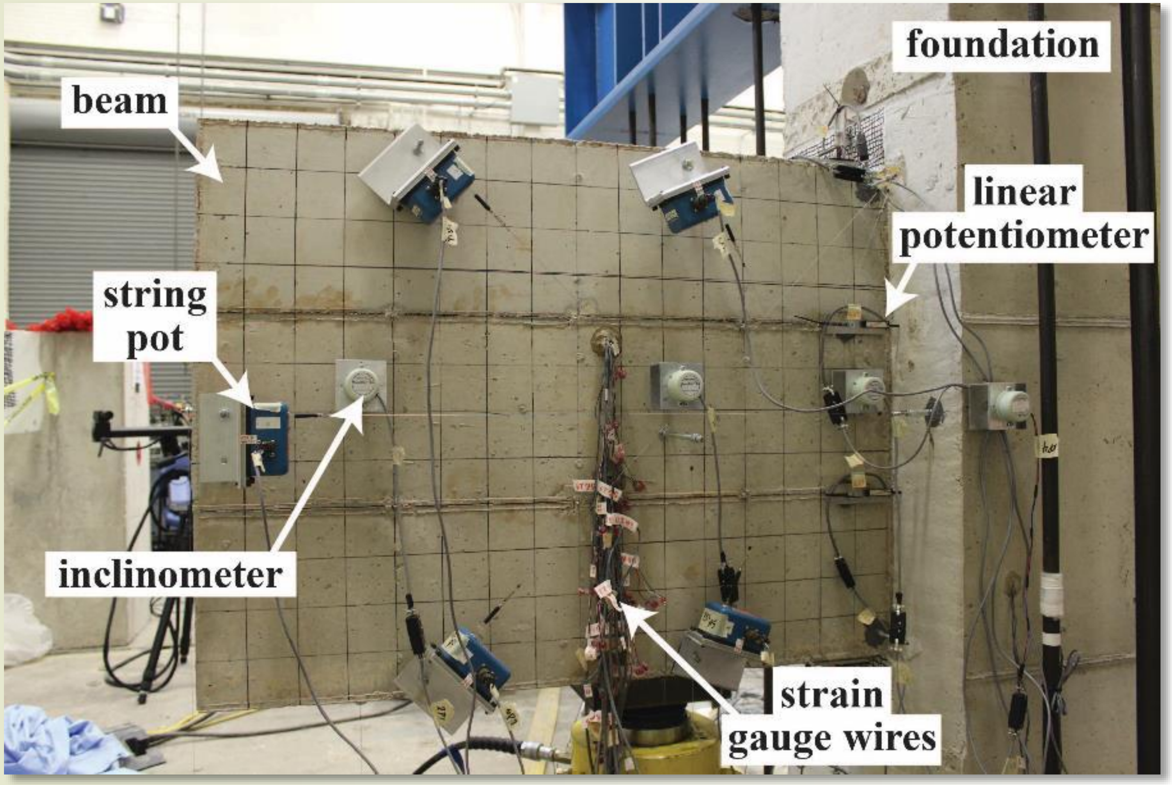
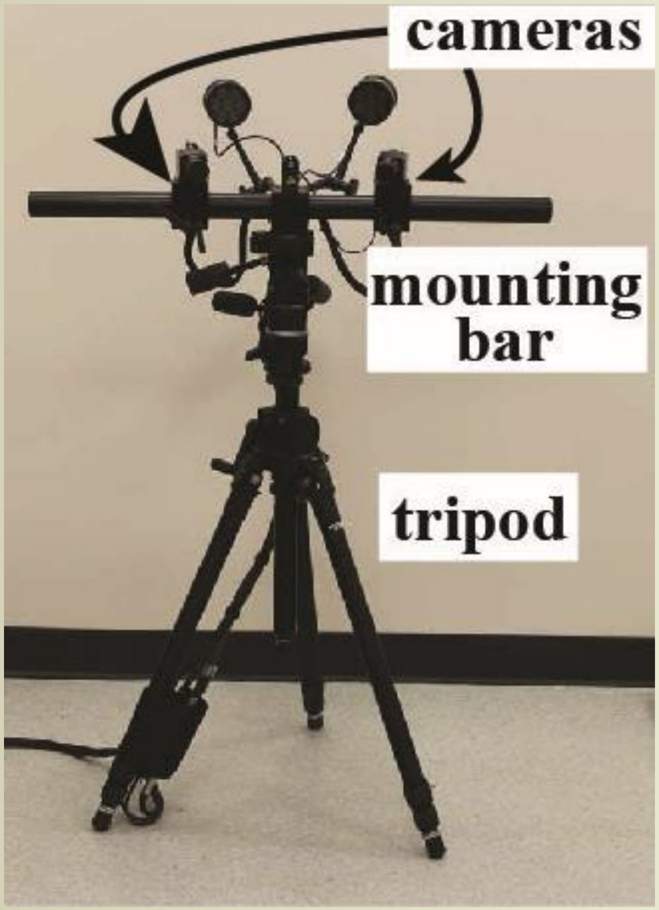
ρ_s – reinforcement ratio, symmetric for longitudinal and transverse rebar

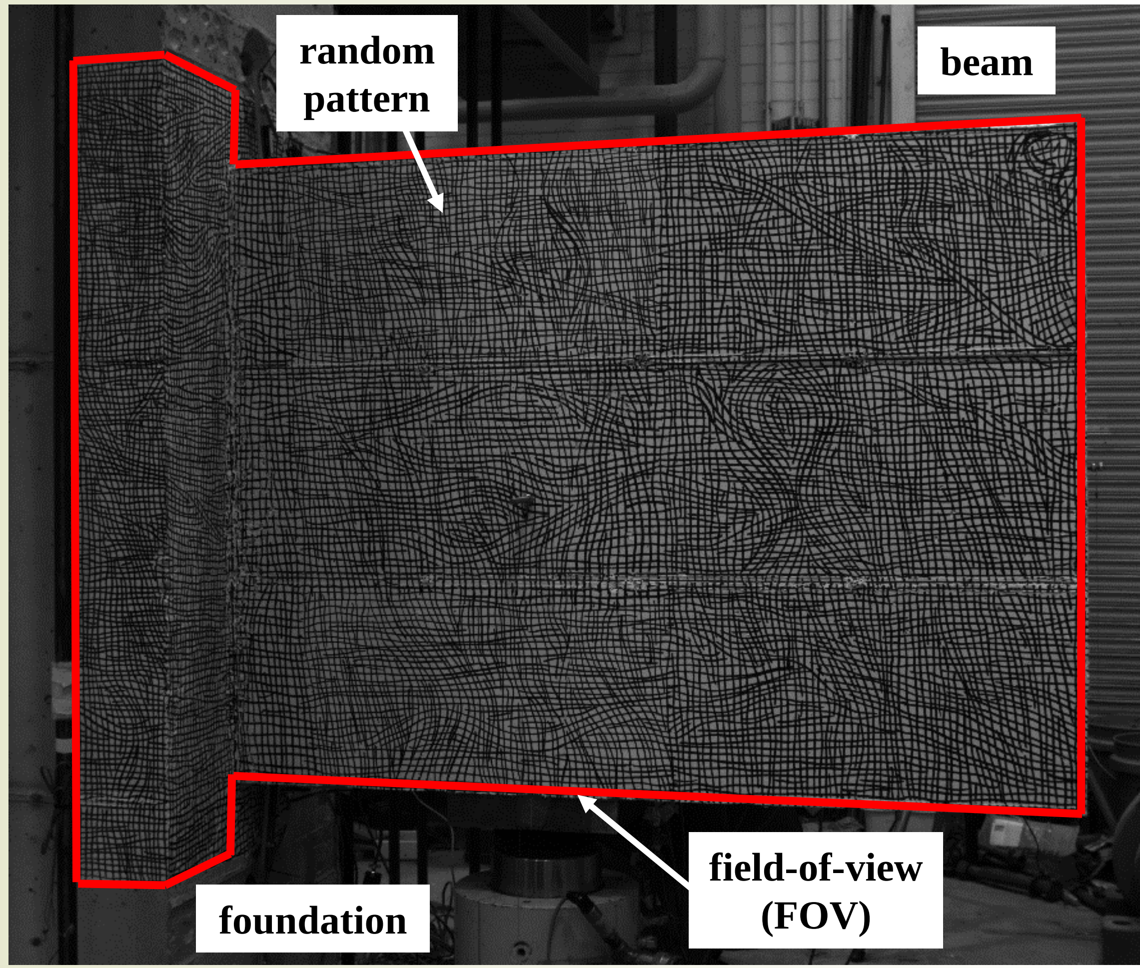
Deep Beam Instrumentation

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



3D Digital Image Correlation





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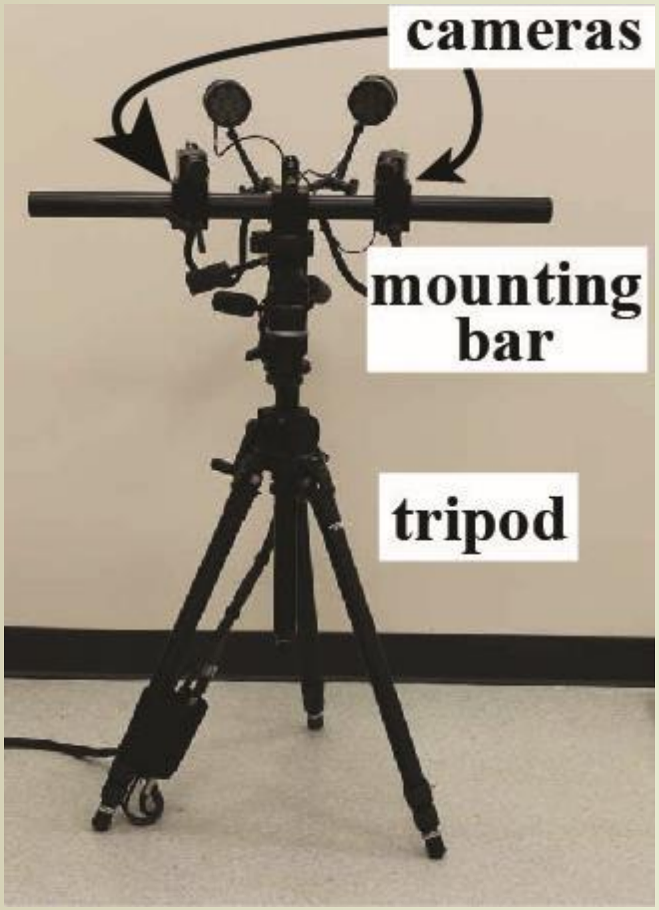
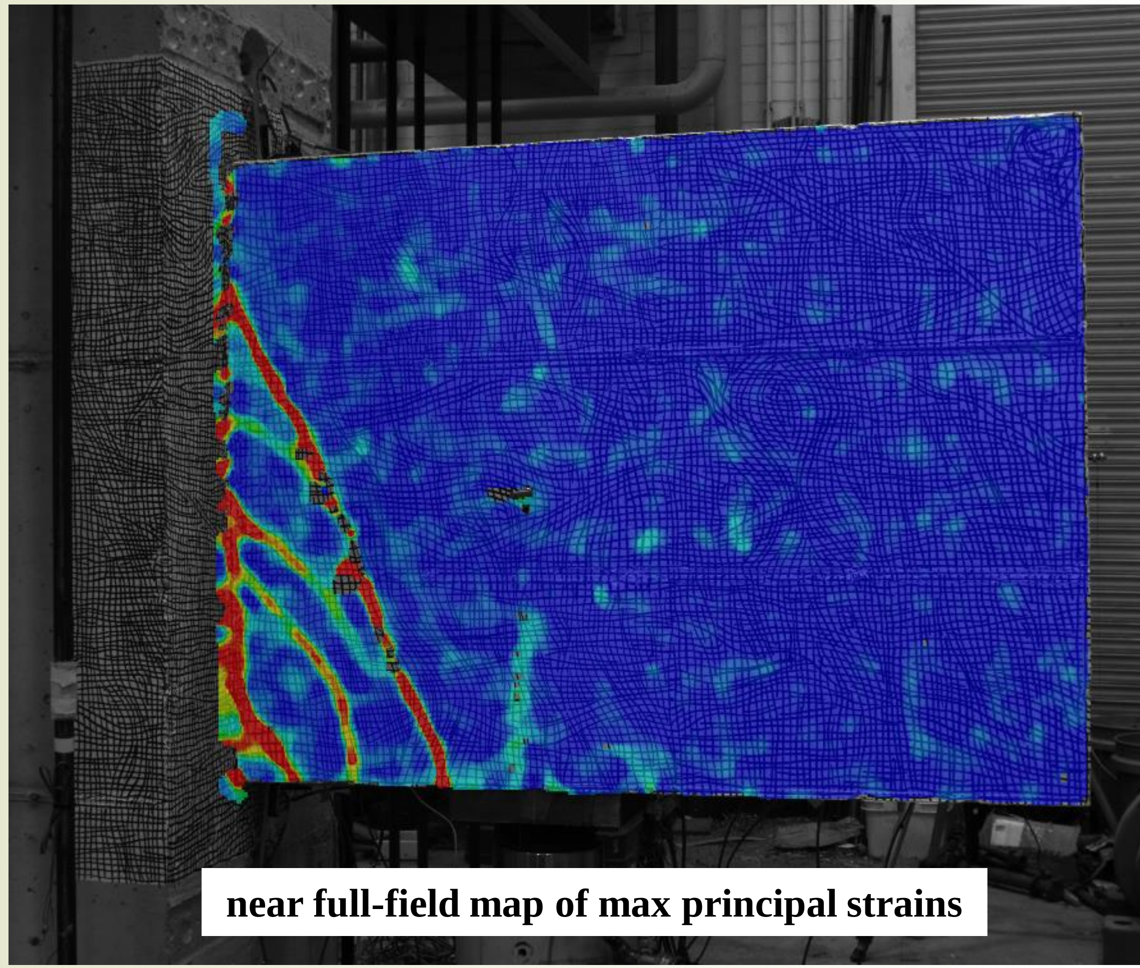
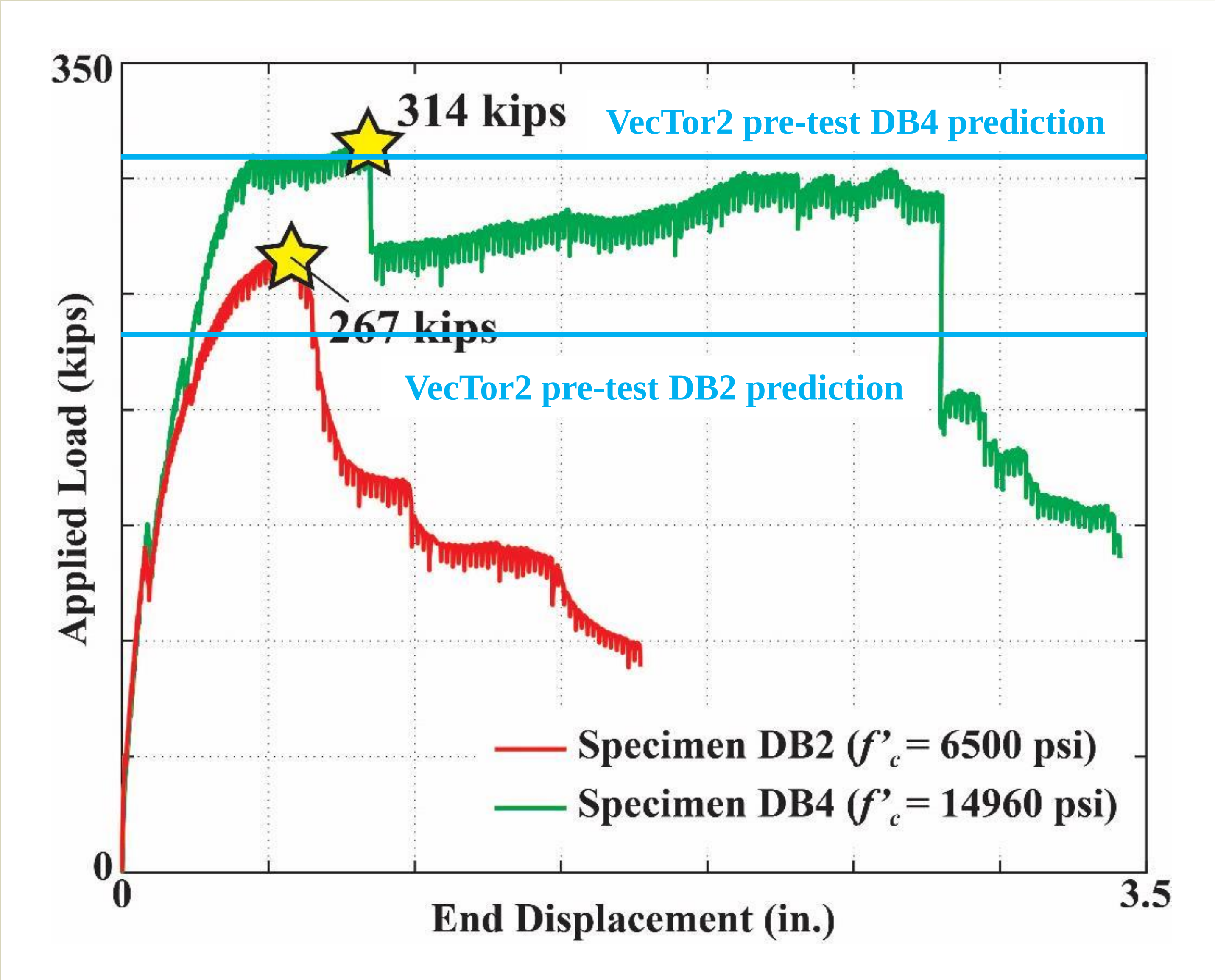
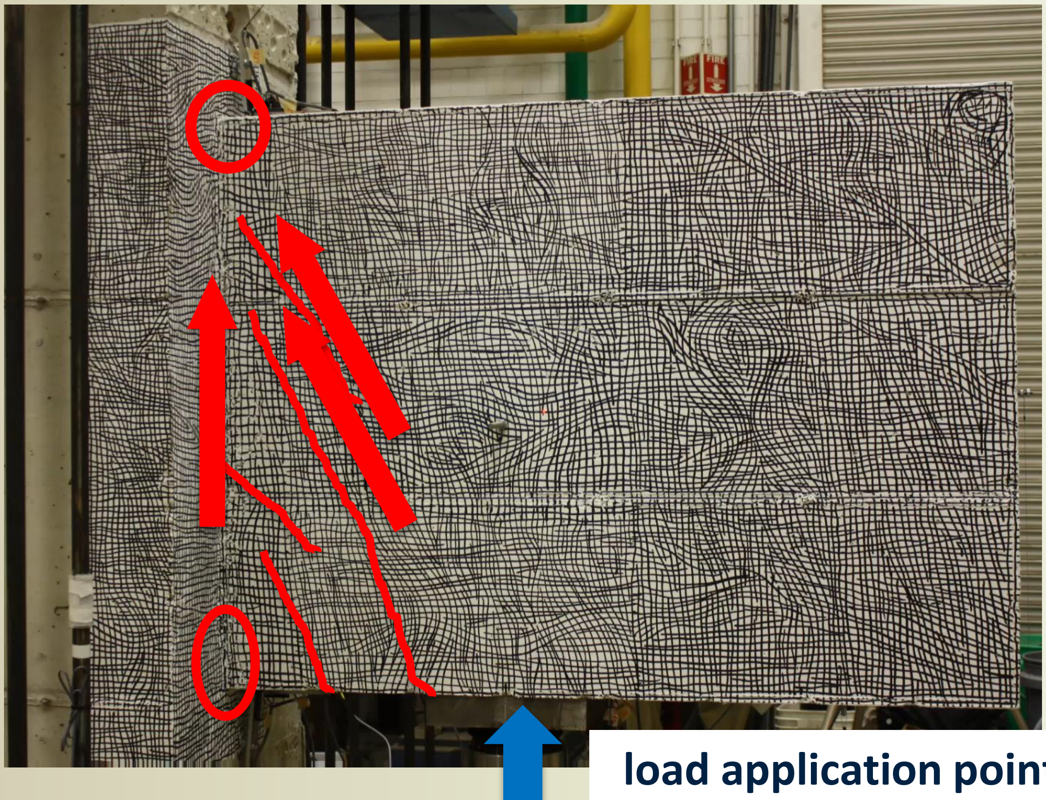




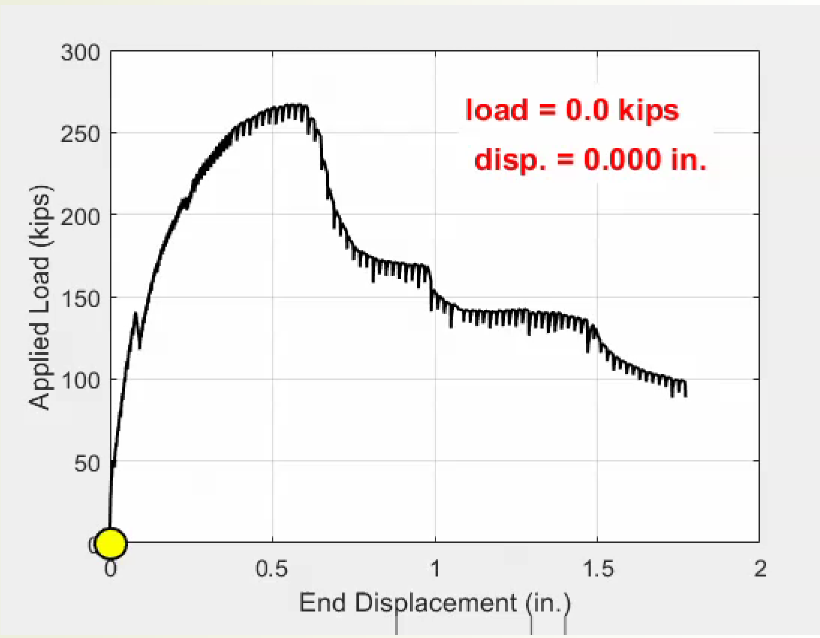
Specimens DB2 and DB4 Response



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

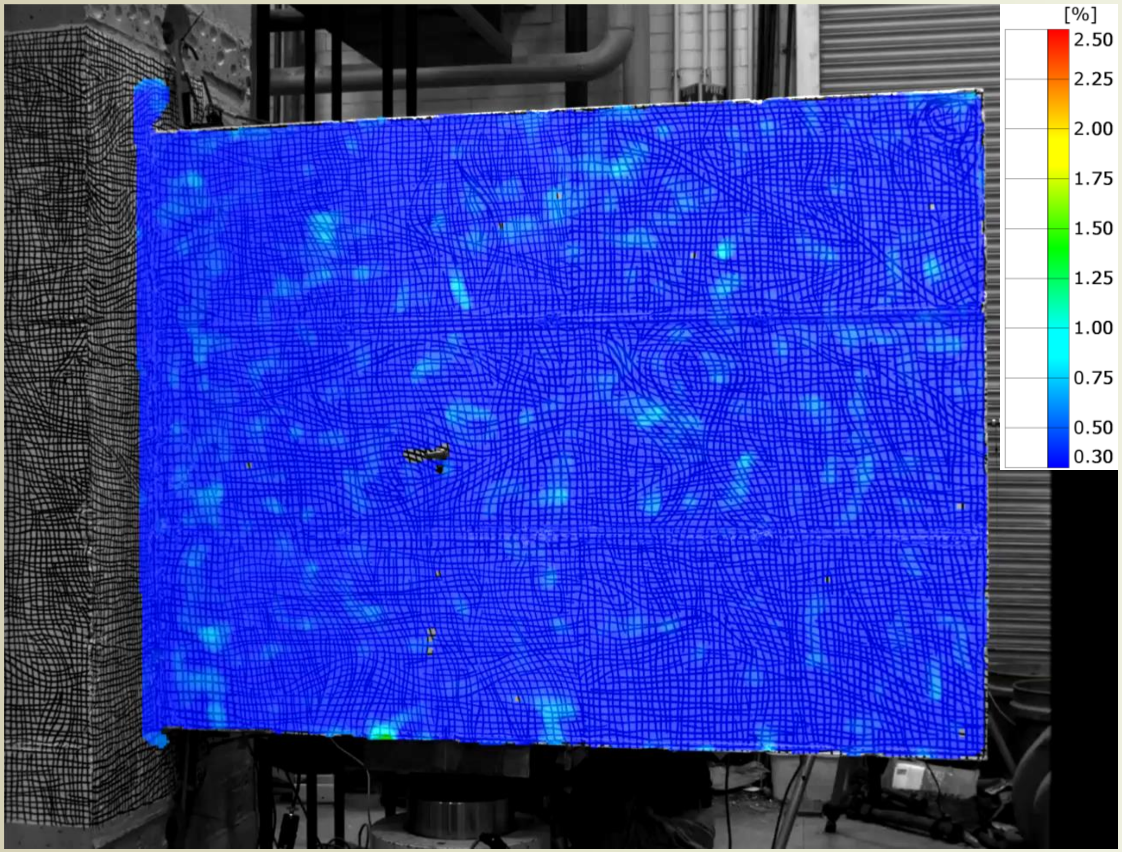


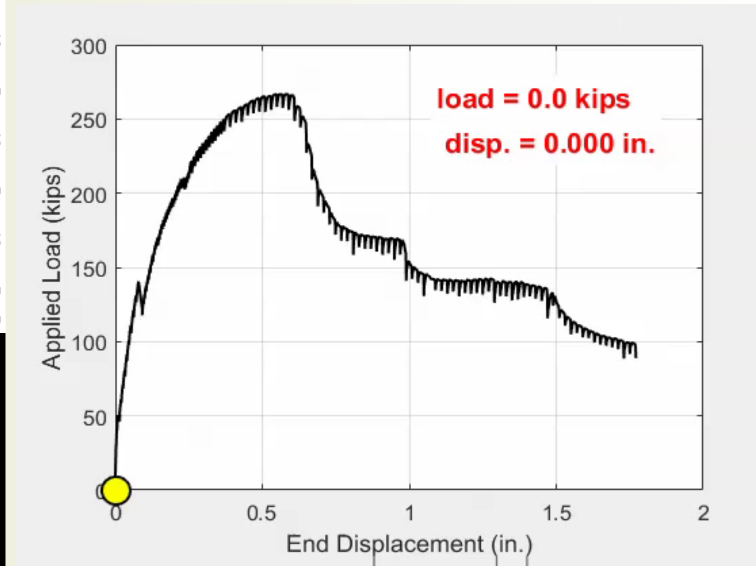
load application point



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

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





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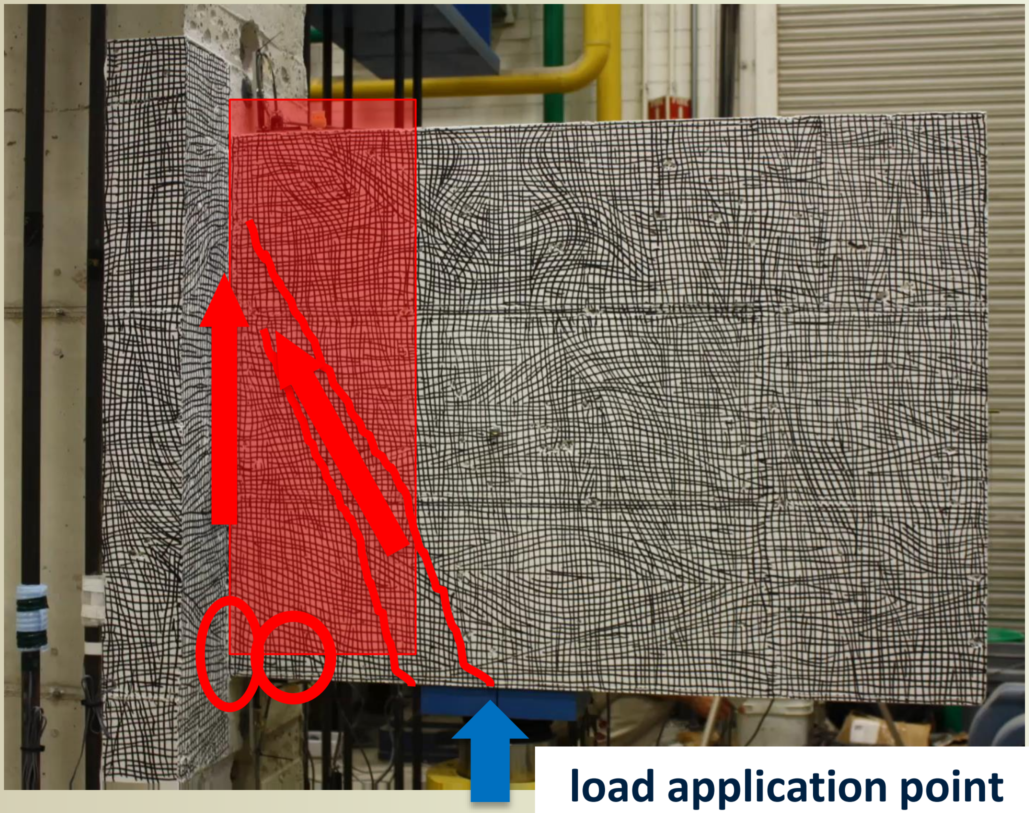
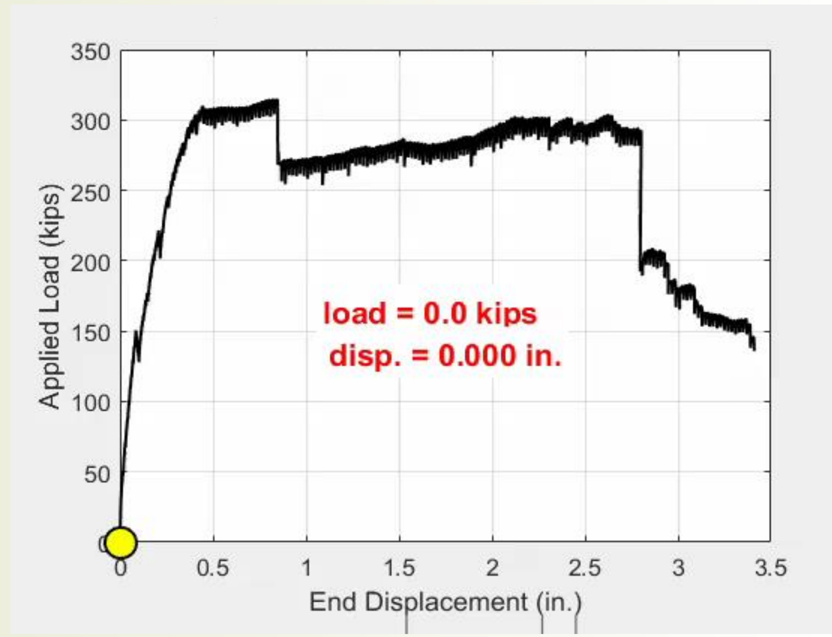
DB4 ($f'_c = 14960$ psi, $f_y = 133$ ksi)





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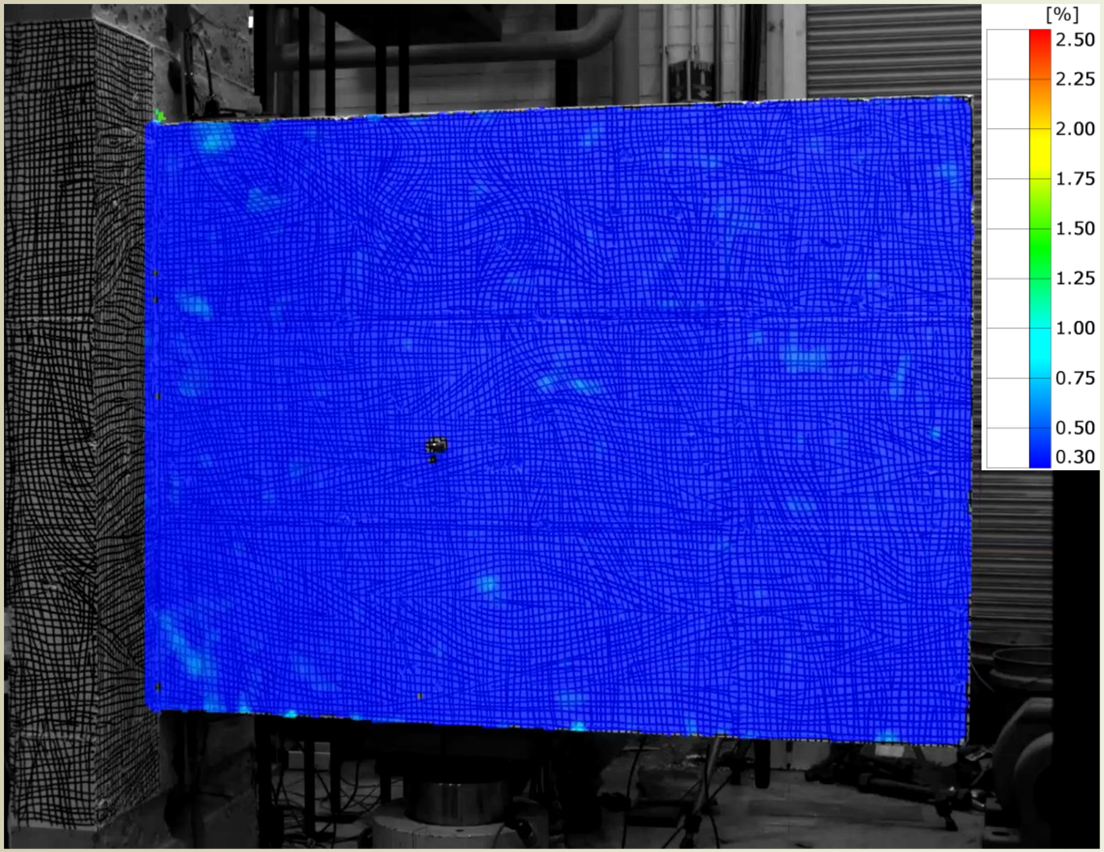

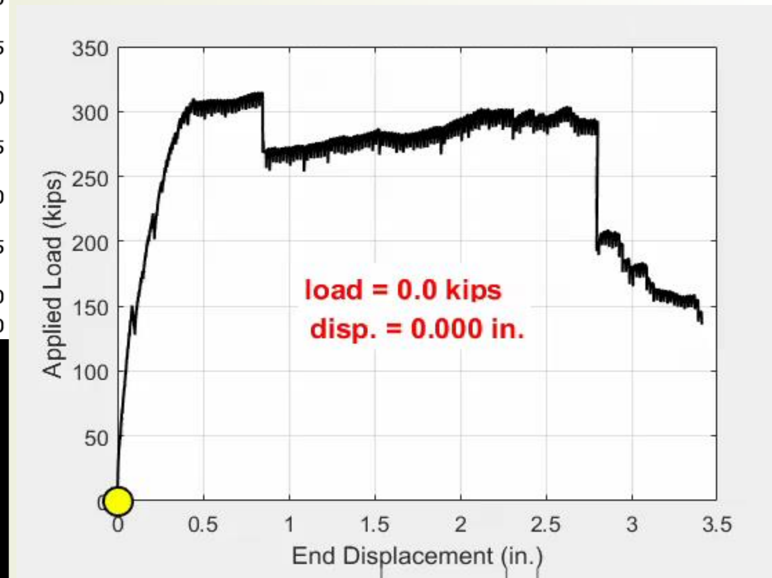

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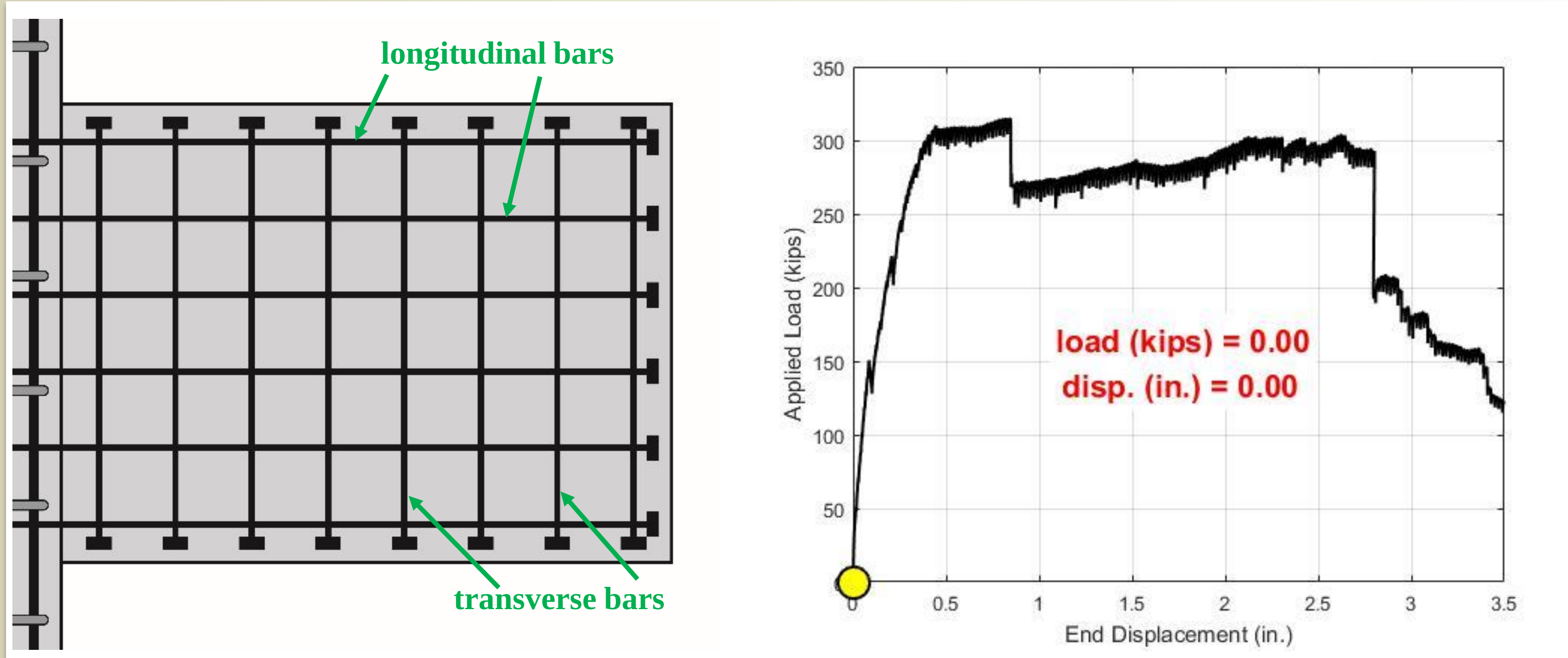
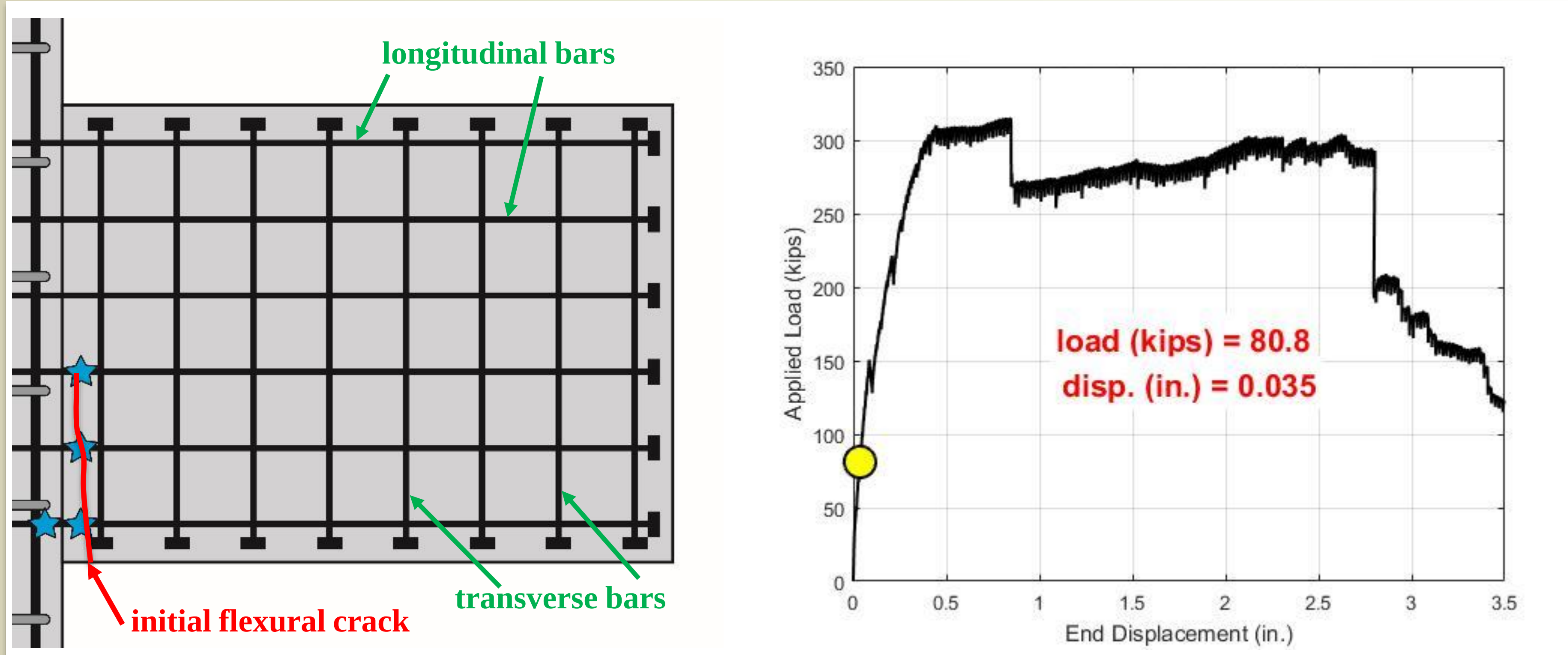


DB4 (f'_c = 14960 psi, f_y = 133 ksi)

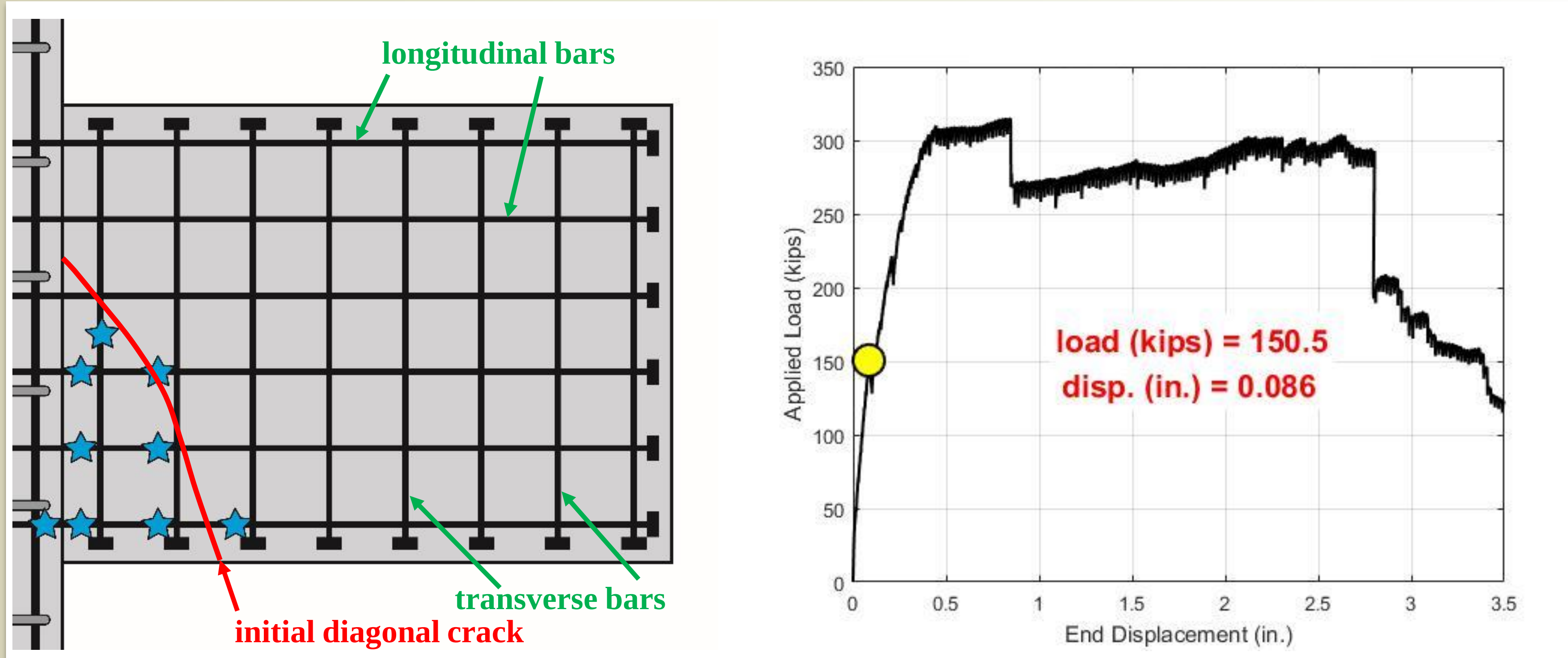


★ active tension strain

★ tension yield (6.85 mε)

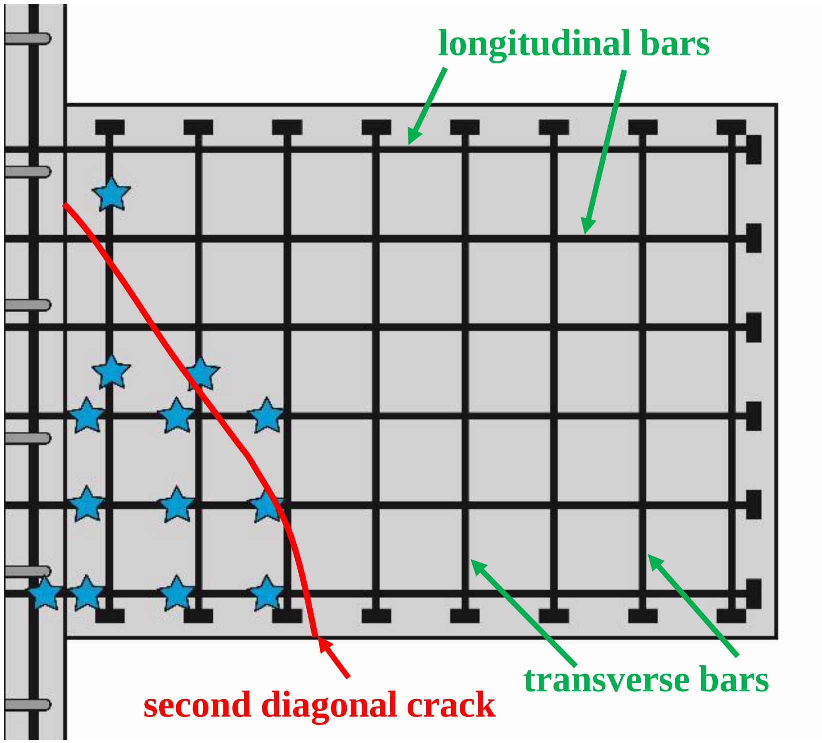
Initial flexural cracking, bottom three longitudinal layers active in tension

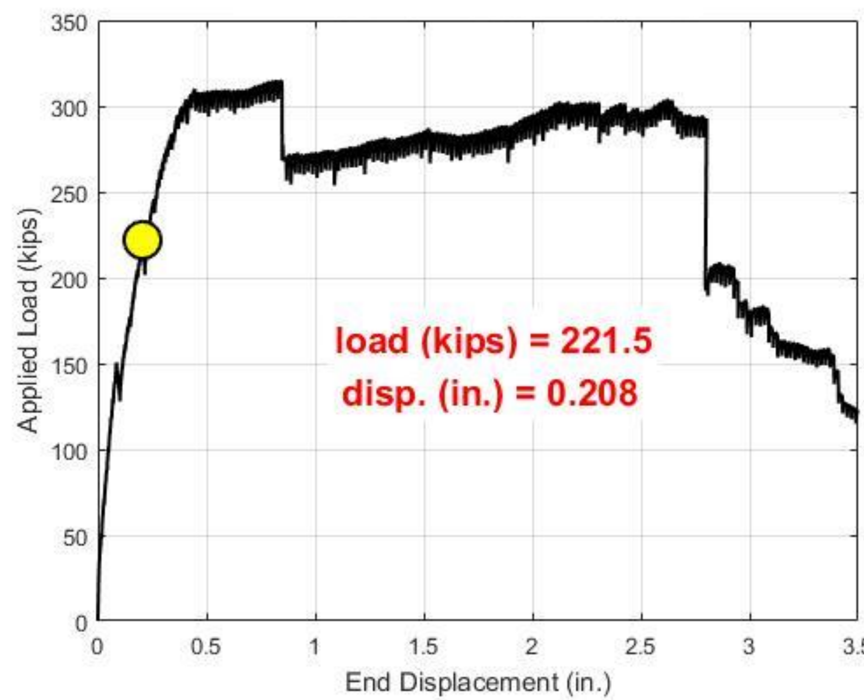
DB4 (f'_c = 14960 psi, f_y = 133 ksi)



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

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



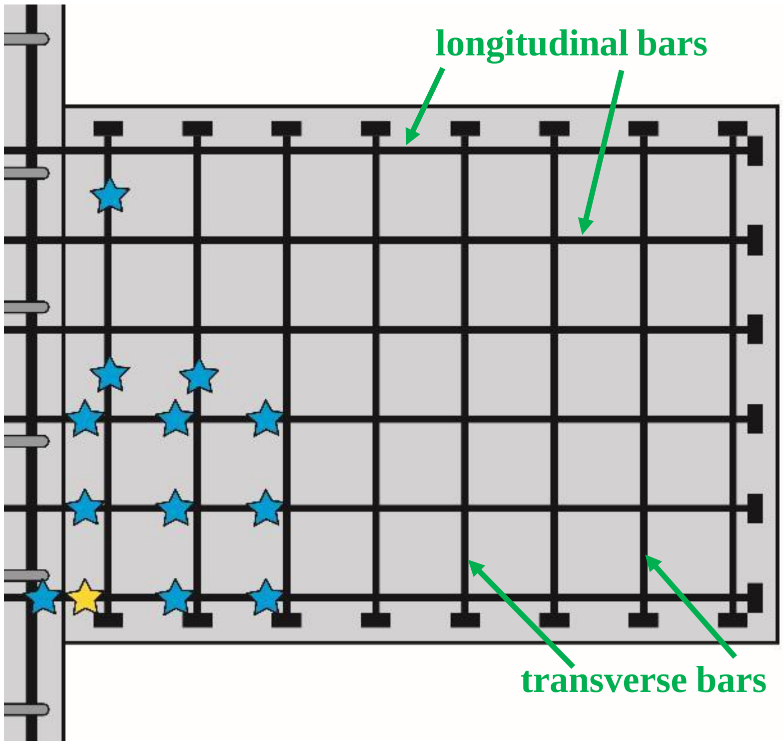


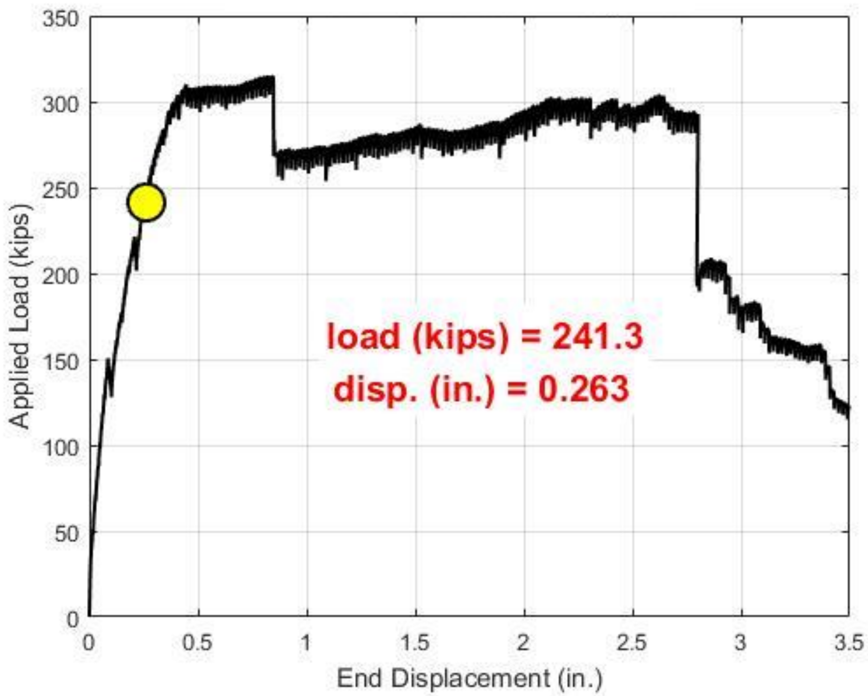
★ active tension strain

★ tension yield (6.85 mε)

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

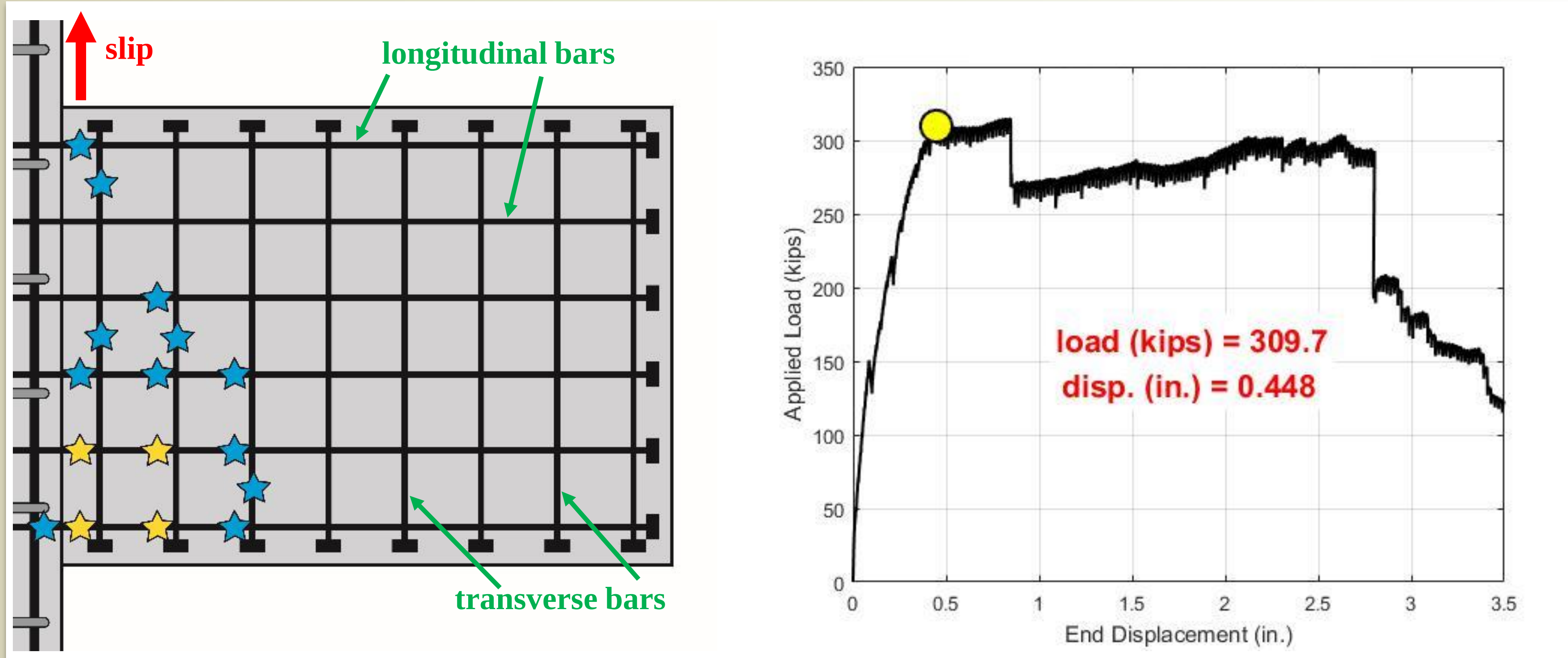
DB4 ($f'_c = 14960$ psi, $f_y = 133$ ksi)





Initiation of longitudinal reinforcement yielding

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

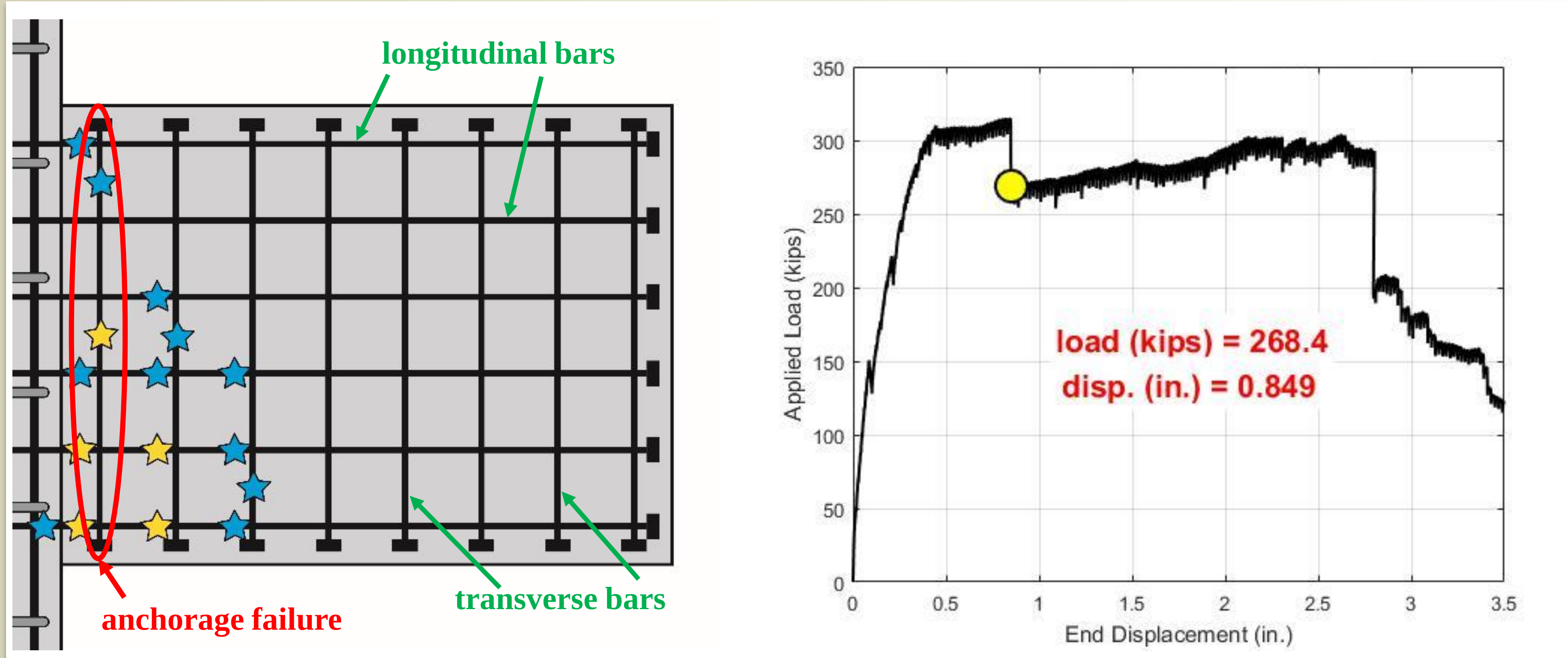


★ active tension strain

★ tension yield (6.85 mε)

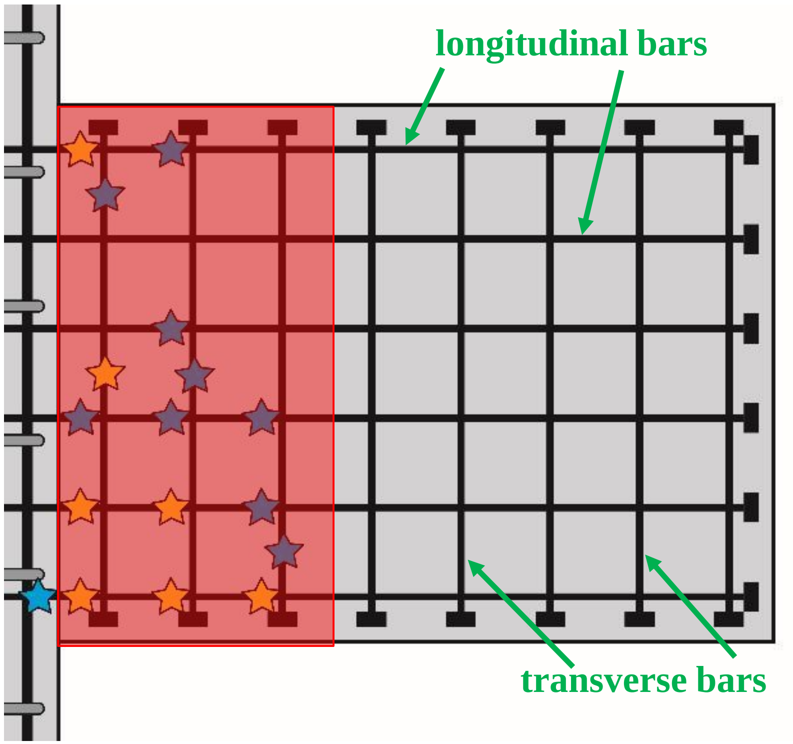
Slip at foundation interface
Extensive yielding of longitudinal reinforcement

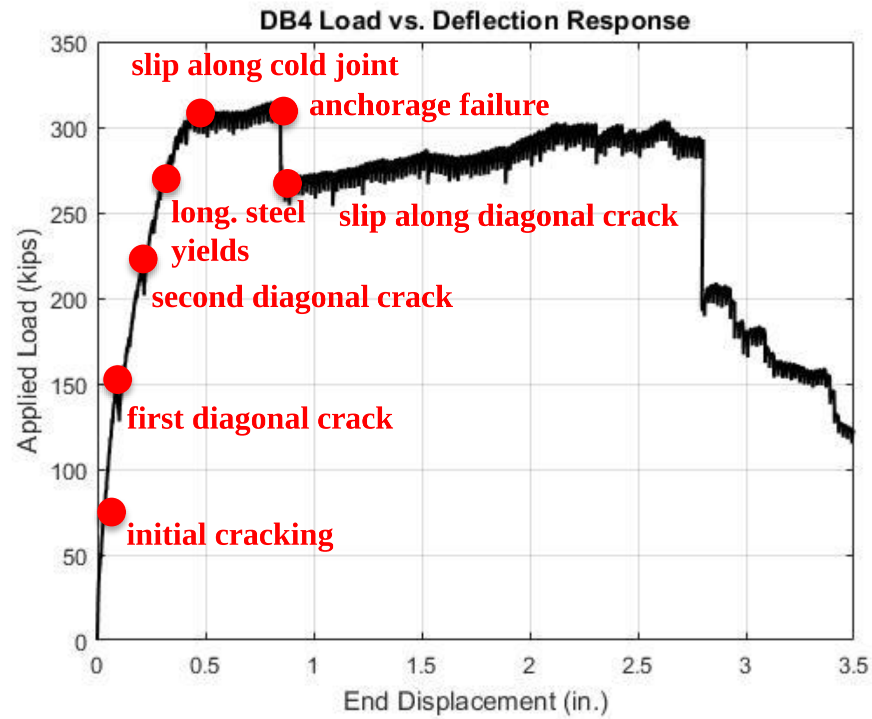
DB4 (f'_c = 14960 psi, f_y = 133 ksi)



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

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



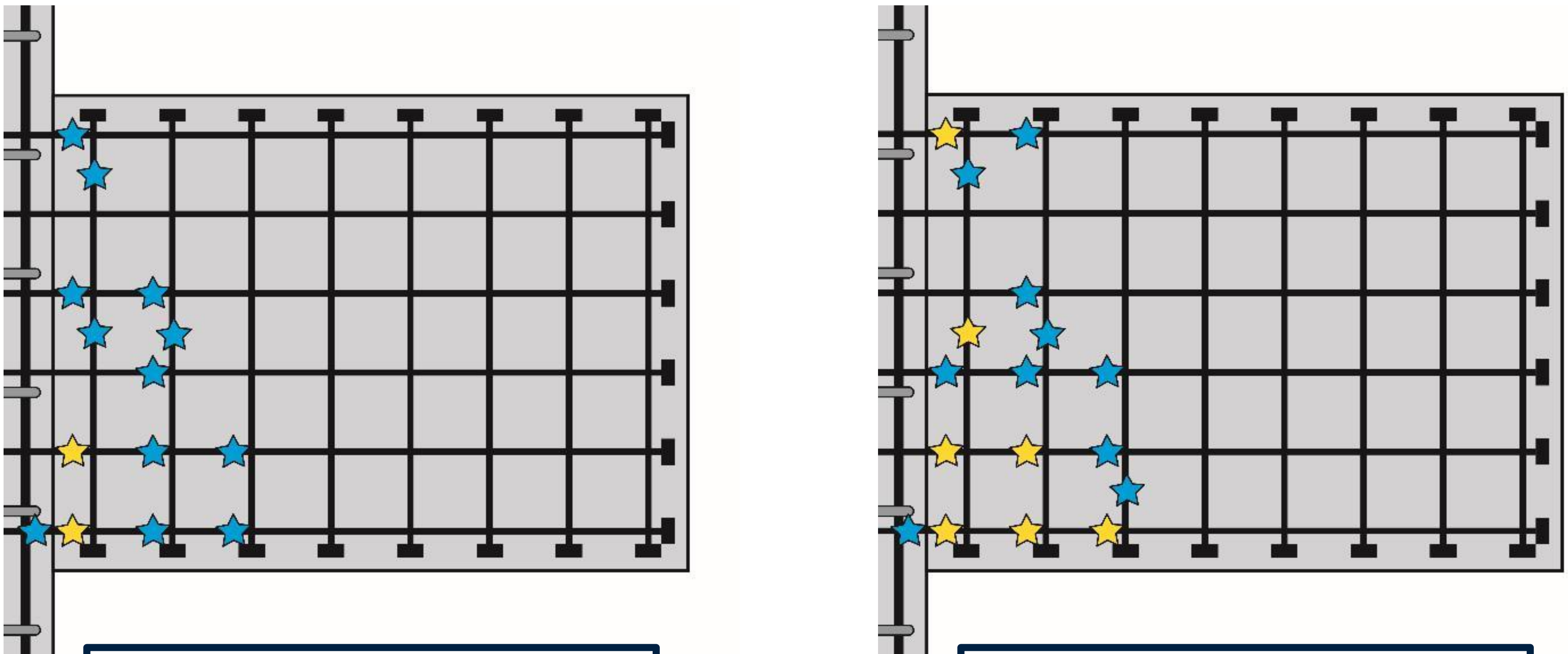


★ active tension strain

★ tension yield (6.85 mε)

Extensive concrete degradation

DB2 and DB4 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)

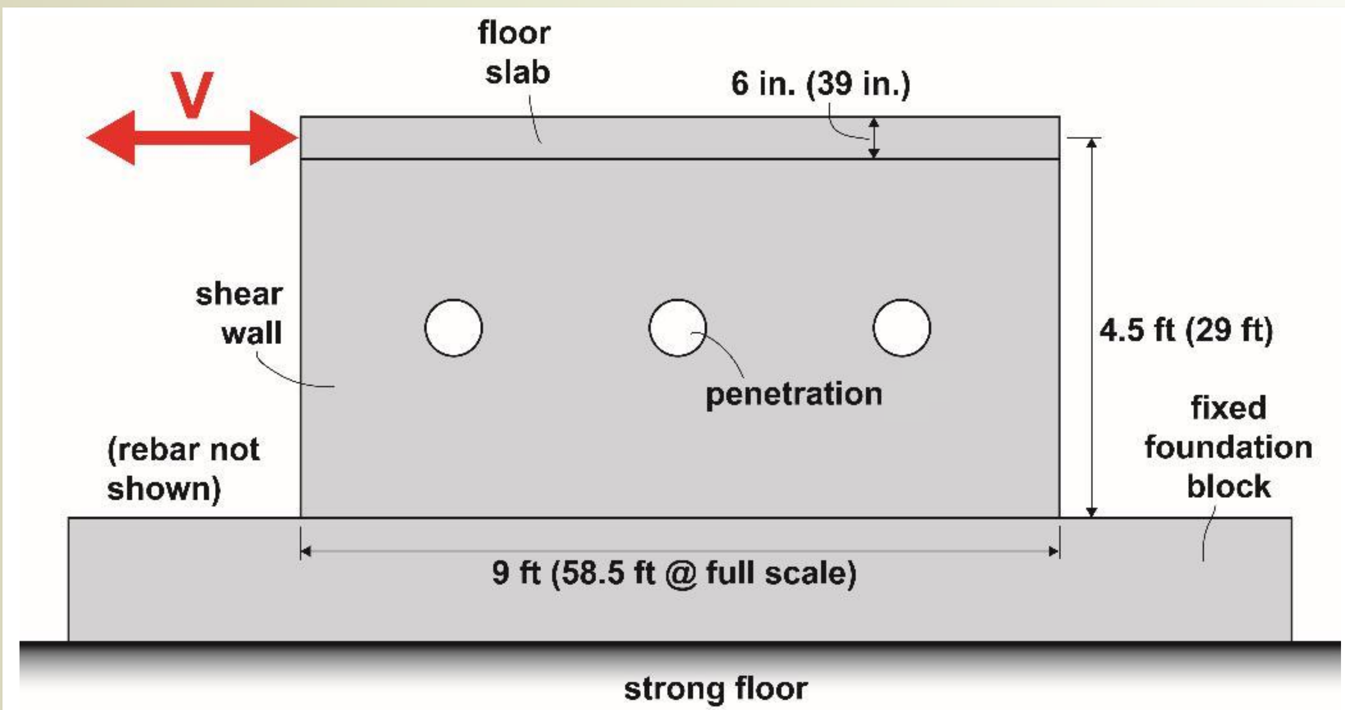
High-strength concrete able to better take advantage of higher yield strengths of reinforcement

Summary of Deep Beam 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

Future Reduced-Scale Shear Wall Tests

- 1:6.5 scale of “generic wall”
- $M/(Vl_w) = 0.50$
- Tested under cyclic and accidental thermal loads
- High-strength steel and concrete



Conclusions to Date

- 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
- Project tasks on schedule

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Research Products

- Journal Paper (submitted):
  - “Effect of High-Strength Materials on Lateral Strength of Shear-Critical Reinforced Concrete Walls,” *ACI Structural Journal.*
- Presentations:
  - Presentation, 2015 Fall ACI Convention, Denver, CO.
  - Poster, 2015 Energy Week, Center for Sustainable Energy, University of Notre Dame, Notre Dame, IN.
  - Presentation, 2016 Fall ACI Convention, Philadelphia, PA.
  - Presentation, 2016 American Nuclear Society Winter Meeting and Nuclear Technology Expo, Las Vegas, NV.

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HIGH STRENGTH MATERIALS PREFABRICATION
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  - Dayton Superior Corp.
  - HRC, Inc.
  - Sika Corp. U.S.

Questions?

http://phsrc-nuclearwalls.nd.edu

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