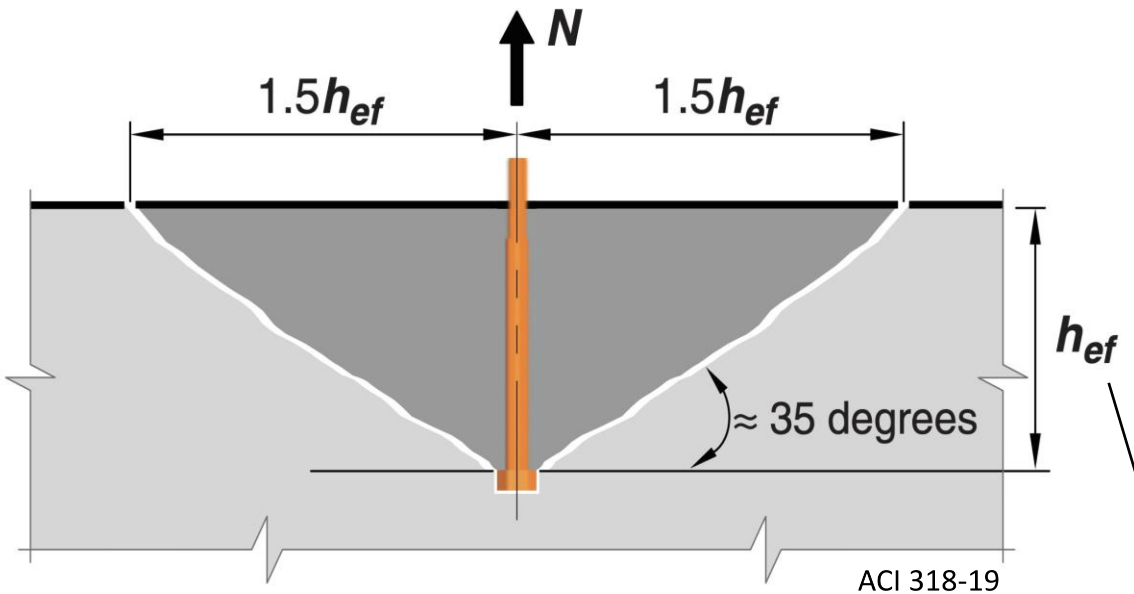
Shear-Reinforced Concrete Breakout Failure

Ben Worsfold, Assistant Prof. U Minnesota
Jack Moehle, Prof. UC Berkeley
John F. Silva, SE Hilti
10/31/23

Concrete Breakout Failure Cone

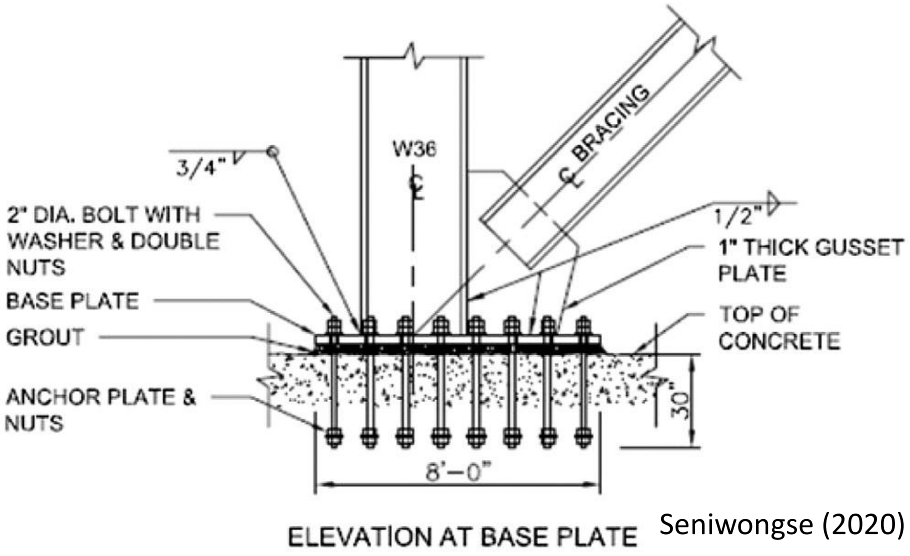


ACI 318-19

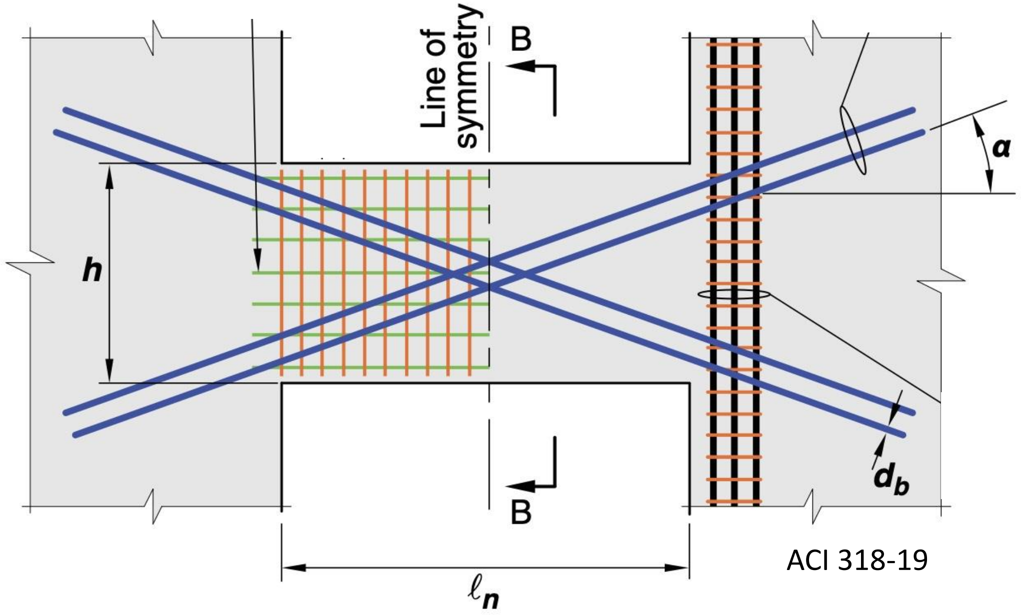
Is breakout failure relevant for large-scale connections involving groups of anchors or reinforcing bars?

Effective depth

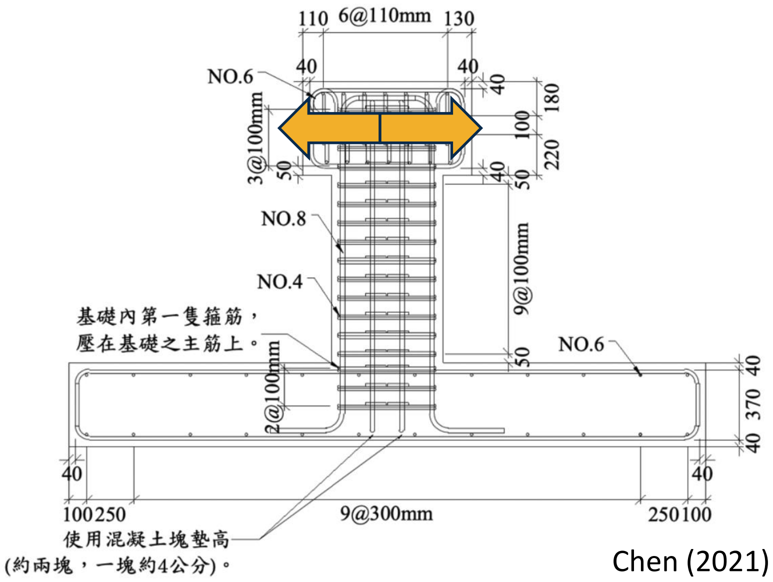
Breakout Potential?



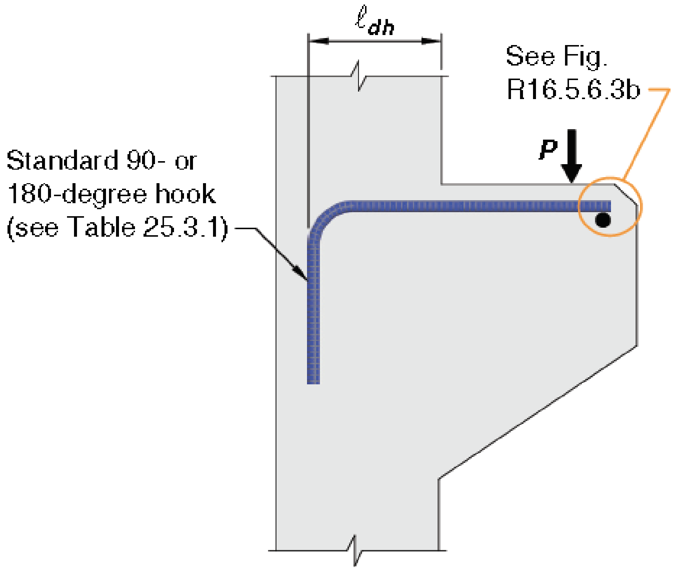
Seniwongse (2020)



ACI 318-19

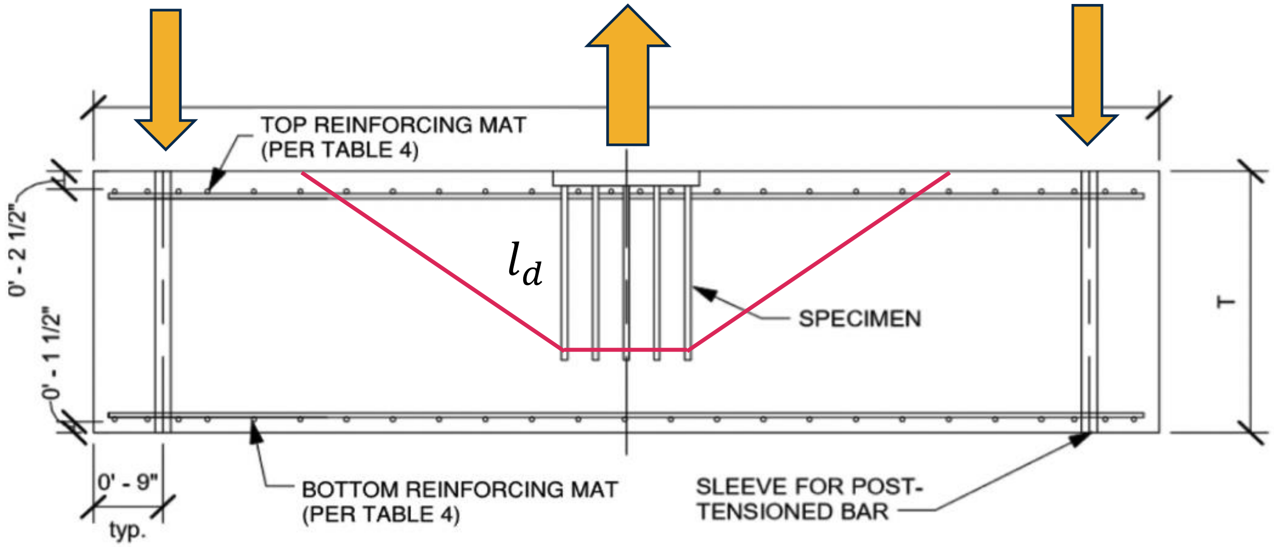


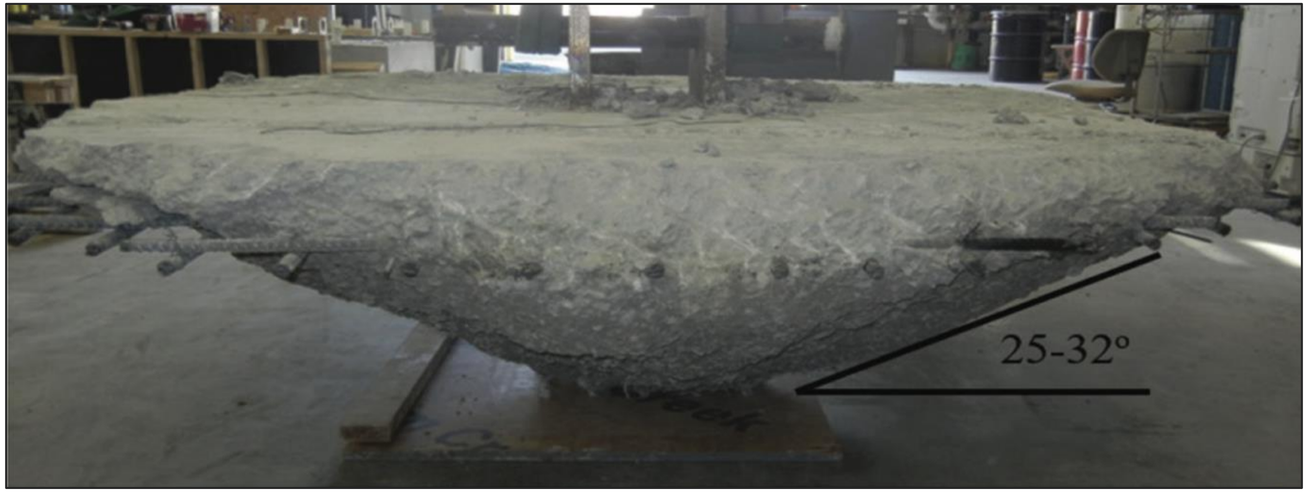
Chen (2021)



ACI 318-19

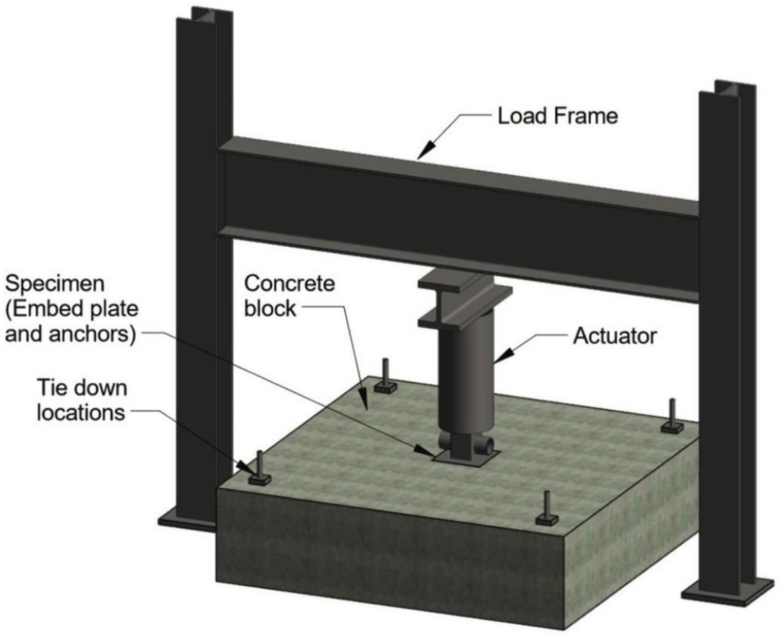
Premature Breakout Failure Examples





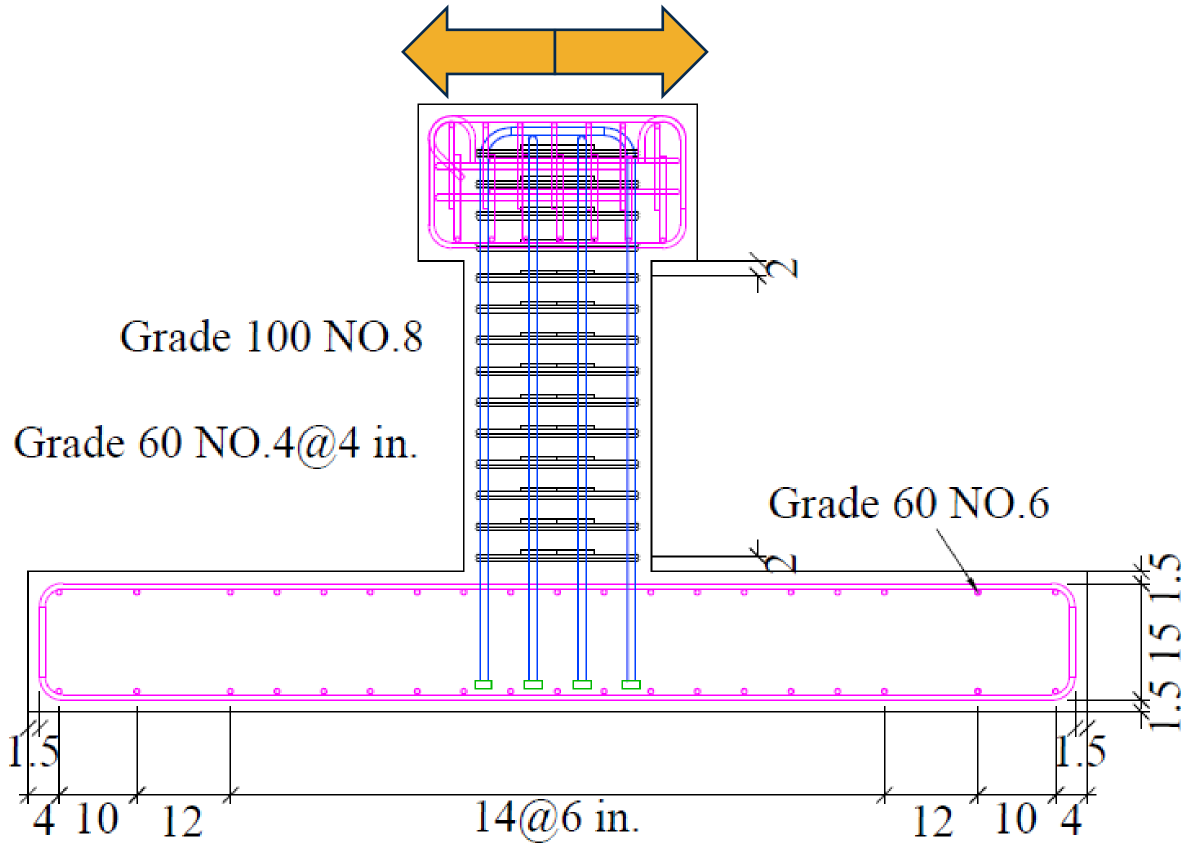
Chicchi et al. (2020)

- Purdue
- Up to 5x5 Groups of straight bars Embedded developed length
- Breakout failure governed before nominal bar yield



Premature Breakout Failure Examples

- Taiwan National University of Science and Technology
- Breakout before nominal bar yield



Chen (2021)

Observations from Physical Tests

1. Breakout failure can govern for large-scale connections even when development length is provided.

> **17.1.6** Reinforcement used as part of an embedment shall have development length established in accordance with other parts of this Code. If reinforcement is used as anchorage, concrete breakout failure shall be considered. Alternatively, anchor reinforcement in accordance with 17.5.2.1 shall be provided.

ACI 318-19

2. Breakout equations in Chapter 17 are conservative.

- Example breakout strength specimen M01:

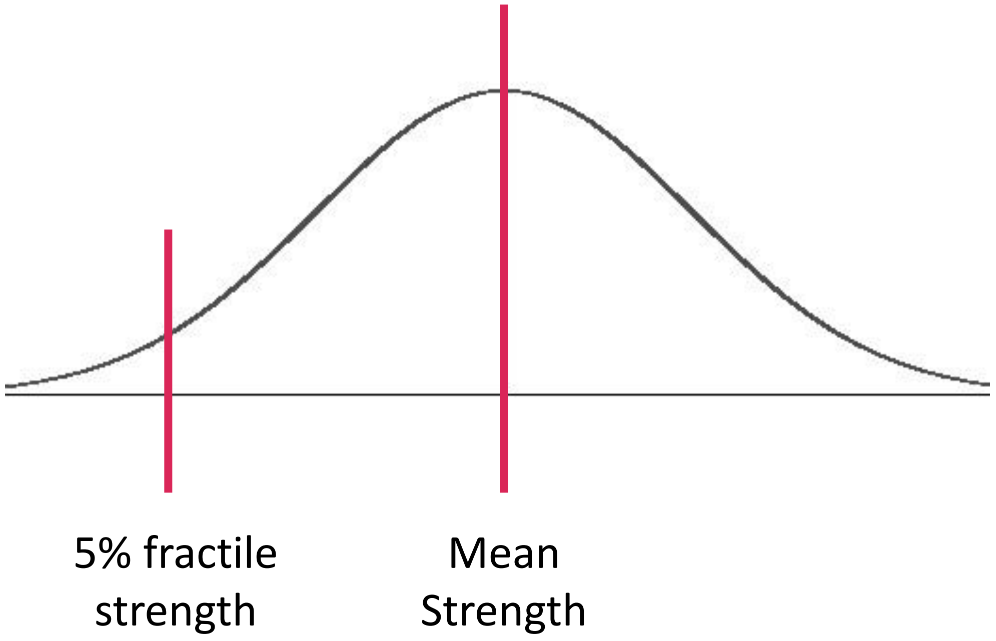
$$N_{test} = 253\ kip$$

$$\Phi N_{cbg} = 77\ kip \text{ (cracked)}$$

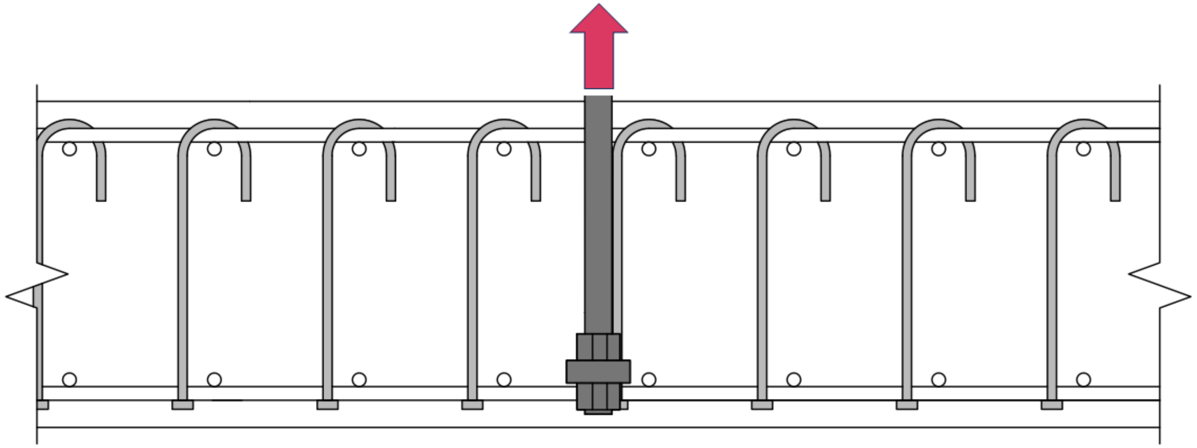
$$\frac{N_{test}}{\Phi N_{cbg}} = 3.3$$

Sources of Breakout Conservatism

5% Fractile Strength



Reinforcement not included in breakout strength



ACI 318 Anchor Reinforcement

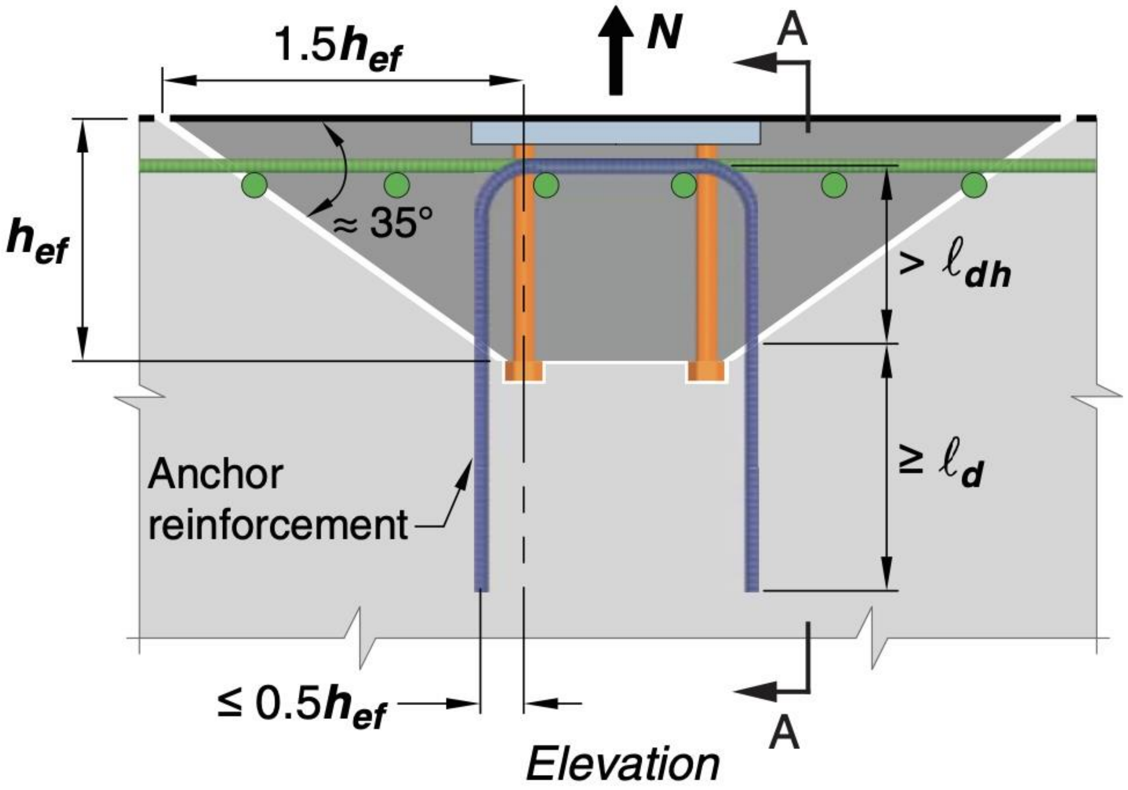


***Fig. R17.5.2.1a**—Anchor reinforcement for tension.*

Breakout failure is precluded (assumption)

Shear-Reinforced Breakout (SRB)

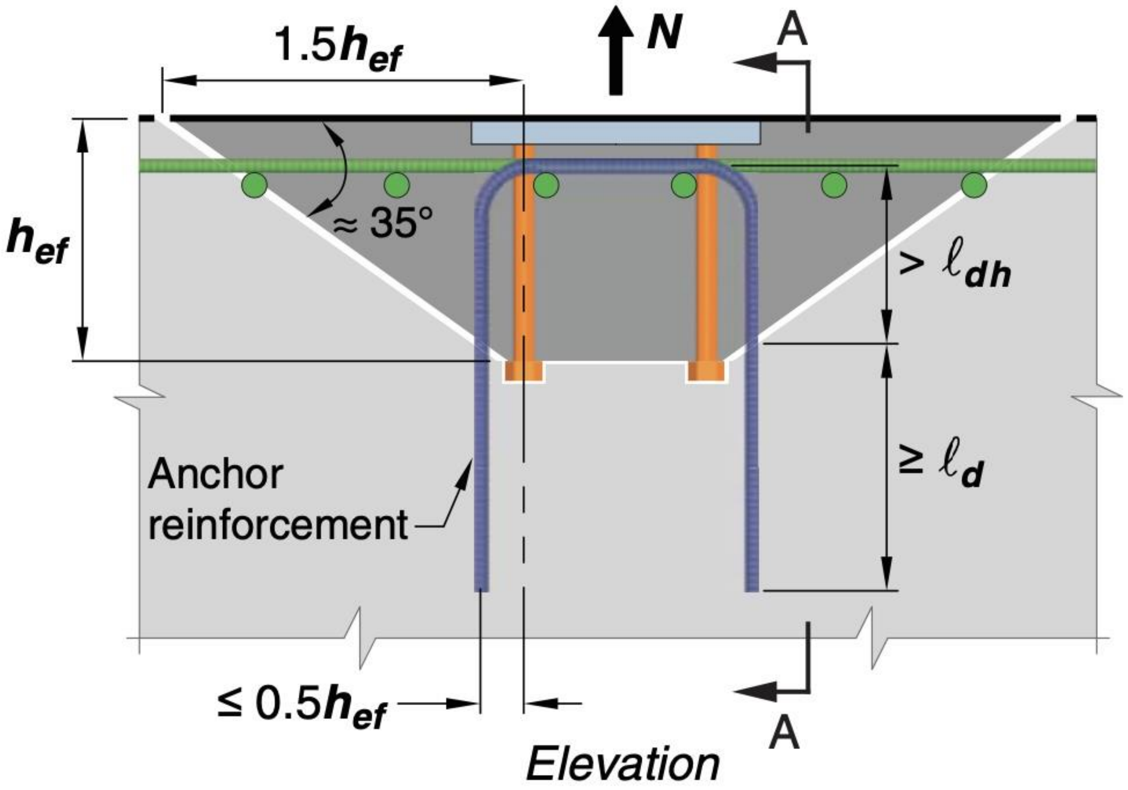


Fig. R17.5.2.1a—Anchor reinforcement for tension.

$$\boxed{N_{n,SRB} = N_c + N_s\ ?}$$

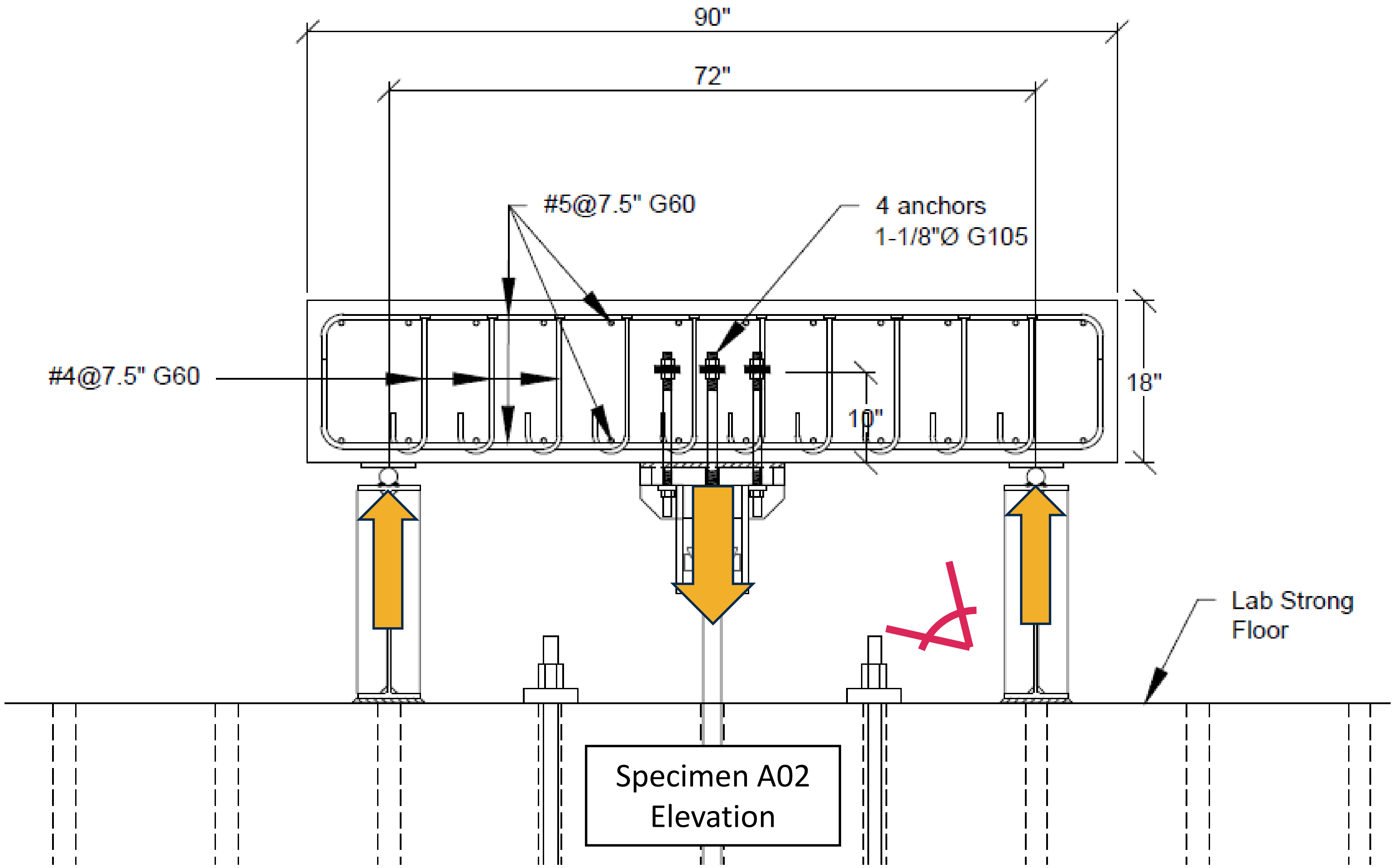
Question:

- Detailing requirements?
- Size of reinforced region?
- Upper limits to steel strength?

Shear-Reinforced Breakout Tests

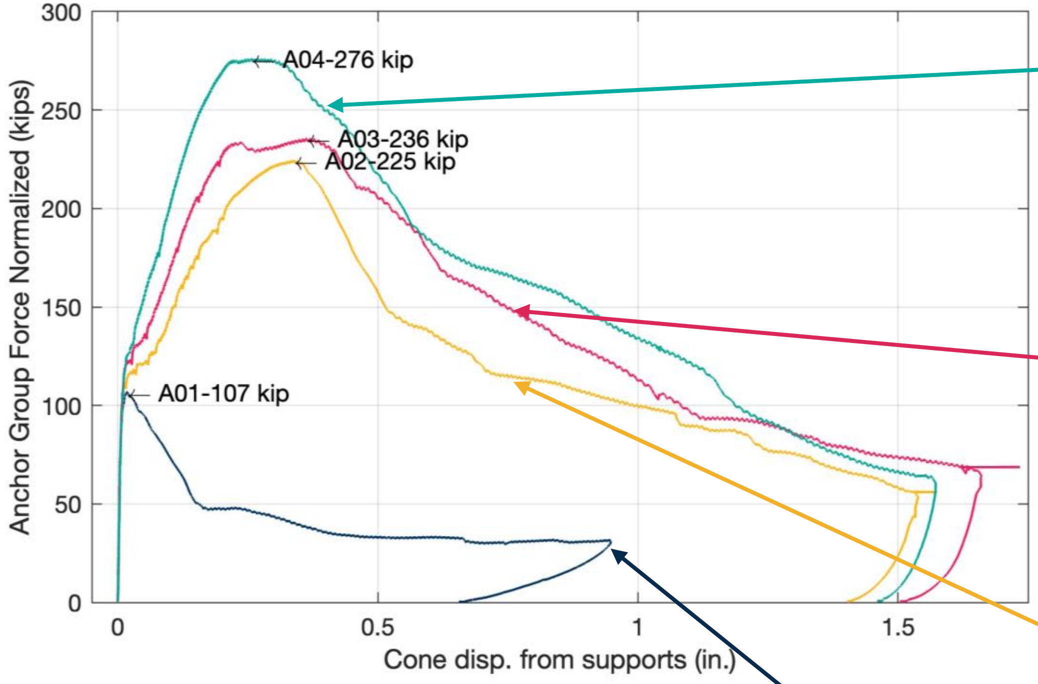
- UC Berkeley
- Four monotonic axial loading tests
- Breakout failures for all specimens

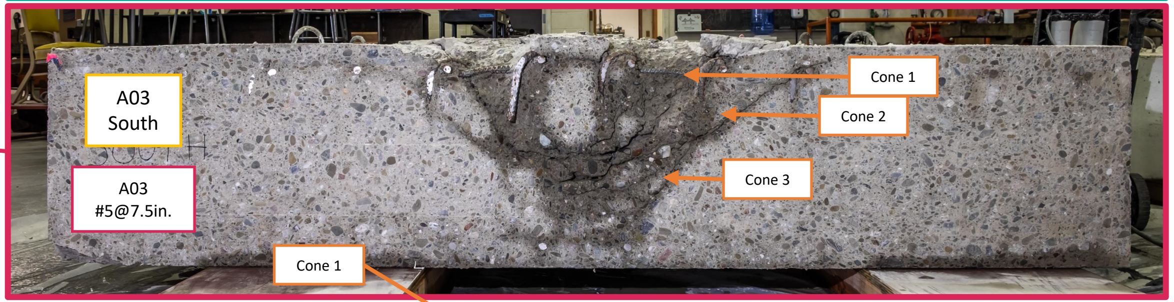
Specimen	Shear Reinforcement	Reinforcing ratio, ρ_{tr} (%)
A01	N/A	0
A02	#4@7.5in.	0.36%
A03	#5@7.5in.	0.55%
A04	#4@6in.	0.56%



Karać (2023)

Shear-Reinforced Breakout Tests

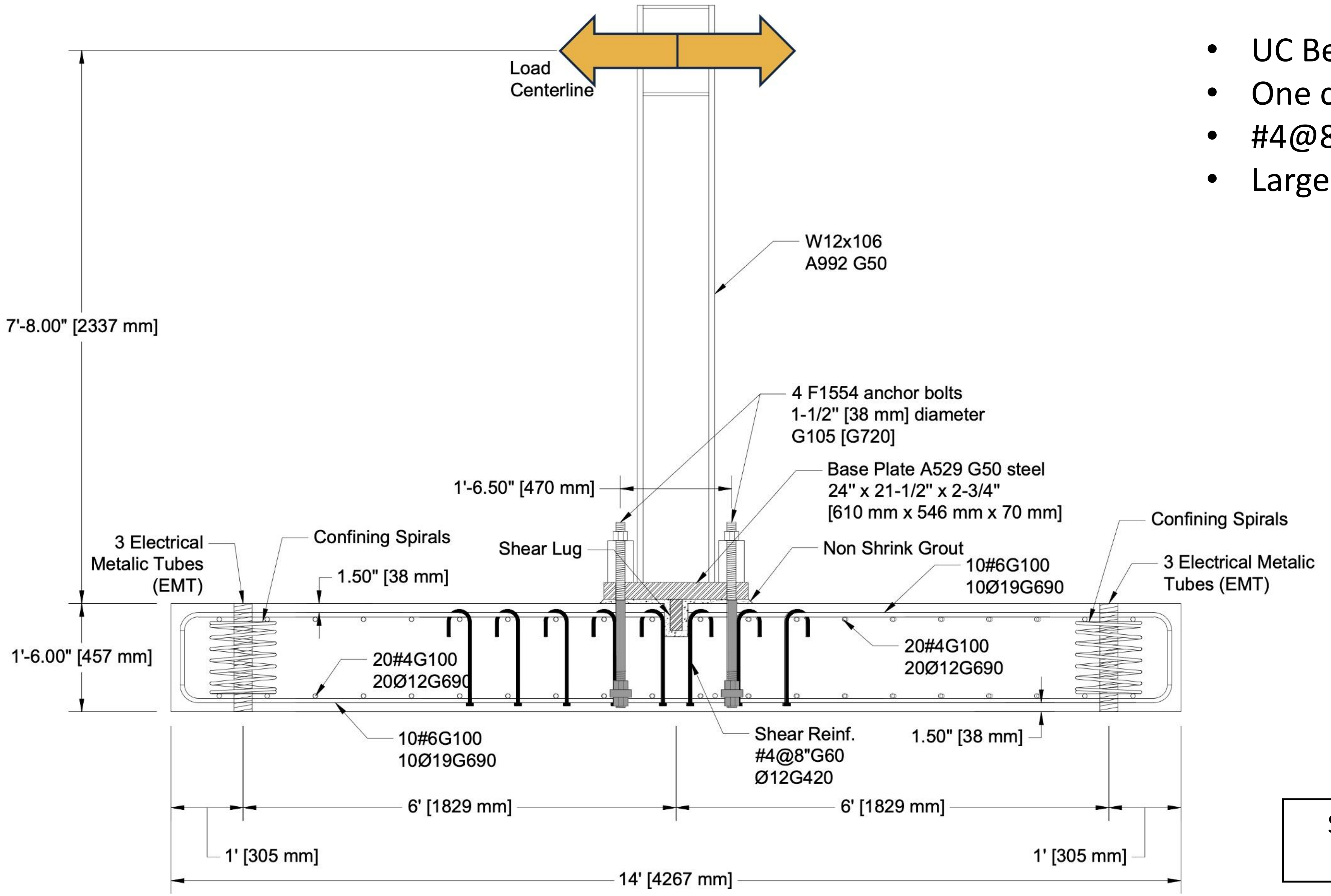




Increased
- Peak strength
- Displacement capacity

Karać (2023)

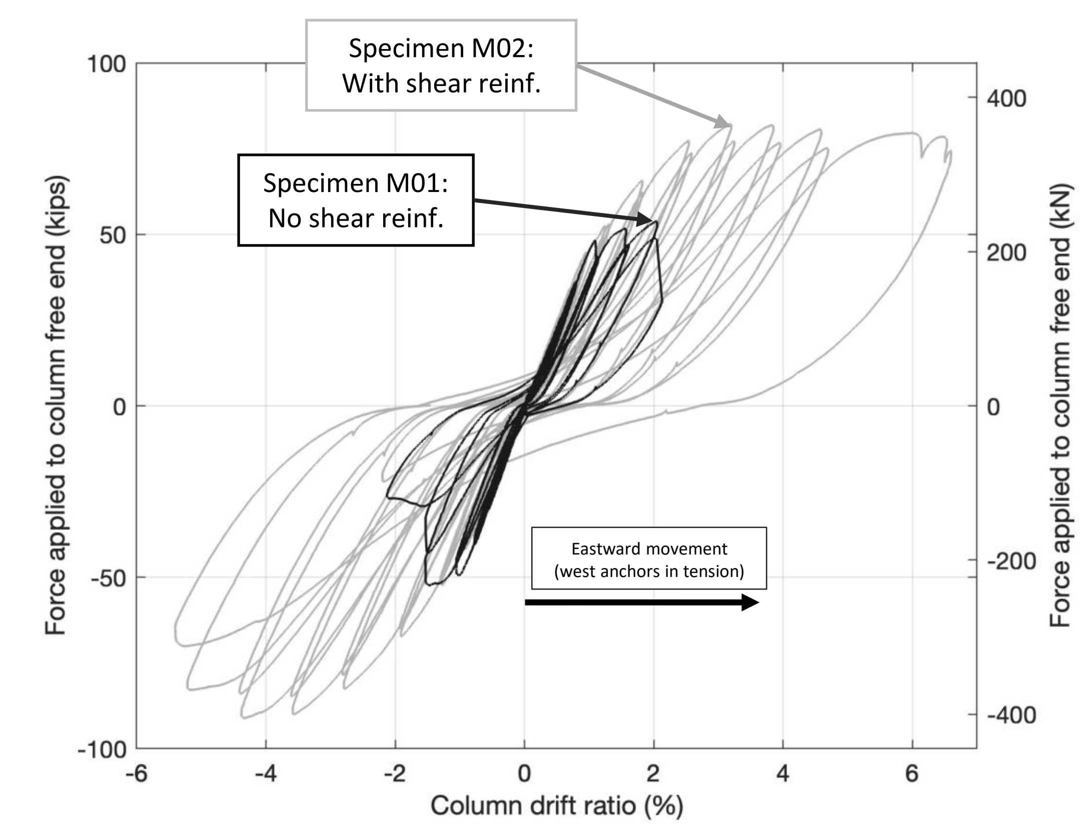
Shear-Reinforced Breakout Tests



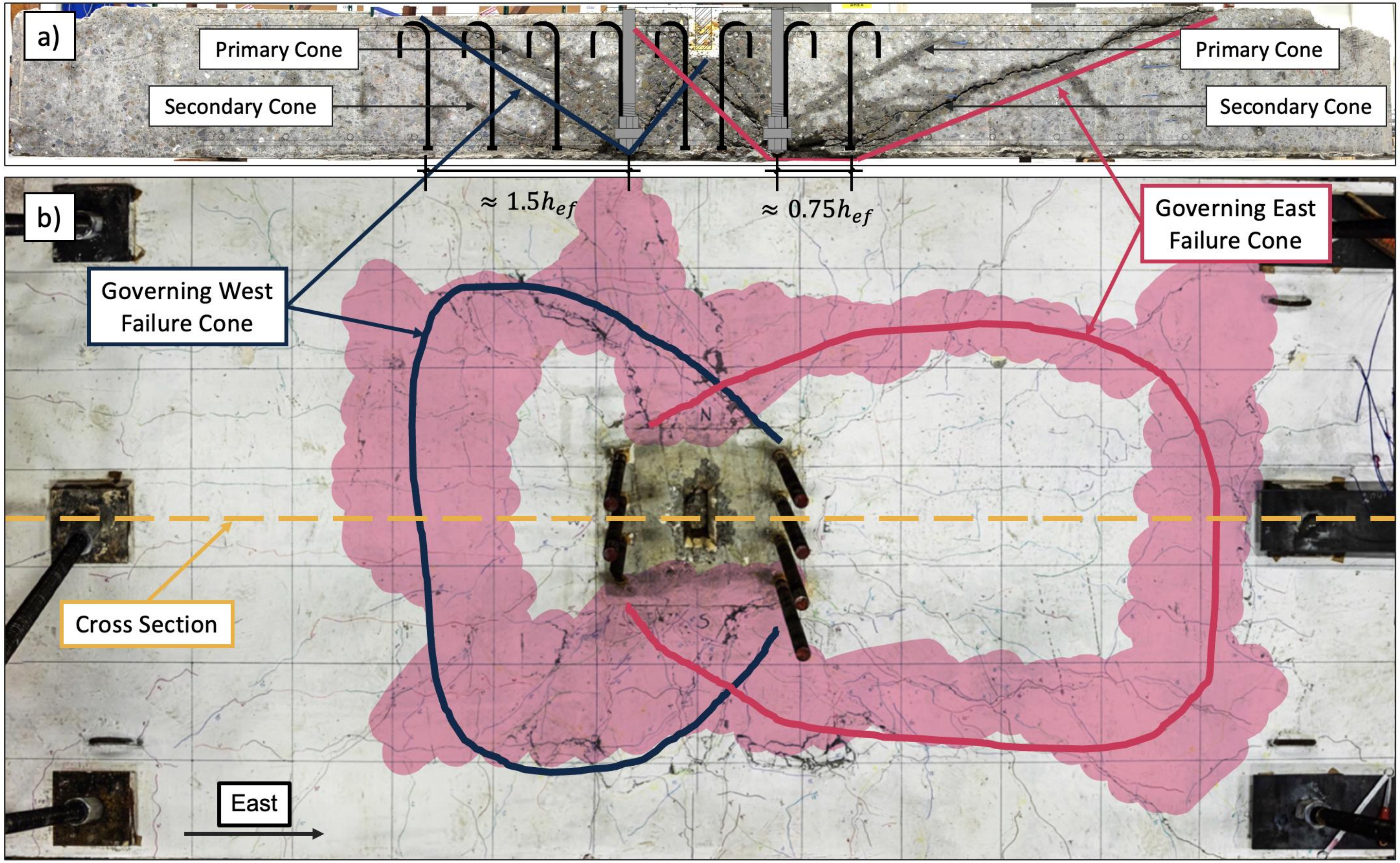
- UC Berkeley
- One cyclic moment-transfer tests
- #4@8” G60
- Larger reinforced region on one side

Specimen M02
Elevation

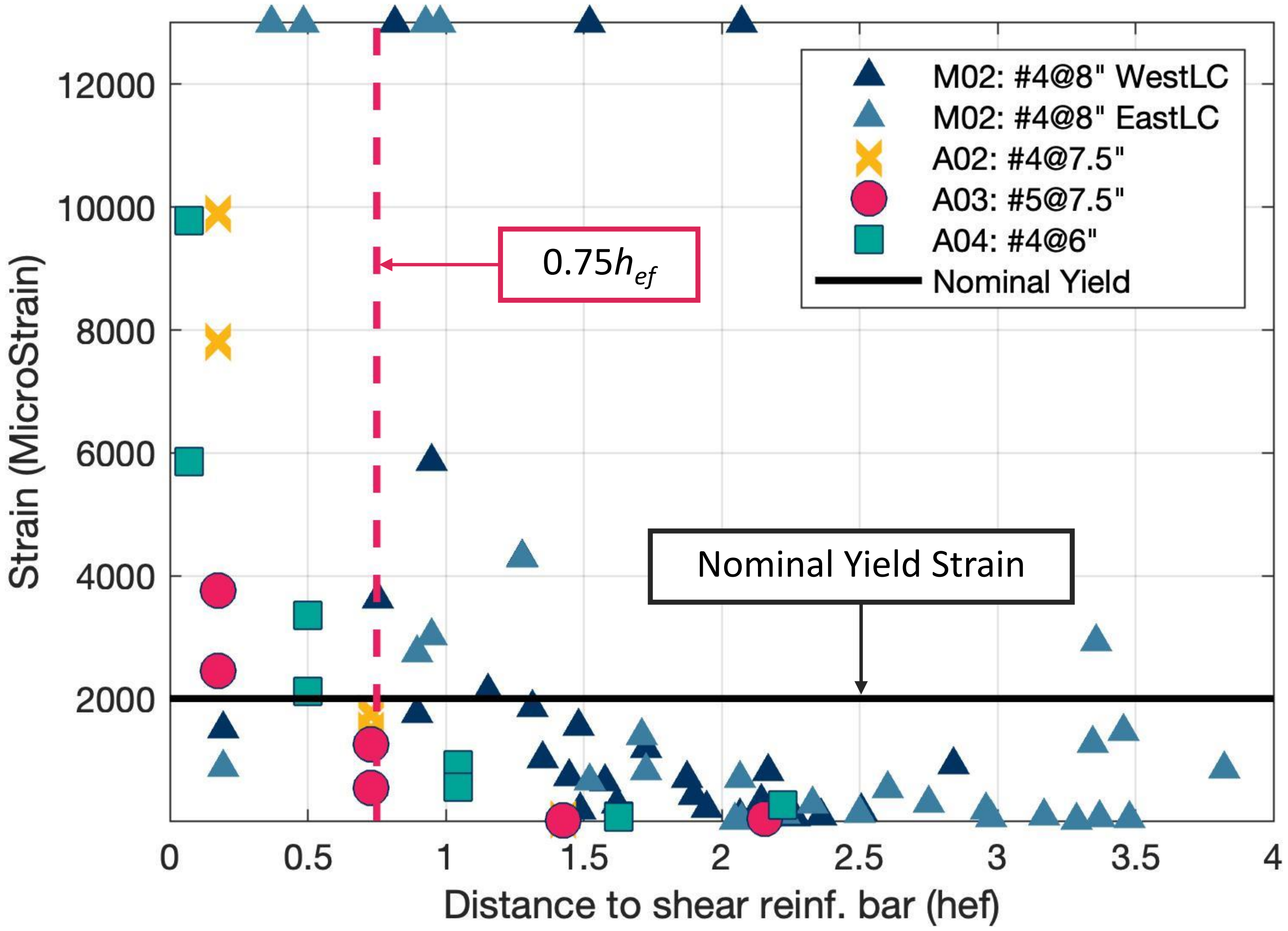
Specimen M02:
#4@8”



Shear-Reinforced Breakout Tests

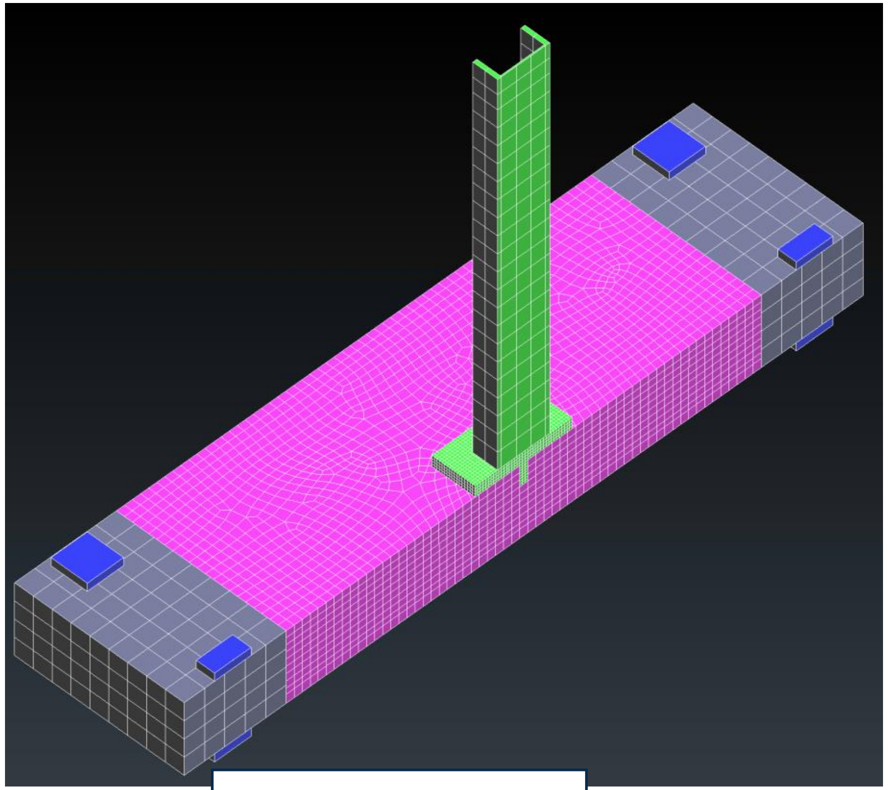


Shear Bar Strains

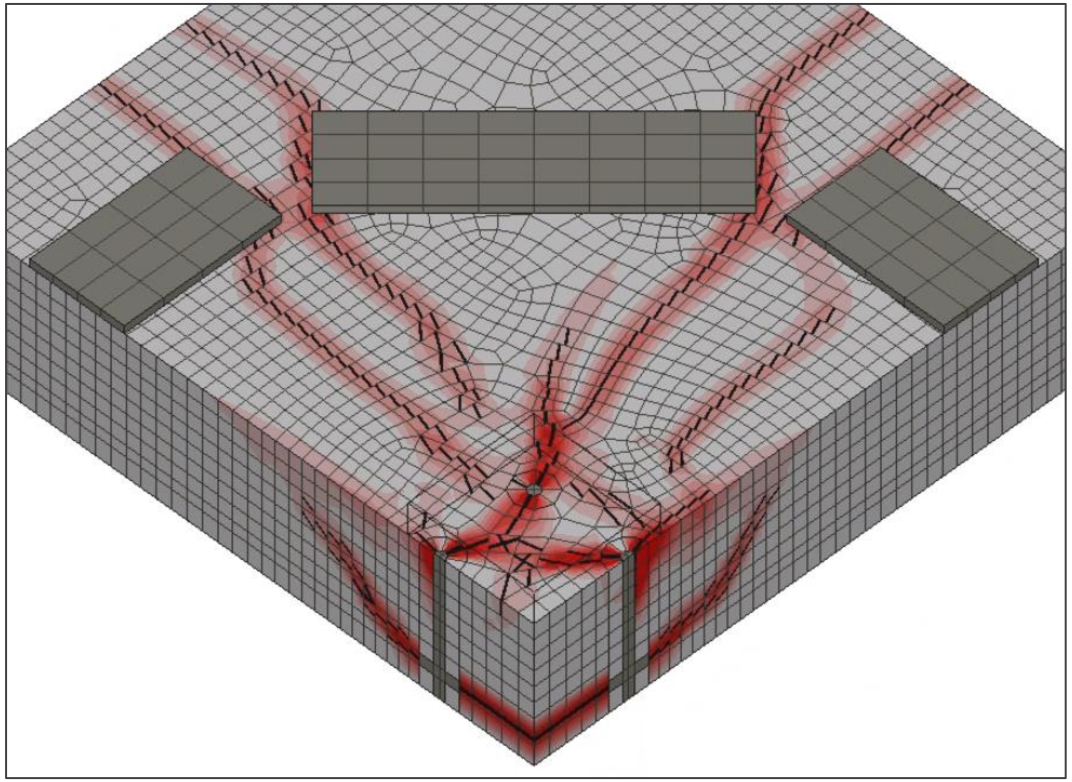


Finite Element Studies

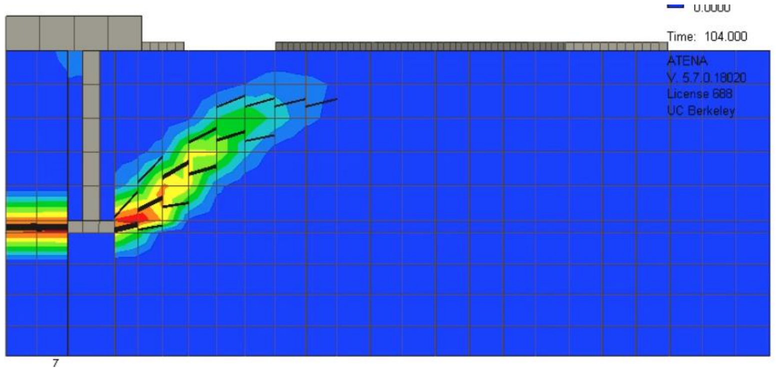
ATENA
Reinforced Concrete Modeling



M01 Model



FE Crack Pattern



FE Crack Pattern

Shear-Reinforced Breakout (SRB) Design Equation

$$\boxed{N_{n,SRB} = N_c + N_s}$$

Nominal anchor strength for shear-reinforced breakout

Mean concrete breakout strength

Mean reinforcement strength

Shear-Reinforced Breakout (SRB) Design Equation

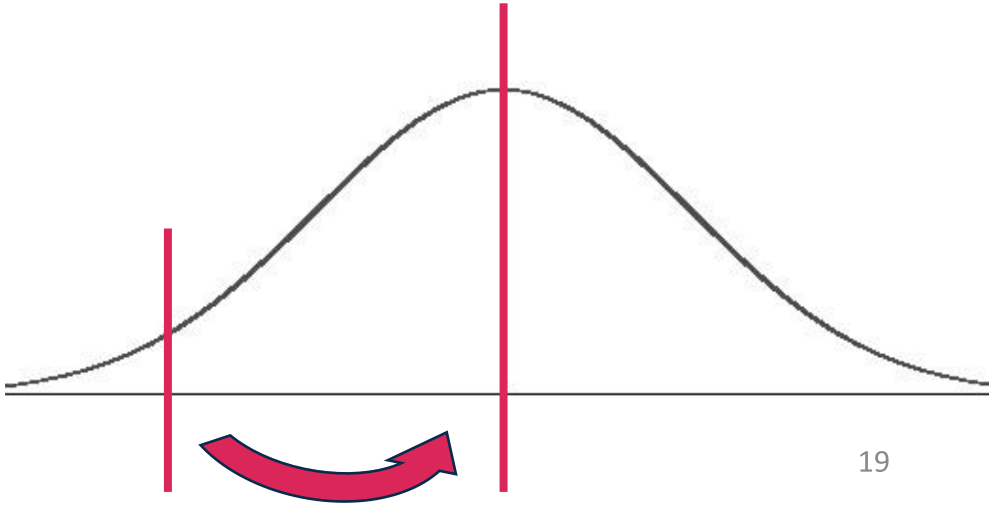
$$\boxed{N_c = 1.33 N_{cbg}}$$

Mean concrete breakout strength

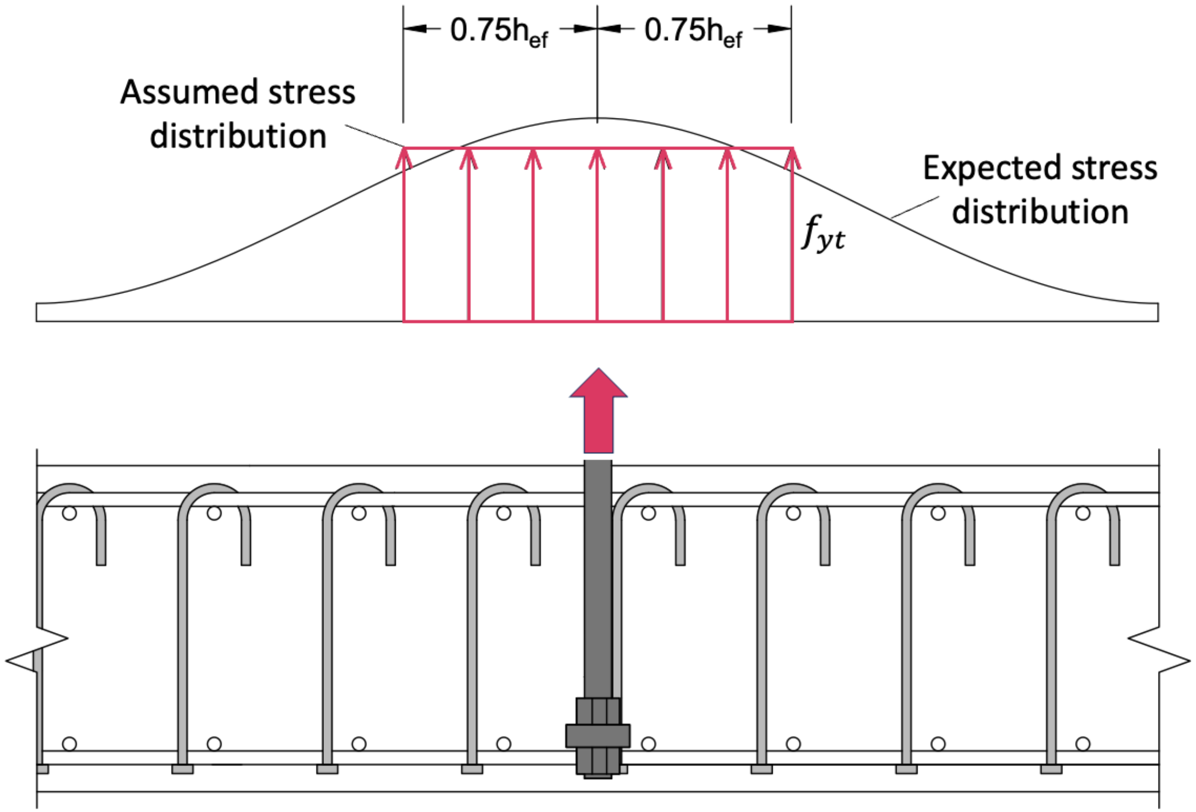
5% fractile strength ACI 318-19 Chap. 17

$$\frac{1}{1 + z_{0.05} * CV} = \frac{1}{1 + (-1.645) * 0.15} = 1.33$$

Fuchs (1995)



Shear-Reinforced Breakout (SRB) Design Equation



Shear-Reinforced Breakout Design Equation

$$\boxed{N_s = A_{eff}\,\rho_{tr}\,f_{yt}}$$

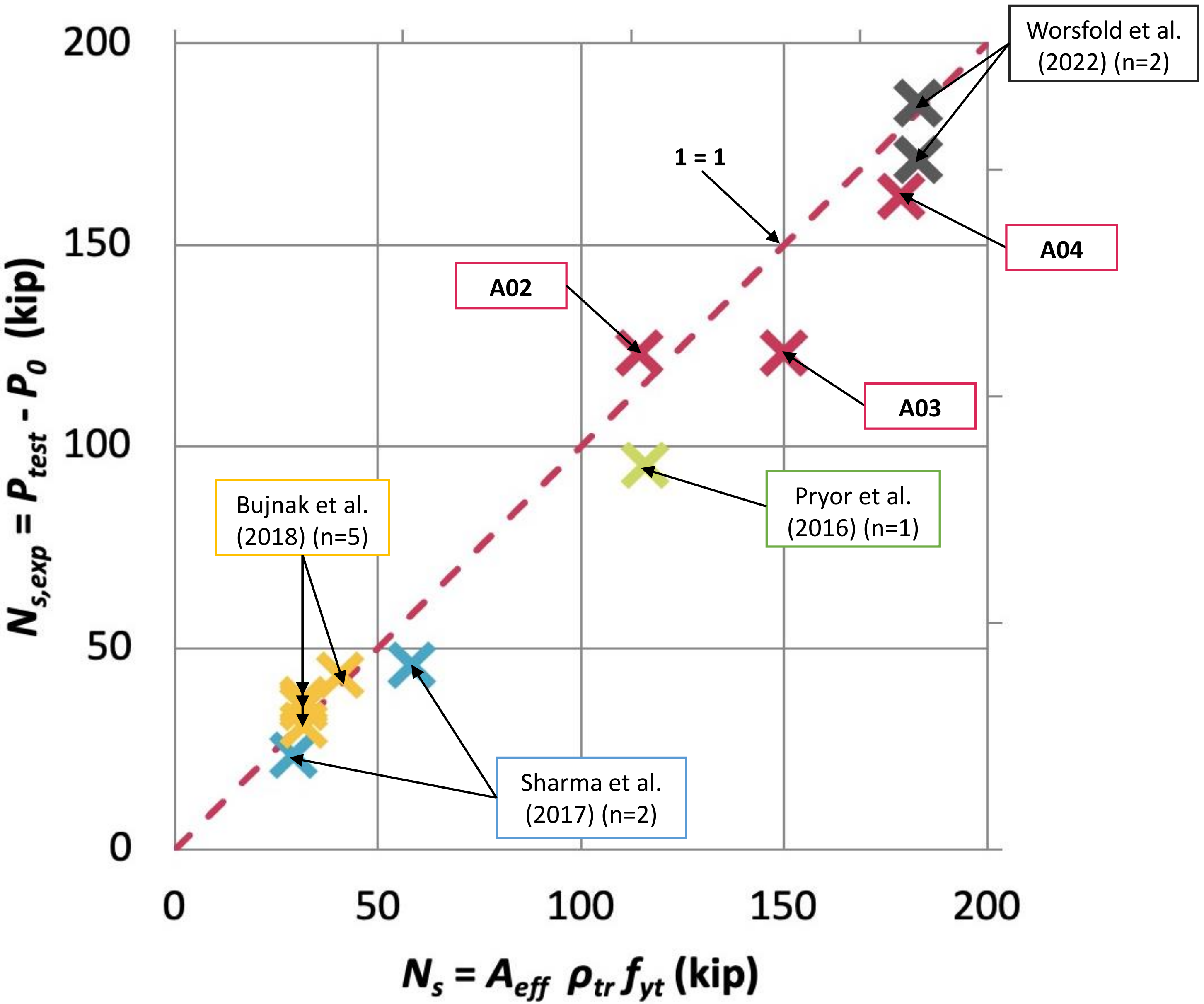
Mean reinforcement strength

Effective Area

Shear reinforcing ratio

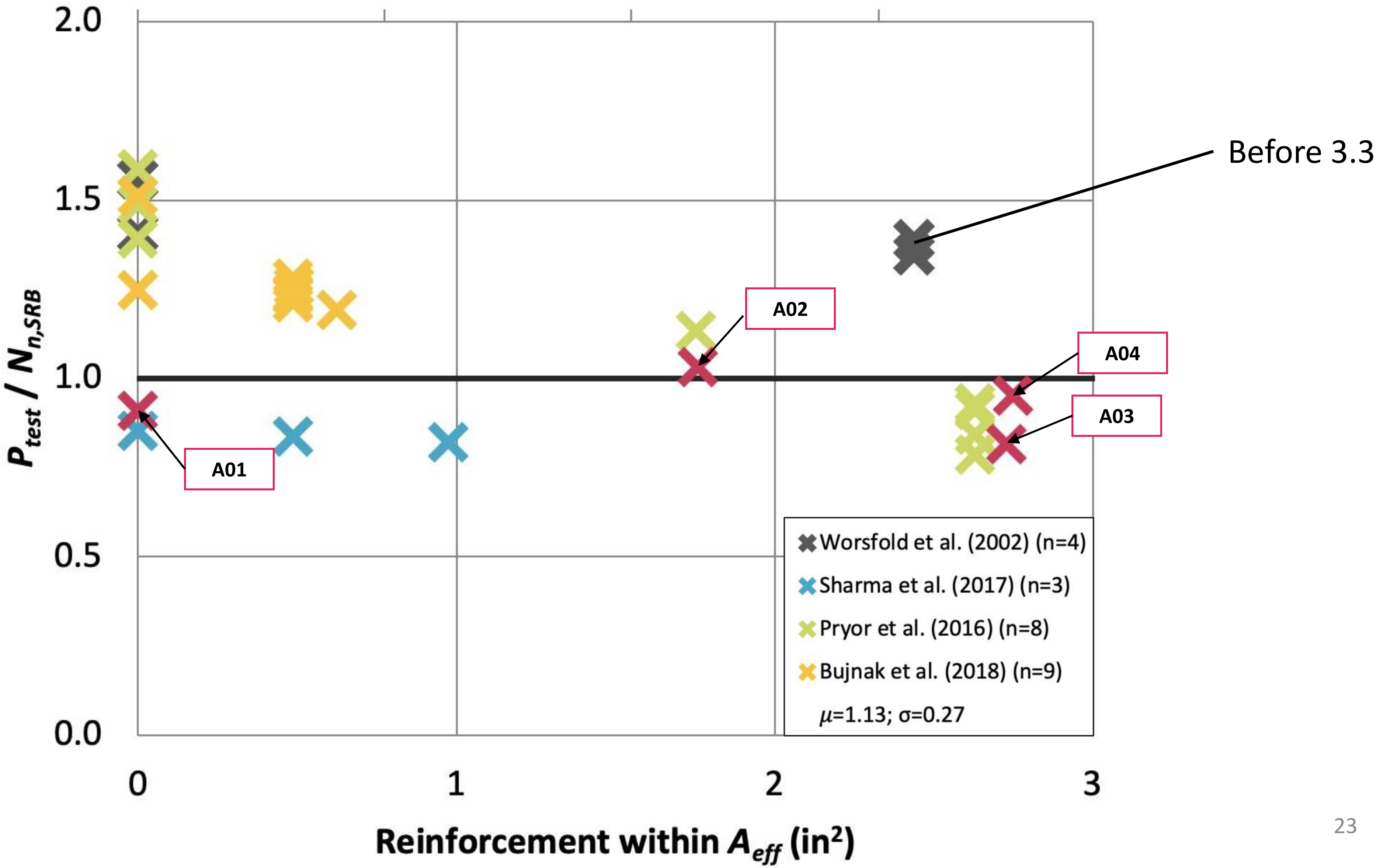
Nominal yield stress

Shear-Reinforced Breakout Design Equation



Strength Ratio

$$\boxed{N_{n,SRB} = N_c + N_s}$$



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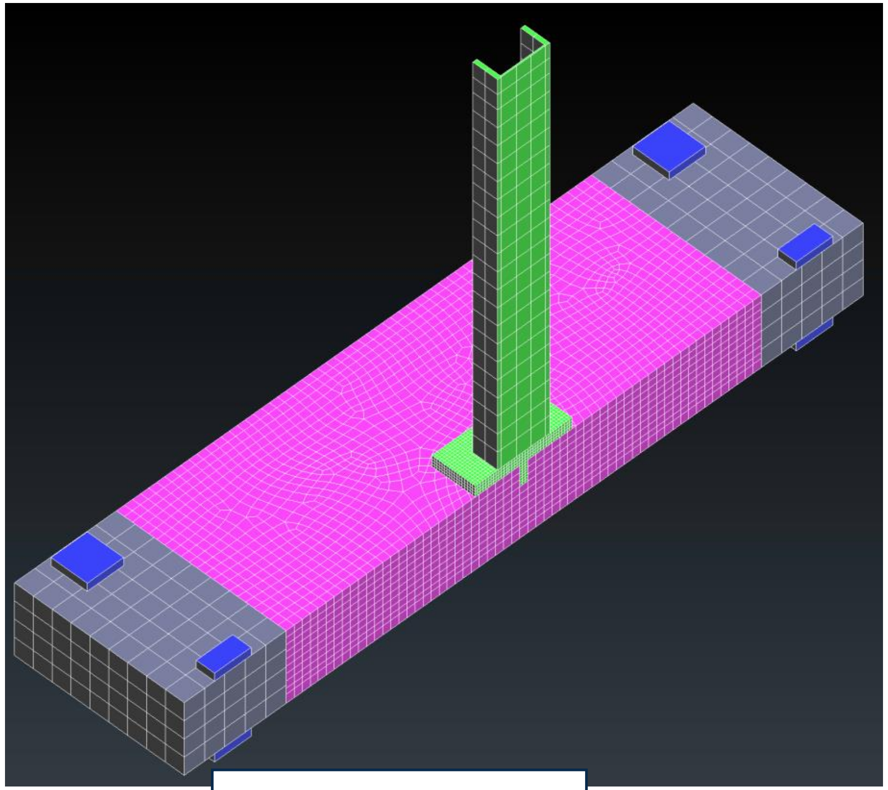
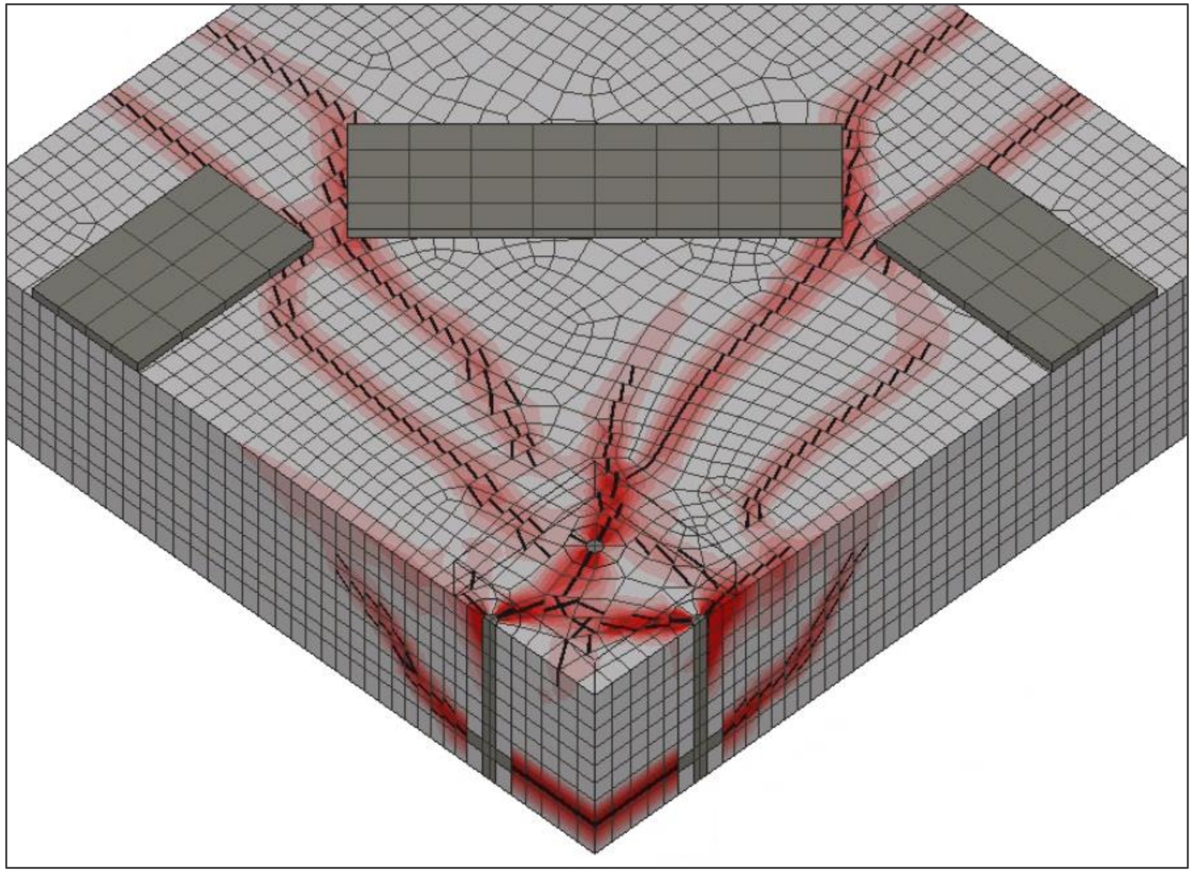
Numerical modeling



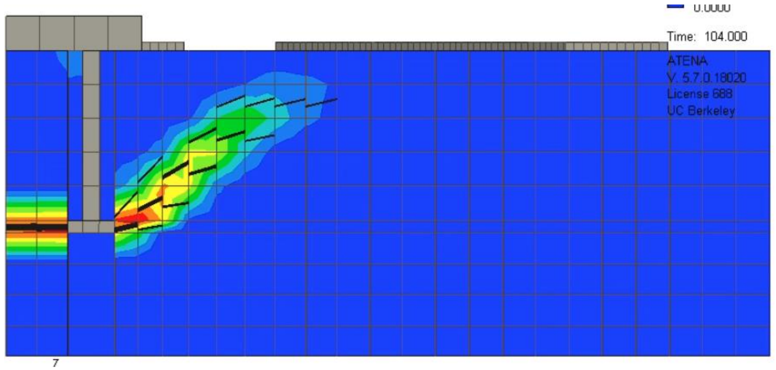
M01 Model



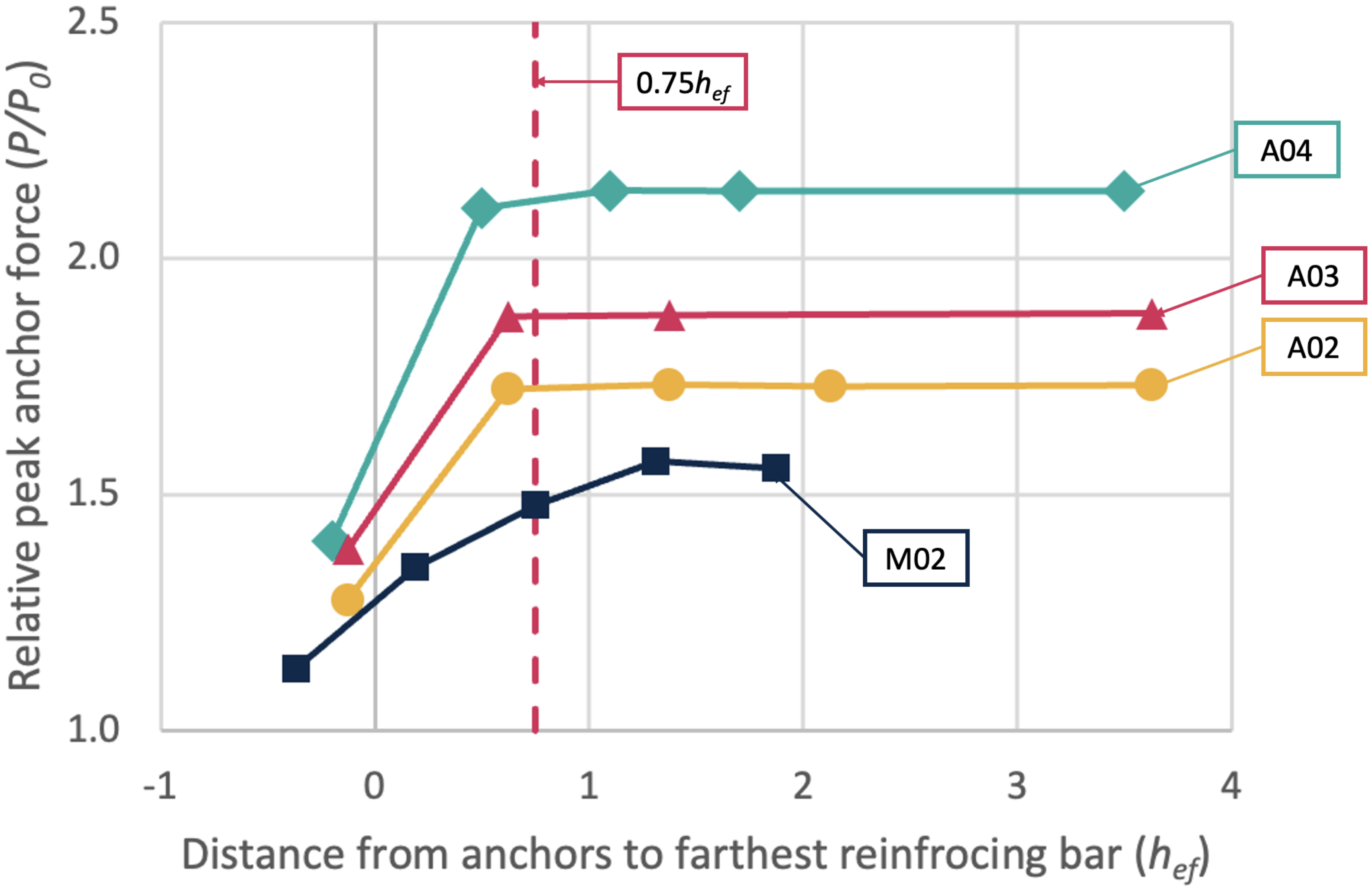
FE Crack Pattern

Finite Element Studies: shear-reinforced region

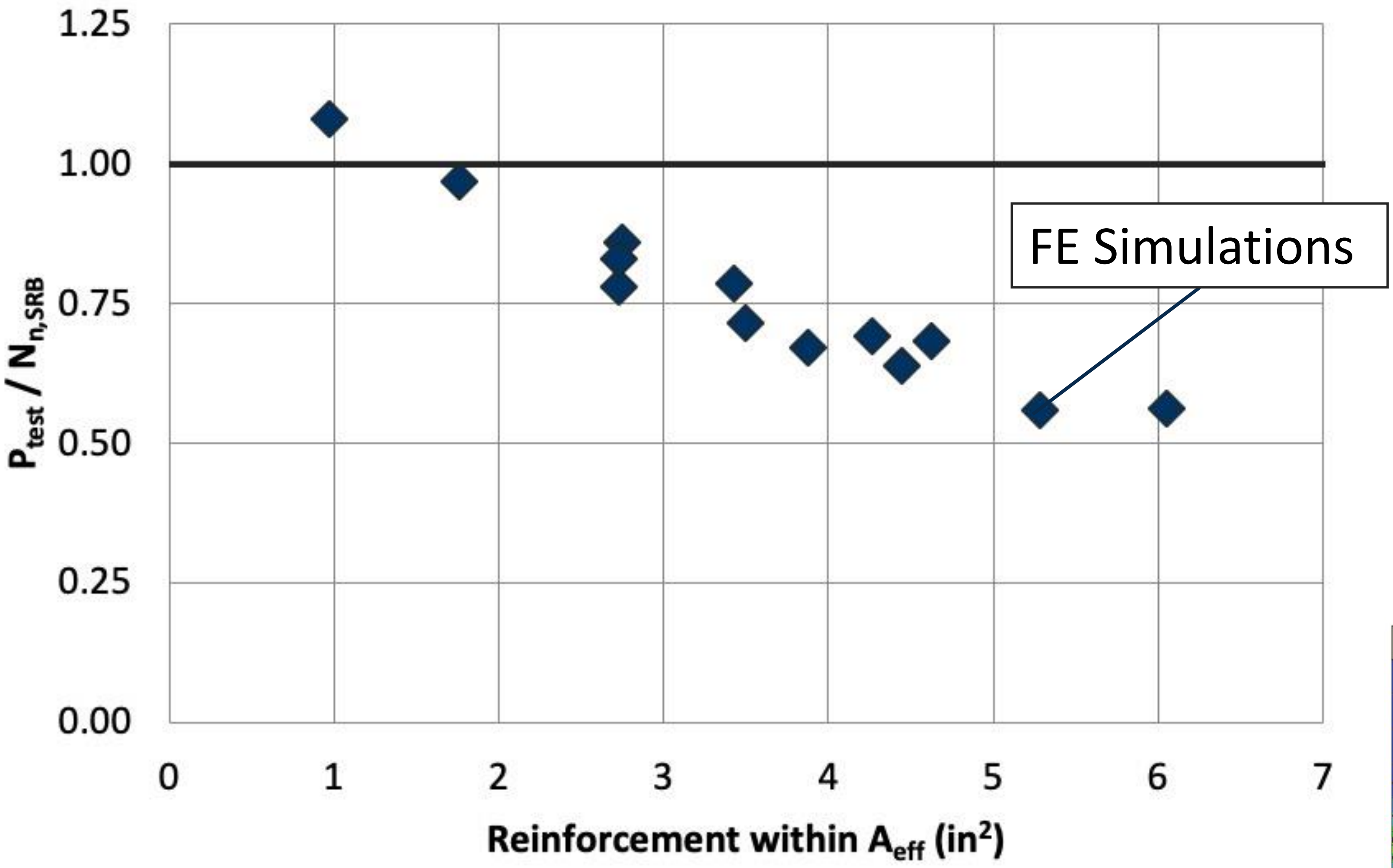
- Shear reinforcing beyond about $0.75h_{ef}$ does not seem to increase peak strength

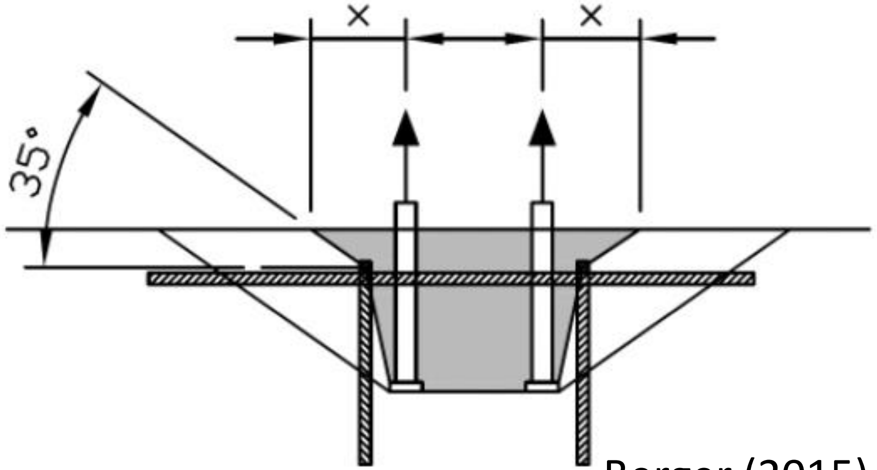


FE Crack Pattern

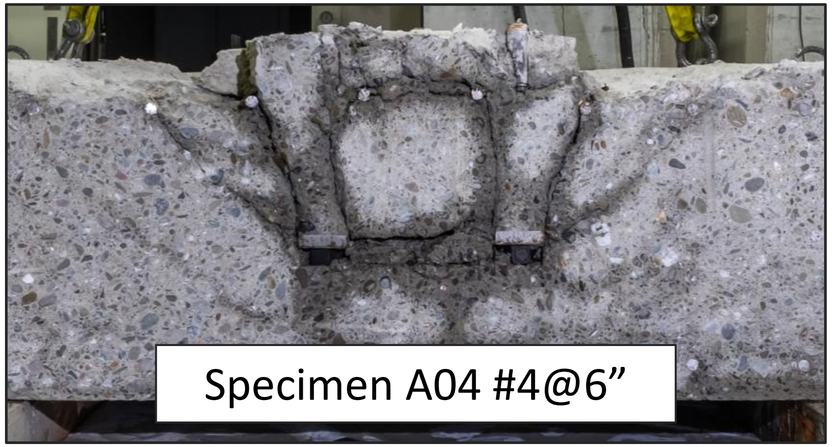


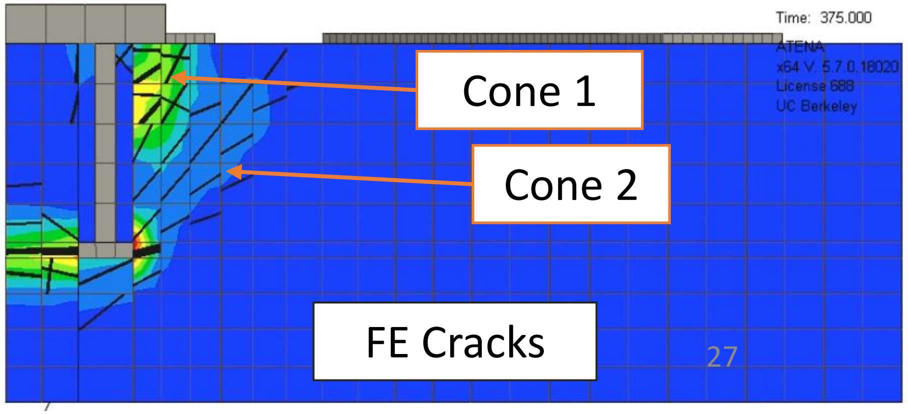
Upper Limit: Steep Cone Strength



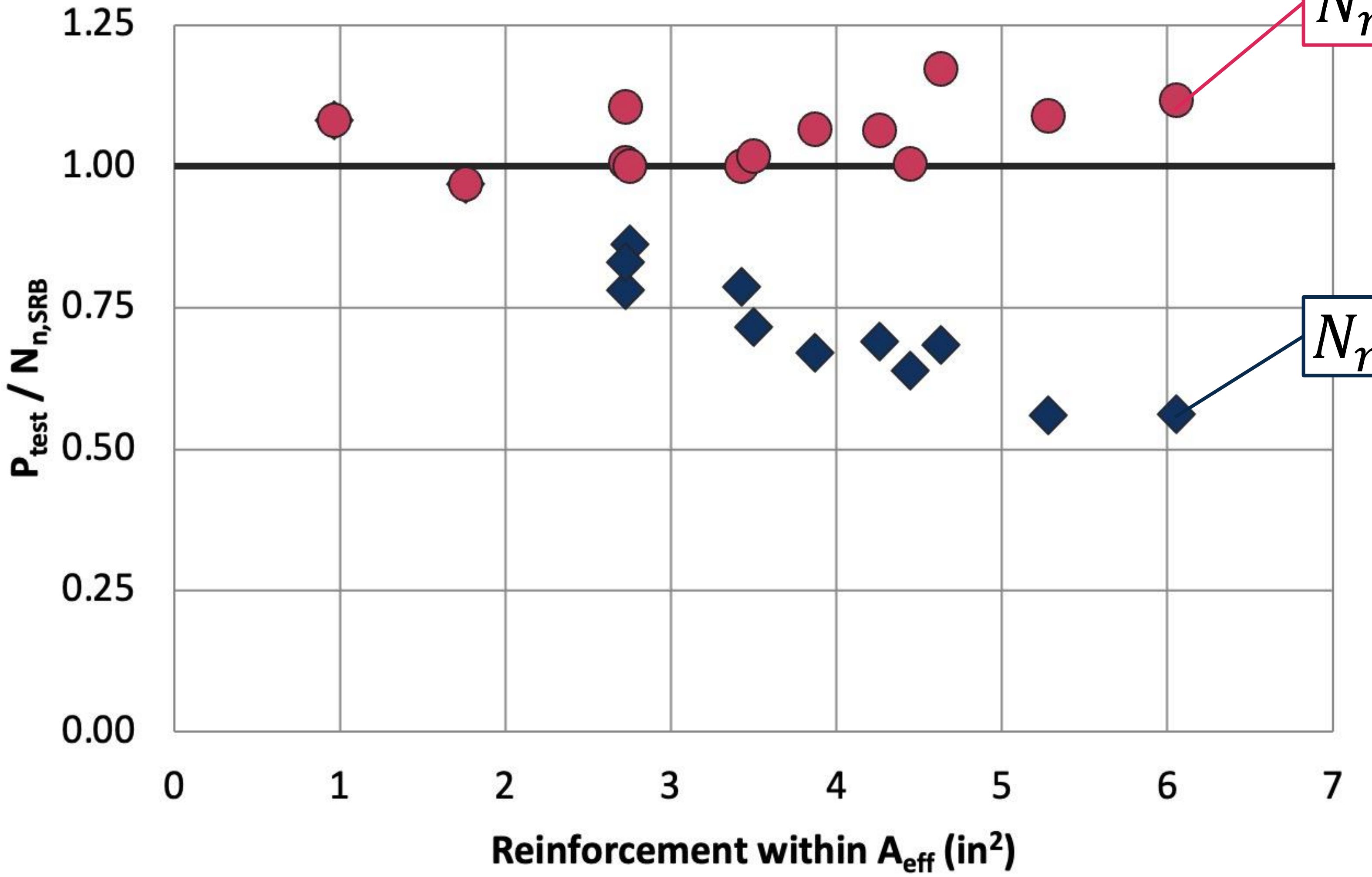


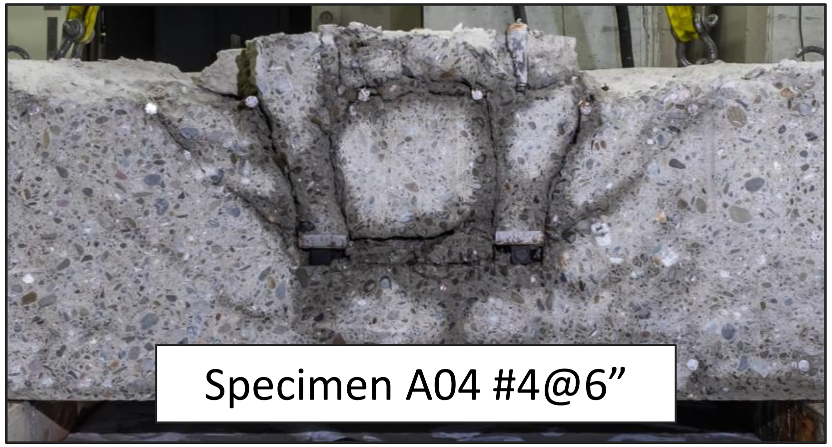
Berger (2015)

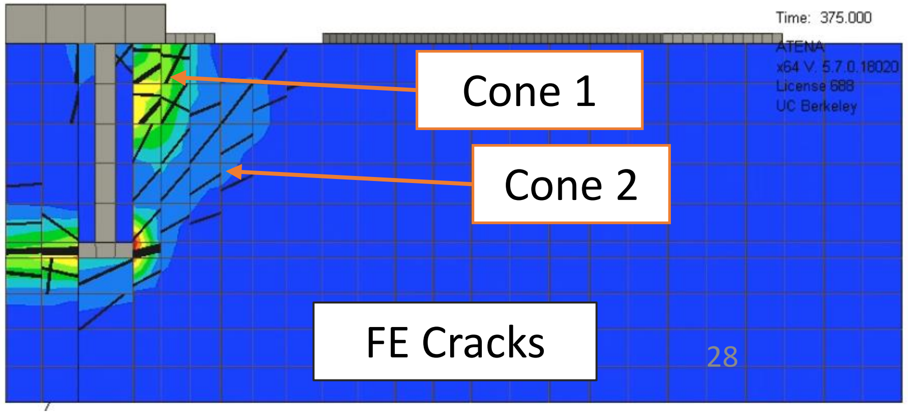




Upper Limit: Steep Cone Strength

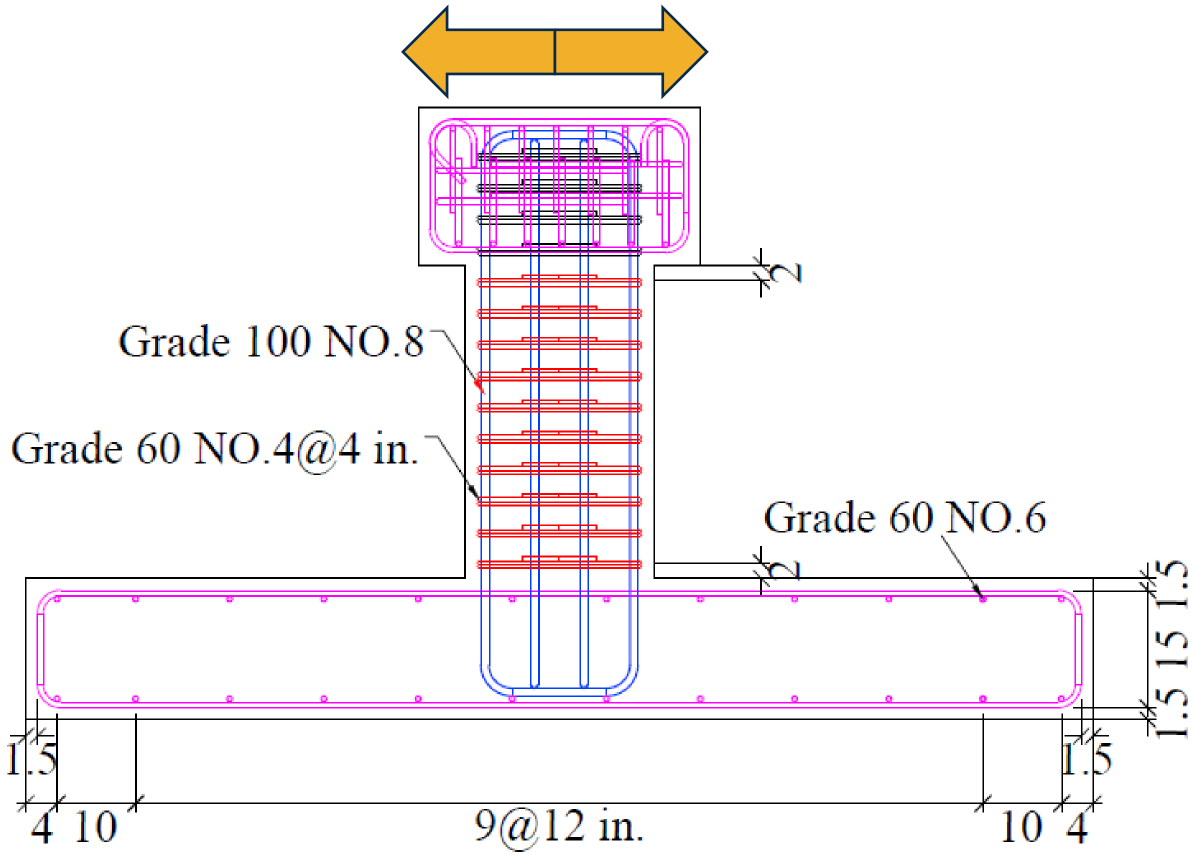






Premature Breakout Failure Examples

- Taiwan National University of Science and Technology
- Breakout before nominal bar yield



Chen (2021)

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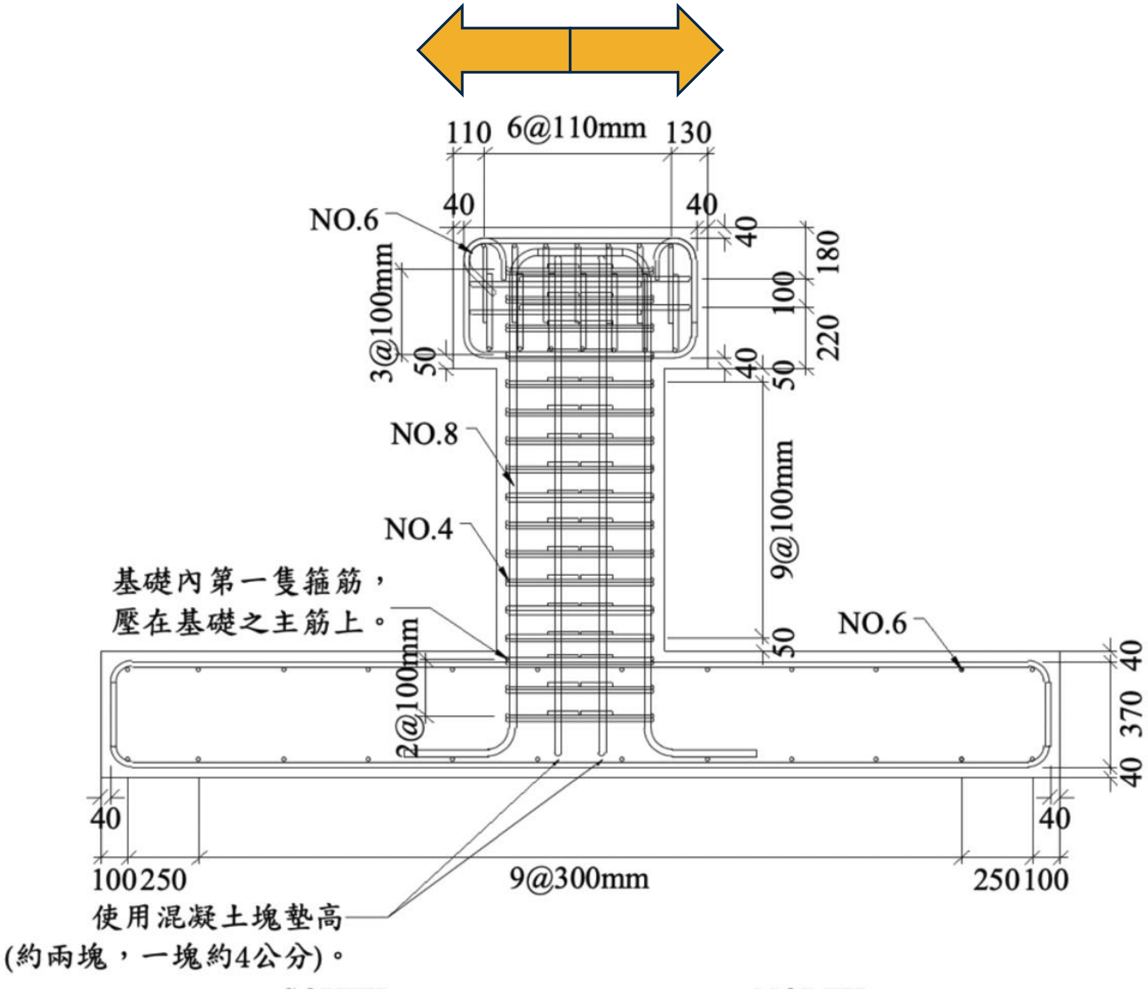


Chen (2021)

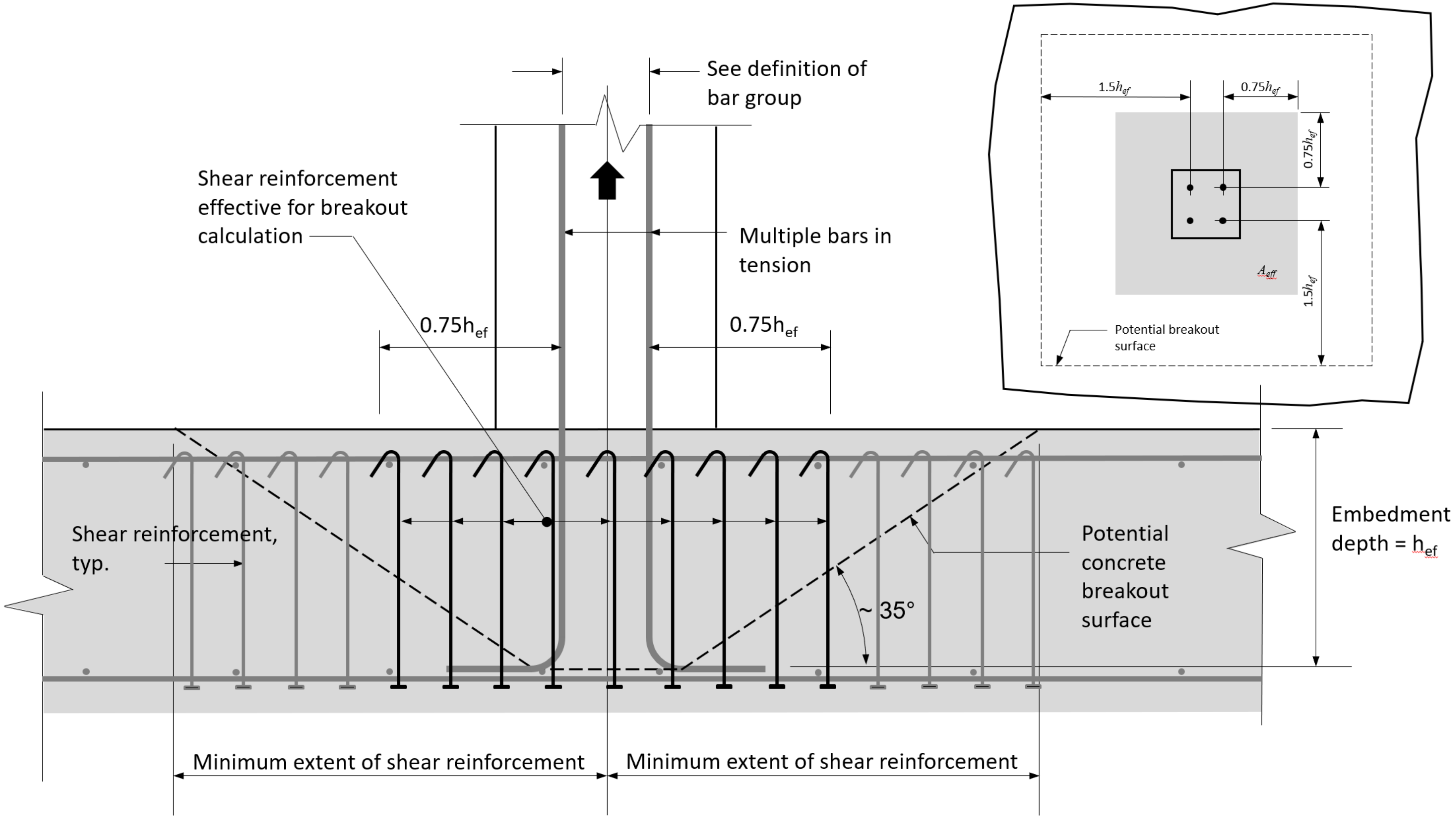
Code Implementation: Detailing Requirements

1. Bars terminate in hooks or heads

2. Shear reinforced region extend at least throughout cone region

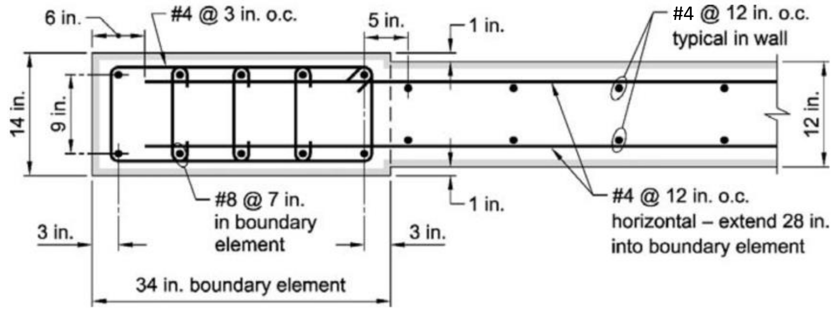
3. Maximum bar spacing
$$s_{max} = 0.5h_{ef}$$

If $N_{n,SRB} \geq 2.5N_c$
$$s_{max} = 0.25h_{ef}$$



Example: Boundary element to thin foundation

Potential exists for concrete breakout failure even if the bars are placed $1.25l_{dt}$ into the foundation

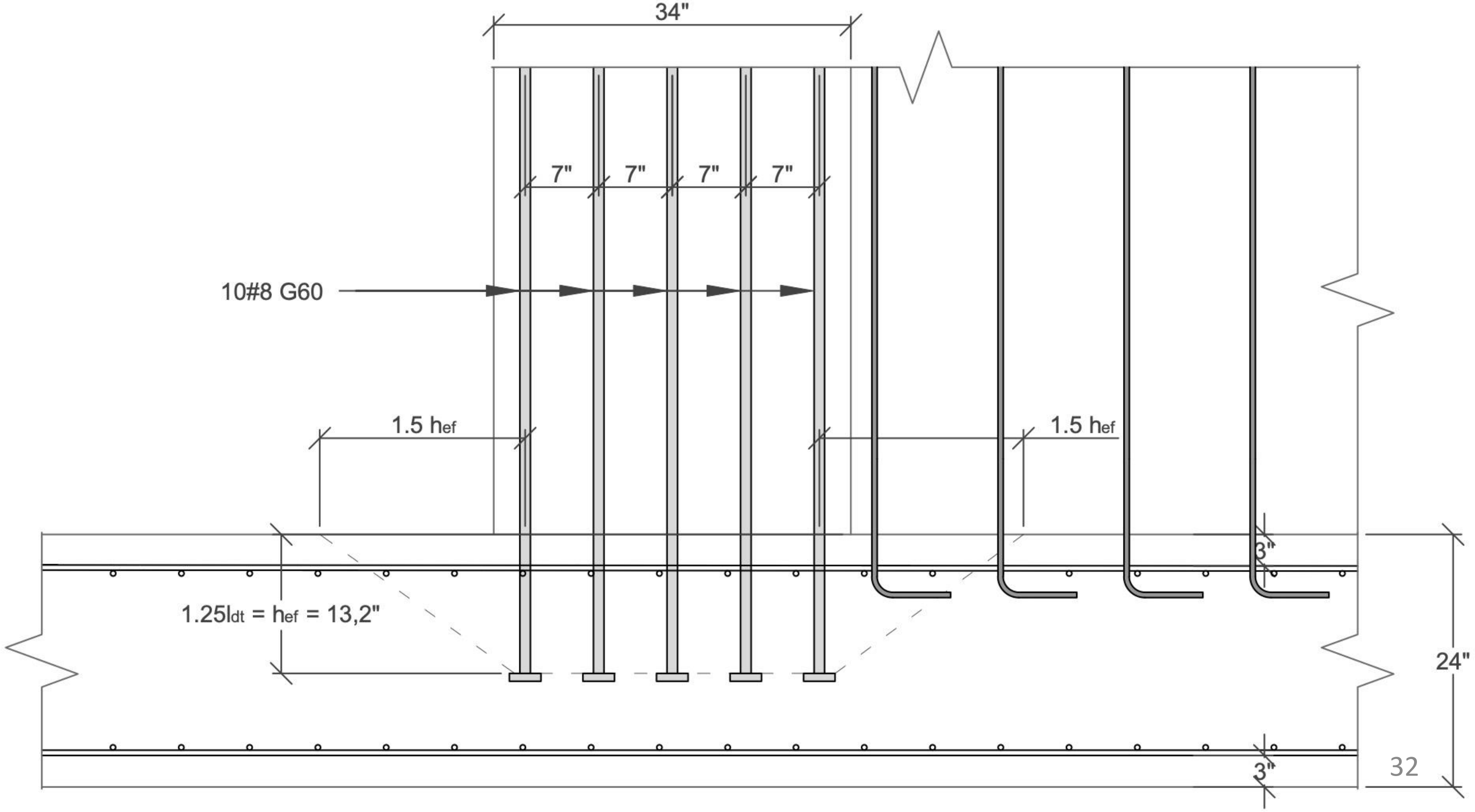


SP-17(14) Design Handbook
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

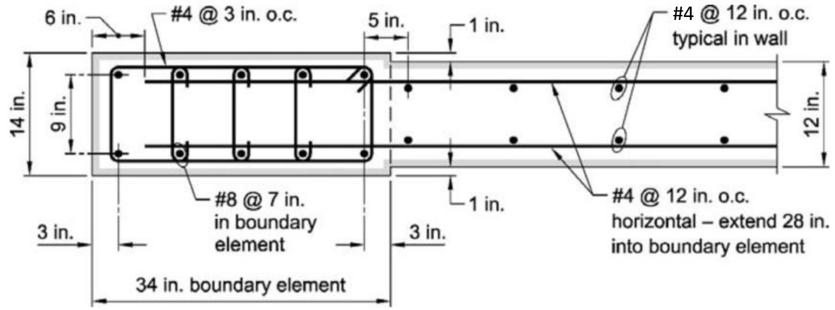
Nominal yield strength:
$T_y = 474\ kips$

Mean breakout strength:
$N_c = 284\ kips$

Difference:
$T_y - N_c = 190\ kips$



Example: Boundary element to thin foundation

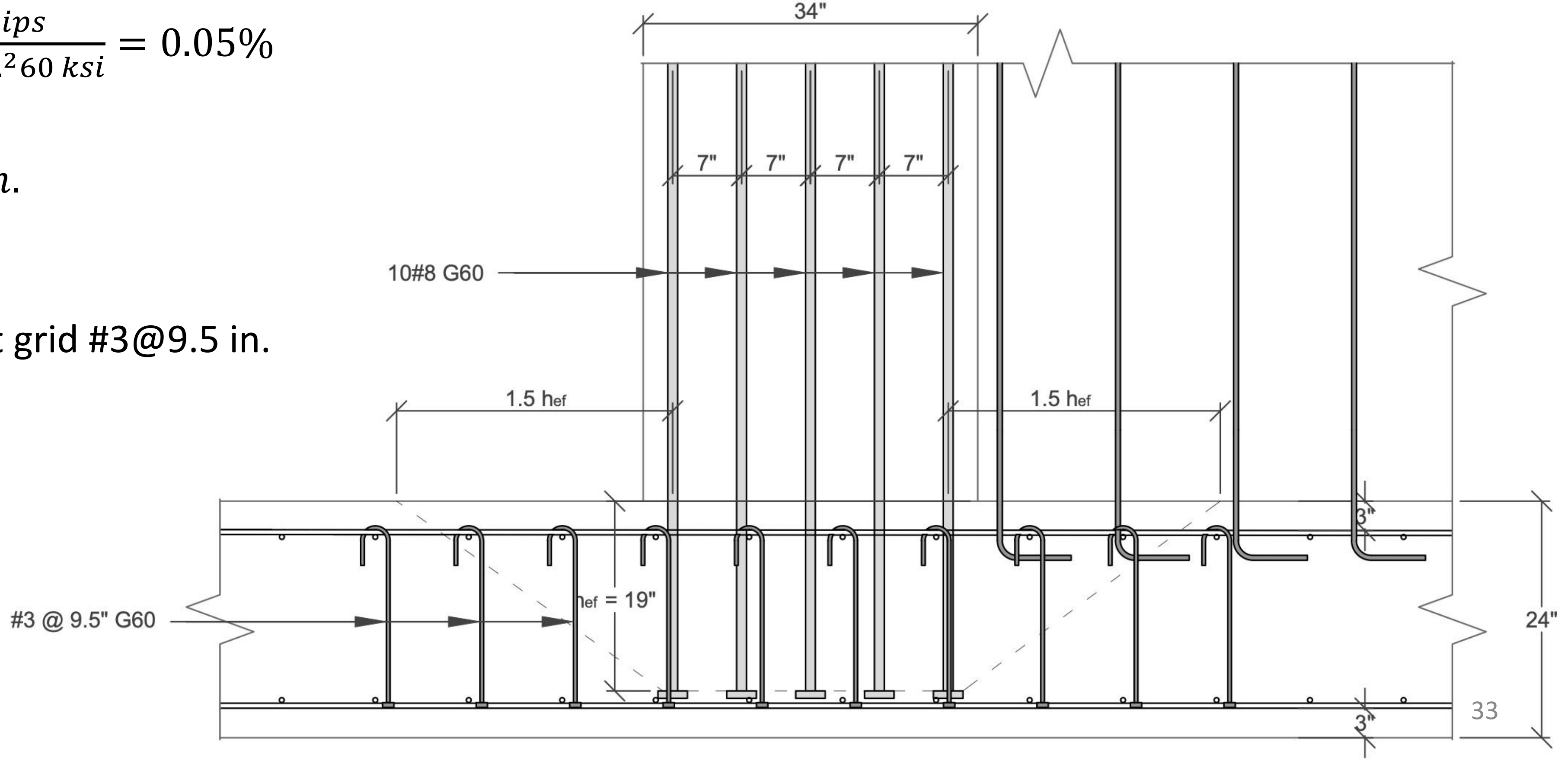


SP-17(14)
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

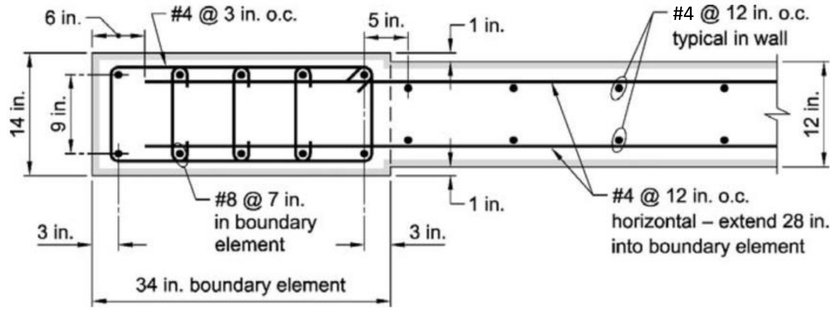
$$\rho_{tr,min} = \frac{N_s}{A_{eff} f_{yt}} = \frac{70kips}{1377\ in.^2 60\ ksi} = 0.05\%$$

$$s_{max} = \frac{h_{ef}}{2} = \frac{19in.}{2} = 9.5in.$$

Select shear reinforcement grid #3@9.5 in.
$\rho_{tr} = 0.12\%$



Example: Boundary element to thin foundation



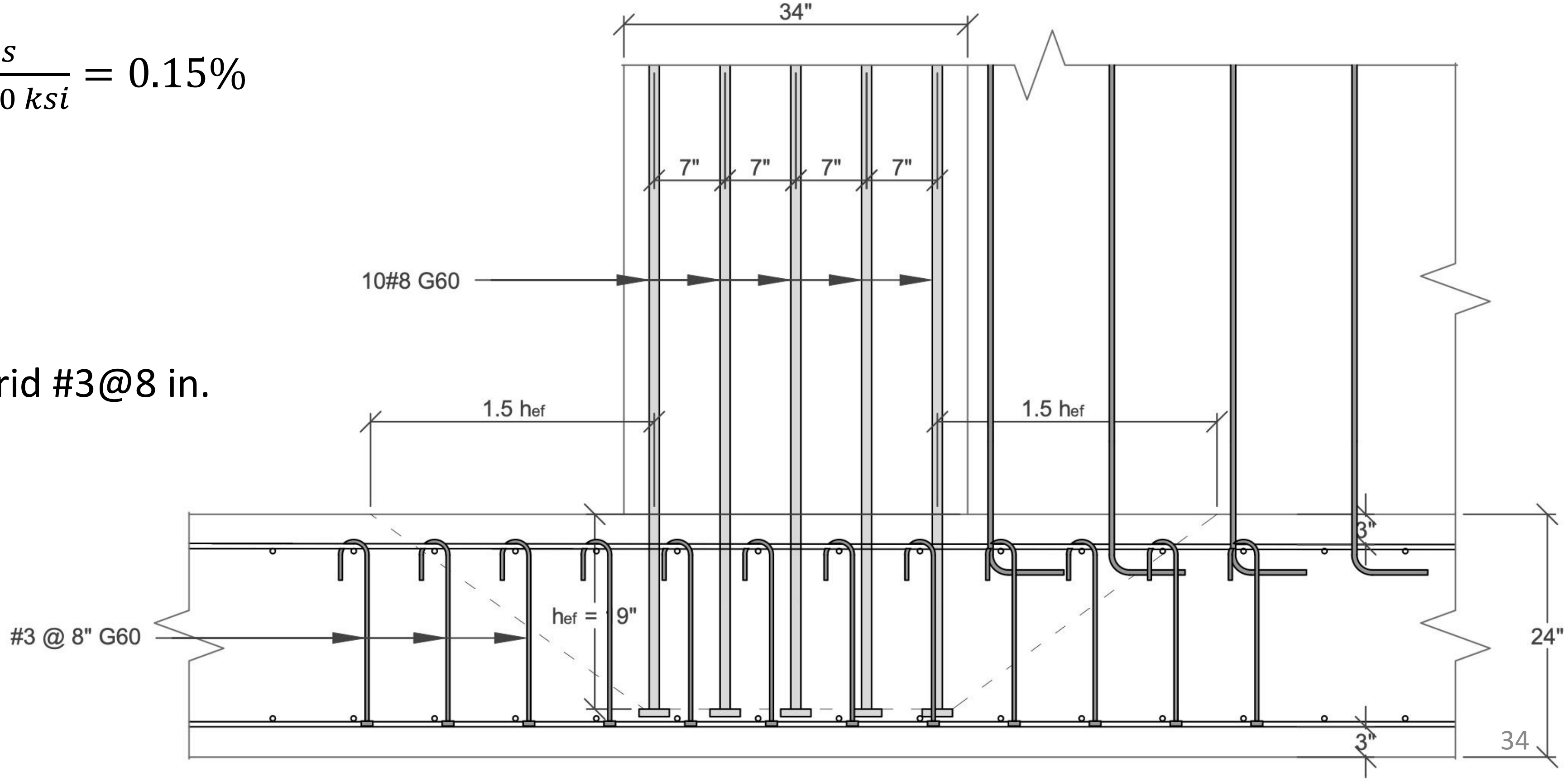
SP-17(14)
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

Boundary element
$1.25f_y$

$$\rho_{tr,min} = \frac{N_s}{A_{eff} f_{yt}} = \frac{188kips}{1377\ in.^2 60\ ksi} = 0.15\%$$

$$s_{max} = \frac{h_{ef}}{2} = \frac{19in.}{2} = 9.5in.$$

Select shear reinforcement grid #3@8 in.
$\rho_{tr} = 0.17\%$



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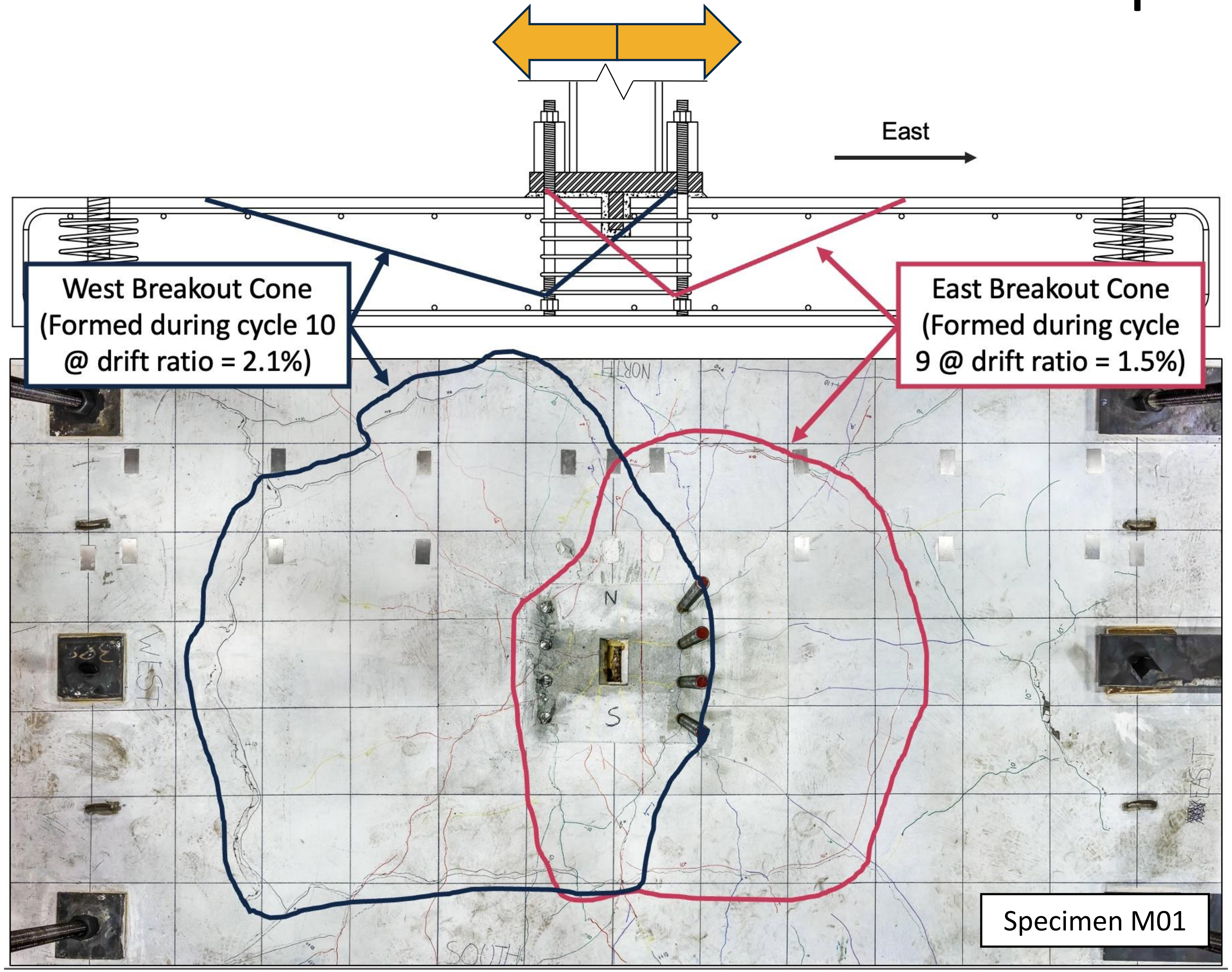
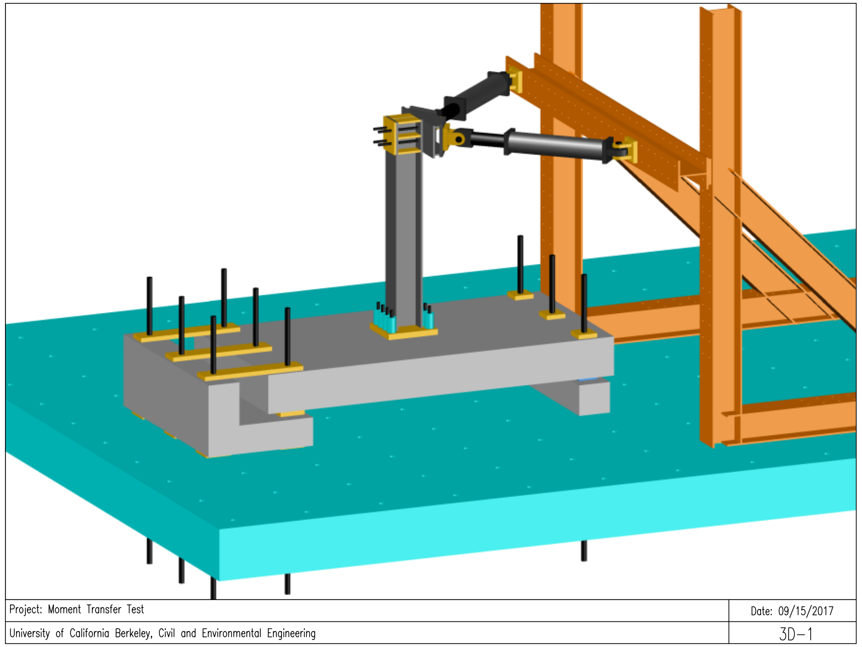
Other Slides

Premature Breakout Failure Examples

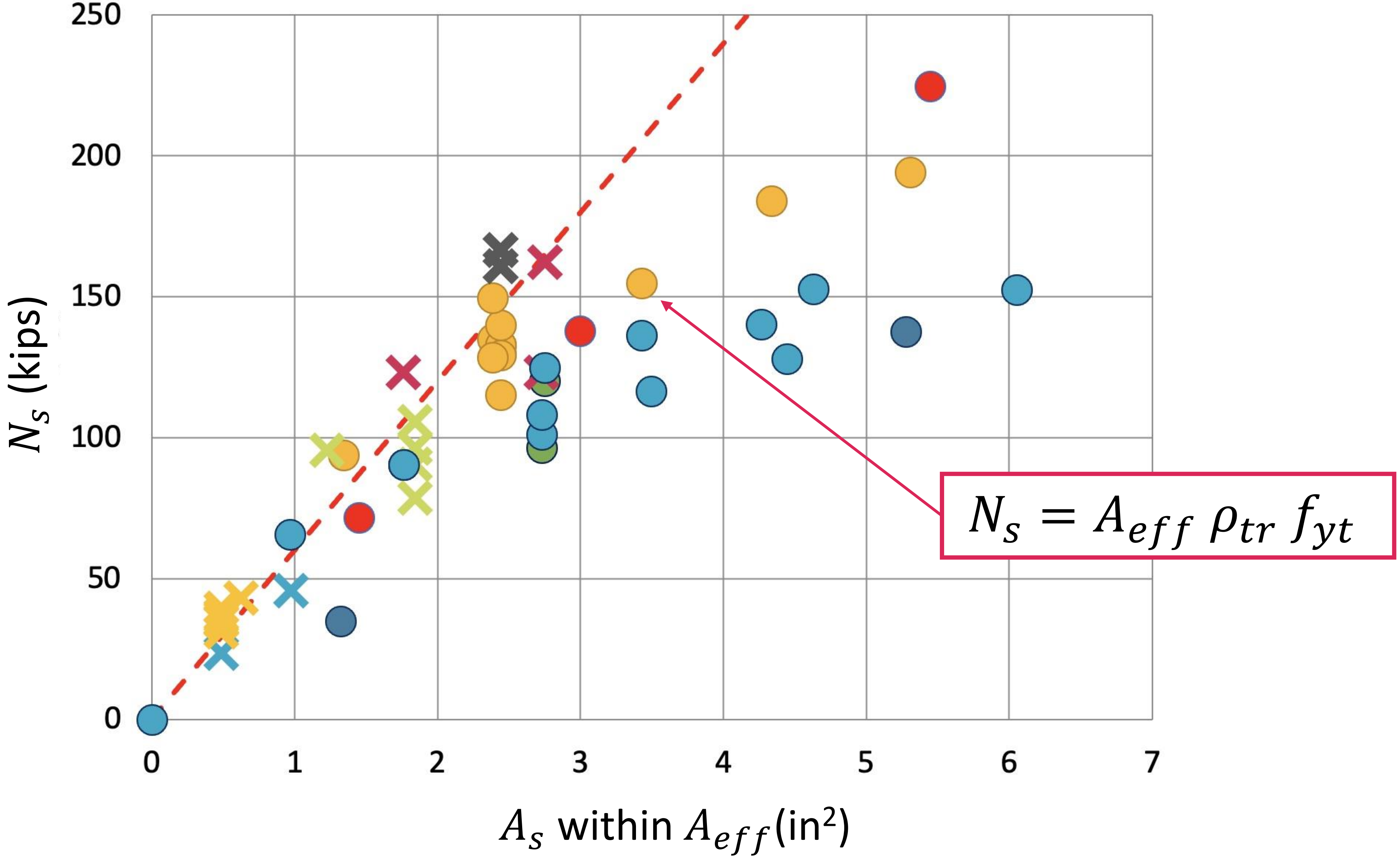


Worsfold et al. (2022a)

- UC Berkeley
- Cyclic loading
- Steel-column-foundation moment-transfer connections.
- Breakout failure before nominal bar yield



Shear-Reinforced Breakout Design Equation

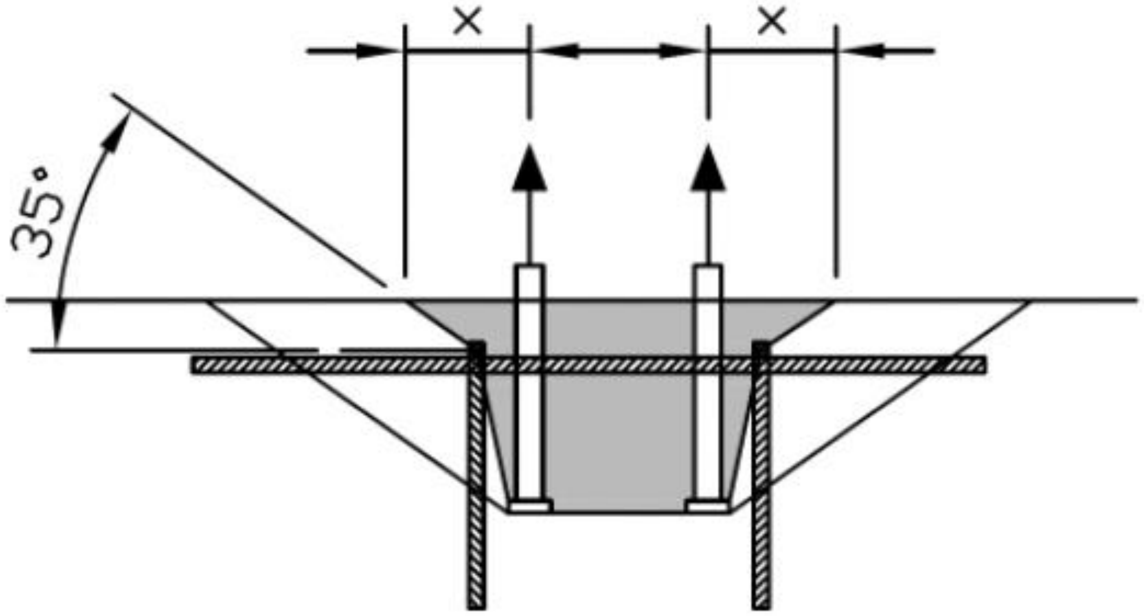


Upper Limit: Steep Cone Strength

$$N_{n,max} = \Psi_{c,steep} N_c + \Psi_{s,steep} N_s$$

$$\Psi_{c,steep} = 2.75 - 1.75\,\frac{A'}{A_{Nc}} \geq 1$$

$$\Psi_{s,steep} = 2\,\frac{A'}{A_{Nc}} - 1 \geq 0$$

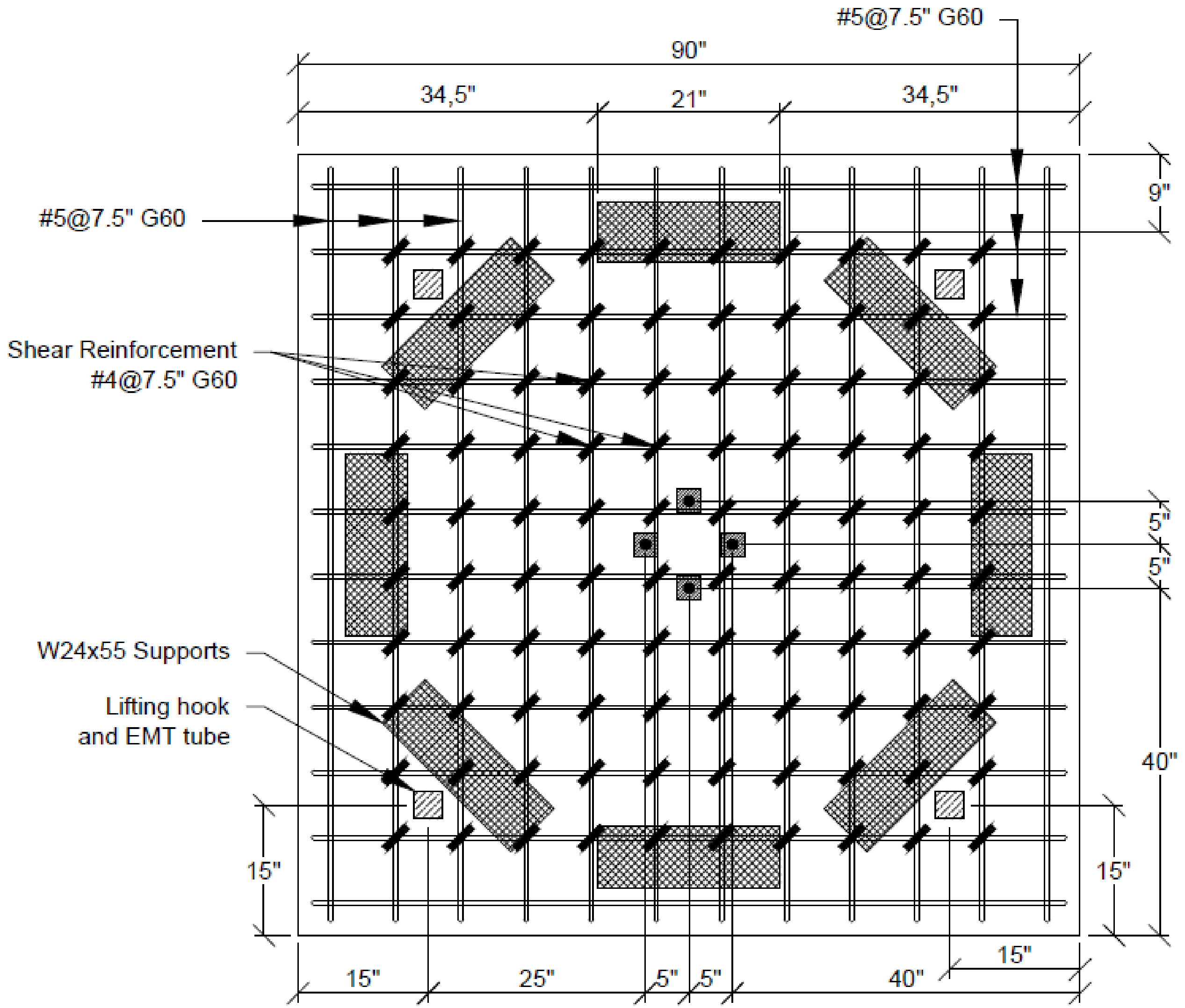


Berger (2015)

Shear-Reinforced Breakout Tests

- UC Berkeley
- Four monotonic axial loading tests
- Breakout failures for all specimens
- Longitudinal bars did not appear to yield

Specimen	Shear Reinforcement	Reinforcing ratio, ρ_{tr} (%)
A01	N/A	0
A02	#4@7.5in.	0.36%
A03	#5@7.5in.	0.55%
A04	#4@6in.	0.56%

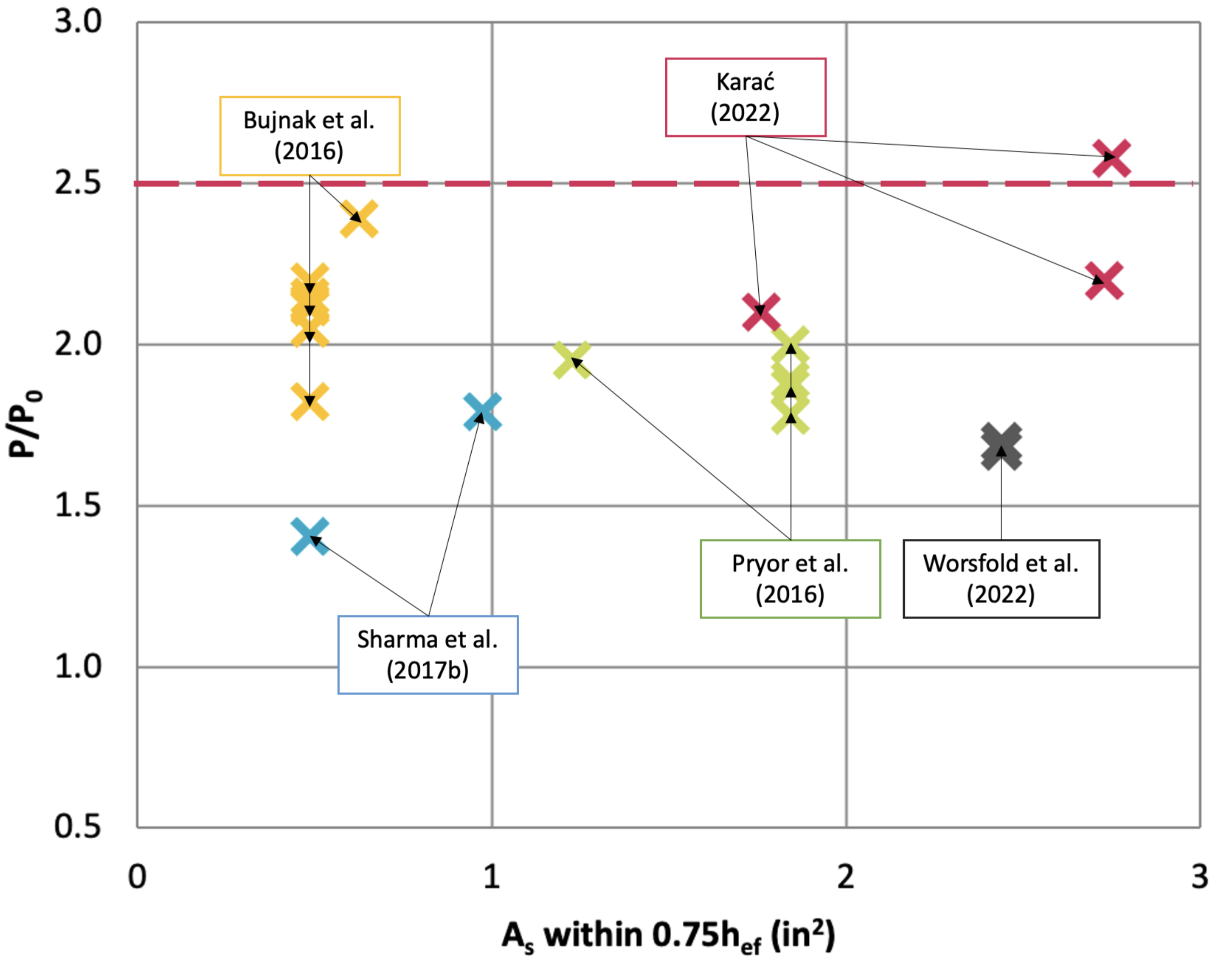


Karać (2023)

Specimen A02 Plan

Shear Bar Strains

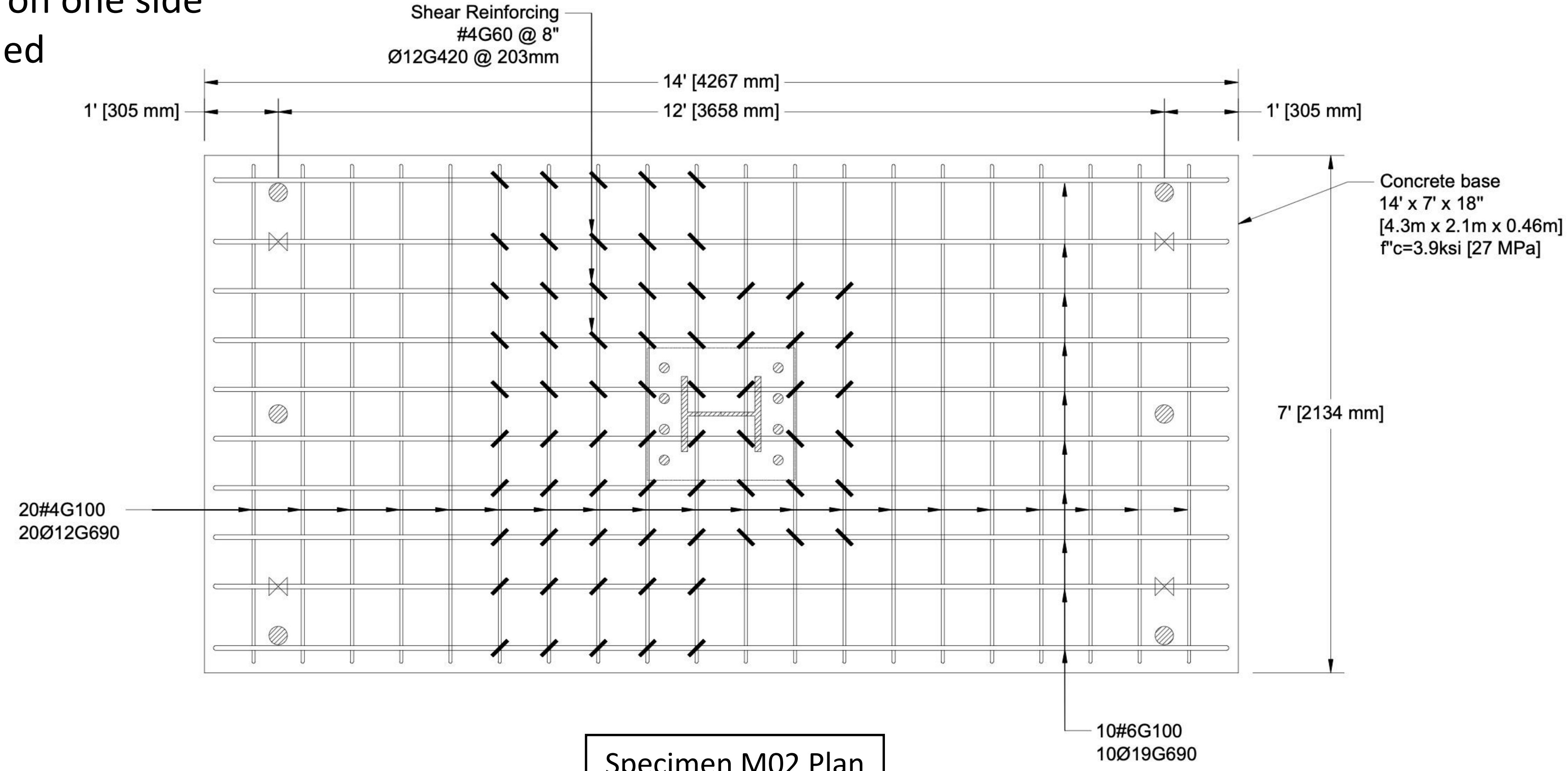
- Bars beyond about $0.75h_{ef}$ less likely to yield



A_s within A_{eff}(in^2)

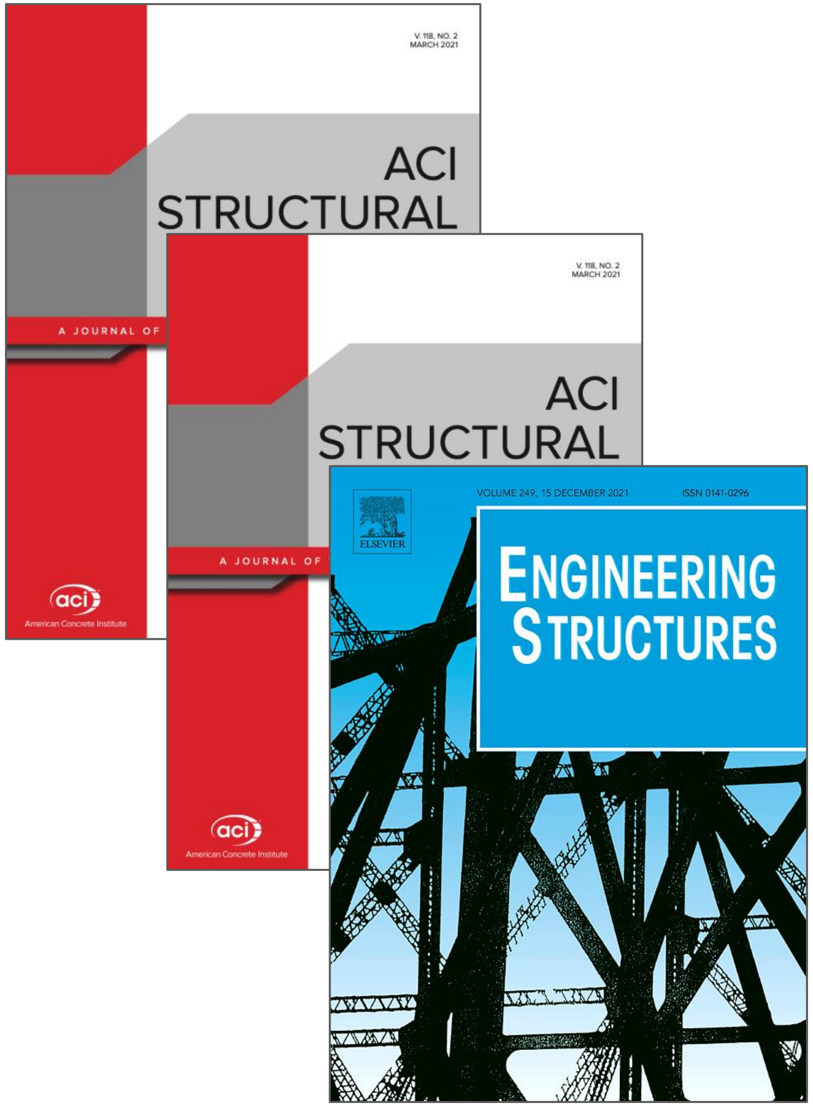
Shear-Reinforced Breakout Tests

- UC Berkeley
- One cyclic moment-transfer tests
- Larger reinforced region on one side
- Breakout failures governed



Specimen M02 Plan

Publications



Title
Moment Transfer at Column-to-Footing Connections: Physical Tests
Moment Transfer at Column-to-Footing Connections: Analytical Simulations
Strengthening Breakout Failure with Distributed Shear Reinforcing

ACI 318 Supplementary Reinforcement

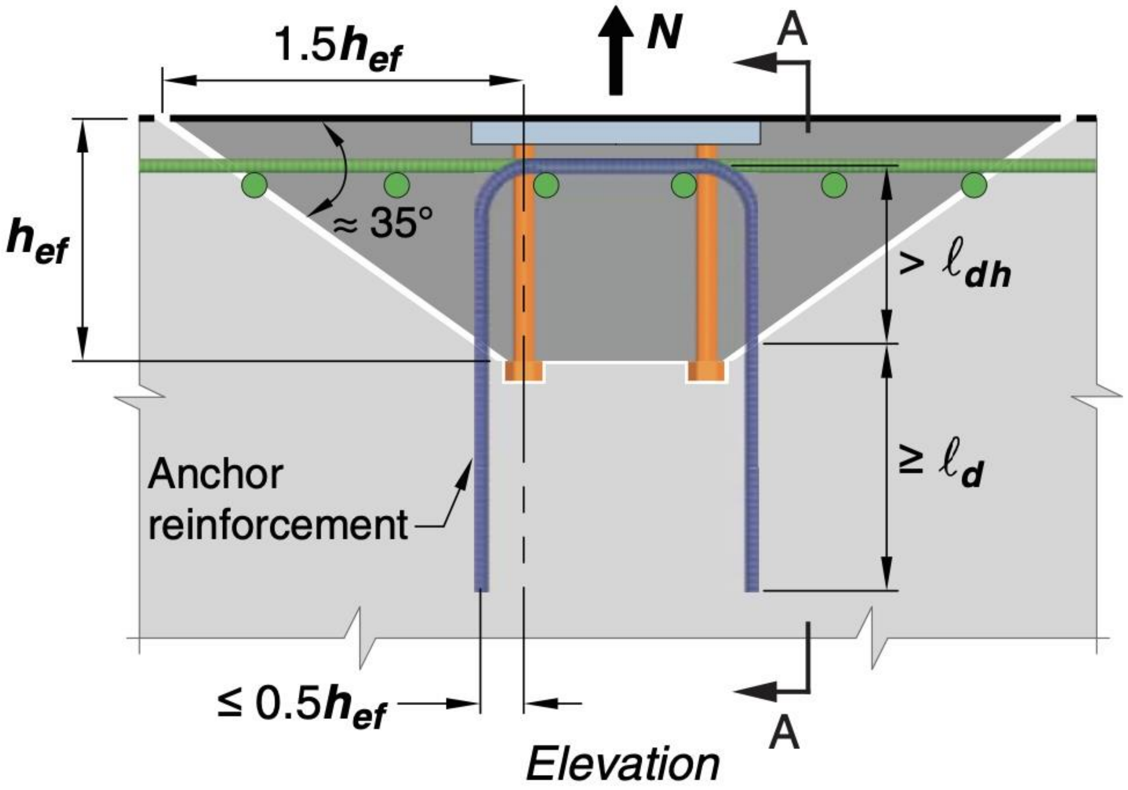
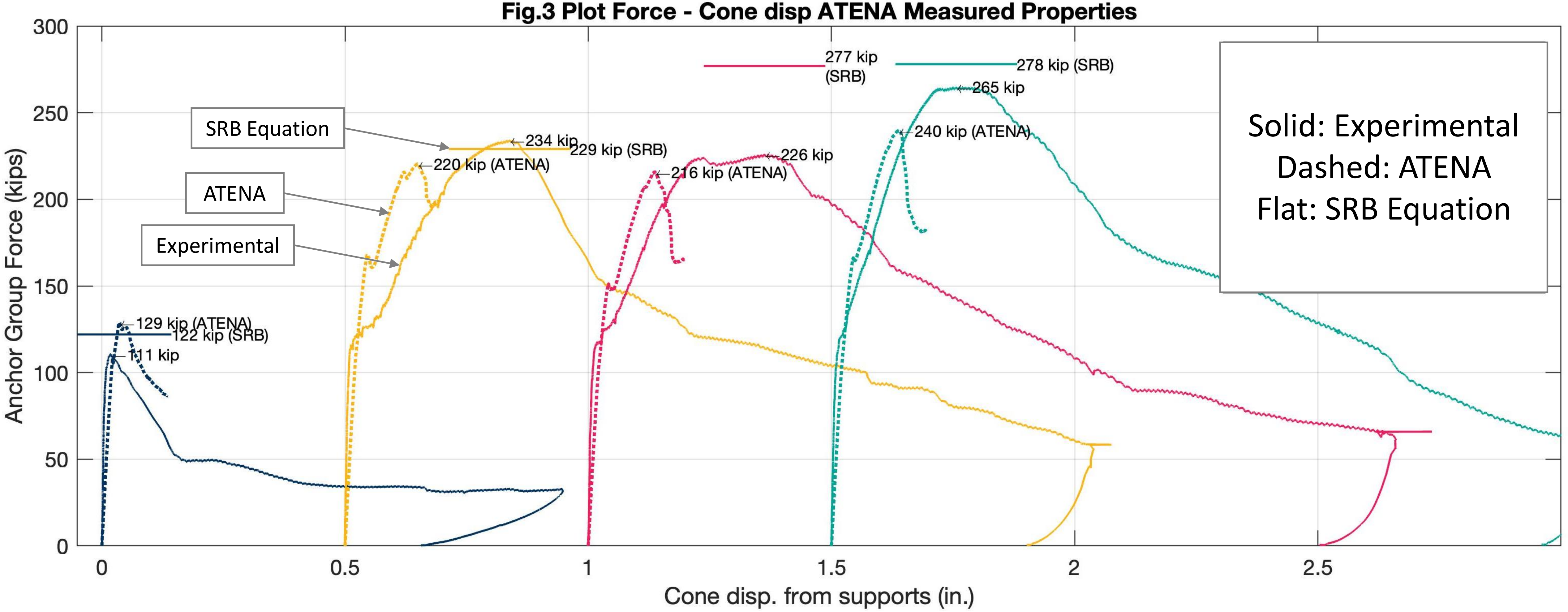
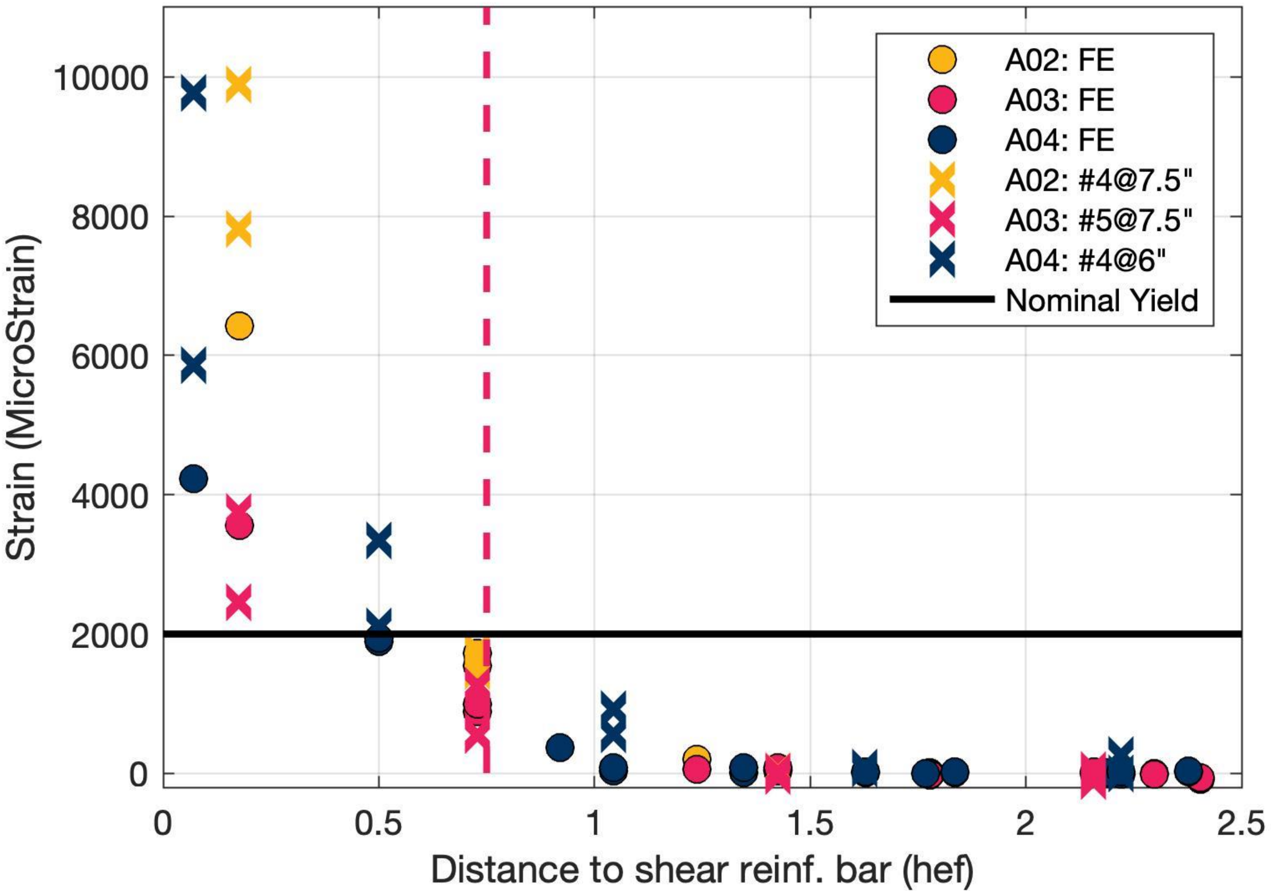


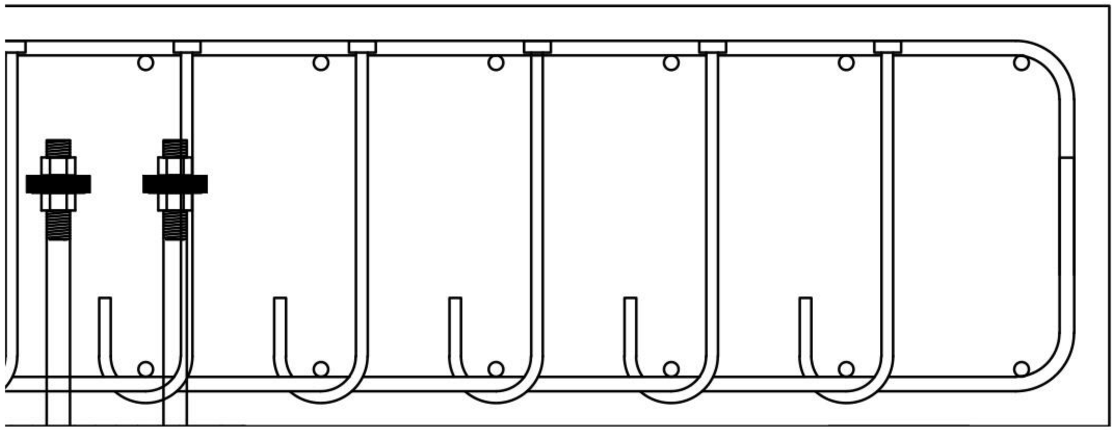
Fig. R17.5.2.1a*—Anchor reinforcement for tension.*

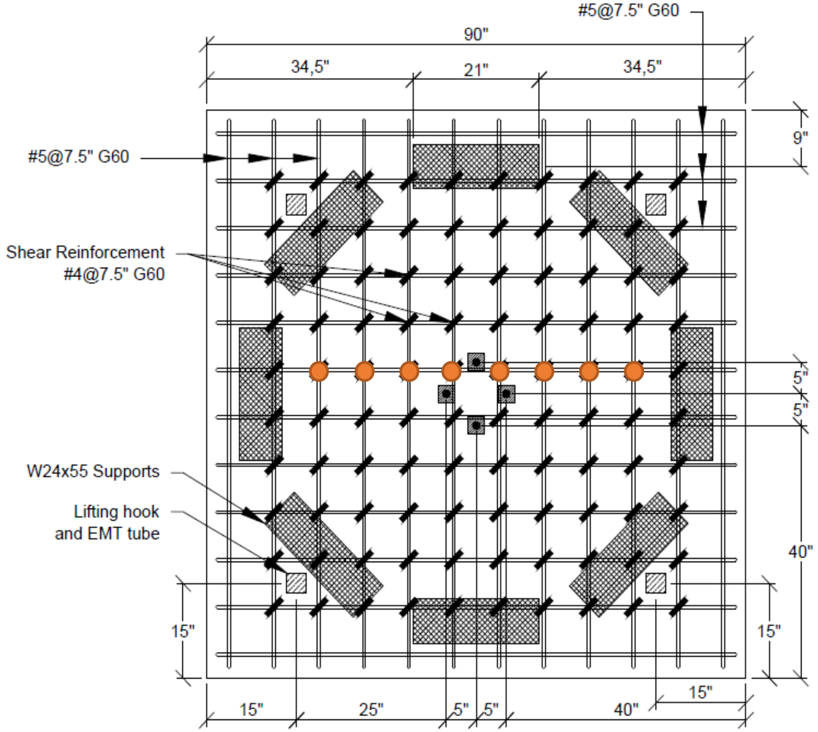
- Supplementary reinforcement: reinforcement that acts to restrain the potential concrete breakout but is not designed to transfer the design load from the anchors into the structural member.
- Slightly increased Φ factor to consider increased displacement capacity.
- Reinforcement strength is ignored

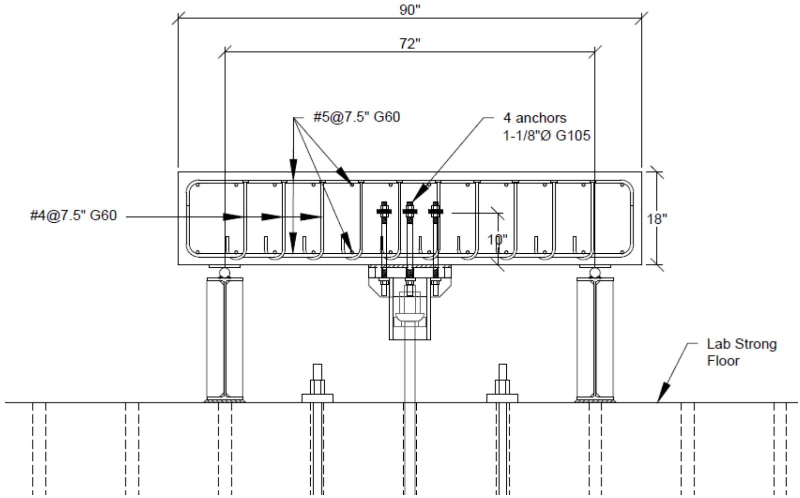


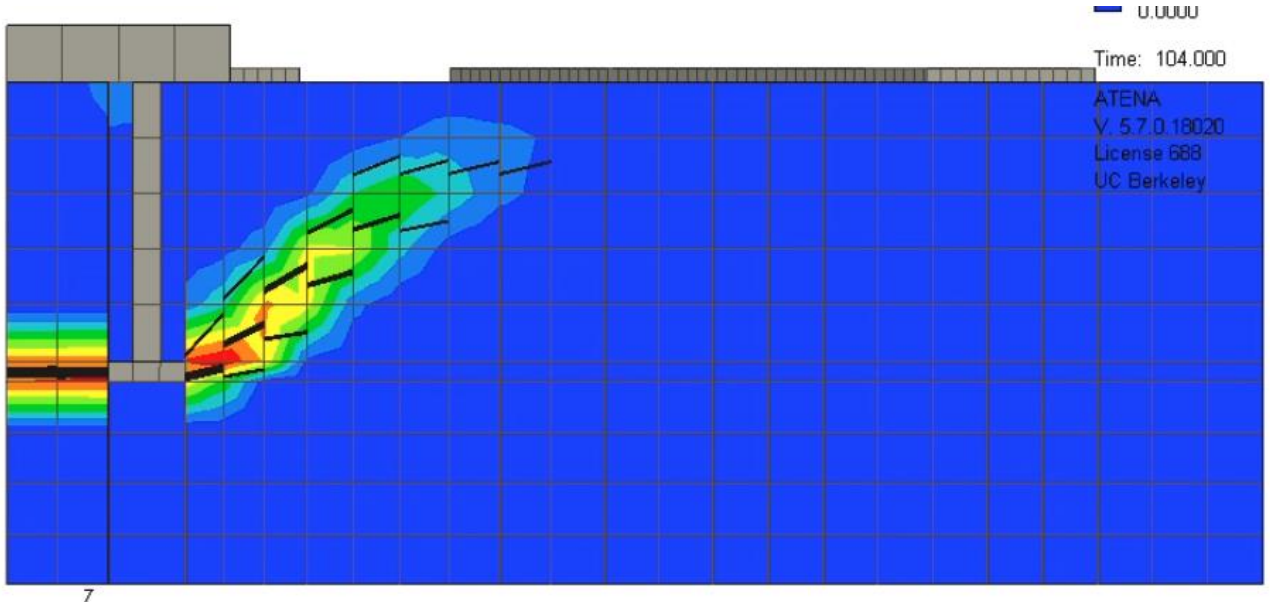
A01	A02	A03	A04
No Shear Reinf.	#4@7.5in.	#5@7.5in.	#4@6in.
	ρ_{tr}=0.36%	ρ_{tr}=0.55%	ρ_{tr}=0.56%


Strain (MicroStrain)
Distance to shear reinf. bar (hef)
0
2000
4000
6000
8000
10000
0
0.5
1
1.5
2
2.5
A02: FE
A03: FE
A04: FE
A02: #4@7.5"
A03: #5@7.5"
A04: #4@6"
Nominal Yield

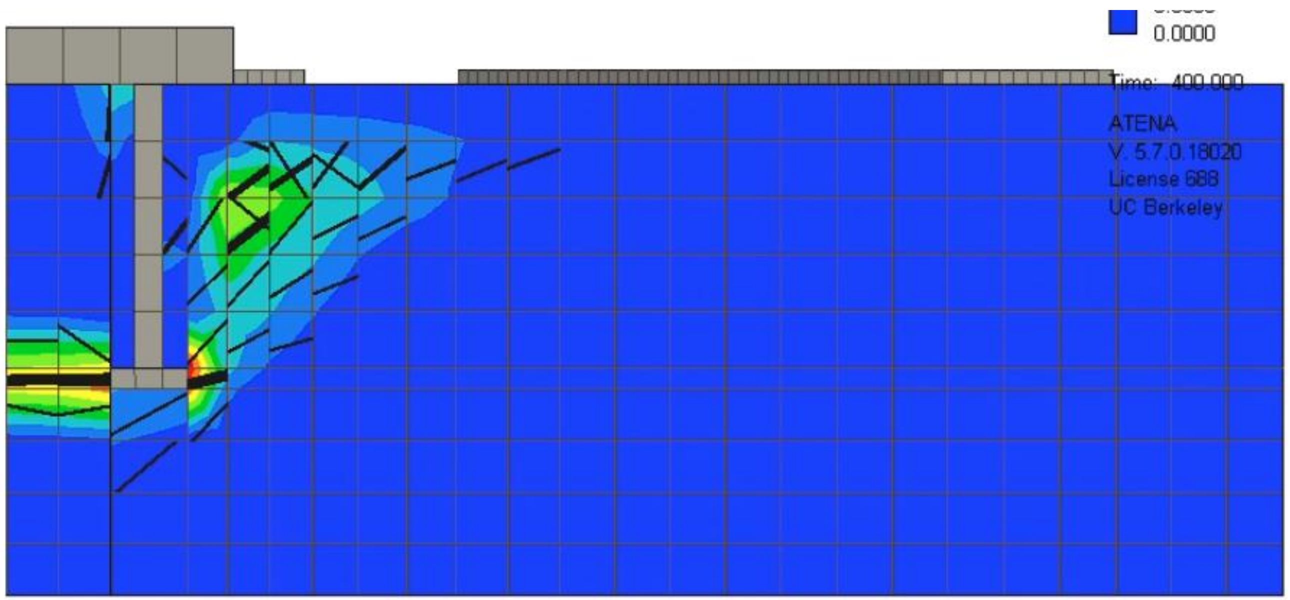



#5@7.5" G60
90"
34,5"
21"
34,5"
9"
#5@7.5" G60
Shear Reinforcement
#4@7.5" G60
5"
5"
W24x55 Supports
Lifting hook
and EMT tube
40"
15"
15"
15"
15"
25"
5"
5"
40"

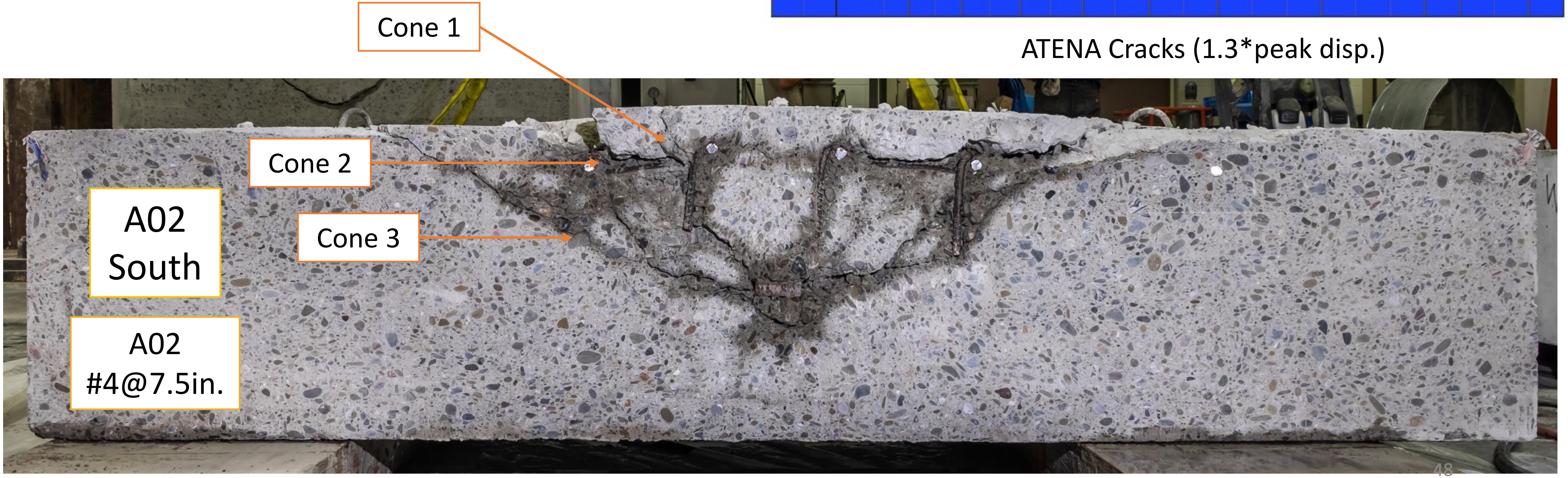

90"
72"
#5@7.5" G60
4 anchors
1-1/8"Ø G105
#4@7.5" G60
18"
10"
Lab Strong
Floor

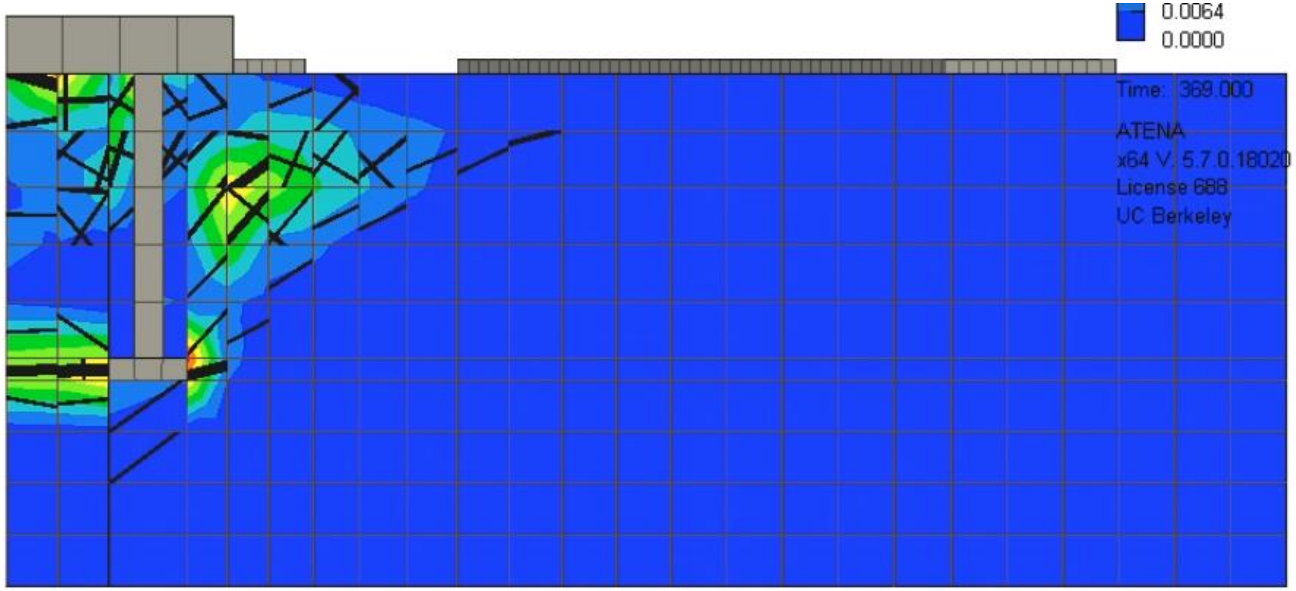


ATENA Cracks (1.3*peak disp.)

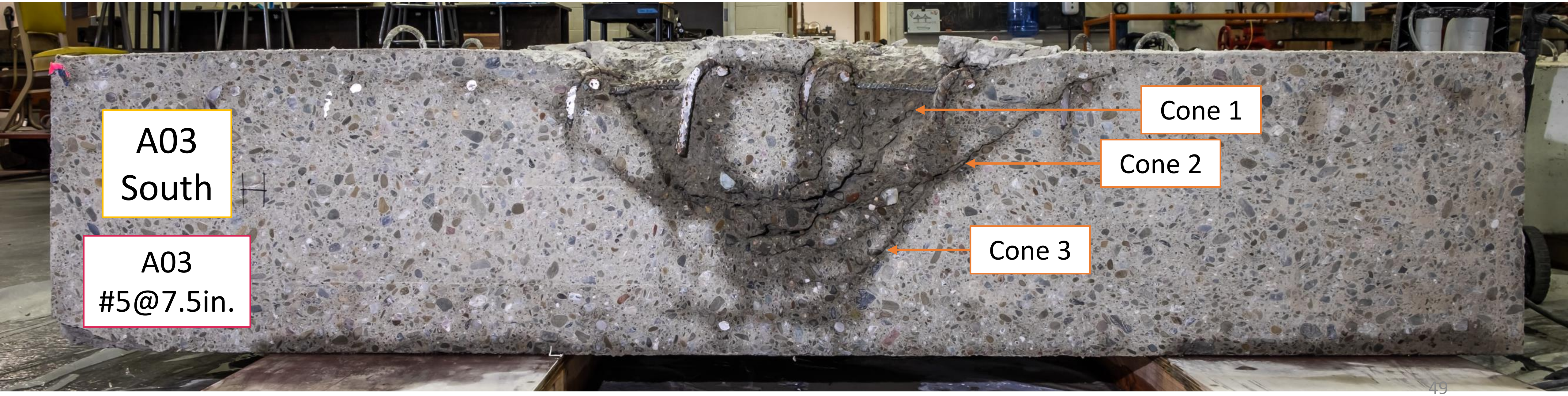


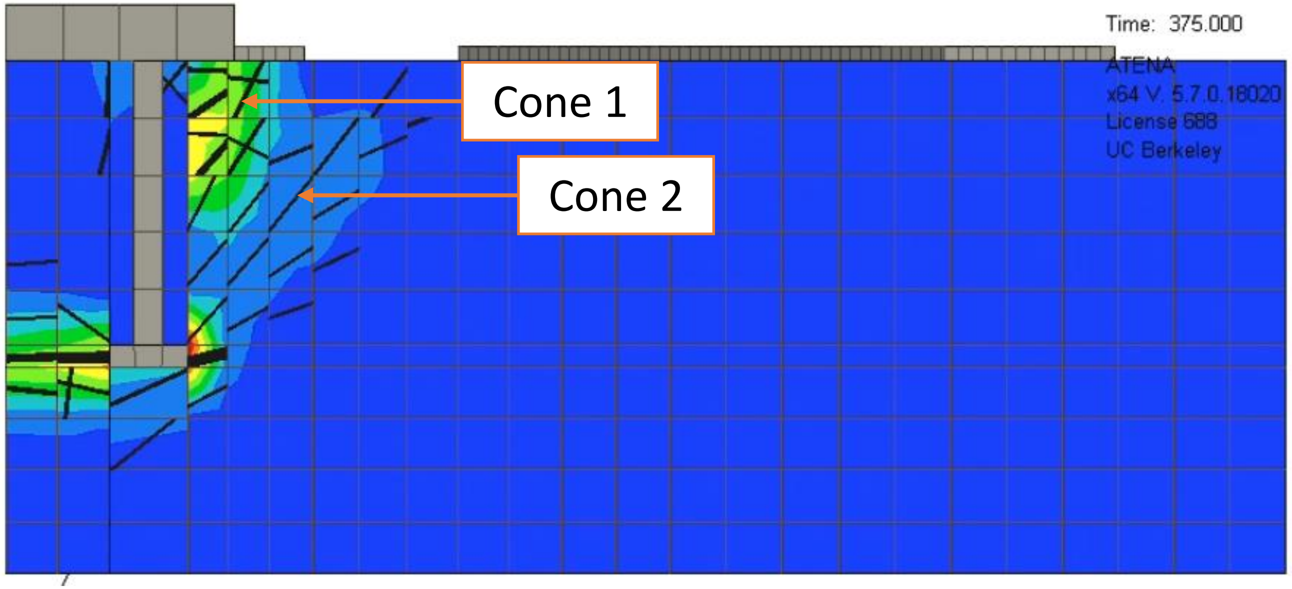
ATENA Cracks (1.3*peak disp.)



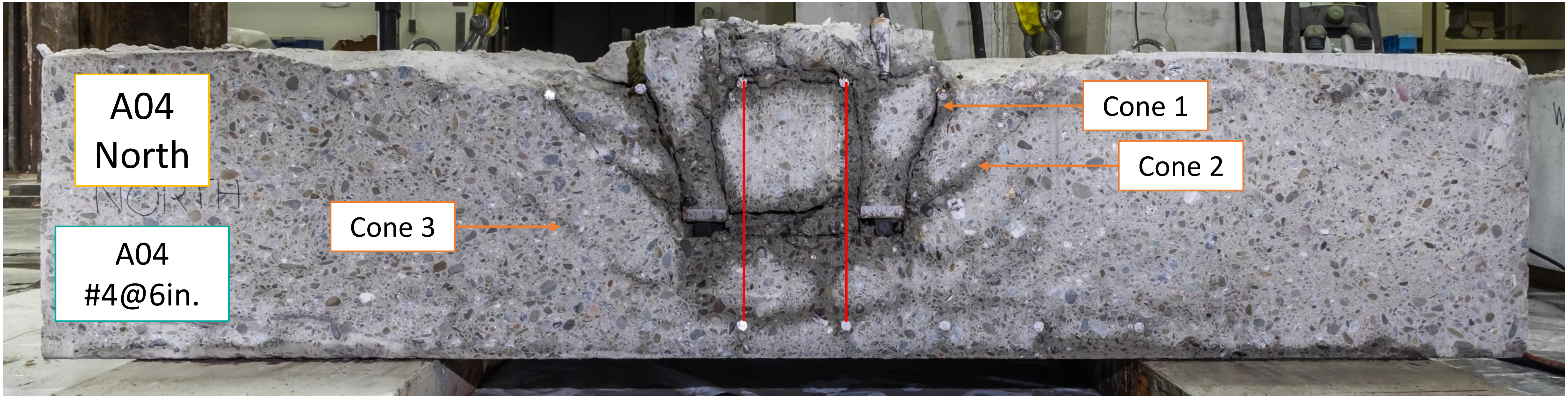


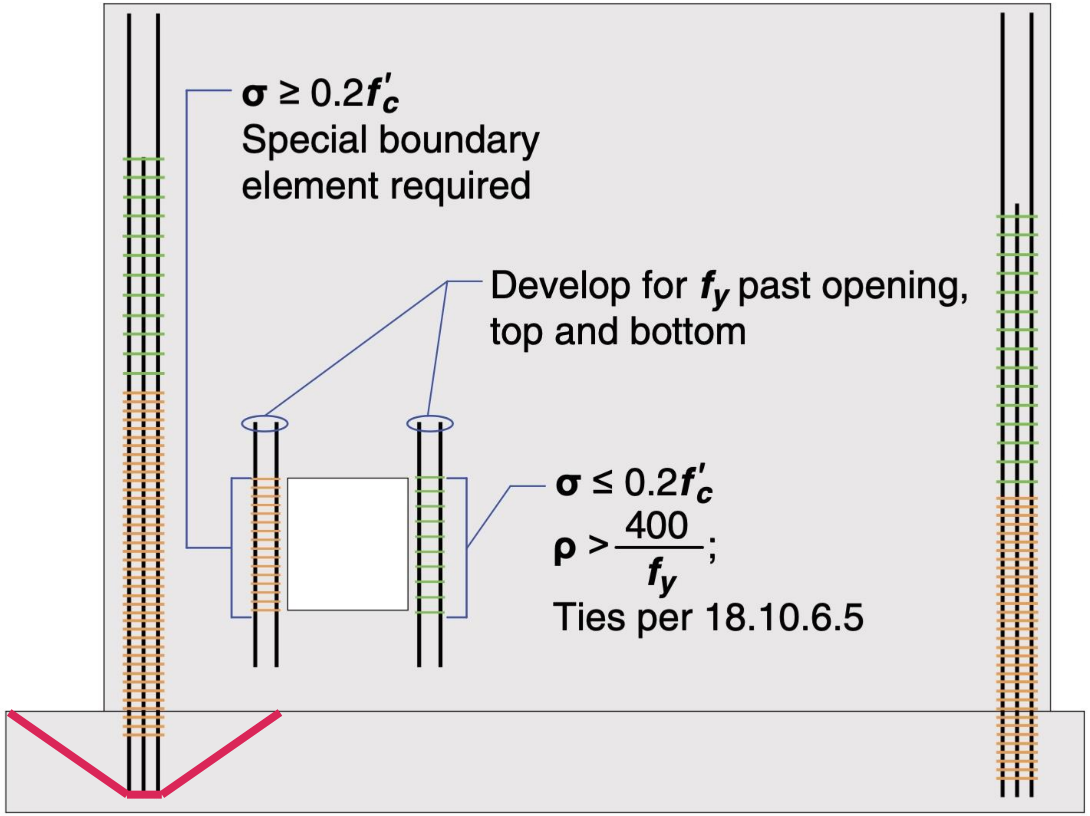
ATENA Cracks (1.3*peak disp.)





ATENA Cracks (1.3*peak disp.)




$\sigma \geq 0.2f'_c$
Special boundary element required
Develop for f_y past opening, top and bottom
$\sigma \leq 0.2f'_c$
$\rho > \frac{400}{f_y}$;
Ties per 18.10.6.5

ACI 318-19