Design Guidelines for Anchorage to Concrete

by H. Wiewel

Synopsis: Design information for concrete anchors is summarized in this paper. Based on recent research, the tension and shear capacities published in the past for concrete anchors are generally unconservative, especially data for proprietary concrete anchors. This paper recommends new design parameters for seven categories of concrete anchors. The parameters, presented in tabular form, are related to tension zone cracking, seismic loading, as well as spacing and edge distance.

Keywords: Anchors (fasteners); shear strength; tensile strength; tension; working stress method

ACI member Harry Wiewel is President of Techmar, Inc., a civil engineering firm primarily involved in research and testing of building construction products. He received his B.S.C.E. degree from California State University at Long Beach and is a licensed Civil Engineer in California. Mr. Wiewel is a member of ACI Committee 355, Anchorage to Concrete.

INTRODUCTION

The designer who specifies concrete anchors today is faced with choosing from a larger variety of concrete anchors than ever before. At the same time, new and stricter test standards result in data that varies substantially from older test results. Not surprisingly, the designer is often frustrated by the variation in published load capacities of similar concrete anchors installed in the same type and strength of concrete.

It is common to see a variation in published anchor capacities for similar anchors produced by different manufacturers because of the variation in concrete and installation practices followed during testing. Data published for wedge anchors by ICBO Evaluation Services, Inc. (Ref. 1) show that 3/4" diameter wedge anchors range in allowable tension capacity from 2420 to 3500 lbs and allowable shear capacity from 1750 to 5440 lbs. This reflects the variations in manufacturer published data. However, when several of the wedge anchors listed in the ICBO ES evaluation reports were tested under identical conditions (Ref. 2), the range in ultimate tension and shear capacities was much smaller than the values published by ICBO ES.

DESIGN METHODS

Both working stress and strength design methods are currently used in the United States to design structural components. The working stress method utilizes proprietary data provided by manufacturers of concrete anchors or data published by organizations such as ICBO Evaluation Service, Inc. (Ref. 1). Working stress methods account for anchor placement and provide for reduction factors accounting for spacing of anchors in groups and edge distances. The strength design method is an analytical approach that utilizes prediction equations as done in Section 2624 of the 1988 Uniform Building Code (Ref. 3), the PCI Design Handbook (Ref. 4), and Appendix B of ACI 349-85, Code Requirements for Nuclear Safety Related Concrete Structures (Ref. 5).

WORKING STRESS METHOD

Testing Requirements

Concrete anchors are typically tested in the United States under ideal conditions. Test samples are installed in concrete slabs simulating the compression zone of a structural member. Average ultimate test values are frequently based on as few as three tests.

The 1976 and 1981 ASTM test standard for concrete anchors, as well as the ICBO ES, Inc. "Standard for Testing Expansion Anchors in Concrete" (Ref. 6), did not address developing the influence of edge distance.

The minimum edge distance to obtain full shear capacity varies for the different types and sizes of anchors, as well as for different embedment depths. The minimum edge distances recommended in the past by most manufacturers were based on limited test data and are generally unconservative. In 1984 and again in 1988, the ASTM test standard for concrete anchors, Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements (E 488) (Ref. 7), was revised requiring that all anchors be tested at specified edge distances determined by the embedment depth of the anchor. Testing to obtain data for edge distances and spacing of anchors is also addressed by ASTM E 488-84.

Tests performed in accordance with ASTM E 488-84 have indicated that the shear capacity of anchors installed at an edge distance of six anchor diameters is as much as 40% lower than the shear capacity when the edge distance is 10 anchor diameters (Ref. 2).

Design Data

Most of the published data on anchor capacity is provided by the manufacturers of proprietary concrete anchors. The published data is usually based on tests performed or witnessed by an independent testing agency. Typically the manufacturer's literature suggests that the designer use a design value of 25% of the anchor's ultimate shear and tensile capacity.

The best sources for design data on proprietary concrete anchors are the evaluation or research reports published by organizations like ICBO Evaluation Services, Inc. (ICBO ES) and Southern Building Code Congress International (SBCCI). These reports are based on test data provided by the manufacturers.

Table 26-F of the 1988 Uniform Building Code lists values (working stress method) for cast-in-place bolts and requires a minimum edge distance of 6 anchor diameters (6D) to avoid considering a reduction due to edge effects. The edge distance may be reduced by as much as 50 percent (3D) provided that the listed design values are also reduced in equal proportion. These edge distance requirements are also used by ICBO Evaluation Services, Inc. for most of the evaluation reports on proprietary concrete anchors.

Spacing and Edge Distances

Tables 1 and 2 list recommended edge and spacing distances for different categories of concrete anchors in stone aggregate concrete installed at three different ranges of anchor embedment (Ref. 8 & 9). Table 1 tabulates edge and spacing requirements for anchors subjected to shear load and Table 2 tabulates edge and spacing requirements for anchors subjected to tensile load. The tabulated edge distances should be increased when softer aggregates (i.e. lightweight) are used in the concrete mix.

The listed edge distances in Tables 1 and 2 for all anchors, except deformation-controlled expansion anchors (Type E), may be reduced up to 50 percent, provided that the design values are also reduced using the reduction factors listed in Table 3.

Edge distances for deformation-controlled expansion anchors (Type E) should not be less than those listed in Tables 1 and 2 because these anchors subject the concrete to very high expansion forces during installation which may cause the concrete to crack when installed at reduced edge distances. Expansion anchors, such as wedge and sleeve expansion anchors (Types C and D) or undercut anchors (Type B), are not recommended for installation at edge distances less than 50% of what is listed in Tables 1 and 2. When an application requires edge distances less than 50% of the recommended edge distances, cast-in-place (Type A) or chemical anchors (Type F) should be used and site-specific tests should be performed to verify their design capacity. Reinforcement should be provided in all areas of potential failure planes when specifying Type A anchors at edge distances less than 50% of the recommended edge distances.

Combined Loading

Three design equations are currently in use when an anchor or group of anchors is simultaneously subjected to both shear and tension loading. They are the straight-line, elliptical curve, and tri-linear interaction equations. The straight-line method, represented by equation 1, is the most conservative approach.

Straight Line Method

$$(P/P_{all}) + (V/V_{all}) \leq 1.0 \qquad (1)$$

where
P = applied tensile load
V = applied shear load
P_{all} = tensile design strength of anchorage
V_{all} = shear design strength of anchorage

Elliptical Curve Method

$$(P/P_{all})^{x} + (V/V_{all})^{y} \leq 1.0 \qquad (2)$$

where $x = y = 5/3$

Tri-linear Equation

$$(P/P_{all}) \leq 1.0$$

$$(V/V_{all}) \leq 1.0 \qquad (3)$$

$$(P/P_{all}) + (V/V_{all}) \leq 1.2$$

STRENGTH DESIGN METHOD

This section is a summary of the strength design approach currently (1989) followed in the United States. The equations listed in this section are generally based on the strength design approach of ACI 349 Appendix B.

The ultimate shear and tensile capacity of a concrete anchor is dependent on one or more of the following factors: anchor type, placement with respect to an edge or corner of the concrete structural member, concrete compressive and/or tensile strength, aggregate type, anchor material, location and size (if any) of steel reinforcement in the structural member and anchor embedment depth.

Also affecting the tensile capacity is whether the anchor is located in the tension zone or compression zone of the structural member. The ultimate tensile capacity of anchors installed in the tension zone of a structural member can be affected by cracks in the area of the anchorage. This must be taken into account when determining the load capacity of a concrete anchor (see section on cracked concrete).

Shear Capacity

The displacement characteristics of anchors loaded in shear depend on the type of anchor, the amount of preload applied, and the amount of load relaxation that has taken place. The preload creates a friction force between the baseplate (or attachment) and the concrete surface. The friction forces must be overcome before the baseplate moves and comes in bearing contact with the anchor. The concrete surrounding the anchor near the surface crushes and creates a small surface spall, allowing the anchor to displace. As the anchor continues to displace, it fails either the concrete or steel, depending on edge distance, type of anchor, steel strength, concrete strength, and/or anchor embedment depth.

Shear failures of the bolt material are common for stud anchors manufactured from softer steels or anchors surrounded by steel shells. The concrete usually crushes a small amount ahead of the anchor in the direction of the shear load. Generally a smooth shear failure plane occurs in the stud as the steel reaches its ultimate shear capacity (see Fig. 1).

The shear design strength of an anchor based on a steel failure (V_s), can be determined from equation 4.

$$V_s = 0.55\ (f_y \times A_s) \qquad \textbf{(4)}$$

The shear strength of an anchor, when based on a steel failure (V_{su}), can be estimated from equation 5.

$$V_{su} = N\ (f_{ut} \times A_s) \qquad \textbf{(5)}$$

where $0.6 \le N \le 0.7$

Bending rupture failures occur when the concrete surrounding the anchor crushes, allowing the anchor to bend and the steel to rupture in shear (see Fig. 2). This type of failure is common for anchors manufactured from hard brittle steels. Bending/pullout failures occur when the concrete surrounding the anchor crushes, allowing the anchor to bend and pull out of the concrete. This type of failure is common for anchors manufactured from soft ductile steels.

Concrete breakout failure (see Fig. 3) usually occurs when anchors are installed at edge distances less than 10 anchor diameters and the anchor is loaded in the direction at the free edge. The shear design strength of an anchor based on a concrete (breakout) failure (V_d) can be determined from equation 6.

$$V_d = 4\emptyset \sqrt{f_c'} \times (A_p/2) \tag{6}$$

The ultimate shear strength of an anchor based on a concrete (breakout) failure (V_c) can be estimated from equation 7.

$$V_c = 4 \sqrt{f_c'} \times (A_p/2) \tag{7}$$

Anchors installed in thin, unreinforced slabs and beams may result in a split structural member where the concrete slab or beam fails in bending (see Fig. 4). Anchors installed in thick slabs at edge distances greater than those listed in Table 1 usually result in anchor failures, including shear, bending/rupture, and bending/pullout failures.

Tensile Capacity

There are four basic failure modes for anchors subjected to tensile loading. They are steel fracture, brittle (cone) failure, concrete splitting failure, and slip (pullout) failure. In addition, chemical and grouted anchors can also experience bond failures.

The type of failure mode affects the tensile capacity of the anchor fracture.

Steel Fracture: Steel fracture is a type of failure common for undercut, chemical, cast-in-place, and heavy-duty expansion anchors. In a steel failure, the concrete does not fail and a steel failure occurs when the steel reaches its ultimate tensile capacity (see Fig. 5). Anchors are generally installed at embedments of 9 anchor diameters (9D) or more.

The tensile design capacity of an anchor based on a steel failure can be determined from equation 8.

$$P_s = 0.9\ f_y \times A_s \tag{8}$$

The ultimate tensile capacity of an anchor based on a steel failure can be estimated from equation 9.

$$P_t = f_{ut} \times A_s \tag{9}$$

<u>Concrete Cone Failure - Brittle Failure</u>: The concrete fails in tension creating a cone (see Fig. 6). This type of failure usually occurs when anchors are manufactured from high strength steels or for anchors installed at shallow embedments. Cone failures are also common for anchor groups or individual anchors installed near an edge. The cone generally starts at the outer edges of the anchor head or expansion mechanism and travels to the concrete surface at an angle between 30 to 45 degrees with respect to the horizontal surface. The concrete cone has a shape which is steeper near the embedded portion of the anchor and flattens out near the surface of the structural member. Anchor embedment also has an effect on the shape of the cone which tends to have a steeper inclination angle as the embedment is increased.

A cone with an inclination angle of 45 degrees is generally accepted in the United States for estimating the pullout strength of the anchor. The tensile design strength of an anchor based on a concrete (cone) failure can be determined from equation 10.

$$P_d = 4\phi \sqrt{f'_c} \times A_p \tag{10}$$

The ultimate tensile capacity of an anchor based on a concrete (cone) failure can be estimated from equation 11.

$$P_c = 4 \sqrt{f'_c} \times A_p \tag{11}$$

<u>Concrete Failure - Split Structural Member</u>: In this failure mode the concrete slab or beam fails in bending. This type of failure is common for anchors installed in thin, unreinforced slabs and beams, or anchors installed near an edge or corner (see Fig. 7). The anchor capacity is greater than the load causing the structural member to fail in flexure.

<u>Slip Failure</u>: The concrete in contact with the headed portion of a cast-in-place anchor or with the expansion mechanism of a post-drilled anchor fails in compression allowing the anchor to pull out of the hole.

<u>Bond Failure</u>: Bond failures are common for chemical and grouted anchors. This type of failure is usually accompanied by a shallow concrete cone with a depth up to one-half of the total stud embedment (see Fig. 8).

<u>Edge Distance and Spacing Requirements</u>

Appendix B of ACI 349-80, Code Requirements for Nuclear Safety Related Structures requires that the minimum edge distance (m_v) for development of the full shear capacity is determined in accordance with equation 12. The commentary also requires that the minimum edge distance (m_t) to prevent bursting failure (tension loading) is determined in accordance with equation 13. Both equations take into account anchor steel strength, concrete compressive strength, and anchor diameter in determining a minimum edge distance for full shear capacity.

$$m_v = D \sqrt{\frac{f_{ut}}{7.5\sqrt{f'_c}}} \tag{12}$$

$$m_t = D\sqrt{\frac{f_{ut}}{56\sqrt{f'_c}}} \tag{13}$$

The 1988 Uniform Building Code (UBC) and the Prestressed Concrete Institute (PCI) Design Manual both require an edge distance equivalent to the anchor embedment (m_t = E) and spacing equal to two times anchor embedment (S = 2E) for full tensile capacity for concrete anchors installed in stone aggregate (granite) concrete when using the strength design method. The Uniform Building Code also requires an edge distance equivalent to ten anchor diameters (m_v = 10 D) and spacing equal to two times anchor embedment (S = 2E) for full shear capacity for concrete anchors installed in stone aggregate concrete when using the strength design method.

CRACKED CONCRETE

Locating an anchor relative to a crack or potential cracking should be accounted for in design. There is no U.S. requirement currently however, this is a design consideration in Europe. Anchors to be located in the tension zone of a structural member should be able to function in cracked concrete. Similarly, anchors used in structures which may be subjected to seismic loading should also function in concrete which may experience cracking up to 3 mm in width. Recent research has provided information on cracking in a concrete structural member and how it affects the ultimate tensile and shear capacity of the anchor (Ref. 10). The reduction in capacity of an anchorage (single or group) due to the concrete cracking is dependent on such variables as anchor type and the size of the crack. Table 4 lists ranges in reduction (in percent) various anchor types can expect in tensile capacity. The table lists two crack widths, the first of which (0.4 mm) can be expected to occur in the tension zone of a structural member. The second crack width (0.8 mm) can occur during a seismic event.

In general, anchor types whose ultimate tensile capacity in cracked concrete falls below 50% of the ultimate capacity in uncracked concrete are not recommended (NR) when the structural member may experience cracking. Applications requiring anchorage in the tensile zone should be limited to Types A, B, and C anchors and their design capacity should be reduced in accordance with the percentages listed. Other anchor types can be specified for use in the tension zone if a manufacturer can establish through tests that their product has a known capacity in cracked concrete. Concrete anchors used in structures which are located in seismic Zones 3 and 4 should also be evaluated for performance in cracked concrete (Fig. 9). The information listed in Table 4 is based on limited test data and only applies to tensile loads. Although very little data is available on shear capacity of anchors in cracked concrete, it is expected that cracks have a much smaller influence on the ultimate shear capacity than they have on the ultimate tensile capacity of concrete anchors.

RECOMMENDATIONS

The author recommends that concrete anchors be rated according to type, size, and concrete strength. Anchors should also be rated for use in cracked concrete (tension zone, seismic) or uncracked concrete (compression zone). An appropriate safety factor, based on the test data and the coefficient of variation of the tests should be applied to determine allowable working loads. This approach assures that similar anchors have the same allowable working loads. Approval and listing agencies should also establish a quality assurance program to ensure that the listed anchors are not changed after the anchors are tested.

The strength design provisions of the 1988 Uniform Building Code and Appendix B of ACI 349-85, Code Requirements for Nuclear Safety Related Concrete Structures should be expanded to provide provisions for post-installed concrete anchors. Design guidelines for concrete failure due to shallow embedment of concrete anchors should also be included in the strength design provisions of the codes.

REFERENCES

1. Evaluation Reports, ICBO Evaluation Service, Inc., Whittier, CA, September-October, 1989.

2. Wiewel, H., "The Wedge Anchor, Discussion and Analysis of Short Term Load Tests Performed on Wedge Expansion Anchors", Test Report No. TR-184, Techmar, Inc., Long Beach, CA, January 1985.

3. Uniform Building Code, International Conference of Building Officials, Whittier, CA, 1988 edition.

4. PCI Design Handbook, Second Edition, Prestressed Concrete Institute, Chicago, IL, 1980.

5. Code Requirements for Nuclear Safety Related Concrete Structures (ACI 349-85) and Commentary - ACI 349R-85, American Concrete Institute, Detroit, MI, March 1986.

6. "Standard for Testing Expansion Anchors in Concrete", International Conference of Building Officials, Whittier, CA, August 1975.

7. "Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements", (ASTM E 488-88), 1988 Annual Book of ASTM Standards, Section 4, Volume 04.07, American Society for Testing and Materials, Philadelphia, PA, November 1988.

8. Eligehausen, R.; Fuchs, W.; Mayer, B. (1987), "Tragverhalten von Dubelbefestigungen bei Zugbeanspruchung" (Loadbearing Behavior of Anchor Fastenings in Tension), Betonwerk + Fertigteil-Technik, Nr. 12, pp. 826-832, and Nr. 1, pp. 29-35.

9. Rehm, G.; Eligehausen, R.; Mallee, R., "Befestigungtechnik" (Fastening Technique), Betonkalender (1988), Teil 2, Berlin, 1988.

10. Eligehausen, R.; Fuchs, W.; Lotze, D.; Reuter, M., "Befestigungen in der Betonzugzone" (Fastenings in the Concrete Tensile Zone), Beton - und Stahlbetonbau 84 (1989), No. 2, pp. 27-32, and No. 3, pp. 71-74.

NOTATION

A_b	=	area of anchor bolt head, in^2.
A_p	=	projected area of stress cone using an inclination angle of 45 deg., in^2.
A_s	=	tensile stress area of threaded anchor, in^2.
D	=	anchor diameter, in.
E	=	anchor embedment, in.
f'_c	=	concrete compressive strength, psi.
f_{ut}	=	minimum specified tensile strength of anchor steel, psi.
f_y	=	minimum specified yield strength of anchor steel, psi.
F_t	=	tension load reduction factor, dimensionless.
F_v	=	shear load reduction factor, dimensionless.
F	=	width across flats of bolt head, in.
L_d	=	anchor development length, in.
P_d	=	tensile design strength of concrete, (concrete failure), lbs.
P_c	=	ultimate tensile strength of anchor (concrete failure), lbs.
P_s	=	tensile design strength of anchor, (steel failure), lbs.
P_t	=	ultimate tensile strength of anchor (steel failure), lbs.
N	=	shear strength factor
m	=	edge distance or side cover distance measured from the center line of the anchor to edge, in.
m_t	=	minimum required anchor edge distance to attain full shear capacity, in.
m_v	=	minimum required anchor edge distance to attain full shear capacity, in.
V_c	=	ultimate shear strength of anchor (concrete failure), lbs.
V_d	=	shear design strength of concrete, lbs.
V_{su}	=	ultimate shear strength of anchor (steel failure), lbs.
V_s	=	shear design strength of anchor, lbs.
S	=	anchor spacing, in.
ϕ	=	strength reduction factor, dimensionless.