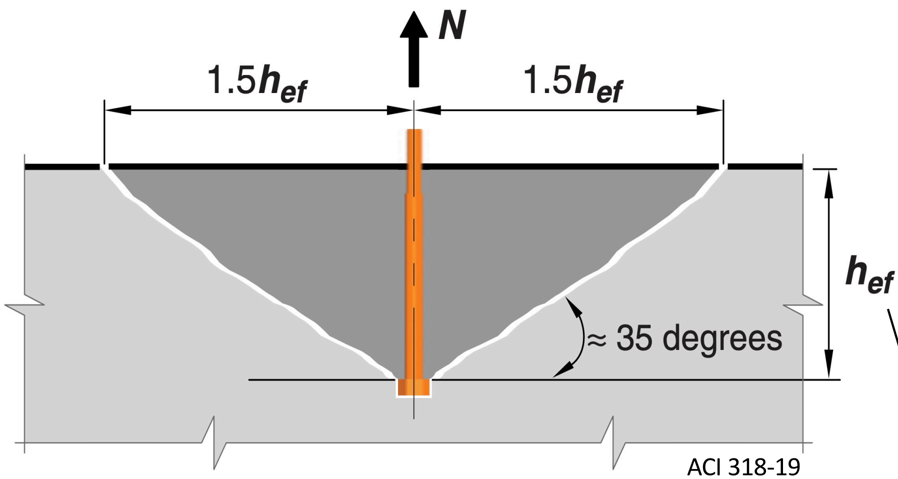
Shear-Reinforced Concrete Breakout Failure

CCAPS Structures Engineering Webinar Series
02/20/2024
Ben Worsfold, PhD PE
Assistant Professor
University of Minnesota
worsfold@umn.edu

University of Minnesota
Driven to Discover®

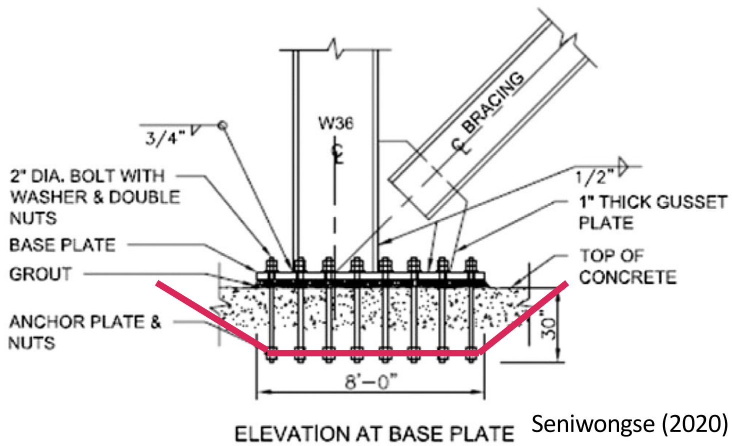
Concrete Breakout Failure Cone



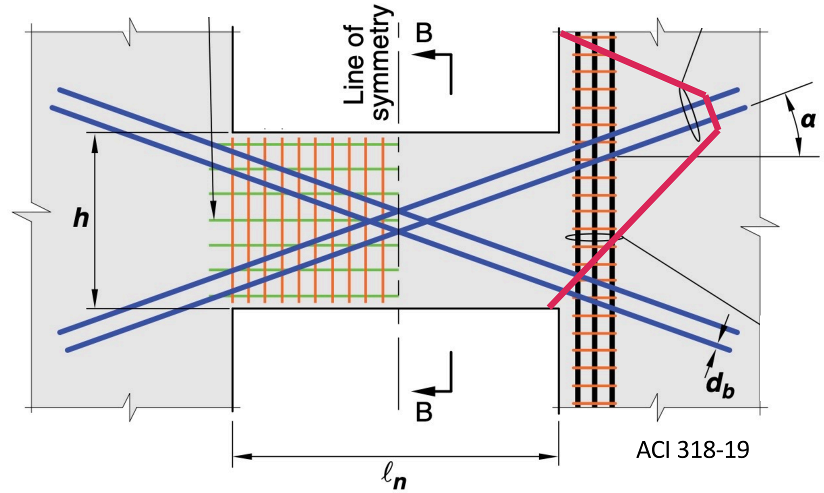
Can breakout failure govern in large-scale connections? (groups of anchor or rebar)

Effective depth

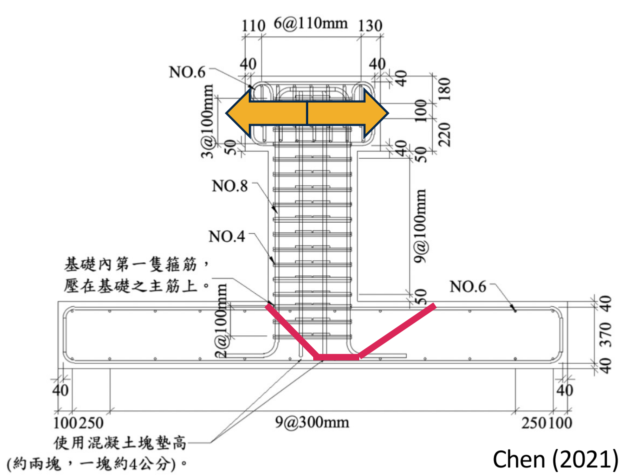
Breakout Potential?



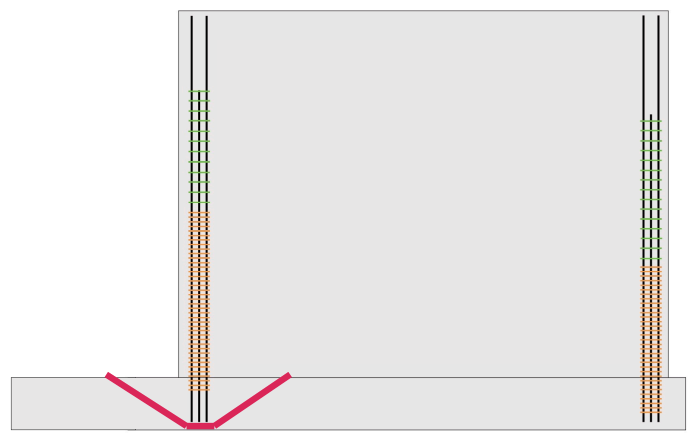
Seniwongse (2020)



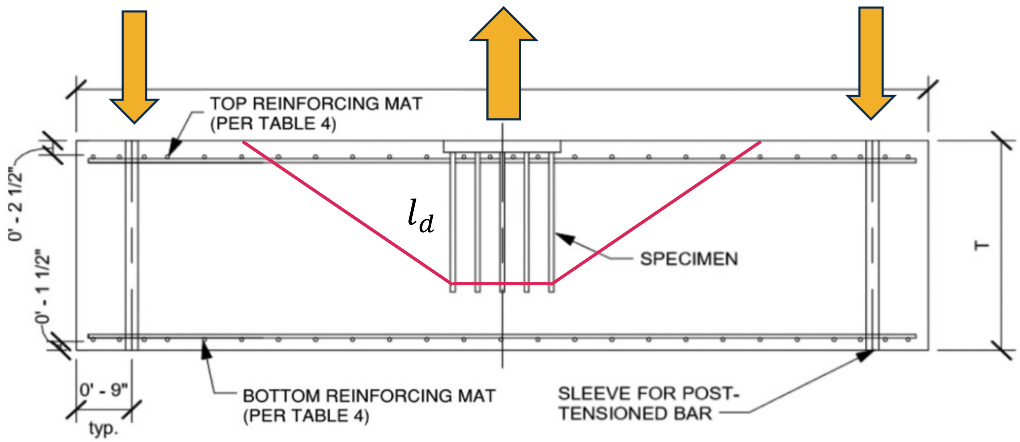
ACI 318-19

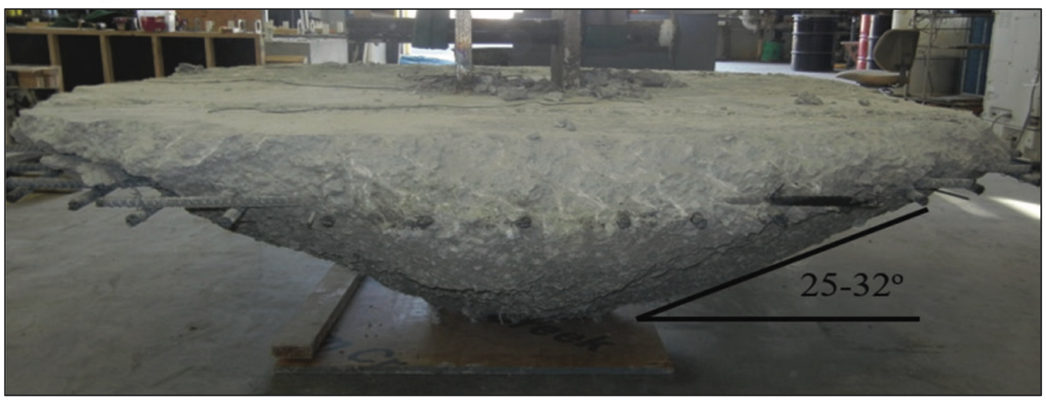


Chen (2021)


ACI 318-19

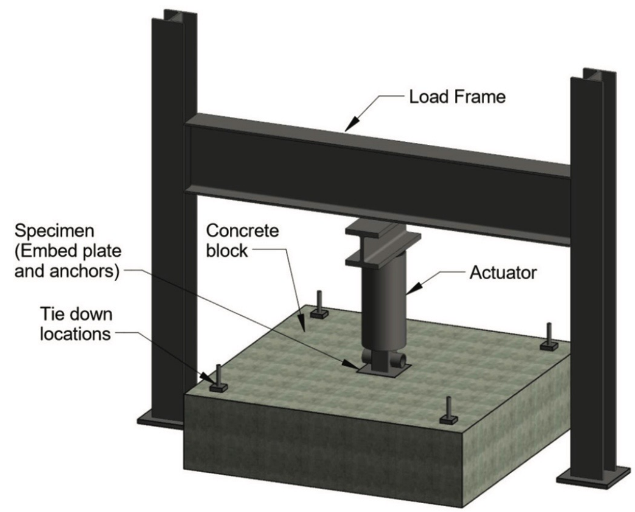
Premature Breakout Failure Examples





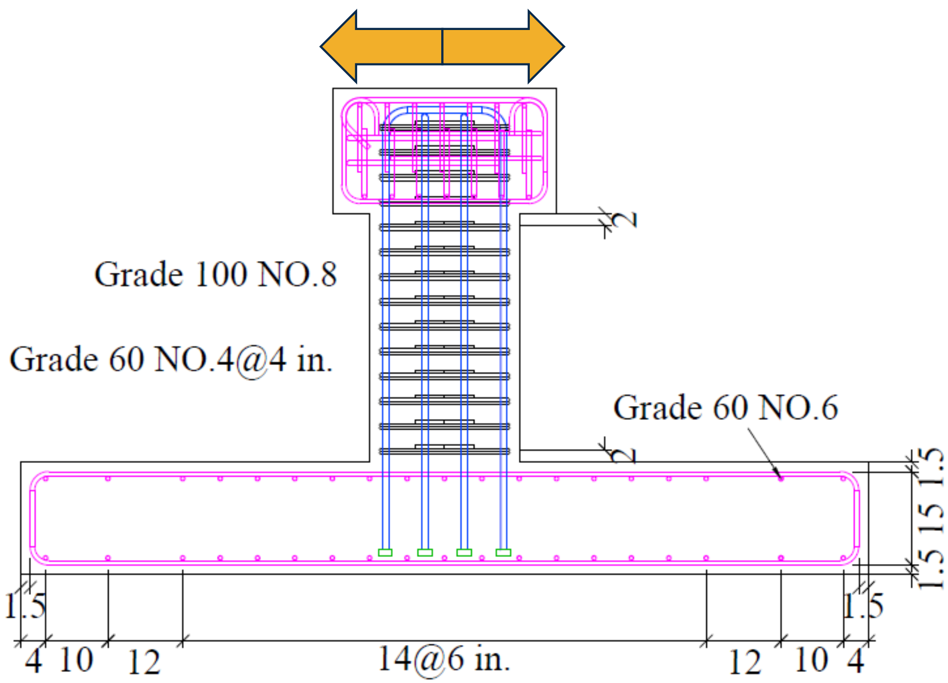
Chicchi et al. (2020)

- Purdue
- Groups of straight bars (up to 5x5 groups)
- 8 Specimens
- Developed length
- Breakout failure governed before nominal bar yield



Premature Breakout Failure Examples

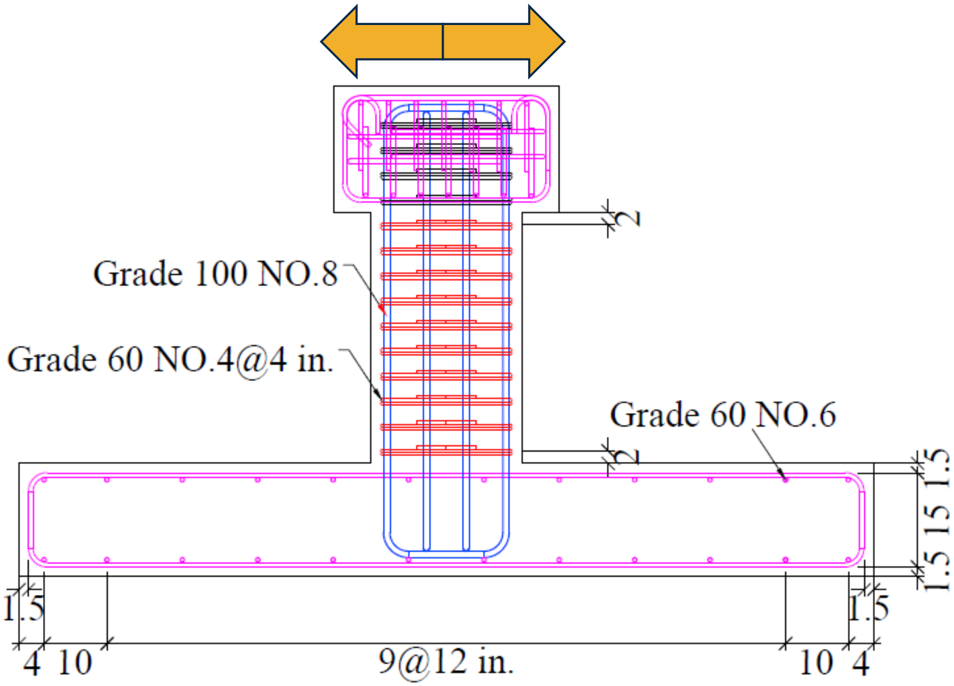
- Taiwan National University of Science and Technology
- Breakout before nominal bar yield



Chen (2021)

Premature Breakout Failure Examples

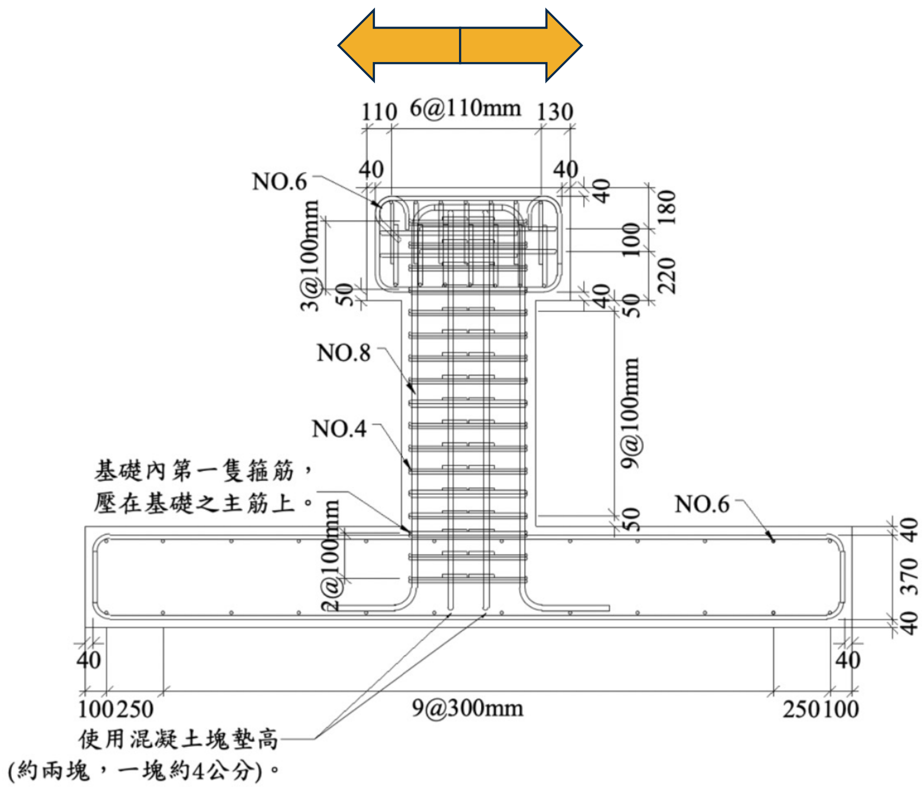
- Taiwan National University of Science and Technology
- Breakout before nominal bar yield



Chen (2021)

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 lengths are 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 can be overly conservative.

- Example breakout strength specimen M01:

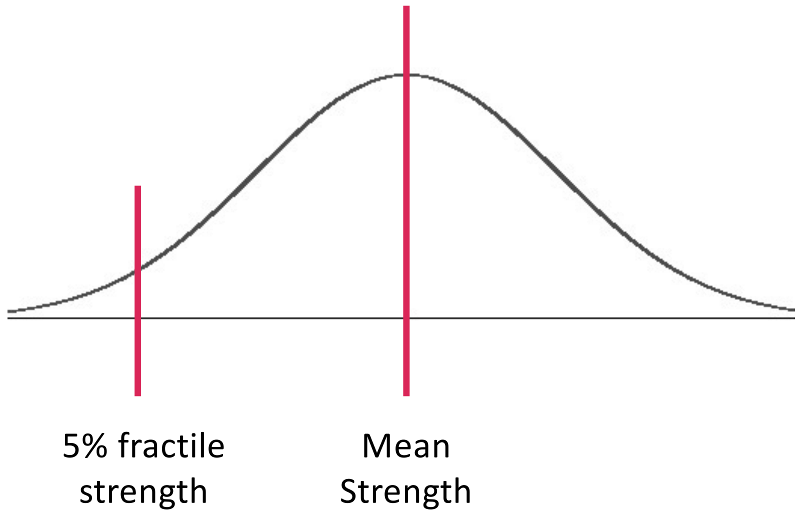
$$N_{test} = 253\ kip$$

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

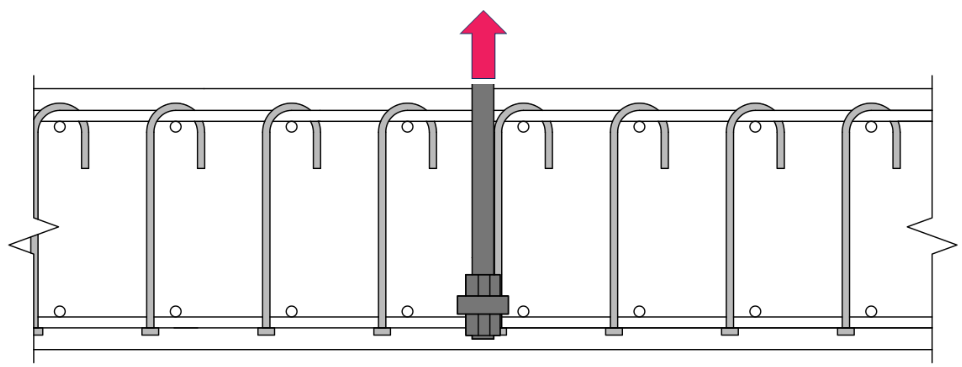
$$\frac{N_{test}}{\Phi N_{cbg}} = 3.3$$

Sources of Breakout Conservatism

1. 5% Fractile Strength



2. Reinforcement ignored



ACI 318 Anchor Reinforcement

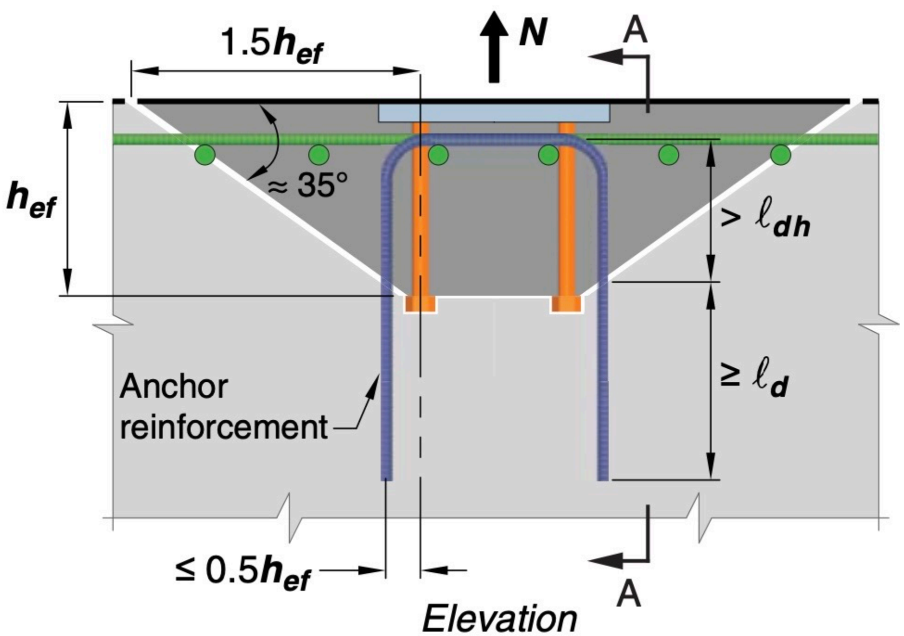


***Fig. R17.5.2.1a**—Anchor reinforcement for tension.*

Concrete strength is ignored

Shear-Reinforced Breakout (SRB)

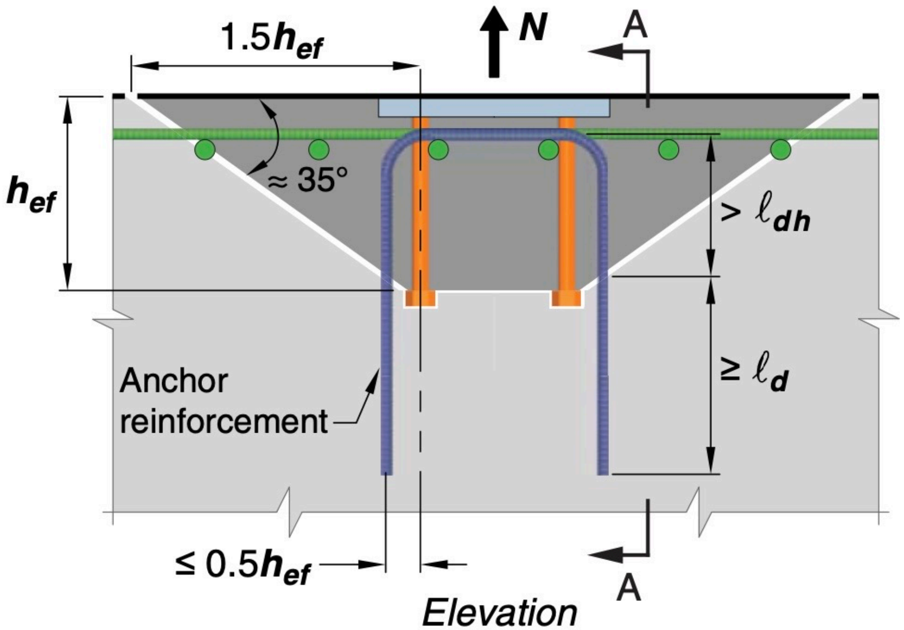


Fig. R17.5.2.1a—Anchor reinforcement for tension.

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

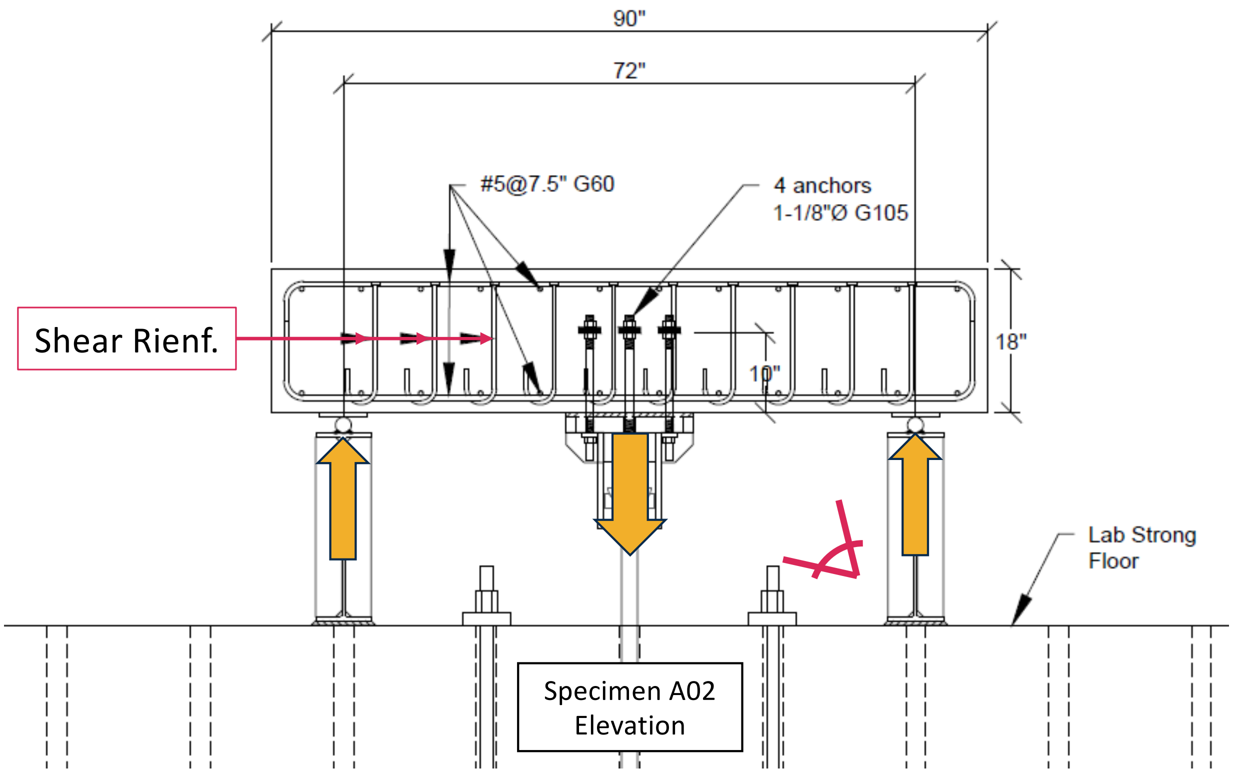
Question:

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

Shear-Reinforced Breakout Tests

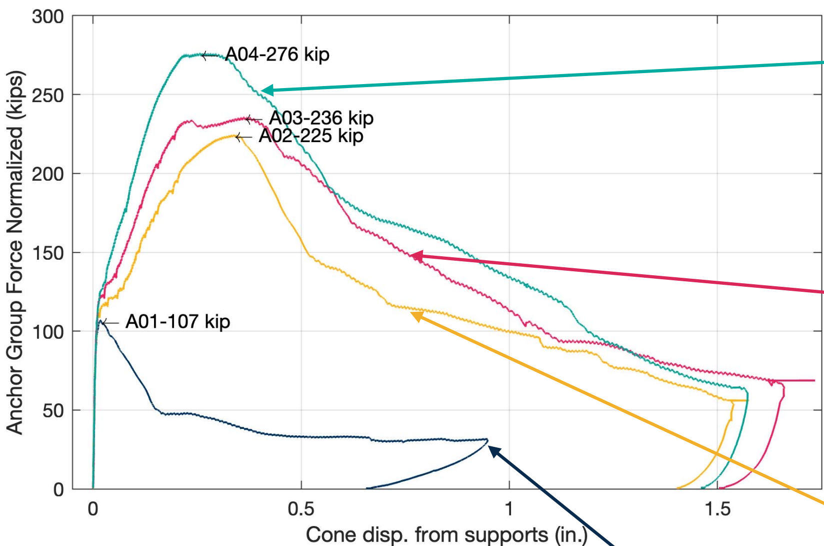
- UC Berkeley
- Four monotonic axial loading tests
- Breakout failures for all specimens
- Longitudinal bars did not appear to yield

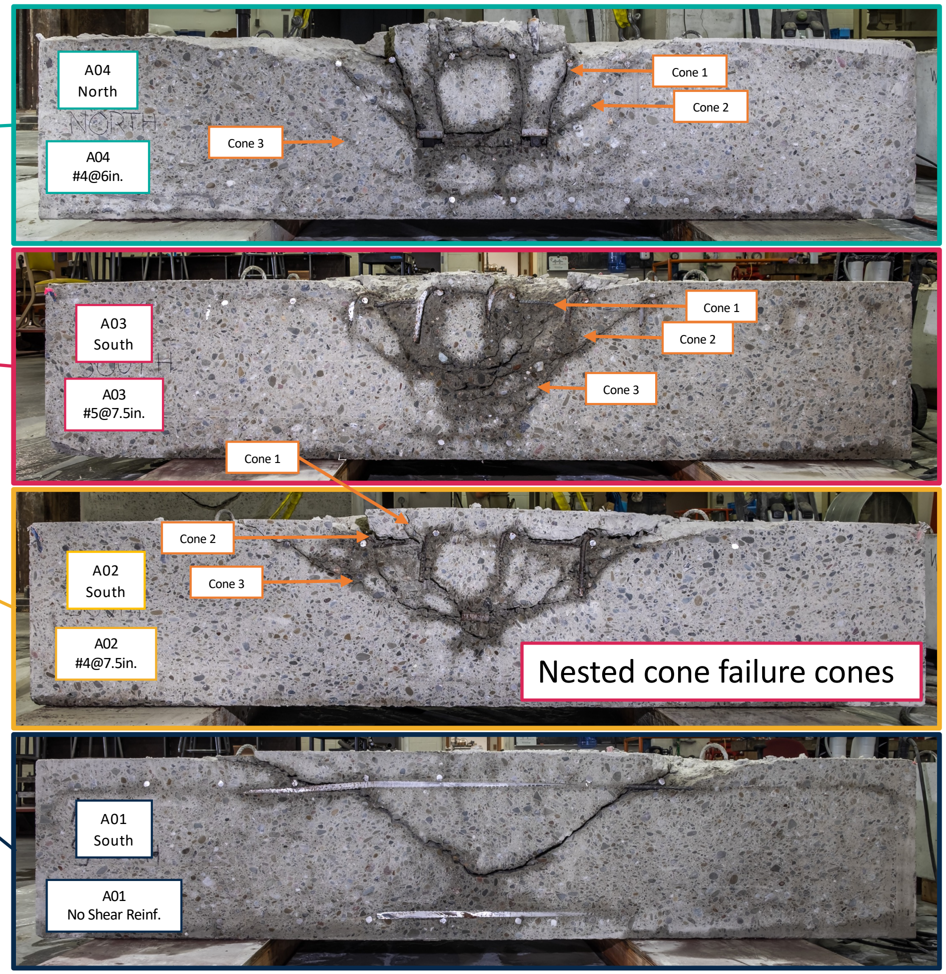
Specimen	Shear Reinforcement	Reinforcing ratio, ρ_{tr} (%)
A01	N/A	0
A02	#4@7.5in.	0.36%
A03	#5@7.5in.	0.55%
A04	#4@6in.	0.56%



Karać (2022)

Shear-Reinforced Breakout Tests



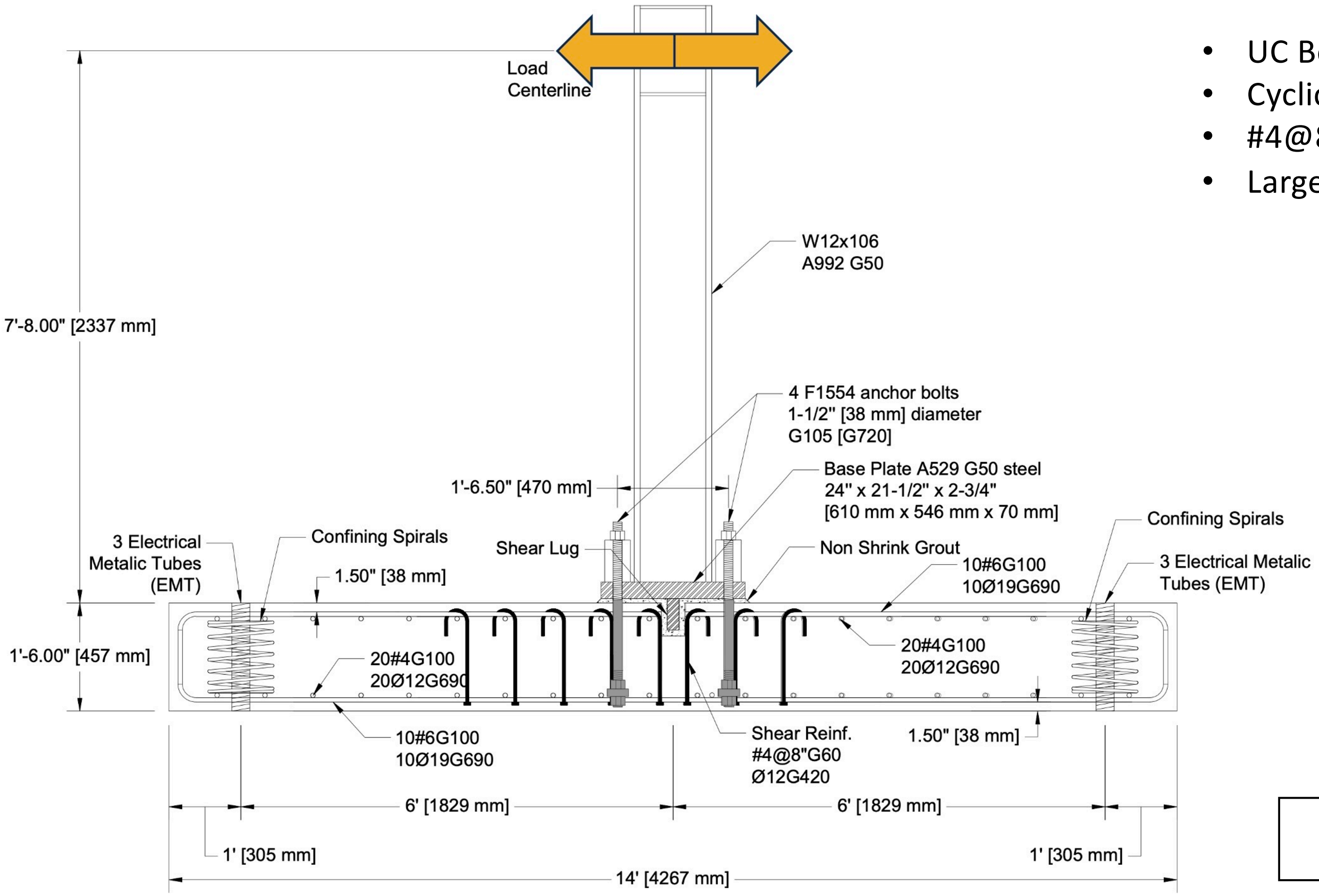


Increased

- Peak strength
- Displacement capacity

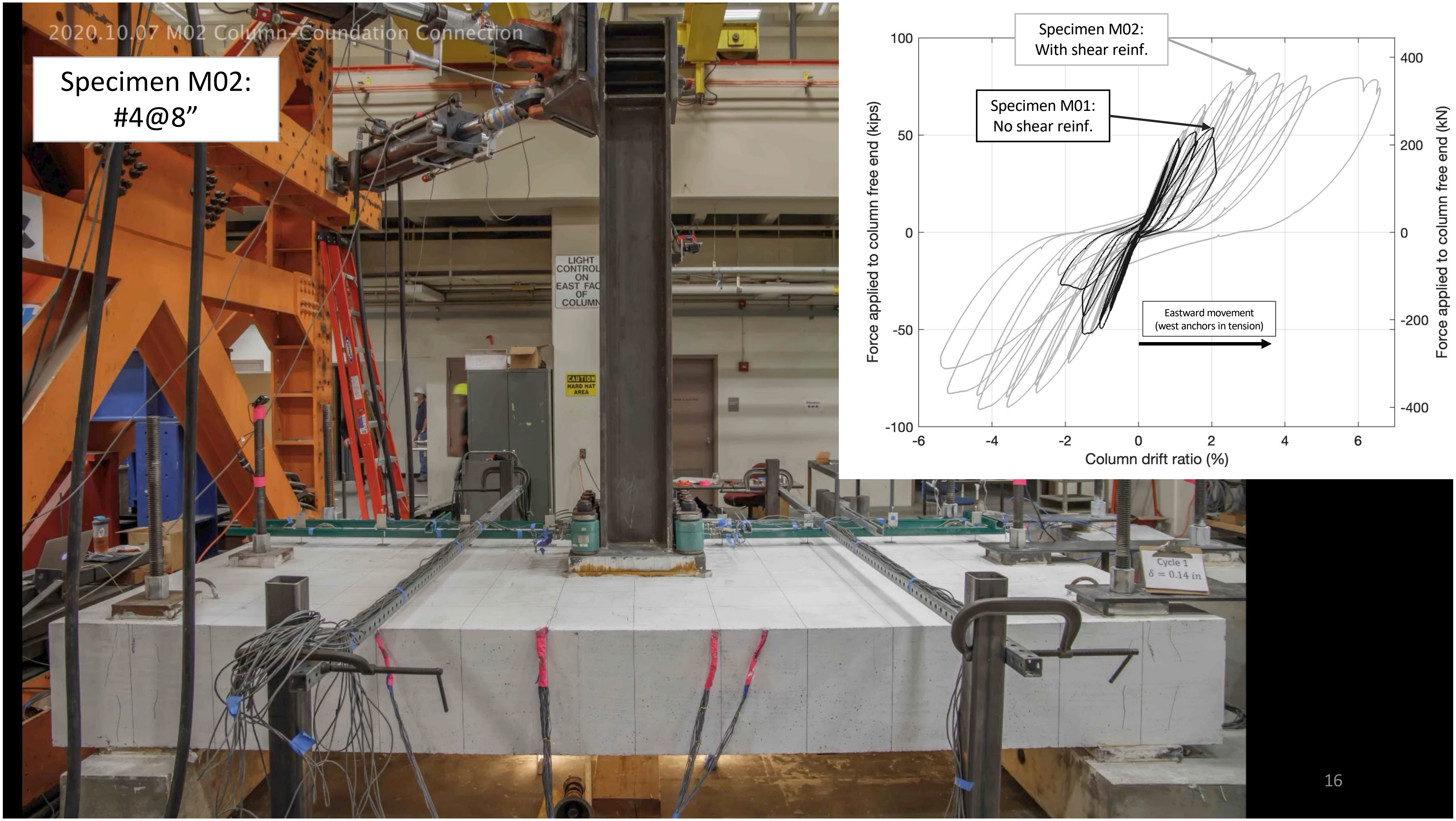
Karać (2022)

Shear-Reinforced Breakout Tests



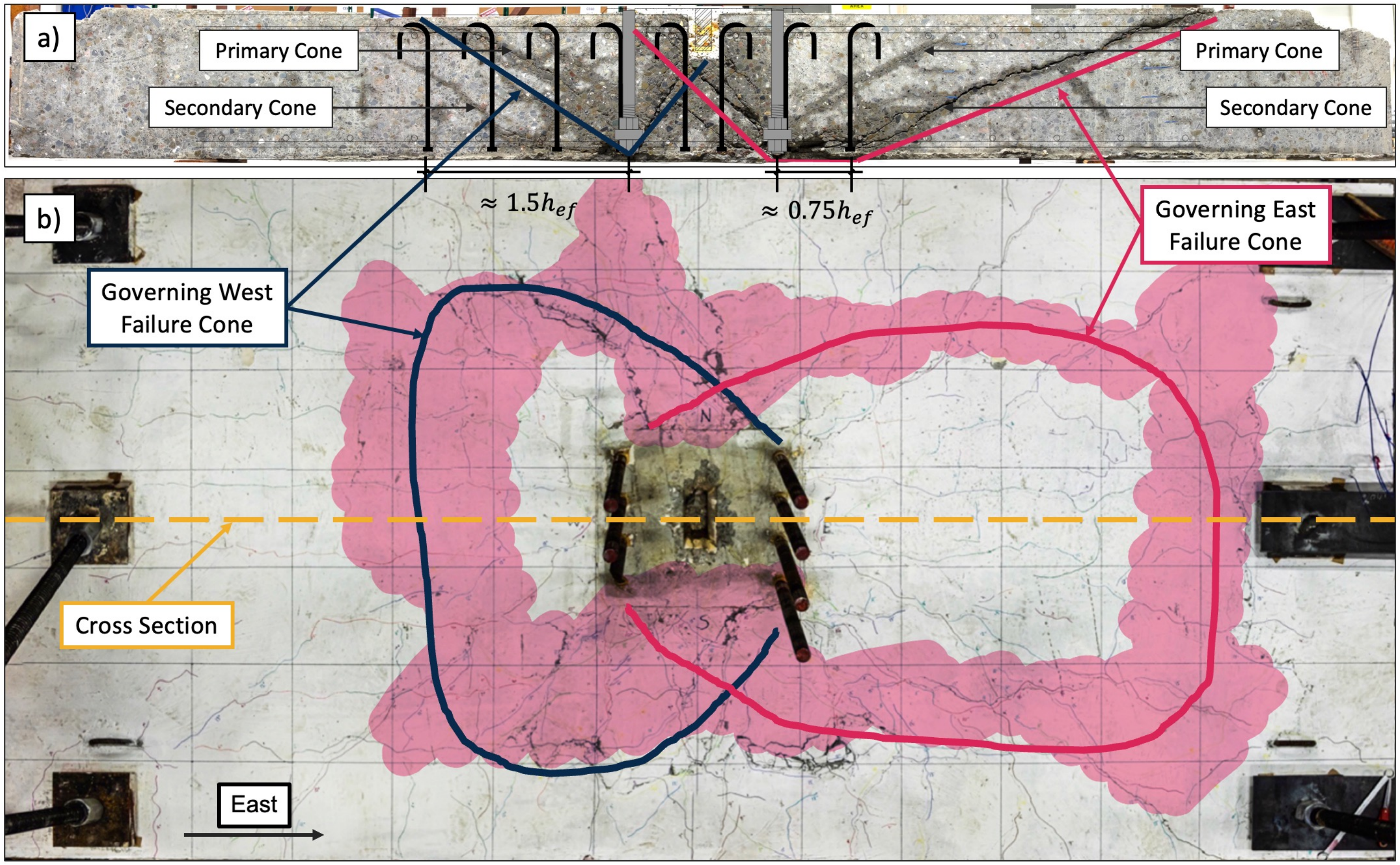
- UC Berkeley
- Cyclic loading
- #4@8" G60
- Larger reinforced region on one side

Specimen M02
Elevation

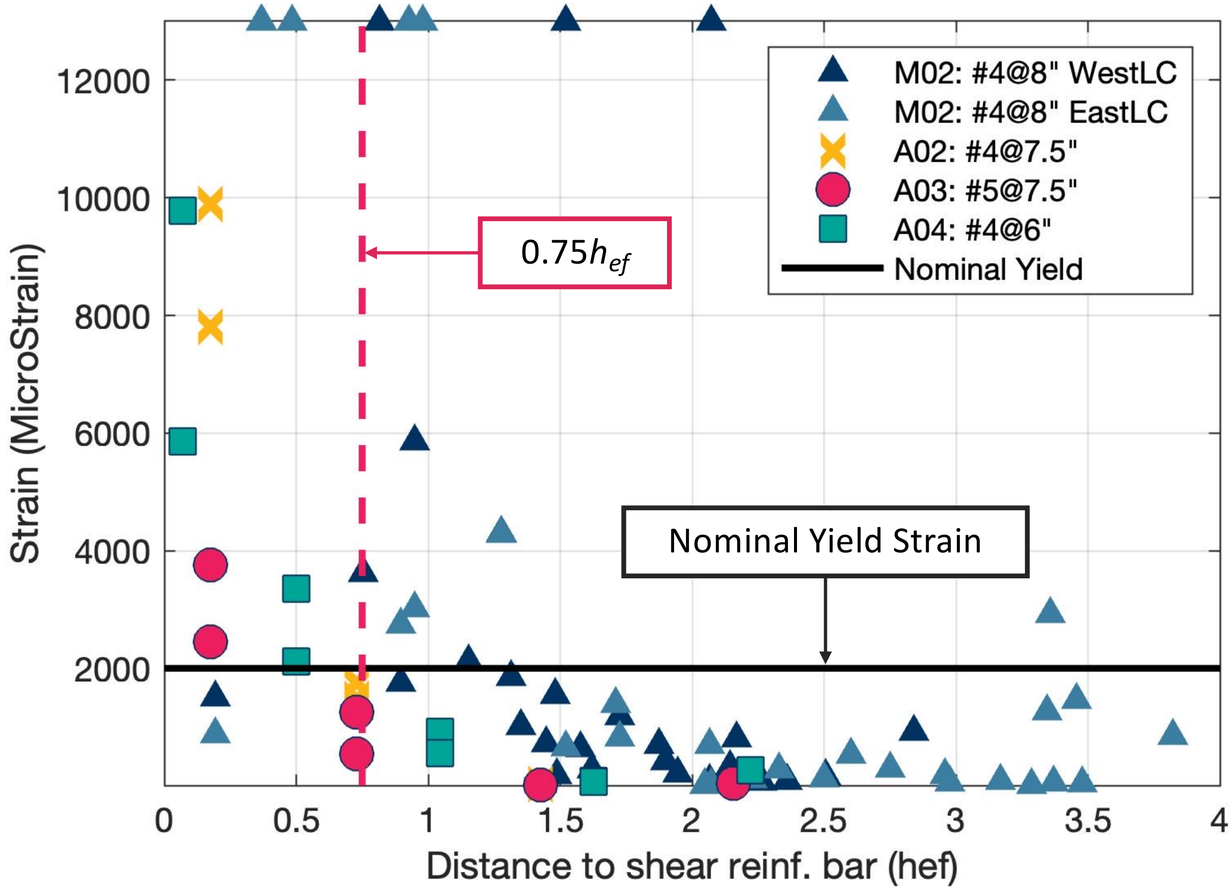


2020.10.07 M02 Column-Coundation Connection
Specimen M02:
#4@8”
LIGHT
CONTROL
ON
EAST FAC
OF
COLUMN
CAUTION
HARD HAT
AREA
Cycle 1
δ = 0.14 in
Specimen M02:
With shear reinf.
Specimen M01:
No shear reinf.
Eastward movement
(west anchors in tension)
Force applied to column free end (kips)
Force applied to column free end (kN)
Column drift ratio (%)
100
50
0
-50
-100
400
200
0
-200
-400
-6
-4
-2
0
2
4
6

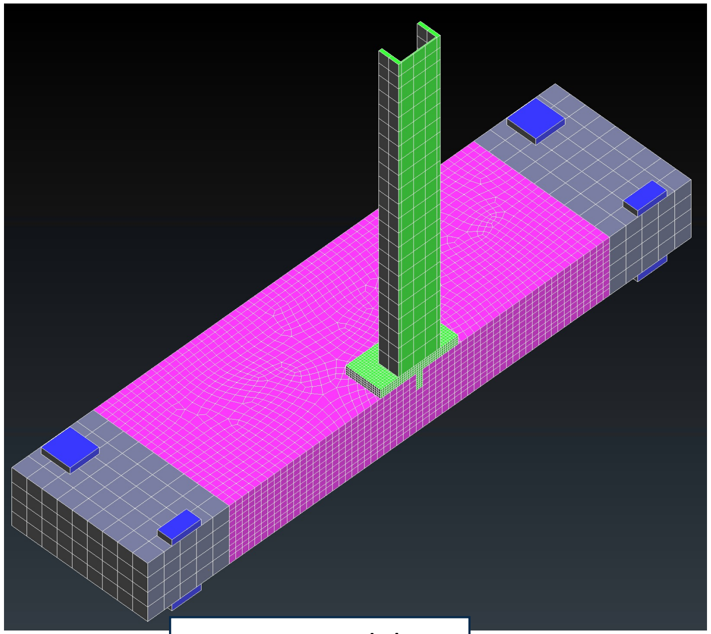
Shear-Reinforced Breakout Tests



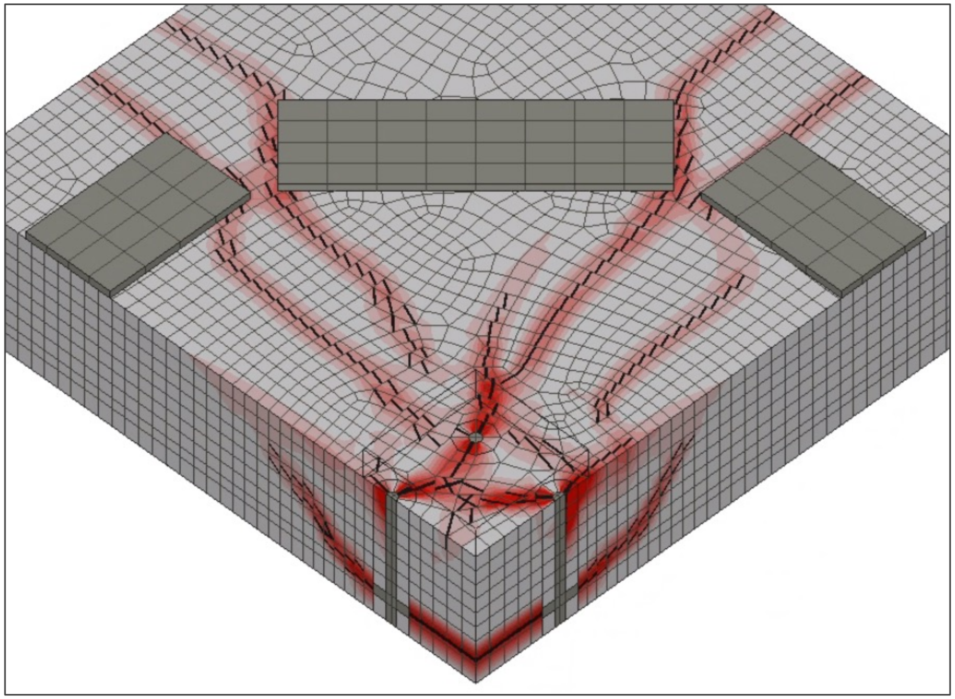
Shear Bar Strains



Finite Element Studies



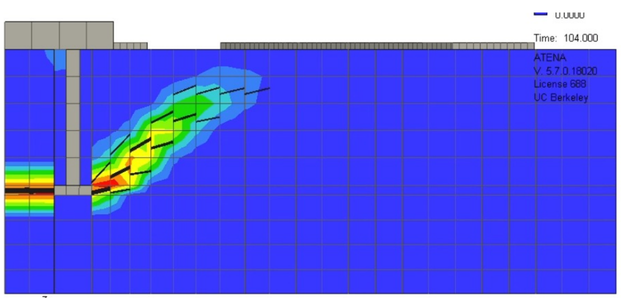
M01 Model



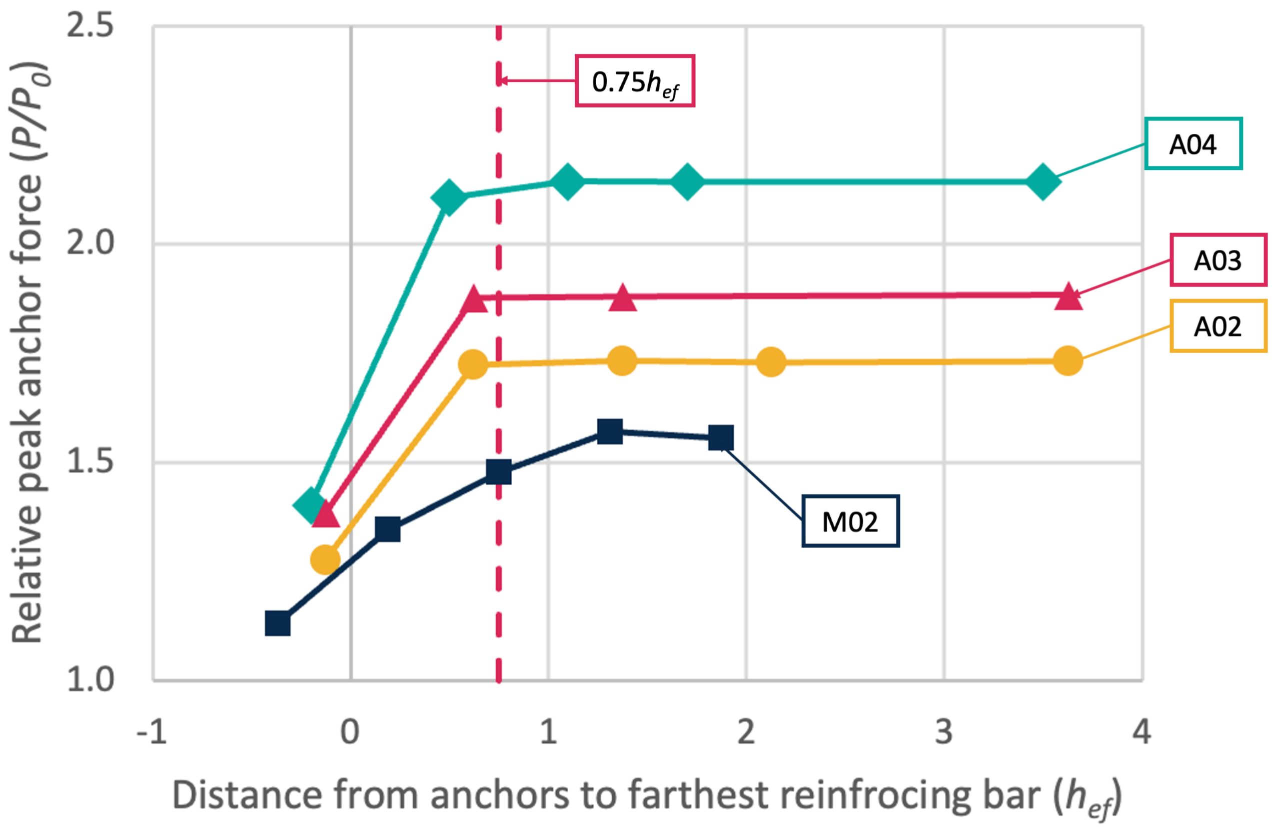
FE Crack Pattern

Finite Element Studies: shear-reinforced region

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



FE Crack Pattern



New Shear-Reinforced Breakout (SRB) Design Equation (ACI 318-25)

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

- $N_{n,SRB}$: Nominal anchor strength for shear-reinforced breakout
- N_c: Mean concrete breakout strength
- N_s: Mean reinforcement strength

Shear-Reinforced Breakout (SRB) Design Equation

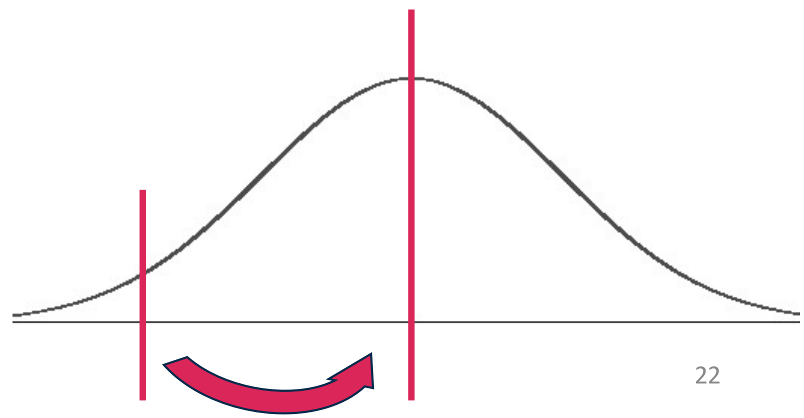
$$N_c = 1.33 N_{cbg}$$

Mean concrete breakout strength

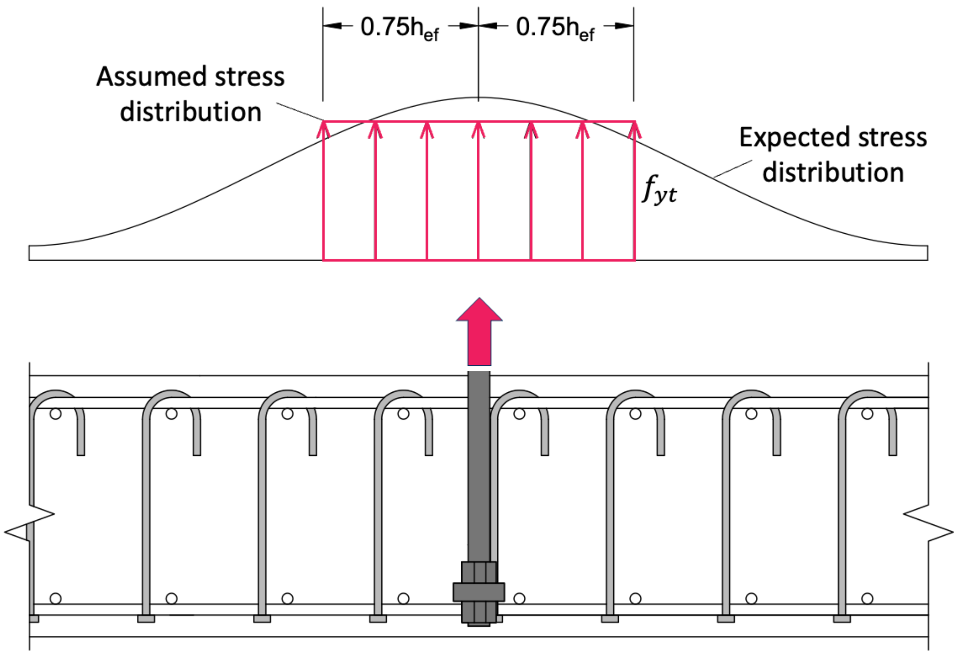
5% fractile strength
ACI 318-19 Chap. 17

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

Fuchs (1995)



Shear-Reinforced Breakout (SRB) Design Equation



Shear-Reinforced Breakout Design Equation

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

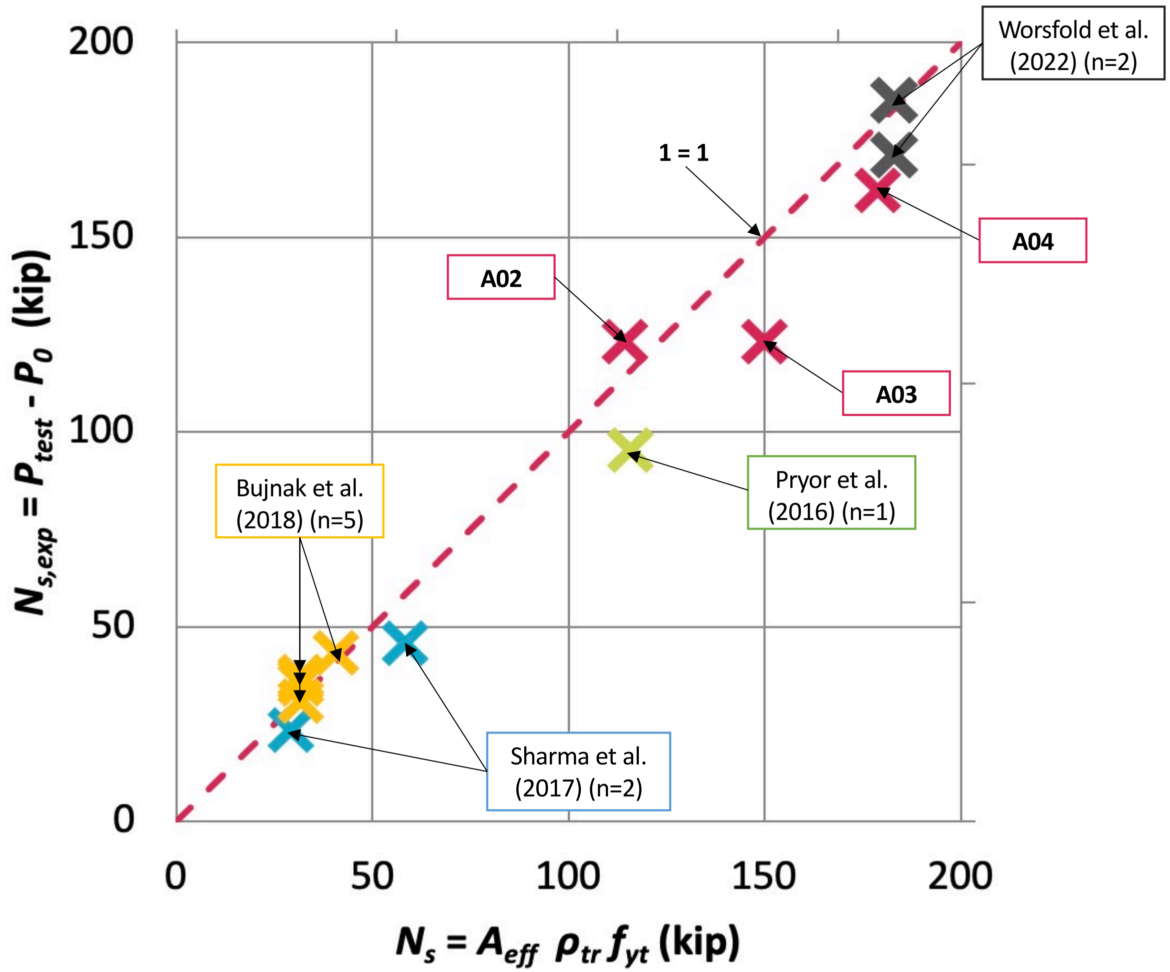
Mean reinforcement strength

Effective Area

Shear reinforcing ratio

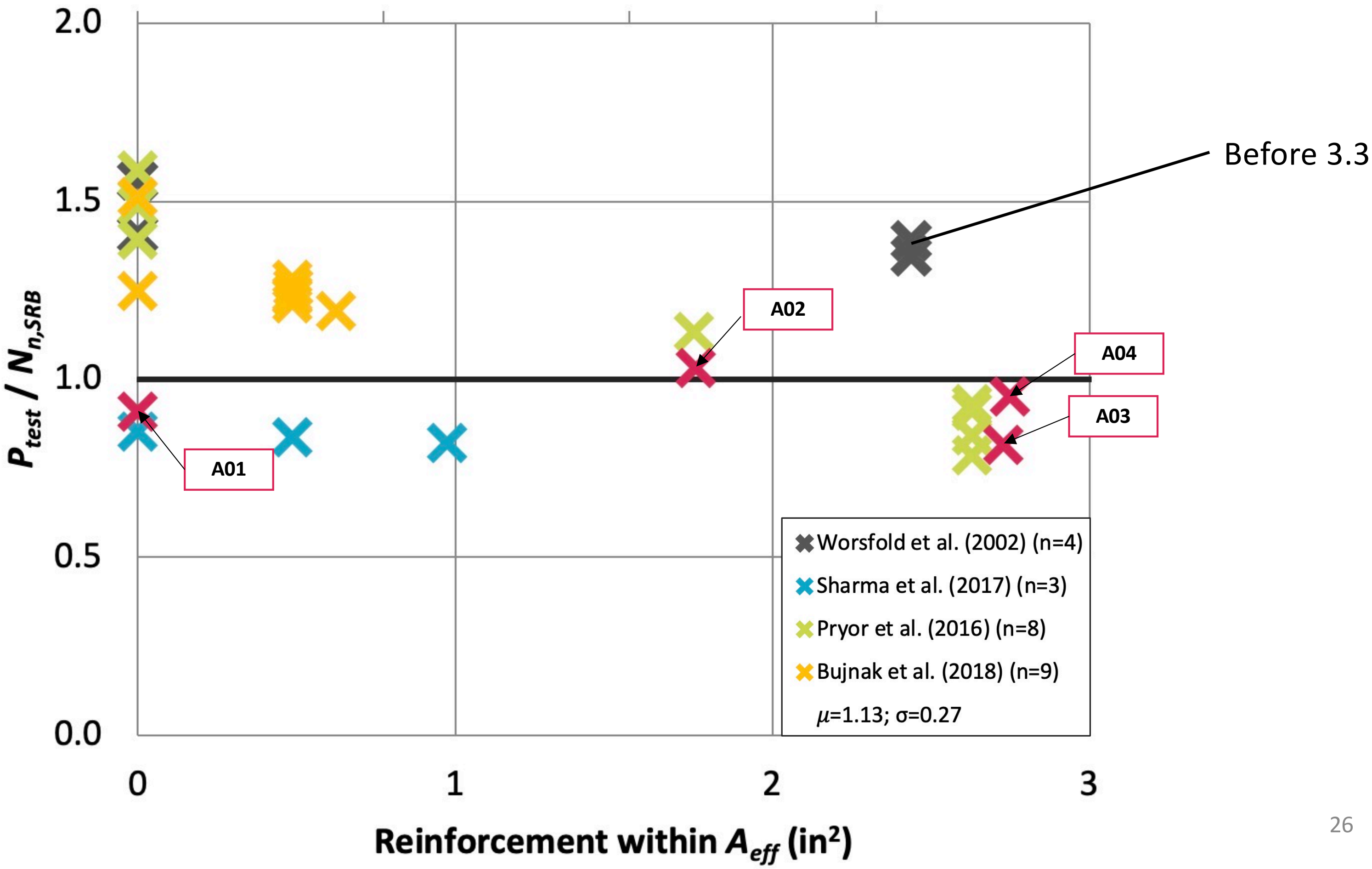
Nominal yield stress

Shear-Reinforced Breakout Design Equation

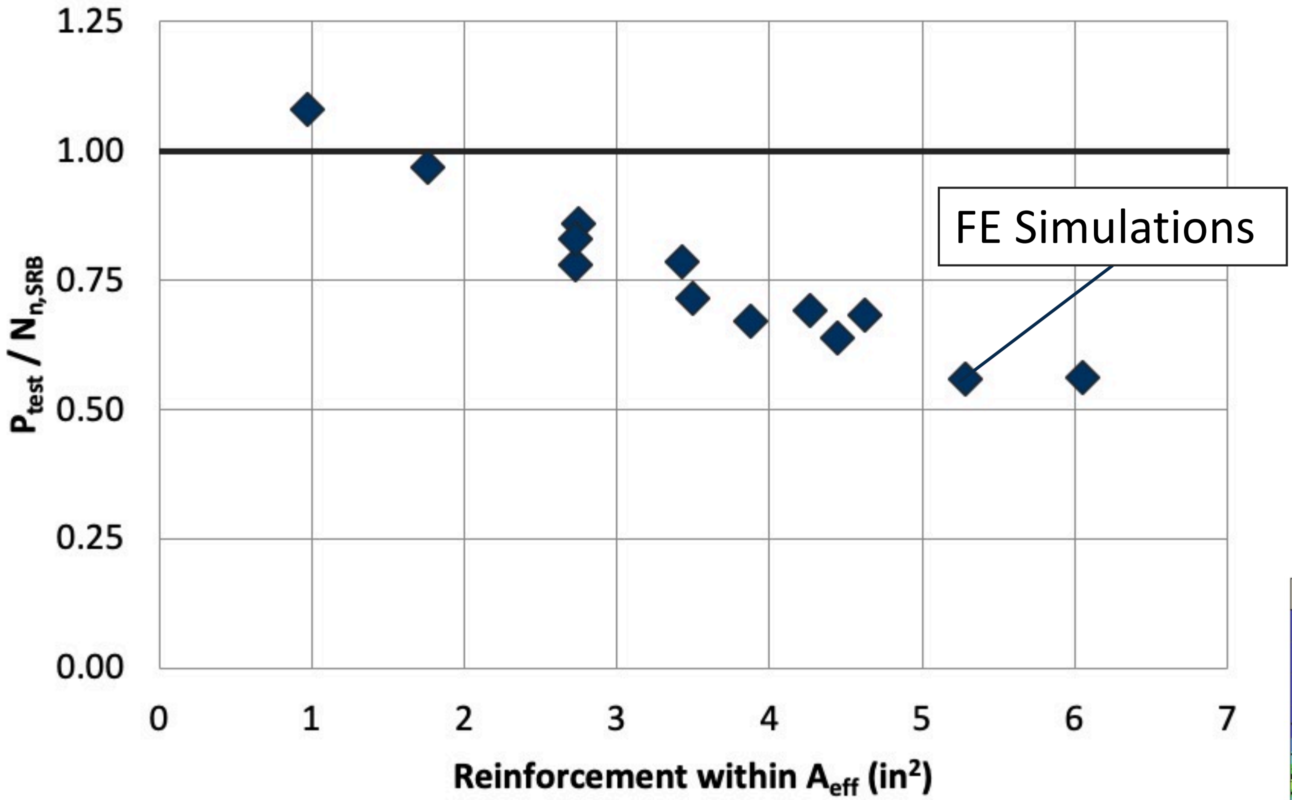


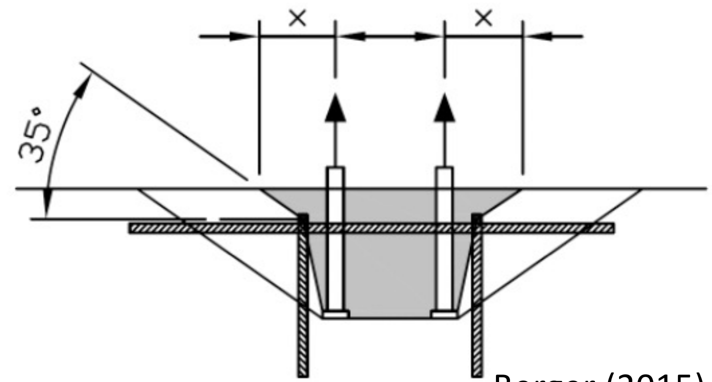
Strength Ratio

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

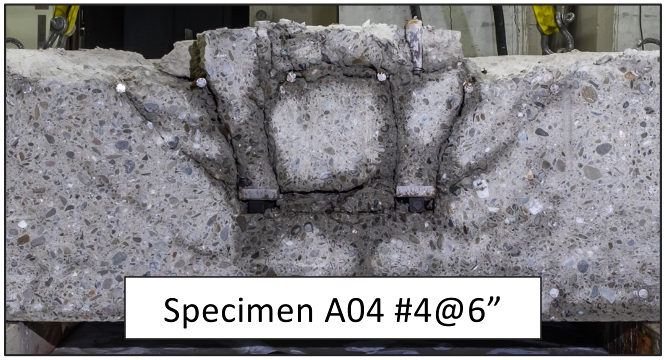


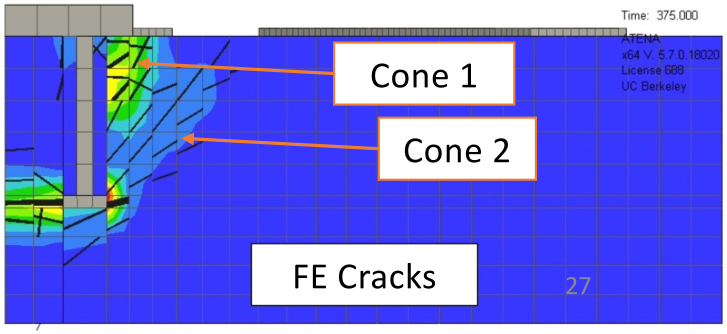
Upper Limit: Steep Cone Strength



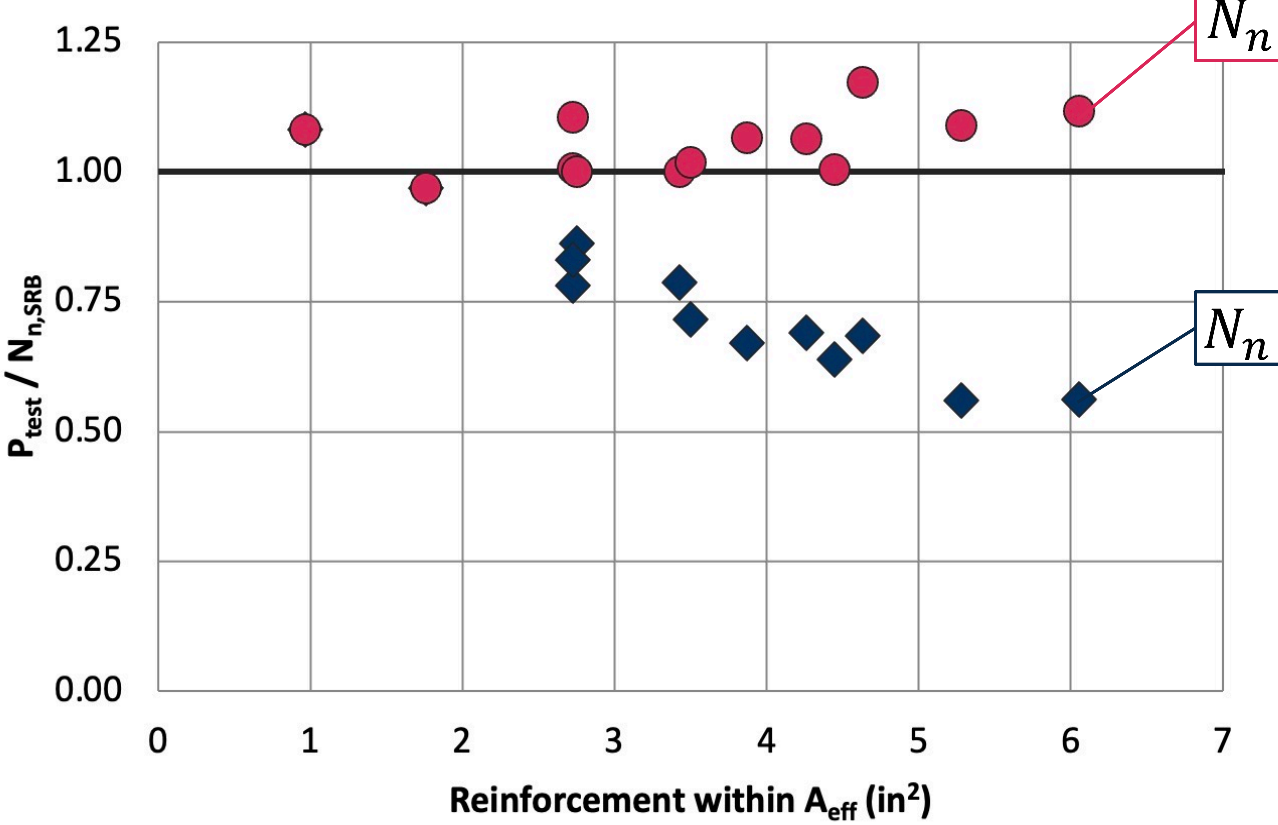


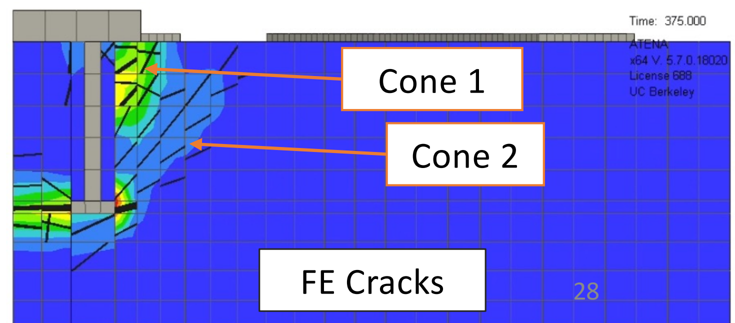
Berger (2015)





Upper Limit: Steep Cone Strength





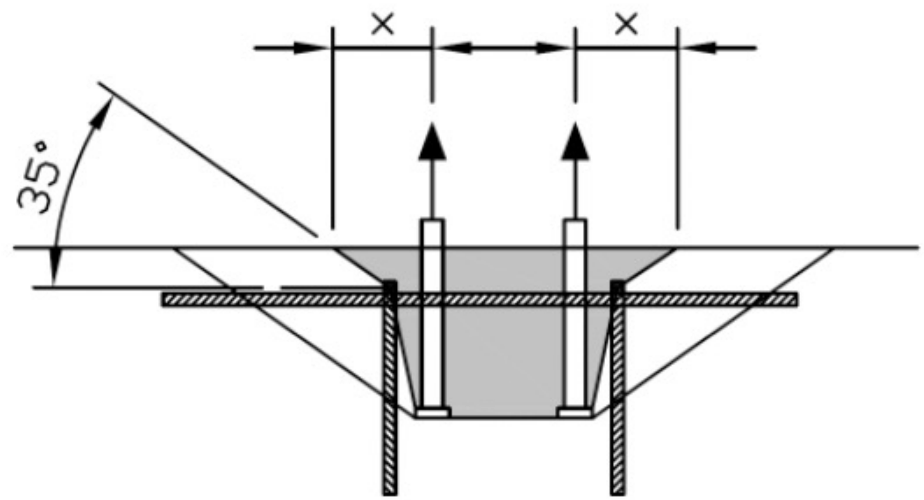
Upper Limit: Steep Cone Strength

- Considered indirectly in ACI implementation

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

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

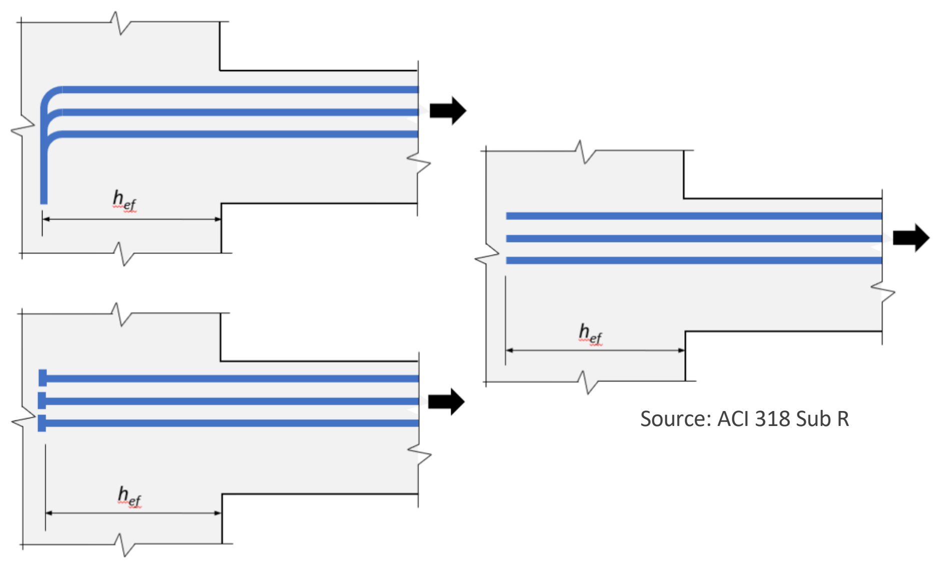
$$\Psi_{s,steep} = 2\,\frac{A'}{A_{Nc}} - 1 \geq 0$$



Berger (2015)

ACI 318-25 New Design Equation

- New provisions require breakout failure checks at the termination of groups of straight, hooked, or headed bars.
- Beam-column joints exempt



Source: ACI 318 Sub R

Code Implementation: Detailing Requirements

1. Shear reinforcement shall be parallel to bar group

2. Shear reinforcement shall terminate in hooks or heads beyond the termination of the bar group satisfying the requirements for stirrups in 25.7.1.3

3. Shear reinforcement bar diameter shall not exceed the diameter of the smallest bar in the bar group

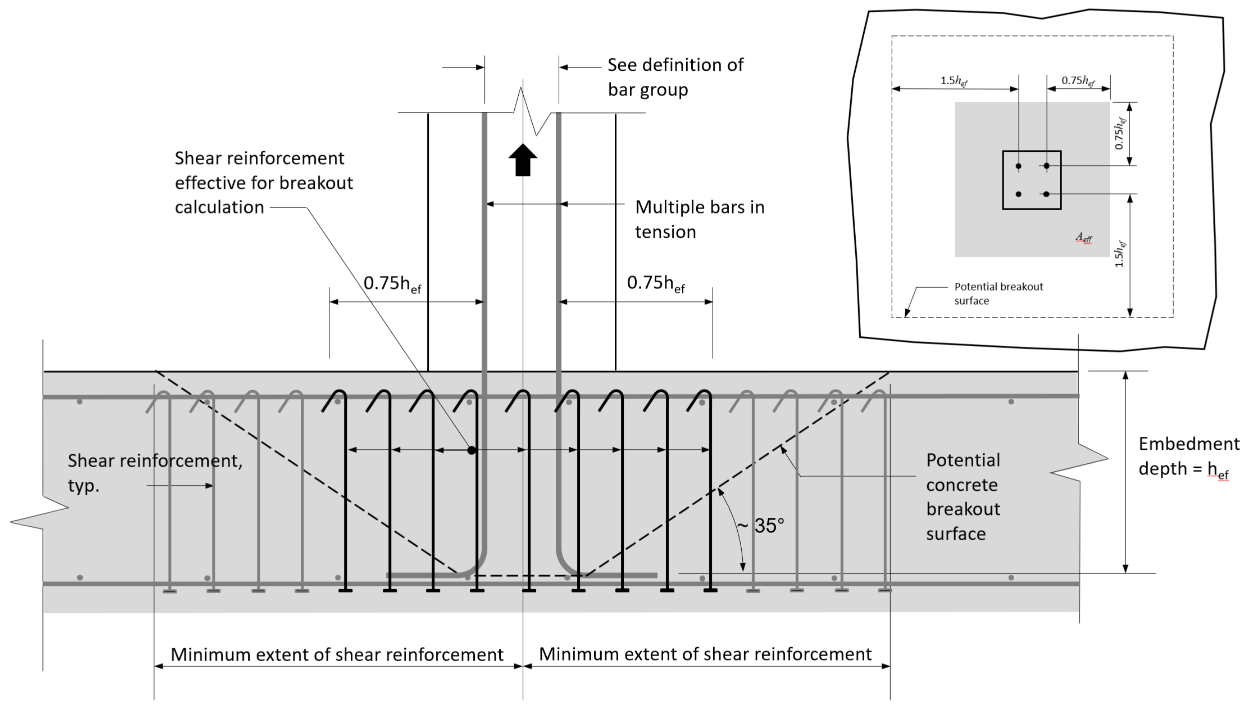
4. Shear reinforced region extends at least throughout projected cone region

5. Maximum bar spacing

$$s_{max} = 0.5h_{ef}$$

If $N_{n,SRB} \geq 2.5N_c$

$$s_{max} = 0.25h_{ef}$$



ACI 318 Anchor Reinforcement

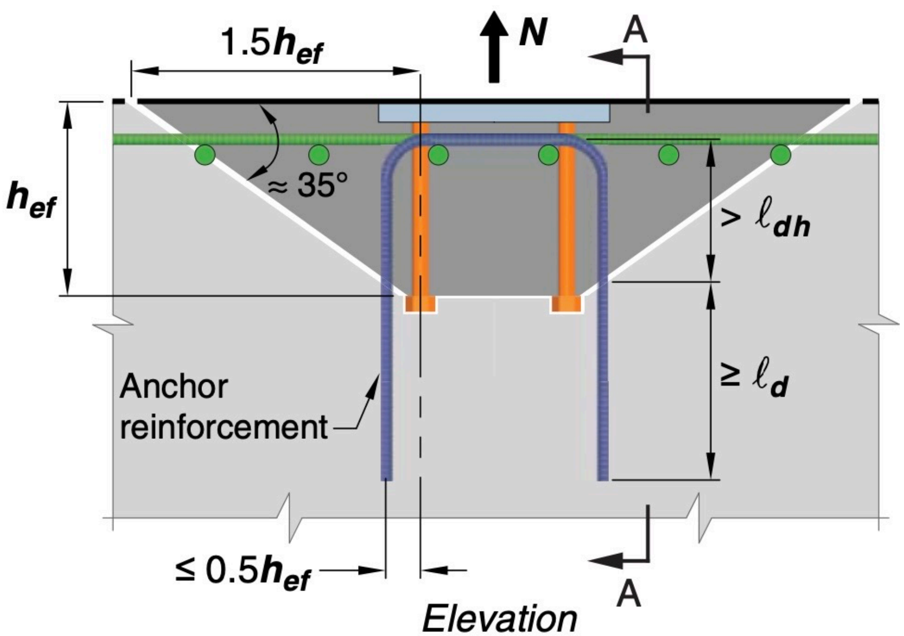


***Fig. R17.5.2.1a**—Anchor reinforcement for tension.*

- Anchor Reinforcement is still an allowable solution
- Concrete strength is ignored

Publications

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title No. 119-S104

Moment Transfer at Column-Foundation Connections: Physical Tests

by Benjamin L. Worsfold, Jack P. Moehle, and John F. Silva

Wason Medal Most Meritorious Paper (2023)

ACI STRUCTURAL JOURNAL TECHNICAL PAPER

Title No. 120-S39

Moment Transfer at Column-Foundation Connections: Analytical Studies

by Benjamin L. Worsfold and Jack P. Moehle

Engineering Structures 283 (2023) 115783

Contents lists available at ScienceDirect

Engineering Structures

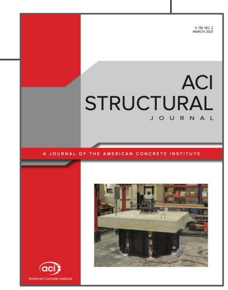
journal homepage: www.elsevier.com/locate/engstruct

ELSEVIER

Shear-reinforced concrete breakout design methodology for moment transfer at column-foundation connections

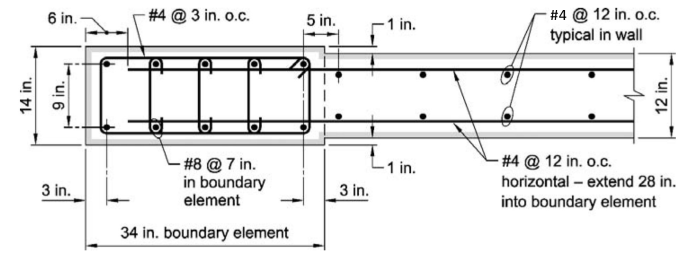
Benjamin L. Worsfold [a,*], Jack P. Moehle [b]

Shear-Reinforced Concrete Breakout Failure in Axially Loaded Anchor Groups by Benjamin Worsfold, Dara Karać, and Jack Moehle



Example: Boundary element to thin foundation

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

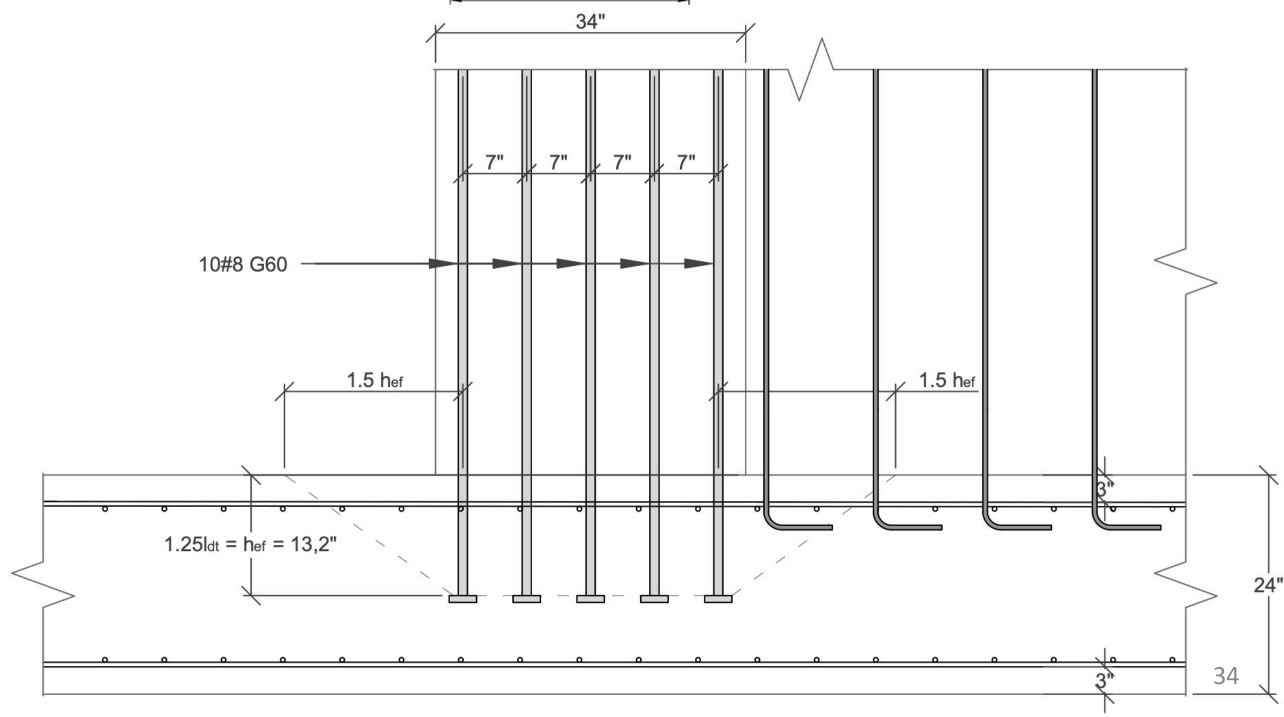


SP-17(14) Design Handbook
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

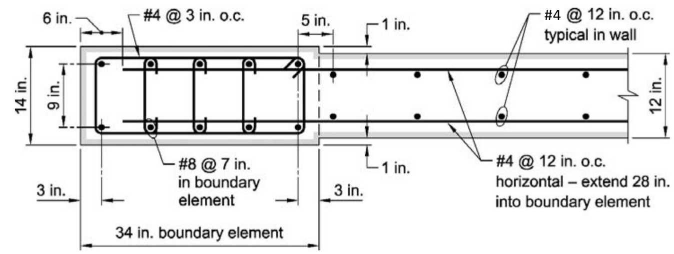
Nominal yield strength:
$T_y = 474\ kips$

Mean breakout strength:
$N_c = 284\ kips$

Difference:
$T_y - N_c = 190\ kips$



Example: Boundary element to thin foundation

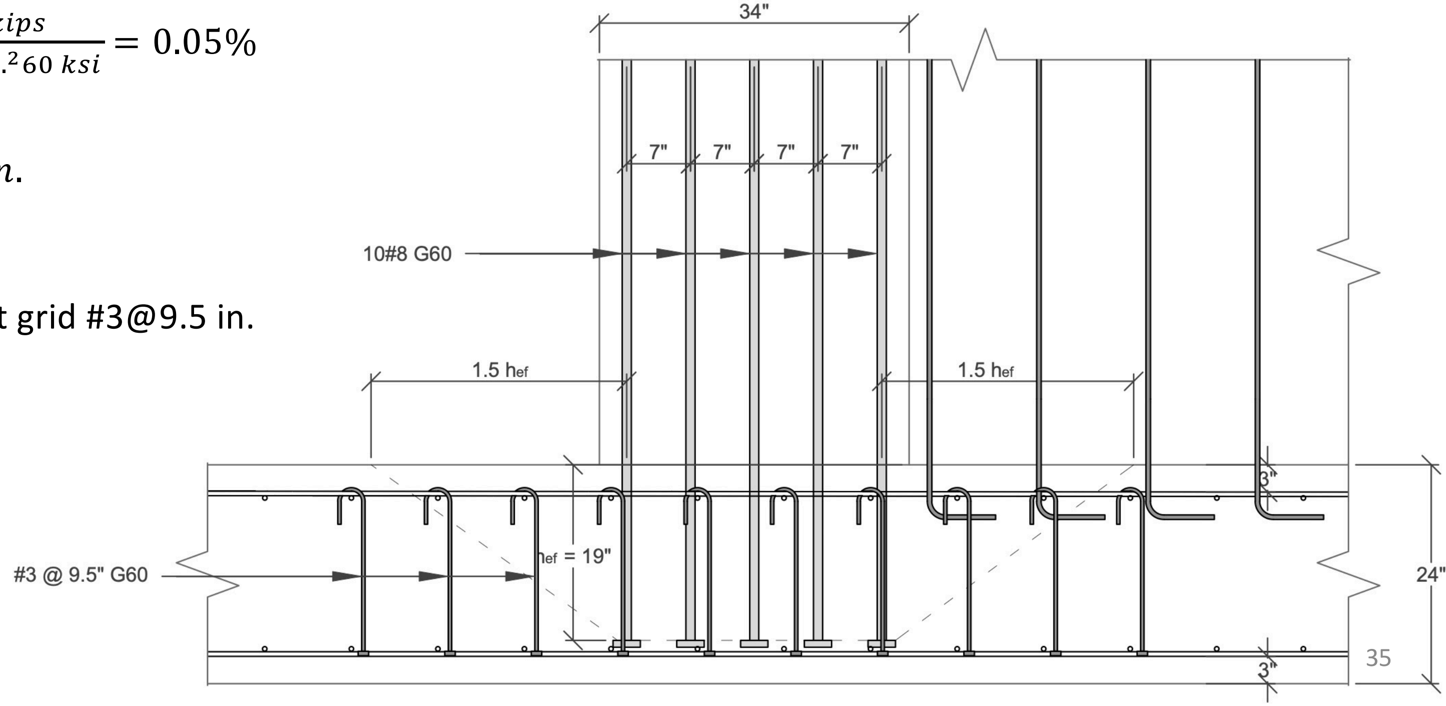


SP-17(14)
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

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

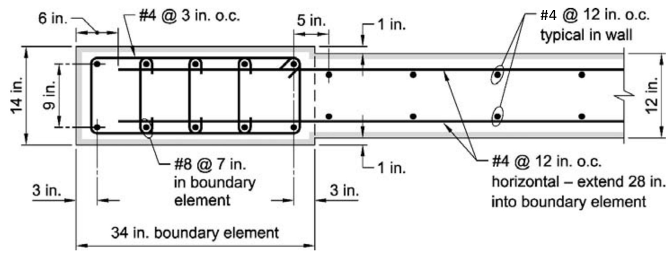
$$s_{max} = \frac{h_{ef}}{2} = \frac{19in.}{2} = 9.5in.$$

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



Example: Boundary element to thin foundation

Boundary element
$1.25f_y$

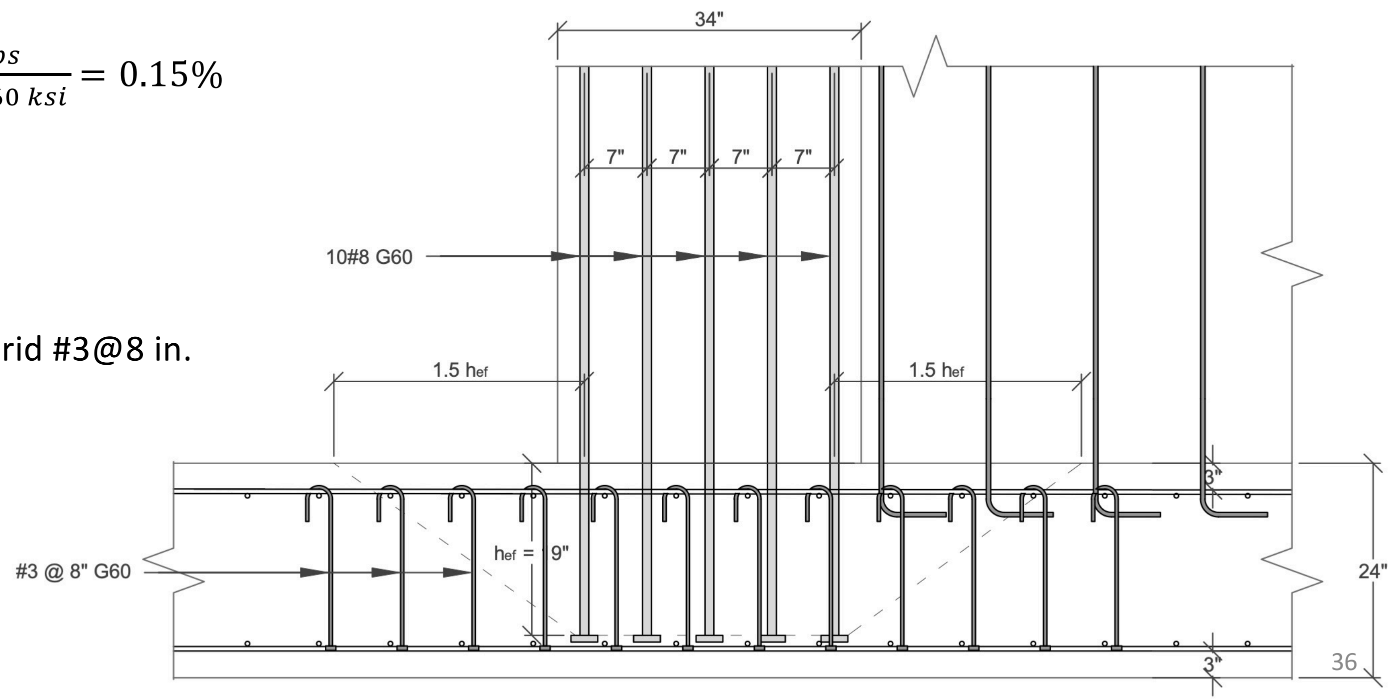


SP-17(14)
SDC D
Special Structural Wall
$f'_c = 5000psi$
$f_y = 60ksi$

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

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

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



UNIVERSITY OF MINNESOTA

Shear-Reinforced Concrete Breakout Failure

CCAPS Structures Engineering Webinar Series

02/20/2024

Ben Worsfold, PhD PE

Assistant Professor

University of Minnesota

worsfold@umn.edu

HILTI

Concrete Research Council
aciFoundation

AMERICAN INSTITUTE OF STEEL CONSTRUCTION ★ FOUNDED 1921 ★ AISC

MAGNUSSON KLEMENCIC ASSOCIATES
Structural + Civil Engineers

References

ACI 318, 2019, Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19), American Concrete Institute, Farmington Hills, MI, 624 pp.

Berger, W., 2015, Load-displacement behavior and design of anchorages with headed studs with and without supplementary reinforcement under tension load, Ph.D. Thesis, Institute of Construction Materials, University of Stuttgart (German).

Bujnák, J. and Farbák, M., 2018, Tests of Short Headed Brs with Anchor Reinforcement Used in Beam-to-Column Joints, ACI Structural Journal, V. 115, No. 1, Jan., pp. 203-210.

Caltrans, 2016, Memo to Design MTD (MTD) 20-7, Seismic Design of Slab Bridges, California Department of Transportation, Sacramento, CA.

Chen, C.H., 2021, Cyclic Behavior of Column-Foundation Connection (Mandarin), M.S. Thesis, National Taiwan University of Science and Technology, Advisor: Min-Yuan Cheng, p. 247, https://hdl.handle.net/11296/7975f5

Chicchi, R., Varma, A. H., Seo, J., Bradt, T., & McCarty, E., 2020, "Experimental testing of tension-loaded deformed anchors in concrete," ACI Structural Journal, 117(5), 133-146.

Eligehausen, R., Mallée, R., and Silva, J. F., 2006, "Anchorage in Concrete Construction," Berlin: Ernst and Sohn.

European Committee for Standardization, 2018, EN 1992-4:2018, "Design of concrete structures. Design of fastenings for use in concrete", Brussels, European Committee for Standardization.

Fuchs, W.; Eligehausen, R.; and Breen, J., 1995, "Concrete Capacity Design (CCD) Approach for Fastening to Concrete" ACI Structural Journal, V. 92, No. 1, Jan.-Feb., pp. 73-94.

Karać, D., 2022, Shear Reinforced Concrete Breakout Failure, MS Thesis, UC Berkeley, Berkeley

Nilforoush, R., Nilsson, M., Elfgren, L., Ožbolt, J., Hofmann, J., and Eligehausen, R., 2017, "Influence of Surface Reinforcement, Member Thickness, and Cracked Concrete on Tensile Capacity of Anchor Bolts," ACI-Structural Journal, V. 114, No. 6, November-December 2017, p. 1543-1556.

Nilforoush, R., Nilsson, M., and Elfgren, L. 2018, "Experimental Evaluation of Influence of Member Thickness, Anchor-Head Size, and Orthogonal Surface Reinforcement on the Tensile Capacity of Headed Anchors in Uncracked Concrete," ASCE Journal of Structural Engineering, January 2018, p. 14 DOI: 10.1061/(ASCE)ST.1943-541X.0001976

Papadopoulos, V., Murcia-Delso, J., Benson Shing, P., 2018, Development of Headed Bars in Slab-Column Joints of Reinforced Concrete Slab Bridges. ACI-Structural Journal, V. 115, No. 5, September 2018, p. 1393-1406.

Pryor, S., Montague, E., Fischer, S., Ding, F., Mochizuki, G., 2016, Detailing for Increased Capacity of Tension-Only Steel Anchor Rods Embedded in Elevated Concrete Slabs, SEAOC Convention Proceedings, Maui

Sharma, A., Eligehausen, R., and Asmus, J., 2017a, Comprehensive analytical model for anchorages with supplementary reinforcement, Proceedings 3rd International Symposium on Connections between Steel and Concrete (ConSC 2017) September 27-29, Stuttgart, p. 253-265

Sharma, A., Eligehausen, R., Asmus, J., 2017b, Comprehensive experimental investigations on anchorages with supplementary reinforcement, Proceedings 3rd International Symposium on Connections between Steel and Concrete (ConSC 2017) September 27-29, Stuttgart, p. 242-252

Worsfold, B. and Moehle, J., 2019, Laboratory Tests of Column-Foundation Moment Transfer Connections with Headed Anchors, Structural Engineering, Mechanics, and Materials (SEMM) Report, University of California, Berkeley, UCB/SEMM-2019/01, 171 pp.

Worsfold, B. and Moehle, J., 2022a, Laboratory Tests of Column-Foundation Moment Transfer Connections with Shear Reinforcement, Structural Engineering, Mechanics, and Materials (SEMM) Report, University of California, Berkeley, UCB/SEMM-2022/01, 243 pp.

Worsfold, B., Moehle, J., and Silva, J., accepted for publication 2022, Moment transfer at column-foundation connections: physical tests, ACI-Structural Journal, V. 119, No. 5, September 2022

Worsfold, B. and Moehle, J., accepted for publication 2022b, Moment Transfer at Column-to-Footing Connections: Analytical Studies, ACI Structural Journal