Design of Headed Anchor Bolts

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In current practice the design of base plates is controlled by bearing restrictions on the concrete (see Fig. 1); shear is transmitted to the concrete largely through anchor bolts, shear lugs or bars attached to the base plate and the tensile anchorage steel is generally proportioned only for direct stress. The embedment requirements for anchorage steel are not clearly defined by most codes and are left largely to the discretion of the design engineer. Also, there are no provisions to prevent a brittle failure in the concrete as opposed to a ductile failure in the anchor bolt, as provided for with a probability-based limit states design or Load and Resistance Factor Design (LRFD) for steel.[8] Larger design forces now mandated in many areas due to the revised seismic and wind loads require design capacities for anchor bolts beyond any existing code values.[6,11] Therefore, there is a need for a complete design procedure for anchor bolts that will accommodate these larger loads and incorporate the proposed design philosophy, i.e., probability-based limit states design (PBLSD).[8]

THE HEADED BOLT AS AN ANCHORAGE

The *headed bolt*, as designed herein, is recommended as the most efficient type of anchorage to use for both tension and shear loads. Other anchorages which have been used are L-bolts, J-bolts, rods with a bolted bearing plate and shear lugs. L-bolts have been shown to be less effective in resisting slip at service load levels than headed bolts.[13] The authors are not aware of any published data that addresses the performance of J-bolts. For a threaded rod with a bolted washer or bearing plate embedded in concrete, tests have shown that unless the plate is properly sized it may actually decrease the anchor capacity by causing a weakened failure plane in the concrete.[7,17] Shear lugs can fail in a brittle mode if not properly confined, and do not lend themselves to a shear friction analysis.[7,17]

The headed bolt, when properly embedded and confined, will develop the full tensile capacity of even A490 high strength bolts.[3] When the tension capacity of the bolt is developed, a ductile failure can be ensured by the shear friction mechanism.[3]

In this paper, anchor bolt design ductility is assured by causing a failure mechanism that is controlled by yielding of the anchor bolt steel, rather than brittle tensile failure of concrete. This is accomplished by designing the pullout strength of the "concrete failure cone" (U_p) such that it equals the minimum specified tensile strength ($F_u A_t$) or "full anchorage value" of the anchor bolt. See Figs. 2 and 10 for illustrations of the concrete failure cone concept. See Appendix A for the derivation of L_d to satisfy this criteria. The design approach presented herein is compatible with the proposed AISC Specification for Nuclear Facilities,[5] ACI 318-77,[2] and the proposed revisions to ACI 318-77.[7] The governing design approach is that presented in ACI 349, Supplement 1979.[3]

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DESIGN PARAMETERS

The design approach presented is generally applicable to any of a number of bolt or concrete strengths. However, the following representative materials are used in developing the design values. Anchor bolt materials used are ASTM A36, A307 (Grade B), A325, A449 and A687. Concrete is assumed to have a minimum compressive strength (f'_c) of 3,000 psi. Anchor bolts are heavy hex bolts or threaded steel bars with one heavy hex nut placed in concrete. Bolt threads at the embedded end of each threaded steel bar are "staked" at two places below the heavy hex nut. All bolts are brought to a "snug tight" condition as defined by AISC[4] to ensure good contact between attachments. The concrete is at least 14 days old prior to tightening the anchor bolts in order to prevent bolt rotation. Anchor bolts are designed for combined shear and tension loads; the area of steel required for tension and shear is considered additive. Criteria will be presented such that either Working Stress Design (WSD) or Ultimate Strength Design (USD) may be used.

COMBINED TENSION AND SHEAR

Many authors have presented data and interaction equations to account for the combined effects of tension and shear

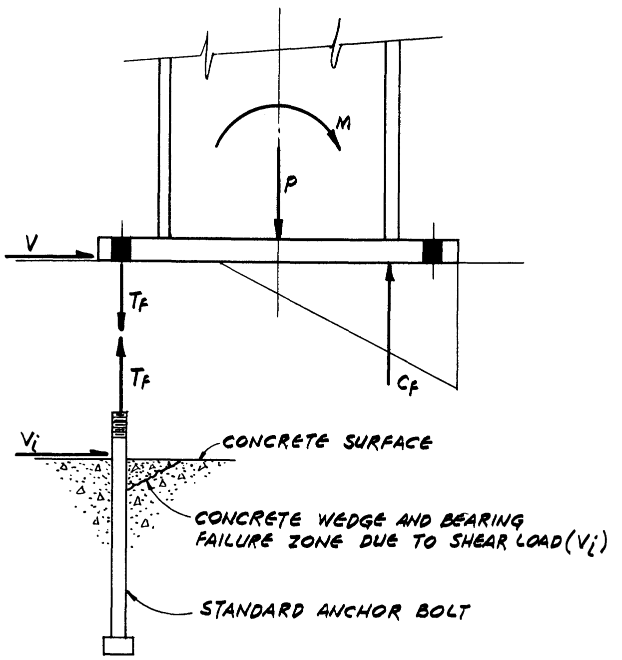

Fig. 1. Example of base plate loading

(see Refs. 1, 3, 12, 14, 15 and 17). In this paper, the total required area of anchor bolt steel to resist tension and shear loads is considered to be additive (see Appendix B, and Figs. 1 and 9).

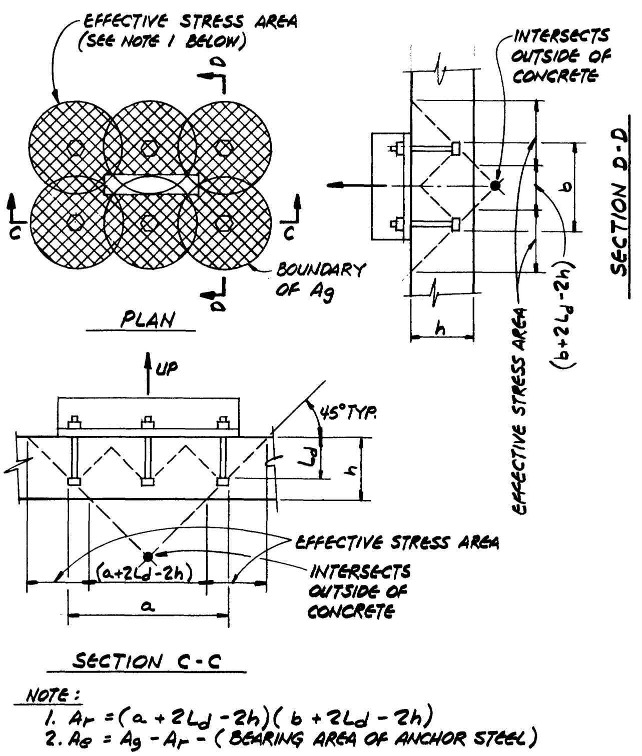

Fig. 2. Effective stress area for limited depth (A_e)

Table 1A. Standard Anchor Bolt Basic Types

Type	Description	Bolt Spacing r	Edge Distance m	Comments
A	Isolated	$r \geq r_m$	$m \geq m_v$	$m_v > r_m/2$, $m_v > m_t$
B	Shear reinforcement only	$r \geq r_m$	$r_m/2 < m < m_v$	$r_m/2 > m_t$
C	Shear reinforcement plus overlapping failure cones	$r < r_m$	$m_t < m < m_v$	$m_t < r_m/2$
D	Tension lap w/ reinforcement	$r < r_m$	$m_t < m < r_m/2$	concrete pier

Note: The bolt embedment depth shall be greater than or equal to L_d, as given in Table 1B for all bolt types.

The rationale for this basis is that the shear force (V_i) causes a bearing failure near the concrete surface and translates the shear load on the anchor bolt into an effective tension load by shear friction. In the absence of tension load (T_F), an anchor bolt is developed for "full anchorage" to resist shear. In terms of Probability-Based Limit States Design (PBLSD), the anchor bolt design resistance is greater than or equal to the effective combined tension (T_F) and shear (V_i) load effects as indicated below (see Appendix C).

$$A_t F_y \geq T$$

where

$A_t F_y$ = Nominal design resistance (capacity) equal to the product of the bolt tensile area (A_t) and the minimum specified steel yield strength (see Table 2A

$$T = \left[\frac{CV_i + T_F}{\phi}\right] \alpha$$

C = Shear coefficient, equal to the inverse of the shear friction value, as per Ref. 3, for the particular base plate mounting

Table 1B. Values for L_d, r_m, m_v, m_t

Bolt Type (ASTM)	Development Length L_d	Minimum Bolt Spacing r_m	Minimum Edge Distance for Shear m_v	Minimum Edge Distance for Tension m_t
A307	$12d$	$16d$	$12d$	$5d$ or 4″ min.
A325	$17d$	$24d$	$17d$	$7d$ or 4″ min.
A449	$17d$	$24d$	$17d$	$7d$ or 4″ min.

Note: The above values were derived per Table 2B and tabulated in Table 2A for various bolt diameters.

Table 2A. Standard Anchor Bolt Basic Design Values

Bolt Diameter d (in.)	Tensile Stress Area A_t (in.^{2})	A_tF_y (kips)					L_d, m_v (in.)			m_t (in.)		r_m (in.)		
		F_y = 36 ksi	F_y = 58 ksi	F_y = 81 ksi	F_y = 92 ksi	F_y = 105 ksi	12d	17d	19d	5d or 4″ min.	7d or 4″ min.	16d	24d	28d
		A36 A307	A449	A325 A449	A325 A449	A687	A36 A307	A325 A449	A687	A36 A307	A325 A449 A687	A36 A307	A325 A449	A687
½	0.142	5.12			13.06	14.91	6	8½	9½	4	4	8	12	14
⅝	0.226	8.14			20.79	23.73	7½	11	12	4	4⅜	10	15	18
¾	0.334	12.02			30.73	35.07	9	13	14½	4	5¼	12	18	21
⅞	0.462	16.64			42.40	48.51	10½	15	17	4⅜	6⅛	14	21	25
1	0.606	21.82			55.75	63.63	12	17	19	5	7	16	24	28
1⅛	0.763	27.46		61.80		80.12	13½	19	21½	5⅝	7⅞	18	27	32
1¼	0.969	34.89		78.49		101.7	15	21¼	24	6¼	8¾	20	30	35
1⅜	1.155	41.59		93.56		121.3	16½	24	26	6⅞	9⅝	22	33	39
1½	1.405	50.59		113.88		147.5	18	25½	28½	7½	10½	24	36	42
1¾	1.90	68.4	110.2			199.5	21	30	33½	8¾	12¼	28	42	49
2	2.50	90.0	145.0			262.5	24	34	38	10	14	32	48	56
2¼	3.25	117.1	188.5			341.3	27	39	43	11¼	15¾	36	54	63
2½	4.00	144.0	232.0			420.0	30	43	48	12½	17½	40	60	70
2¾	4.93	177.5	285.9			517.7	33	47	52	13¾	19¼	44	66	77
3	5.97	214.9	346.3			626.9	36	51	57	15	21	48	72	84

Notes:

1. The following formulas have been conservatively simplified by using the values in Table 2B:

   (a) $L_d = 12d\sqrt{\dfrac{F_u}{58}}$ per ACI-349 Appendix B, Sect. B.4.2

   (b) $m_t = d\sqrt{\dfrac{F_u}{56\sqrt{f'_c}}}$ per ACI-349 Appendix B, Sect. B.5.1.1

   (c) $m_v = d\sqrt{\dfrac{F_u}{7.5\sqrt{f'_c}}}$ per ACI-349 Appendix B, Sect. B.5.1.1

2. Before entering this table, the total effective design load (T) shall include the appropriate load factors, stress increase factors or probability factors, capacity reduction factors (ϕ) and shear coefficient (C).
3. All computations are based on f'_c = 3000 psi.

For PBLSD or Ultimate Strength Design (USD):

V_i = Shear design load effect equal to the product of the load factor(s) and the nominal shear load. The load factors are in accordance with applicable codes. For example, using ACI 318-77, $V_i = 1.4D + 1.7L$

T_F = Tension design load effect equal to the product of the load factor(s) and the nominal tension load. The load factors shall be in accordance with applicable codes. For example, using ACI 318-77, $T_F = 1.4D + 1.7L$

ϕ = Capacity reduction factor
= 0.90 for factored design loads under USD

Table 2B. Values Based on ACI 349-76 Provisions

F_u (ksi)	$L_d = 12d\sqrt{\dfrac{F_u}{58000}}$		$m_t = d\sqrt{\dfrac{F_u}{56\sqrt{f'_c}}}$		$m_v = \sqrt{\dfrac{F_u}{7.5\sqrt{f'_c}}}$	
	Actual	Use	Actual	Use	Actual	Use
58	12d	12d	4.34d	5d	11.88d	12d
90	14.95d	17d	5.42d	7d	14.80d	17d
105	16.15d	17d	5.85d	7d	15.99d	17d
120	17.26d	17d	6.25d	7d	17.09d	17d
150	19.30d	19d	6.99d	7d	19.10d	19d

Note: Values listed in this table are based on f'_c = 3000 psi.

α = 1.0 for USD. Probability considerations are included in the load factors.

For Working Stress Design (WSD):

V_i = Nominal shear load. For example, $V_i = D + L$

T_f = Nominal tension load. For example, $T_F = D + L$

ϕ = Capacity reduction factor, which includes a safety factor, used to convert yield capacity to working loads = 0.55

α = Probability factor (PF) or reciprocal of the stress increase factor ($1/SIF$), i.e., seismic loads combined with dead loads and live loads. $PF = 0.75$; therefore, $\alpha = PF = 0.75$. $SIF = 1.33$; therefore, $\alpha = 1/SIF = 0.75$.

ANCHOR BOLT DESIGN

The following section establishes limitations for the combined effects of bolt spacing, embedment depth and edge distance, such that the heavy hex head on a standard anchor bolt provides "full anchorage" in concrete equal to the tensile capacity of the bolt. Several agencies/authors have published reports representing their test data and/or recommendations to account for these variables, (see Refs. 9, 10, 13, 16 and 17). The recommendations which follow represent a composite of the published literature, modified for compatibility with ACI 349.[3] Where plain bars are used, the equivalent anchorage may be accomplished by threading the embedded end of the bar and using one American Standard heavy hex nut of equal or higher strength steel with bolt threads "staked" at two places below the heavy hex nut.

Refer to Tables 1A and 1B for a summary of the various anchor bolt classifications and criteria for which design procedures are herein provided. Note that anchor bolts are defined as type A, B, C or D. These types represent various design conditions of anchor bolts such as spacing, edge distance and development length.

Type A Anchor Bolts—Anchor bolts are classified as Type A, or isolated, when all the following apply:

- The closest bolt spacing (r) is greater than or equal to the minimum spacing (r_m) as specified in Table 1B, (i.e., no overlapping failure cones).
- The closest edge distance (m) is greater than or equal to the minimum edge distance for shear (m_v) as specified in Table 1B. Note: $m_v > r_m/2$; $m_v > m_t$
- The bolt embedment depth is greater than or equal to L_d as specified in Table 1B.

The size of Type A anchor bolts is selected such that the design load (T) does not exceed the basic Nominal Design Resistance (A_tF_y) values tabulated in Table 2A.

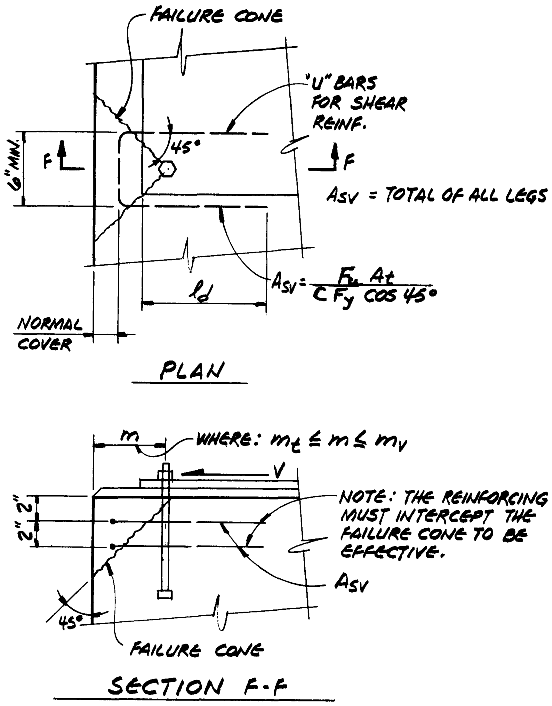

Fig. 3. Shear reinforcement

Type B Anchor Bolts—Anchor bolts are classified as "Type B," or shear reinforcement only, when all of the following apply:

- The closest bolt spacing (r) is greater than or equal to r_m.
- The closest edge distance (m) is greater than or equal to $r_m/2$ but less than m_v. Note: $r_m/2 > m_t$
- The bolt embedment depth is greater than or equal to L_d.

The size of Type B anchor bolts is selected as per Type A anchor bolts. In addition, shear reinforcement (A_{sv}) is provided on both sides of any critical plane of potential failure (see Fig. 3). The total area of horizontal shear reinforcing steel (A_{sv}) is determined as follows:

$$A_{sv} = \frac{F_{ut}A_t}{CF_y \cos 45}$$

where F_y is the specified minimum yield strength of the reinforcing steel.

Type C Anchor Bolts—Anchor bolts are classified as Type C, or shear reinforcement plus overlapping failure cone considerations, when all the following apply:

- The closest bolt spacing (r) is less than r_m.
- The closest edge distance (m) is greater than or equal to m_t and less than m_v. Note: $m_t < r_m/2$

Table 3. Standard Anchor Bolt Tensile Capacities

Bolt Diameter d (in.)	Tensile Stress Area A_t (in.^{2})	F_uA_t (kips)				
		F_y = 58 ksi	F_y = 90 ksi	F_y = 105 ksi	F_y = 120 ksi	F_y = 150 ksi
		A36 A307	A449	A325 A449	A325 A449	A687
½	0.142	8.24			17.06	21.3
⅝	0.226	13.11			27.12	33.9
¾	0.334	19.37			40.08	50.1
⅞	0.462	26.80			55.44	69.3
1	0.606	35.15			72.72	90.9
1⅛	0.763	44.25		80.12		114.5
1¼	0.969	56.20		101.7		145.4
1⅜	1.155	66.99		121.3		173.3
1½	1.405	81.49		147.5		210.8
1¾	1.90	110.2	171.0			285.0
2	2.50	145.0	225.0			375.0
2¼	3.25	188.1	292.5			487.5
2½	4.00	232.0	360.0			600.0
2¾	4.93	285.9	443.7			739.5
3	5.97	346.3	537.3			895.5

- The bolt embedment depth must be determined by considering the effect of overlapping concrete tensile stress cones (see Fig. 2). Note: L_d (required) > L_d as tabulated in Table 1B.
- Under no condition will the closest bolt edge distance be less than m_t or 4 in.

The size of Type C anchor bolts is selected as per Type A anchor bolts. Shear reinforcement is provided as per Type B anchor bolts. Also, the bolt embedment depth is calculated as follows:

- First, calculate the effective concrete tensile stress area A_e (see Fig. 2) based on r, m and an assumed embedment depth greater than L_d. The effective concrete tensile stress area (A_e) is the projected area bounded by the intersection between 45 degree lines radiating from the edge of the bolt head and the concrete surface at which the loads are applied, minus the area of the bolt heads (refer to Fig. 2).
- Then, calculate the pullout strength (U_p), where $4\beta\sqrt{f'_c}$ is the allowable uniform concrete tensile stress applied over the effective stress area A_e:

$$U_p = [4\beta\sqrt{f'_c}]A_e > F_uA_t$$

- Note that U_p must be greater than or equal to the minimum specified tensile strength (F_uA_t) of the standard anchor bolt as tabulated in Table 3. If U_p is less than F_uA_t, continue to increase the bolt embedment depth until a solution is obtained.
- The tensile strength of the concrete failure cone in a slab or wall is limited by the thickness of concrete and the out-to-out dimensions of the anchors. If 45 degree lines extending from the exterior bolt heads toward the compression face do not intersect within the concrete, then the effective stress area is limited as shown in Fig. 2.

Type D Anchor Bolts—Anchor bolts are classified as Type D, or tension lap with reinforcement, when all the following apply:

- The closest bolt spacing (r) is less than r_m.
- The closest edge distance (m) is greater than or equal to m_t and less than $r_m/2$.
- The required bolt embedment depth is greater than or equal to L_d.
- The projected area of the overlapping concrete tensile stress cones (A_e) are extremely limited, such that failure mechanism is controlled by the reinforced section rather than by the yielding of the anchor bolt steel. Such situations commonly arise in concrete piers.

The size of Type D anchor bolts is selected as per Type A anchor bolts. Shear reinforcement is provided as per Type B anchor bolts. Additional tension reinforcement is provided as follows:

- Additional tension reinforcement is provided by concentrically located reinforcing steel (A_{st}), such that the anchor bolts are developed for "full anchorage." Refer to Fig. 4 for the recommended tension reinforcement practice.
- The total area of tension reinforcement (A_{st}) as determined by the following equation is developed on

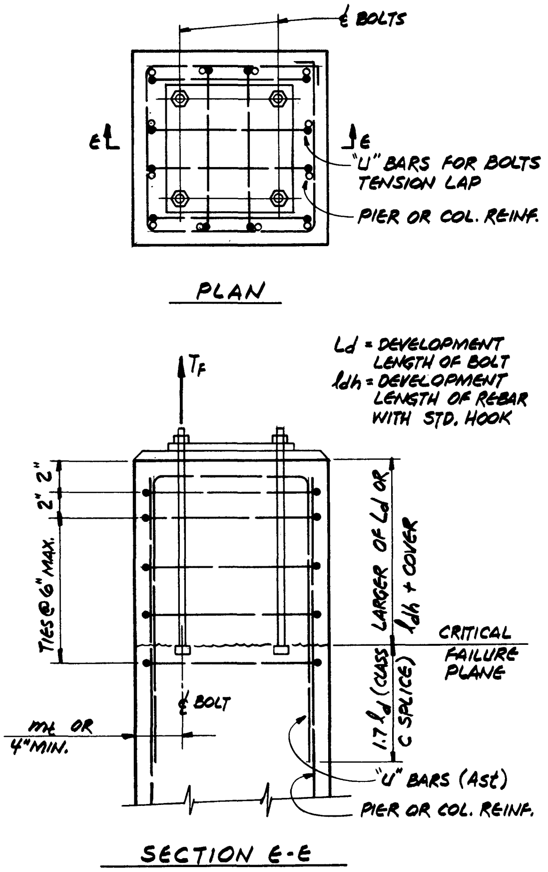

Fig. 4. Tension lap

both sides of the critical plane of potential failure:

$$A_{st} = nF_uA_t/F_y$$

where

n = total number of bolts in the bolt group
F_y = minimum yield strength of reinforcing steel

NUMERICAL EXAMPLES

The application of the criteria presented in this paper is illustrated by the following three example problems. The examples demonstrate Type A and D anchor bolts. An example is also presented for a column base plate for which special attention is given to concrete strength and anchor bolt head placement.

Example 1: Type A (Isolated Bolt), see Fig. 5

Design Data:

$$\left.\begin{array}{l} T_F = 35 \text{ kips} \\ V_i = 15 \text{ kips} \end{array}\right\} \text{DL + LL + WL}$$

f'_c = 3000 psi
SIF = 1.33; $\alpha = 1/SIF = 0.75$
ϕ = 0.55 (working stress design)
C = 1.85 (grouted base plate)

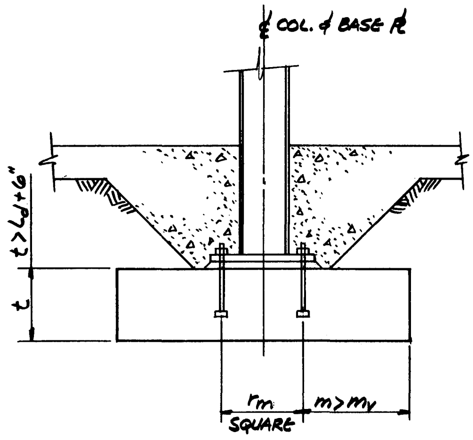

Fig. 5. Example 1: Type A anchor bolt

Design:

$$T = \left[\frac{CV_i + T_F}{\phi}\right] \alpha = \left[\frac{1.85(15) + 35}{0.55}\right] 0.75 = 86 \text{ kips}$$

Refer to Table 2A and select 1⅜-in. dia. A325 bolts:

A_tF_y = 93.6 kips > 86 kips

Use 1⅜-in. dia. A325 bolts; r_m = 33 in. and L_d = 24 in.

Example 2: Type D (Bolts in a Confined Pier), see Figs. 6 and 7

Design Data:

Design anchor bolts for cylindrical heater foundation.

For empty + wind load combination:

T_F = 1 kip; V_i = 3 kips
F_y = 60 ksi; f'_c = 3000 psi
SIF = 1.0; α = 1.0
r = 12; m = 4
ϕ = 0.55 (working stress design)
C = 1.85 (grouted base plate)

Design:

$$T = \left[\frac{CV_i + T_f}{\phi}\right] \alpha \left[\frac{1.85(3) + 1}{0.55}\right] = 11.9 \text{ kips}$$

From Table 2A, for ¾-in. dia. A307 anchor bolt:

A_tF_y = 12.02 kips ≥ 11.9 kips

r = 12 in. ≤ r_m = 12 in.

$m_t \le m < m_v$, where m_t = 4 in.

L_d = 9 in.

F_uA_t = 19,370 lbs (see Table 3)

$$A_e \text{ (required)} = \frac{f_{ut}A_t}{4\beta\sqrt{f'_c}} = \frac{19{,}370}{4(0.65)\sqrt{3000}}$$

$$= 136 \text{ sq. in.}$$

$A_e = 10^2$ = 100 sq. in. < 136 sq. in. **n.g.**

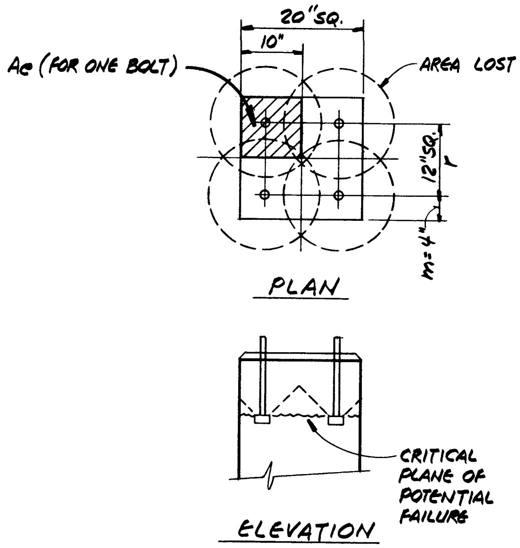

Fig. 6. Example 2: Type D anchor bolt

Increase pier size to 24 in. square, (to avoid placement of tension reinforcement), such that:

$A_e = 12^2 = 144$ sq. in. $>$ 136 sq. in. **o.k.**

Next, check the reinforced section and provide tension lap reinforcement.

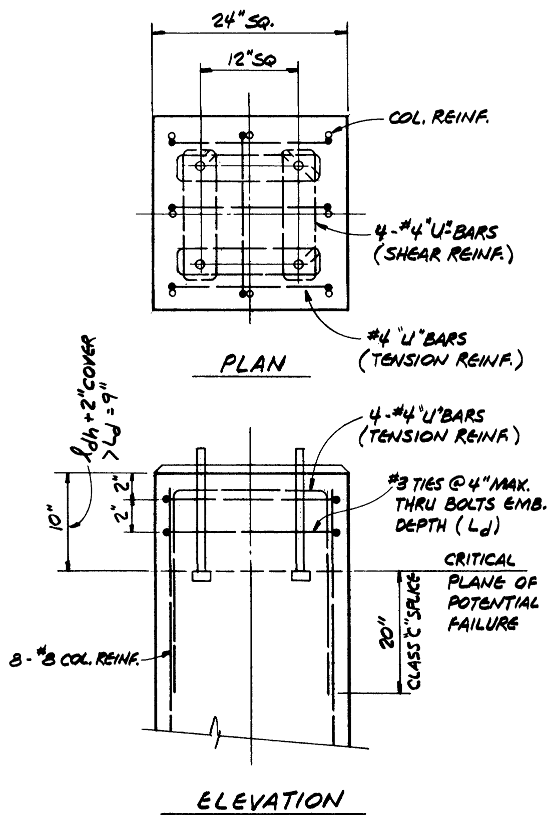

Fig. 7. Example 2: Pier for Type D anchor bolt

Thus, we have a Type D anchor bolt.

$$A_{st} = \frac{nF_uA_t}{F_y} = \frac{4(19.37)}{(60)}$$

$= 1.29$ sq. in. $<$ 1.60 sq. in. (8-#4 bars)

Use 4-#4 U-bars.

Shear reinforcement must also be provided.

$$A_{sv} = \frac{F_uA_t}{CF_y \cos 45°} = \frac{19.37}{(1.85)(60)(.707)}$$

$= 0.25$ sq. in. $<$ 0.40 sq. in. (1-#4 U-bar)

Use: 1-#4 U-bar in each direction.

Example 3: (See Figs. 8 and 9)

Design:

$A_e \cong \pi r^2 = \pi(28)^2 = 2463$ in.^{2}

$U_p = 4\beta \sqrt{f'_c}\, A_e \geq F_uA_t$

$= 4\ (.85)\ 4000\ (2463) = 529{,}630$ lbs

$F_uA_t = 110{,}200(4) = 440{,}600$ lbs $<$ 529,630 lbs (see Table 3)

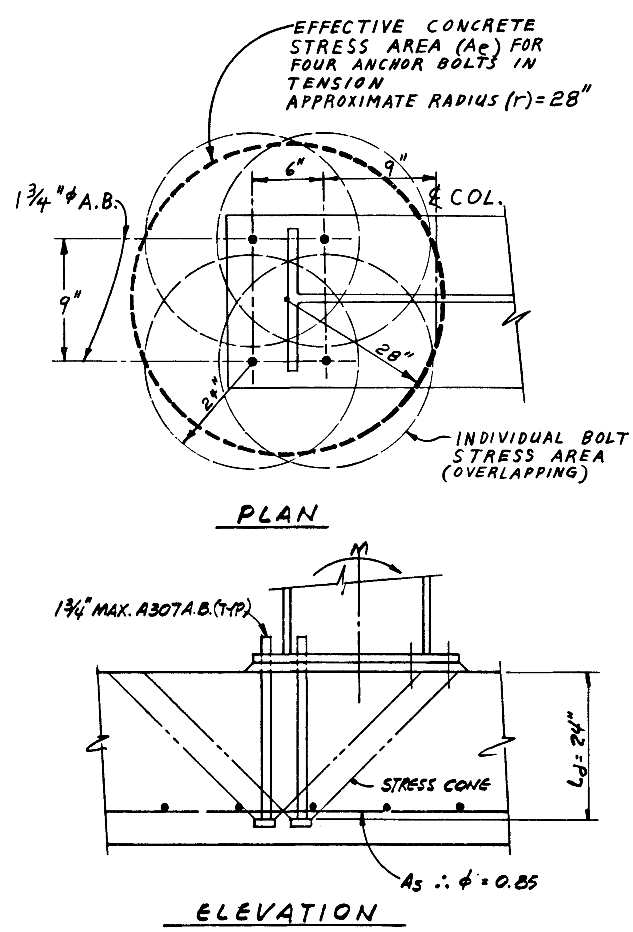

Fig. 8. Example 3: Column base plate

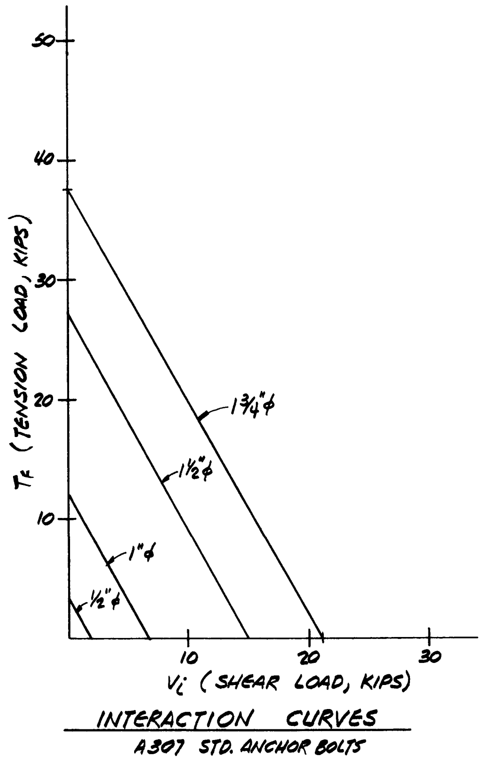

Fig. 9. Example 3: Interaction curves

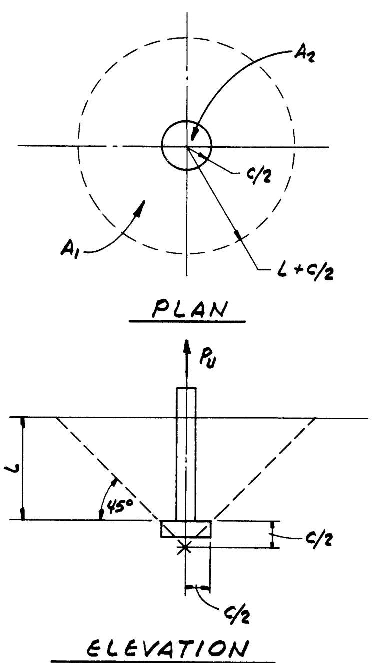

Fig. 10. Projected area of heavy hexagonal head

Therefore, 4-1¾-in. maximum diameter bolts may be used.

Note: L_d = 24 in. not adequate if f'_c = 3000 psi and β = 0.65, i.e., anchor bolt head *within* far face reinforcement.

$$A_tF_y \geq T = \left[\frac{CV_i + T_F}{\phi}\right]\alpha$$

$$T\phi = \phi A_tF_y = 0.55A_tF_y = CV_i + T_f$$

$$C = 1.85, \alpha = 1.0$$

$$\phi = 0.55(\text{WSD})$$

$$T = A_tF_y \text{ (Table 2A)}$$

Anchor Bolt Working Stress Loads: See Fig. 9 for plot.

A307 Bolt Dia. (in.)	$0.55A_tF_y$	V_i	T_F
½	2.82	0 1.52	2.82 0
1	12.00	0 6.49	12.00 0
1½	27.82	0 15.04	27.82 0
1¾	37.62	0 20.34	37.62 0

NOMENCLATURE

A_e = Effective projected stress area to which the allowable uniform concrete tensile stress is applied to determine the pullout strength of concrete

A_{st} = Total area of reinforcing steel across a potential tension failure plane(s)

A_{sv} = Total area of reinforcing steel across a potential shear failure plane(s)

A_t = Tensile stress area of anchorage per AISC[4]

C = Shear coefficient applied to standard anchors which accounts for effects of various shear failure surfaces
= 1.10 when steel plates are embedded with exposed surface flush with concrete surface
= 1.25 when steel plates are recessed in grout with bottom of plate in concrete surface
= 1.85 when steel plates are supported on grout mortar with exposed surface exterior to concrete surface

c = Equivalent circle for hex head

d = Nominal diameter of a bolt or plain bar

f'_c = Specified compressive strength of concrete

F_y = Minimum specified yield strength of steel or rebar as tabulated below:

F_y (ksi)	ASTM	Bolt Diameter (in.)
36	A307	All
92	A325	½ to 1, incl.
81	A325	Over 1 to 1½, incl.
92	A449	½ to 1, incl.
81	A449	Over 1 to 1½, incl.
58	A449	Over 1½ to 3, incl.
105	A687	⅝ to 3, incl.
60	A615	Type S, Grade 60 Rebar
40	A615	Grade 40 Rebar

F_u = Minimum specified tensile strength of steel as tabulated below:

F_u (ksi)	ASTM	Bolt Diameter (in.)
58	A307	All
120	A325	½ to 1, incl.
105	A325	Over 1 to 1½, incl.
120	A449	1/2 to 1, incl.
105	A449	Over to 1 to 1½, incl.
90	A449	Over 1½ to 3, incl.
150	A687	⅝ to 3, incl.

h = Thickness of a concrete slab or wall
L_d = Minimum embedded length required to fully develop the tensile strength of an anchor bolt
l_d = Basic development length for reinforcement
l_{dh} = Development length of reinforcement with a standard hook
m = Edge distance from the center of an anchor to the edge of concrete
m_t = Minimum edge distance to prevent failure due to lateral bursting forces at a standard anchor bolt head
m_v = Minimum edge distance to develop the full tensile capacity of an anchor bolt in shear within additional reinforcement when the shear load acts toward the free edge
n = Number of bolts in a bolt group
PF = Probability Factor
r = Spacing of multiple anchors
r_m = Minimum spacing of multiple anchor bolts
SIF = Stress Increase Factor
T = Total effective anchor bolt design tension load due to bending and direct load
T_F = Tension load acting on an individual anchor bolt or wedge anchor
U_p = Pullout strength of concrete equal to the tensile capacity of the concrete failure cone
V = Total shear in an anchorage
V_i = Shear load acting on an individual anchor
ϕ = Capacity reduction factor
= 0.90 for factored design loads under Ultimate Strength Design (USD) for steel tensile stress
= 0.55 for service design loads under Working Stress Design (WSD); complies with AISC allowable F_t values
μ = Coefficient of friction
α = Probability Factor (PF) or reciprocal of the stress increase factor ($1/SIF$)
β = Concrete tensile stress reduction factor
= 0.65 for concrete tensile stress when embedded anchor head is *within* far face reinforcement
= 0.85 for concrete tensile stress when embedded anchor head is *beyond* the far face reinforcement

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APPENDIX A. MINIMUM SPACING AND EMBEDMENT

An equivalent circle is assumed equal to the projected area of a heavy hexagonal head (see Fig. 10).

$$A_{hex} = \left(\frac{\sqrt{3}}{2}\right) F^2 = 0.866F^2$$

$$A_{circle} = \pi C^2/4$$

$$0.866F^2 = \pi C^2/4$$

$$C = \sqrt{\frac{0.866F^2(4)}{\pi}} = 1.05F$$

Tensile stress area $A_e = A_1 - A_2$

$$= \pi\,(L + C/2)^2 - \pi\,(C/2)^2$$
$$= \pi\,[L^2 + CL + C^2/4 - C^2/4]$$
$$= \pi\,[L^2 + CL]$$

$$U_p = A_e[4\beta\sqrt{f'_c} \qquad \text{(assume } \beta = 0.65)$$
$$= \pi[L^2 + CL][4(0.65)\sqrt{3000}]$$
$$= \pi[L^2 + CL]142$$
$$= 447(L^2 + CL)$$

Also, $U_p = F_u A_t$, in pounds (see Table 3).

Therefore,

$$0 = 447.4L^2 + 447.4CL - F_u A_t$$
$$0 = L^2 + CL - (F_u A_t/447.4)$$
$$L = \frac{-C \pm \sqrt{C^2 + 4\left[\frac{F_u A_t}{447}\right]}}{2}$$
$$= \frac{\sqrt{C^2 + \left[\frac{F_u A_t}{112}\right]} - C}{2}$$

See Table 4 for tabulated values. The design criteria are as follows:

1. Minimum spacing of bolts (r_m):
   For A307: $2 \times 8.0d = 16d$
   For A325/A449: $2 \times 12.0d = 24d$
   For A687: $2 \times 14.0d = 28d$

Table 4. Tabulated Values of *L*

Bolt Diameter d (in.)	Tensile Stress Area A_t (in.^{2})	Heavy Hex Width Across Flats F (in.)	Eff. Dia. C (in.)	A36, A307		A325, A449		A687	
				L (in.)	*L/d	L (in.)	*L/d	L (in.)	*L/d
½	0.142	0.875	0.92	3.9	7.8	5.8	11.6	6.5	12.9
⅝	0.226								
¾	0.334	1.25	1.32	6.0	8.0	8.9	11.9	10.0	13.3
⅞	0.462								
1	0.606	1.625	1.71	8.1	8.1	12.0	12.0	13.4	13.4
1¼	0.969								
1½	1.41	2.375	2.50	12.4	8.3	17.0	11.4	20.5	13.6
1¾	1.90								
2	2.50	3.125	3.28	16.5	8.3	22.7	11.4	27.3	13.7
2¼	3.25								
2½	4.00	3.875	4.07	20.9	8.4	28.7	11.5	34.6	13.8
2 ¾	4.93								
3	5.97	4.625	4.86	25.5	8.5	35.1	11.7	42.3	14.1

* To ensure ductile failure, use the value of L/d obtained by multiplying the largest L/d value in each column by an arbitrary factor of safety of 1.33:
For A36, A307: $L/d = 1.33\,(8.5) = 12$
For A325, A449: $L/d = 1.33\,(12.0) = 16$
For A687: $L/d = 1.33\,(14.1) = 19$

2. Formula for embedment length (L_d):

$$L_d = 12d\sqrt{\frac{f_u}{58000}}, \qquad \text{where } F_u \text{ is in ksi.}$$

3. Embedment length (L_d):

   For A307: $L_d = 12d$

   For A325/A449: $L_d = 17d$

   For A687: $L_d = 19d$

4. Values are tabulated in Table 2.

APPENDIX B. BOLT TENSION/ SHEAR INTERACTION EQUATIONS

The area of steel required for tension and shear is considered additive.

$$A_v = \frac{\alpha CV}{F_v} = \text{area of steel required for shear}$$

$$A_T = \frac{\alpha T_F}{F_A} = \text{area of steel required for tension}$$

where

F_v = allowable shear stress
F_A = allowable tension stress
α = Probability factor (PF) or reciprocal of the stress increase factor ($1/SIF$).
Note: $\alpha \leq 1.0$.

$$A_v + A_T = A_t$$

where A_t = tensile stress area of anchorage

$$\frac{\alpha CV}{F_v} + \frac{\alpha TF}{F_A} = A_t$$

$$\frac{CV}{F_v A_t} + \frac{T_F}{F_A A_t} = \frac{1}{\alpha}$$

The shear force (V) causes a crushing/bearing failure near the surface and translates the shear load into an effective tension load in the anchorage.

$$F_v = F_A$$

$$F_v A_t = F_A A_t = \phi T$$

$$\frac{CV}{\phi T} + \frac{T_F}{\phi T} = \frac{1}{\alpha}$$

$$T = \left[\frac{CV + T_F}{\phi}\right]\alpha$$

Note that A_T may be solved for as follows:

$$\frac{\alpha CV}{F_v} + \frac{\alpha T_F}{F_A} = A_t$$

$$F_v = F_A = \phi F_y$$

$$A_t = \left[\frac{CV + T_F}{\phi F_y}\right]\alpha$$

Expressed as an interaction equation:

$$\frac{CV}{\phi F_y A_t} + \frac{F}{\phi F_y A_t} \leq \frac{1}{\alpha}$$

APPENDIX C. PROBABILITY-BASED LIMIT STATES DESIGN (PBLSD)

1. The PBLSD design criterion is expressed in general form as follows:

   Design Resistance ≥ Effect of Design Loads

   In equation form: $\phi R \geq \gamma_e \sum_{k=1}^{j} Q_k \gamma_k$

   where

   ϕ = resistance factor, less than 1.0, accounts for uncertainties in material strength
   R = nominal design resistance (capacity), equal to the plastic strength of a structural member
   γ_e = analysis factor
   γ_k = load factor, normally greater than 1.0, and provides for load variations
   Q_k = nominal design load effect
   $\sum_{k=1}^{j}$ = denotes the combined load effects from various causes

2. The PBLSD uses the concept of "limit state" design. The nominal resistance (R) is always related to a specific "limit state." Two classes of limit states are pertinent to structural design: the "ultimate limit state" and the "serviceability or working limit state." Violation of the "ultimate limit state" involves loss of all or parts of the structure mechanism. "Serviceability limit state" involves excessive deflection, excessive vibration and gross yielding.

3. The anchor bolt design equation expressed in PBLSD form may be derived as follows:

   $$\phi R \geq \gamma_e \sum_{k=1}^{j} Q_k \gamma_k$$

   Let $R = F_y A_t$

   where

   F_y = minimum yield strength of steel
   A_t = bolt tensile area

   Let $\gamma_e = \alpha$

   Let $\sum_{k=1}^{j} \gamma_k Q_k = CV_i + T_F$

   (the combined effect of tension and shear loads as derived in Appendix B.)

   where

   C = Shear coefficient

$$V_i = \gamma_1 V_1 + \gamma_2 V_2 + \ldots \gamma_k V_k$$
$$T_F = \gamma_1 T_1 + \gamma_2 T_2 + \ldots \gamma_k T_k$$
γ_1 = Load factor for load case number 1
γ_2 = Load factor for load case number 2

By substitution: $\phi F_y A_t \geq [CV_i + T_F]\alpha$

$$F_y A_t \geq \left[\frac{CV_i + T_F}{\phi}\right] \alpha = T$$

where $F_y A_t$ values are tabulated in Table 2A.

Note: ϕ = 0.90 is a resistance factor which accounts for uncertainties in material strength (USD).
ϕ = 0.55 is a resistance factor which converts the yield capacity to working loads (WSD)