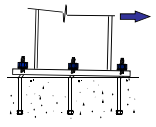



Concrete Anchor Design

In Accordance with ACI 318-11 Appendix D

ASCE-SEI New Orleans Chapter
New Orleans, LA
January 26, 2012




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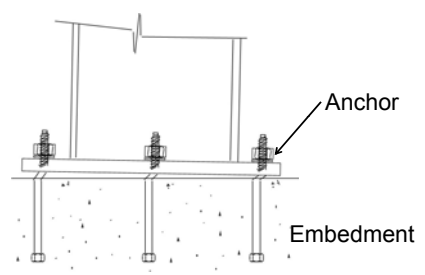
Outline

- Background and definitions
- History of ACI 318-11 Appendix D (Anchoring to Concrete)
- “New Stuff”
 - Miscellaneous
 - Adhesive anchors
 - Seismic
 - Inspection
- Qualification & Testing




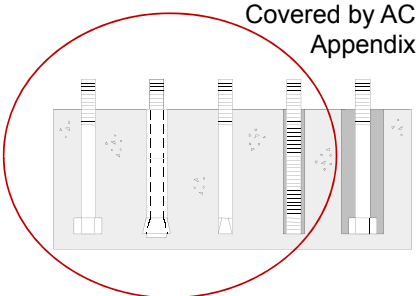
Background & Definitions

Attachment




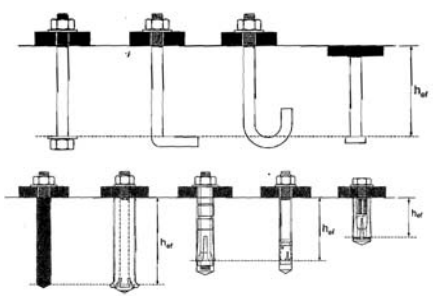
Types of Anchors

Covered by ACI 318-11 Appendix D


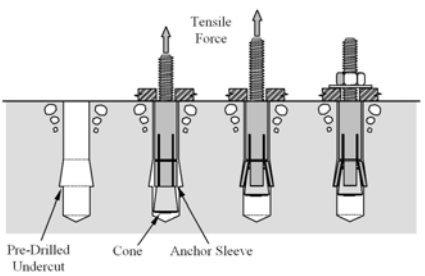


h_{ef} for Cast-in-Place Anchors

Effective embedment depth



Undercut Anchors



Torque-Controlled Expansion

Heavy duty sleeve fastener Wedge Fastener Sleeve Fastener

Displacement-Controlled Expansion

Drop-in Fastener Self-Drilling Fastener Stud Fastener

Adhesive Anchors

Threaded Rod Rebar

Grouted Anchors

Not covered in ACI 318-11 Appendix D

Hole cannot exceed 1.5 times anchor diameter **[D.1]**

Background & Definitions

Effects of Cracking

Cracking reduces tensile breakout capacity

Background & Definitions

Failure Modes in Tension

- Yield and fracture of anchor steel
- Concrete breakout
- Pullout
- Concrete side-face blowout

Weakest governs

Background & Definitions

Failure Modes in Shear

- Yield and fracture of anchor steel
 - Concrete breakout
 - Concrete pryout

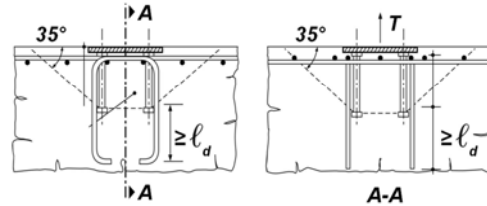
Weakest governs

(Splitting failure must be precluded)



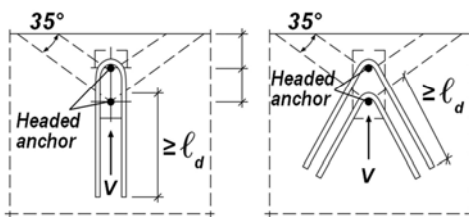
Background & Definitions

Supplementary reinforcement for tension



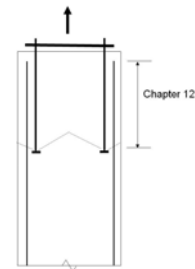
Background & Definitions

Supplementary reinforcement for shear



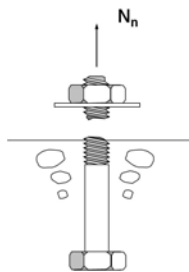
Background & Definitions

Supplementary reinforcement for tension



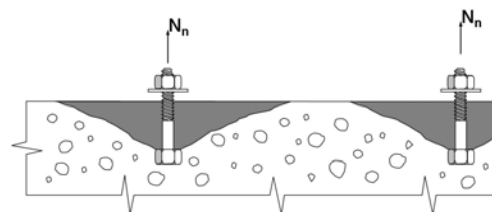
Background & Definitions

Steel failure - tension



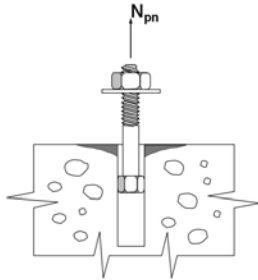
Background & Definitions

Concrete breakout failure - tension



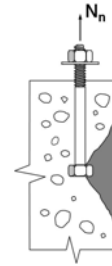
Background & Definitions

Pullout failure - tension



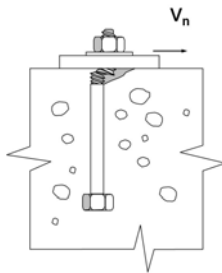
Background & Definitions

Side-face blowout - tension



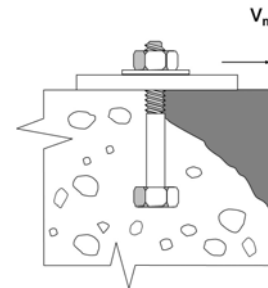
Background & Definitions

Steel failure - shear



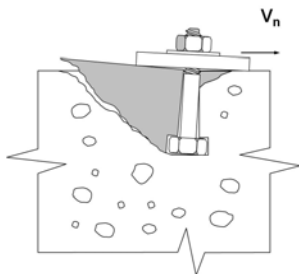
Background & Definitions

Concrete breakout failure - shear



Background & Definitions

Concrete pryout failure - shear



History of ACI 318 Appendix D

Prior to 2002

- Legacy model codes (UBC, ACI 349 Nuclear Structures, or PCI guidelines)
 - Cast-in place anchors only
- Steel failure, concrete pullout, concrete breakout based on 45 degree cone




History of ACI 318 Appendix D

Appendix D arrives in 2002

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

Errors/typos fixed in 2005

Cleaned up in 2008




History of ACI 318 Appendix D

Expansion in 2011:

- Added adhesive anchors
- Added seismic design requirements
- Added installation and inspection

Coming next:


- Screw anchors



History of ACI 318 Appendix D

Code reorganization (?) in 2014:


1. Become a chapter
2. Stay an appendix
3. Become a separate document



2011 Group Effects

Failure Mode Under Investigation	Critical Spacing
Concrete breakout in tension	$3h_{ef}$
Bond strength in tension	$2c_{Na}$
Concrete breakout in shear	$3c_{a1}$

[D.3.1.1]




2011 Lightweight Concrete

Failure Mode Under Investigation	λ_a
Cast-in and undercut anchor concrete failure	1.0λ
Expansion and adhesive anchor concrete failure	0.8λ
Adhesive anchor bond failure per D-22	0.6λ

[D.3.6]

λ in accordance with 8.6.1

Alternate λ_a can be found through testing




2011 Required Strength of Anchors

TABLE D.4.1.1 — REQUIRED STRENGTH OF ANCHORS, EXCEPT AS NOTED IN D.3.3

Failure mode	Anchor group*		
	Single anchor	Individual anchor in its group	Anchor as a group
Steel strength in tension (D.5.1)	$\phi N_{sa} \geq N_{sa}$	$\phi N_{sa} \geq N_{sa}$	-
Concrete breakout strength in tension (D.5.2)	$\phi N_{cb} \geq N_{cb}$	-	$\phi N_{cbg} \geq N_{cbg}$
Pullout strength in tension (D.5.3)	$\phi N_{ps} \geq N_{ps}$	$\phi N_{ps} \geq N_{ps}$	-
Concrete side-face blowout strength in tension (D.5.4)	$\phi N_{sb} \geq N_{sb}$	-	$\phi N_{sbg} \geq N_{sbg}$
Bond strength of adhesive anchor in tension (D.5.5)	$\phi N_b \geq N_b$	-	$\phi N_{bg} \geq N_{bg}$
Steel strength in shear (D.6.1)	$\phi V_{sa} \geq V_{sa}$	$\phi V_{sa} \geq V_{sa}$	-
Concrete breakout strength in shear (D.6.2)	$\phi V_{cb} \geq V_{cb}$	-	$\phi V_{cbg} \geq V_{cbg}$
Concrete pryout strength in shear (D.6.3)	$\phi V_{cp} \geq V_{cp}$	-	$\phi V_{cpg} \geq V_{cpg}$

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



Narrow Sections of Limited Thickness

2011

Plan: $c_{ei} = 12$ in., $s = 9$ in., $c_{e2} = 5$ in., $c_{e1} = 7$ in.

Side section: $h_p = 8$ in., slope 1.5.

2011 Limitations

Anchor diameter ≤ 4 inches [D.4.2.2]

$f'_c \leq 10,000$ psi cast-in, 8,000 psi post installed [D.3.7]

h_{ef} between $4d_a$ and $20d_a$. [D.4.2.3]

h_{ef} can exceed $2/3 h_a$ if there is test data [D.8.5]

2011 Adhesive Anchors

ONLY covered by ACI 318-11 Appendix D if they meet the assessment criteria of

ACI 355.4 -11
 Qualification of Post-Installed Adhesive Anchors in Concrete

[D.2.3]

2011 Adhesive Anchors

Horizontally or upwardly inclined anchors must be qualified per ACI 355.4 [D.3.4]

Installed in concrete ≥ 21 days [D.2.2]

2011 Adhesive Anchors

Under sustained loading:

$$0.55\phi N_{ba} \geq N_{ua,s} \quad [D-1]$$

Basic bond strength in tension

Factored sustained tension load

2011 Adhesive Anchors

Bond Strength of Adhesive Anchor in Tension:

$$N_a = (A_{Na}/A_{Na0})\psi_{ed,Na}\psi_{cp,Na}N_{ba} \quad [D-18]$$

- Splitting from installation
- Proximity to edges
- A_{Na} not limited by edge distance or spacing
- Projected influence area of adhesive anchor in tension

2011 Adhesive Anchors

Influence Areas

Section through anchor showing principal stress trajectories
 Section through anchor group showing principal stress trajectories

change in stress pattern with increasing embedment

(a) Single adhesive anchor away from edges and other anchors
 (b) Group of four adhesive anchors located near a corner

Fig. RD.5.5.1—Calculation of influence areas A_{Na} and A_{Ng}

2011 Adhesive Anchors

Influence Areas

Plan view
 $A_{Na} = (2C_{Na})^2$

Plan view
 $A_{Ng} = (C_{Na} + S_1 + C_{a1})(C_{Na} + S_2 + C_{a2})$ if
 c_{a1} and $c_{a2} < C_{Na}$
 S_1 and $S_2 < 2C_{Na}$

2011 Adhesive Anchors

Critical Distance

$$c_{Na} = 10 d_a \sqrt{\frac{\tau_{un-cr}}{1100}} \quad [D-21]$$

c_{Na} is the same if the concrete is cracked or uncracked, so the uncracked bond strength is used

2011 Adhesive Anchors

Bond Strength in Tension in Cracked Concrete

$$N_{ba} = \lambda_a \tau_{cr} \pi d_a h_{ef} \quad [D-22]$$

Can use τ_{un-cr} if concrete is uncracked (by analysis)

2011 Adhesive Anchors

Can use minimum bond stress values if:

- Anchors meet ACI 355.4
- Rotary impact drill or rock drill used
- $f'_c \geq 2,500$ psi at installation
- Age ≥ 21 days at installation
- Concrete temperature $\geq 50^\circ\text{F}$ at installation

[D.5.5.2]

2011 Adhesive Anchors

TABLE D.5.5.2 — MINIMUM CHARACTERISTIC BOND STRESSES[†]


Installation and service environment	Moisture content of concrete at time of anchor installation	Peak in-service temperature of concrete, °F	τ_{cr} , psi	τ_{un-cr} , psi
Outdoor	Dry to fully saturated	175	200	650
	Dry	110	300	1000

[†]Where anchor design includes sustained tension loading, multiply values of τ_{cr} and τ_{un-cr} by 0.4.
[†]Where anchor design includes earthquake loads for structures assigned to Seismic Design Category C, D, E, or F, multiply values of τ_{cr} by 0.8 and τ_{un-cr} by 0.4.

2011 Adhesive Anchors

Adhesive anchors are dependent on:

1. Type and duration of loading
2. Concrete cracking
3. Anchor size
4. Drilling method
5. Degree of concrete saturation (drilling & installation)
6. Concrete temperature at installation
7. Concrete age at installation
8. Peak temperatures during service life
9. Chemical exposure




2011 Adhesive Anchors

Typical qualification:

“1/2 inch to 3/4 inch diameter anchors installed in impact-drilled holes in dry concrete where use is limited to indoor conditions in uncracked concrete”

τ_{uncr} can be 2000 to 2500 psi




2011 Seismic Design Requirements

Structures in categories C, D, E, or F

- C: Very dense soil and soft rock
- D: Stiff soil
- E: Soft clay soil
- F: Soils requiring a site analysis

[D.3.3.1]




2011 Seismic Design Requirements

Appendix D does not apply to anchors in plastic hinge zones of concrete structures under earthquake forces

Plastic hinges:

- extend 2d from any column or beam face
- Anywhere reinforcing yields from seismic forces

[D.3.3.2]



2011 Seismic Design Requirements

Simulated Seismic Tests


Expansion and Undercut Anchors (355.2)

N_p \equiv pullout strength
 V_{sa} \equiv steel strength in shear

Adhesive Anchors (355.4)

t_{uncr} and t_{cr} \equiv characteristic bond stresses
 V_{sa} \equiv steel strength in shear

[D.3.3.3]




2011 Exceptions to Seismic Requirements

If tensile seismic component \leq 20% total factored tensile load

[D.3.3.4.1]

If shear seismic component \leq 20% total factored shear load

[D.3.3.5.1]




Seismic Anchor Design - Tension

2011

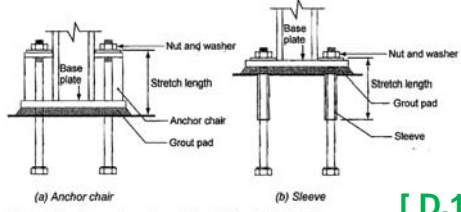
Four options

- Anchor yield & ultimate behavior is well defined
- Yield of a steel attachment governs
- Failure of non-yielding attachment governs
- Amplify earthquake loads

[D.3.3.4.3]




2011 Stretch Length & Ductility



[D.1]

Ductile Steel Element:
 ≥ 14% elongation in a tensile test
 ≥ 30% area reduction




2011 Option (a)

Concrete governed strength > Steel strength

- Steel strength = 1.2 nominal steel strength
- Concrete governed strength (pullout, side-face blowout, concrete breakout, & bond strength)
- Stretch length ≥ 8 inches or analysis
- Protect anchor against buckling
- $f_{uta}/f_{ya} \geq 1.3$
- Rebars are ASTM A706 Grade 60 (or 21.1.5.2 compliant)

[D.3.3.4.3(a)]



2011 Option (b)

Ductile yield mechanism in attachment

- Flexure
- Shear
- Bearing
- Combination

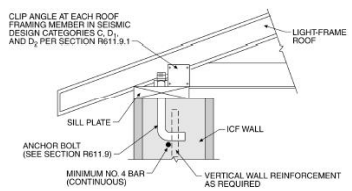
[D.3.3.4.3(b)]

Design anchors as per D.3.3.4.4 based on the design strength of the attachment




2011 Option (c)

Non-ductile failure mechanism in attachment




Design anchors as per D.3.3.4.4 based on the design strength of the attachment



2011 Option (d)

Increase seismic loads by Ω_o

Design anchors for amplified loads as per non-seismic




2011 Options (b & c)

Design tensile strength by considering:

- ϕN_{sa} for a single anchor*
- $0.75\phi N_{cb}$ or $0.75\phi N_{cbg}$ (unless additional reinforcement per D.5.2.9)
- $0.75\phi N_{pn}$ for a single anchor*
- $0.75\phi N_{sb}$ or $0.75\phi N_{sbg}$
- $0.75\phi N_a$ or $0.75\phi N_{ag}$

*Or most stressed single anchor in a group




Seismic Anchor Design - Shear

2011

Three options

- Yield of a steel attachment governs
- Failure of non-yielding attachment governs
- Amplify earthquake loads

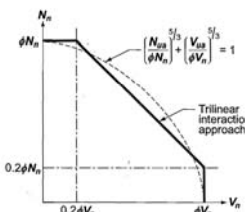
[D.3.3.5.3]



Seismic Anchor Design - Combination


2011

Use the tensile design strength from D.3.3.4.4



Design using D.7 (interaction equations)

Fig. RD.7—Shear and tensile load interaction equation.




2011 Installation and Inspection

MPII – Manufacturer’s Printed Installation Instructions

Typical anchor inspection per 1.3

AND

Additional requirements for adhesives




2011 Installation and Inspection

Adhesive anchors:

Possible proof loading if required by 355.4

Installation conditions to be specified in contract documents

Horizontally or upwardly inclined adhesives installed by ACI/CRSI certified Adhesive Anchor Installer




2011 Installation and Inspection

Adhesive anchors, continued:

Horizontally or upwardly inclined adhesives “continuously inspected” during installation

Report to both the PE and the building official that the materials and installation complies with the MPII

IBC requires special inspection of all post installed anchors




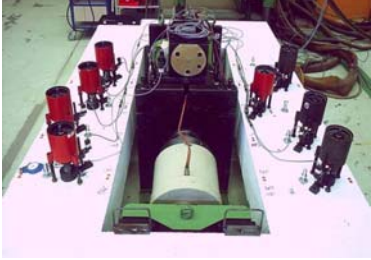
2011 Qualification & Testing

Static testing in cracked concrete



2011 Qualification & Testing

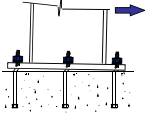
Cyclic crack test



Concrete Anchor Design

Questions?

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