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Guide for Design of Anchorage to Concrete: Examples Using ACI 318 Appendix D

Reported by ACI Committee 355

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Guide for Design of Anchorage to Concrete: Examples Using ACI 318 Appendix D

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This guide presents worked examples using the design provisions in ACI 318 Appendix D. Not all conditions are covered in these examples. The essentials of direct tension, direct shear, combined tension and shear, and the common situation of eccentric shear, as in a bracket or corbel, are presented.

Keywords: anchorage; combined tension and shear; design examples; eccentric shear; embedded bolts; headed-stud anchors; post-installed anchors; shear; tension.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

This guide was prepared by the members of ACI 355, Anchorage to Concrete, to provide design examples that demonstrate the provisions of ACI 318-05 Appendix D. Appendix D, which was first introduced in ACI 318-02, contains design provisions for determining the strength of anchors based on the Concrete Capacity Design (CCD) method for concrete breakout failure. The CCD method has its origins in research work done at the University of Stuttgart in Germany (Eligehausen et al. 1987; Eligehausen and Fuchs 1988; Rehm et al. 1992) and was formalized at the University of Texas at Austin in the 1990s (Fuchs et al. 1995). The CCD method calculates the concrete breakout strength using a model that is based on a breakout prism having an angle of approximately 35 degrees, rather than the traditional 45-degree cone model used since the early 1970s.

Appendix D design provisions are for both cast-in-place anchors and prequalified post-installed mechanical anchors. Separate design equations are frequently provided because cast-in-place anchors behave differently than post-installed anchors. The provisions for post-installed anchors are only intended for those post-installed anchors that are qualified under comprehensive testing protocols. The testing and evaluation requirements in ACI 355.2 are the standard for qualifying post-installed anchors used in design with Appendix D. Similar procedures, which are expected to be completed soon, are under development for adhesive anchors and concrete screw anchors.

Table 1.1—List of anchor failure modes

Tension failure mode	Shear failure mode
Steel strength of anchor	Steel strength of anchor
Concrete breakout strength	Concrete breakout strength
Concrete side-face blowout strength	Concrete pryout strength
Pullout and pull-through strength	

1.2—Discussion on design example problems

The example problems presented in this guide were developed using the code provisions in Appendix D of ACI 318-05, which were current at the time the examples were developed. The new provisions of ACI 318-08 will alter the calculations and results in these examples. Commentary in this guide describes how the new ACI 318-08 provisions modify the design results. The ACI 318-08 Appendix D provisions clarify issues when dealing with earthquake forces, ductile failure, anchor reinforcement, and supplemental reinforcement.

The design approach used in the example problems follows a basic outline of evaluating each potential failure mode in tension and shear for the anchor using the provisions of Appendix D of ACI 318-05. The provisions include modification factors that account for the effects of edges, eccentricity, and the presence or lack of cracking in the concrete, to determine the nominal strengths for each failure mode. The types of failure modes considered are shown in Table 1.1.

In addition to the failure modes in Table 1.1, minimum edge distance, anchor spacing, and thickness of the concrete member are checked to preclude the splitting of concrete. The calculated nominal strengths for each failure mode are modified by the appropriate modification factors. The minimum calculated design strength becomes the controlling design strength of the anchor or group of anchors.

1.3—Commentary on seismic requirements for Appendix D of ACI 318-02 and ACI 318-05

ACI 318-02 and ACI 318-05 use the terminology "low," "moderate," and "high" to describe the levels of seismic risk. The design strength of anchors that include earthquake forces and that are located in regions of moderate or high seismic risk are required to be controlled by failure in tension, shear, or both, of a ductile steel element. In addition, the design strengths for steel and concrete are reduced by a factor of 0.75. The nonductile, concrete failure modes include all the concrete breakout modes in tension and shear, plus the pullout and pull-through failure modes in tension. Nonductile failure can occur if the steel behaves in a brittle fashion. It is not always possible, due to geometric or material constraints, to design the anchorage for a ductile failure. Therefore, code provisions allow the attachment, which the anchor connects to the structure, to be considered as the ductile steel element.

Design Examples 1, 2, 11, and 12 demonstrate the provisions of Appendix D when earthquake forces are involved. They show the design of the anchors governed by the steel strength of a ductile steel element, according to Section D.3.3.4 of

Table 1.2—Description of design example problems

Design example problem	Description of problem
Example 1—Single headed anchor in tension away from edges	A single cast-in anchor under tension loading unaffected by edges and located in a high seismic region.
Example 2—Single hooked anchor in tension away from edges	Same problem as Example 1 but the anchor is an L-bolt with similar geometry; the intent is to show the inherent lower capacity of the L-bolt compared with the headed bolt.
Example 3—Single post-installed anchor in tension away from edges	Determines the optimum post-installed anchor embedment and diameter to support a tension load using anchor qualification testing data.
Example 4—Group of headed studs in tension near an edge	A group of headed anchors welded to plate supporting a tension load near free edge of concrete.
Example 5—Single headed bolt in shear near an edge	Determines the service wind load that can be applied to a single cast-in anchor near a free edge by calculating the design shear strength with reductions due to edge effects.
Example 6—Single headed bolt in tension and shear near an edge	The same anchor geometry of Example 5 is subjected a reversible shear load and a tension load. Edge effects and tension/shear interaction are evaluated.
Example 7—Single post-installed anchor in tension and shear near an edge	A post-installed anchor near a free edge of concrete is subjected to shear and tension using anchor qualification testing data. Edge effects and tension/shear interaction are evaluated.
Example 8—Group of cast-in anchors in tension and shear with two free edges and supplemental reinforcement	A column base plate with oversize holes is anchored with a group of cast-in anchors. Tension and shear loads are applied. Edge effects, tension/shear interaction, and considerations for supplemental reinforcement are evaluated.
Example 9—Group of headed studs in tension near an edge with eccentricity	A similar group of headed anchors welded to a plate shown in Example 4 is supporting an eccentric tension load near a free edge of concrete. Unequal force distribution and edge effects in the anchors are considered.
Example 10—Multiple headed anchor connection subjected to seismic moment and shear	A group of eight welded headed anchors supports an embedded plate with an eccentric shear load that produces unequal force distribution among the anchor group. The free edges require consideration of edge effects. Supplemental reinforcement and tension/shear interaction are evaluated.
Example 11—Multiple post-installed anchor connection subjected to seismic moment and shear	A group of six post-installed undercut anchors supports a plate with an eccentric seismic shear load that produces unequal force distribution among the anchor group. Single anchor and group strength are evaluated using sample anchor qualification testing data to provide ductile failure. Tension/shear interaction is evaluated.
Example 12—Multiple headed anchor connection subjected to seismic moment and shear	A group of six headed anchors welded to a plate supports an eccentric seismic shear load that produces unequal force distribution among the anchor group. Plastic design is used to evaluate the anchor and plate strength. Tension/shear interaction is evaluated.
Example 13—Group of tension anchors on a pier with shear lug	A concrete pier supporting a column base with cast-in anchors is evaluated for large shear and tension forces. Concrete breakout strength is exceeded and the pier reinforcing steel is used to transfer the tension force. Shear lug design using provisions of ACI 349 is included.

ACI 318-05, thus avoiding the potential problem of brittle failure associated with concrete breakout.

1.4—Commentary on seismic requirements for Appendix D of ACI 318-08

Several changes were made from the previous seismic requirements for Appendix D stated in Section 1.3 of this guide. The levels of seismic risk from previous ACI 318 editions have been correlated in ACI 318-08 to the corresponding design methods, categories, and zones shown in the model building codes. The seismic reduction factor of 0.75 that is applied to the design strength of ductile steel has been eliminated. For Examples 1, 2, 11, and 12, which are discussed in Section 1.3 of this guide, the removal of this reduction factor for steel would indicate that a brittle concrete breakout failure would control the design in most cases. Nonductile failure modes are allowed to control seismic design in ACI 318-08 by imposing an additional reduction factor of 0.4 to the concrete breakout strength. This factor, when combined with the required seismic reduction factor of 0.75, which is associated with concrete failure modes, results in a total reduction of 0.3, and reduces the concrete breakout design strength from the ACI 318-05 levels. The intent of reducing the permissible strength is to force the anchorage system to resist the earthquake load elastically and avoid brittle failure in the concrete.

1.5—Commentary on notation and definitions for Appendix D ACI 318-08

A new definition, "anchor reinforcement" has been defined in ACI 318-08 Appendix D to include the situation where reinforcing steel is specifically designed to transfer all the anchorage forces into the structure without considering the concrete breakout strength. This anchor reinforcement design approach occurs in cases where the concrete breakout strength is insufficient due to geometric restraints. Example 13 provides information on designing the anchorage using anchor reinforcement. Adding this new definition helped to distinguish the term from supplemental reinforcement. Supplemental reinforcement present in the direction of the load can provide restraint and improve ductility for the anchorage. Although supplemental reinforcement is not explicitly designed to transfer the load, it has been experimentally shown to improve ductility, thereby allowing an increase in the design strength of the connection through an increase in the phi factor. Examples 8 and 10 demonstrate the use of supplemental reinforcement.

A new term $\psi_{c,V}$ has been included in ACI 318-08 Appendix D to provide a modification factor to increase the basic concrete breakout strength in shear when the thickness of the section, h_a, is less than $1.5c_{a1}$.

The term for anchor diameter was changed from d_o to d_a in ACI 318-08 Appendix D.

1.6—Anchor designs featured in example problems

Table 1.2 contains a brief description of the anchor designs featured in each example problem.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Notations are defined in Chapter 2 of ACI 318-05 and in Examples 1 through 13 of this guide.

A_{brg} = net bearing area of the head of stud, anchor bolt, or headed deformed bar, in.^{2}

A_{Nc} = projected concrete failure area of a single anchor or group of anchors, for calculation of strength in tension, in.^{2}

A_{Nco} = projected concrete failure area of a single anchor, for calculation of strength in tension if not limited by edge distance or spacing, in.^{2}

A_{se} = effective cross-sectional area of anchor, in.^{2}

A_{Vc} = projected concrete failure area of a single anchor or group of anchors, for calculation of strength in shear, in.^{2}

A_{Vco} = projected concrete failure area of a single anchor, for calculation of strength in shear, if not limited by corner influences, spacing, or member thickness, in.^{2}

c_{ac} = critical edge distance required to develop the basic concrete breakout strength of a post-installed anchor in uncracked concrete without supplementary reinforcement to control splitting, in.

$c_{a,max}$ = maximum distance from center of an anchor shaft to the edge of concrete, in.

$c_{a,min}$ = minimum distance from center of an anchor shaft to the edge of concrete, in.

c_{a1} = distance from the center of an anchor shaft to the edge of concrete in one direction, in. If shear is applied to anchor, c_{a1} is taken in the direction of the applied shear. If tension is applied to the anchor, c_{a1} is the minimum edge distance

c'_{a1} = limiting value of c_{a1} when anchors are located less than $1.5c_{a1}$ from three or more edges (Fig. RD.6.2.4), Appendix D

c_{a2} = distance from center of an anchor shaft to the edge of concrete in the direction perpendicular to c_{a1}, in.

d_o = outside diameter of anchor or shaft diameter of headed stud, headed bolt, or hooked bolt, in.

e'_N = distance between resultant tension load on a group of anchors loaded in tension and the centroid of the group of anchors loaded in tension, in.; e'_N is always positive

f_c' = specified compressive strength of concrete, psi

f_{uta} = specified tensile strength of anchor steel, psi

f_{ya} = specified yield strength of anchor steel, psi

h_a = thickness of member in which an anchor is located, measured parallel to anchor axis, in.

h_{ef} = effective embedment depth of anchor, in.

h'_{ef} = limiting value of h_{ef} when anchors are located less than $1.5h_{ef}$ from three or more edges (Fig. RD.5.2.3), Appendix D

k_c = coefficient for basic concrete breakout strength in tension

k_{cp} = coefficient for pryout strength

ℓ_d = development length in tension of deformed bar, deformed wire, plain and deformed welded wire reinforcement, or pretensioned strand, in.

ℓ_{dh} = development length in tension of deformed bar or deformed wire with a standard hook, measured from critical section to outside end of hook (straight embedment length between critical section and start of hook [point of tangency], plus inside radius of bend and one bar diameter), in.

ℓ_e = load-bearing length of anchor for shear, in.

N_b = basic concrete breakout strength in tension of a single anchor in cracked concrete, lb

N_{cb} = nominal concrete breakout strength in tension of a single anchor, lb

N_{cbg} = nominal concrete breakout strength in tension of a group of anchors, lb

N_n = nominal strength in tension, lb

N_p = pullout strength in tension of a single anchor in cracked concrete, lb

N_{pn} = nominal pullout strength in tension of a single anchor, lb

N_{sa} = nominal strength of a single anchor or group of anchors in tension as governed by the steel strength, lb

N_{sb} = side-face blowout strength of a single anchor, lb

N_{sbg} = side-face blowout strength of a group of anchors, lb

N_{ua} = factored tensile force applied to anchor or group of anchors, lb

n = number of anchors

s = center-to-center spacing of anchors, in.

V_b = basic concrete breakout strength in shear of a single anchor in cracked concrete, lb

V_{cb} = nominal concrete breakout strength in shear of a single anchor, lb

V_{cbg} = nominal concrete breakout strength in shear of a group of anchors, lb

V_{cp} = nominal concrete pryout strength of a single anchor, lb

V_{cpg} = nominal concrete pryout strength of a group of anchors, lb

V_{sa} = nominal strength in shear of a single anchor or group of anchors as governed by the steel strength, lb

V_{ua} = factored shear force applied to a single anchor or group of anchors, lb

ϕ = strength reduction factor

$\psi_{c,N}$ = factor used to modify tensile strength of anchors based on presence or absence of cracks in concrete

$\psi_{c,P}$ = factor used to modify pullout strength of anchors based on presence or absence of cracks in concrete

$\psi_{c,V}$ = factor used to modify shear strength of anchors based on presence or absence of cracks in concrete and presence or absence of supplementary reinforcement

$\psi_{cp,N}$ = factor used to modify tensile strength of post-installed anchors intended for use in uncracked concrete without supplementary reinforcement

$\psi_{ec,N}$ = factor used to modify tensile strength of anchors based on eccentricity of applied loads

$\psi_{ed,N}$ = factor used to modify tensile strength of anchors based on proximity to edges of concrete member

$\psi_{ed,V}$ = factor used to modify shear strength of anchors based on proximity to edges of concrete member

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org.

Refer to Chapter 3 for definitions used in this guide.

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Chapter 3 of ACI 355.3R—Reprint of ACI 318-05 Appendix D

APPENDIX D — ANCHORING TO CONCRETE

CODE

D.1 — Definitions

Anchor — A steel element either cast into concrete or post-installed into a hardened concrete member and used to transmit applied loads, including headed bolts, hooked bolts (J- or L-bolt), headed studs, expansion anchors, or undercut anchors.

Anchor group — A number of anchors of approximately equal effective embedment depth with each anchor spaced at less than three times its embedment depth from one or more adjacent anchors.

Anchor pullout strength — The strength corresponding to the anchoring device or a major component of the device sliding out from the concrete without breaking out a substantial portion of the surrounding concrete.

Attachment — The structural assembly, external to the surface of the concrete, that transmits loads to or receives loads from the anchor.

Brittle steel element — An element with a tensile test elongation of less than 14 percent, or reduction in area of less than 30 percent, or both.

Cast-in anchor — A headed bolt, headed stud, or hooked bolt installed before placing concrete.

Concrete breakout strength — The strength corresponding to a volume of concrete surrounding the anchor or group of anchors separating from the member.

Concrete pryout strength — The strength corresponding to formation of a concrete spall behind short, stiff anchors displaced in the direction opposite to the applied shear force.

Distance sleeve — A sleeve that encases the center part of an undercut anchor, a torque-controlled expansion anchor, or a displacement-controlled expansion anchor, but does not expand.

Ductile steel element — An element with a tensile test elongation of at least 14 percent and reduction in area of at least 30 percent. A steel element meeting the requirements of ASTM A 307 shall be considered ductile.

COMMENTARY

RD.1 — Definitions

Brittle steel element and ductile steel element The 14 percent elongation should be measured over the gage length specified in the appropriate ASTM standard for the steel.

CODE

Edge distance — The distance from the edge of the concrete surface to the center of the nearest anchor.

Effective embedment depth — The overall depth through which the anchor transfers force to or from the surrounding concrete. The effective embedment depth will normally be the depth of the concrete failure surface in tension applications. For cast-in headed anchor bolts and headed studs, the effective embedment depth is measured from the bearing contact surface of the head.

Expansion anchor — A post-installed anchor, inserted into hardened concrete that transfers loads to or from the concrete by direct bearing or friction or both. Expansion anchors may be torque-controlled, where the expansion is achieved by a torque acting on the screw or bolt; or displacement-controlled, where the expansion is achieved by impact forces acting on a sleeve or plug and the expansion is controlled by the length of travel of the sleeve or plug.

Expansion sleeve — The outer part of an expansion anchor that is forced outward by the center part, either by applied torque or impact, to bear against the sides of the predrilled hole.

Five percent fractile — A statistical term meaning 90 percent confidence that there is 95 percent probability of the actual strength exceeding the nominal strength.

Hooked bolt — A cast-in anchor anchored mainly by mechanical interlock from the 90-deg bend (L-bolt) or 180-deg bend (J-bolt) at its lower end, having a minimum e_h of $3d_o$.

Headed stud — A steel anchor conforming to the requirements of AWS D1.1 and affixed to a plate or similar steel attachment by the stud arc welding process before casting.

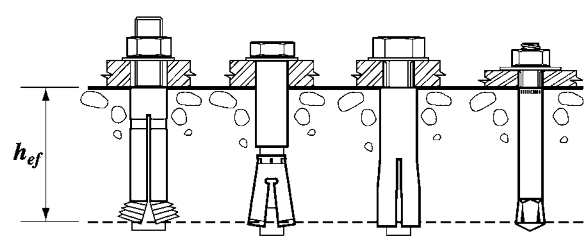
Post-installed anchor — An anchor installed in hardened concrete. Expansion anchors and undercut anchors are examples of post-installed anchors.

Projected area — The area on the free surface of the concrete member that is used to represent the larger base of the assumed rectilinear failure surface.

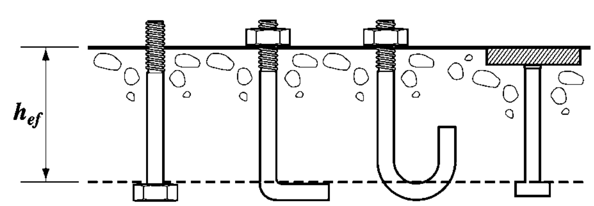
COMMENTARY

Effective embedment depths for a variety of anchor types are shown in Fig. RD.1.

Five percent fractile — The determination of the coefficient K_{05} associated with the 5 percent fractile, $\bar{x} - K_{05}s_s$, depends on the number of tests, n, used to compute the sample mean, $\bar{x}$, and sample standard deviation, s_s. Values of K_{05} range, for example, from 1.645 for $n = \infty$, to 2.010 for $n = 40$, and 2.568 for $n = 10$. With this definition of the 5 percent fractile, the nominal strength in D.4.2 is the same as the characteristic strength in ACI 355.2.



(a) Post-installed anchors



(b) Cast-in-place anchors

Fig. RD.1—Types of anchors.