Guide to the Concrete Capacity Design (CCD) Method—Embedment Design Examples

Reported by ACI Committee 349

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ACI 349.2R-07 supersedes ACI 349.2R-97 and was adopted and published November 2007.

INTRODUCTION

This report was prepared by the members of the ACI 349 Subcommittee on Steel Embedments to provide examples of the application of ACI 349 to the design of steel embedments. The first edition of this report, published in 1997, was based on ACI 349-97 that used the 45-degree cone breakout model for determining the concrete breakout strength. The 2001 edition of the Code* marked a major departure from the previous editions with the adoption of the concrete capacity design (CCD) method. The model for the concrete breakout strength used in the CCD method is a breakout prism having an angle of approximately 35 degrees. In addition, the concrete breakout strength for a single anchor away from the edge is proportional to the embedment depth raised to the power of 1.5 and not embedment depth squared, as used in the previous versions of the Code. These and other changes in the Code result in designs that are somewhat different than those obtained using previous editions of the Code. The examples used in this report are based on the ACI 349-06, Appendix D, and illustrate how the CCD method is applied. In previous editions of ACI 349, the anchorage design was given in Appendix B. Because ACI 349 is a dependent code, the chapters and Appendixes in ACI 349 are updated to be consistent with ACI 318.

As in previous Codes, the underlying philosophy in the design of embedments is to attempt to assure a ductile failure mode. This is similar to the philosophy of the rest of the concrete building codes wherein, for example, flexural steel for a beam is limited to assure that the reinforcement steel yields before the concrete crushes. In the design of an embedment for direct loading, the philosophy leads to the requirement that the concrete breakout, concrete pullout, side-face blowout, and pryout strength should be greater than the tensile or shear strength of the steel portion of the embedment.

This report includes a series of design examples starting with simple cases and progressing to more complex cases for ductile embedments. The format for each example follows the format of the *ACI Design Handbook*, SP-17, and provides a reference to the Code paragraph for each calculation procedure.

NOTATION

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

$A_{brg,pl}$ = the effective bearing area of a steel base plate, in.^{2}

A_D = gross cross-sectional area of anchor, in.^{2}

A_H = gross cross-sectional area of anchor head, in.^{2}

A_{Nc} = projected concrete failure area of a single anchor or group of anchors, for calculation of strength in tension (A_{Nc} shall not be taken greater than nA_{Nco}), in.^{2}, see D.5.2.1

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}, see D.5.2.1

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

$A_{se,t}$ = effective cross-sectional area of anchor (required to resist tension loads), in.^{2}

$A_{se,v}$ = effective cross-sectional area of anchor (required to resist shear loads), in.^{2}

A_{Vc} = projected concrete failure area of a single anchor or group of anchors, for calculation of strength in shear (A_{Vc} shall not be taken greater than nA_{Vco}), in.^{2}, see D.6.2.1

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}, see D.6.2.1

a = moment arm from row of anchors to mid-thickness of adjacent steel tube wall, in.

b = width of steel base plate, in.

b_{eff} = effective width of steel base plate, in.

b_f = flange width of supported steel member, in.

C = anchor head dimension, see figure in Tables 4(a) through (c), in.

C_F = the compressive resultant force between the embedment and the concrete resulting from factored moment and factored axial load applied to the embedment, lb

C_m = the resultant compressive force in concrete due to factored moment acting on a steel base plate, kips

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

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

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., see D.8.6

$c_{a,max}$ = 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.

d = moment arm from resultant compression force on base plate to center of tension force in anchors, in.

d_c = distance from resultant compression force to adjacent edge of supported steel member, in.

d_e = distance from edge of steel base plate to the resultant compression force, in.

d_h = nominal diameter of anchor head, in.

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

d_s = depth of supported steel member, in.

*Note: Wherever the term "Code" is used, it signifies ACI 349.

d_t = distance from center of tension force in anchors and adjacent edge of supported steel member, 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 (e'_N is always positive), in.

e'_V = distance between resultant shear load on a group of anchors loaded in shear in the same direction and the centroid of the group of anchors loaded in shear in the same direction (e'_V is always positive), in.

F = anchor head dimension, see figure in Tables 4(a) through (c), in.

F_d = ductility factor, 0.85, per D.3.6.1

F_y = specified minimum yield strength of steel plate, ksi

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 = anchor head thickness, see figure in Tables 4(a) through (c), in.

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., see D.8.5

ID = inside diameter of steel washer, in.

k_c = coefficient for basic concrete breakout strength in tension

k_{cp} = coefficient for pryout strength

L = overall length of anchor, in.

ℓ_e = load bearing length of anchor for shear, not to exceed $8d_o$, in., see D.6.2.2

M_n = nominal flexural strength at section, kip·in.

M_p = plastic moment of steel plate, kip·in.

M_u = factored moment at section, kip·in.

M_y = moment corresponding to onset of yielding at extreme fiber of steel plate, kip·in.

N_b = basic concrete breakout strength in tension of a single anchor in cracked concrete, lb, see D.5.2.2

N_{cb} = nominal concrete breakout strength in tension of a single anchor, lb, see D.5.2.1

N_{cbg} = nominal concrete breakout strength in tension of a group of anchors, lb, see D.5.2.1

N_n = nominal strength in tension, lb

N_p = pullout strength in tension of a single anchor in cracked concrete, lb, see D.5.3.4

N_{pn} = nominal pullout strength in tension of a single anchor, lb, see D.5.3.1

N_{sa} = nominal strength of a single anchor or group of anchors in tension as governed by the steel strength, lb, see D.5.1.1 or D.5.1.2

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 in a group

OD = outside diameter of steel washer, in.

P_u = factored axial force; to be taken as positive for compression and negative for tension, lb

s = center-to-center spacing of items, such as anchors, in.

T = factored tensile force in a single anchor or a row of anchors, kips

t = thickness of washer or plate, in.

t_f = flange thickness of supported steel member, in.

t_w = web thickness of supported steel member, in.

V_b = basic concrete breakout strength in shear of a single anchor in cracked concrete, lb, see D.6.2.2 or D.6.2.3

V_{cb} = nominal concrete breakout strength in shear of a single anchor, lb, see D.6.2.1

V_{cbg} = nominal concrete breakout strength in shear of a group of anchors, lb, see D.6.2.1

V_{cp} = nominal concrete pryout strength of a single anchor, lb, see D.6.3

V_{cpg} = nominal concrete pryout strength of a group of anchors, lb, see D.6.3

V_f = shear resisting force provided by friction resulting from compressive forces on steel base plate, kips

V_n = nominal shear strength, lb

V_{sa} = nominal strength in shear of a single anchor or group of anchors as governed by the steel strength, lb, see D.6.1.1 or D.6.1.2

V_u = factored shear force at section, kips

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

w = moment arm from corner anchor to midthickness of adjacent steel tube wall, in.

Z = plastic section modulus of steel base plate, in.^{3}

ϕ = strength reduction factor, see D.4.4 and D.4.5

$\psi_{c,N}$ = factor used to modify tensile strength of anchors based on presence or absence of cracks in concrete, see D.5.2.6

$\psi_{c,P}$ = factor used to modify pullout strength of anchors based on presence or absence of cracks in concrete, see D.5.3.6

$\psi_{c,V}$ = factor used to modify shear strength of anchors based on presence or absence of cracks in concrete and presence or absence of supplementary reinforcement, see D.6.2.7

$\psi_{cp,N}$ = factor used to modify tensile strength of post-installed anchors intended for use in uncracked concrete without supplementary reinforcement, see D.5.2.7

$\psi_{ec,N}$ = factor used to modify tensile strength of anchors based on eccentricity of applied loads, see D.5.2.4

$\psi_{ec,V}$ = factor used to modify shear strength of anchors based on eccentricity of applied loads, see D.6.2.5

$\psi_{ed,N}$ = factor used to modify tensile strength of anchors based on proximity to edges of concrete member, see D.5.2.5

$\psi_{ed,V}$ = factor used to modify shear strength of anchors based on proximity to edges of concrete member, see D.6.2.6

Note: When used in the design examples that follow, kips is used instead of lb (1 kip = 1000 lb). Also, kip-inch or kip-in. is used interchangeably with in.-kip.

COMMENTARY

ACI 349-06 specifies acceptance criteria for tension and shear loads on individual anchors and on groups of anchors. It specifies that the loads be determined by elastic analysis. Plastic analysis is permitted provided that deformational compatibility is taken into account, equilibrium is satisfied on the deformed geometry (taking into account the change in stiffness due to yielding), deformation does not lead to structural instability, and the nominal strength of the anchor is controlled by ductile steel elements. This document does not provide detailed methods of analyses as to how to calculate the loads on anchors, but does specify design rules when the internal tension or shear loads are eccentric.

The evaluation of loads in each anchor and the effects on the group strength is well defined in the design examples for single anchors (Examples A1 to A4) and four anchors under tension (Examples B1 and B4).

Examples B2 and B3 have four anchors under applied shears and moments. The embedment depth is selected such that the anchor strength under tension loads is controlled by ductile yielding of the steel.

When designing the base plates in each problem, no distinction between the AISC load factors (and ϕ-factors) and the ACI load factors (and ϕ-factors) is made. The Engineer should reconcile the differences between these two codes when designing the base plate.

When the Engineer is faced with base plate and anchorage configuration differing from those used in these design examples, the Engineer must apply the Code requirements and use rational assumptions appropriate for these other design configurations.

Strength reduction factor ϕ for frictional resistance is not explicitly defined in the Code. As frictional resistance is not related to a steel mode of failure, the examples have used the ϕ-factor from D.4.4c or D.4.5c (depending on whether 9.2 or C.2 of the Code is used, respectively).

PART A—Examples: Ductile single embedded element in semi-infinite concrete

Example A1—Single stud, tension only, no edge effects

Design an embedment using a stud welded to an embedded plate. The stud is located sufficiently away from the edges on the concrete so that there are no edge effects.

Given:

Concrete edges
$c_{a1} = c_{a2} = 12$ in.
$h_a = 18$ in.

Concrete
$f_c' = 4000$ psi

Stud material (A29/A108)*
$f_{ya} = 51$ ksi
$f_{uta} = 65$ ksi

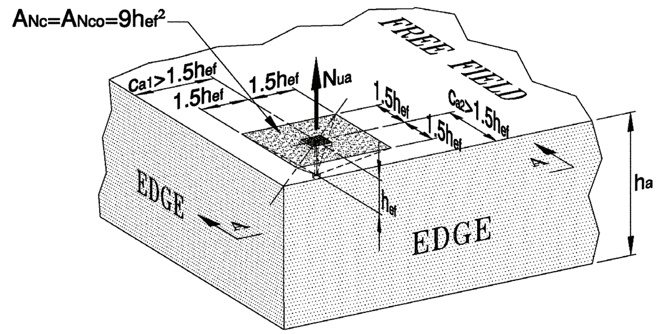
Plate
3 x 3 x 3/8 in. thick
$F_y = 36$ ksi

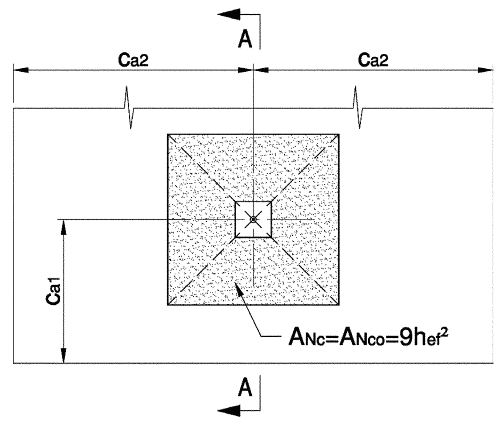
Loads
$N_{ua} = 8$ kips

Where N_{ua} is the applied factored external load using load factors from Appendix C of the Code.

Assumptions:
- Concrete is cracked.
- ϕ-factors are based on Condition B in D.4.5 of the Code (no supplementary reinforcement).

*Stud material is A29/A108, material properties per AWS D1.1, 2006, Table 7.1, Type B stud. Yield strength = 51 ksi; tensile strength = 65 ksi. It has elongation of 20% and reduction in area of 50%; meets the definition of a ductile steel element given in D.1, and meets the tensile strength requirements of D.5.1.2 and D.6.1.2: $f_{uta} \leq 1.9 f_{ya}$ ($65 \leq 1.9 \times 51 = 96.9 < 125$ ksi).





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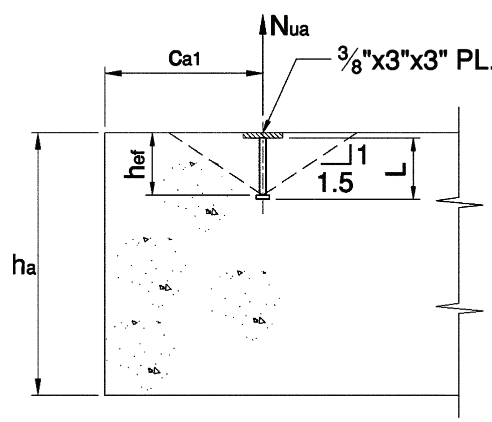

SECTION A-A