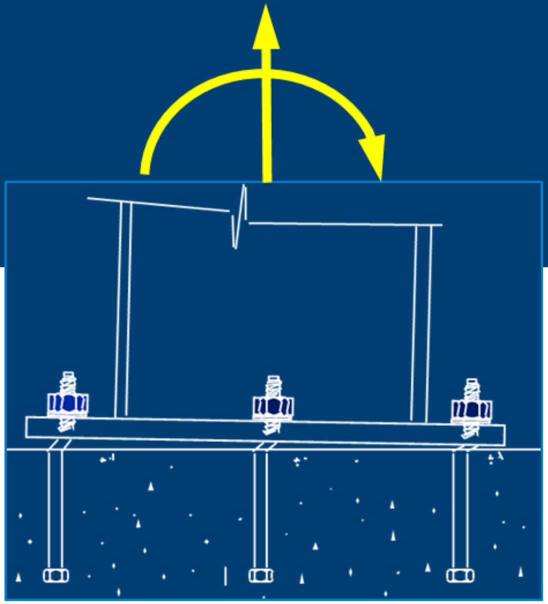
American Concrete Institute

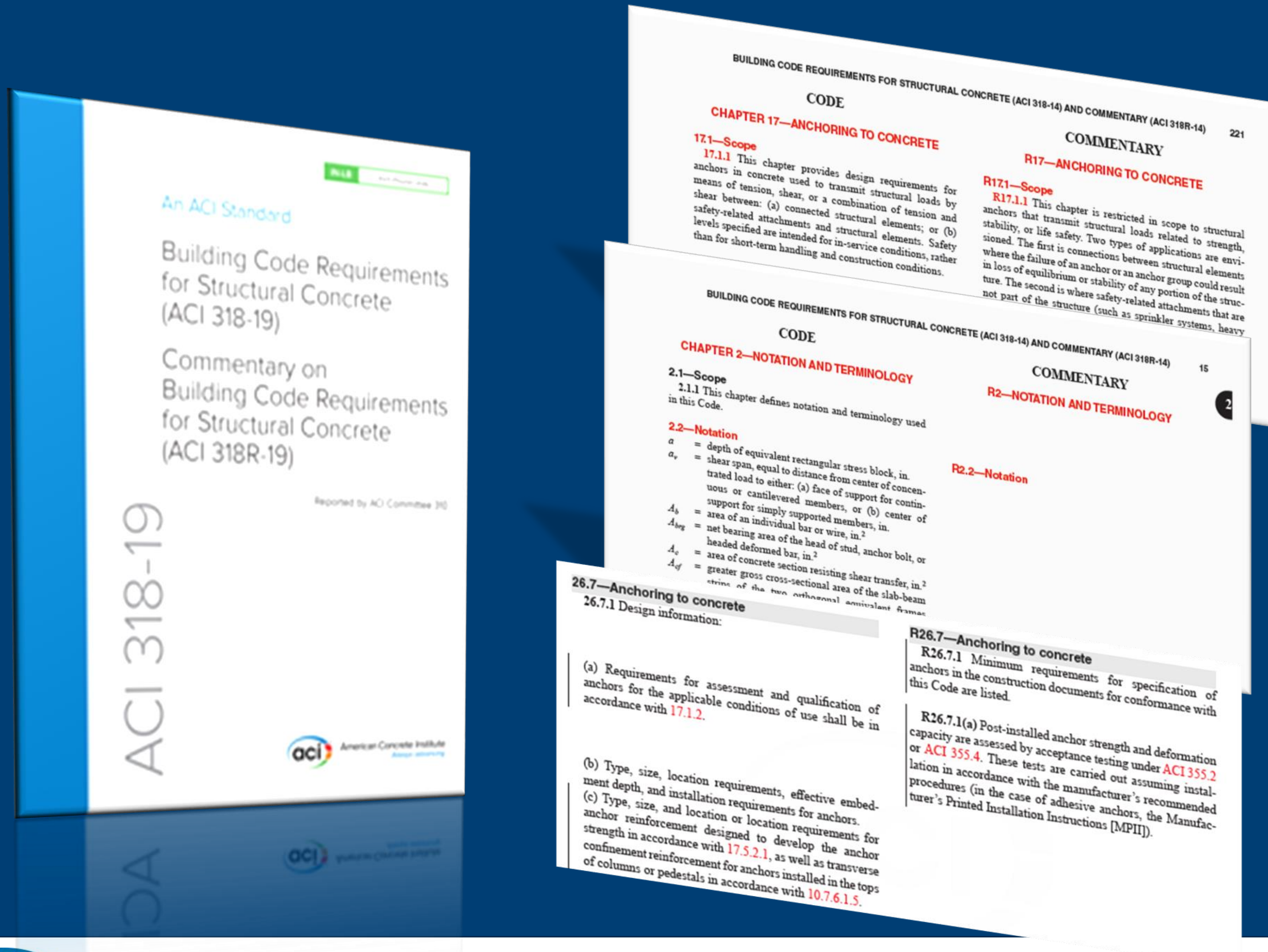


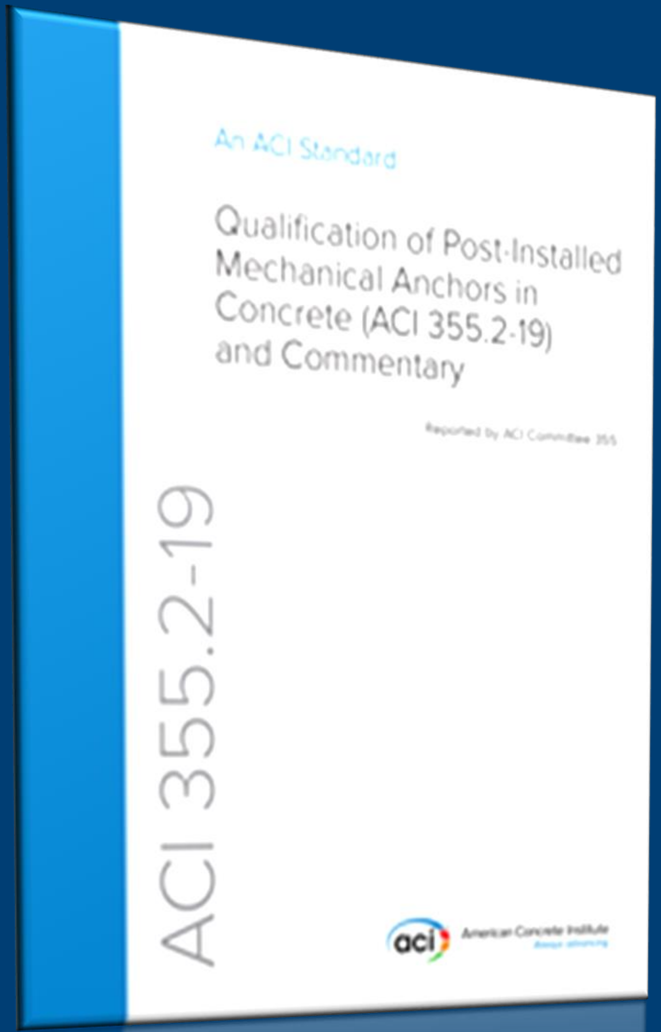
ANCHORAGE TO CONCRETE

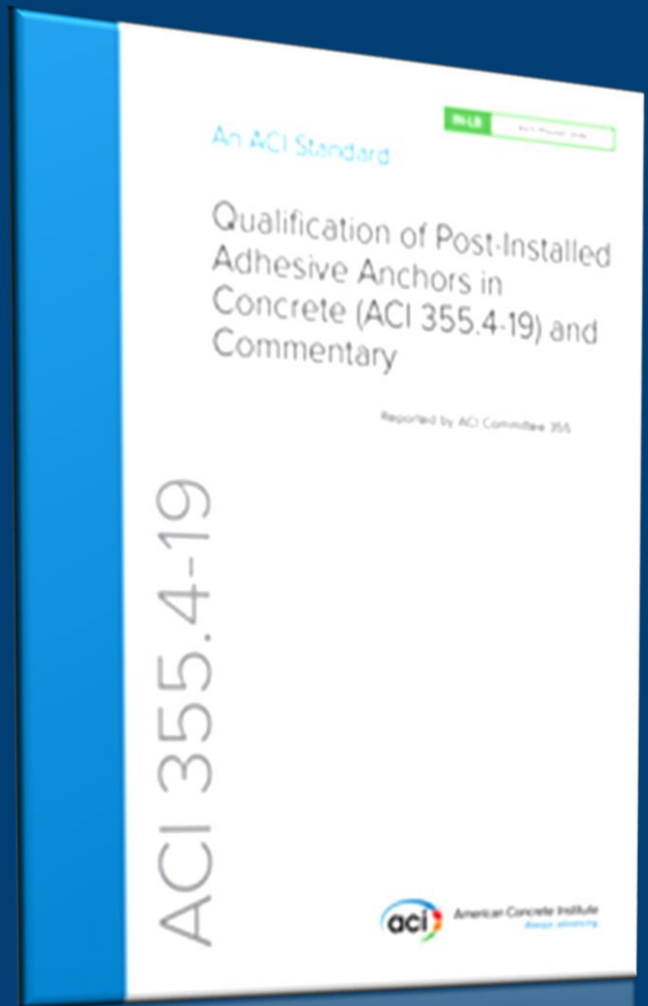
Matthew Senecal, Director Engineering

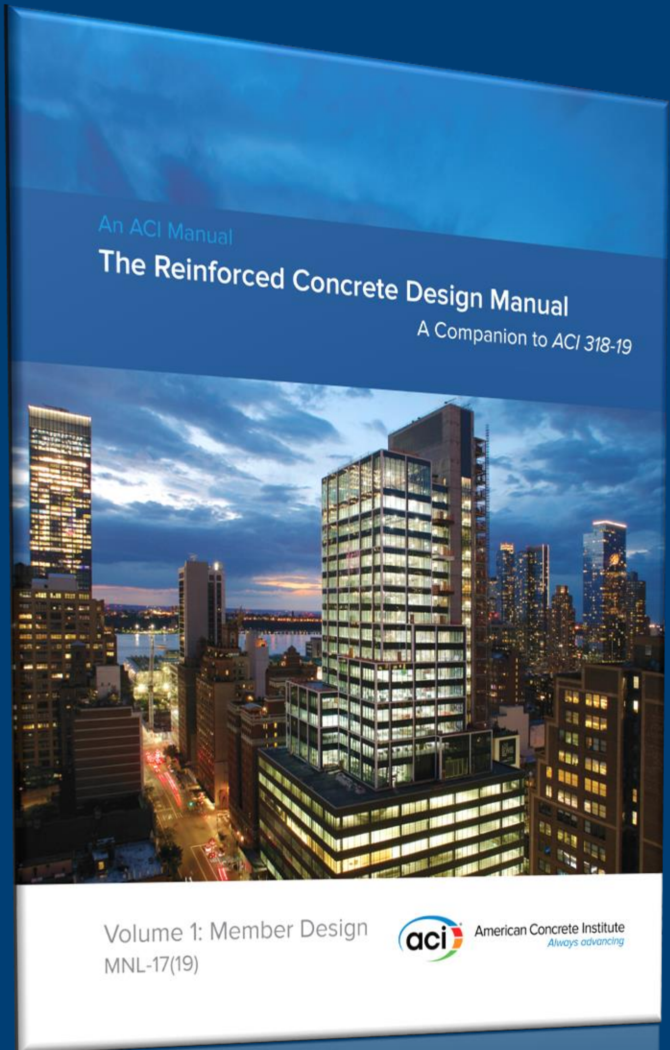
Overall Objectives

- Recognizing types of anchors and qualification requirements for anchors
- Both cast-in-place and post-installed anchors are considered
- Recognizing the different failure modes related to anchorage to concrete
- Understanding the importance of selecting qualified post - installed mechanical and adhesive anchors


An ACI Standard
Building Code Requirements for Structural Concrete (ACI 318-19)
Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19)
ACI 318-19
BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-14) AND COMMENTARY (ACI 318R-14) 221
CODE
CHAPTER 17—ANCHORING TO CONCRETE
17.1—Scope
17.1.1 This chapter provides design requirements for anchors in concrete used to transmit structural loads by means of tension, shear, or a combination of tension and shear between: (a) connected structural elements; or (b) safety-related attachments and structural elements. Safety levels specified are intended for in-service conditions, rather than for short-term handling and construction conditions.
COMMENTARY
R17—ANCHORING TO CONCRETE
R17.1—Scope
R17.1.1 This chapter is restricted in scope to structural anchors that transmit structural loads related to strength, stability, or life safety. Two types of applications are envisioned. The first is connections between structural elements where the failure of an anchor or an anchor group could result in loss of equilibrium or stability of any portion of the structure. The second is where safety-related attachments that are not part of the structure (such as sprinkler systems, heavy
BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-14) AND COMMENTARY (ACI 318R-14) 15
CODE
CHAPTER 2—NOTATION AND TERMINOLOGY
2.1—Scope
2.1.1 This chapter defines notation and terminology used in this Code.
2.2—Notation
a = depth of equivalent rectangular stress block, in.
a_v = shear span, equal to distance from center of concentrated load to either: (a) face of support for continuous or cantilevered members, or (b) center of support for simply supported members, in.
A_b = area of an individual bar or wire, in.²
A_brg = net bearing area of the head of stud, anchor bolt, or headed deformed bar, in.²
A_c = area of concrete section resisting shear transfer, in.²
A_cf = greater gross cross-sectional area of the slab-beam
COMMENTARY
R2—NOTATION AND TERMINOLOGY
R2.2—Notation
26.7—Anchoring to concrete
26.7.1 Design information:
(a) Requirements for assessment and qualification of anchors for the applicable conditions of use shall be in accordance with 17.1.2.
(b) Type, size, location requirements, effective embedment depth, and installation requirements for anchors.
(c) Type, size, and location or location requirements for anchor reinforcement designed to develop the anchor strength in accordance with 17.5.2.1, as well as transverse confinement reinforcement for anchors installed in the tops of columns or pedestals in accordance with 10.7.6.1.5.
R26.7—Anchoring to concrete
R26.7.1 Minimum requirements for specification of anchors in the construction documents for conformance with this Code are listed.
R26.7.1(a) Post-installed anchor strength and deformation capacity are assessed by acceptance testing under ACI 355.2 or ACI 355.4. These tests are carried out assuming installation in accordance with the manufacturer's recommended procedures (in the case of adhesive anchors, the Manufacturer's Printed Installation Instructions [MPII]).

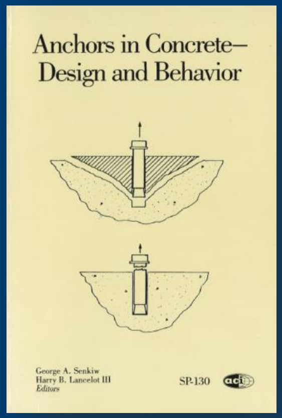

An ACI Standard
Qualification of Post-Installed Mechanical Anchors in Concrete (ACI 355.2-19) and Commentary
ACI 355.2-19

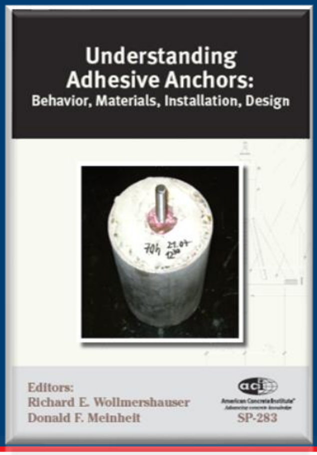

An ACI Standard
Qualification of Post-Installed Adhesive Anchors in Concrete (ACI 355.4-19) and Commentary
Reported by ACI Committee 355
ACI 355.4-19
aci
American Concrete Institute


An ACI Manual
The Reinforced Concrete Design Manual
A Companion to *ACI 318-19*
Volume 1: Member Design
MNL-17(19)
aci
American Concrete Institute
Always advancing

ACI Symposiums

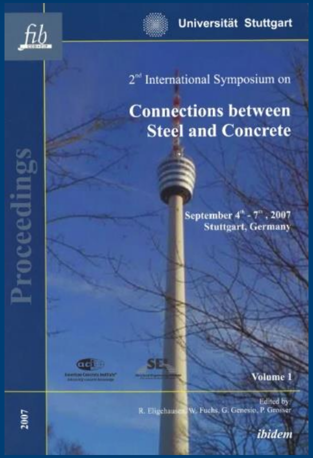
- SP-103 Anchorage to Concrete (1987)
- SP-130 Anchors in Concrete – Design and Behavior (1995)
- SP-283 Understanding Adhesive Anchors: Behavior, Materials, Installation, Design (2010)

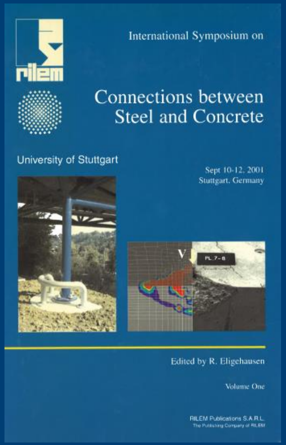




Stuttgart Symposiums

- 2001 - 1st International Symposium – Connections between Steel and Concrete (University of Stuttgart)
- 2007 - 2nd International Symposium – Connections between Steel and Concrete (University of Stuttgart)
- 2012 – Symposium Honoring Dr. Rolf Eligehausen (University of Stuttgart)
- 2017 - 3rd International Symposium – Connections between Steel and Concrete (University of Stuttgart)

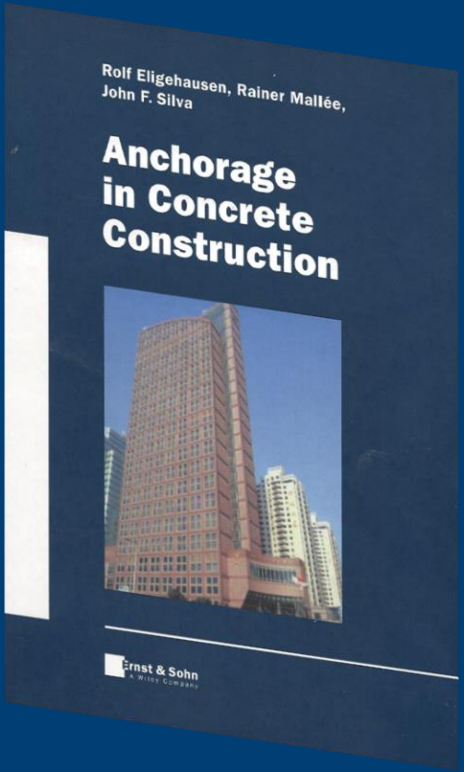


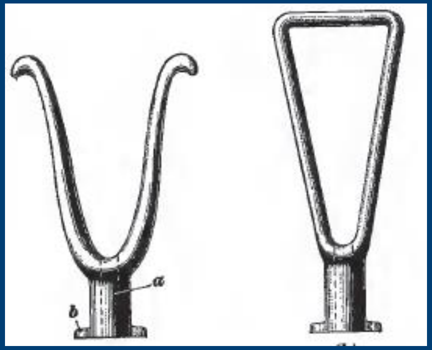


Referenced Book

Anchorage in Concrete Construction – 2006

Eligehausen, Mallée, and Silva





Malleable-iron
and cast-steel, circa. 1909

“Rawl” expansion anchor, circa 1938

Definitions, History, Behavior, Theory

2.3—Terminology

adhesive—chemical components formulated from organic polymers, or a combination of organic polymers and inorganic materials that cure if blended together.

admixture—material other than water, aggregate, cementitious materials, and fiber reinforcement used as an ingredient, which is added to grout, mortar, or concrete, either before or during its mixing, to modify the freshly mixed, setting, or hardened properties of the mixture.

aggregate—granular material, such as sand, gravel, crushed stone, iron blast-furnace slag, or recycled aggregates including crushed hydraulic cement concrete, used with a cementing medium to form concrete or mortar.

aggregate, lightweight—aggregate meeting the requirements of ASTM C330 and having a loose bulk density of 70 lb/ft^3 or less, determined in accordance with ASTM C29.

alternative cement—an inorganic cement that can be used as a complete replacement for portland cement or blended hydraulic cement, and that is not covered by applicable specifications for portland or blended hydraulic cements.

R2.3—Terminology

aggregate—The use of recycled aggregate is addressed in the Code in 2019. The definition of recycled materials in ASTM C33 is very broad and is likely to include materials that would not be expected to meet the intent of the provisions of this Code for use in structural concrete. Use of recycled aggregates including crushed hydraulic-cement concrete in structural concrete requires additional precautions. See 26.4.1.2.1(c).

aggregate, lightweight—In some standards, the term "lightweight aggregate" is being replaced by the term "low-

ϕ = strength reduction factor

ϕ_p = strength reduction factor for moment in pretensioned member at cross section closest to the end of the member where all strands are fully developed

τ_{cr} = characteristic bond stress of adhesive anchor in cracked concrete, psi

τ_{uncr} = characteristic bond stress of adhesive anchor in uncracked concrete, psi

$\psi_{brg,sl}$ = shear lug bearing factor used to modify bearing strength of shear lugs based on the influence of axial load

ψ_c = factor used to modify development length based on concrete strength

$\psi_{c,N}$ = breakout cracking factor used to modify tensile strength of anchors based on the influence of cracks in concrete

$\psi_{c,P}$ = pullout cracking factor used to modify pullout strength of anchors based on the influence of cracks in concrete

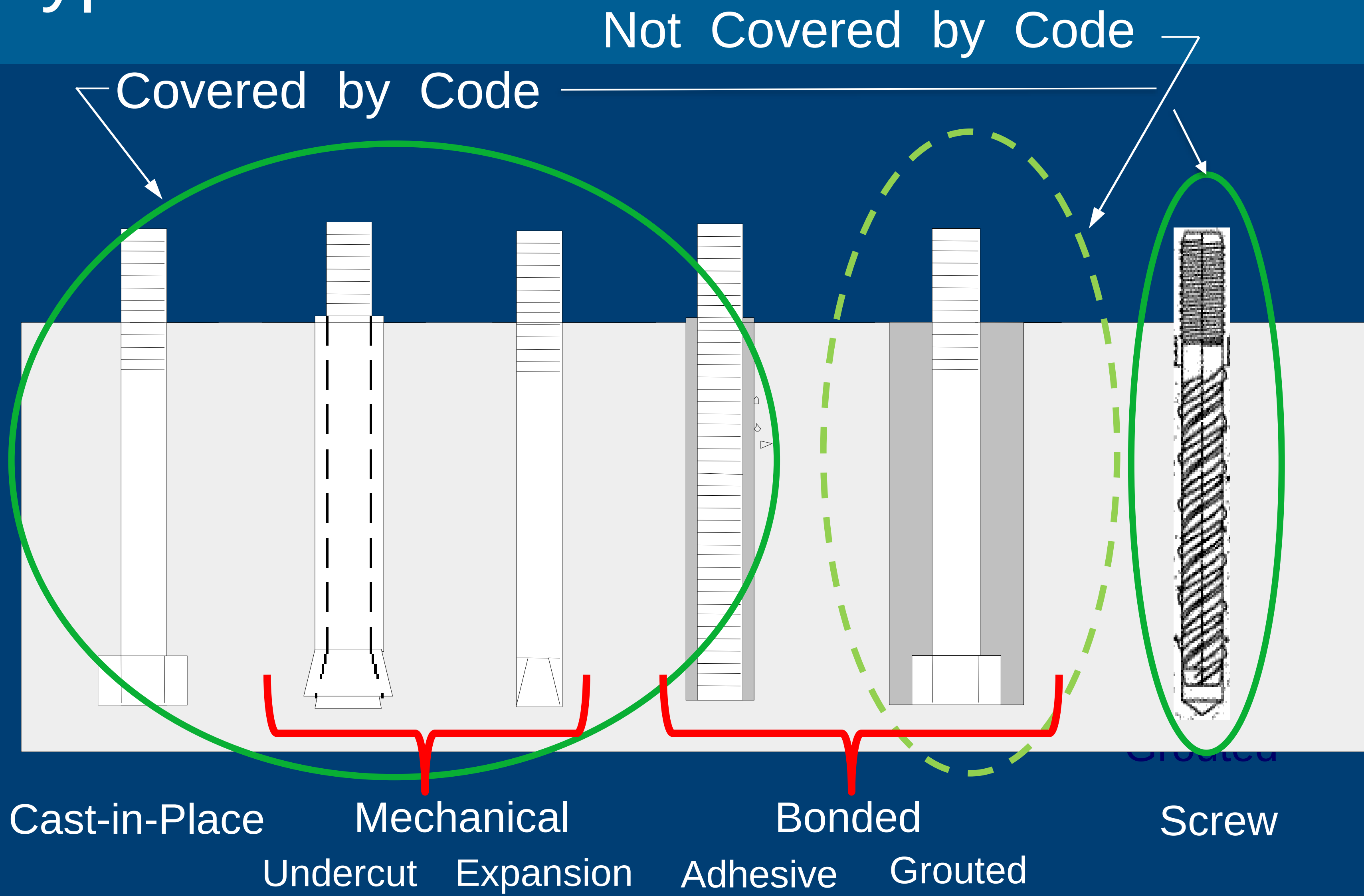
ϕ_K = stiffness reduction factor

σ = wall boundary extreme fiber concrete nominal compressive stress, psi

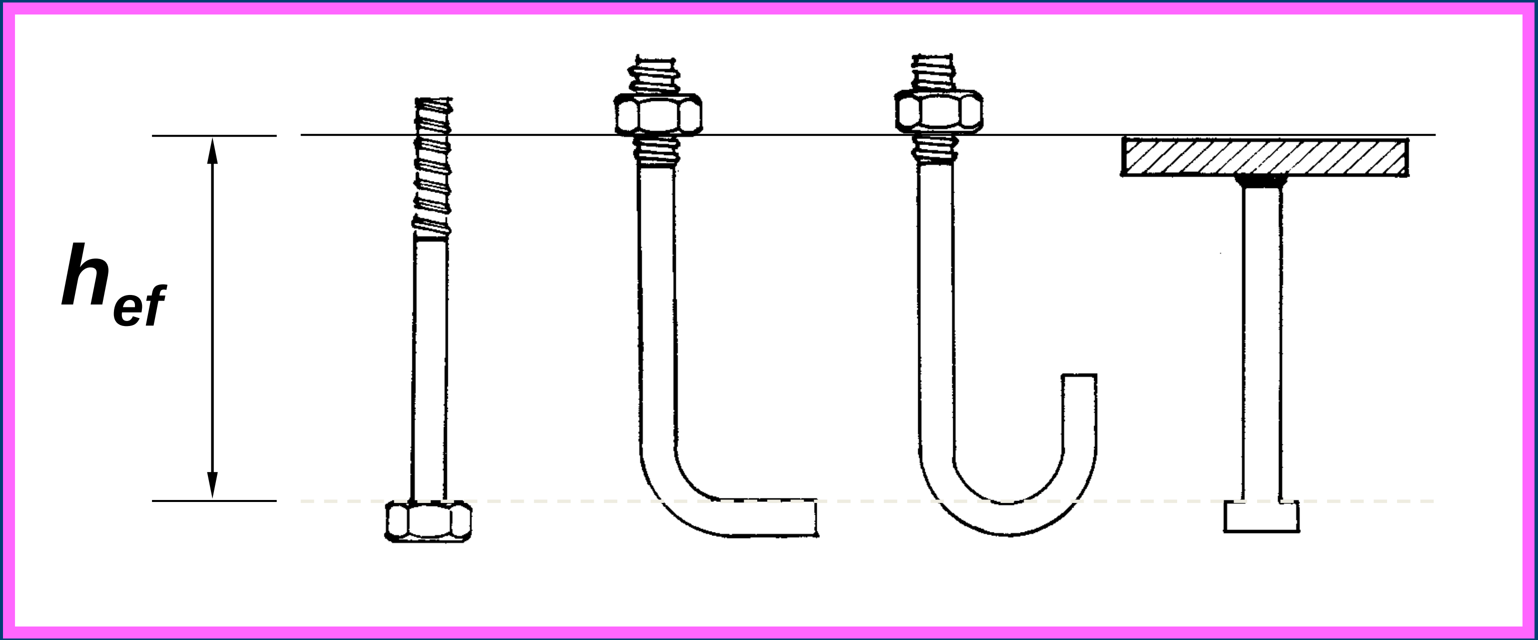
τ = shear stress, psi

Definitions

Types of Anchors

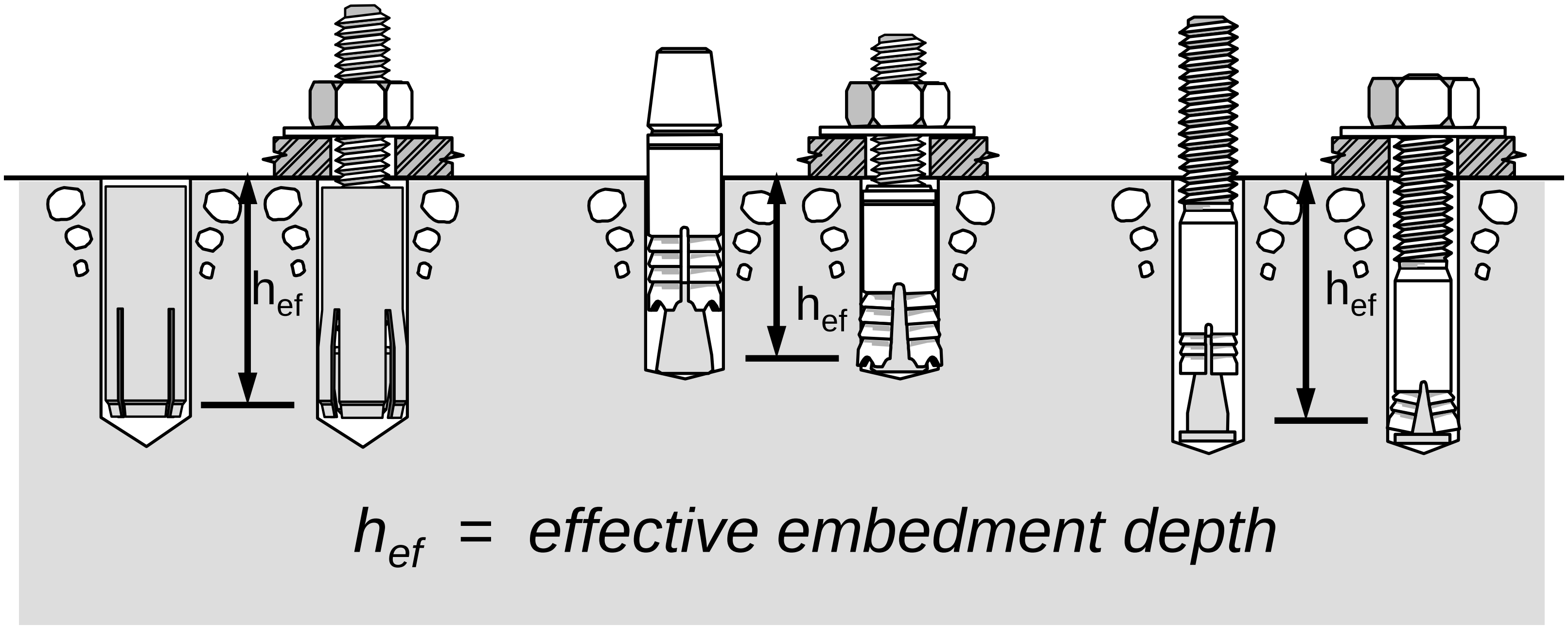


Cast–in–Place Anchors



h_{ef} = *effective embedment depth*

Post–installed Mechanical Types
Displacement – Controlled Expansion Anchors



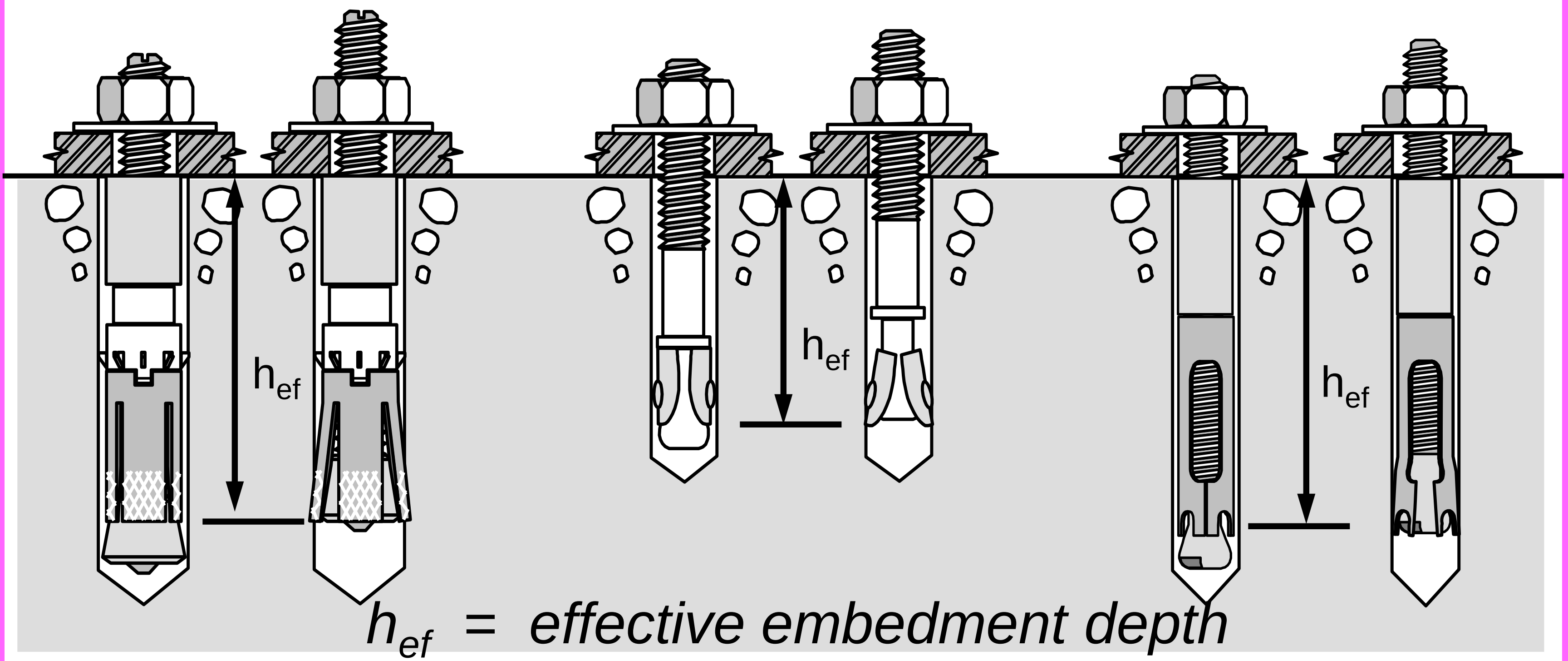
(1) Drop-In Fastener

(2) Self-Drilling Fastener

(3) Stud Fastener

Post–installed Mechanical Types

Torque – Controlled Expansion Anchors



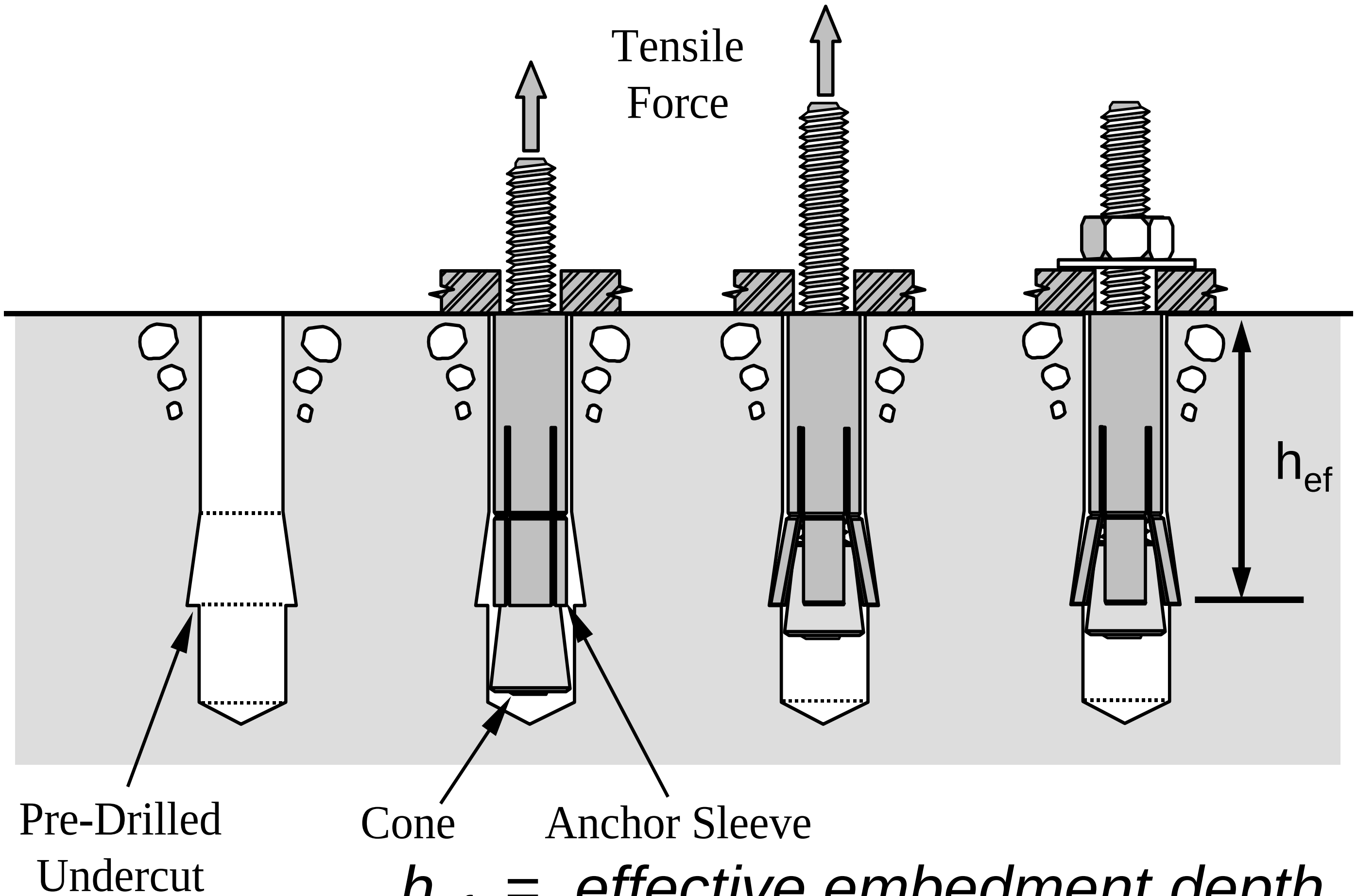
(1) Heavy Duty Sleeve Fastener

(2) Wedge Fastener

(3) Sleeve Fastener

Post–Installed Mechanical Types

Undercut Anchors (Multiple Types [6])



h_{ef} = *effective embedment depth*

Bonded Anchors

- Adhesive anchors
- Grouted anchors
- Of the two bonded anchor types, ACI currently provides design rules for only Adhesive Anchors
- So, what is the difference?

Grouted Anchors

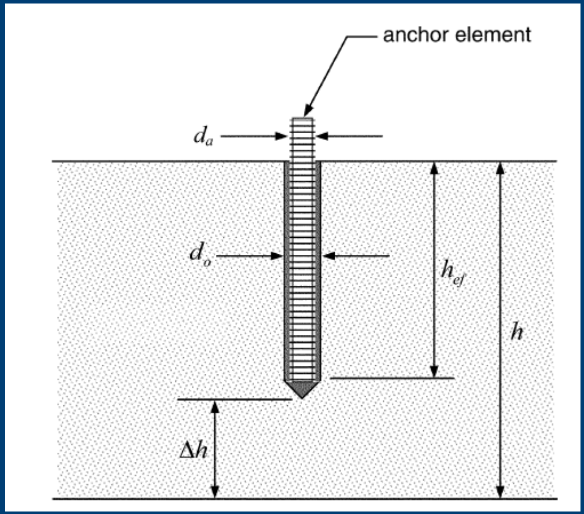
- Hole diameter > 1.5 x bar diameter
  - Cementitious or polymer binders with filler
  - Generally vertical downhand installations (although some firms have developed horizontal installation materials)
  - Typically headed anchor rods or headed reinforcing bars used

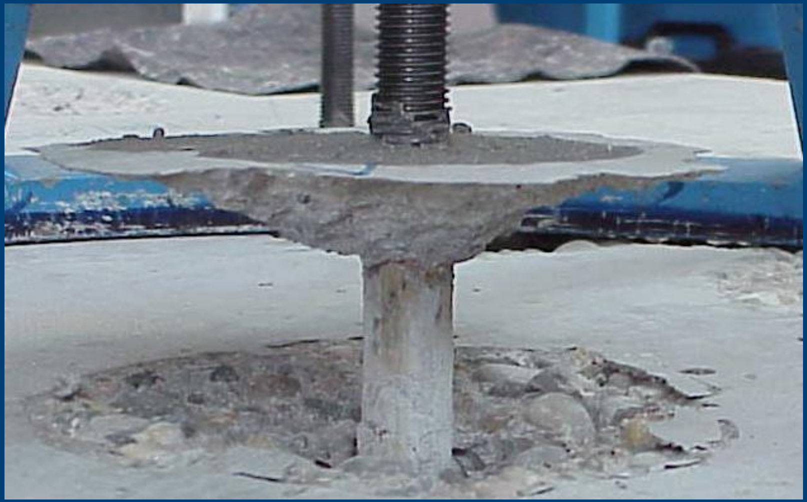
Zamora, N. A., Cook, R. A., Konz, R., and Consolazio, G. R., *Behavior and Design of Single, Headed and Unheaded, Grouted Anchors,* ACI Structural Journal, American Concrete Institute, V. 100, No. 2, March-April 2003, pp. 222-230.

Cook, R. A., Burtz, J. L., *Design Guidelines and Specifications for Engineered Grouts used in Anchorages and Pile Splice Applications* Report No. BC 354 RPWO #48 Florida Department of Transportation , Tallahassee, FL, August 2003, 119 pp.

Adhesive Anchors

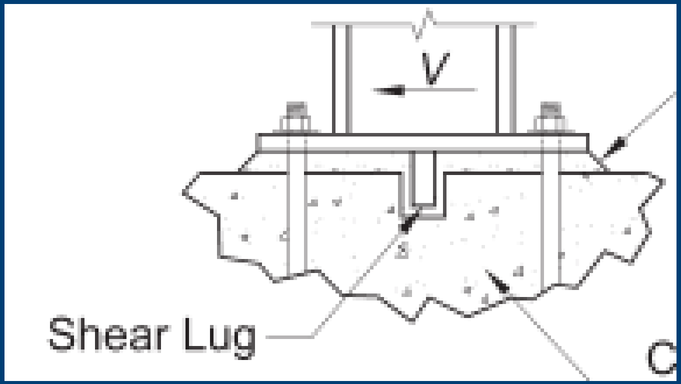
- Hole diameter < 1.5 x bar diameter
  - Covered by ACI
  - Typically, polymer binders but cementitious fillers can be mixed with polymer available
  - Threaded rods or reinforcing bars used





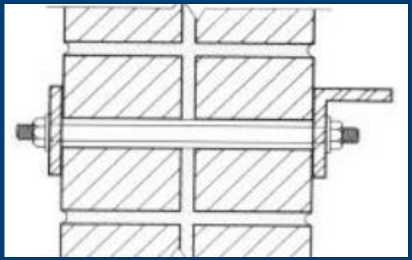
Anchors – New Addition

- Shear lugs
- Concrete screws



17.1.2 – Anchors Not Included

- Specialty inserts – coil loops
- Through – bolts
- Multiple anchors connected to single plate at the embedded end of the anchors
- Channel anchors
- Powder or pneumatic driven anchors
- Grouted anchors



BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-02) AND COMMENTARY (ACI 318R-02)

APPENDIX D 318/318R-399

APPENDIX D — ANCHORING TO CONCRETE

CODE	COMMENTARY
D.0 — Notation	**RD.0 — Notation**
A_{brg} = bearing area of the head of stud or anchor bolt, in.^{2}	
A_{No} = projected concrete failure area of one anchor, for calculation of strength in tension when not limited by edge distance or spacing, in.^{2} (see 5.2.1)	See Fig. RD.5.2.1(a)
A_N = projected concrete failure area of an anchor or group of anchors, for calculation of strength in tension, as defined in, in.^{2} (see D.5.2.1) A_N shall not be taken greater than nA_{No}.	See Fig. RD.5.2.1(b)
A_{se} = effective cross-sectional area of anchor, in.^{2}	A_{se} The effective cross-sectional area of an anchor should be provided by the manufacturer of expansion anchors with reduced cross-sectional area for the expansion mechanism. For threaded bolts, ANSI/ASME B1.1[D.1] defines A_{se} as:

ACI Code History

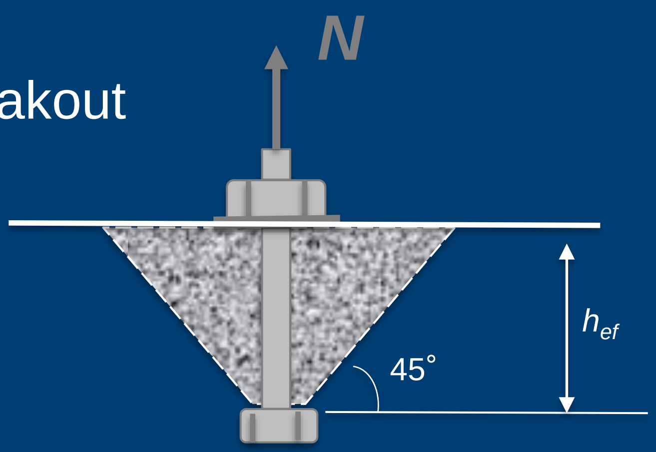
History of ACI 318 Provisions

Prior to 2002

- Model codes (UBC), ACI 349 (Nuclear Structures), Industry guidelines – PCI Design Handbook
- Considered only cast – in – place anchors in uncracked concrete
  - Failure modes

    Steel failure

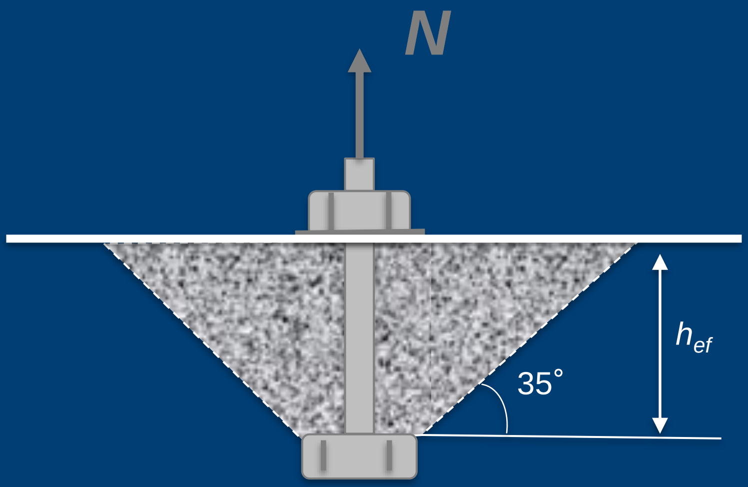
    Concrete breakout



History of ACI 318 Provisions

2002 : ACI 318-02 Appendix D published

- Cast – in – place and post – installed mechanical anchors
- CCD Method (35-degree pyramid)
- Cracked concrete

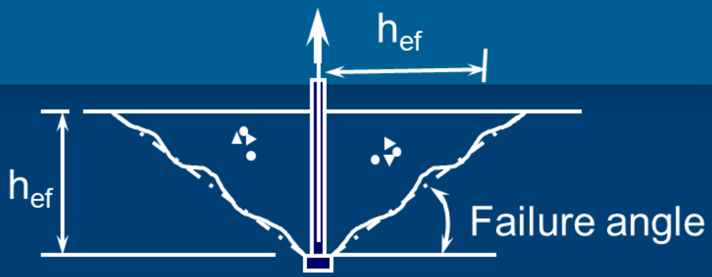


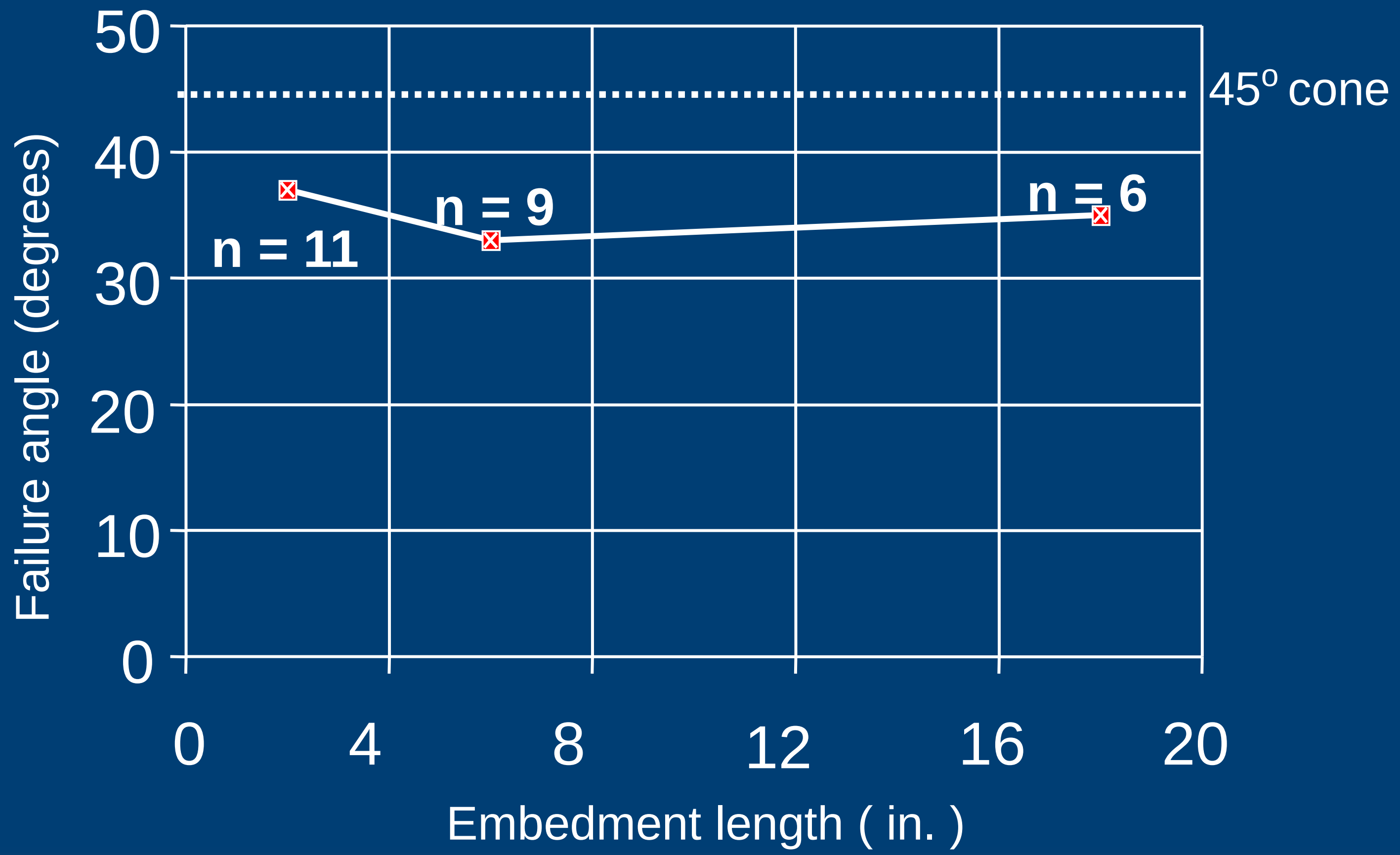
Concrete Breakout Failure Mode – Tension Cone Breakout

Differences Between Models

45° Cone	CCD
45° Failure Angle	35° Failure Angle
$N_c = k_{c,45} \sqrt{f_c'}\, h_{ef}^{2}$	$N_c = k_{c,CCD} \sqrt{f_c'}\, h_{ef}^{1.5}$

Failure Angle





History of ACI 318 Provisions

2011: ACI 318-11 Appendix D

- Included bonded anchors but only adhesive anchors (polymeric adhesives)
- Defines installation orientation
- Introduces Manufacturer's Printed Installation Instructions (MPII)
- Introduces a new adhesive design model to the ACI 318 code based on work of Eligehausen, Cook, and Appl

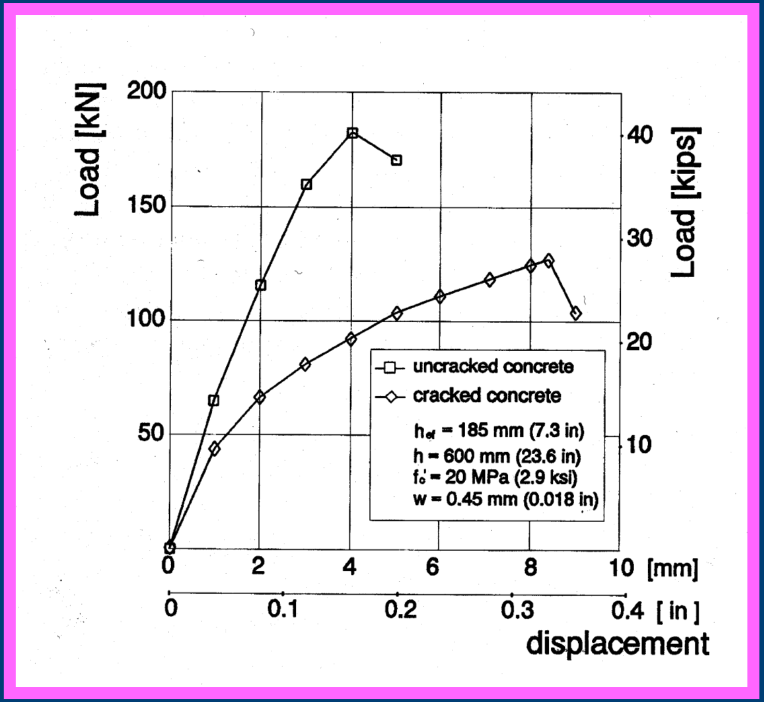
History of ACI 318 Provisions

2014: ACI 318-14

- Moved design provisions from ACI 318-11 Appendix D to Chapter 17 of 318-14
- No significant changes

2019: ACI 318-19

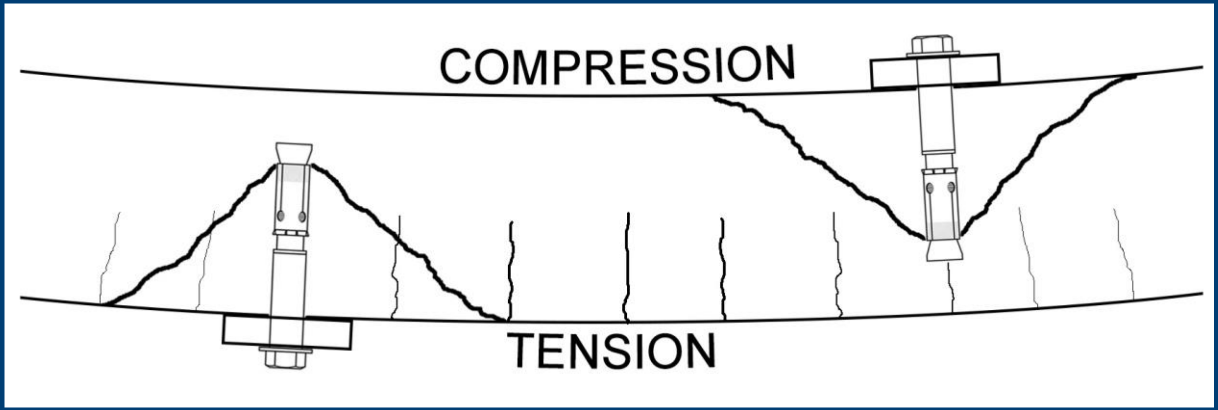
- Reorganized Chapter 17 to be consistent with general 318 format
- Added concrete ***screws*** and ***shear lugs***
- Moved inspection and certification to Chapter 26



Anchor behavior

Behavior Background

- Overview of different failure modes



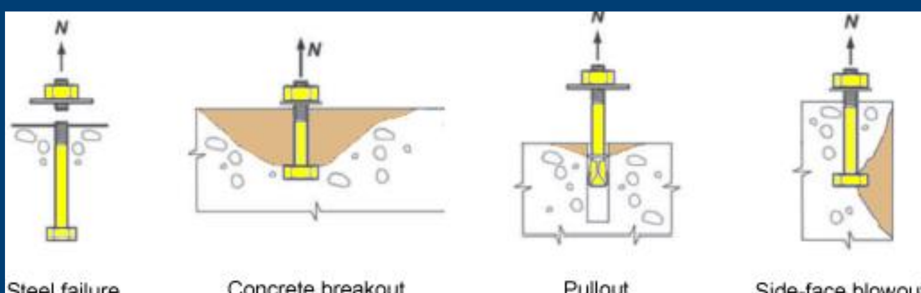
Failure Modes

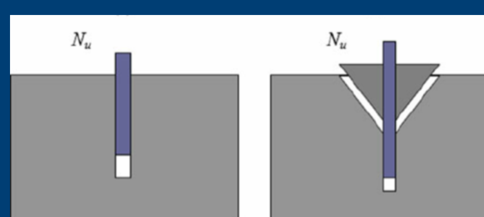
Tension

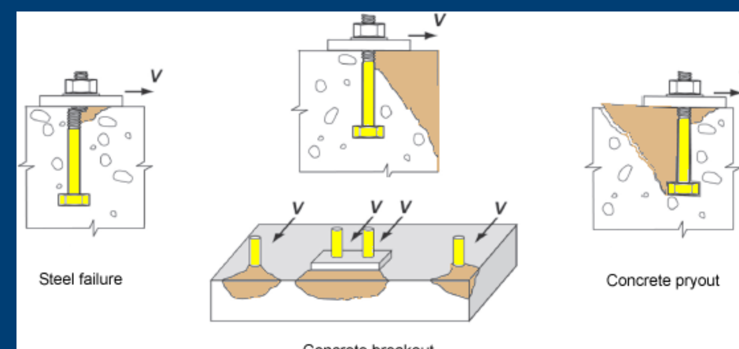
- Steel failure
- Concrete breakout failure
- Pullout/Pull-through failure
- Side-face blowout failure
- Bond failure

Shear

- Steel failure
- Concrete breakout failure
- Pryout failure



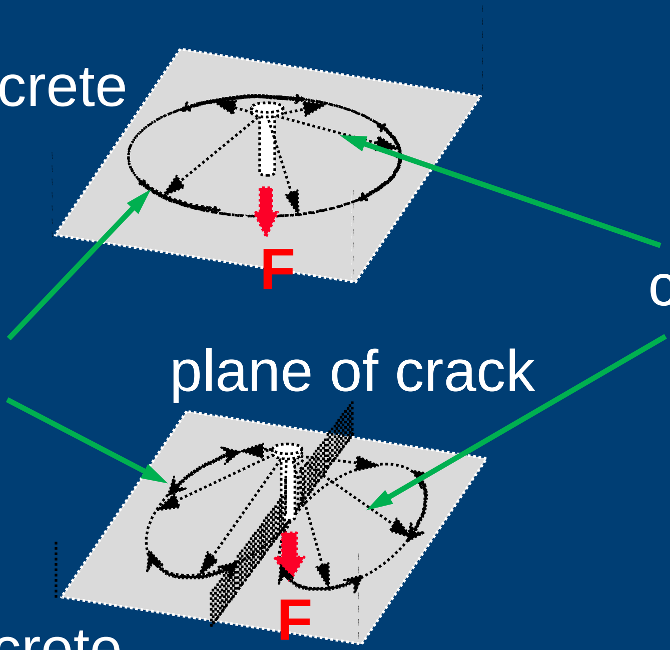




17.6.2.5.1 – Cracking Effect

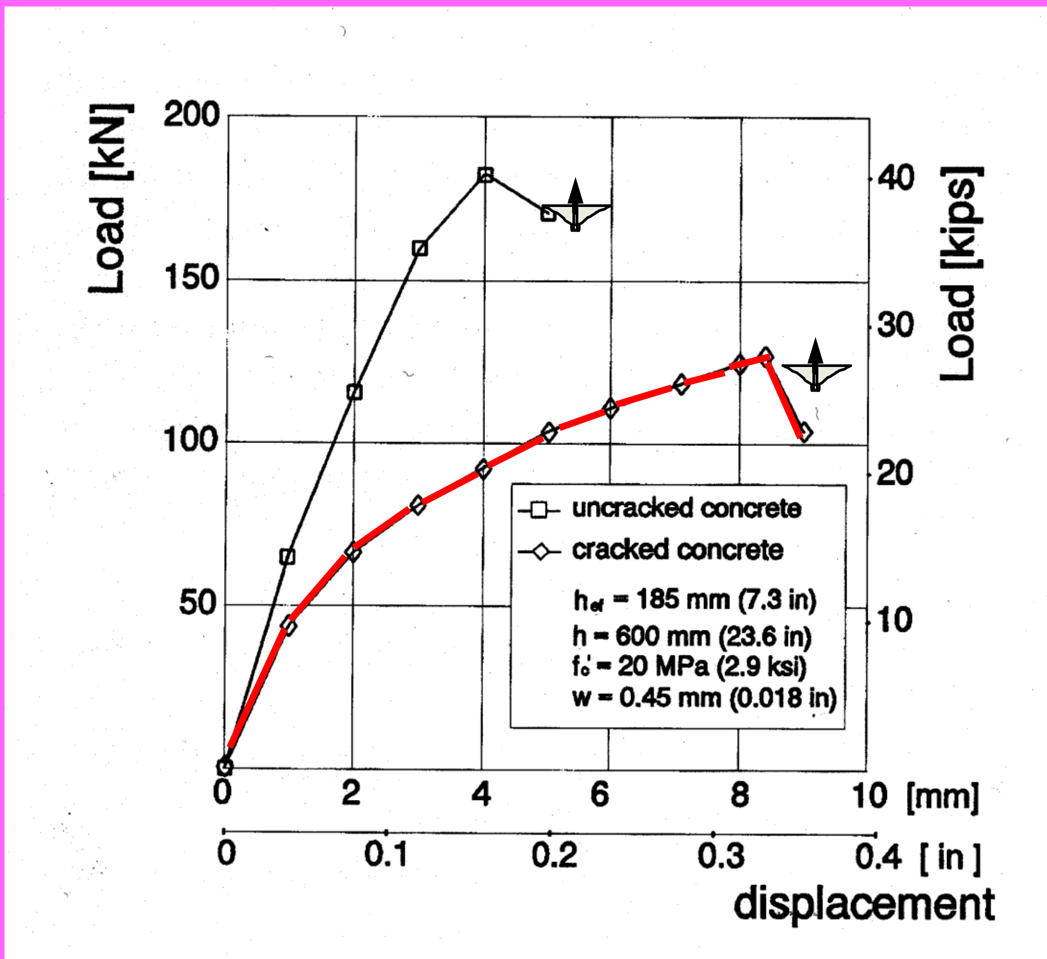
- Cracked Concrete ($f_t > f_r$ at service load)

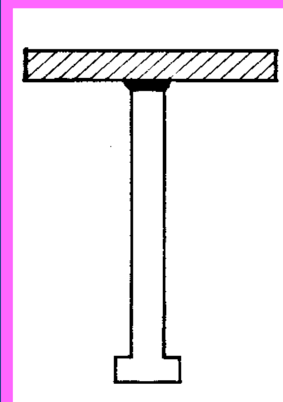
Cast-in anchors and post-installed anchors: $\psi_{c,N} = 1.0$



Cracking reduces tensile breakout capacity

Anchors Affected by Cracking

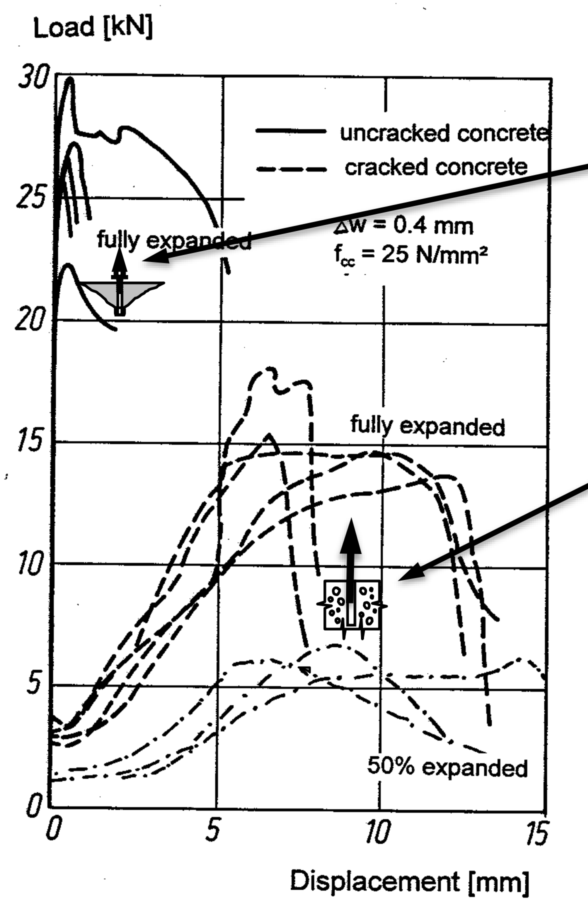




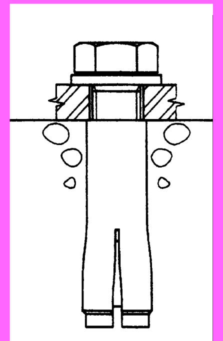
Headed Studs

Behavior in uncracked and cracked concrete

Anchors Drastically Affected by Cracking



Breakout

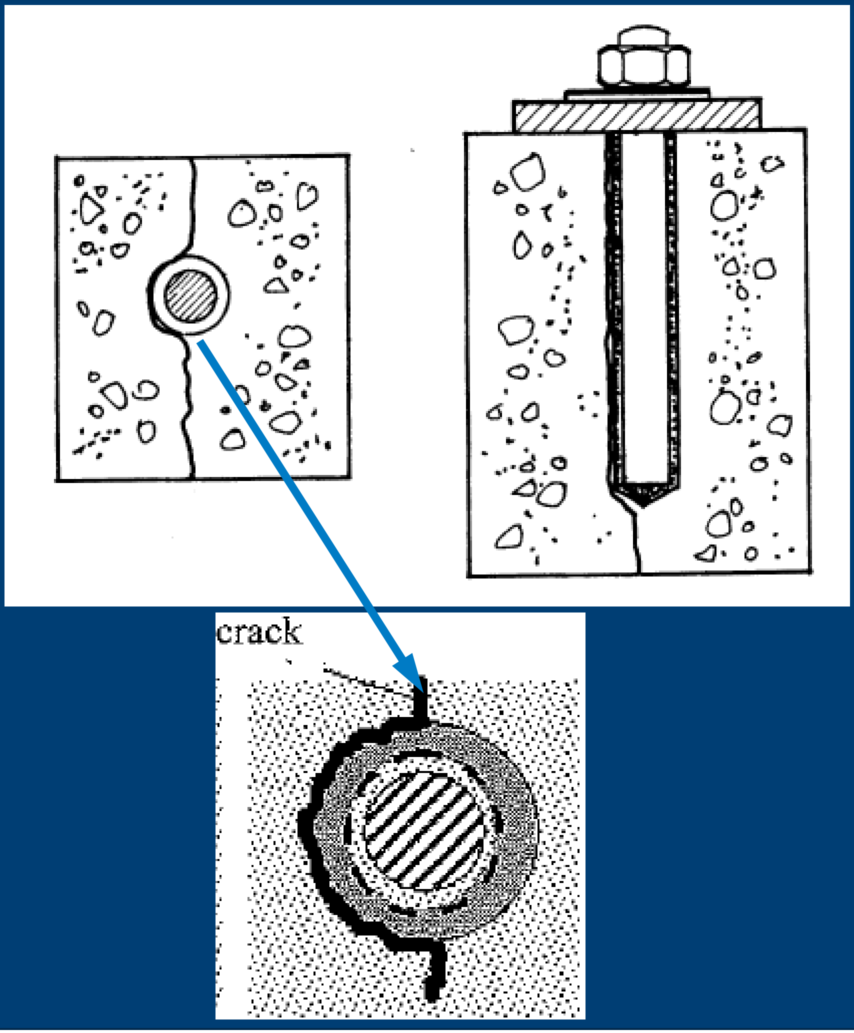


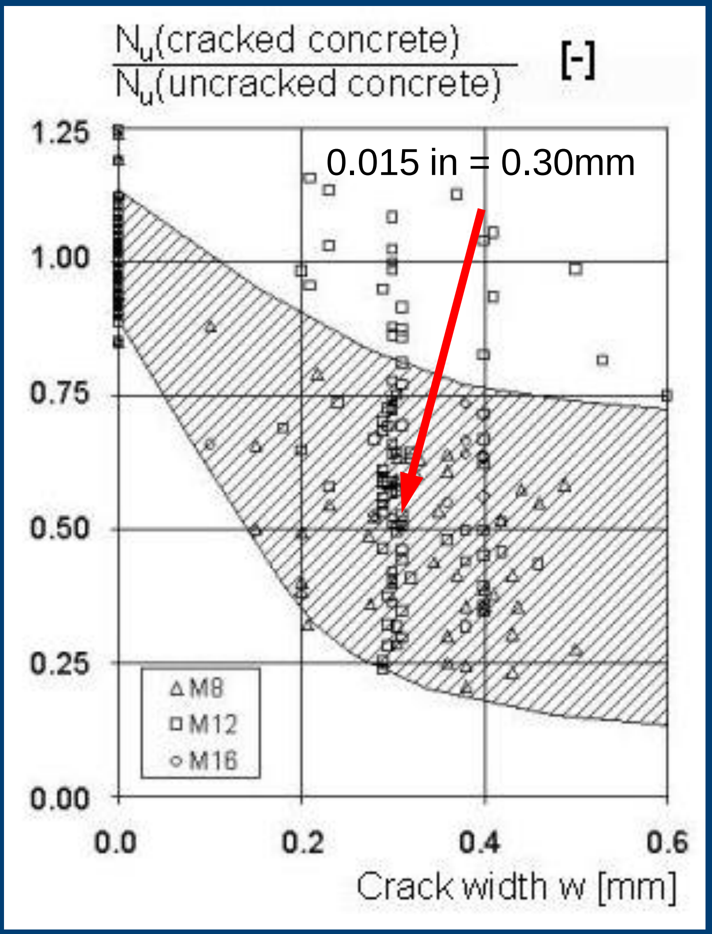
Slip

Displacement controlled post-installed anchors

Behavior of fully and partially expanded anchors in uncracked and cracked concrete

Influence of Cracked Concrete





Meszaros, J. (2001)

CCD Method Addresses Cracking

Concrete does crack

- Applied loads
- Restrained shrinkage and thermal movement

ACI 318 Chapter 17 and ACI 355.2 and ACI 355.4

- Want post-installed anchors that perform well in cracks or have known cracked concrete performance
- Crack width as wide as the thickness of a fingernail (0.012 in.)

17.1.3 through 17.1.6 – Scope

- The removal and resetting of post-installed mechanical and concrete screw anchors is prohibited.
- Post – installed adhesive anchors do not have generically predictable pullout capacities
- Post – installed adhesive anchors must be qualified by testing according to ACI 355.4
- High – cycle fatigue and impact (blast) are excluded

17.1.3 through 17.1.6 – Scope

- 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.

17.5.1.3.1 – Design strength

- Factored loads from elastic analysis
  - Load combinations by § 6.6 and ϕ by § 17.3.3
- Plastic analysis permitted if ductile steel elements used in the anchor
  - Must consider deformation compatibility and ductility of anchor (more information later)
- Must consider group effects (see § 17.5.1.6.1)

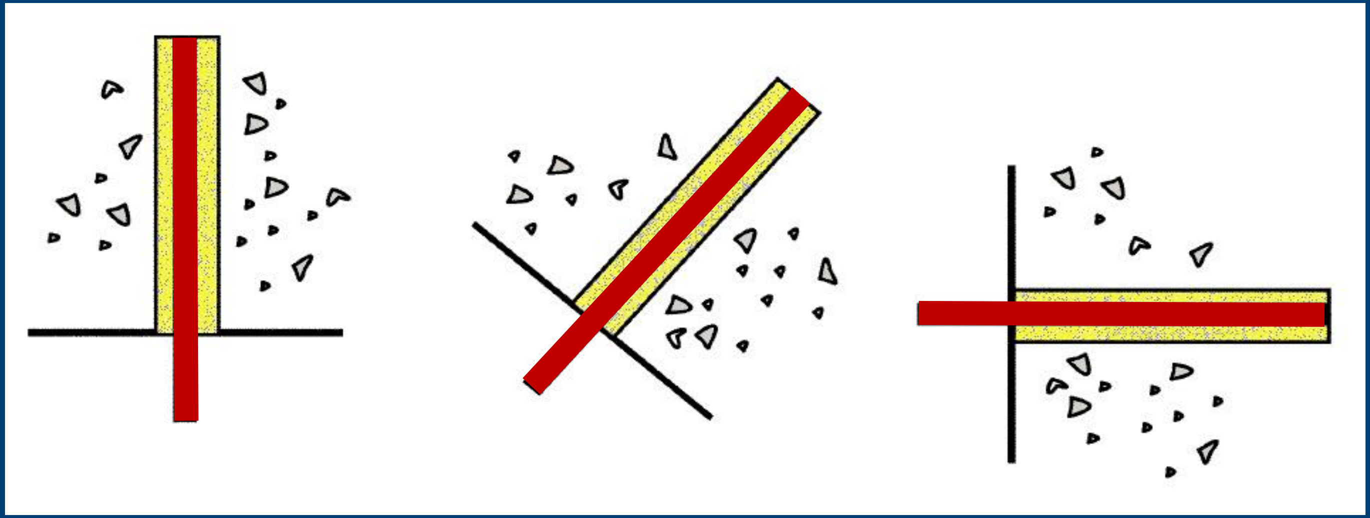
Table 17.5.1.3.1—Critical spacing

Failure mode under investigation	Critical spacing
Concrete breakout in tension	$3h_{ef}$
Bond strength in tension	$2c_{Na}$
Concrete breakout in shear	$3c_{a1}$

17.2.3 – General Requirements

Adhesive anchors installed horizontally or upwardly inclined

- Must be qualified by ACI 355.4
- Must be installed by certified installer when subjected to sustained load



17.2.4 – Lightweight Concrete

- For lightweight concrete; use modification factor, λ_a, for:
  - Cast – in and undercut concrete failure: $\lambda_a = 1.0\lambda$
  - Expansion and adhesive anchors concrete failure: $\lambda_a = 0.8\lambda$
  - Adhesive anchor bond failure: $\lambda_a = 0.6\lambda$

  λ determined by § 19.2.4
  - $\lambda = 1.0$ normal weight
  - $\lambda = 0.85$ sand – lightweight
  - $\lambda = 0.75$ all – lightweight

17.3.1 – Design Limits

Code equations are valid for :

$f_c' \leq$ 10,000 psi for cast – in anchors

$f_c' \leq$ 8,000 psi for post – installed anchors

Post – installed anchors in concrete with

$f_c' >$ 8,000 psi

must be tested according to ACI 355.2 or ACI 355.4

17.5.2 – Failure Modes in Tension

- Yield and fracture of anchor steel (17.6.1.2)
- Concrete breakout (17.6.2)
- Pullout / pull – through (17.6.3)
- Concrete side – face blowout (17.6.4)
- Bond failure for adhesive anchors (17.6.5)
  - Sustained loading limit for adhesive anchors

$$0.55\,\phi\, N_{ba} > N_{ua,sustained} \qquad (17.5.2.2)$$

Weakest Governs

- Splitting failure must be precluded (17.9)

17.5.2 – Failure Modes in Shear

- Yield strength of anchor steel (17.~~5~~7.1)
- Concrete breakout (17.7.2)
- Concrete pryout (17.7.3)

Weakest Governs

- Splitting failure must be precluded (17.9)

Table 17.5.2 – Required Strength

Table 17.5.2—Design strength requirements of anchors

Failure mode	Single anchor	Anchor group[1]	
		Individual anchor in a group	Anchors as a group
Steel strength in tension (17.4.1)	$\phi N_{sa} \geq N_{ua}$	$\phi N_{sa} \geq N_{ua,i}$	
Concrete breakout strength in tension (17.4.2)	$\phi N_{cb} \geq N_{ua}$		$\phi N_{cbg} \geq N_{ua,g}$
Pullout strength in tension (17.4.3)	$\phi N_{pn} \geq N_{ua}$	$\phi N_{pn} \geq N_{ua,i}$	
Concrete side-face blowout strength in tension (17.4.4)	$\phi N_{sb} \geq N_{ua}$		$\phi N_{sbg} \geq N_{ua,g}$
Bond strength of adhesive anchor in tension (17.4.5)	$\phi N_{a} \geq N_{ua}$		$\phi N_{ag} \geq N_{ua,g}$

[1]Required strengths for steel and pullout failure modes shall be calculated for the most highly stressed anchor in the group.

[2]Sections referenced in parentheses are pointers to models that are permitted to be used to evaluate the nominal strengths.

[3]If anchor reinforcement is provided in accordance with 17.5.2.1, the design strength of the anchor reinforcement shall be permitted to be used instead of the concrete breakout strength

Table 17.5.2 – Required Strength

Table 17.5.2—Design strength requirements of anchors

Failure mode	Single anchor	Anchor group[1] Individual anchor in a group	Anchor group[1] Anchors as a group
Steel strength in shear (17.5.1)	$\phi V_{sa} \geq V_{ua}$	$\phi V_{sa} \geq V_{ua,i}$	
Concrete breakout strength in shear (17.5.2)	$\phi V_{cb} \geq V_{ua}$		$\phi V_{cbg} \geq V_{ua,g}$
Concrete pryout strength in shear (17.5.3)	$\phi V_{cp} \geq V_{ua}$		$\phi V_{cpg} \geq V_{ua,g}$

1]Required strengths for steel and pullout failure modes shall be calculated for the most highly stressed anchor in the group

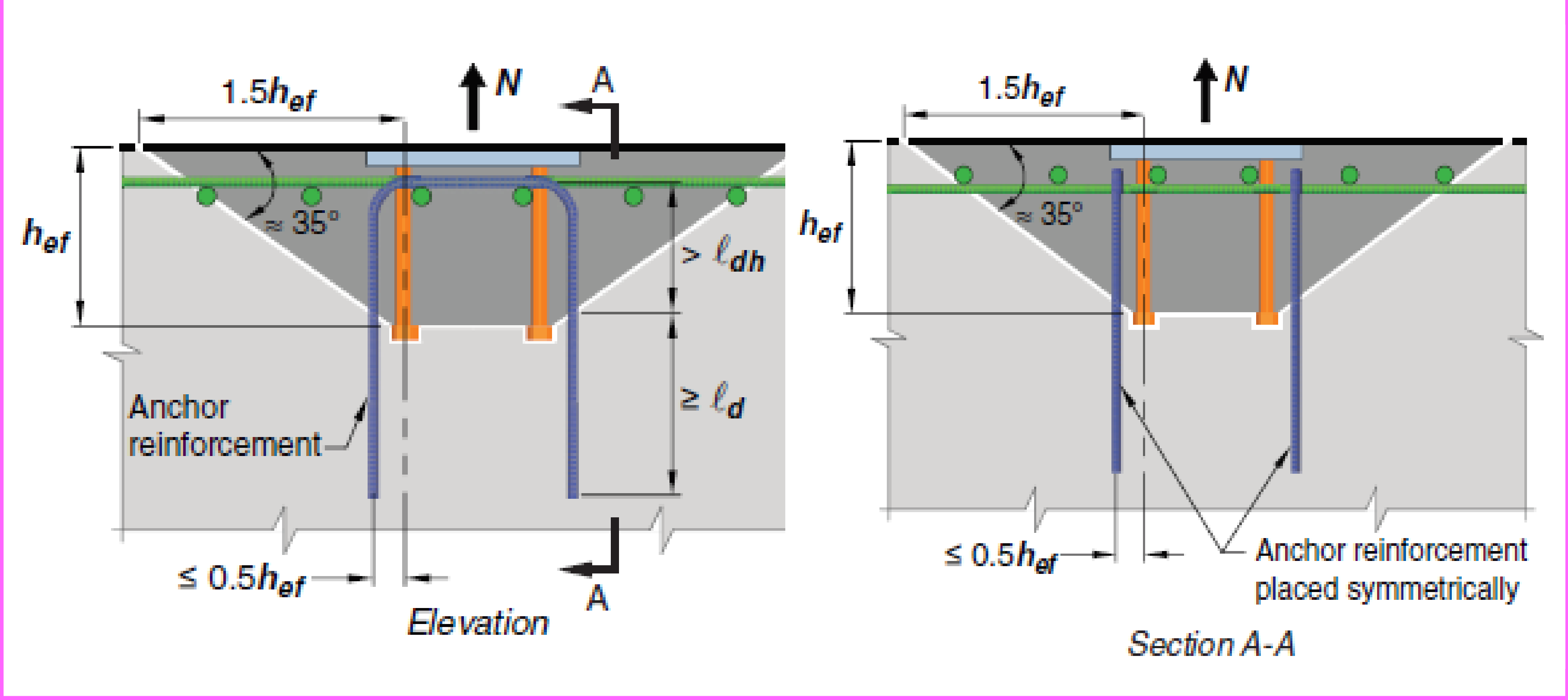
[2]Sections referenced in parentheses are pointers to models that are permitted to be used to evaluate the nominal strengths.

[3]If anchor reinforcement is provided in accordance with 17.5.2.1, the design strength of the anchor reinforcement shall be permitted to be used instead of the concrete breakout strength

17.5.2 – Supplementary and Anchor Reinforcement

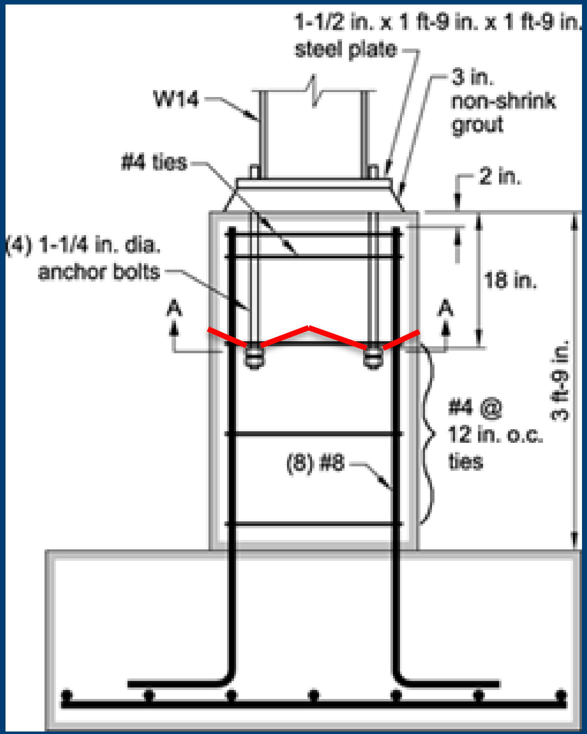
- Supplementary reinforcement
  - Reinforcement that acts to restrain the concrete breakout but is not designed to transfer the full design load (with supplemental reinforcment, higher Φ's)
- Anchor Reinforcement
  - Reinforcement used to transfer full design load
  - Anchor reinforcement takes the user out of Chapter 17 and into the reinforcing bar development length rules of Chapter 25

Anchor Reinforcement for Tension



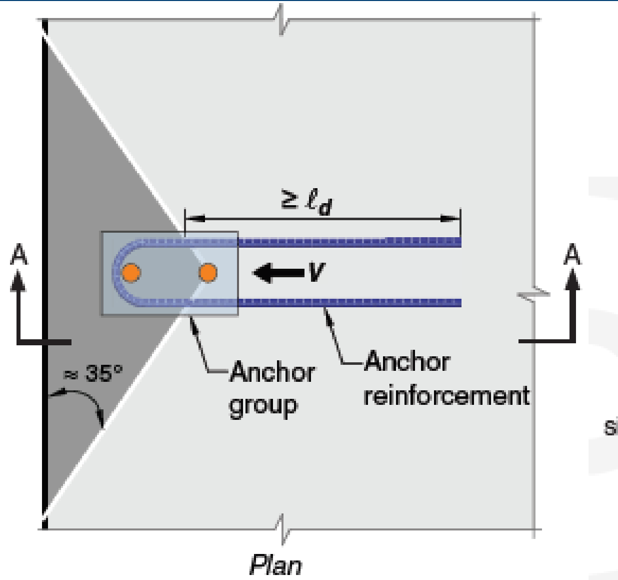
Note : Reinforcement perpendicular to direction of load is ***not*** *effective as shear – friction reinforcement by the code*

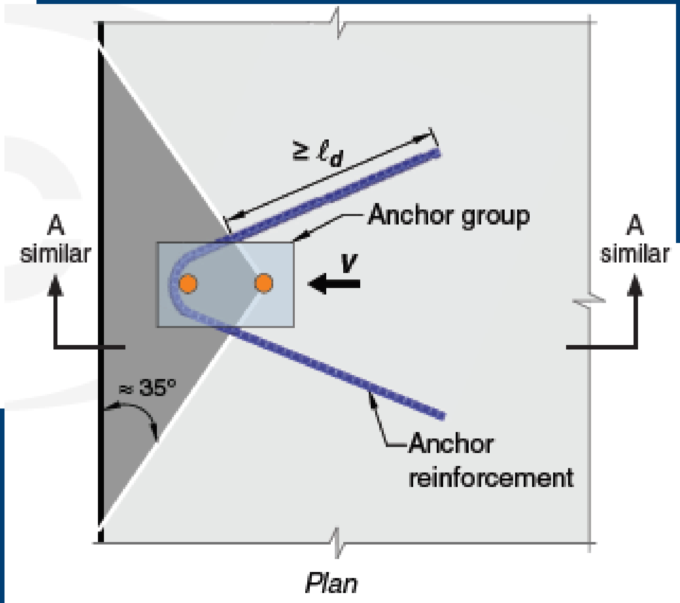
17.5.2.1 – Anchor reinforcement for tension

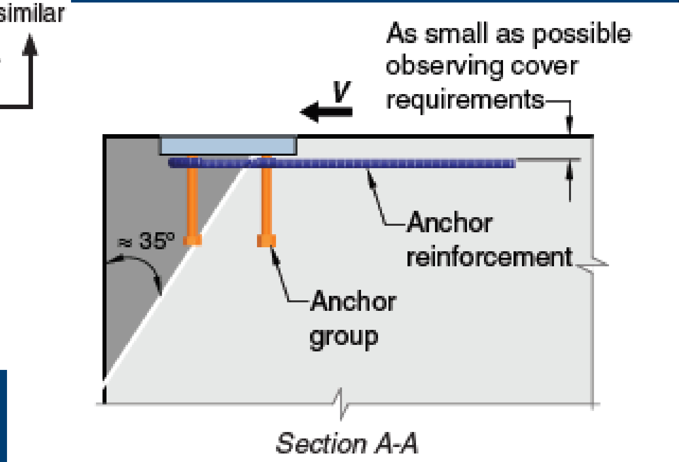


- Concrete breakout strength by Ch. 17 is insufficient – breakout will occur
- Increasing ϕ for concrete breakout does not help
- Use the provisions of ACI 318 Ch. 25, and splice anchors to reinforcement to resist the design actions
- A strength reduction factor of 0.75 is used in design of anchor reinforcement

Anchor Reinforcement for Shear







Anchor reinforcement has to be in the direction of the applied force and near the point of crack initiation

17.3.2 – Size Limitation (any anchor type)

For concrete breakout only

- Diameter ≤ 4 in
- No limitation on embedment depth (h_{ef})

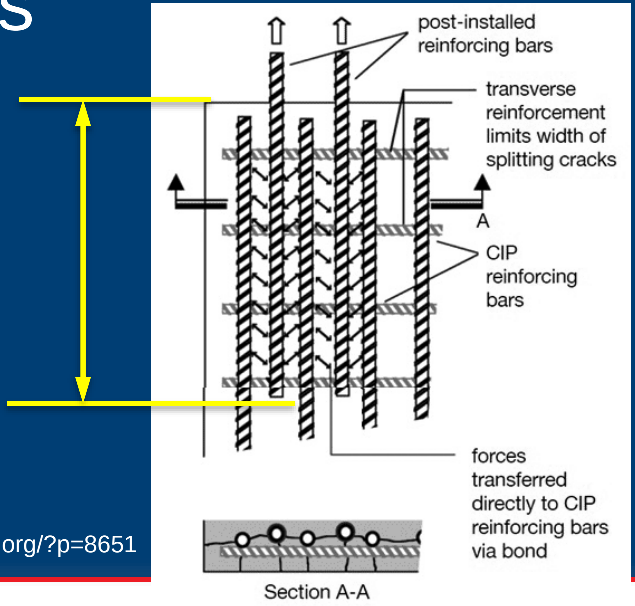
17.3.3 – Embedment Depth Limitations - Adhesive Anchors

- Limits of embedment depth for adhesive anchors

$$4d_a \le h_{ef} \le 20d_a$$

➔ Design using bond model of 17.64.5 produce satisfactory results

max $20d_a$



http://www.structuremag.org/?p=8651

Questions

Code Design Provisions - Tension
ACI 318 -19 Section 17.6

17.6 – Design for Tensile Loading

- 17.6.1 – Steel Strength
- 17.6.2 – Concrete Breakout Strength
- 17.6.3 – Pullout Strength
- 17.6.4 – Concrete Side-face Blowout Strength
  - (Applies to headed anchors only)
- 17.6.5 –Bond Strength of Adhesive Anchors

Design Model – Tension

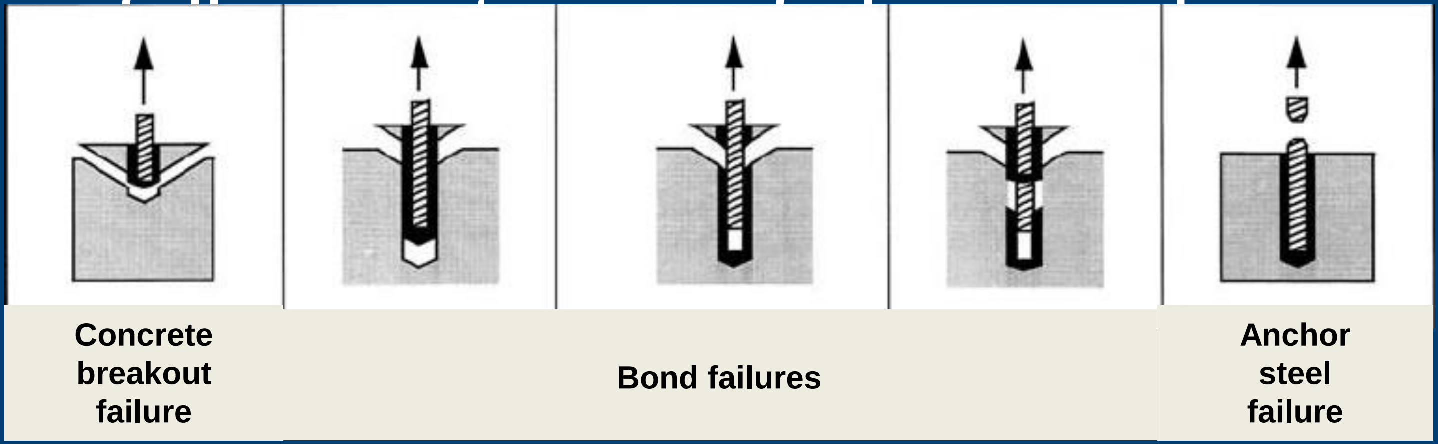
- Basic single anchor tensile strength
- Influence of anchor type
- Effects of anchor spacing
- Effects of cracking
- Effects of unit weight of concrete
- Effects of free edges
- Effects of eccentricity
- Effects of installation and load splitting

Design Model – Tension

- Post–installed mechanical and adhesive anchors do not have a generically predictable pullout capacities
- Post–installed mechanical and adhesive anchors must be qualified by testing according to ACI 355.2 and ACI 355.4

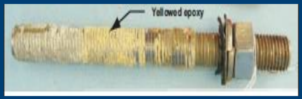
Tension Design – Adhesive Anchors

Designer must consider the



Adhesive/substrate

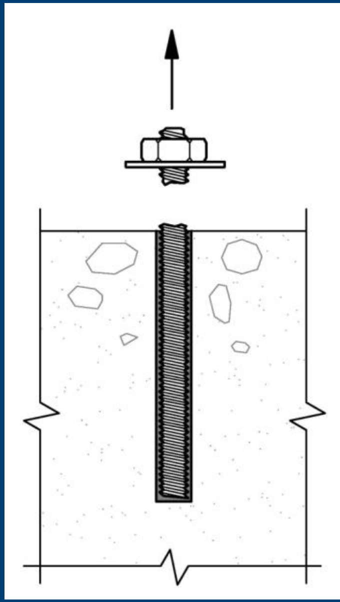
Adhesive/threaded

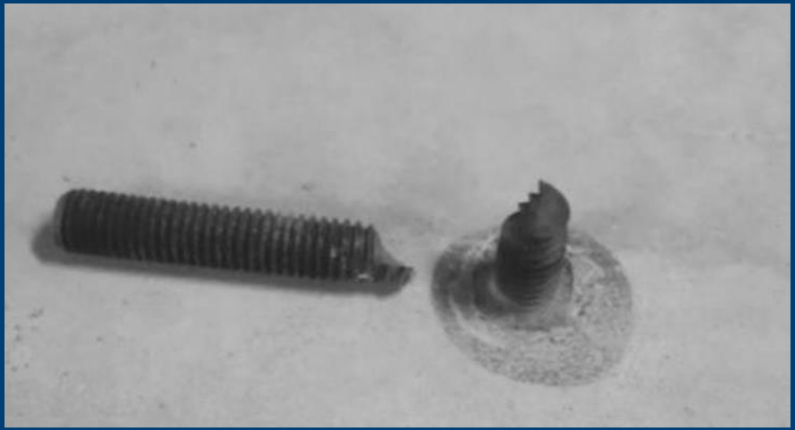


Mixed

17.6.1 – Steel Failure – Tension

- *Steel rupture*

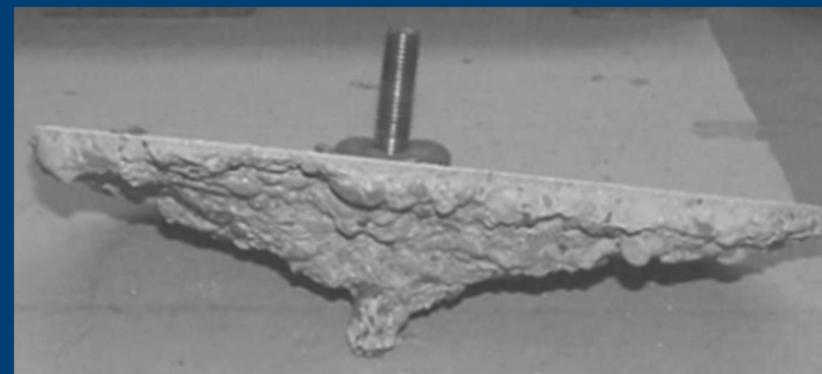




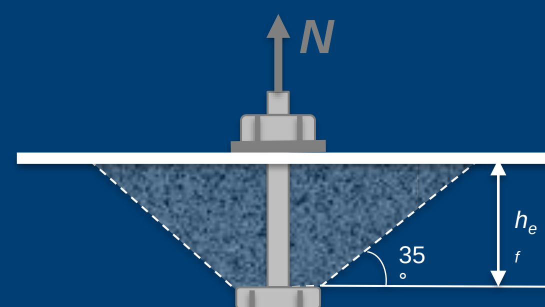
$$N_{sa} = A_{se} f_{uta} \quad (17.6.1.2)$$

17.6.2 – Concrete Breakout Failure – Tension Cone Breakout

https://www.researchgate.net/publication/259441676_A_Study_on_Effect_of_Anchor_Plate_on_Concrete_Breakout_Capacity_and_Elasticity-Based_Analysis_Model_of_Anchor_Plate

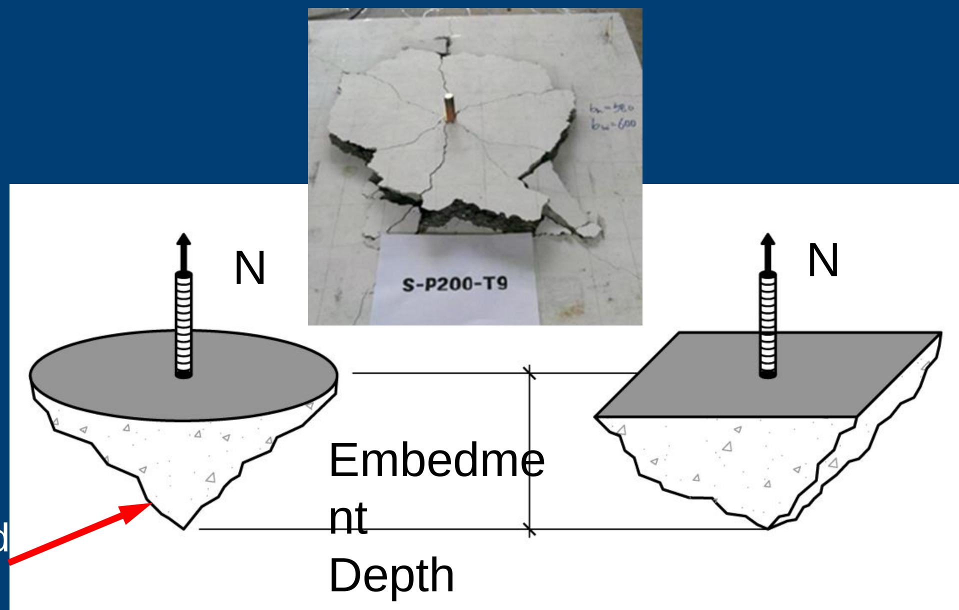


Courtesy of University of Stuttgart



Idealized Cone – Breakout Model

A_{Nco}



Fractured Concrete

Model reflecting actual behavior

Model used in design

17.1.6 – Reinforcement used as anchorage

Check anchorage for bars developed per Ch. 25

- Check concrete breakout in tension (and maybe shear)
- Greater development length should be considered

17.1.6 – Reinforcement used as anchorage

- Straight bars behave like adhesive anchors
- Hooked and headed bars behave like headed anchors
- Anchor reinforcement may be an alternative

Edge Distance Tension Breakout

Photograph Courtesy of:
Andy Fennell, (ERG)

17.6.2 – Concrete Breakout Strength of Anchor Group (Tension)

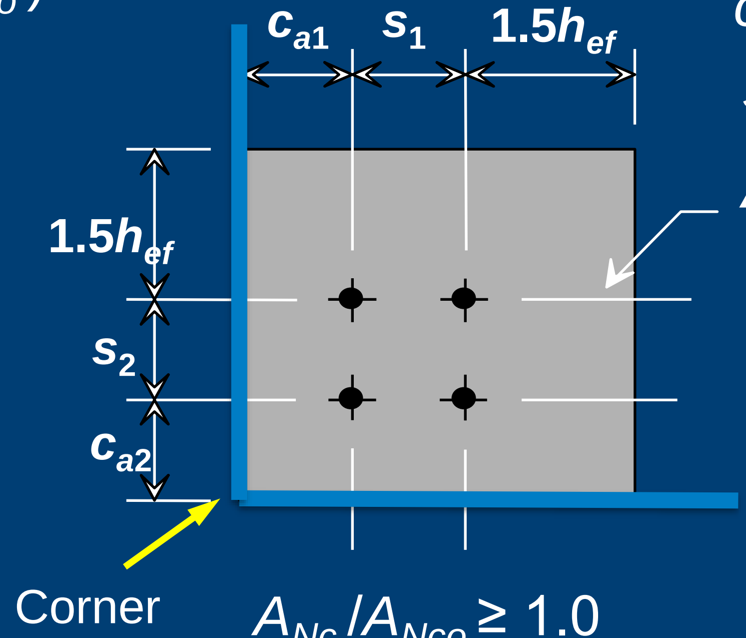
$$N_{cbg} = (A_{Nc}/A_{Nco})\ \psi_{ec,N}\ \psi_{ed,N}\ \psi_{c,N}\ \psi_{cp,N}\ N_b \quad (17.6.2.1.b)$$

- A_{Nc}/A_{Nco}: Accounts for projected area of failure surface
- $\psi_{ec,N}$: Accounts for eccentricity
- $\psi_{ed,N}$: Accounts for edge effects
- $\psi_{c,N}$: Accounts for cracking
- $\psi_{cp,N}$: Accounts for post - installed anchor (splitting)
- N_b: Basic single anchor strength

Applies to anchors in tension only

Concrete Breakout with Groups and Edges – Projected Area A_{Nc}

(A_{Nc}/A_{Nco}):



$A_{Nc}/A_{Nco} \geq 1.0$

$c_{a1} \leq 1.5h_{ef}$

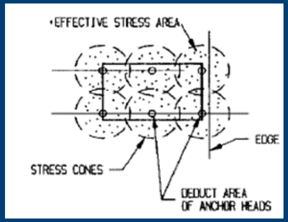
$s_1 \leq 3.0h_{ef}$

$\boldsymbol{A_{Nc} \leq nA_{Nco}}$

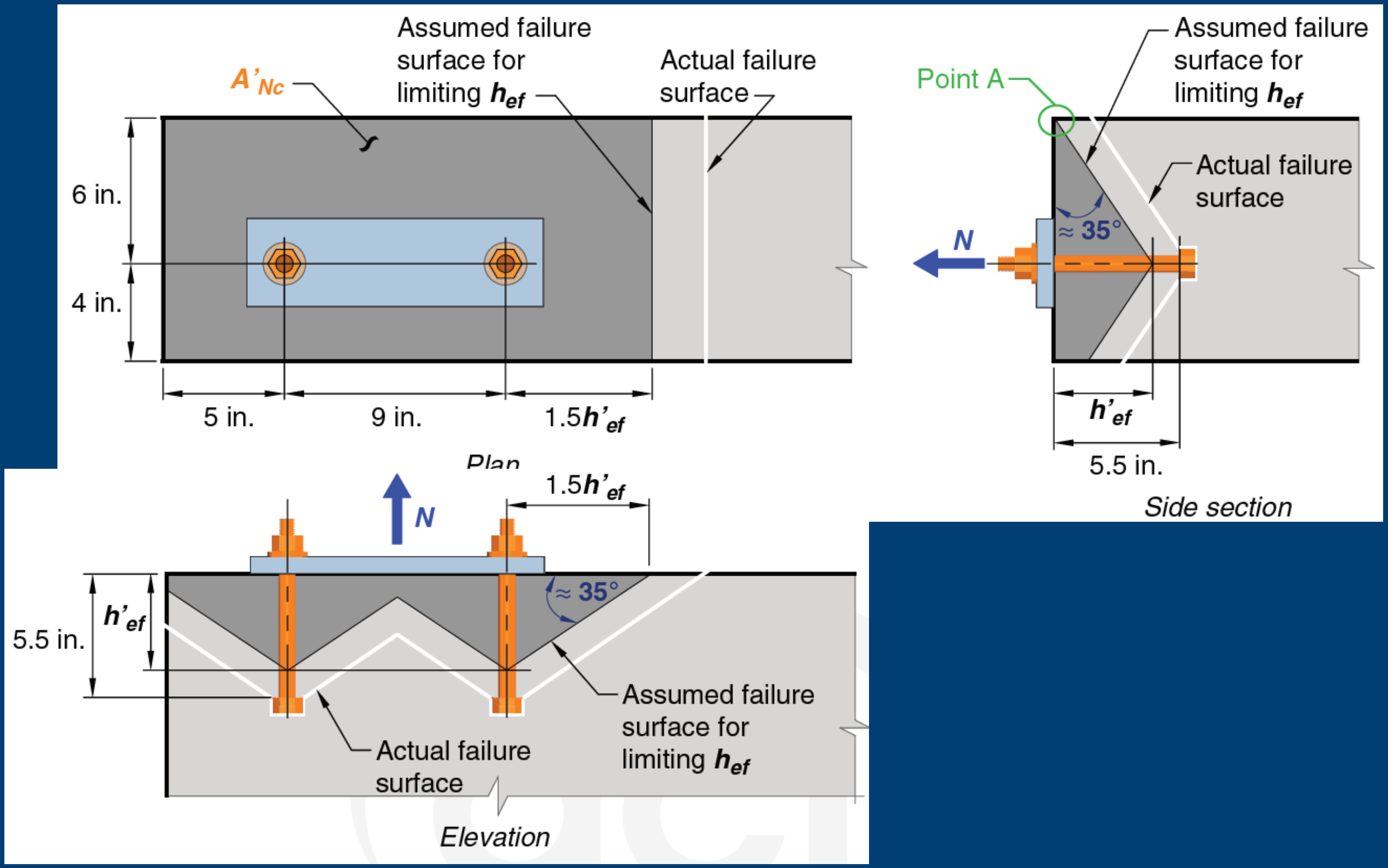
Limit

$s_2 \leq 3.0h_{ef}$

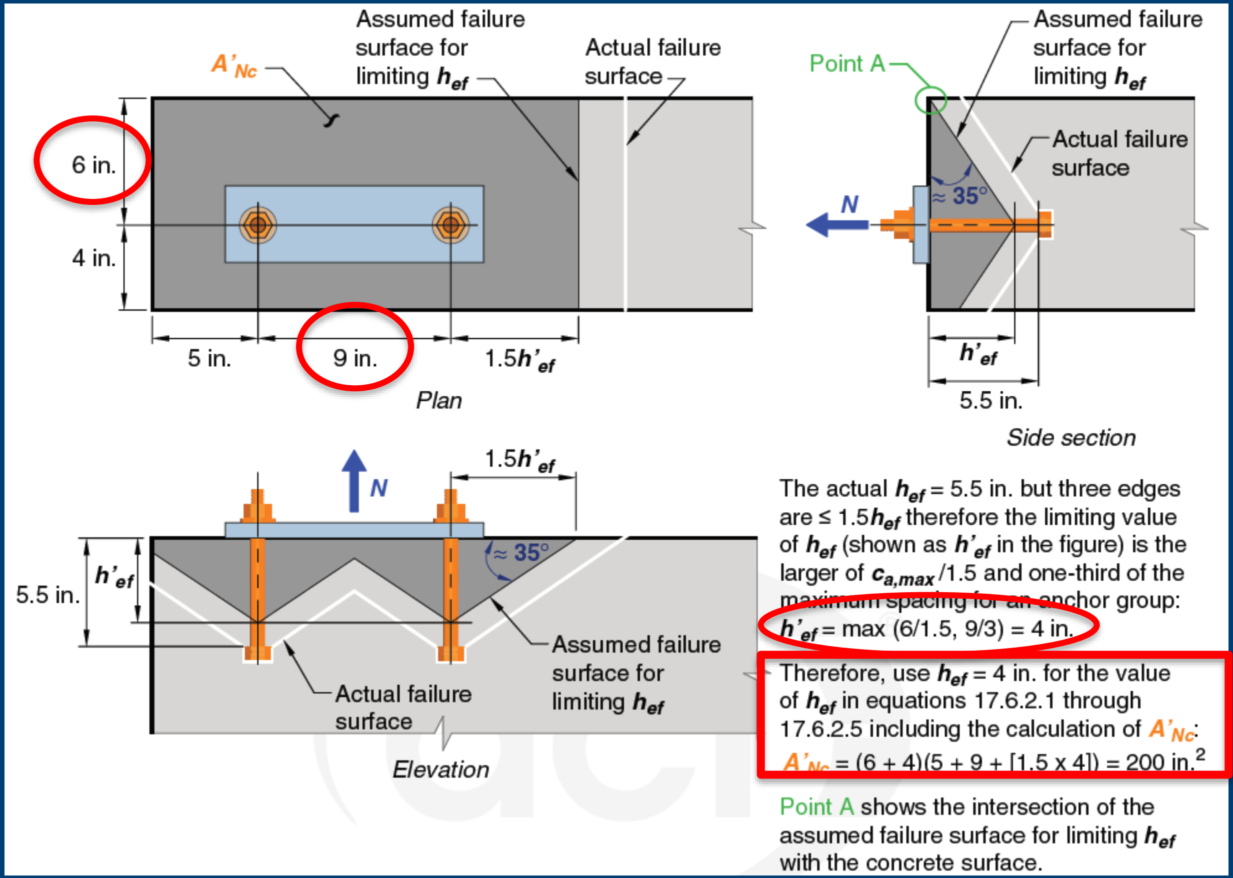
$c_{a2} \leq 1.5h_{ef}$



17.6.2.1.2 – Anchors Close to 3 or 4 Edges



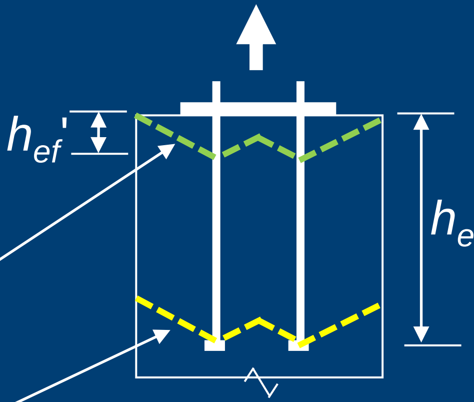
Fictitious Embedment, h_{ef}'



Determine Fictitious Embedment Depth, h_{ef}'

Consider a square concrete pier:

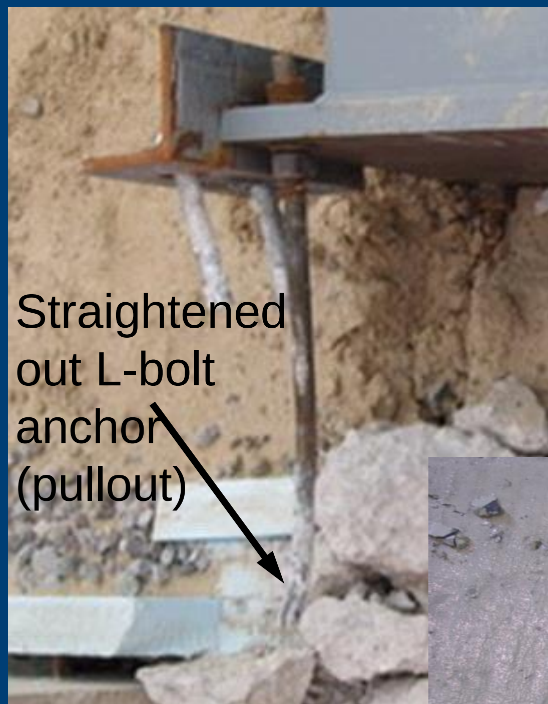
- Fictitiously move the actual concrete breakout surface toward the free surface of concrete

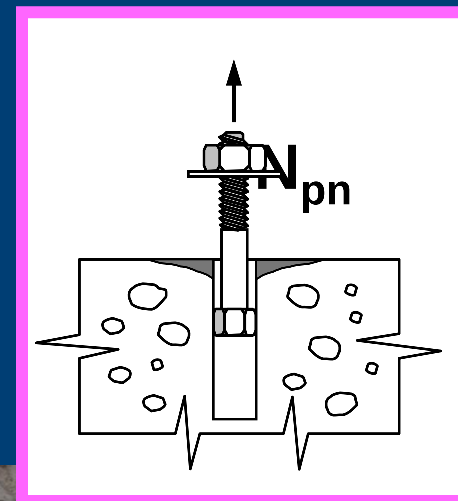


Fictitious concrete breakout surface, by § 17.6.2.1.2 (for calculations only)

Actual concrete breakout surface

17.6.3 – Pullout Strength





17.6.3.2.1 – Pullout Strength

- Post-installed expansion and undercut anchors, N_p, cannot be calculated using generic formulas
- N_p must be based on results of tests performed and evaluated per ACI 355.2

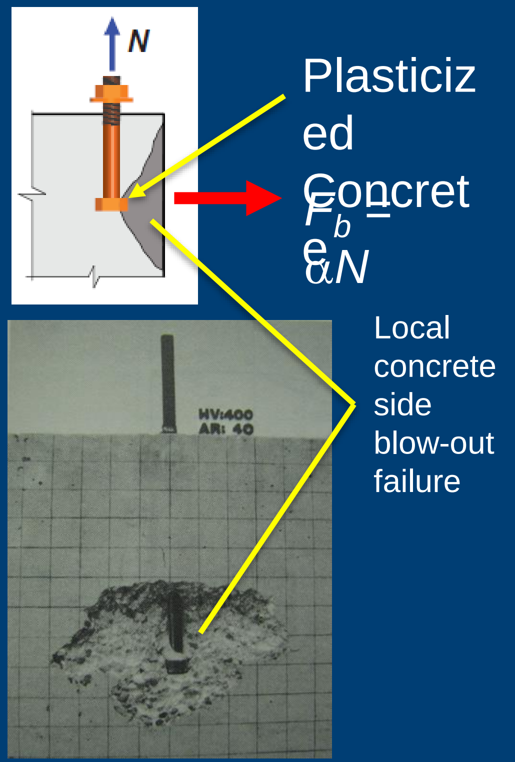
Characteristic	Symbol	Units	Nominal anchor diameter							
Installation information										
Outside diameter	d_a	in.	3/8		1/2		5/8		3/4	
			h_{ef}	N_p	h_{ef}	N_p	h_{ef}	N_p	h_{ef}	N_p
Pullout or pull-through resistance from tests	$N_p^{\dagger}$	lb	1.75	1354	2.5	2312	3	4469	3.5	5632
			2.75	2667	3.5	3830	4.5	8211	5	9617
			4.5	5583	5.5	7544	6.5	14,254	8	19,463
Tension resistance of single anchor for seismic loads	N_{eq}	lb	1.75	903	2.5	1541	3	2979	3.5	3755
			4.5	3722	5.5	5029	6.5	9503	8	12,975
Shear resistance of single anchor for seismic loads	V_{eq}	lb	2906		5321		8475		12,543	

17.6.4 – Side–face Blowout Failure

Local side-face blowout caused by bearing pressure (stress) of head on concrete (in the range of $8f_c'$) producing lateral force

$$N_{sb} = 1/\alpha \ N_b$$

- ***Lateral force*** (N_{sb}) is a function of the tension force on anchor
- α depends on the bearing pressure beneath the head



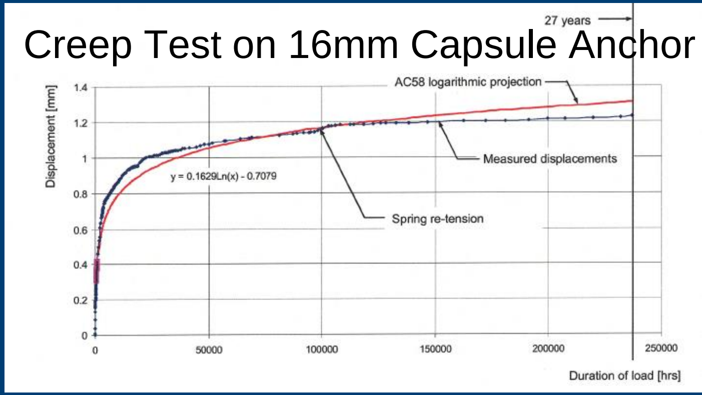
Failures for Adhesive Anchors

- Concrete Breakout Failure
- Adhesive Anchor Bond Failure
- Adhesive Anchor and Sustained Loads

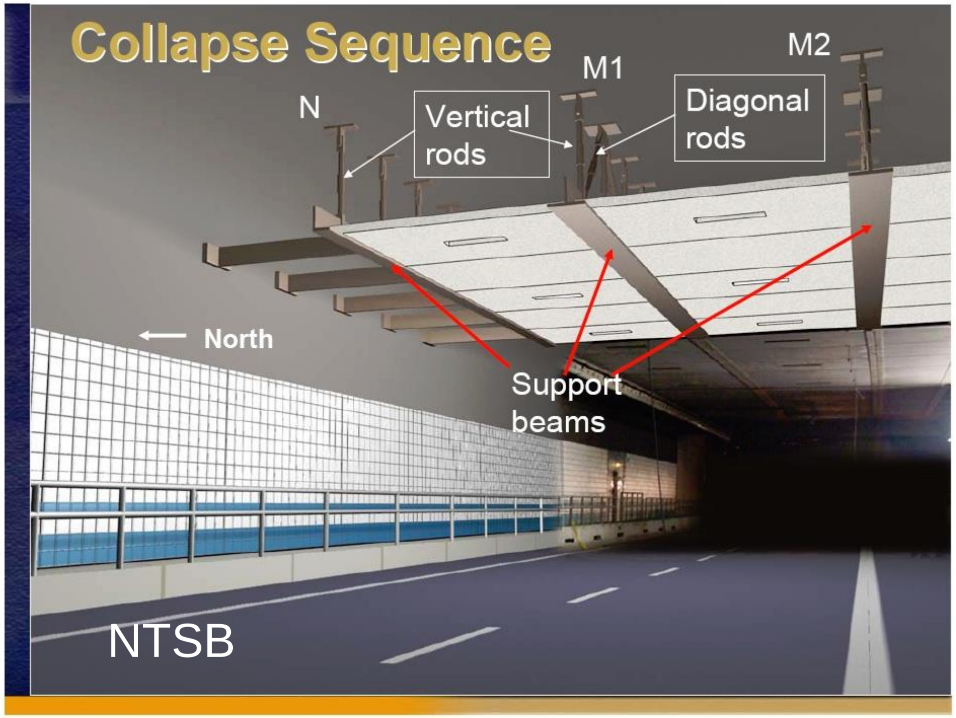
Bond Failure – Tension

Bottom Line on Sustained Loads

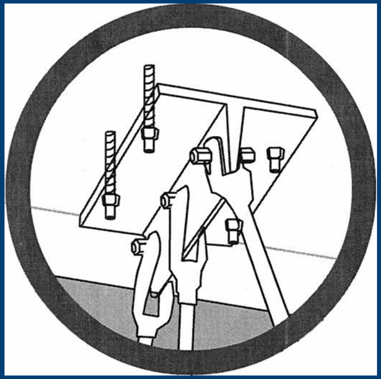
- Keep bond stress at an appropriate lower level
- Design Life: 50 years, 100 years?
- Temperature expectations: Indoor, Outdoor?
- ACI 318-19 & ACI 355.4-19: 50 years with up to 10 years at 110 ^{o} F [43 ^{o} C]



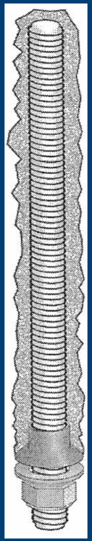
Boston “Big Dig” Tunnel



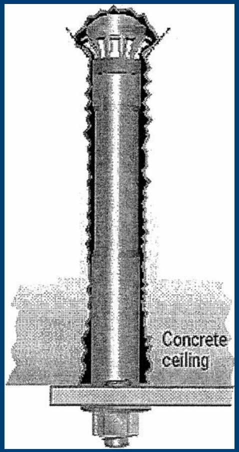
Boston Tunnel Decision



The
Application



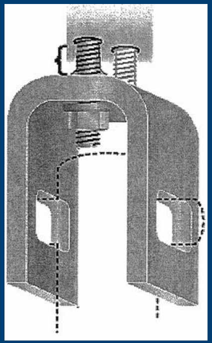
The Choice



Hanger
Plate

The Rejected
Solution

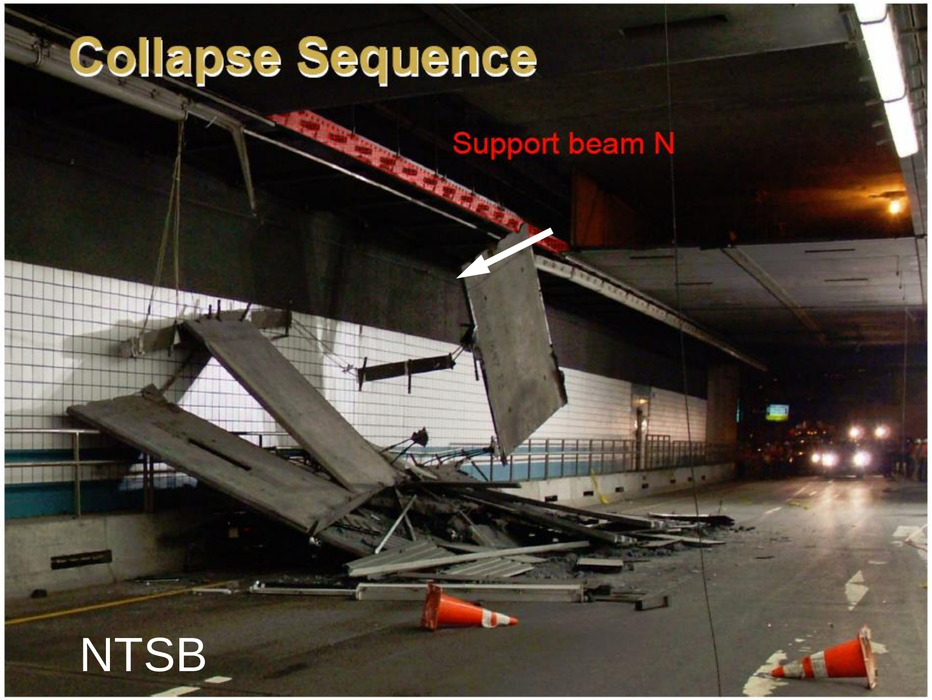
One hanger
was found an
inch below
the ceiling,
another
half an
inch
low.



Hanger rod
connects to ceiling

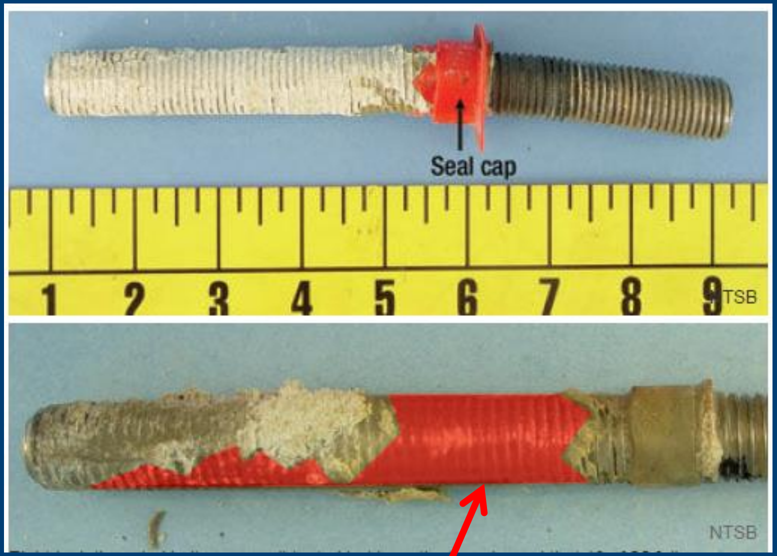
The
Aftermath

Boston "Big Dig" Tunnel



Boston "Big Dig" Tunnel

Poor Installation (photos from NTSB Files)



Red area is adhesive
unbonded to concrete

Proof Loading Guidelines

- Note, testing of installed anchors as a means of establishing in-situ strength is often confused with proof loading.
- While the test methodologies are similar, testing to establish values for design is conducted with different objectives
  - There are different acceptance criteria, sampling rates, types of tests, grading requirements, etc.

Proof-loading Guidelines – Adhesive Anchor

- Proof loading is the application of tension load
  - For adhesive anchors, apply a tension load to an installed anchor to verify that no gross issue exists with installation
  - The load level is selected sufficiently high to provide assurance of bond
  - Load level not so high as to result in damage to a correctly installed anchor
- No yielding
- No permanent slip ?

Tension Proof Testing Suggestions – Adhesive Anchors

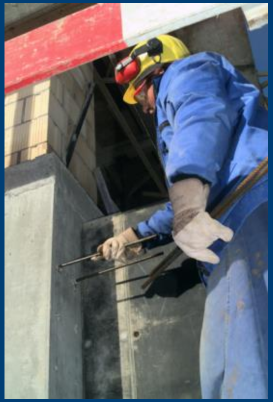
- 2x allowable service load
  - ~ 0.7 characteristic bond strength
  - ~ 0.5 average ultimate bond strength
    - Note that the allowable service load is used, not the calculated service load
- 80 percent of the rod steel yield strength
- Obviously use whichever is smaller
- Short-term loading

Silva, J. and Mattis, L. [2011], Special Inspection Guidelines for Post-installed Anchors, Concrete Anchor Manufacturers Association (CAMA), St. Charles, Missouri, June, 2011, 13 pp. (available from the CAMA website)

Mechanical Anchor – Acceptable Test Frequency and Displacements

- Frequency
  - Testing: **[10%] [25%] _______** of each type and size of drilled-in anchor shall be proof loaded by the independent testing laboratory.
  - If **[any] [more than 10%] _______** of the tested anchors fail to achieve the specified proof load, test all anchors of the same diameter and type
- Displacement
  - Loads shall be applied with a calibrated hydraulic ram. Displacement of mechanical anchors at proof load shall not exceed D/10, where D is the nominal anchor diameter.

Questions



Photograph courtesy of Hilti AG

Code Design Provisions - Shear
ACI 318 -19 Section 17.7

17.7 – Design for Shear Loading

17.7.1 – Steel Strength

17.7.2 – Concrete Breakout Strength

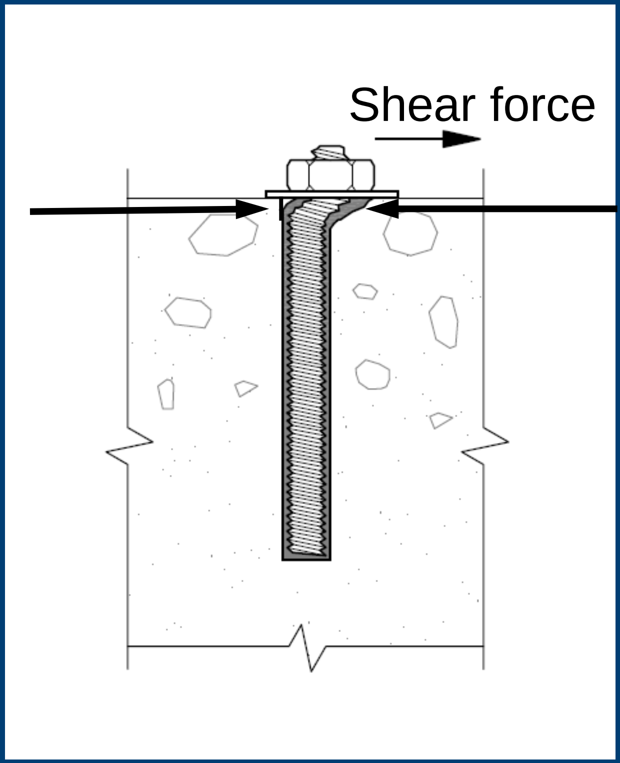
17.7.3 – Concrete Pryout Strength

Note: All anchor types are considered equivalent.
There are no special code clauses for
cast – in – place, post – installed expansion,
adhesive, or screw anchors for shear design

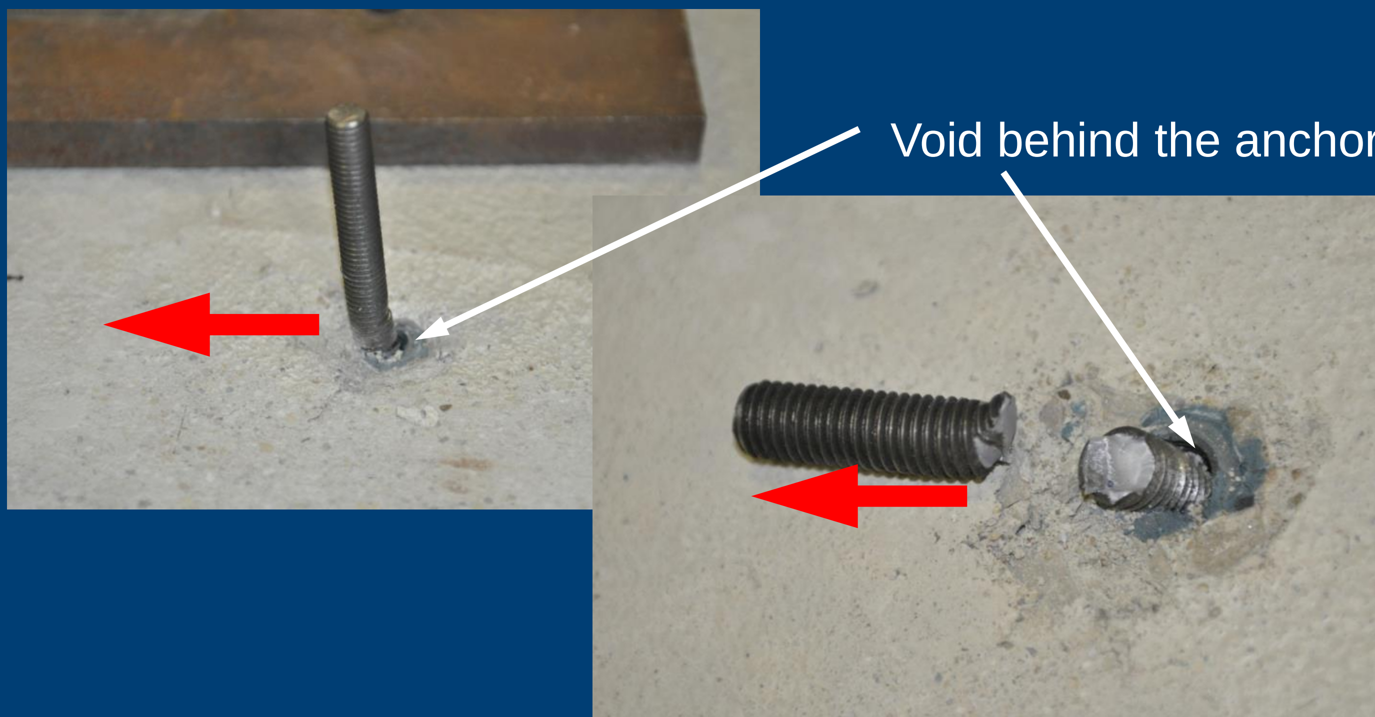
Design Model – Shear

- Basic single anchor shear strength
- Effects of anchor spacing
- Effects of free edges
- Effects of eccentricity
- Effects of cracking
- Effects of unit weight of concrete
- Effects of installation and load splitting

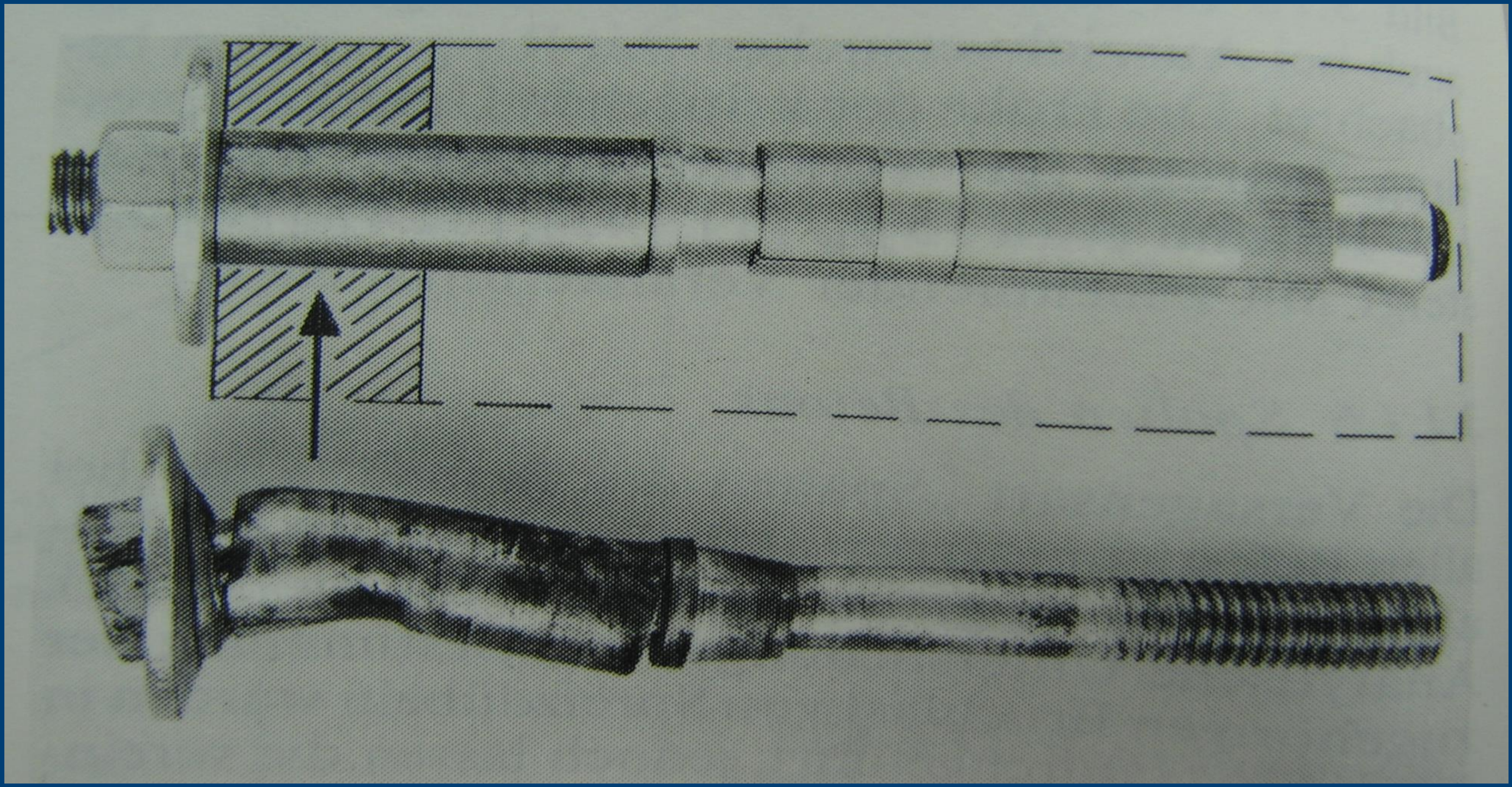
17.7.1 – Steel Failure (Shear)



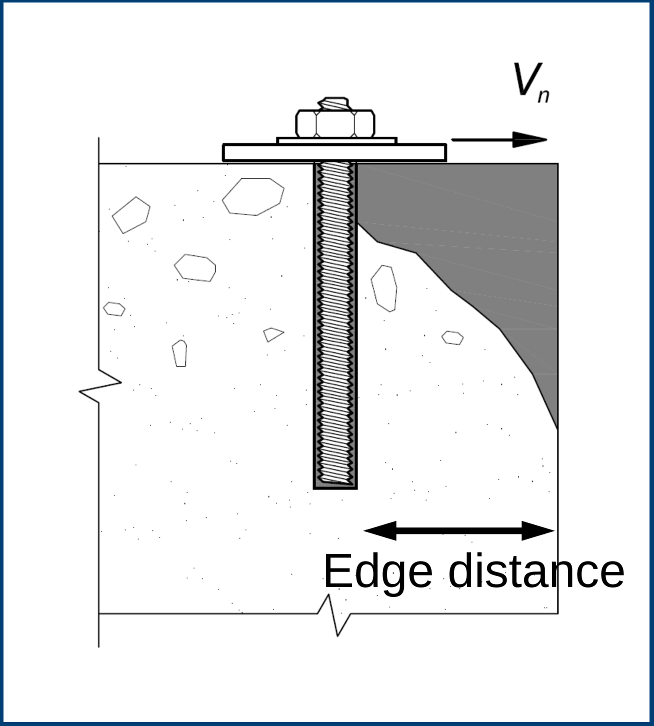
Steel Failure – Shear

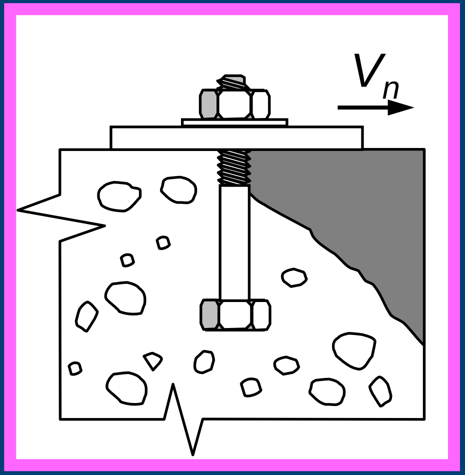


Steel Failure – Shear

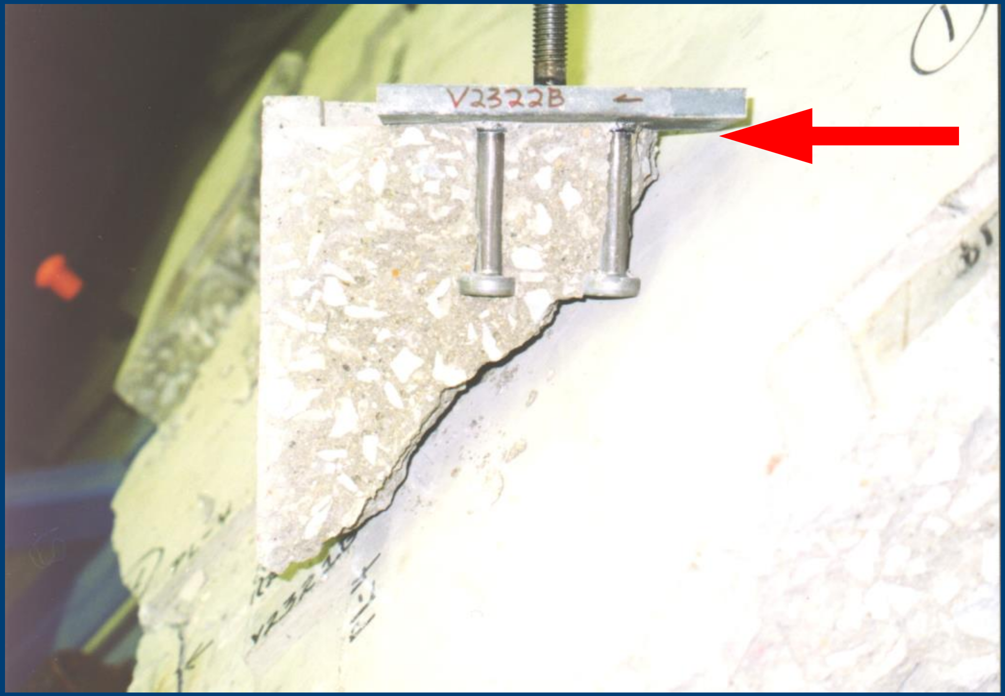


17.7.2 Concrete Breakout (Shear)

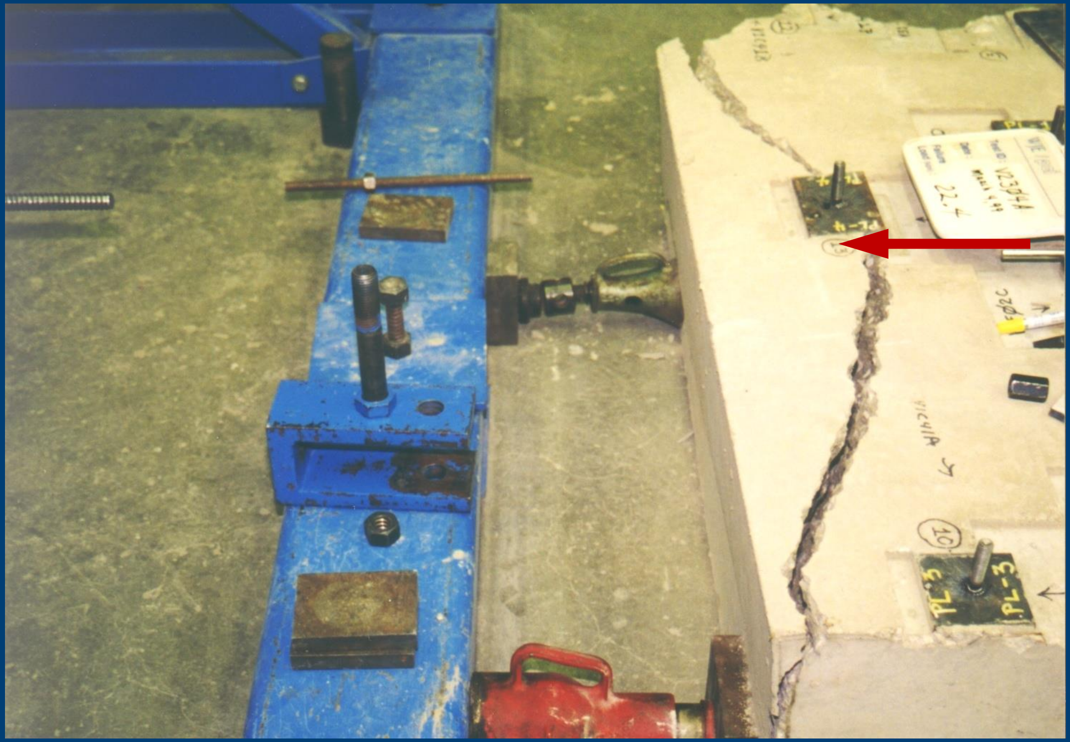




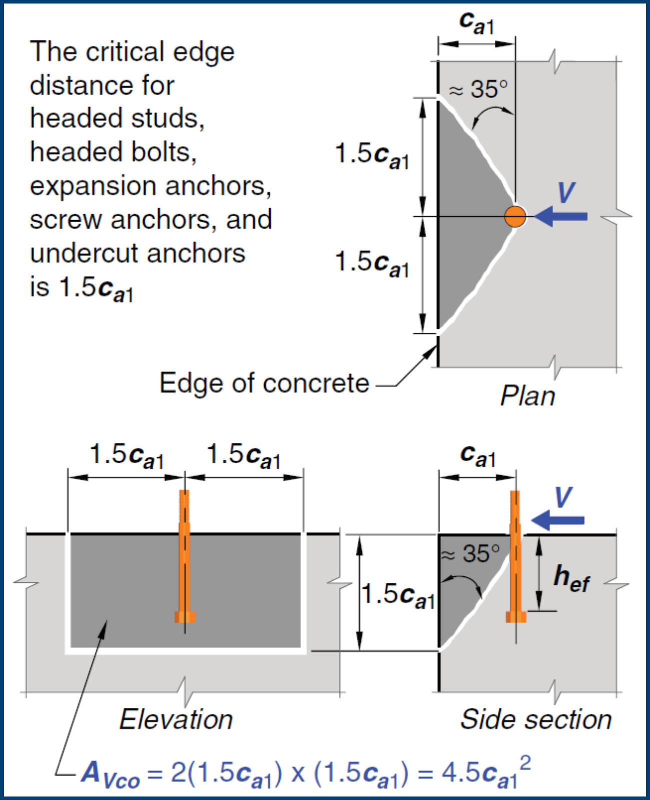
Concrete Breakout (Shear)



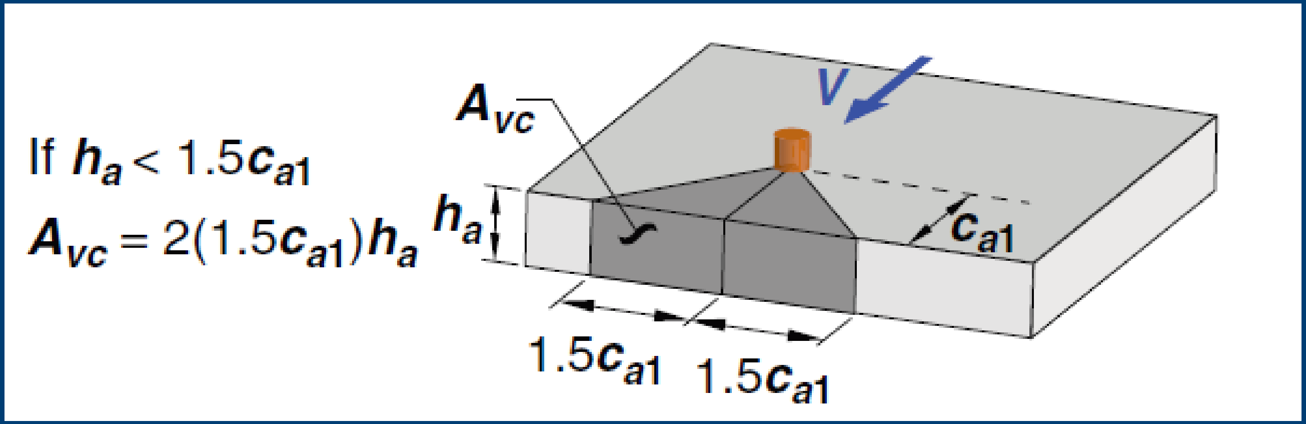
Concrete Breakout (Shear)



Projected Area for Single–Anchor Shear Breakout



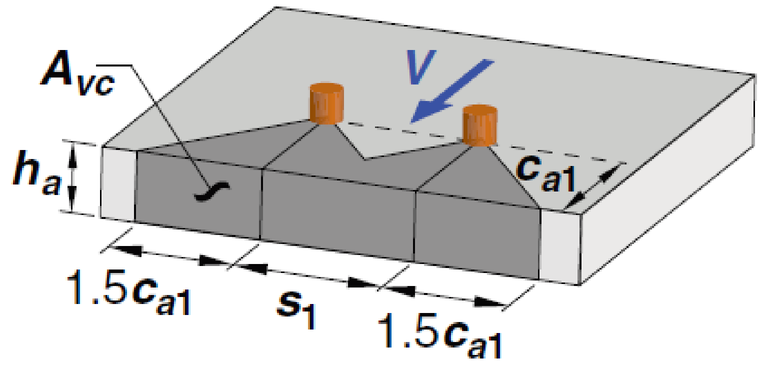
17.7.2.1 – Projected Area for Shear Breakout



Projected Area for Shear Breakout (Groups)

If $h_a < 1.5c_{a1}$ and $s_1 < 3c_{a1}$

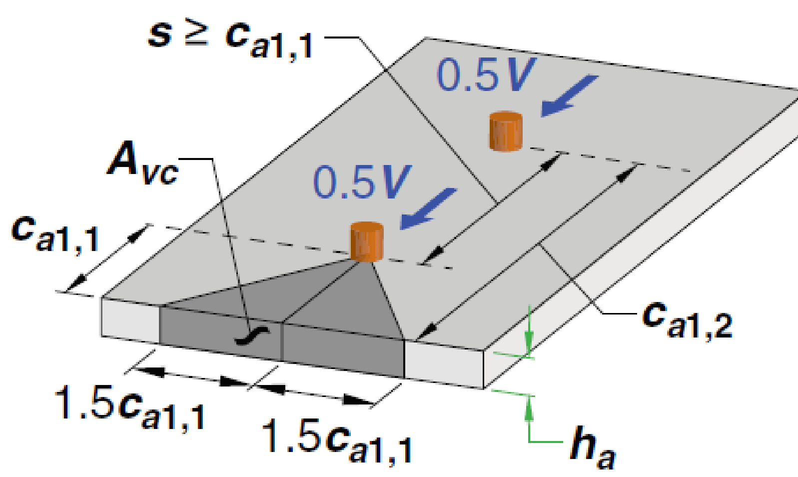
$$A_{Vc} = [2(1.5c_{a1}) + s_1]h_a$$



Projected Area for Shear Breakout (Groups)

If $h_a < 1.5c_{a1,1}$

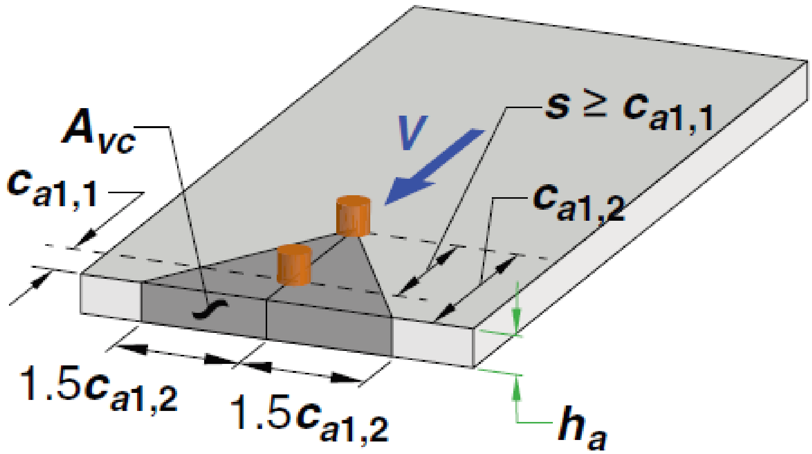
$$A_{vc} = 2(1.5c_{a1,1})h_a$$



Projected Area for Shear Breakout (Groups)

If $h_a < 1.5c_{a1,2}$

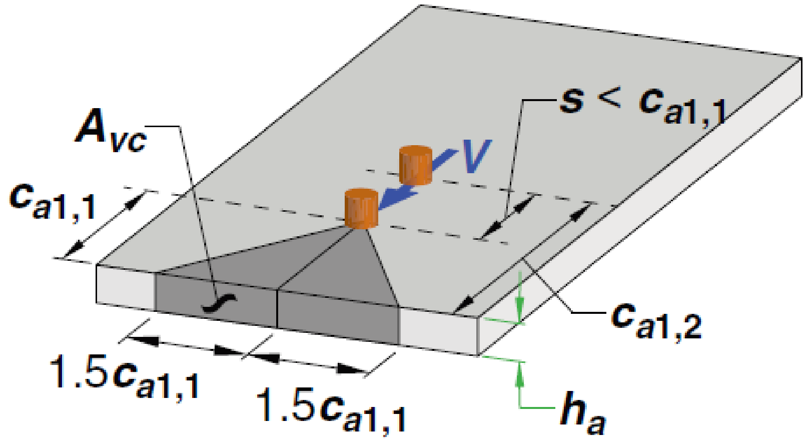
$A_{vc} = 2(1.5c_{a1,2})h_a$



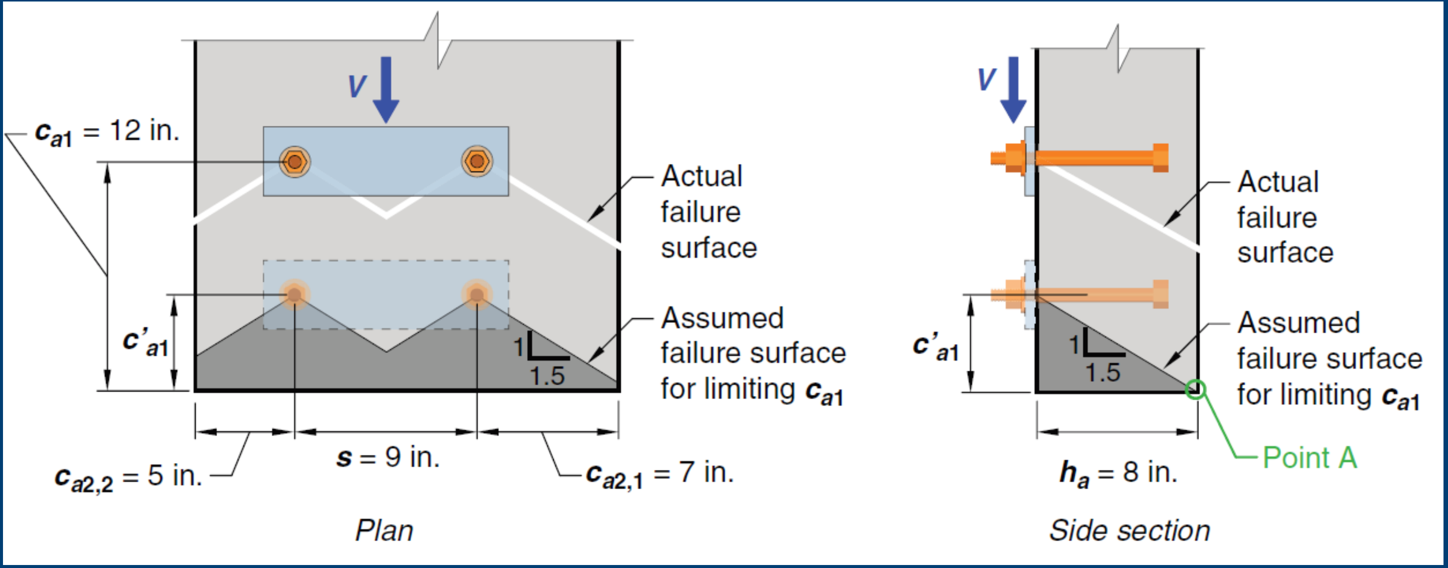
Projected Area for Shear Breakout (Groups)

If $h_a < 1.5c_{a1,1}$

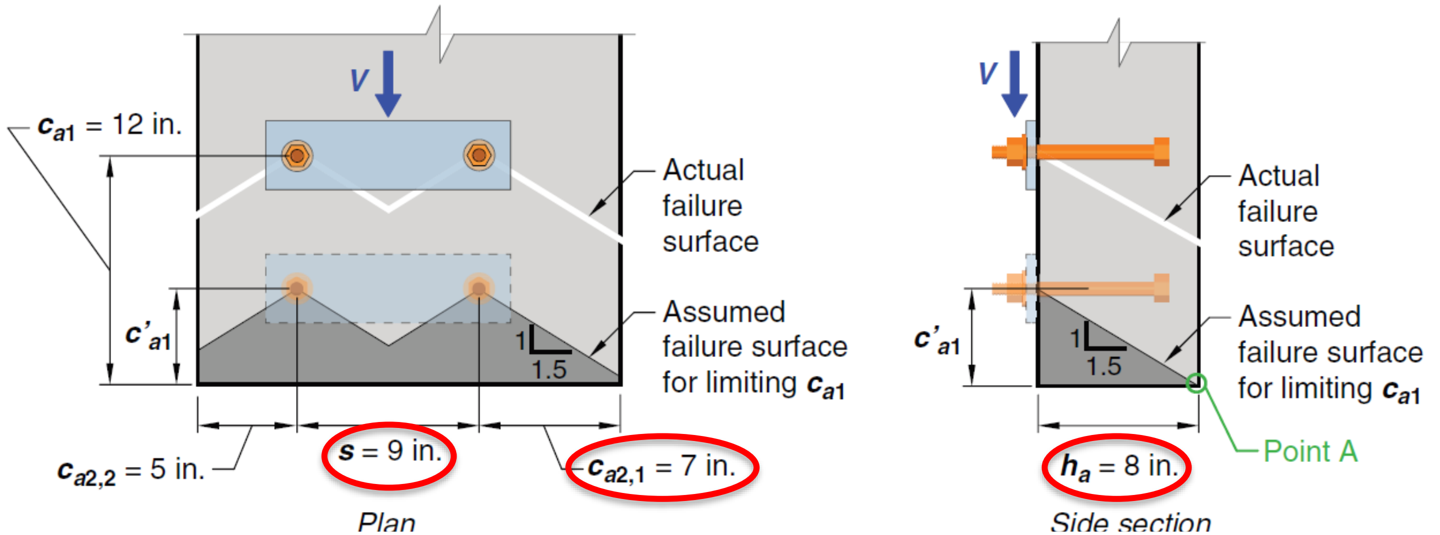
$A_{Vc} = 2(1.5c_{a1,1})h_a$



17.7.2.1.2 Anchors Close to 3 or 4 Edges



17.7.2.1.2 Anchors Close to 3 or 4 Edges

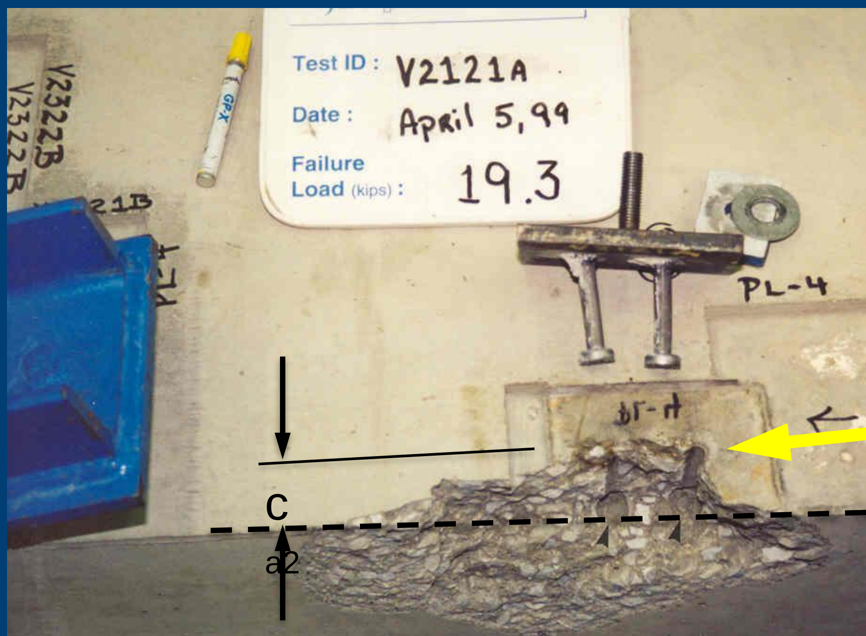


$c_{a2,max}/1.5 = 7/1.5 = 4.67$ in.

$h_a/1.5 = 8/1.54 = 5.33$ in.

$s/3 = 9/3 = 3$ in.

Shear Parallel to Free Edge

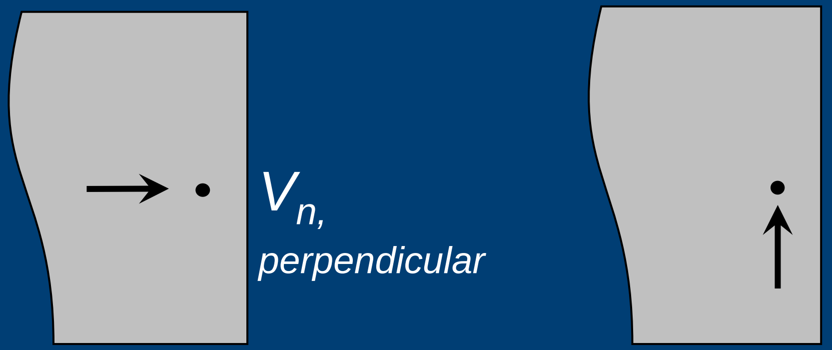


Concrete breakout

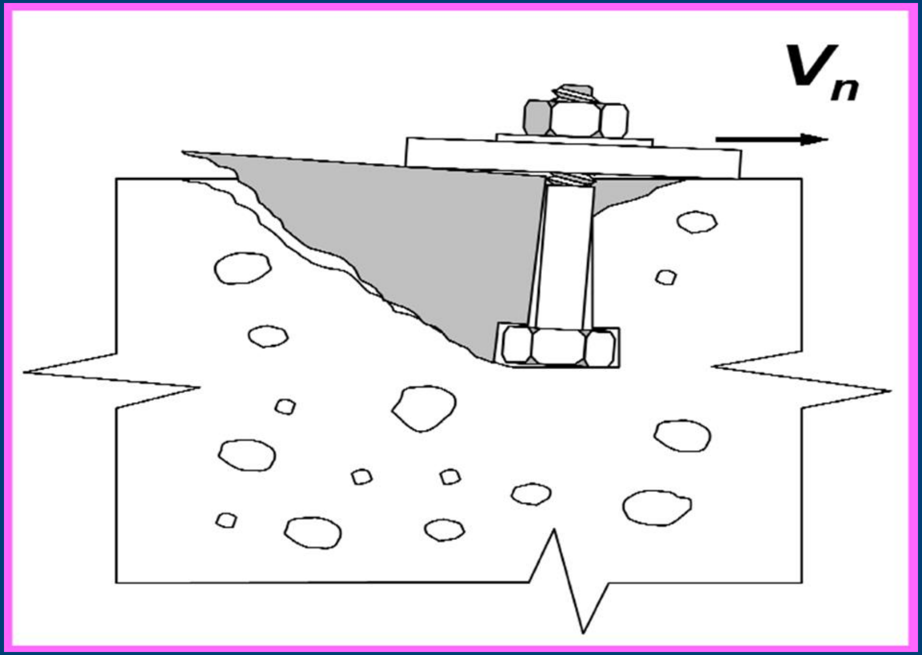
$c_{a2} = 4d_a$

17.7.2.1(c) & (d) Shear Parallel to Edge

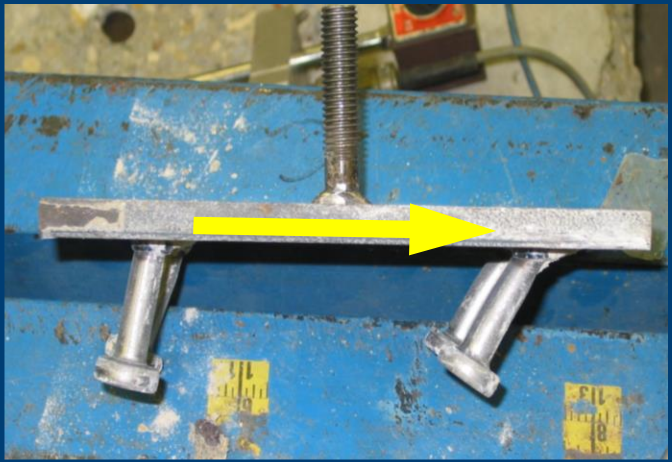
- Compute shear strength perpendicular to edge, $V_{n\ perp}$
- Based on testing, shear strength parallel to edge = 2 $V_{n,\ perpendicular}$



17.7.3 Concrete Pryout



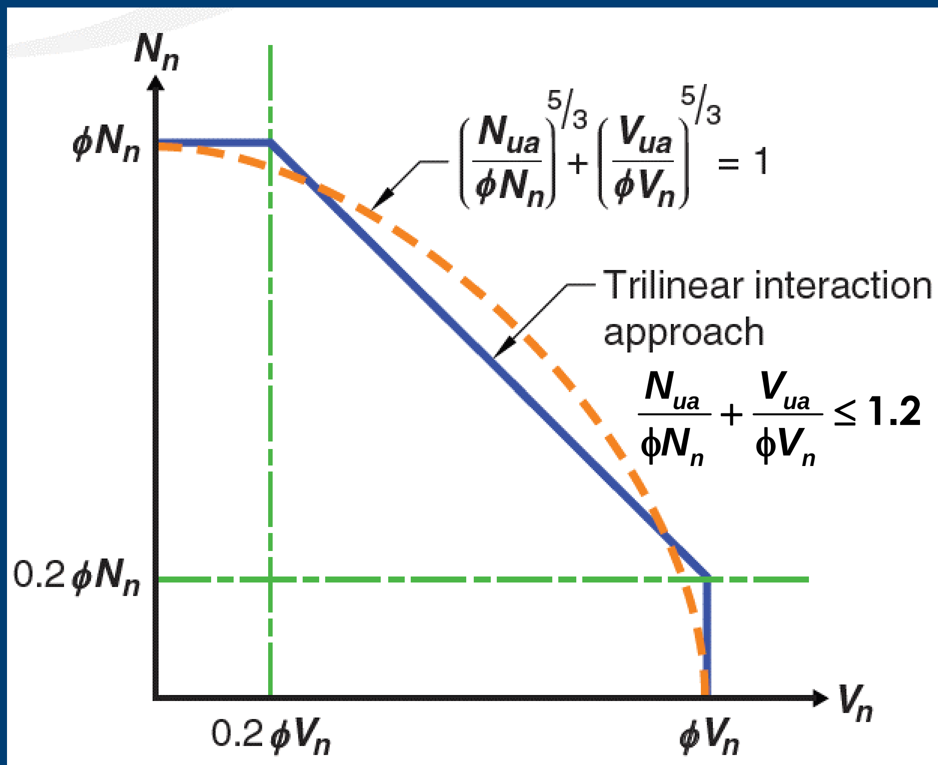
Concrete Pryout – Shear



Questions

Code Design Provisions - N-V interaction
ACI 318 -19 Section 17.8

17.8 – Tension / Shear Interaction



17.8 – Tension / Shear Interaction

- The values used in the denominator of the interaction equation are the required strengths determined in 17.5.2 or 17.10 (seismic)

Table 17.5.2—Design strength requirements of anchors

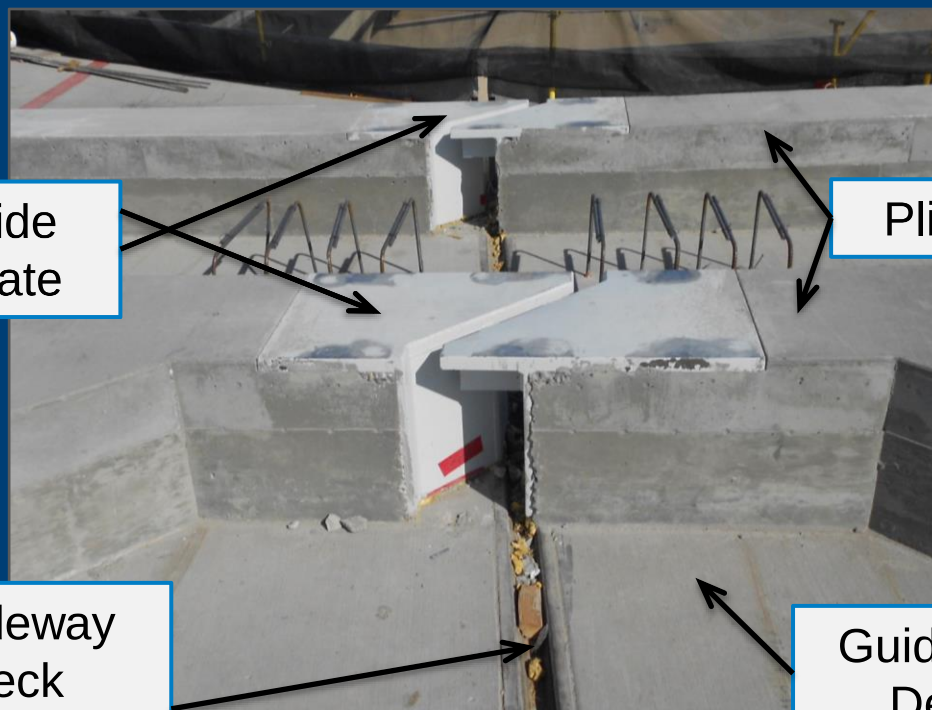
Failure mode	Single anchor	Anchor group[1]	
		Individual anchor in a group	Anchors as a group
Steel strength in tension (17.6.1)[2]	$\phi N_{sa} \geq N_{ua}$	$\phi N_{sa} \geq N_{ua,i}$	
Concrete breakout strength in tension[3] (17.6.2)	$\phi N_{cb} \geq N_{ua}$		$\phi N_{cbg} \geq N_{ua,g}$
Pullout strength in tension (17.6.3)	$\phi N_{pn} \geq N_{ua}$	$\phi N_{pn} \geq N_{ua,i}$	
Concrete side-face blowout strength in tension (17.6.4)	$\phi N_{sb} \geq N_{ua}$		$\phi N_{sbg} \geq N_{ua,g}$
Bond strength of adhesive anchor in tension (17.6.5)	$\phi N_{a} \geq N_{ua}$		$\phi N_{ag} \geq N_{ua,g}$
Steel strength in shear (17.7.1)	$\phi V_{sa} \geq V_{ua}$	$\phi V_{sa} \geq V_{ua,i}$	
Concrete breakout strength in shear[3] (17.7.2)	$\phi V_{cb} \geq V_{ua}$		$\phi V_{cbg} \geq V_{ua,g}$
Concrete pryout strength in shear (17.7.3)	$\phi V_{cp} \geq V_{ua}$		$\phi V_{cpg} \geq V_{ua,g}$

17.8 – Tension / Shear Interaction

What happens if anchor reinforcement is used?

The code implies that if you design *anchor reinforcement* for either tension or shear, or both, the interaction equation does not have to be checked

Ride Plate

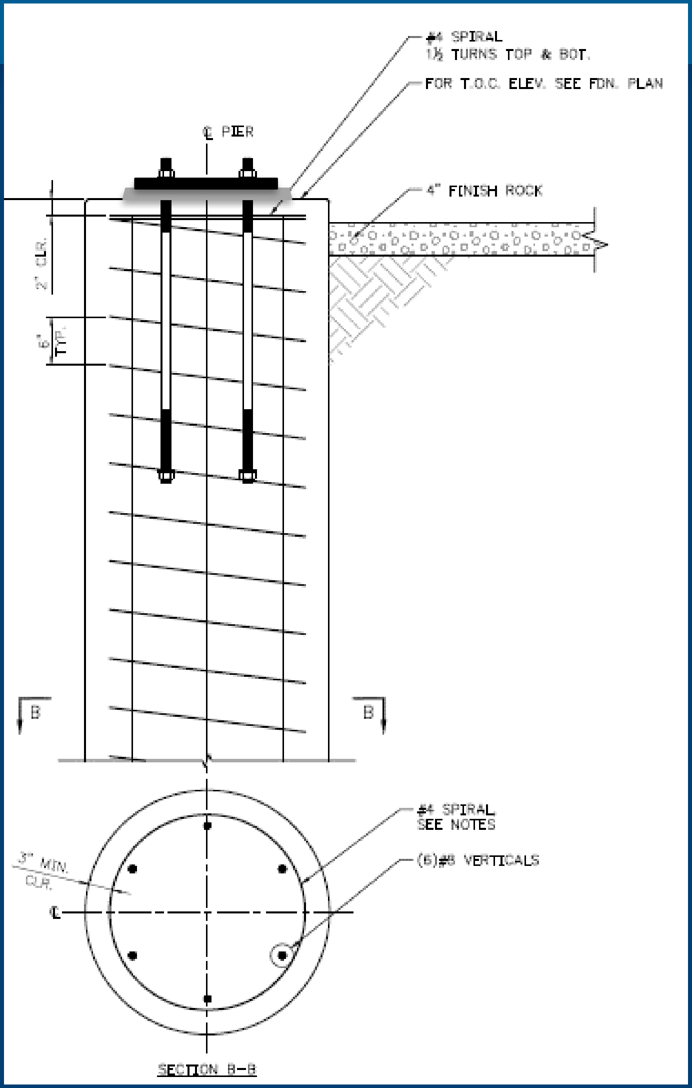

Ride Plate
Plinth
Guideway Deck Expansion Joint
Guideway Deck

Ride Plate Failure – Analysis

- Analysis found for Design Demand-Capacity Ratio (DCR):
  - DCR = 2.0 for shear only
  - DCR = 2.2 for combined shear and tension
- Review of original design calculations found:
  - Overturning moment assumed to be resisted entirely by HSA in tension
  - Controlling failure mode assumed to be tension pullout
  - Concrete breakout strength in tension not checked
  - Shear demand on HSA not considered
  - Concrete breakout strength in shear not checked

Shear-Tension Interaction Example

- NWC foundation with f_c' = 4500 psi supports a steel post, with 1'-2" x 1'-2" x 1.0" thick A36 steel plate.
- Steel plate is attached to pedestal w/ (4) 3/4 in. ASTM F1554 GR. 55 cast-in bolts with heavy hex nuts.
- Anchors are spaced at s = 10 in. on center in each direction



Shear-Tension Interaction Example

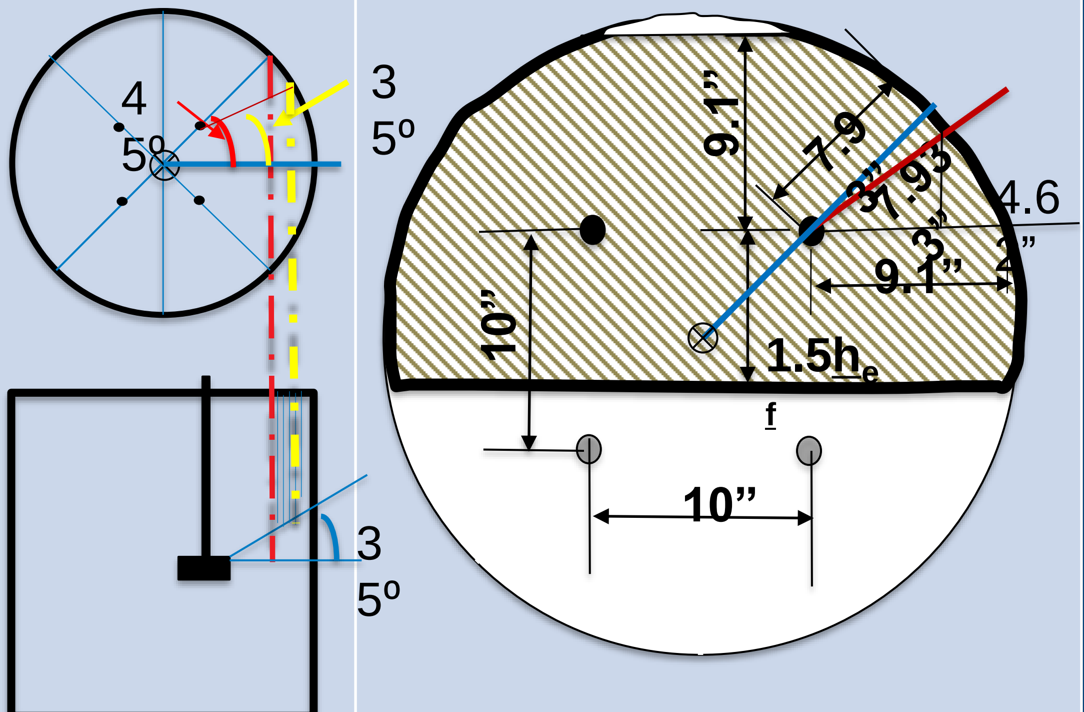
Step 3: Design tensile and shear strength requirements		
17.5.2	The anchor design strengths must satisfy the following inequalities: $N_{ua,g} \leq \begin{cases} \phi N_{sa} \text{(steel strength in tension)} \\ \phi N_{cbg} \text{(concrete breakout)} \\ \phi N_{pn} \text{(anchor pullout)} \\ \phi N_{sb} \text{(side-face blowout)} \end{cases}$ and $V_{ua,g} \leq \begin{cases} \phi V_{sa} \text{(steel strength in shear)} \\ \phi V_{cbg} \text{(concrete breakout)} \\ \phi V_{cpg} \text{(anchor pryout)} \end{cases}$ $\frac{N_{ua,g}}{\phi N_n} + \frac{V_{ua,g}}{\phi V_n} \leq 1.2$	N_{ua} = 9115 lb/bolt; $N_{ua,g}$ = 18,230 lb $V_{ua,g}$ = 1530 lb

Shear-Tension Interaction Example

Step 6: Concrete breakout

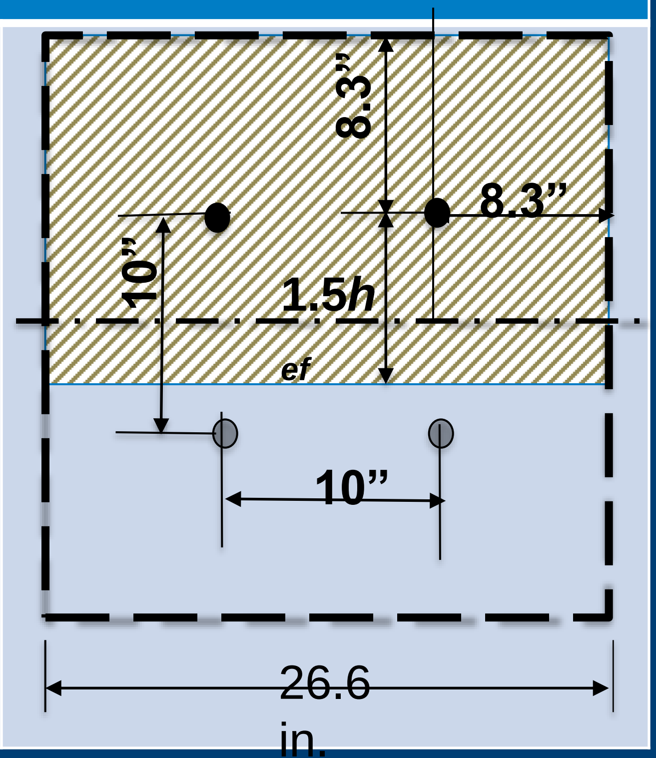
c_{a1} = 9.1 in.

c_{a2} = 9.1 in.



Shear-Tension Interaction Example

Step 6: Concrete breakout	
13.2.7.3	Circular or regular polygon-shaped concrete Columns or pedestals shall be permitted to be treated as square members of equivalent area when locating critical sections for moment, shear, and development of reinforcement. $A_{circ} = \pi r^2 = \pi\ (15\ \text{in.})^2 = 707\ \text{in.}^2$ Equivalent square area: $a = b = \sqrt{709} = 26.6$ in. $c_{a1} = c_{a2} = 8.3$ in.



Shear-Tension Interaction Example

Step 6: Concrete breakout

17.6.2.1 $N_{cbg} = \frac{A_{Nc}}{A_{Nco}} \psi_{ec,N} \psi_{ed,N} \psi_{c,N} \psi_{cp,N} N_b$ (17.6.2.1b)

Spacing s = 10 in. in both directions.

17.6.2.1.2 The projected tension breakout prism terminates below the top surface of the pedestal. h_{ef} = 15", $1.5h_{ef}$ >> **8.3**" Accordingly, the failure plane is the entire pedestal cross section. Therefore, effective embedment depth used in calculations is limited to the larger of:

$$h'_{ef} \text{ (Fig. 2)} \begin{cases} \dfrac{c_{a,max}}{1.5} \\ \dfrac{s_{max}}{3} \end{cases}$$

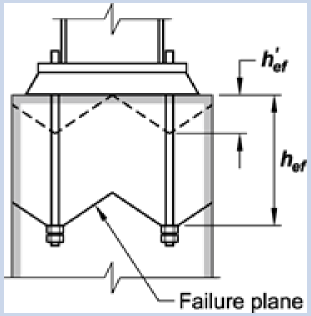


Fig. 2—Projected tension breakout of anchor group.

8.3 in./1.5 = 5.53 in. (controls)

10 in./3 = 3.33 in.

Therefore, h_{ef}' = 5.53 in.

Shear-Tension Interaction Example

Step 7: Anchor pullout		
17.5.3	The basic pullout strength is either calculated from Eq. (17.4.3.4) $N_p = (8)A_{brg} f_c'$ (17.6.3.2.2a) For a cast-in headed bolt with supplementary reinforcement: Check that design strength is greater than required strength:	From Table 1c: A_{brg} = 0.654 in.^{2} $N_p = (8)(0.654\ \text{in.}^2)(4500\ \text{psi})$ $= 23{,}544\ \text{lb/anchor}$ ϕ = 0.70 ϕN_{pn} = (0.70)(1.0)(23,544 lb) = 16,480 lb $\phi N_{pn} > \phi N_{ua,g}$ ϕN_{pn} = 16,480 lb > $\phi N_{ua,g}$ = 9115 lb **OK**

Table 1b—Hex head bolt and hex nuts with washers*

Bolt diameter d_a, in.	Gross area of bolt unthreaded A_D[†§], in.^{2}	Threaded bolt		Hex bolt or hex nut		Bearing area A_{brg}[†]
		Number of threads per in. (n)	Area A_D[†‡], in.^{2}	Width F, in.	Area A_H[†], in.^{2}	Hex head bolt or threaded rod with hex nut[†], in.^{2}
1/4	0.049	20	0.032	0.438	0.166	0.117
3/8	0.110	16	0.078	0.563	0.274	0.164
1/2	0.196	13	0.142	0.750	0.487	0.291
5/8	0.307	11	0.226	0.938	0.761	0.454
3/4	0.442	10	0.334	1.125	1.096	0.654
7/8	0.601	9	0.462	1.313	1.492	0.891
1	0.785	8	0.606	1.500	1.949	1.163
1-1/8	0.994	7	0.763	1.688	2.466	1.472
1-1/4	1.227	7	0.969	1.875	3.045	1.817
1-3/8	1.485	6	1.16	2.063	3.684	2.199
1-1/2	1.767	6	1.41	2.250	4.384	2.617
1-3/4[‖]	2.405	5	1.90	2.625	5.967[‖]	3.562[‖]
2[‖]	3.142	4-1/2	2.50	3.000	7.794[‖]	4.653[‖]

*All washers need to meet the minimum thickness requirements of ACI 318, 17.4.2.8 or the bolt/nut bearing area may conservatively be used to calculate A_{brg}.

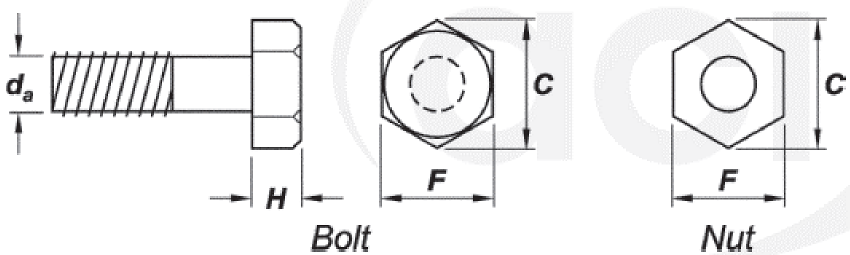
†$A_{brg} = A_H - A_D$.

‡$A_{se,N} = A_{se,V} = \pi/4(d_a - (0.9743/n))^2$, where n is the number of threads.

§$A_{se,N} = A_{se,V} = \pi/4(d_a)^2$

‖Applies to hex head bolt only.

Note: Dimensions and data taken from ANSI 18.2.1 and 18.2.2.



Shear-Tension Interaction Example

Step 8: Side-face blowout		
17.6.4 17.6.4.1	Side-face blowout failure is considered for multiple headed anchors if geometry checks (a) and (b) are true: *(a)* $h_{ef} > 2.5c_{a1}$ (b) $s < 6c_{a1}$ $N_{sb} = (160c_{a1}\sqrt{A_{brg}})\lambda_a\sqrt{f'_c}$ (17.6.4.1)	(a) 15 in. > 2.5(8.3 in.) = 20.75 in. **Not True** (b) 10 in. < 6(8.3 in.) = 50 in. **True** Therefore side-face blowout is not considered

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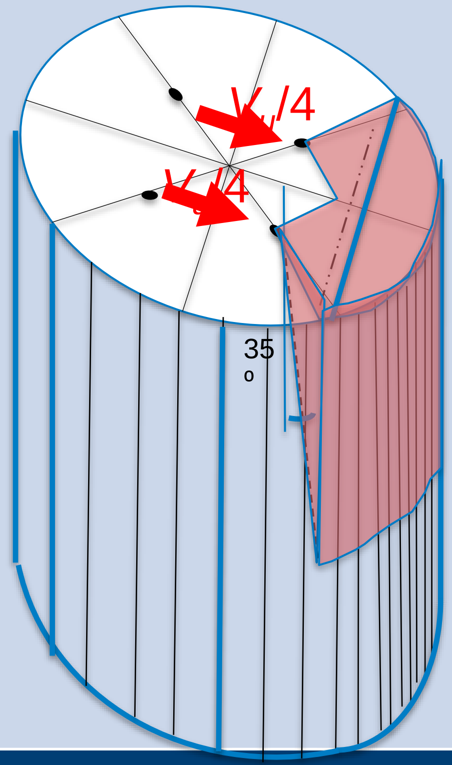
Shear-Tension Interaction Example

Step 9: Tension force summary					
ACI 318	**Failure mode**	**Design strength**	**Strength, lb**	**Ratio = $N_{ua,g}/\phi N_n$**	**Controls design?**
17.6.1	Steel strength/anchor	ϕN_{sa}	18,780	0.49	No
17.6.2	Concrete breakout with supplemental reinforcement/group	ϕN_{cbg}	25,200	**0.72**	**Yes**
17.6.3	Pullout/anchor	ϕN_{pn}	16,480	0.55	No
17.6.4	Side-face blowout	Not applicable			

Shear-Tension Interaction Example

Step 14: Case 1	
R17.7.2.1	Case 1: Two bolts close to the edge resist $V_{ua}/2$—



Shear-Tension Interaction Example

Step 13: Concrete breakout – Case 1

A shear breakout failure is assumed to initiate at points defined by the anchors' centerline and the top surface, and to propagate away from the defined points at 35 degrees both horizontally and vertically toward the edges.

Case 1: All bolts resist V_{ua} equally—

17.7.2.1

Nominal concrete breakout shear strength of the two anchors closest to the edge is:

$$V_{cbg} = \frac{A_{Vc}}{A_{Vco}} \psi_{ec,V} \psi_{ed,V} \psi_{c,V} \psi_{h,V} V_b$$

17.7.2.1

(17.7.2.1b)

A_{Vc} is the proj. shear failure area for the anchor group.

$A_{Vc} = (c_{a2} + s + c_{a2})(1.5c_{a1})$

c_{a1} = 8.3 in. c_{a2} = 8.3 in.

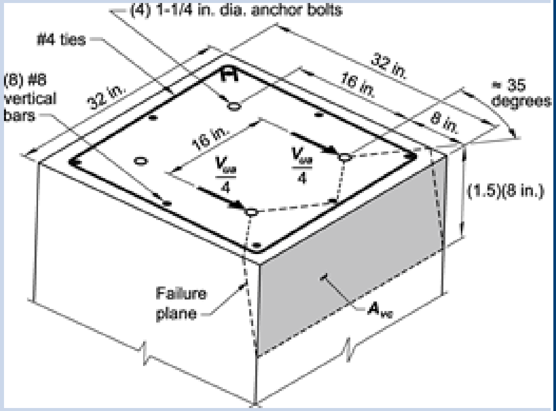


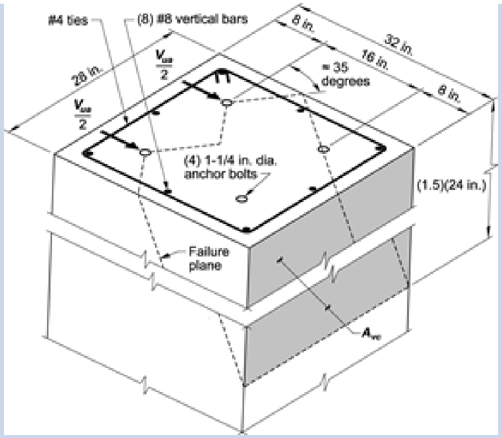
Fig. 2—Shear breakout Case 1.

Using equivalent square cross section with 26.6 in. side

A_{Vc} = (8.3 in. + 10 in. + 8.3 in.)(1.5(8.3 in.))

A_{Vc} = 331 in.^{2}

Shear-Tension Interaction Example

Step 14: Case 2		
R17.7.2.1	Case 2: Two farthest bolts from edge resist V_{ua}— By inspection, $c_{a1,back} > c_{a1,front}$, the two farthest (back) bolts from edge will result in more conservative results. There is no need to use an effective c_{a1}' in calculation because all requirements in 17.6.2.1.2 are not satisfied. Therefore, calculations will not be performed. .	 *Fig. 3—Shear breakout Case 2*

Shear-Tension Interaction Example

Step 15: Concrete pryout		
	See Step 11 for A_{Nco} and all modification factors:	$A_{Nco} = 9(5.53)^2 = 275\ \text{in.}^2$ $\psi_{ec,N} = 1.0$ $\psi_{ed,N} = 1.0$ $\psi_{c,N} = 1.0$ $\psi_{cp,N} = 1.0$
17.6.2.1	$N_{cbg} = \frac{A_{Nc}}{A_{Nco}} \psi_{ec,N} \psi_{ed,N} \psi_{c,N} \psi_{cp,N} N_b$ (17.6.2.1b) N_b = 14,506 lb (Step 11)	$N_{cbg} = \frac{441\ \text{in.}^2}{275\ \text{in.}^2}(1.0)(1.0)(1.0)(1.0)(20{,}937\ \text{lb})$ N_{cbg} = 33,575 lb V_{cpg} = (2.0)(33,575 lb) = 67,150 lb
17.5.3	Reduction factor ϕ = 0.75, cast-in anchor: Check that design strength is greater than required strength:	ϕV_{cpg} = (0.75)(67,150 lb) = 50,363 lb say 50,300 lb . ϕV_{cpg} = 50,300 lb > $V_{ua,g}$ = 1530 lb **OK**

Shear-Tension Interaction Example

Step 16: Shear strength summary						
ACI 318	**Failure mode**		**Design strength**	**Strength, lb**	**Ratio = $Vug/\phi Vn$**	**Controls design?**
17.5.1	Steel strength/anchor		ϕV_{sa}	7816	0.05	No
17.5.2	Concrete breakout/ group	Case 1	ϕV_{cbg}	12,500	0.06	No
		Case 2		18,900	0.08	**Yes**
17.5.3	Concrete Pryout/group		ϕV_{cpg}	42,500	0.04	Note 1

Note 1: The length of the anchor embedment and the supplemental reinforcement would preclude concrete pryout failure mode.

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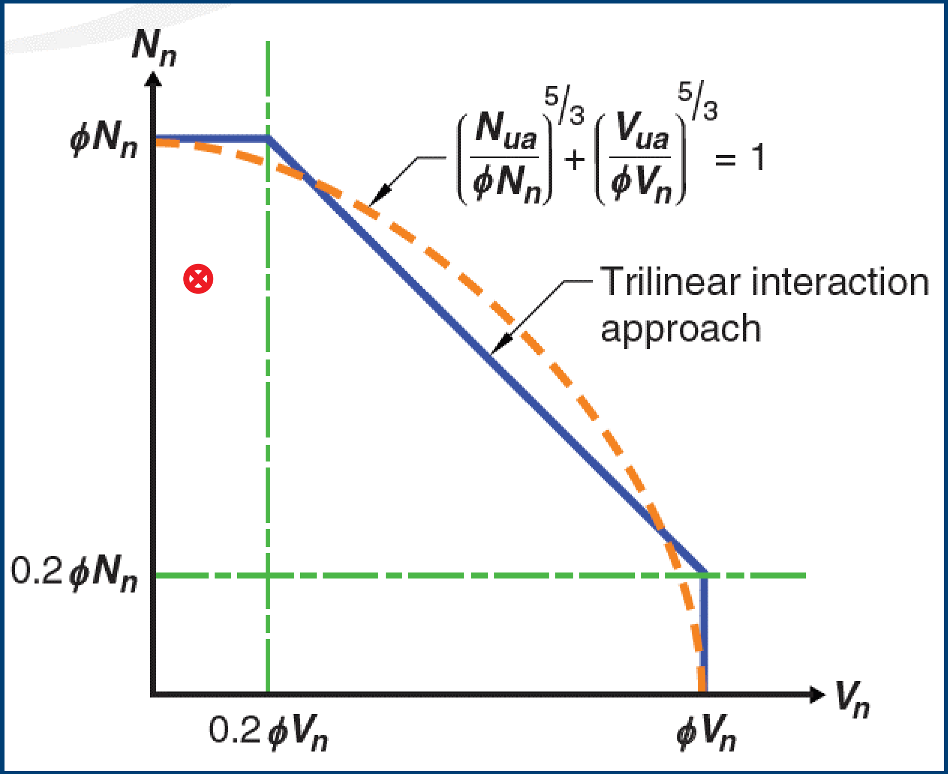
17.8 – Shear-Tension Interaction Example

Step 17: Interaction of tensile and shear forces		
17.8.2	Check if: $\frac{V_{ua}}{\phi V_n} \leq 0.2$	$\frac{1530\text{ lb}}{18{,}900\text{ lb}} = 0.08 < 0.2$
	and $\frac{N_{ua}}{\phi N_n} \leq 0.2$	Therefore, full tension design is permitted. $\frac{18{,}230\text{ lb}}{25{,}360\text{ lb}} = 0.72 > 0.2$
17.8.3	Check interaction of shear and tension: $\frac{N_{ua}}{\phi N_n} + \frac{V_{ua}}{\phi V_n} \leq 1.2$	Accordingly, shear-tension interaction calculation is not required

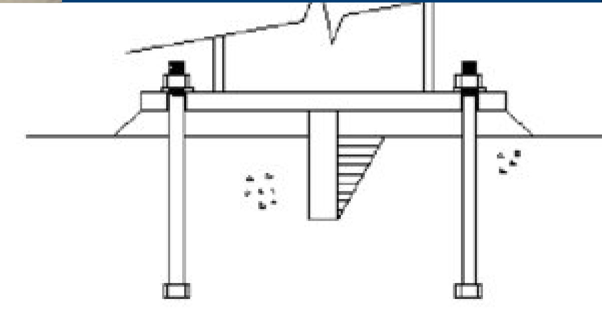
Shear-Tension Interaction Example



Shear Lugs (17.11.1)

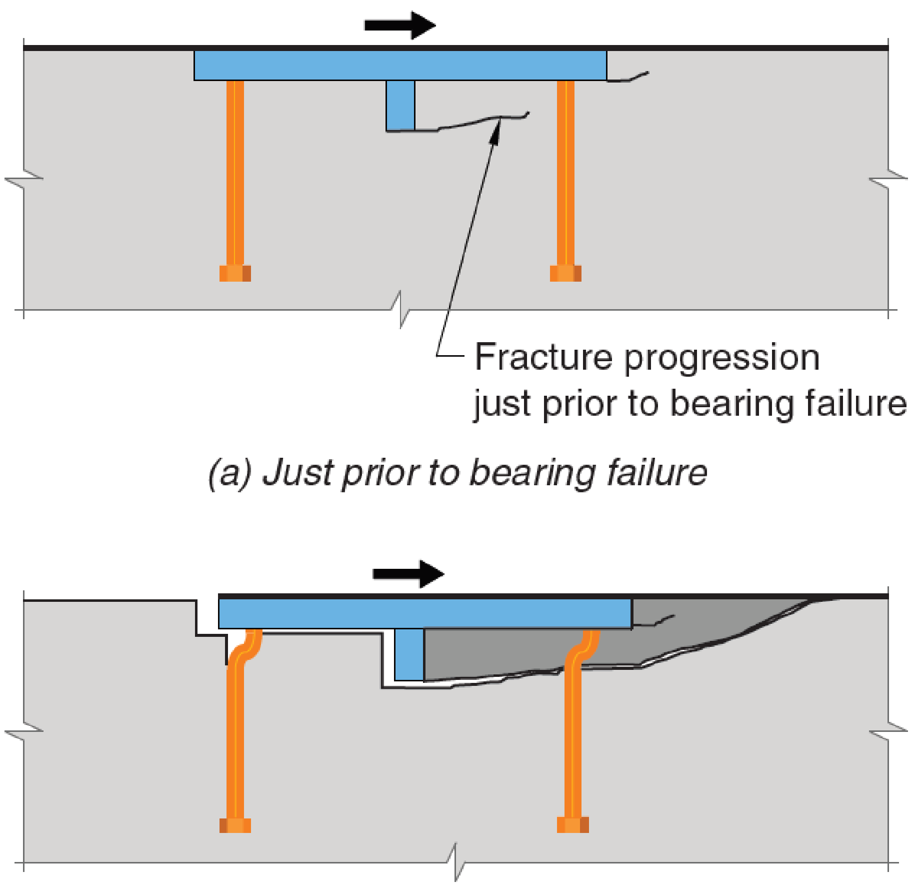
Shear lugs are fabricated from:

- Rectangular plates or
- Steel shapes composed of plate-like elements, welded to an attachment base plate



17.11.1 – Shear Lugs

- Minimum four anchors
- Anchors do not need to resist shear forces if not welded
- Anchors welded to steel plate carry portion of total shear load

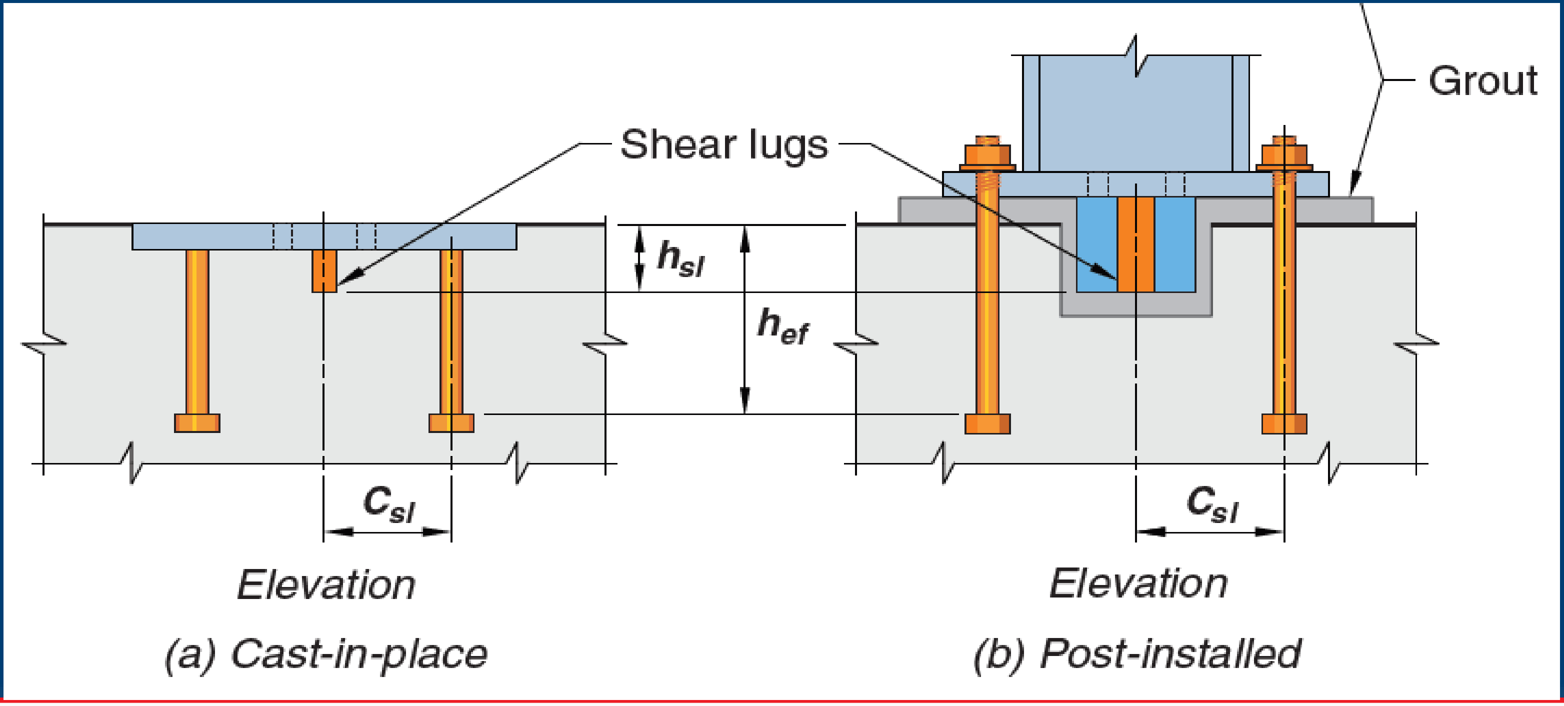


(a) Just prior to bearing failure

(b) Just prior to anchor steel failure

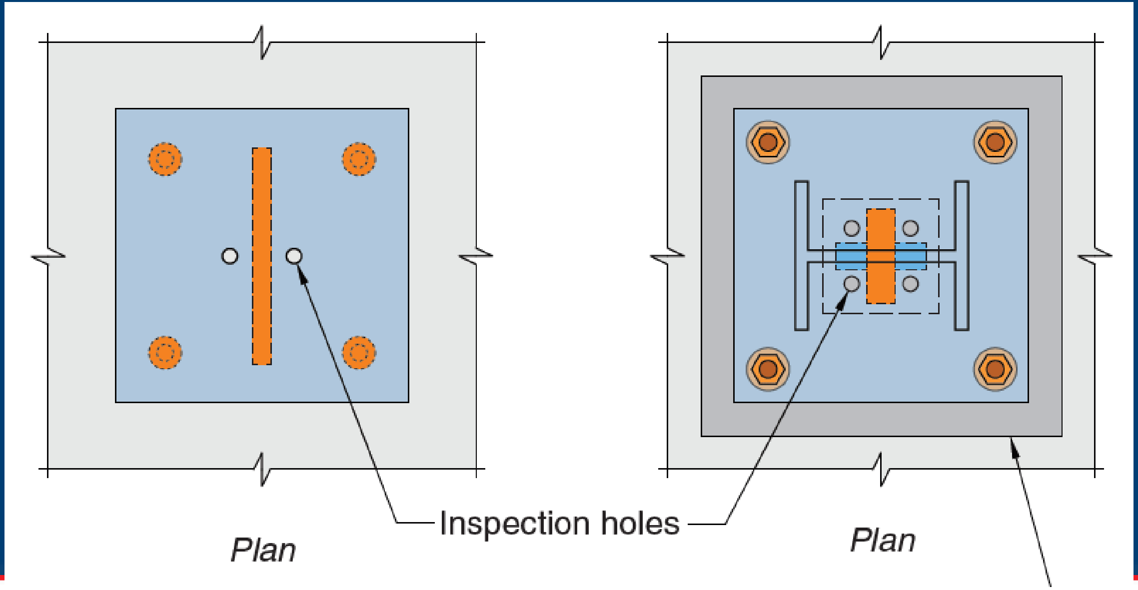
17.11.1.1.8 – Shear Lug Detailing

- Anchors in tension, satisfy both (a) and (b):
  - (a) $h_{ef}/h_{sl} \geq 2.5$
  - (b) $h_{ef}/c_{sl} \geq 2.5$

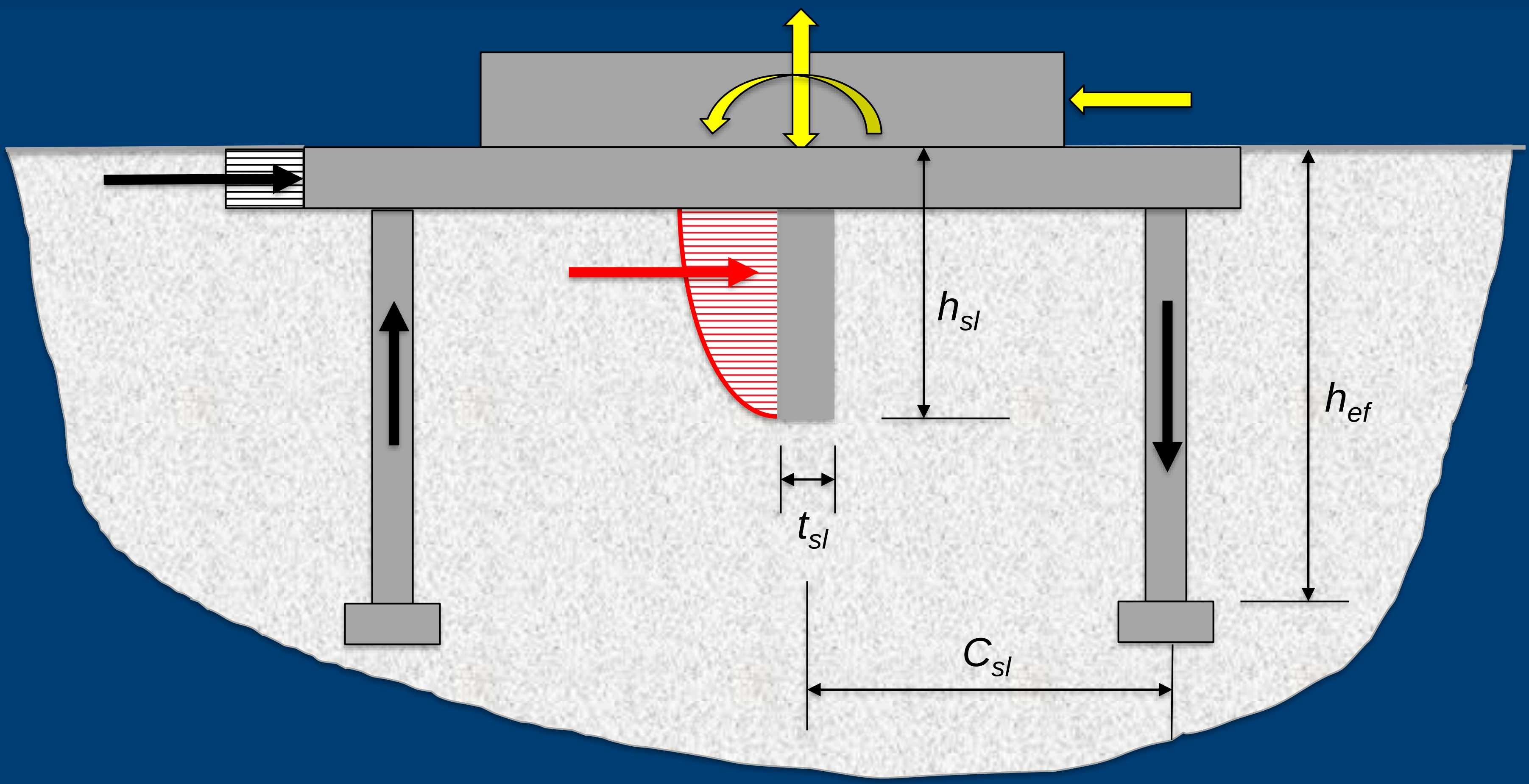


17.11.1.2 – Shear Lug Detailing

- Steel plate to have 1 in. dia. (min.) hole
- Single plate – one on each side
- Cross / cruciform plate - one each quadrant
- More vent holes are not detrimental

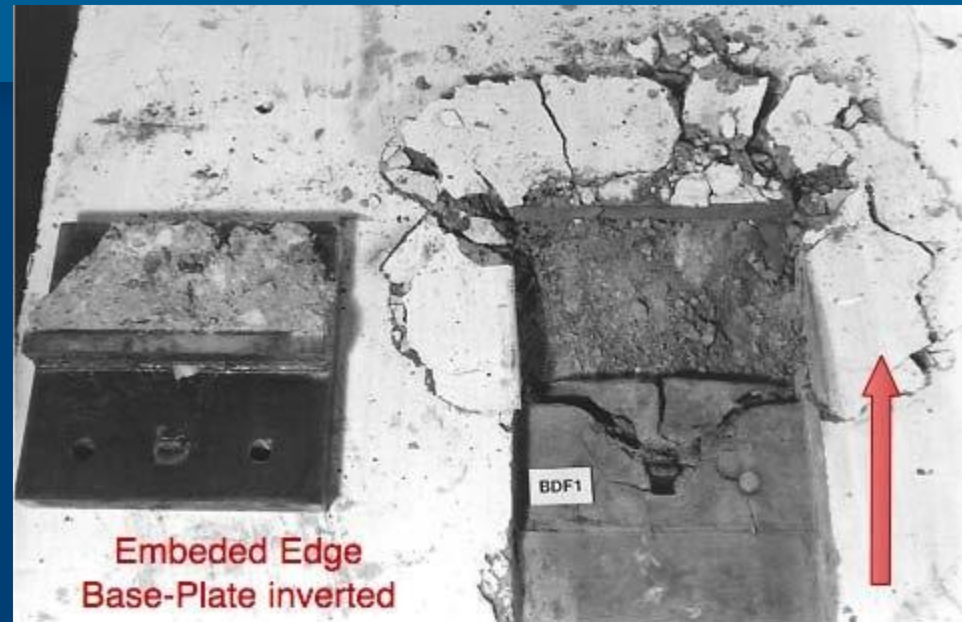


17.11.1.1.9 – Shear Lug Overturning

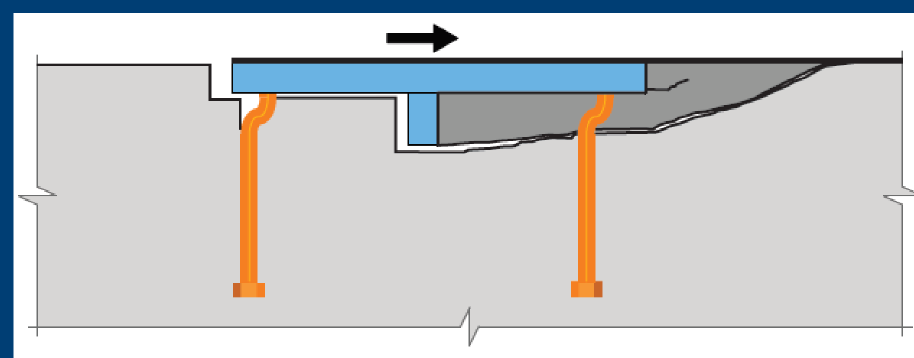


17.11.2 – Bearing

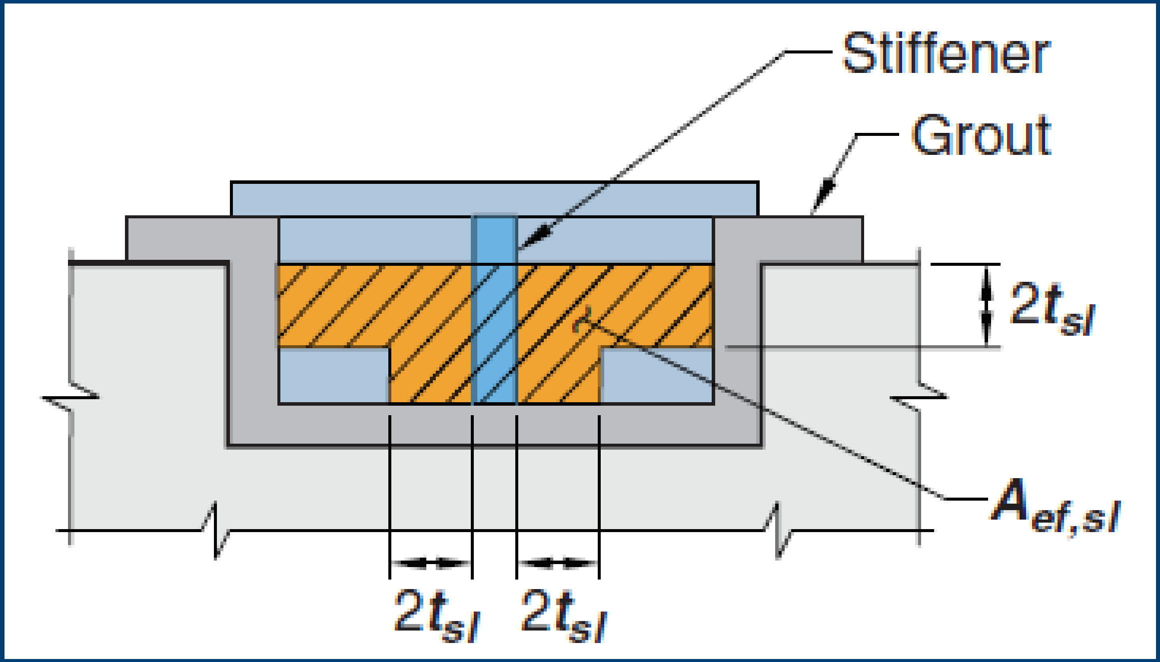
- $\phi V_{brg,sl} \geq V_u$
- Where $\phi = 0.65$



Source: Peter Carrato

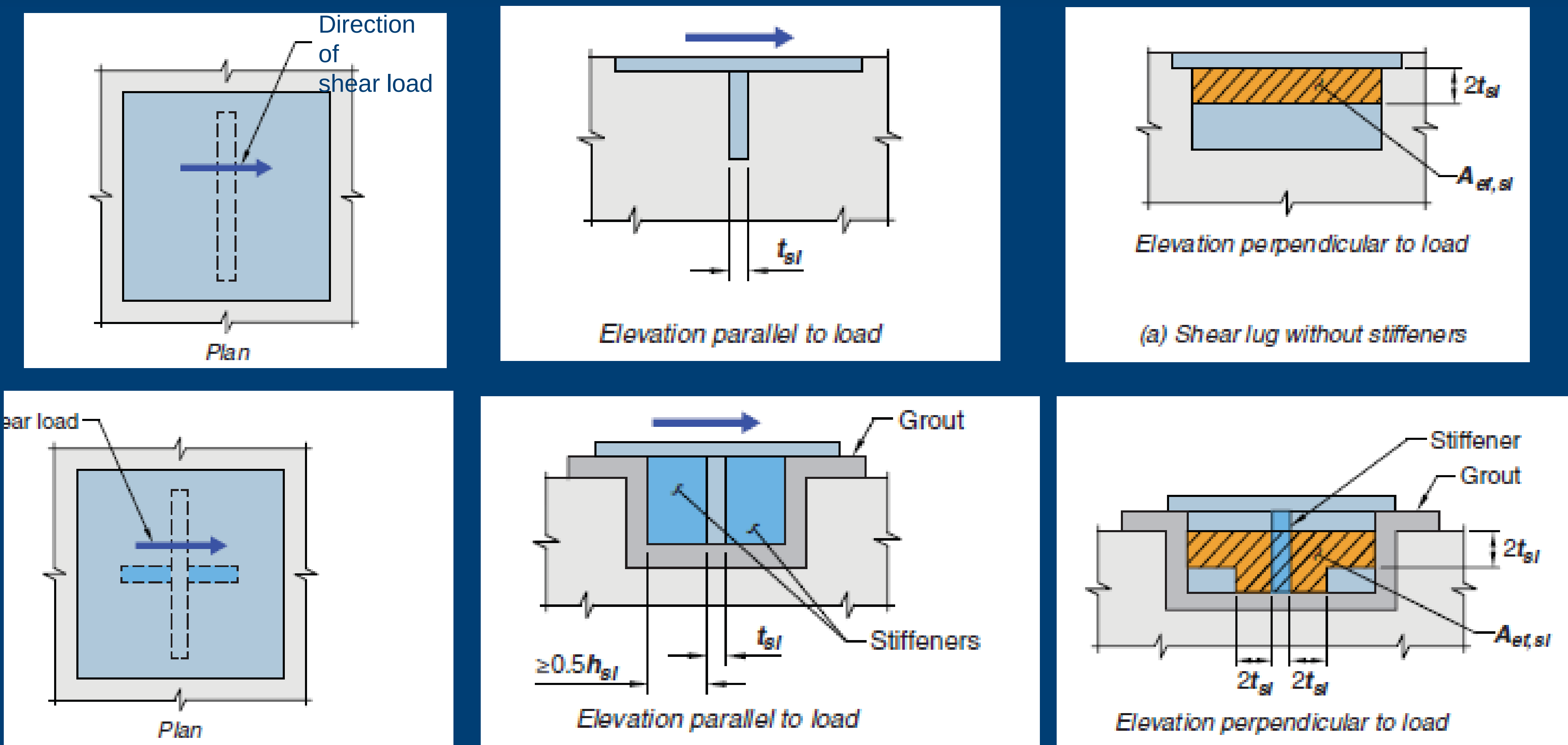


17.11.2 Bearing Strength



$$V_{brg,sl} = 1.7 f_c' A_{ef,sl} \psi_{brg,sl}$$

Bearing Area



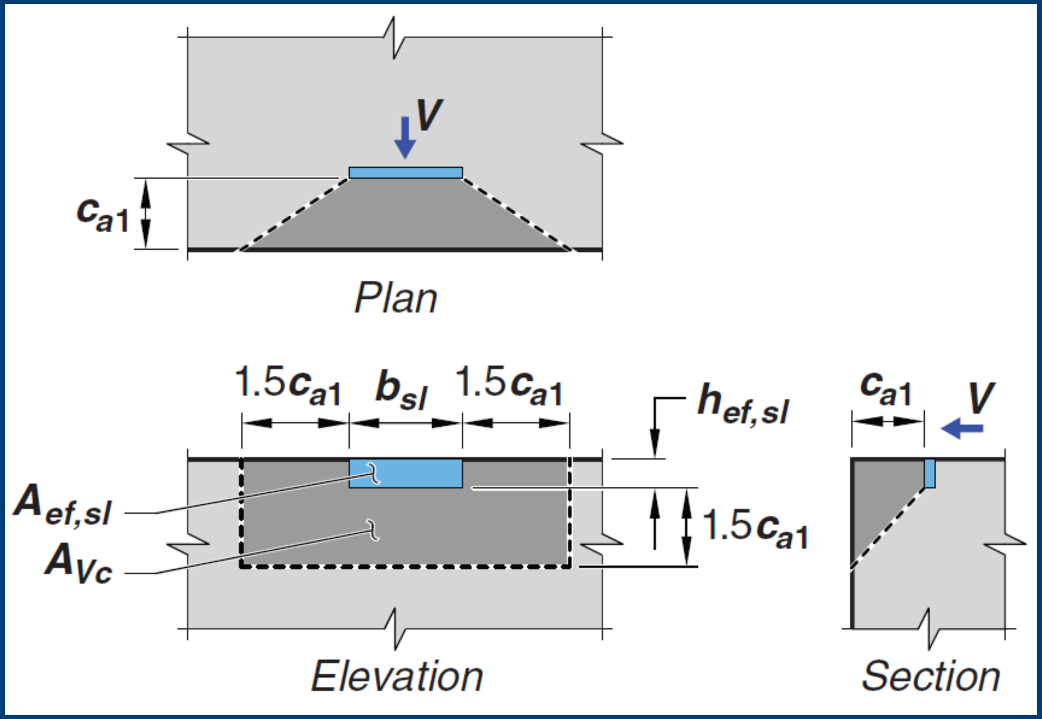
17.11.3 – Concrete breakout strength of shear lugs

- Nominal concrete breakout strength of a shear lug
  - Use Anchor provisions of 17.7.2

$$V_{cb,sl} = \frac{A_{Vc}}{A_{Vco}} \psi_{ed,V} \psi_{c,V} \psi_{h,V} V_b$$

- Where:

$$V_b = 9\lambda_a \sqrt{f_c'} (c_{a1})^{1.5}$$



Questions