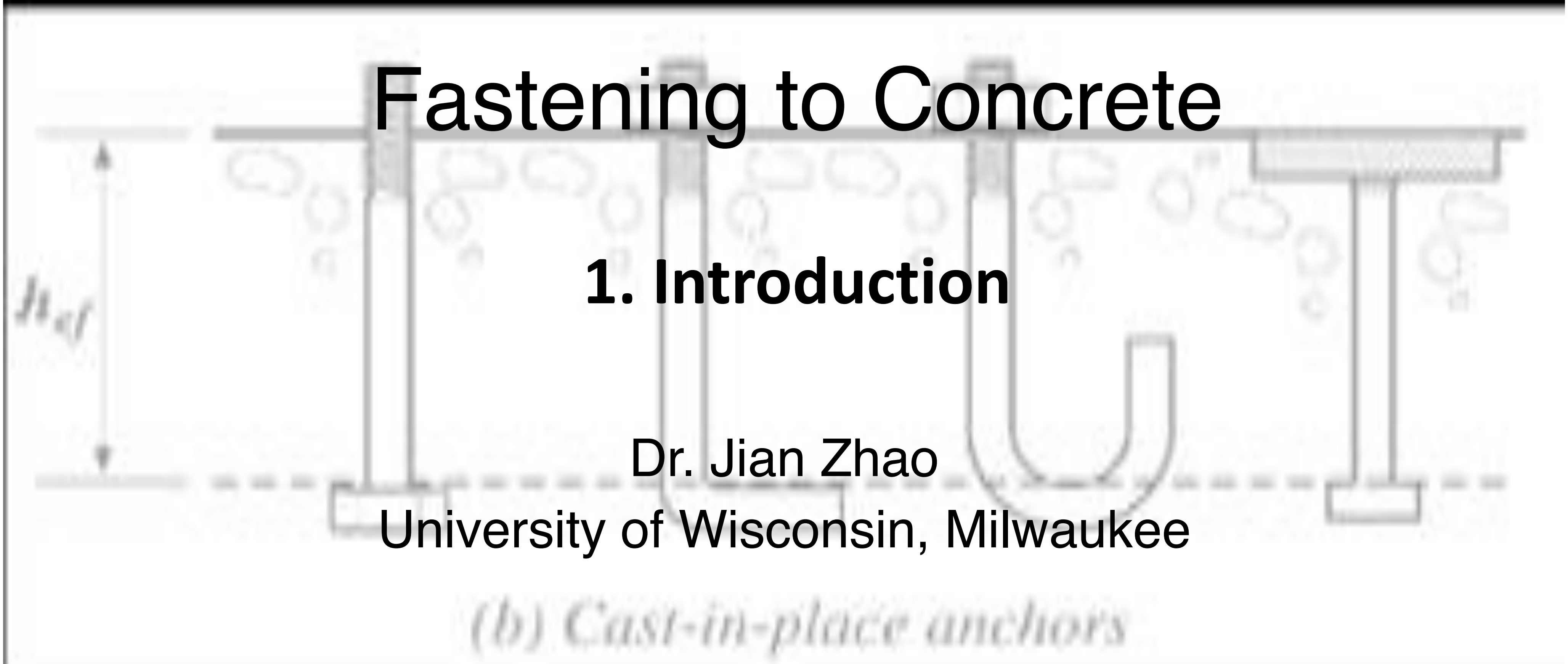


Fastening to Concrete

1. Introduction

Dr. Jian Zhao
University of Wisconsin, Milwaukee

Outlines

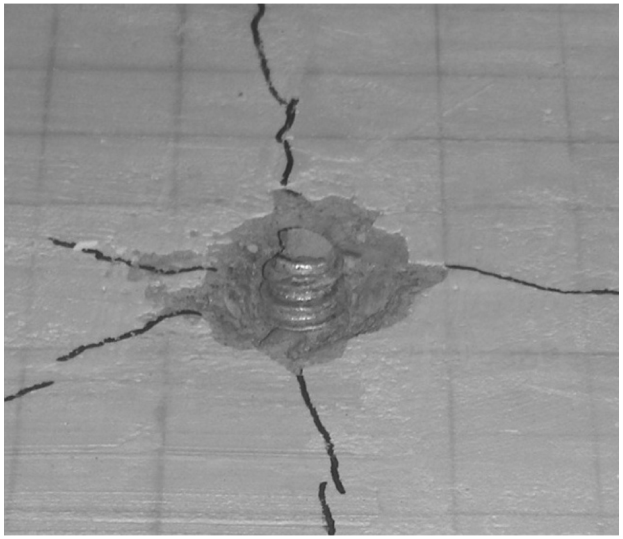
- Brief History of Anchor Design
- ACI 318-11, Appendix D
  - Design Equations
  - Phi (Φ) Factors
  - Interaction Equation
  - Seismic Provisions
  - Reinforcements to Prevent Breakout
  - Edge Distances, Thicknesses & Spacing
- Anchor Design in Seismic Zones

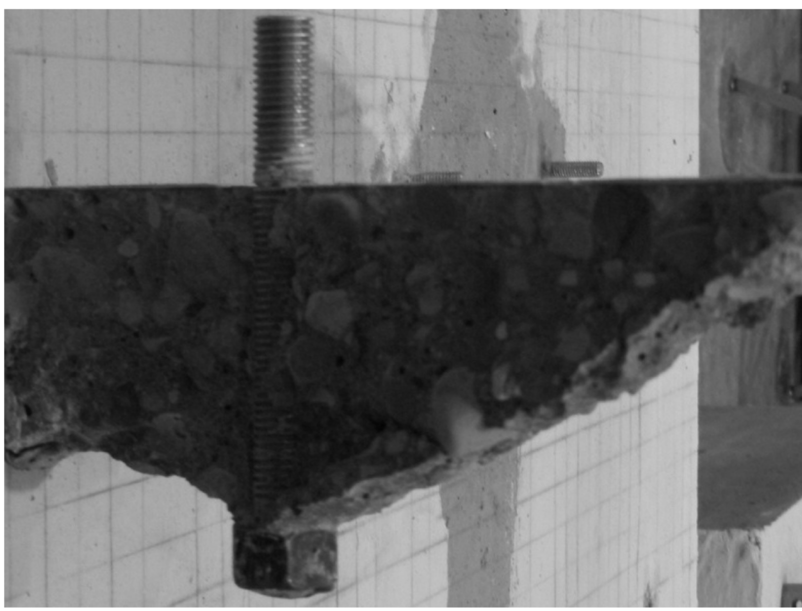
Concrete Anchors

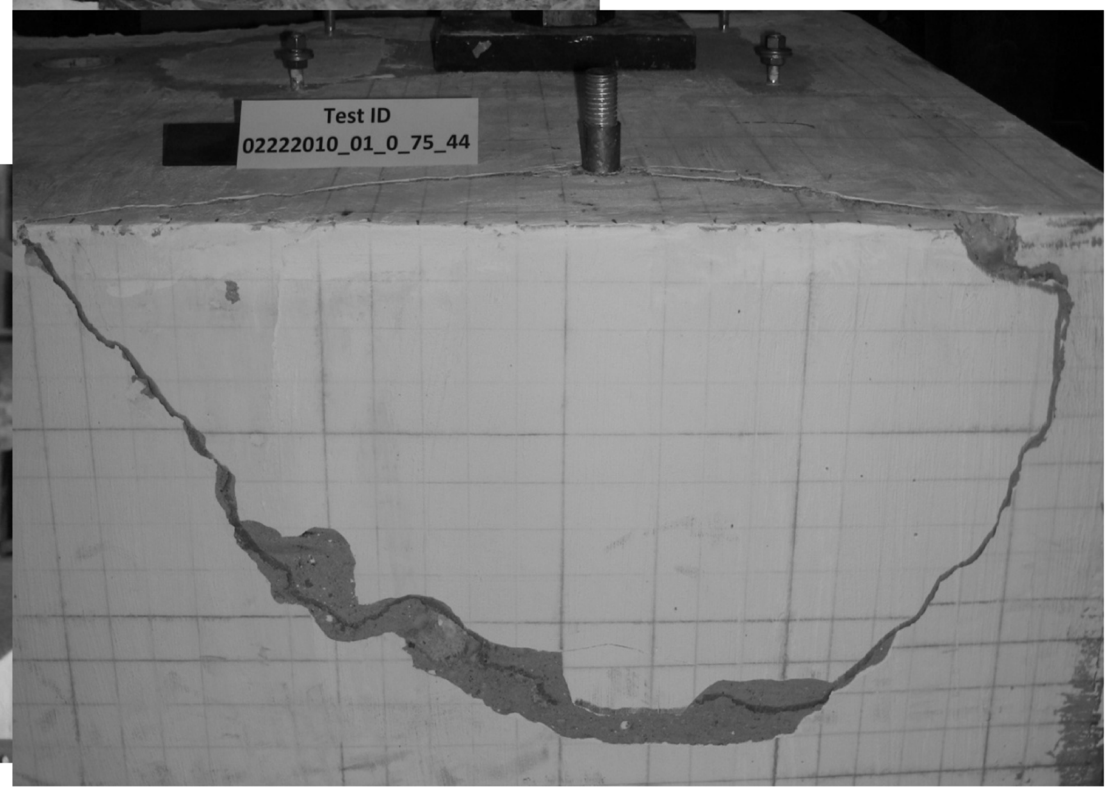





Concrete Anchor Failures







Prior to ACI 318-02

- Cast-In-Place anchors:
  - PCI / ACI 349
  - UBC / IBC codes listed <u>allowable stress</u> capacities for CIP bolts
- Design of Post-Installed anchors:
  - Individual manufacturers supplied load values based on testing
  - Values found in catalogs and ICBO/ICC reports
  - Methodology was <u>allowable stress</u> and assumed an uncracked and unreinforced section.

Since ACI 318-08

- Strength design for anchorage to concrete

$$N_{ua} \leq \Phi N_n \text{ or } V_{ua} \leq \Phi V_n$$

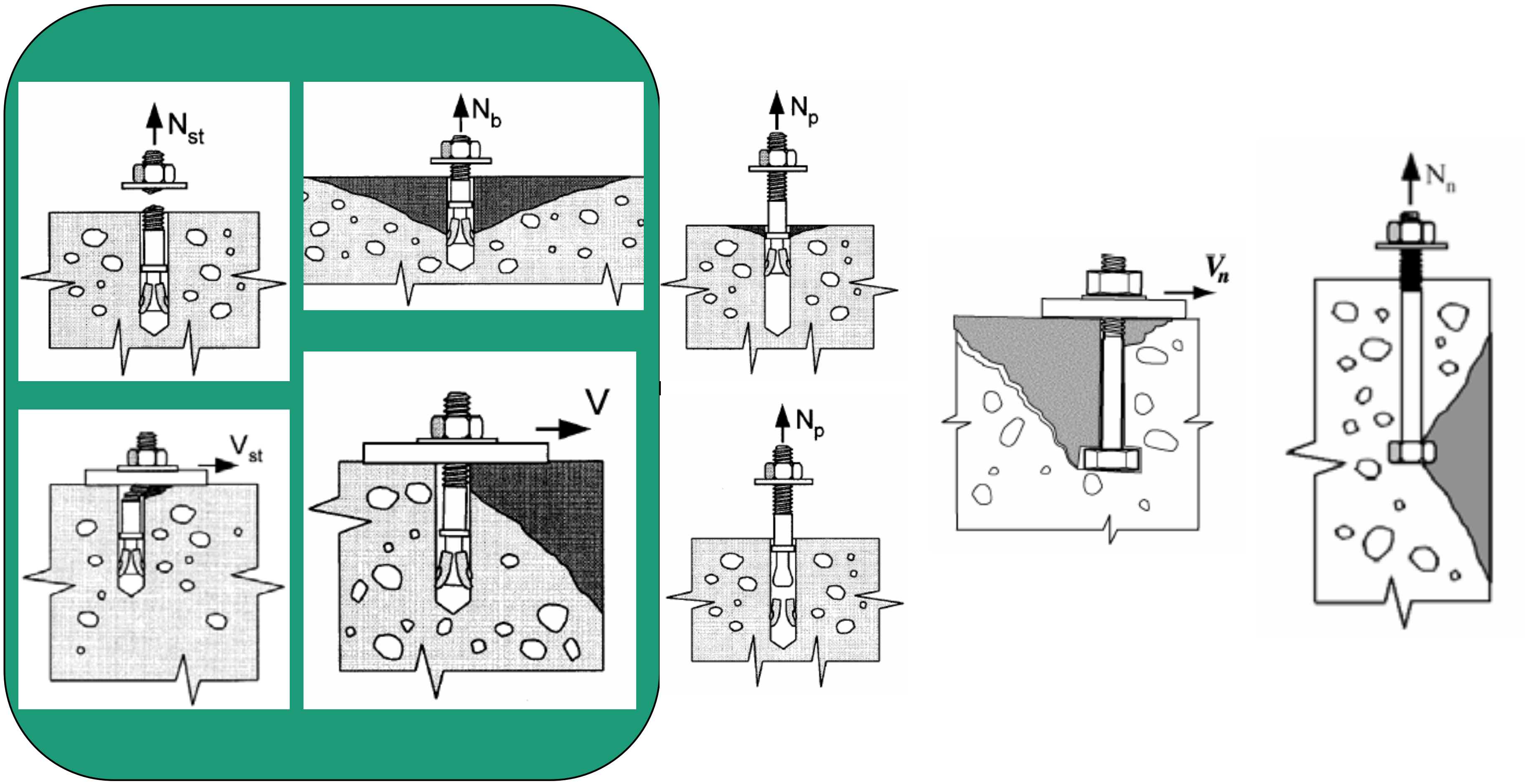
  - Cast-In-Place (CIP) anchors
  - Post-Installed (PI) anchors
    - Undercut anchors
    - Torque-controlled anchors
    - Deformation-controlled anchors
    - PI anchors must be prequalified per ACI 355.2

Design Equations & Failure Modes

Design equations check Multiple failure modes

- Steel capacity
  - Tension and Shear
- Concrete breakout capacity
  - Tension and Shear
- Pullout/Pull-through capacity
  - Tension only
- Concrete Pryout
  - Shear only
- Concrete side-face blowout
  - Tension and CIP only.

Failure Modes



Design Equations

Tension Capacities

- $N_{sa} = nA_{se,N}f_{uta}$
- $N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})N_b$
- $N_{pn} = \Psi_{c,P}N_p$
- $N_{sb} = (160c_{a1}\sqrt{A_{brg}})\lambda\sqrt{f'c}$

Shear Capacities

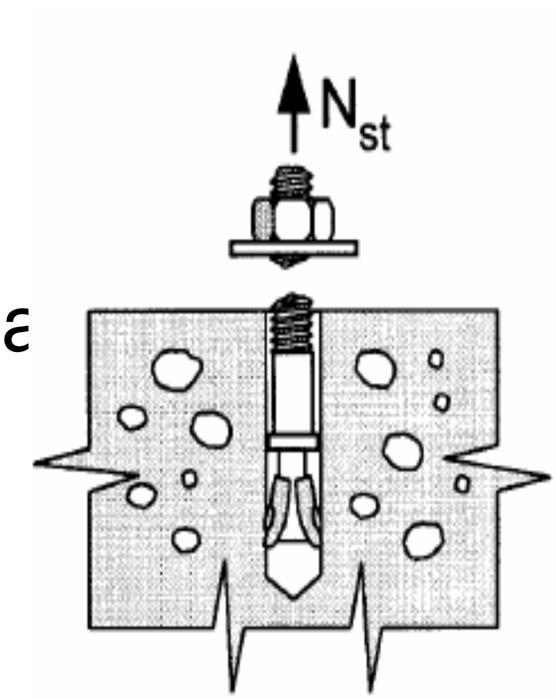
- $V_{sa} = n\ 0.6\ A_{se,V}f_{uta}$
- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$
- $V_{cpg} = k_{cp}N_{cbg}$

Steel Strength In Tension – D.5.1

$N_{sa} = nA_{se,N}f_{uta}$

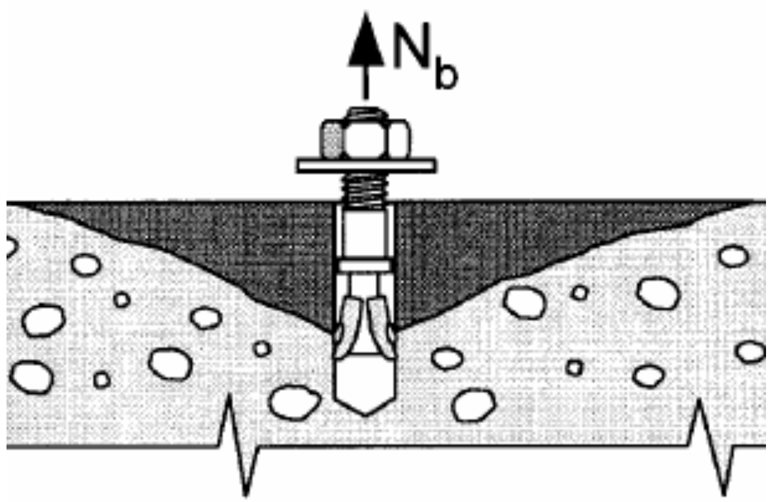
N_{sa} – Nominal tensile strength of an anchor group

- n – Number of anchors
- $A_{se,N}$ – Effective cross sectional area of anchor in tension
- f_{uta} – Specific ultimate tensile strength of anchor



Concrete Breakout In Tension – D.5.2

$$N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

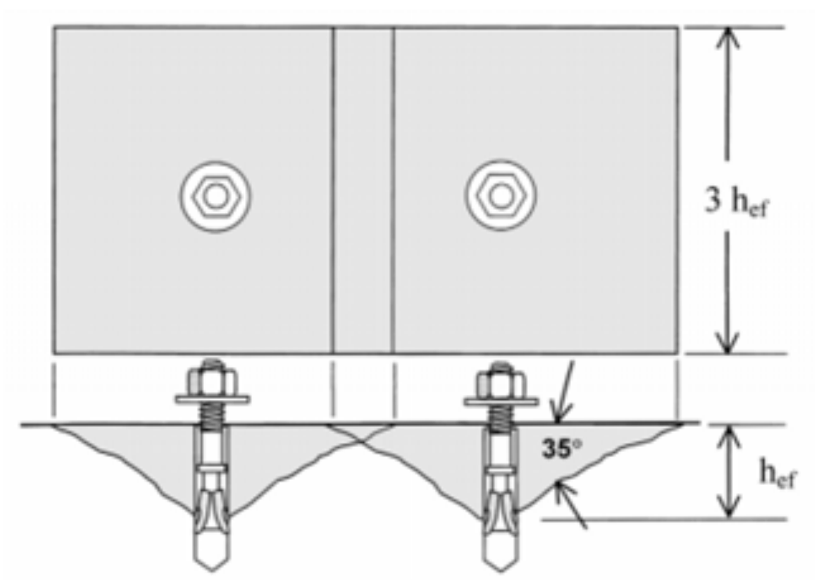


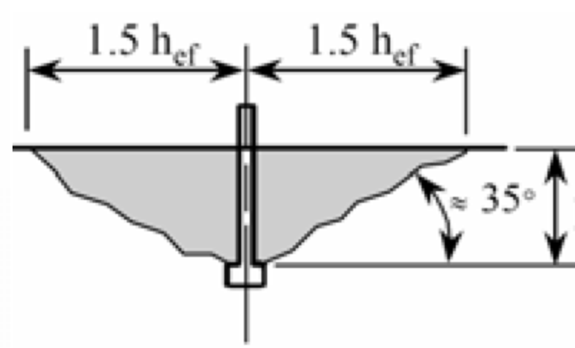
Concrete Breakout In Tension – D.5.2

$$N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

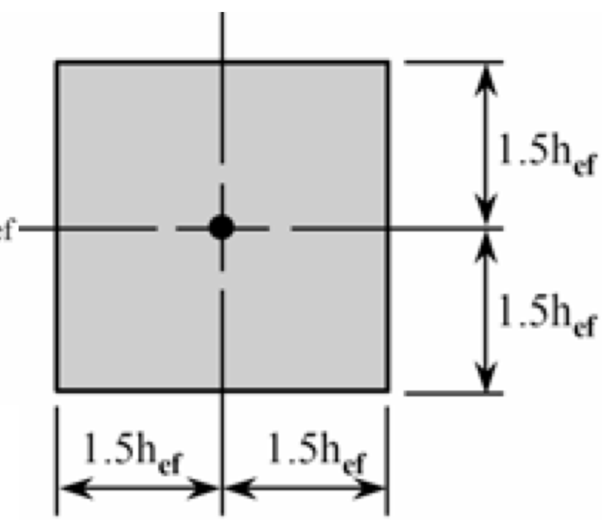
A_{Nc} = Projected failure area of group

A_{Nco} = 9h_{ef}, Projected failure area of one anchor (Eq. D-6)





Section through failure cone



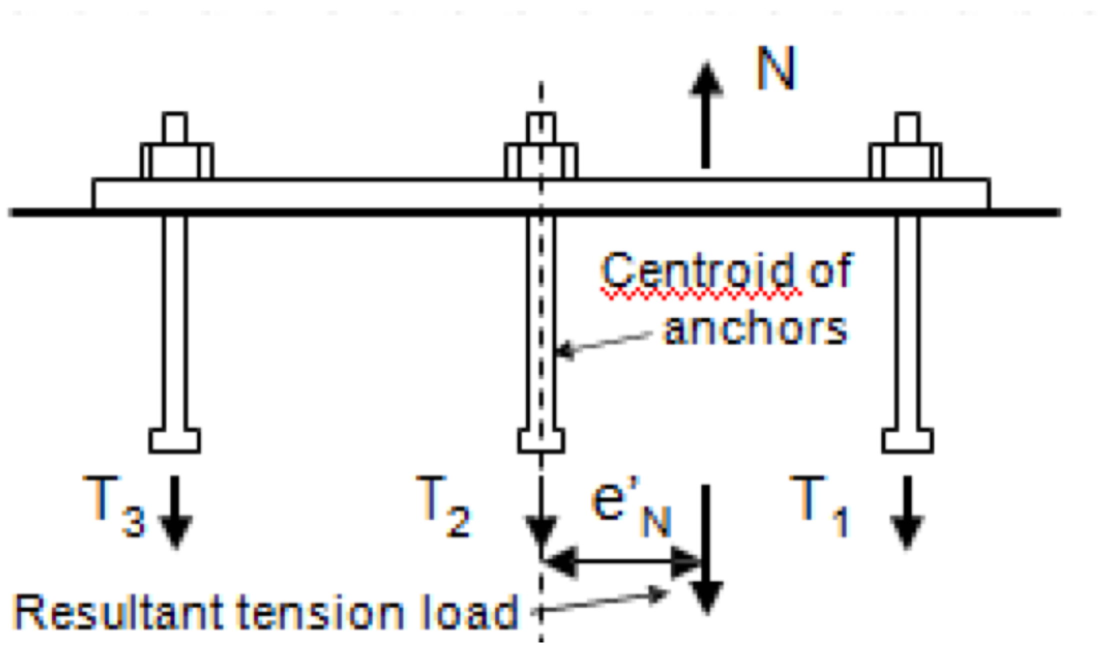
Plan view

Concrete Breakout In Tension – D.5.2

$N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$

$\Psi_{ec,N}$: Modification for eccentric load

$\Psi_{ec,N} = 1/[1+(2e'_N/3h_{ef})]$ (Eq. D-9)



Concrete Breakout In Tension – D.5.2

$$N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

$\Psi_{ed,N}$: Modification for edge effects

- If $c_{a,min} \geq 1.5h_{ef}$ then:
- Eq. D-10 $\Psi_{ed,N} = 1.0$
- If $c_{a,min} < 1.5h_{ef}$ then
- Eq. D-11 $\Psi_{ed,N} = 0.7 + 0.3(c_{a,min} / 1.5h_{ef})$

Concrete Breakout In Tension – D.5.2

$$N_{cb}=A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

- $\Psi_{c,N}$: Modification for cracking
- $\Psi_{c,N}$ =1.4 for uncracked section if kc = 17 in eq. (D-7)
- $\Psi_{c,N}$ per evaluation report (ER) if kc from ER used in eq. (D-7)
- $\Psi_{c,N}$ =1.0 for cracked section

Concrete Breakout In Tension – D.5.2

$$N_{cb} = A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

- $\Psi_{cp,N}$: Modification for Post-Installed Anchors (Uncracked concrete, No supplemental reinforcements to control splitting)
- If $c_{a,min} \geq c_{ac}$ then:

  $\Psi_{cp,N} = 1.0$ (Eq. D-12)
- If $c_{a,min} < c_{ac}$ then:

  $\Psi_{cp,N} = c_{a,min}/c_{ac}$ (Eq. D-13)

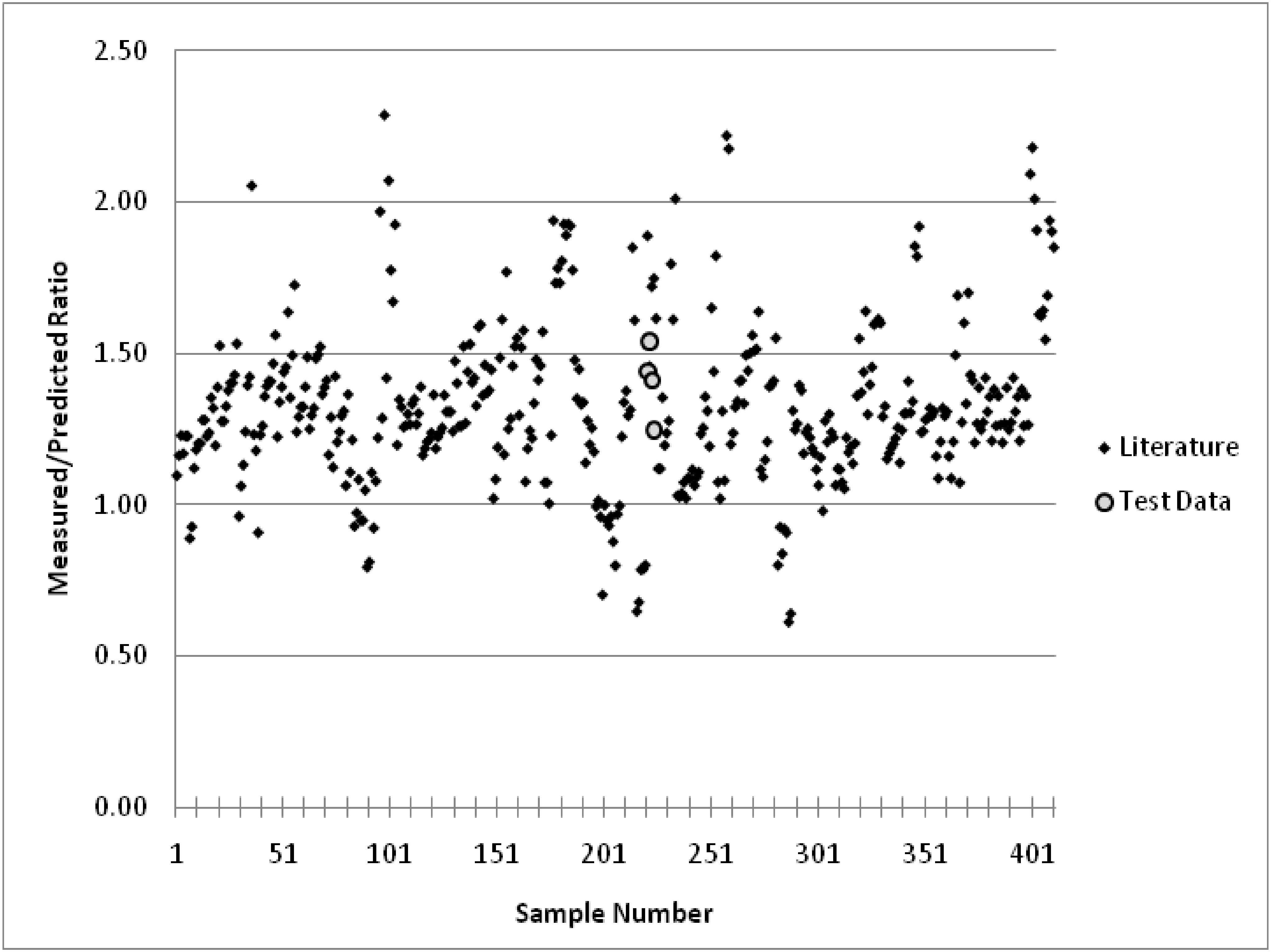
Where $c_{ac} = 2.5h_{ef}$ (undercut anchors)

$4.0h_{ef}$ (wedge anchors)

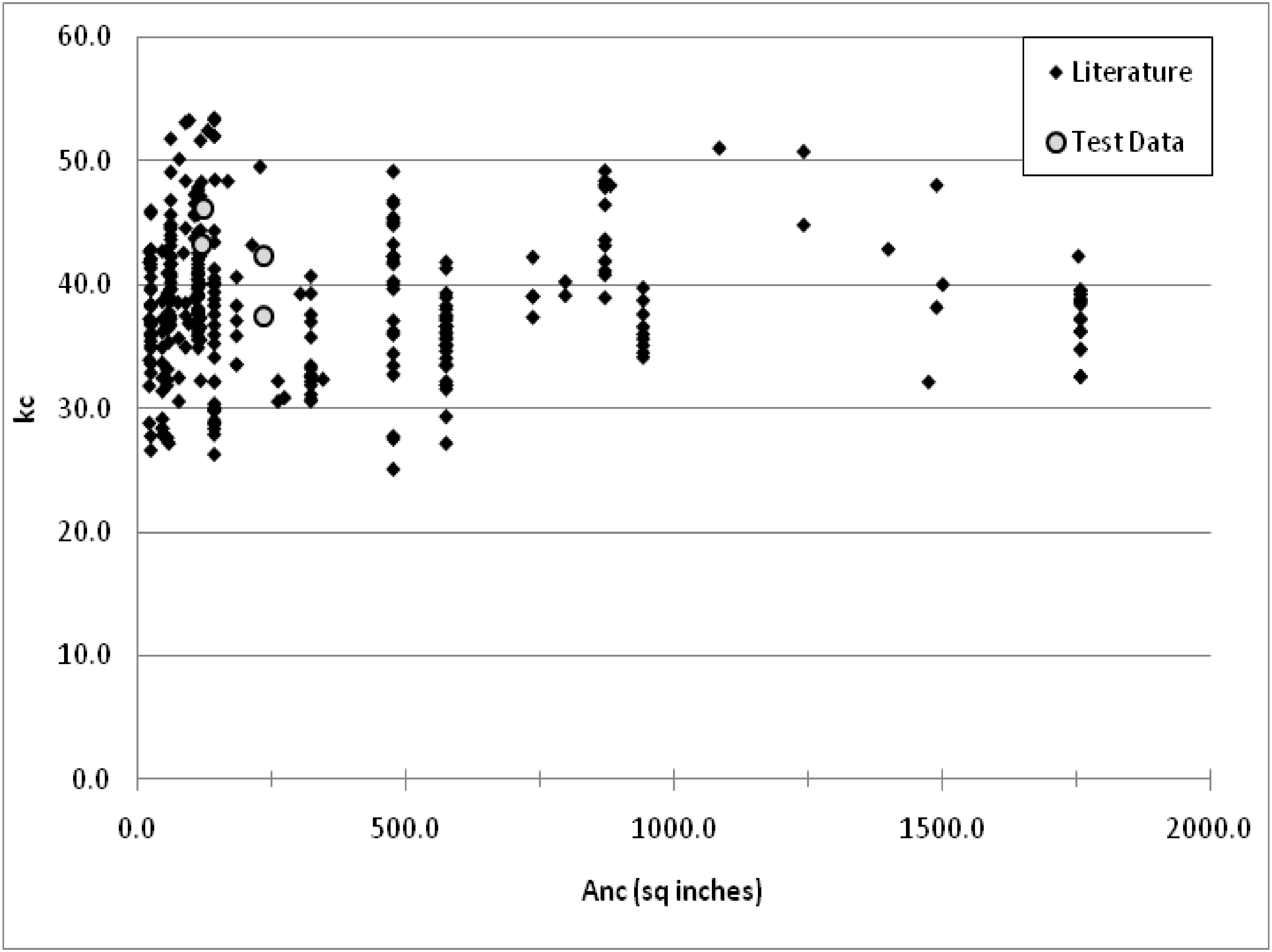
Concrete Breakout In Tension – D.5.2

$$N_{cb}=A_{Nc}/A_{Nco}(\Psi_{ec,N}\ \Psi_{ed,N}\ \Psi_{c,N}\ \Psi_{cp,N})\ N_b$$

- $N_b=k_c\ \lambda\ \sqrt{f'_c}\ h_{ef}^{1.5}$ (Basic concrete breakout strength)
- k_c – Coefficient for basic concrete breakout strength
  - Found in either App. D or per product ER
- λ – Modification factor for lightweight concrete
- $f'c$ – Concrete compressive strength
- h_{ef} – Effective embedment depth



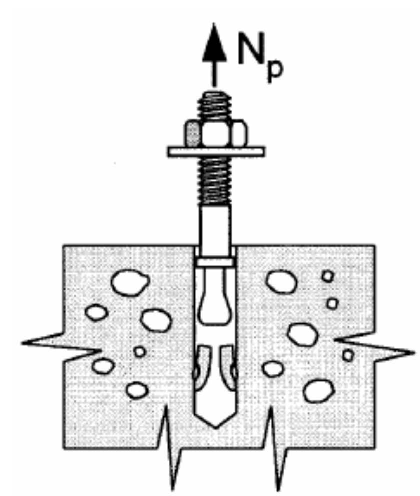
2.50
2.00
1.50
1.00
0.50
0.00
Measured/Predicted Ratio
1
51
101
151
201
251
301
351
401
Sample Number
Literature
Test Data



60.0
50.0
40.0
30.0
20.0
10.0
0.0
kc
0.0
500.0
1000.0
1500.0
2000.0
Anc (sq inches)
Literature
Test Data

Pull-out Strength – D.5.3

- $N_{pn} = \Psi_{c,P} N_p$ (Eq. D-14)
- N_{pn} – Nominal pullout strength
- $\Psi_{c,P}$ – Modification for cracking
  - 1.0 for cracked
  - 1.4 for uncracked
- N_p – Pullout strength in tension



Pull-out Strength – D.5.3

- $N_{pn} = \Psi_{c,P} N_p$ (Eq. D-14)
- N_p – Pullout strength in tension

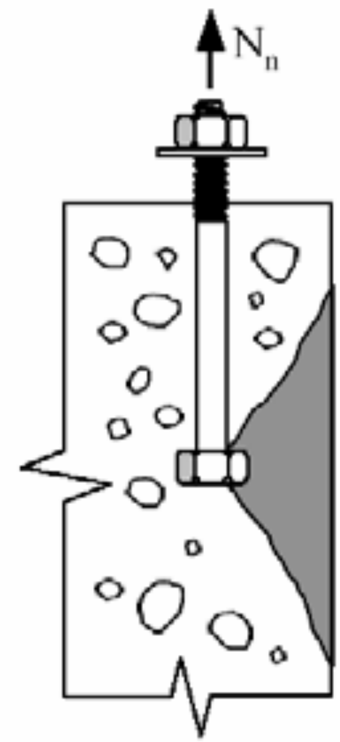
  For PI anchors N_p based on ACI 355.2 test results

  For CIP anchors, N_p based on:

  - – $N_p = 8 A_{brg} f'_c$ (Eq. D-15) headed bolts
  - – $N_p = 0.9 f'_c e_h d_a$ (Eq. D-16) hooked bolts

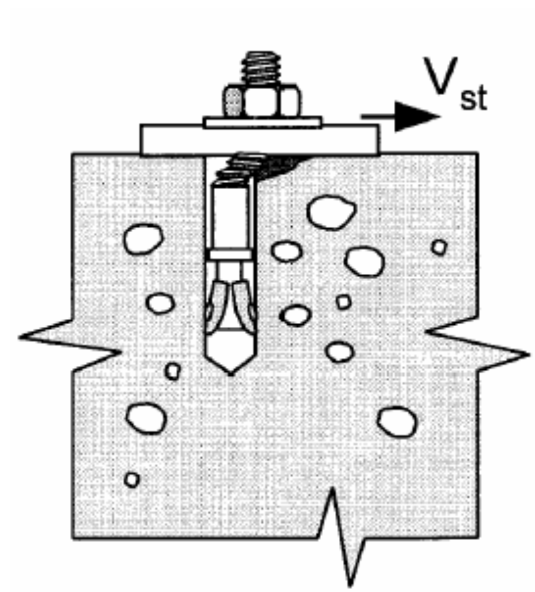
Side-Face Blowout Strength – D.5.4

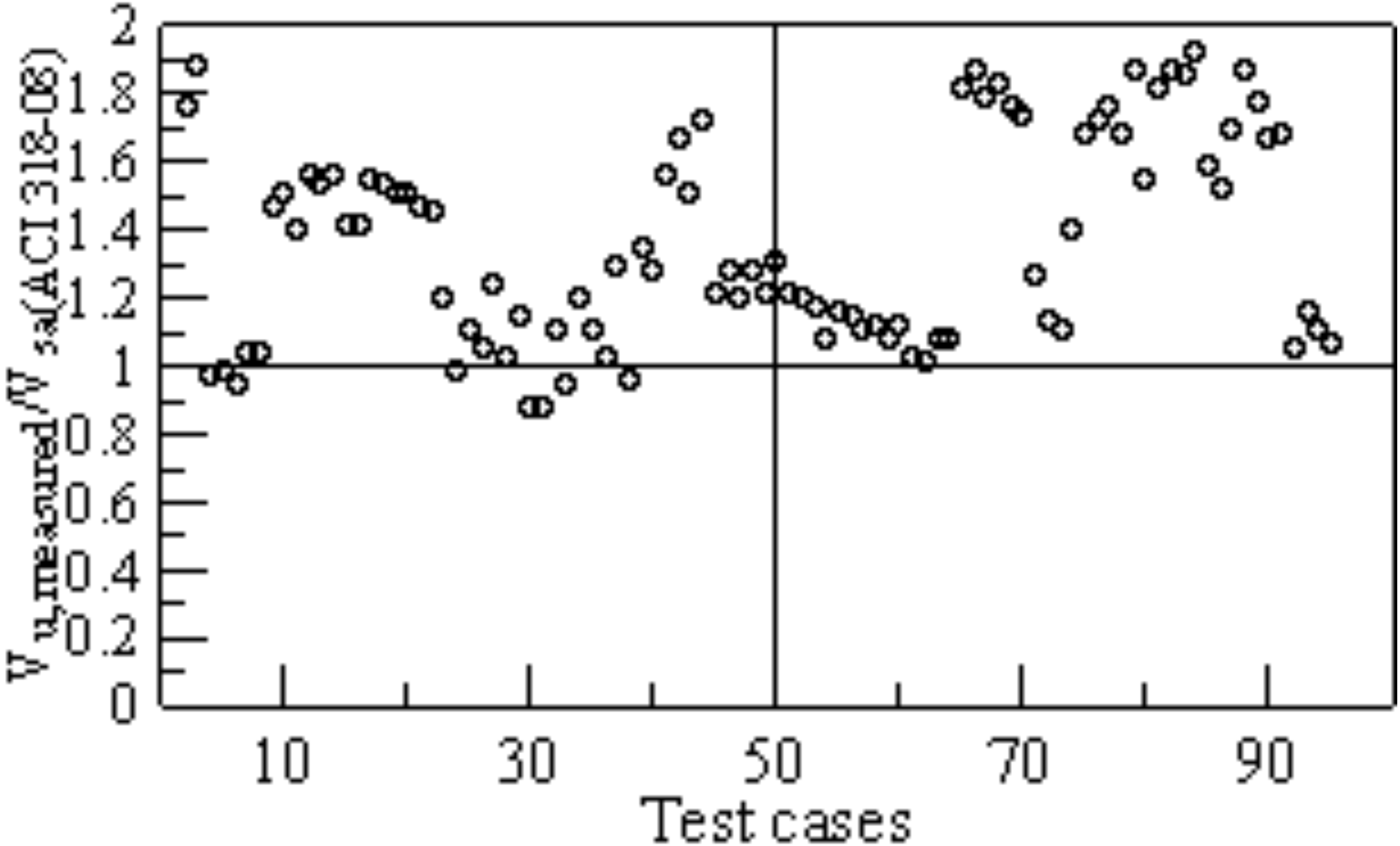
- $N_{sb} = (160c_{a1}\sqrt{A_{brg}})\lambda\sqrt{f'_c}$ (Eq. D-17)
- N_{sb} – Side-face blowout strength (headed anchors only)
- c_{a1} – edge distance
- A_{brg} – Net bearing area of the head of anchor
- λ – Modification factor for lightweight concrete



Steel Strength In Shear – D.6.1

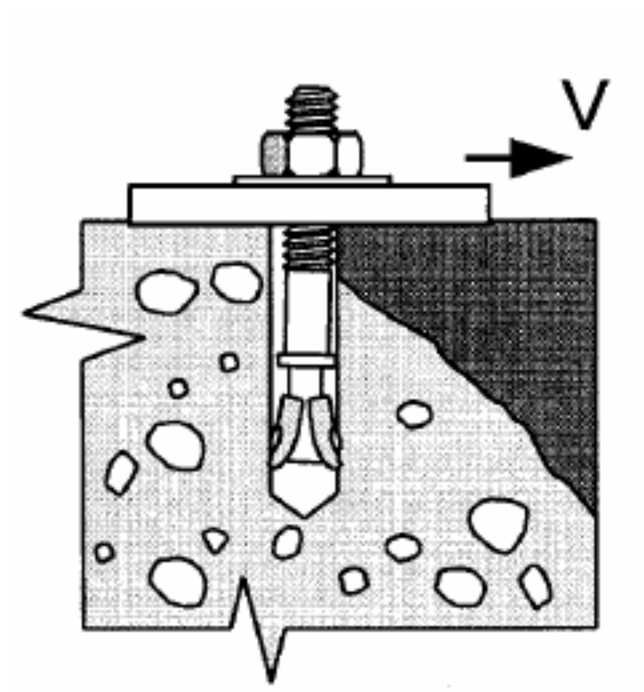
- $V_{sa} = n\, A_{se,V}\, f_{uta}$ (Eq. D-19) CIP
- $V_{sa} = n\, 0.6\, A_{se,V}\, f_{uta}$ (Eq. D-20)
- n – number of anchors
- $A_{se,V}$ – effective cross sectional area of a single anchor in shear
- f_{uta} – specified tensile strength of anchor steel




V u,measured /V sa(ACI 318-08)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10
30
50
70
90
Test cases

Concrete Breakout In Shear – D.6.2

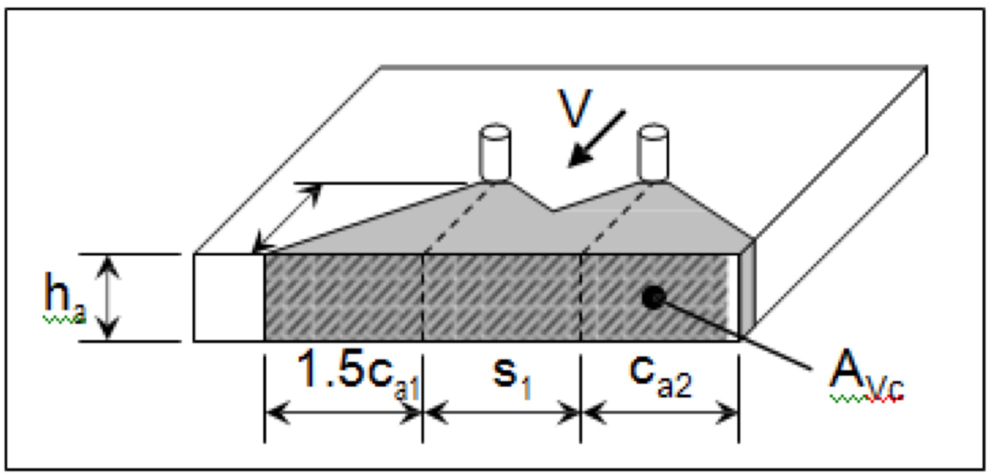
- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$
  (Eq. D-22)
- Vcbg – Concrete breakout strength in shear



Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\,\Psi_{ed,V}\,\Psi_{c,V}\,\Psi_{h,V})V_b$

  A_{Vc} – projected concrete failure area of a group of anchors

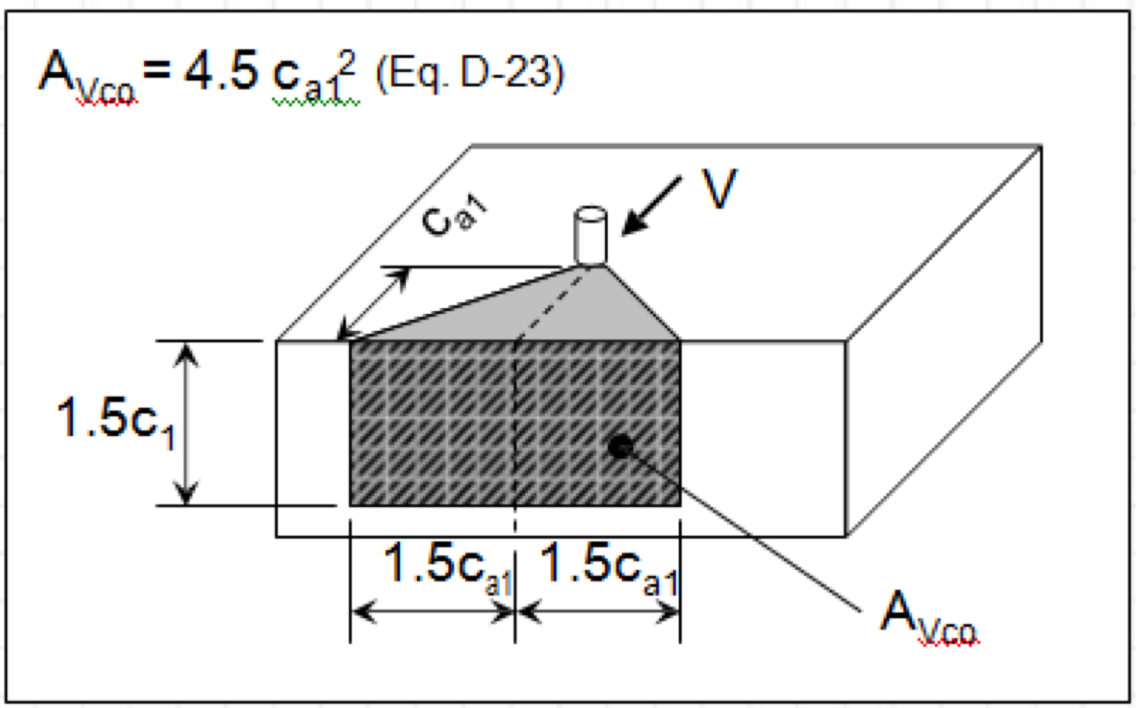


$$A_{Vc} = (1.5c_{a1} + s_1 + c_{a2})\,h_a$$

Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\,\Psi_{ed,V}\,\Psi_{c,V}\,\Psi_{h,V})V_b$

  A_{Vco} –maximum projected concrete failure area of a single anchor

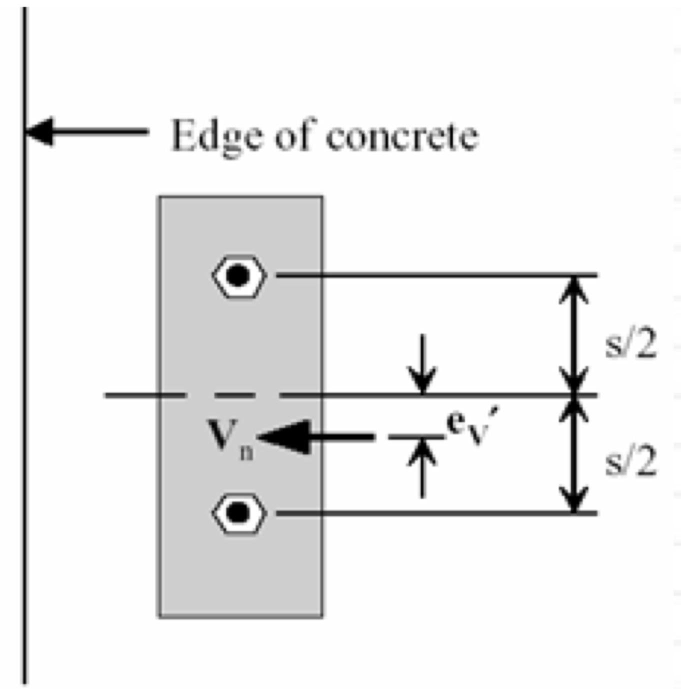


Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

  $\Psi_{ec,V}$ – Modification for eccentric load (Eq. D-26)

$$\Psi_{ec,V} = \frac{1}{\left(1 + \frac{2e_V'}{3c_{a1}}\right)} \leq 1$$



Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

$\Psi_{ed,V}$ - Modification for edge effects

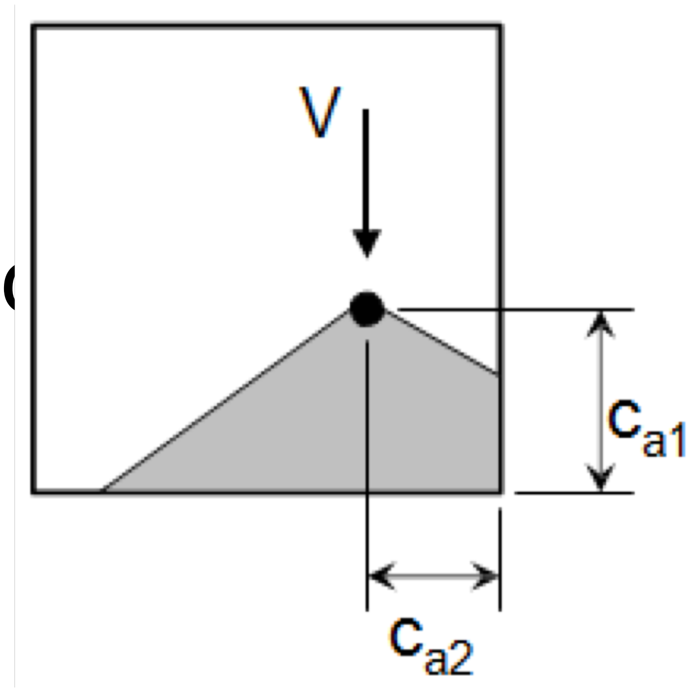
If $c_{a2} > 1.5c_{a1}$

$\Psi_{ed,V} = 1.0$ (Eq. D-27)

If ca2 < 1.5ca1

$\Psi_{ed,V} = 0.7 + 0.3c_{a2}/1.5c$

(Eq. D-28)



Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

  $\Psi_{c,V}$ - Modification factor for cracking

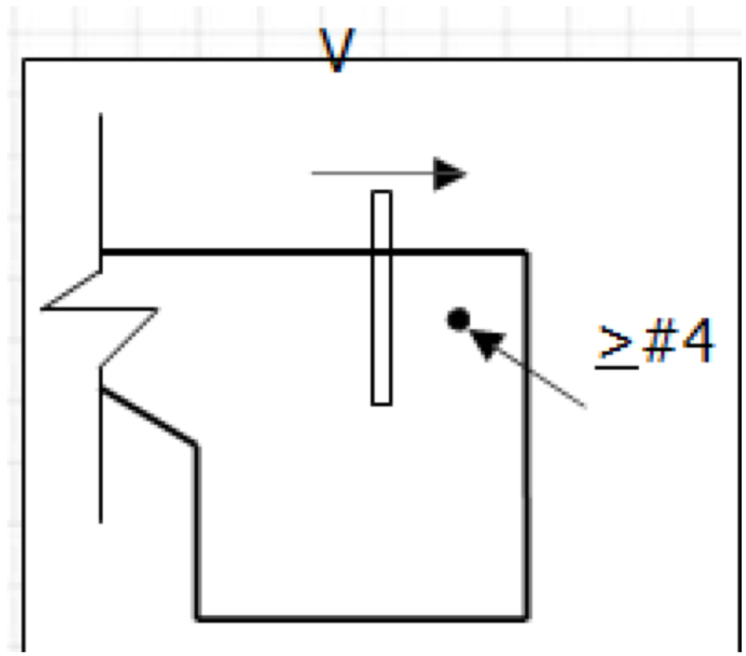
  $\Psi_{c,V}$ = 1.4 for anchors located in a region where analysis indicates no cracking at service loads

  $\Psi_{c,V}$ = 1.0 for anchors in cracked concrete with no supplemental reinforcement or edge reinforcement smaller than a #4 bar

Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

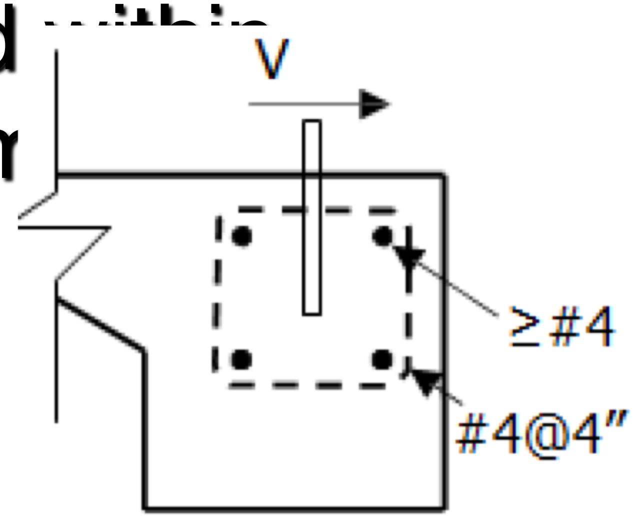
  $\Psi_{c,V}$ = 1.2 for anchors in cracked concrete with reinforcement of a #4 bar or greater between the anchor and the edge



Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

  $\Psi_{c,V} =$ 1.4 for anchors in cracked concrete with reinforcement of a #4 bar or greater between the anchor and the edge, and with the reinforcement enclosed
  stirrups spaced at not m



Concrete Breakout In Shear – D.6.2

- $V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$

  $\Psi_{h,V}$ = Modification factor for shear strength of anchors located in concrete members with $h_a < 1.5c_{a1}$

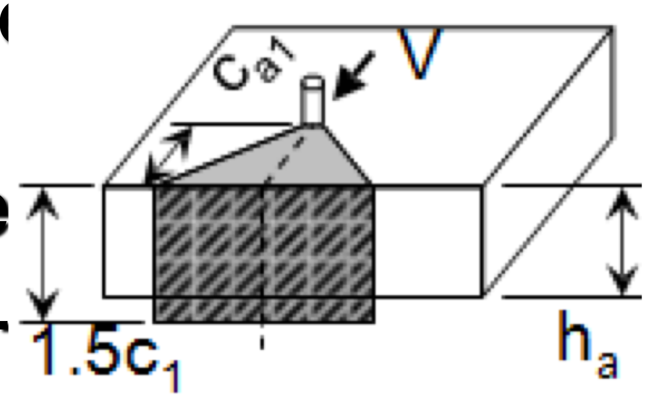
  $\Psi_{h,V} = \sqrt{1.5c_{a1}/ha}$ but not less than 1.0

  When $h_a < 1.5c_{a1}$, A_{Vc} is reduc

  However, breakout strength is

  directly proportional to membe

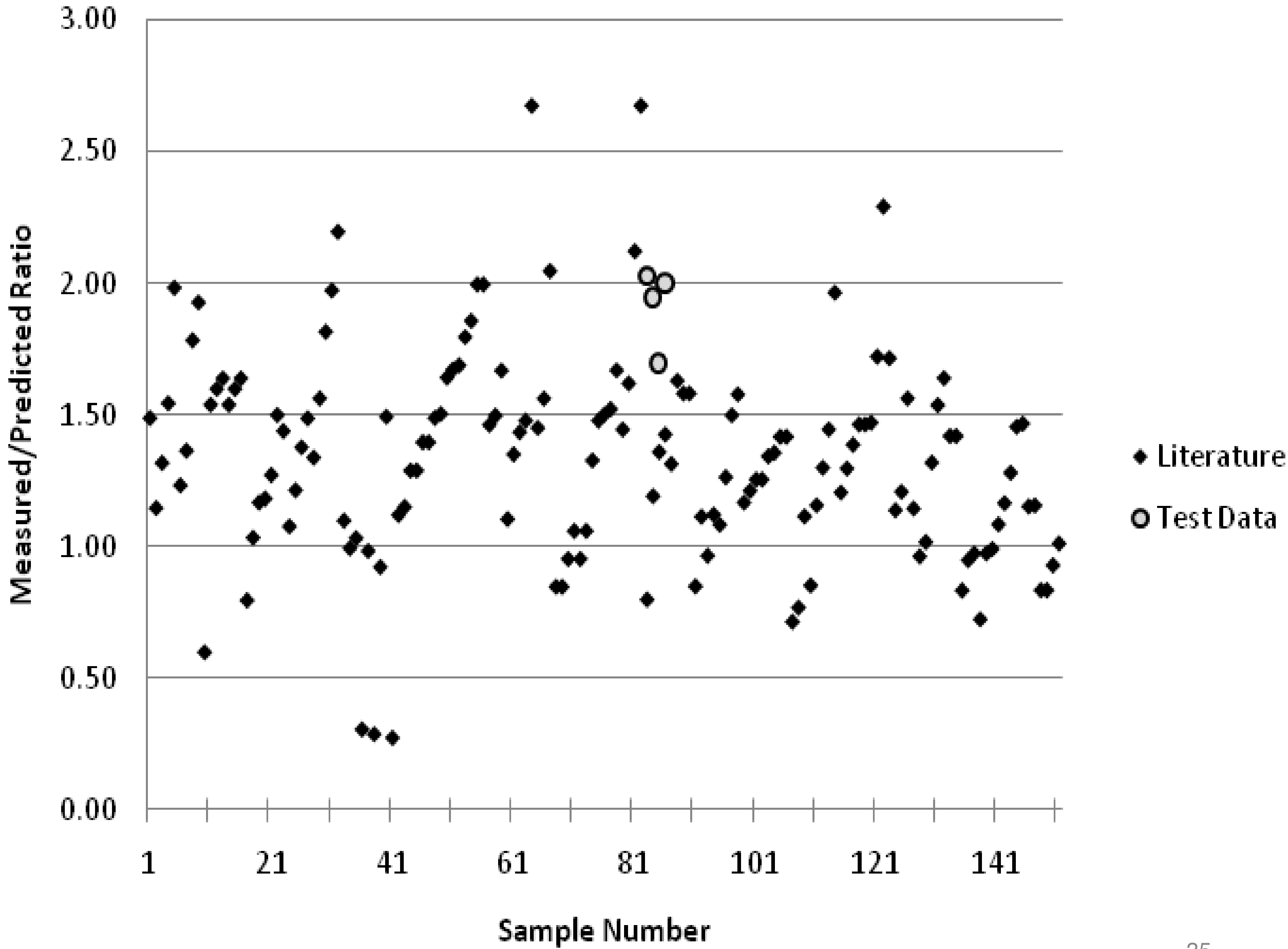
  thickness. $\Psi_{h,V}$ adjusts for this.



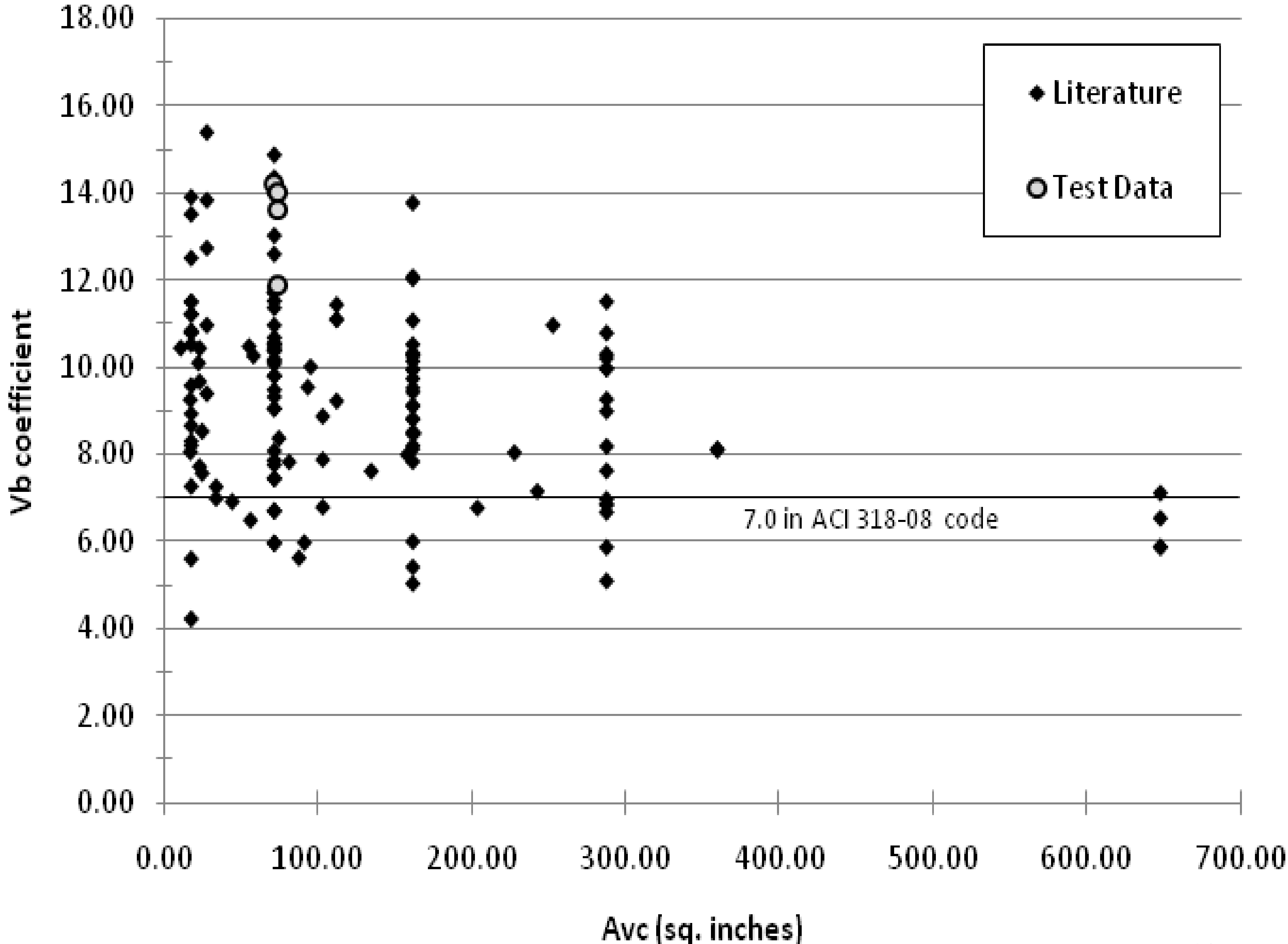
Concrete Breakout In Shear – D.6.2

$$V_{cbg} = A_{Vc}/A_{Vco}(\Psi_{ec,V}\ \Psi_{ed,V}\ \Psi_{c,V}\ \Psi_{h,V})V_b$$

- $V_b = (7(□_e/d_a)^{0.2}\sqrt{d_a})\lambda\sqrt{f'_c}\,(c_{a1})^{1.5}$ (Eq. D-24)
- – $□_e$ – load bearing length of anchor
  - Same as h_{ef} if there is no sleeve on anchor
  - Per manufacturer if there is a sleeve
- – d_a – outside diameter of anchor
- – λ – adjustment for lightweight concrete
- – f'_c – concrete compressive strength
- – c_{a1} – edge distance



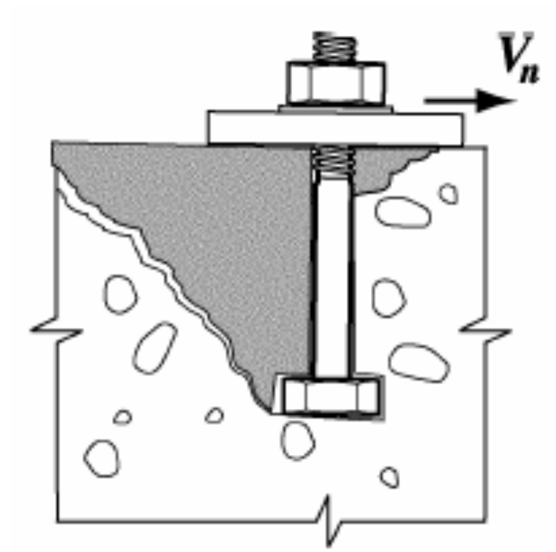
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Measured/Predicted Ratio
1
21
41
61
81
101
121
141
Sample Number
Literature
Test Data



18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Vb coefficient
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
Avc (sq. inches)
Literature
Test Data
7.0 in ACI 318-08 code

Concrete Pryout In Shear – D.6.3

- $V_{cpg} = k_{cp}N_{cbg}$ (Eq. D-30)
  - $k_{cp} = 1.0$ for $h_{ef} < 2.5$”
  - $k_{cp} = 2.0$ for $h_{ef} \geq 2.5$”
- N_{cbg} – Nominal concrete breakout strength in tension



Phi (Φ) factors

- $N_{ua} \leq \Phi N_n$ or $V_{ua} \leq \Phi V_n$
- Φ-factors are applied to nominal capacities before comparing with factored forces
- Based on:
  - – Supplemental reinforcement
  - – Failure mode
  - – Load type
  - – Anchor property

Phi (Φ) factors D.4.4

Failure Mode	Anchor Property	Φ Factor			
		Condition A		Condition B	
		Tension	Shear	Tension	Shear
Steel	Ductile	Use Condition B		0.75	0.65
	Brittle			0.65	0.60
Side Face Blowout	CIP	0.75	0.75	0.70	0.70
Breakout	CIP	0.75	0.75	0.70	0.70
	Cat. 1	0.75	0.75	0.65	0.70
	Cat. 2	0.65	0.75	0.55	0.70
	Cat. 3	0.55	0.75	0.45	0.70
Pullout	CIP	Use Condition B		0.70	0.70
	Cat. 1			0.65	0.70
	Cat. 2			0.55	0.70
	Cat. 3			0.45	0.70
Pryout	CIP	Use Condition B		0.70	0.70
	Cat. 1			0.65	0.70
	Cat. 2			0.55	0.70
	Cat. 3			0.45	0.70

Phi (Φ) factors D.4.4

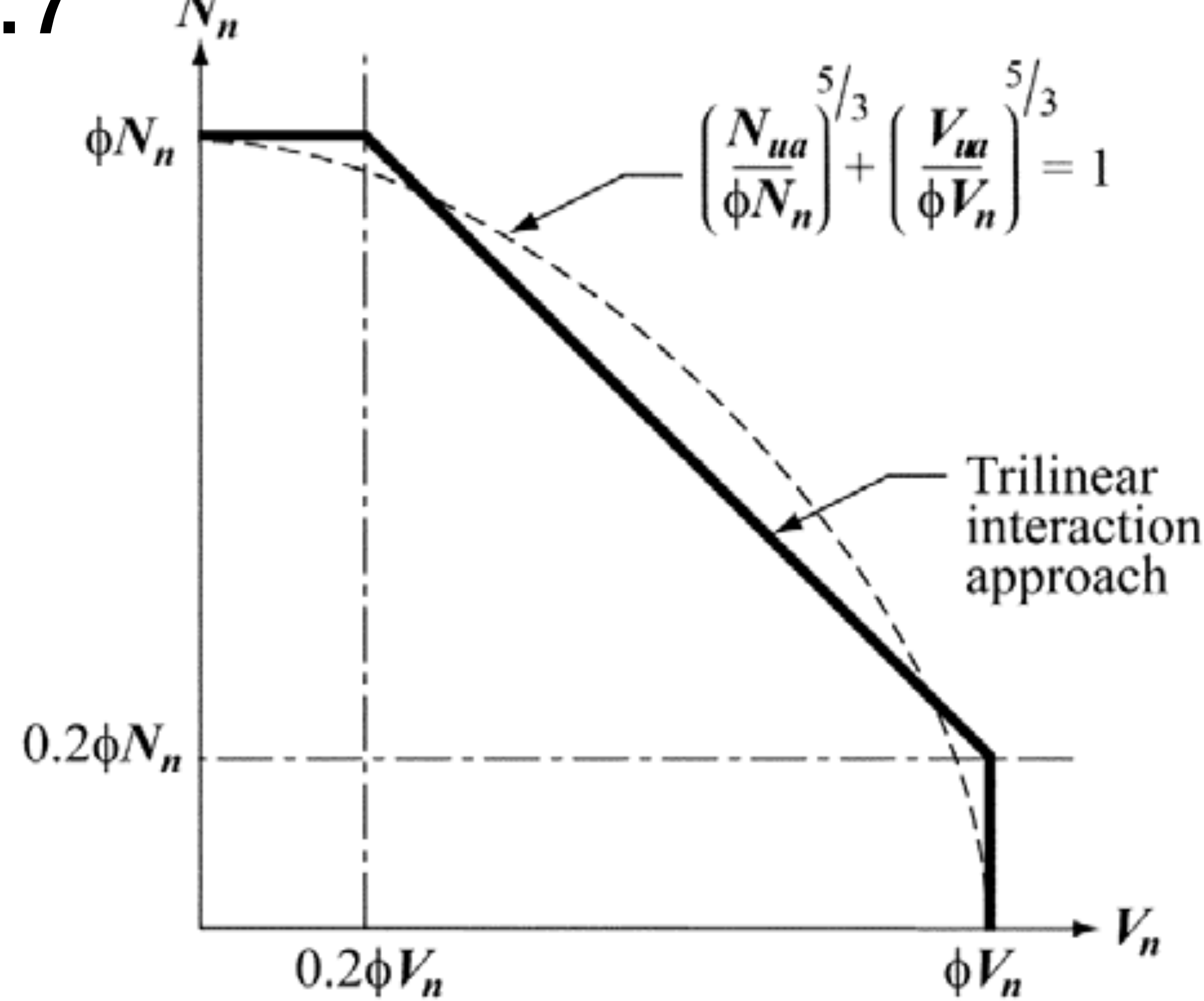
Condition A

- Applies where supplementary reinforcement is present except for pullout and pryout strengths.

Condition B

- Applies where supplementary reinforcement is not present, and for pullout or pryout strength.

Interaction of Tension and Shear – D.7



Questions?

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WHERE DISCOVERIES BEGIN

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