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

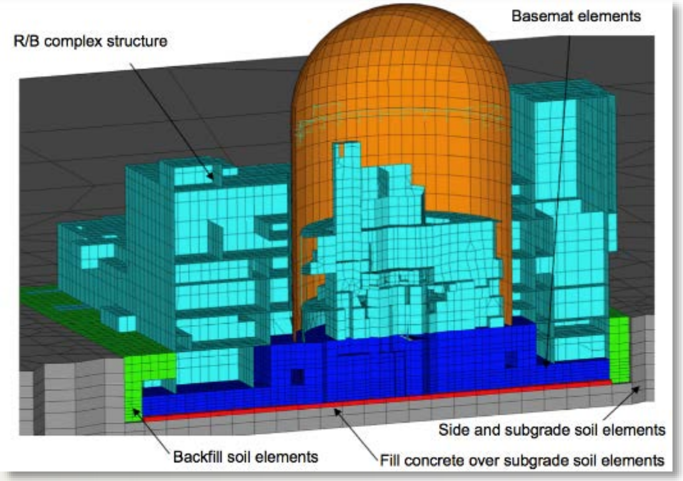
Primary Objective

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

UNIVERSITY OF NOTRE DAME

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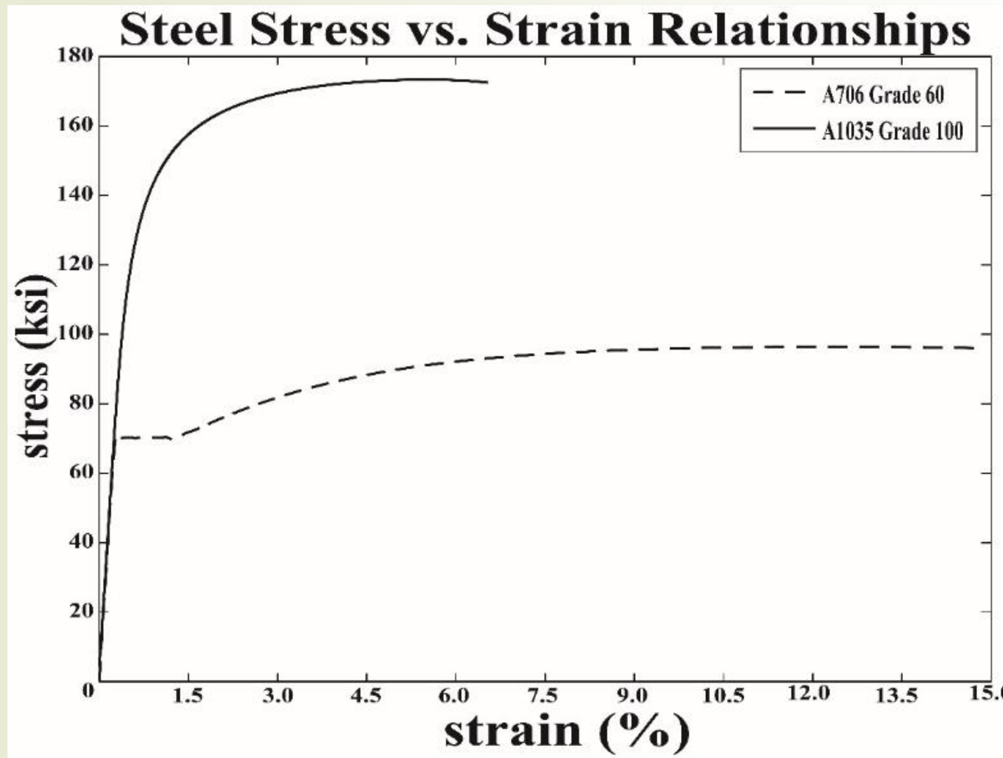
Project Tasks

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

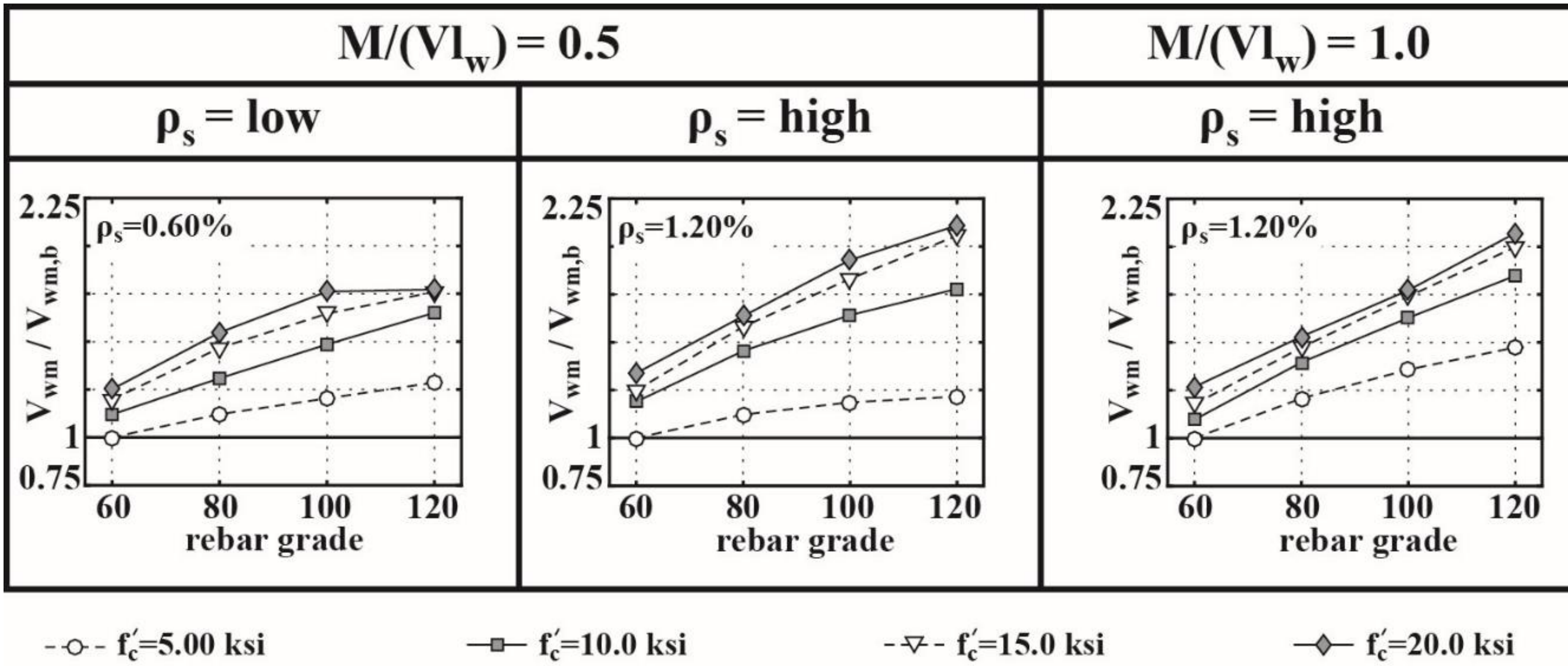
Numerical limit-benefit study to establish effects of high-strength materials on peak lateral strength of low-aspect-ratio shear walls:

- 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

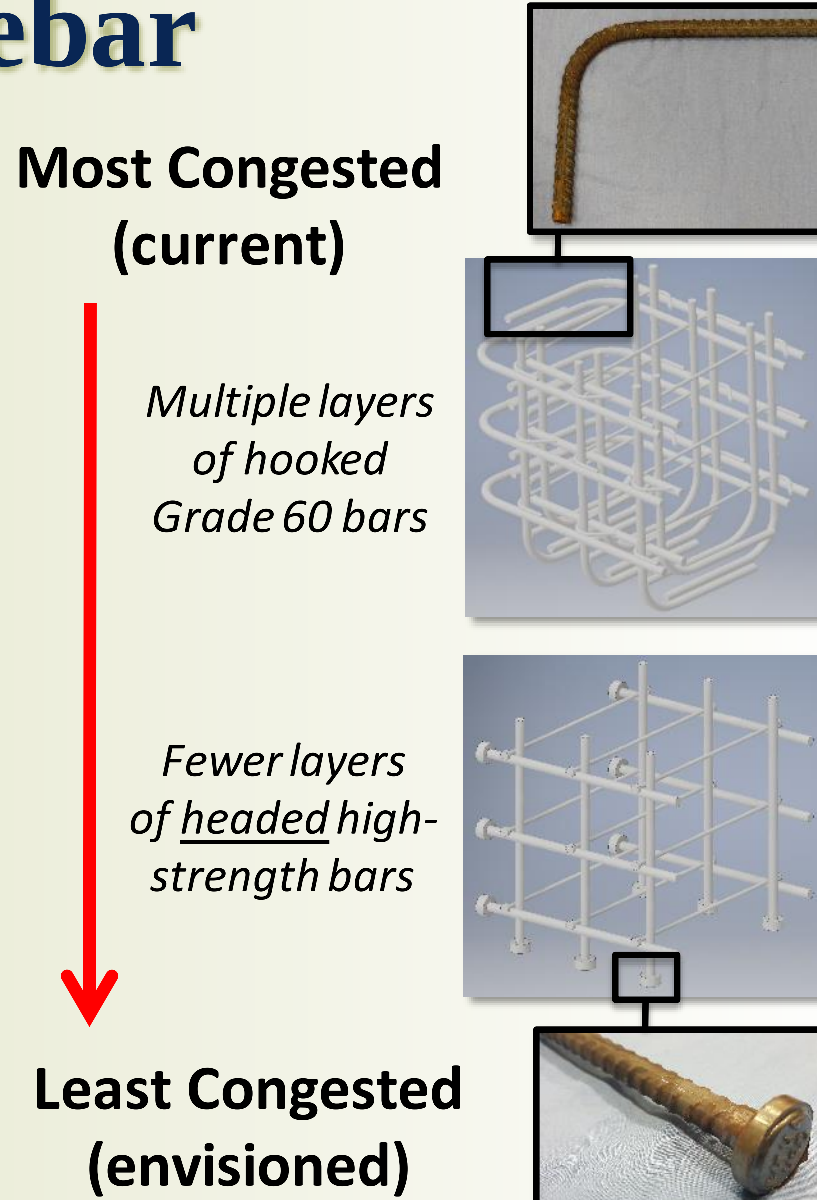
Summary of results of cost-benefit analysis:

- 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

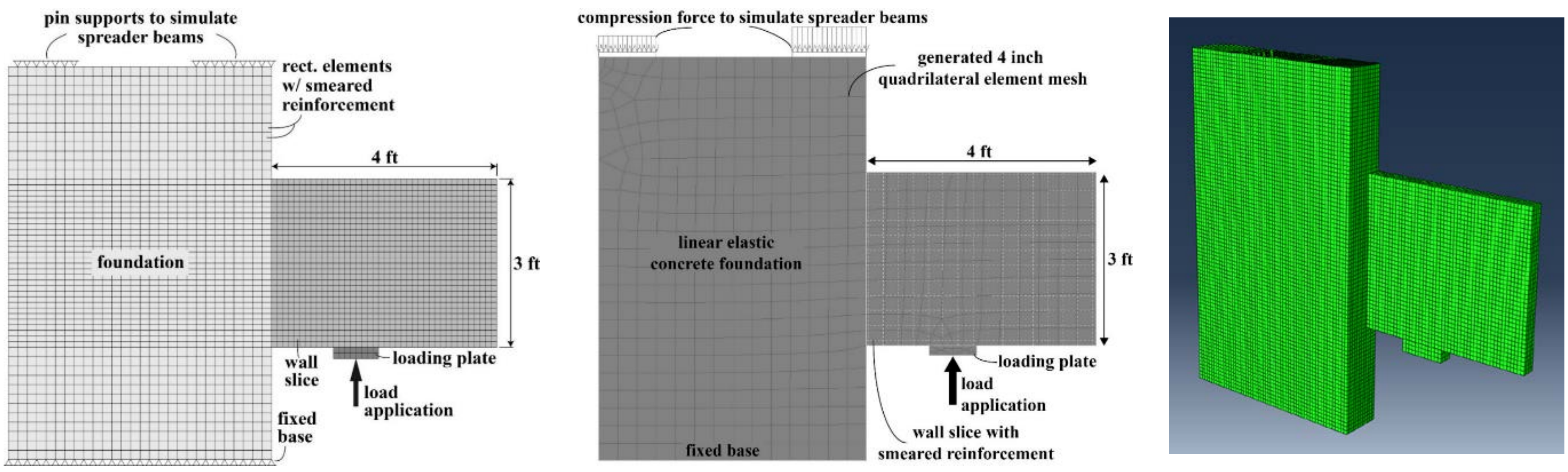
- Evaluating prefab rebar cages for:
  - transportability
  - liftability
  - modularity
- Using mini-scale rapid prototyping

3D printed rebar cage



3. Optimization, Modeling and Design

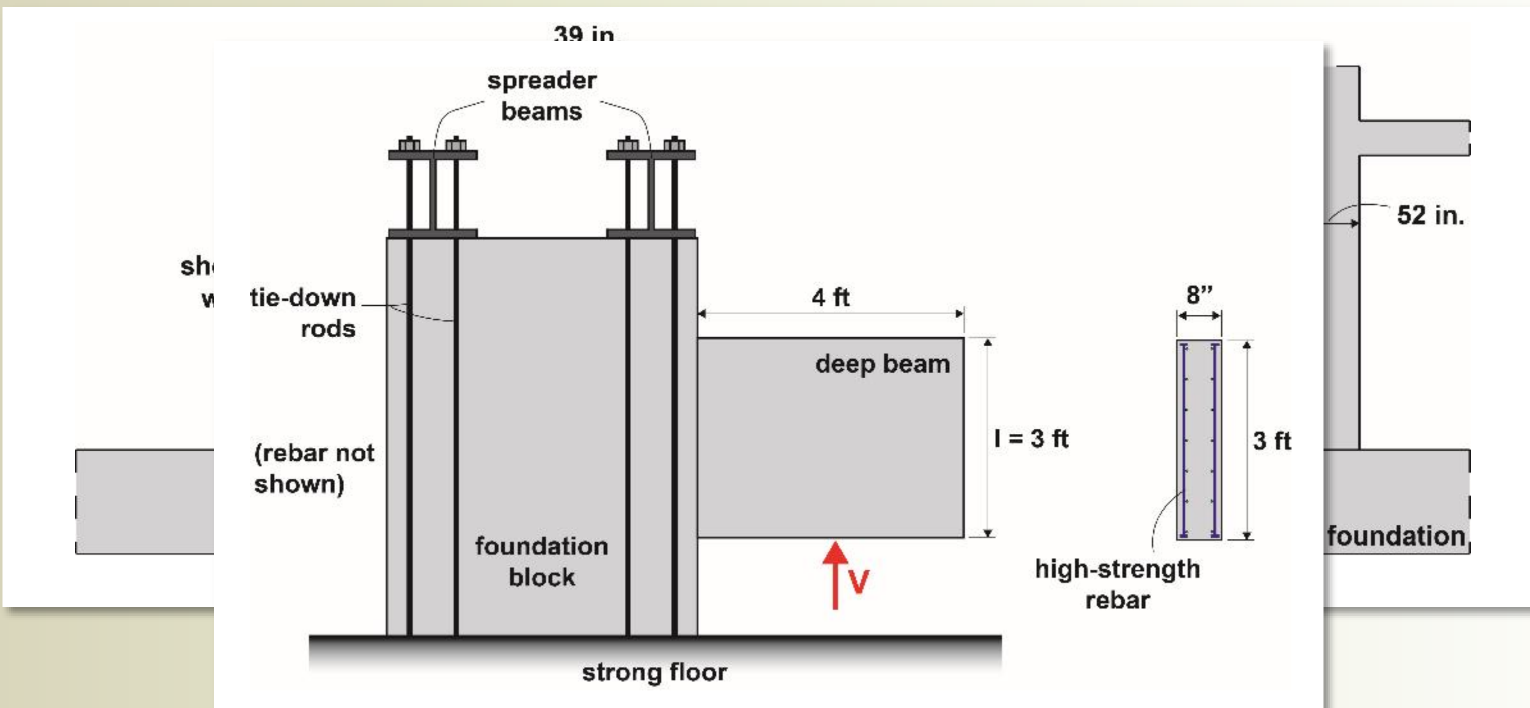
Pre-test Analyses of Deep Beam (Wall Slice) and Shear Wall Specimens in Vector2, ATENA, and ABAQUS



Vector2 ATENA ABAQUS

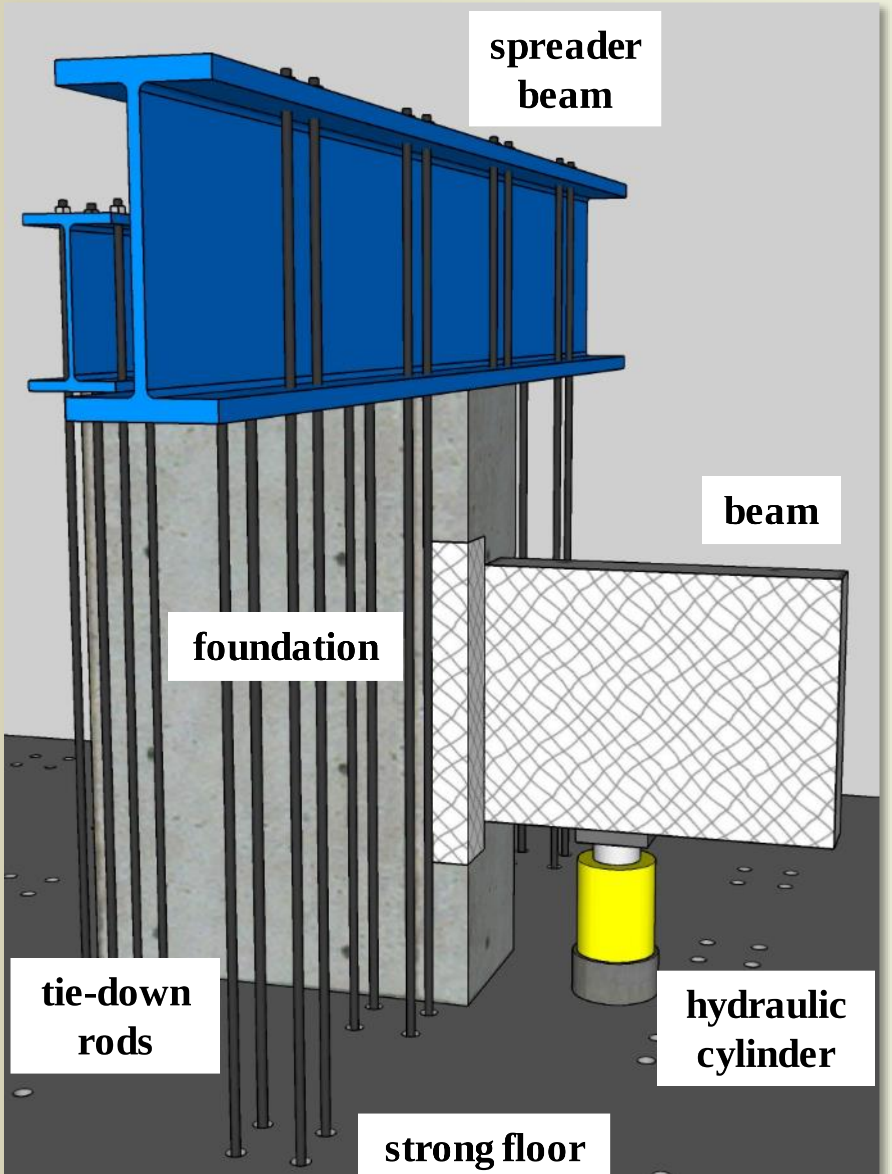
4. Experimental Testing

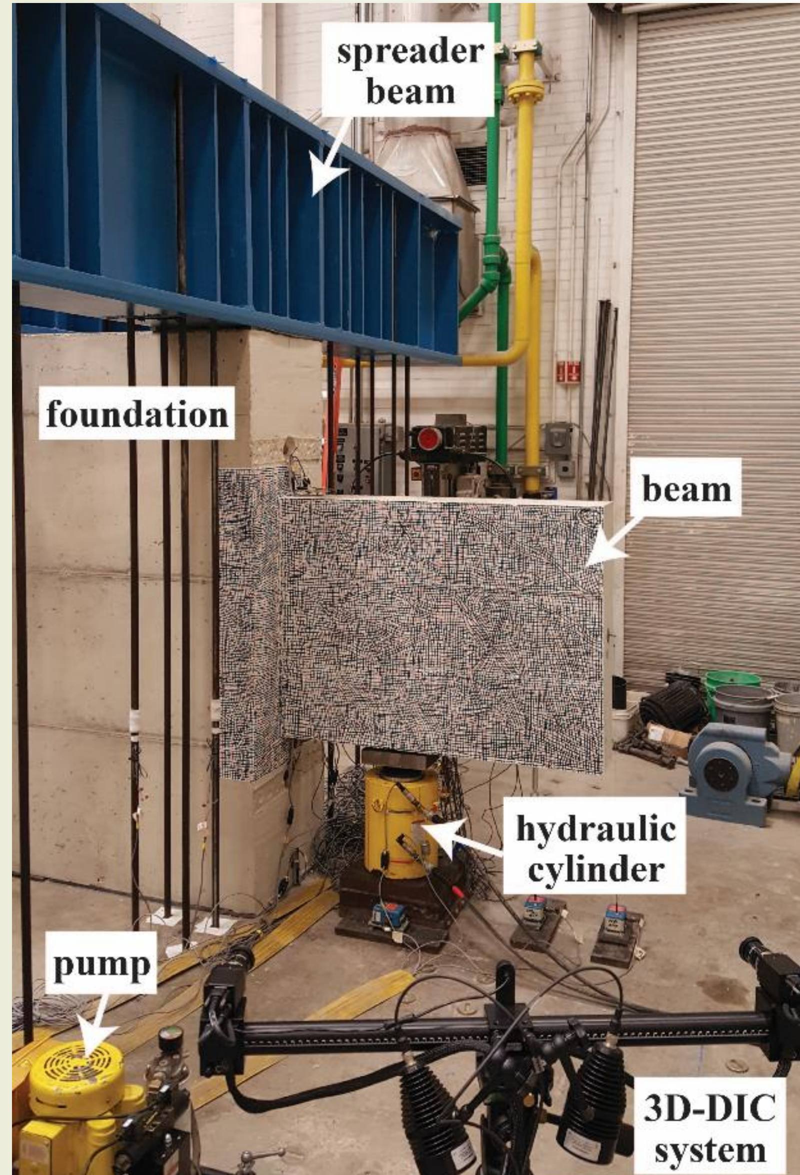
- "Generic wall" dimensions determined using publicly-available design control documents
- Provides basis for future deep beam and shear wall tests



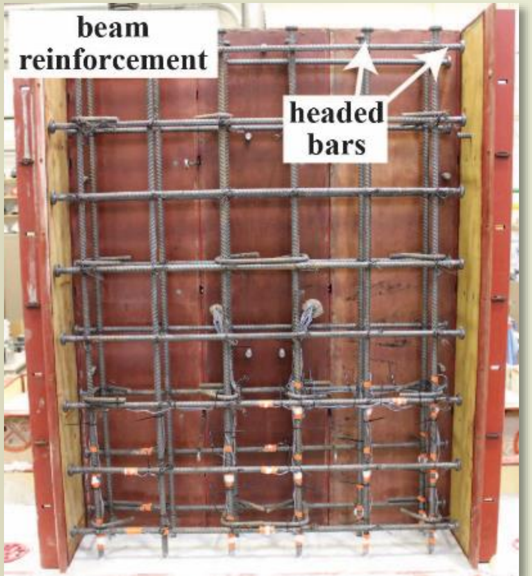
for deep beam tests (@ 1:6.5 scale)

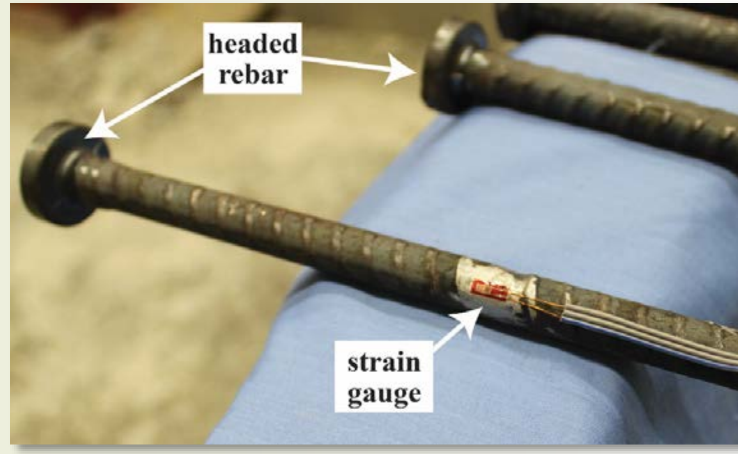
Deep Beam Test Setup

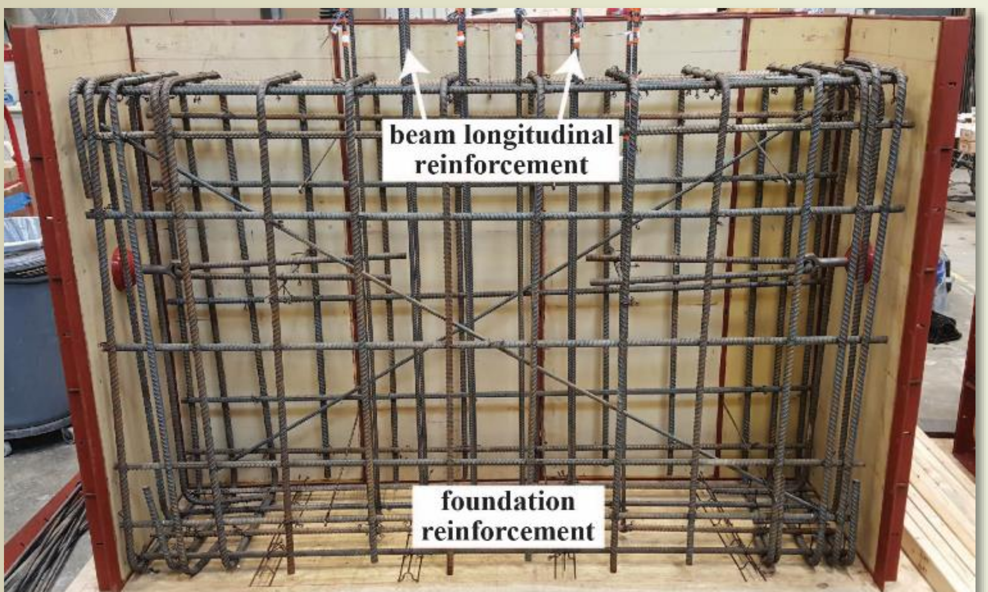


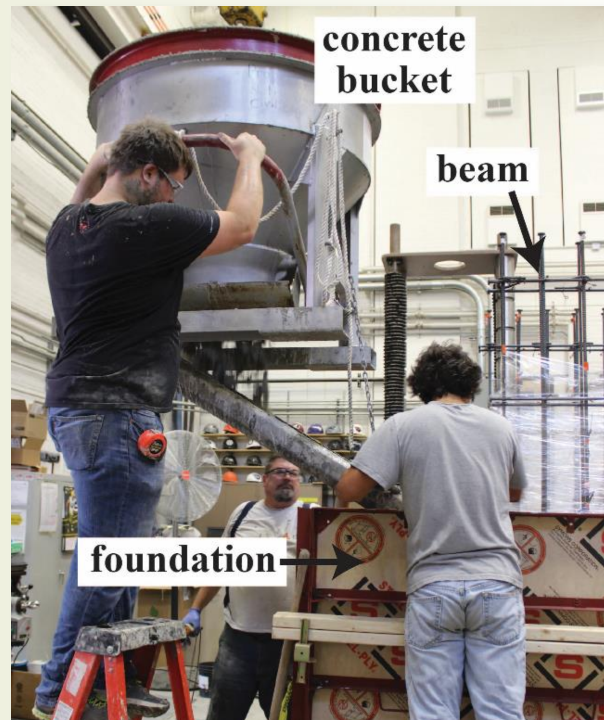


Deep Beam Construction









Deep Beam Construction

Normal-Strength Concrete

f'_c = 6500 psi

slump = 8 in.

High-Strength Concrete

f'_c = 14690 psi

slump = 8.75 in.

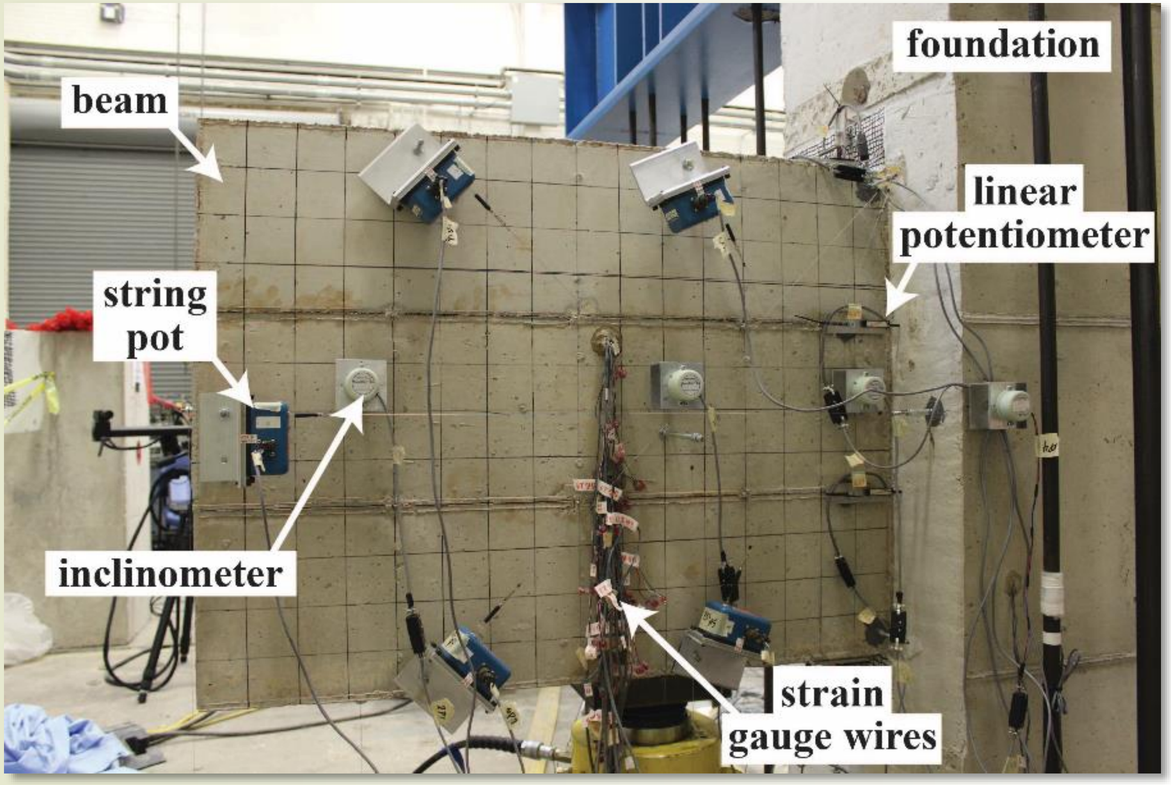
Deep Beam Test Parameters

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**

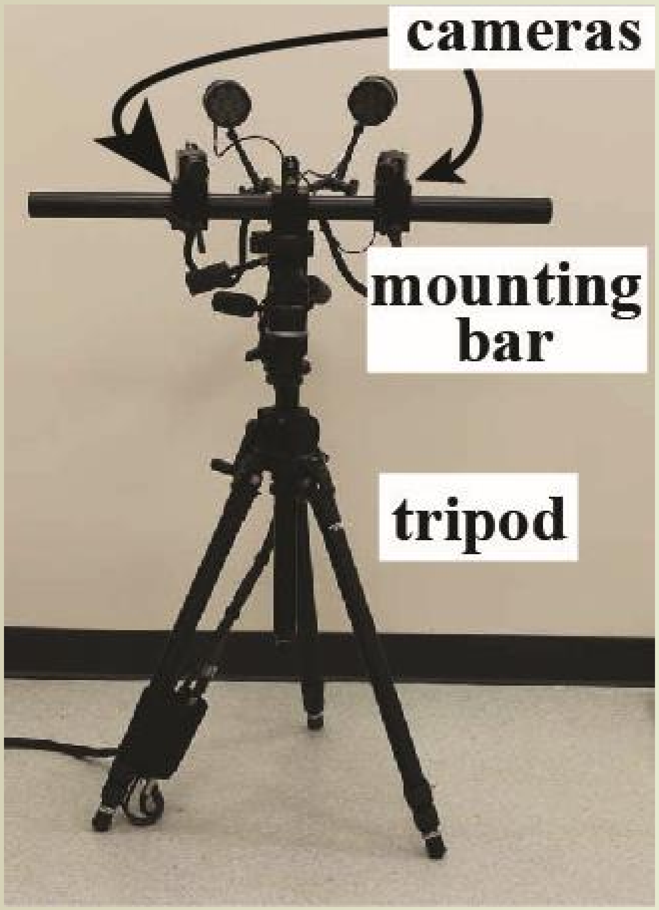
<u>Definitions:</u> f'_c – concrete 28 day compressive strength
f_y – rebar yield strength, determined by tensile tests and 0.2% offset method
ρ_s – reinforcement ratio, symmetric for longitudinal and transverse rebar

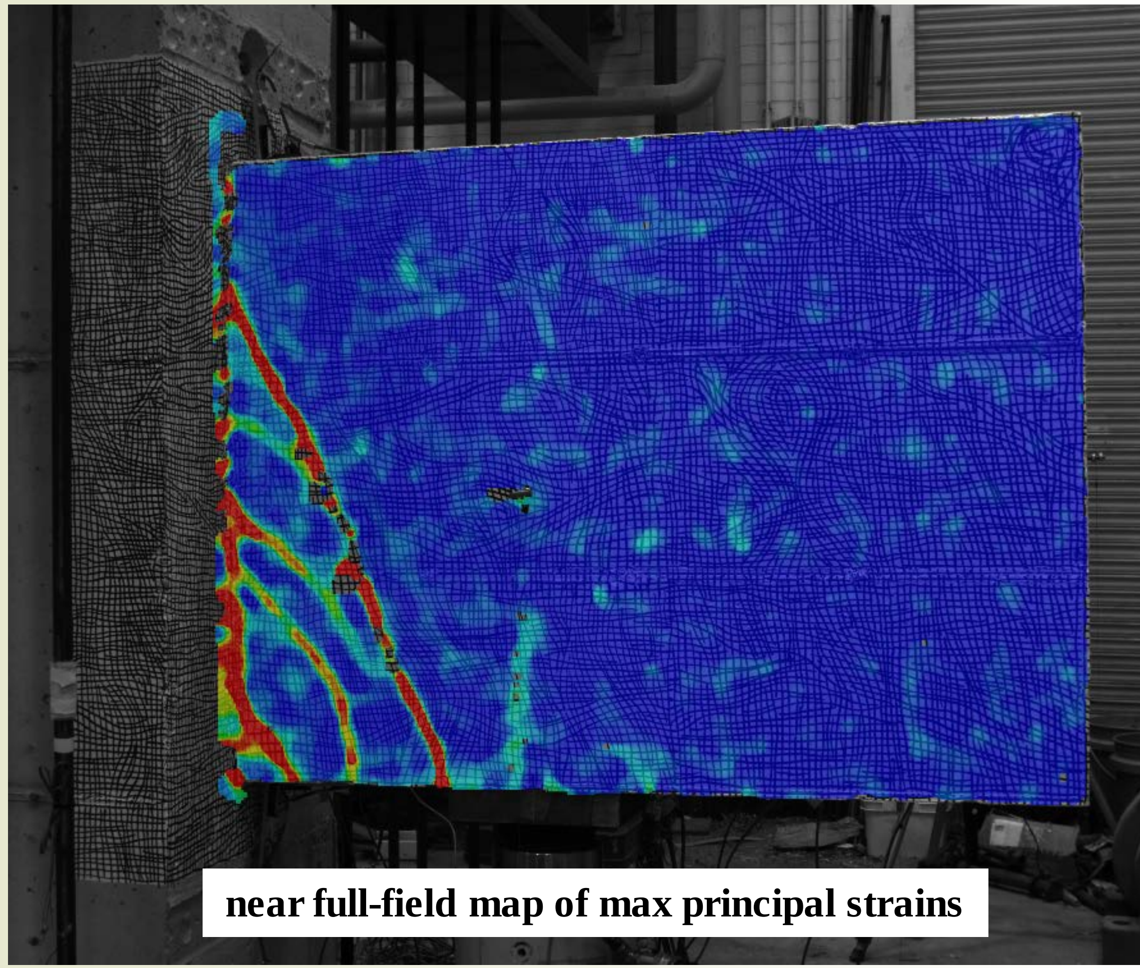
Deep Beam Instrumentation

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

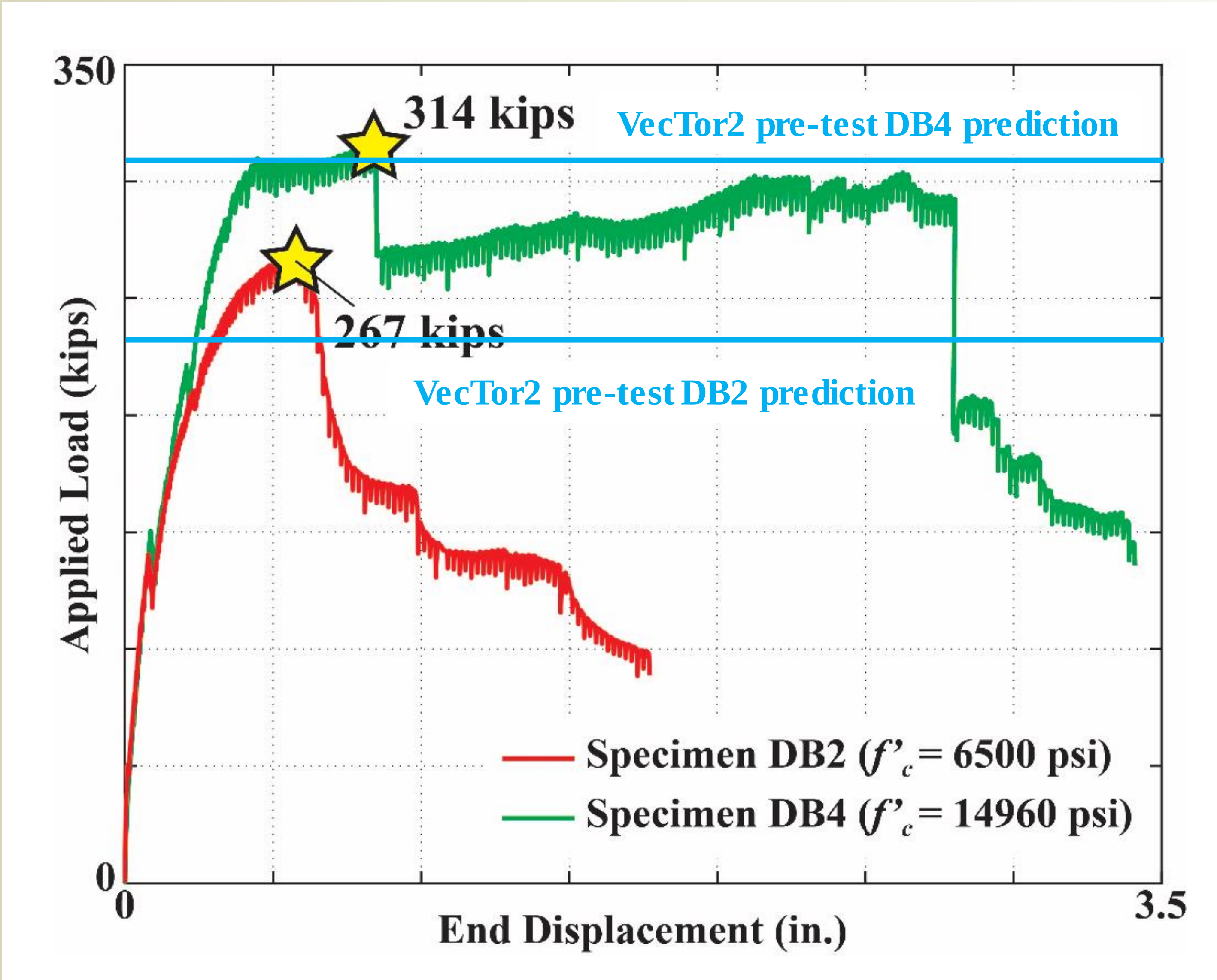


3D Digital Image Correlation

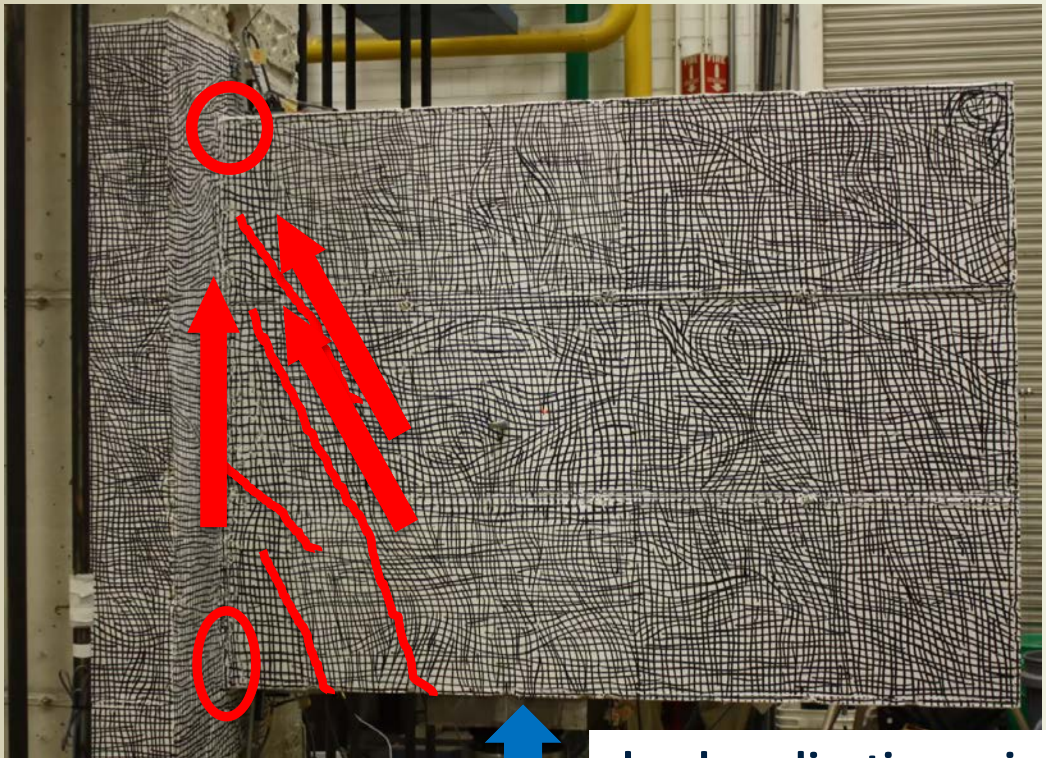


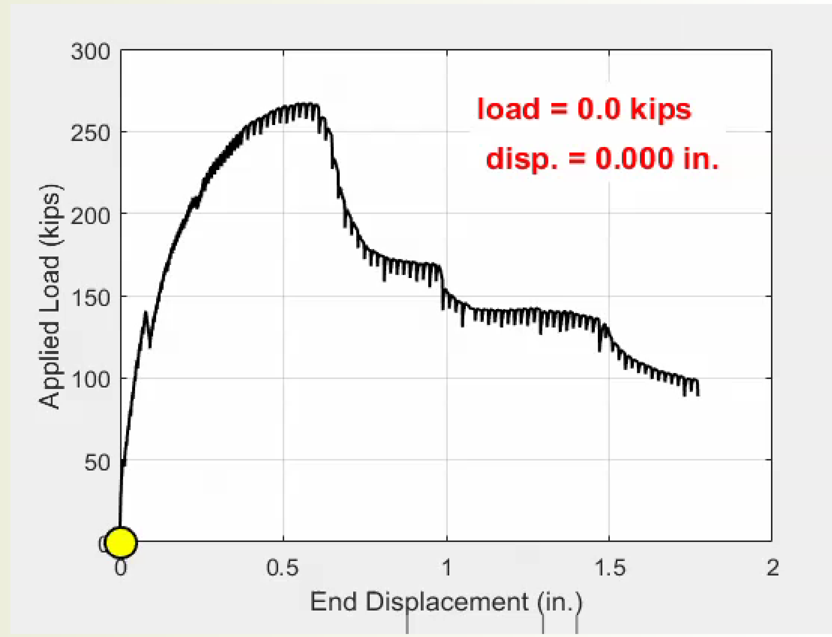


Specimens DB2 and DB4 Response



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

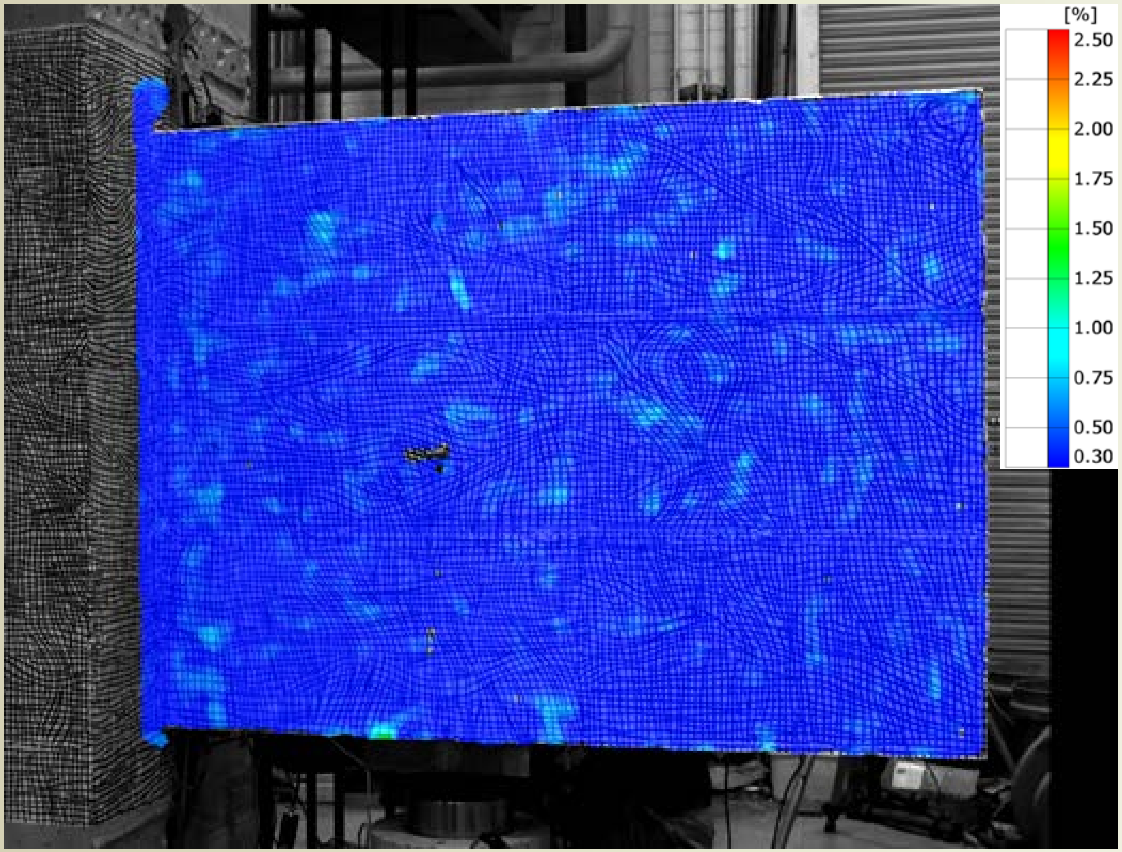


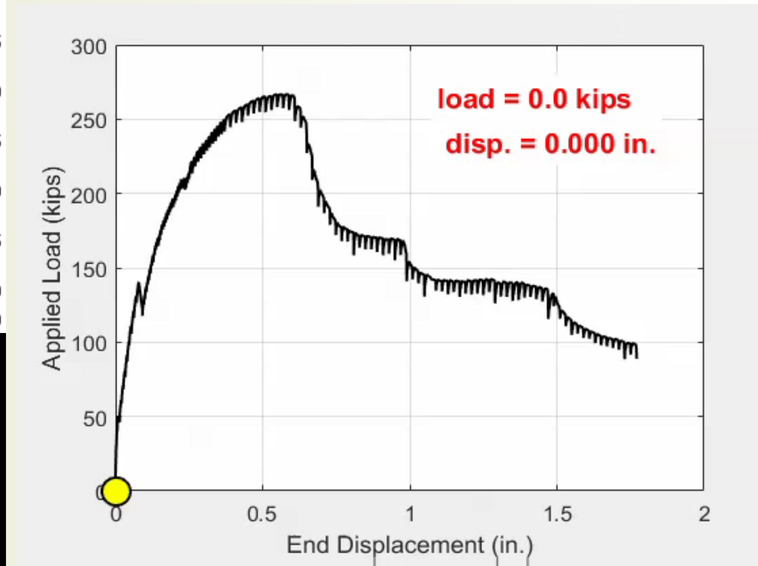


load application point

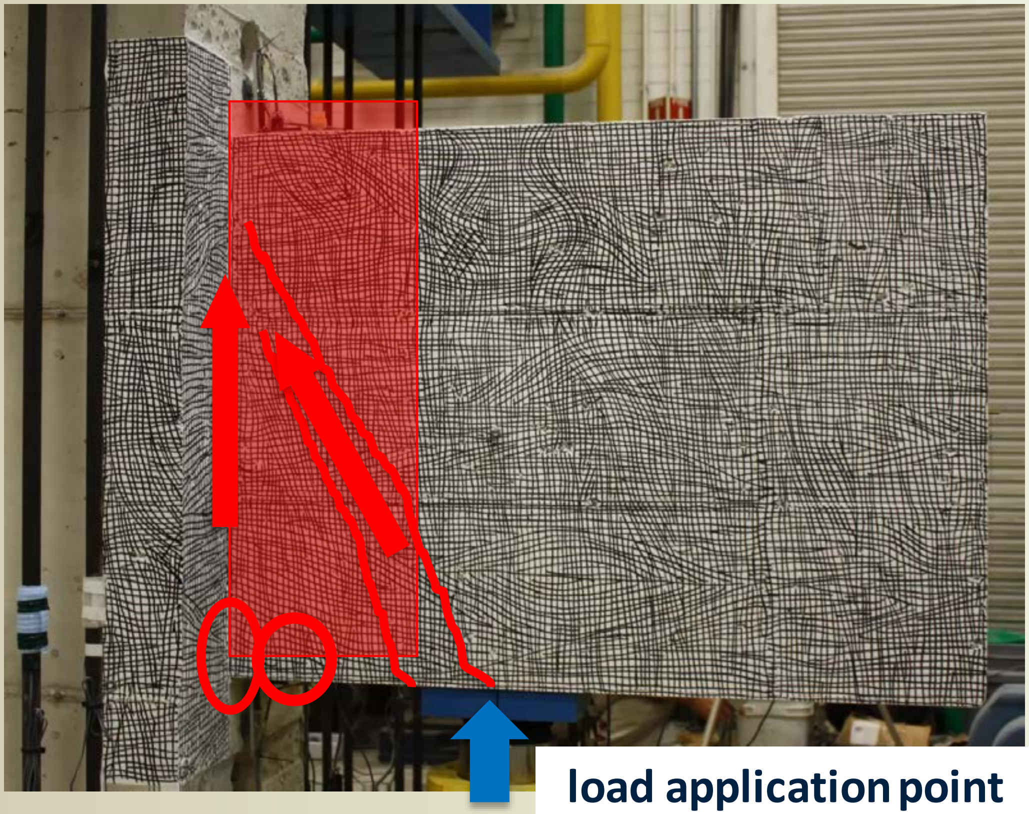
Slipping along 2nd diagonal crack

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



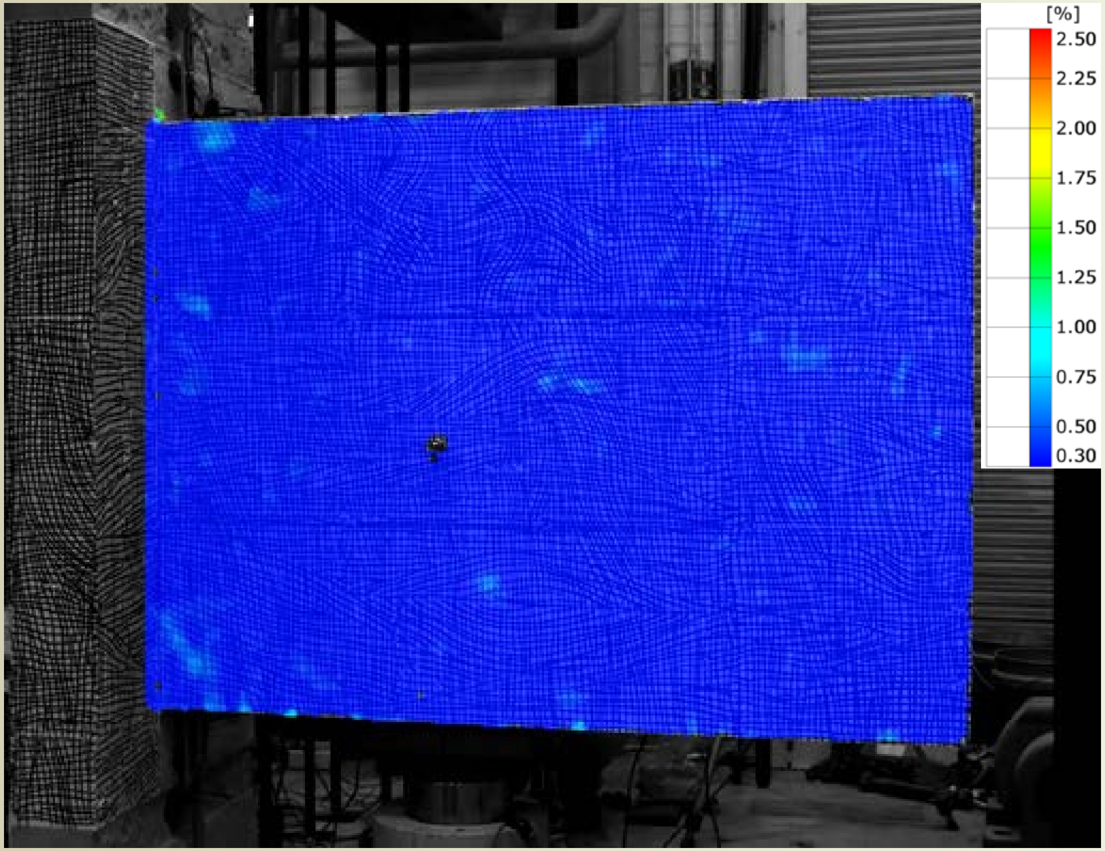


DB4 (f'_c = 14960 psi, f_y = 133 ksi)

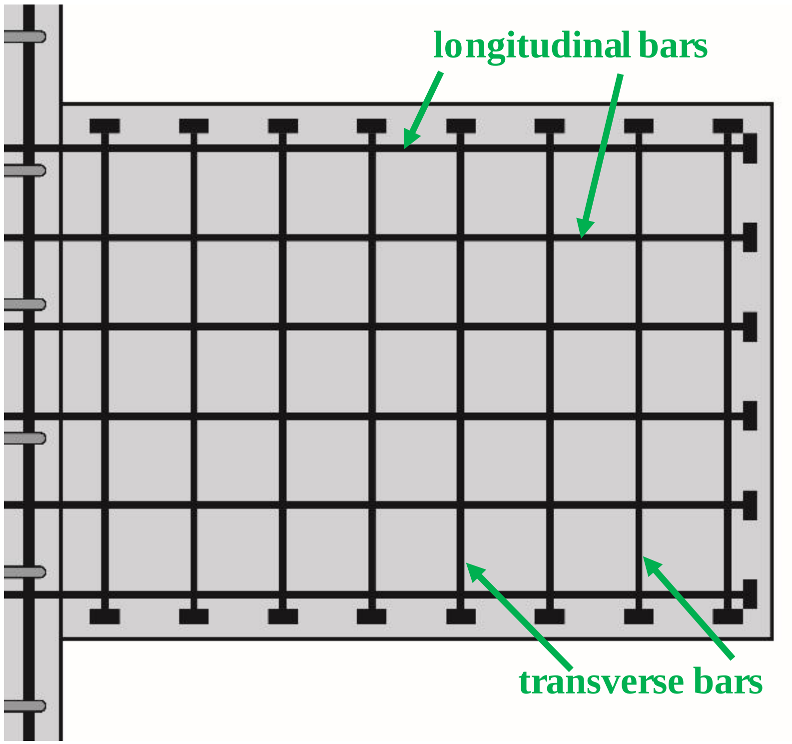


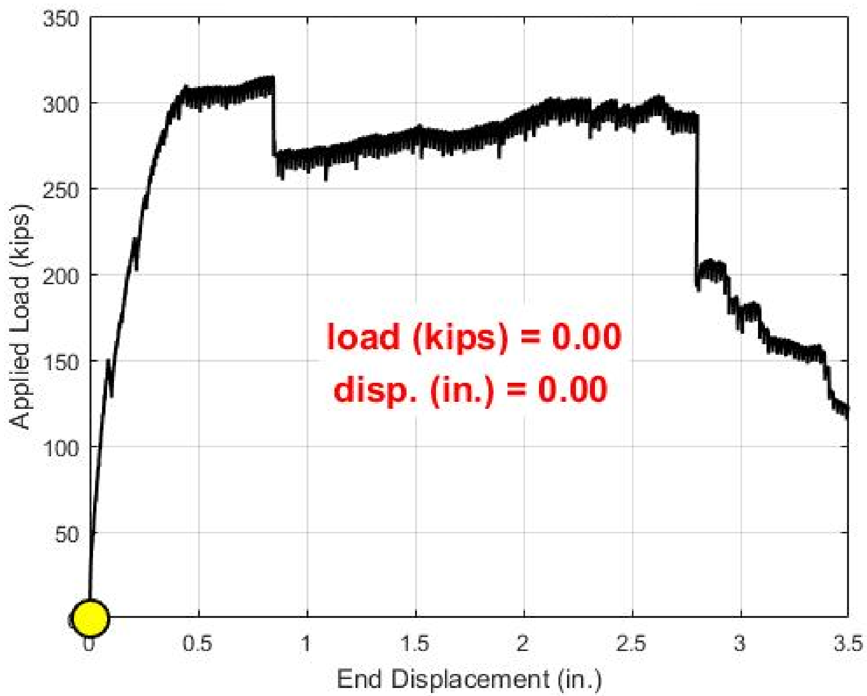
Significant concrete degradation through beam depth

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

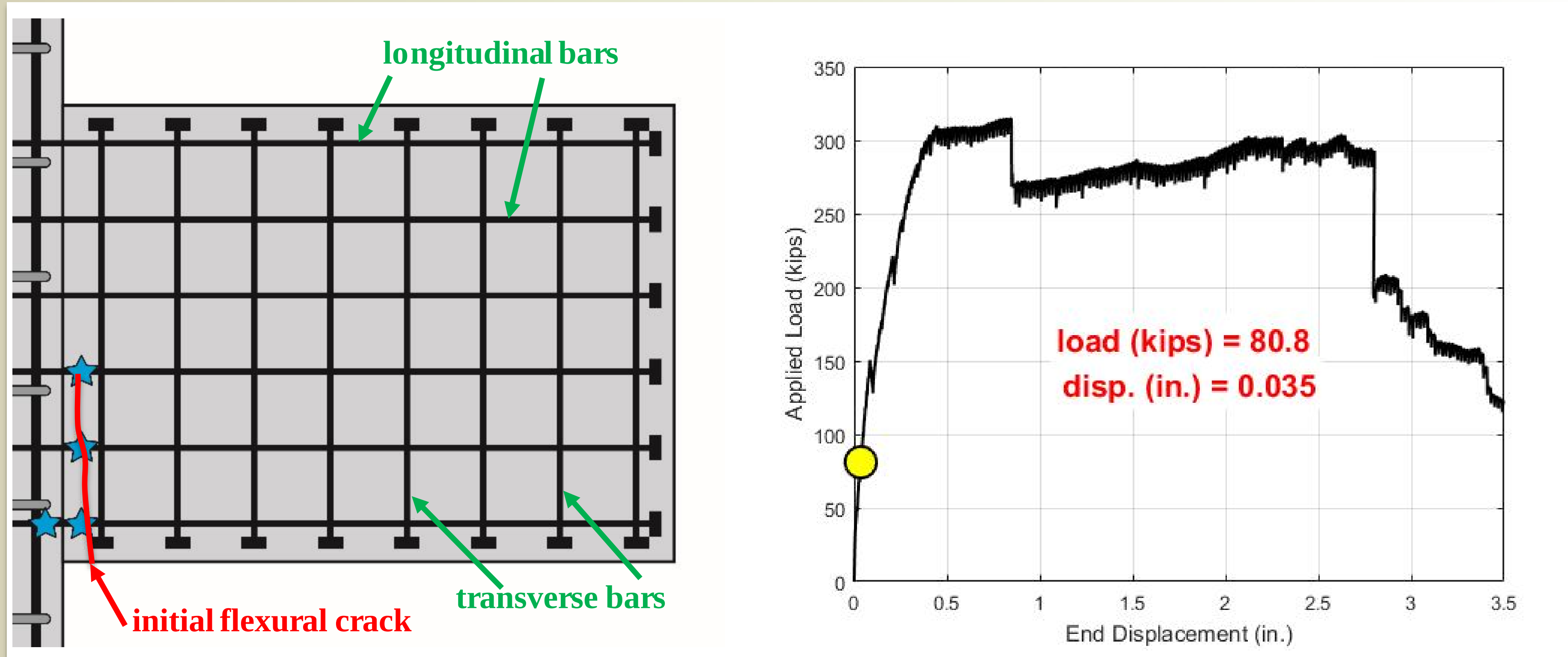


DB4 (f'_c = 14960 psi, f_y = 133 ksi)



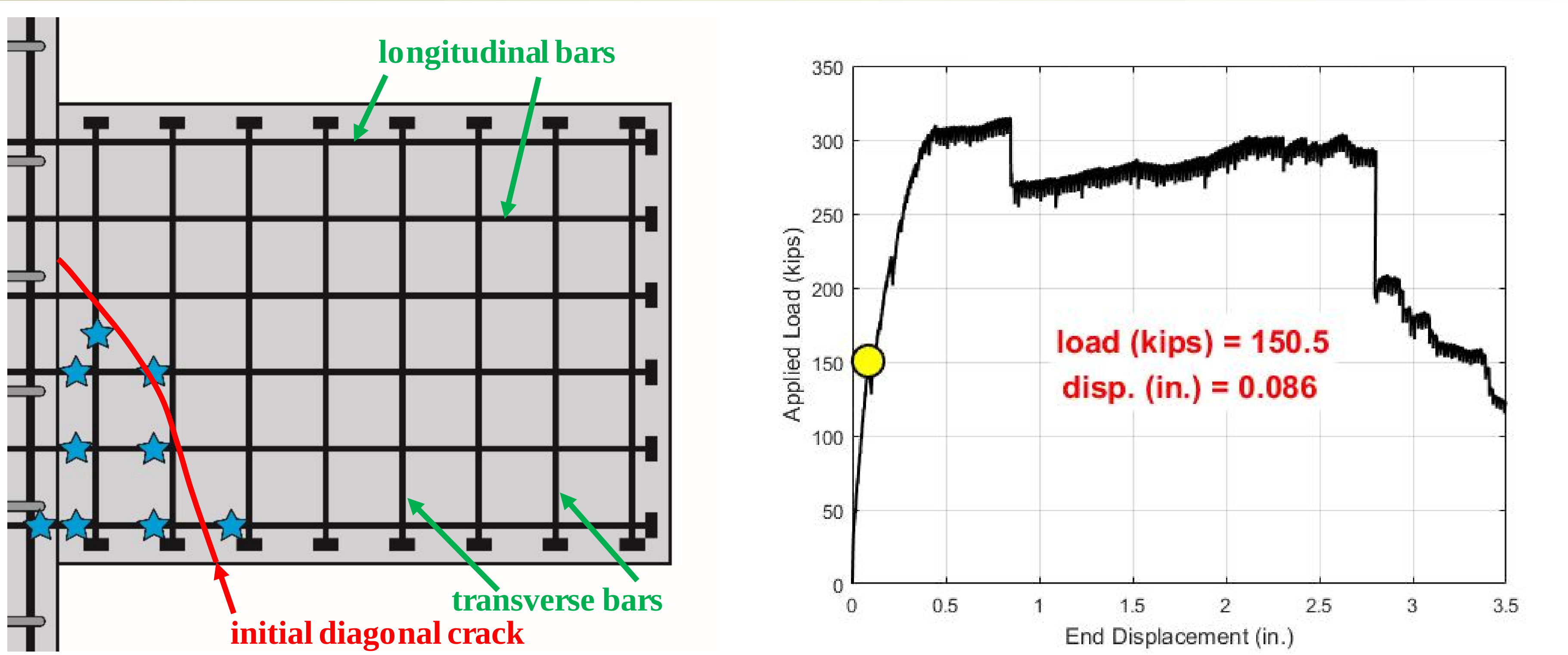


DB4 (f'_c = 14960 psi, f_y = 133 ksi)



Initial flexural cracking, bottom three longitudinal layers active in tension

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

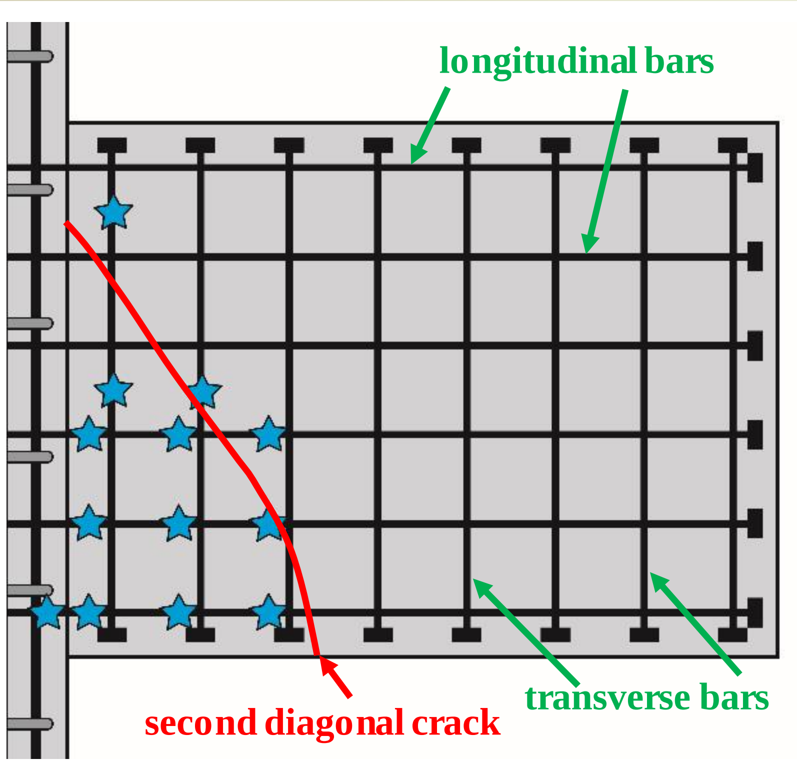


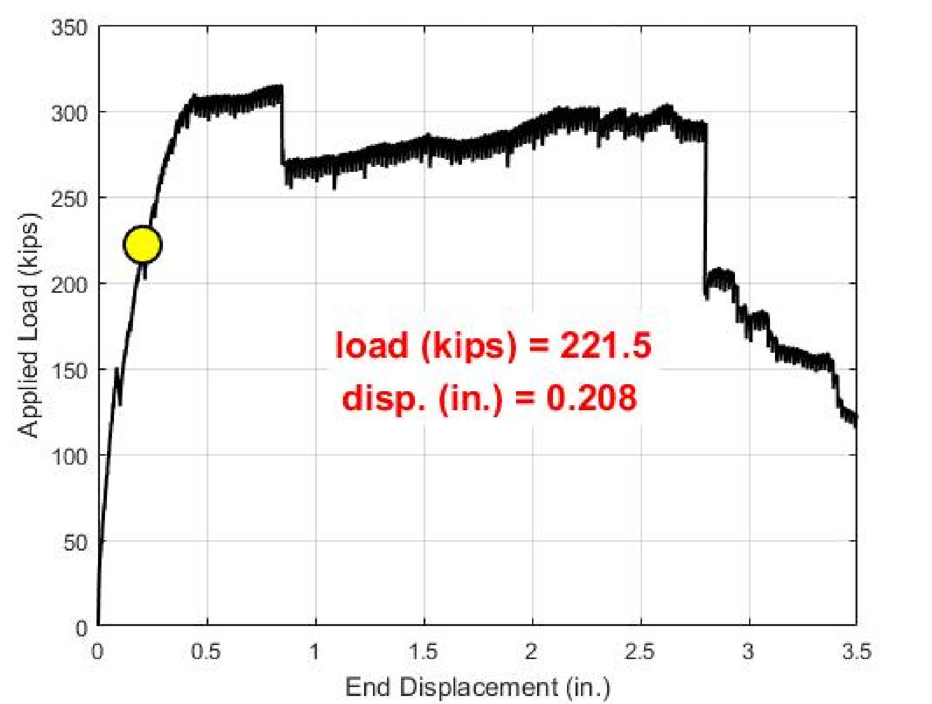
★ active tension strain

★ tension yield (6.85 mε)

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

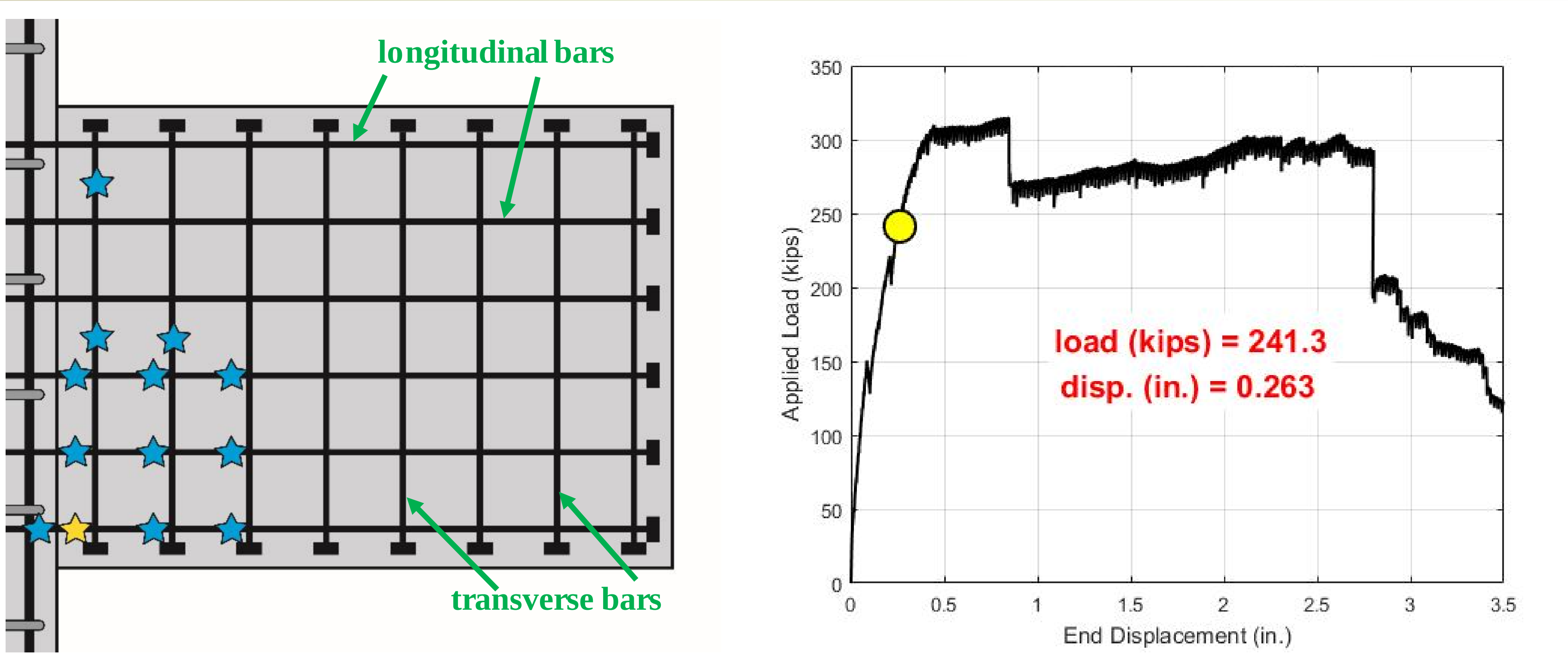
DB4 (f'_c = 14960 psi, f_y = 133 ksi)





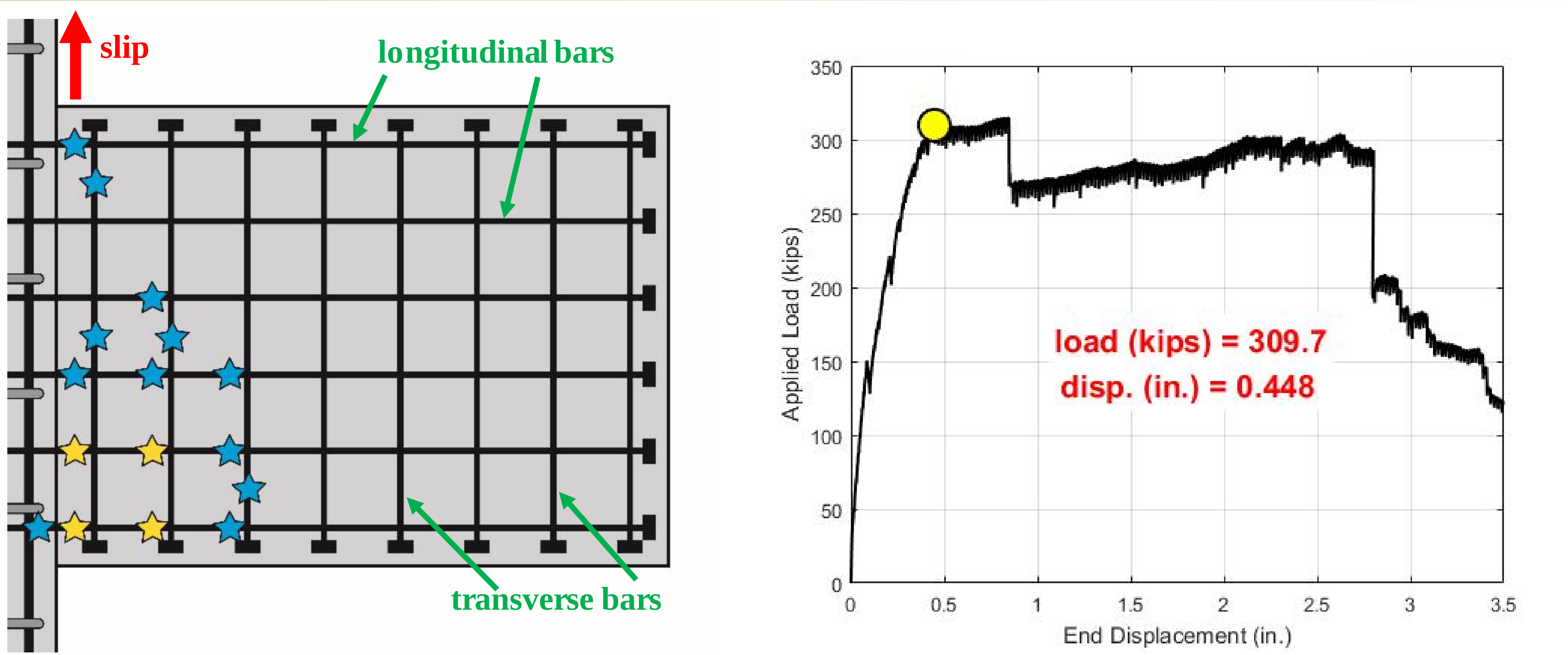
Two transverse bar layers and two longitudinal bar layers above the bottom experience strain increase

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



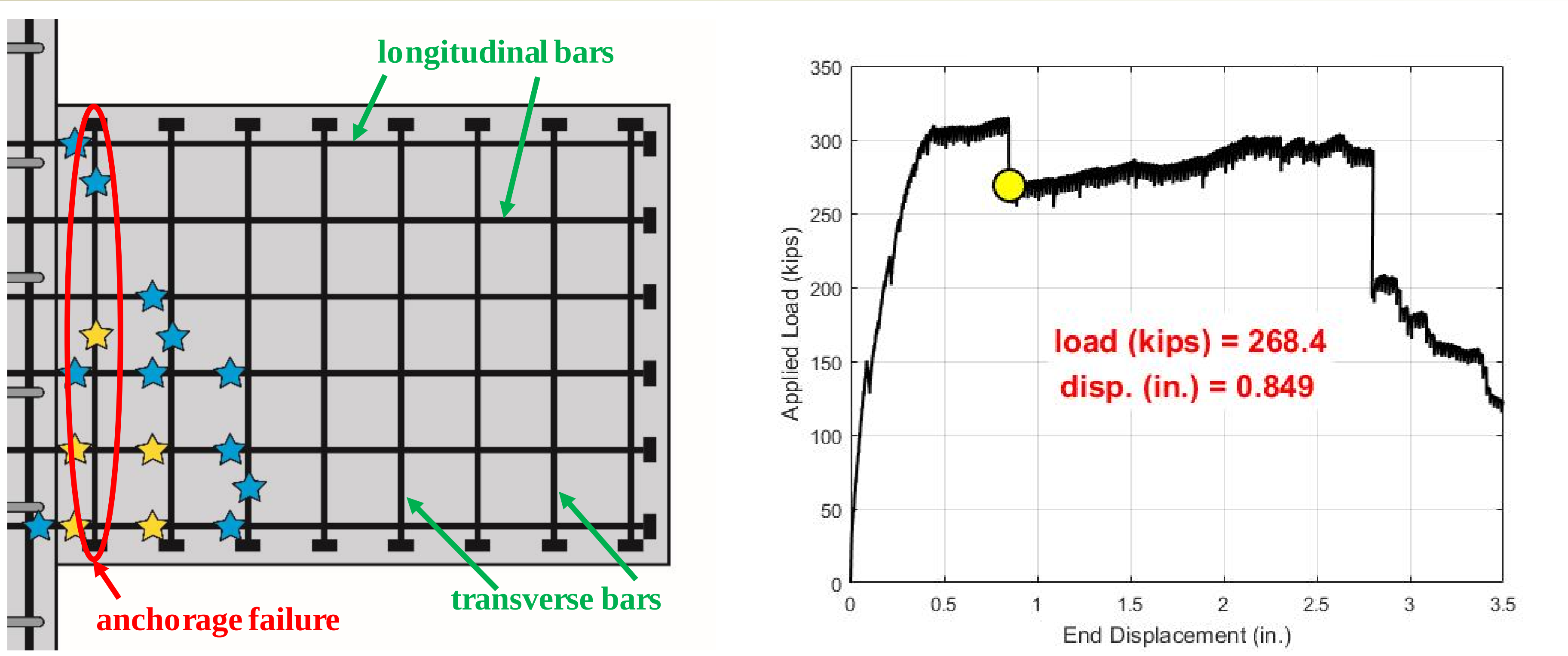
Initiation of longitudinal reinforcement yielding

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



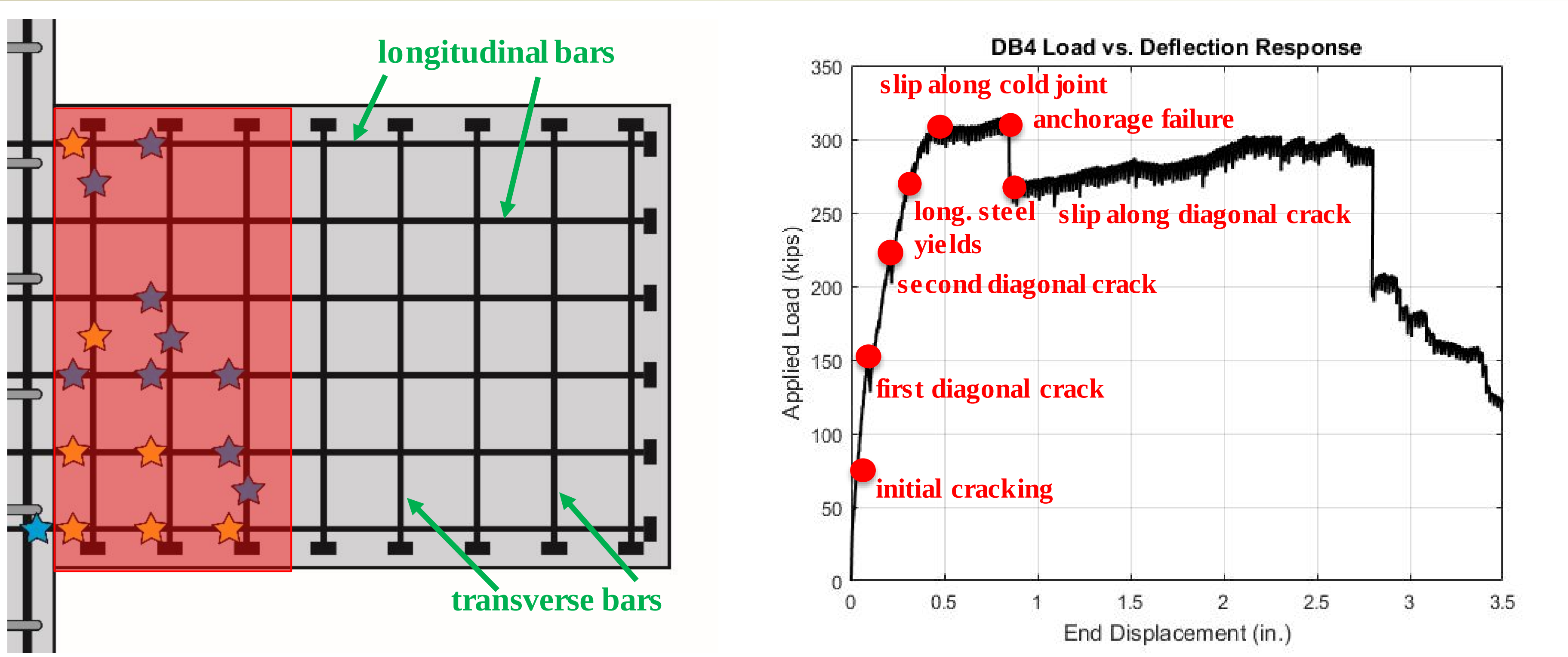
Slip at foundation interface
Extensive yielding of longitudinal reinforcement

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)

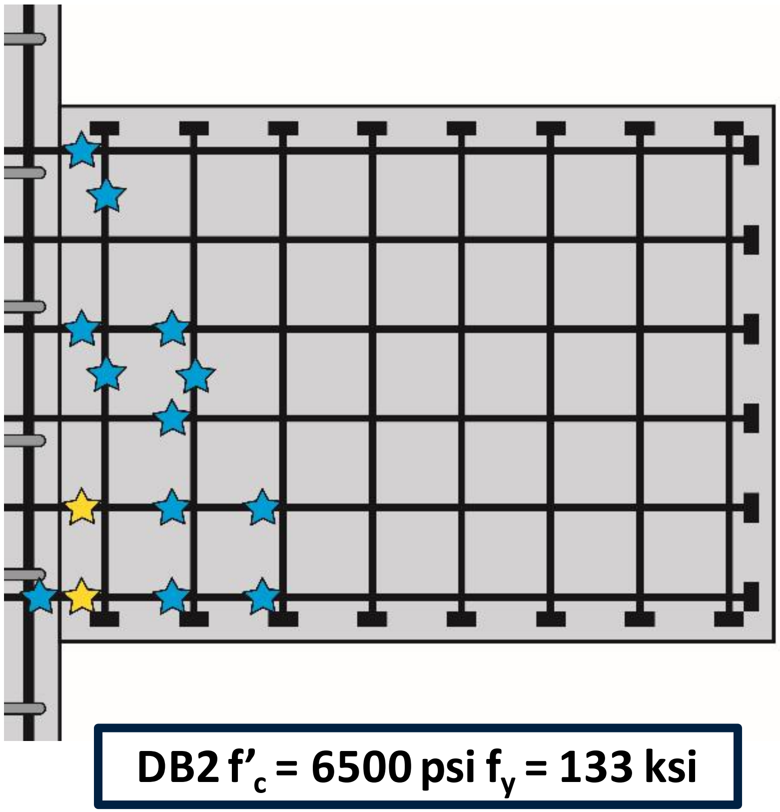


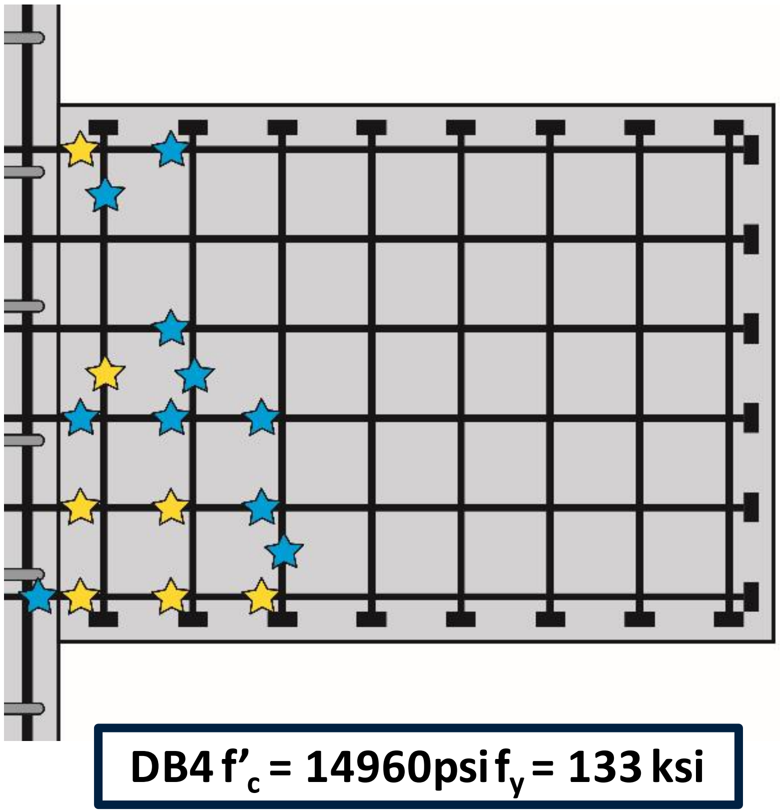
active tension strain

tension yield (6.85 mε)

Extensive concrete degradation

DB2 and DB4 Strain Comparisons





★ active tension strain

★ tension yield (6.85 mε)

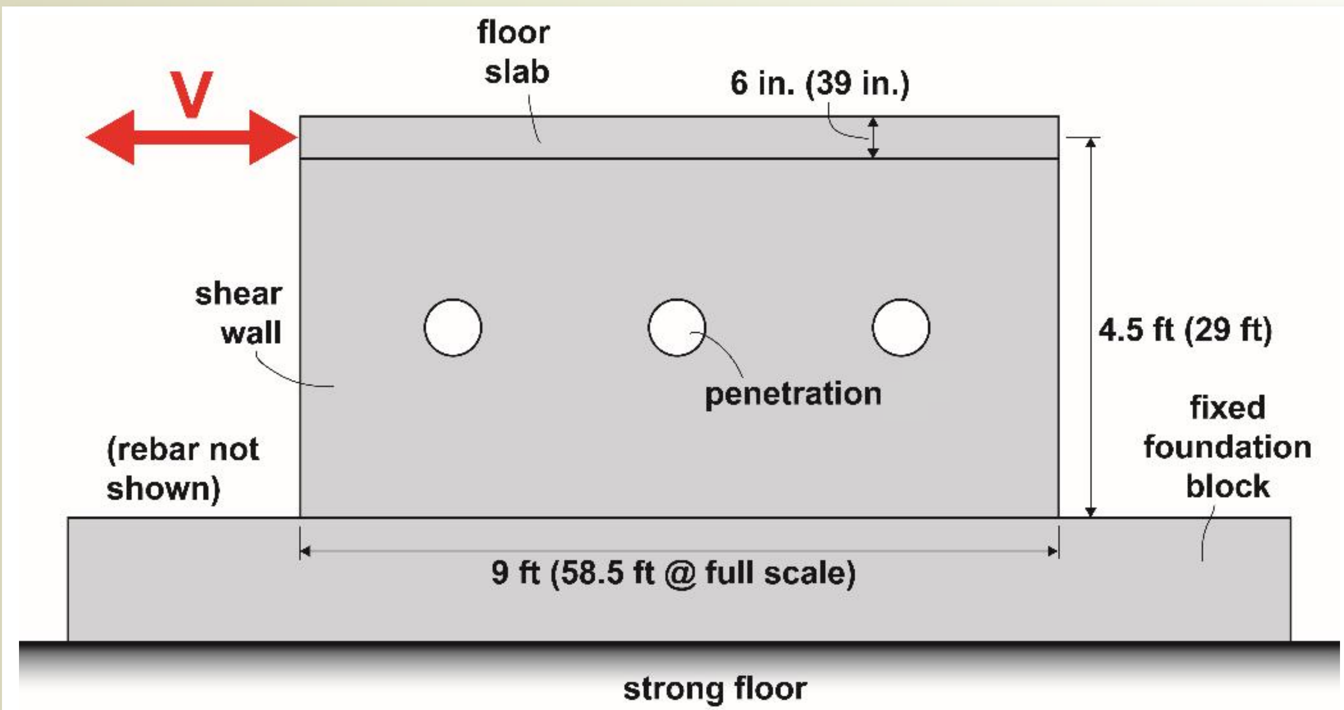
High-strength concrete able to better take advantage of higher yield strengths of reinforcement

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

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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- Federal Point of Contact: Alison Hahn
- Technical Point of Contact: Jack Lance
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- Material/Fabrication Donations:
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  - Dayton Superior Corp.
  - HRC, Inc.
  - Sika Corp. U.S.

Questions?

http://phsrc-nuclearwalls.nd.edu

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