Anchor Bolt Design

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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Course Description

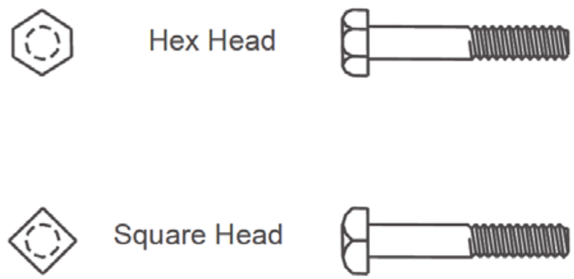
There were two major changes to the anchor bolt design provisions in the 2016 edition of TMS 402. One change was to increase the calculated shear crushing strength by 67%. The other change was to go from a linear interaction equation for combined bending and shear to an elliptical interaction equation. This webinar will cover the basis for these changes. In addition to the changes in TMS 402, ASCE 7-16 reduced the required load increase for seismic applications when the anchor bolt failure is not yielding from 2.5 to 2.0. The webinar will also cover general anchor bolt design in masonry, will provide practical design tips, and show examples of anchor bolt design.

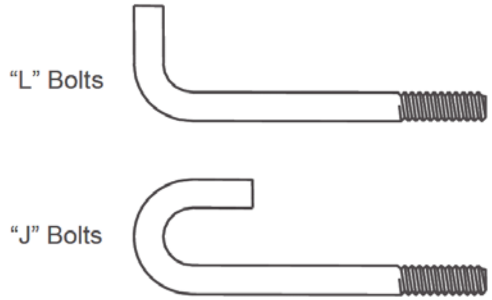
Learning Objectives

- Understand the changes, and the basis for the changes, to anchor bolt design provisions in TMS 402.
- Understand the design of anchors bolts in tension.
- Understand the design of anchor bolts in shear.
- Understand the design of anchor bolts in combined tension and shear.

General Anchor Bolt Information

Types of Anchor Bolts

<table>
<tr><th>Headed Anchor Bolts</th><th>Bent-Bar Anchor Bolts</th></tr>
<tr><td>


TMS 402 *Figure CC-6.3-1*
</td><td>


TMS 402 *Figure CC-6.3-1*
</td></tr>
<tr><td>
ASTM A307, Grade A

ASTM A307: no specified yield strength
TMS 402 Commentary recommends a yield strength of 37 ksi; results in anchor capacities similar to AISC provisions
Many designers use a yield strength of 36 ksi

</td><td>
ASTM A36

<u>ASTM F1554 anchor bolts</u>

Not included in TMS 602
Three specified yield strengths : 36, 55, and 105 ksi
36 ksi usually sufficient for masonry

</td></tr>
</table>

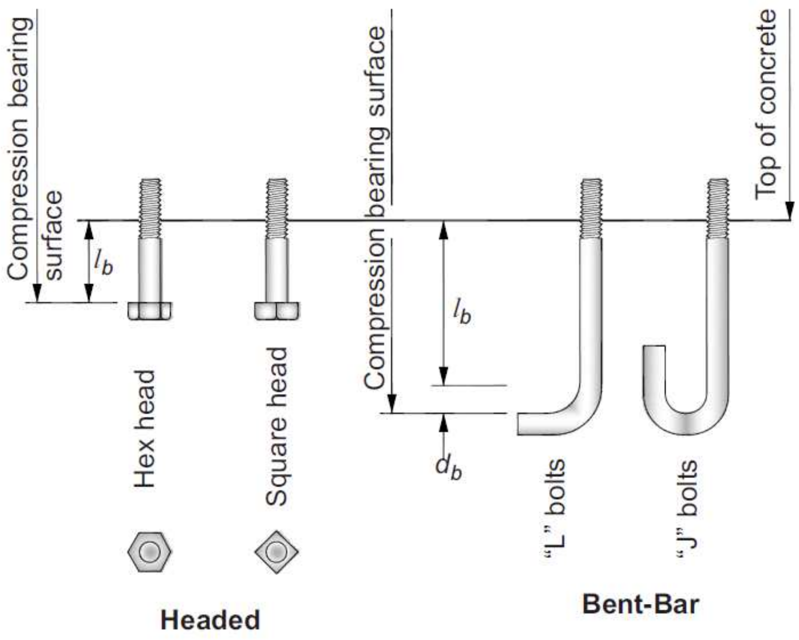
TMS 602 Article 2.4 D

Placement of Anchor Bolts

Provision	TMS 402 Ref.
Placed in grout; Exception: 1/4 in. anchor bolts may be placed in 1/2 in. mortar joints. Thickness of grout between masonry unit and anchor bolt Coarse grout: 1/2 in. Fine grout: 1/4 in. Anchor bolts in drilled holes of face shell permitted to contact face shell Clear distance between bolts ≤ max{ d_b, 1 in.}	6.3.1

Embedment Length

Provision	TMS 402 Ref.
Headed bolts: masonry surface to compression bearing surface of head	6.3.4
Bent-bar bolts: masonry surface to the compression bearing surface of the bent end, minus one anchor bolt diameter.	6.3.5
Minimum l_b = max{$4d_b$, 2in.}	6.3.6



Reinforced Masonry Engineering Handbook Figure 5.45

Anchor Bolt Sizes

A = nominal area

A_b = effective tensile stress area

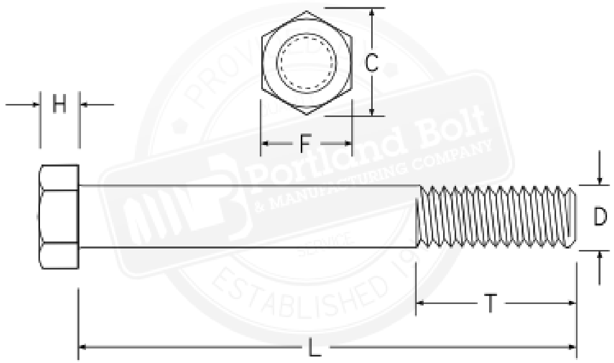
F = width across flats

C = width across corners

H = height of head

d_0 = nominal anchor diameter

n_t = number of threads per inch



http://www.portlandbolt.com/print/?table=1601

$$A_b = \frac{\pi}{4}\left(d_0 - \frac{0.9743}{n_t}\right)^2$$

Bolt	A (in.^{2})	A_b (in.^{2})	F (in.)	C (in.)	H (in.)
1/2 - 13	0.196	0.142	3/4	0.866	11/32
5/8 - 11	0.307	0.226	15/16	1.083	27/64
3/4 - 10	0.442	0.334	1-1/8	1.299	1/2
7/8 - 9	0.601	0.462	1-5/16	1.516	37/64
1 - 8	0.785	0.606	1-1/2	1.732	43/64

Anchor Bolt Testing: TMS 402

8.1.3.2.1 Anchors shall be tested in accordance with ASTM E 488 under stresses and conditions representing intended use, except that a minimum of five tests shall be performed.

8.1.3.2.2 Allowable loads shall not exceed 20 percent of the average tested strength.

9.1.6.2.2 Anchor bolt nominal strengths used for design shall not exceed 65 percent of the average failure load from the tests.

ASCE 7-16 Modifications

ASCE 7-16 Modification:

13.4.2.2 Non-structural components

14.4.5 Material specific design and detailing requirements

IBC Section 1613 excludes Chapter 14 of ASCE 7

15.4.9.2 Non-building structures

ASCE 7-16 Modifications

13.4 Nonstructural Component Anchorage

ASCE 7-10

13.4.2.2 Anchors in Masonry.

- Designed by TMS 402.
- Designed to be governed by tensile or shear yielding.

EXCEPTION:

1. Support or component that is being anchored undergoes ductile yielding at a load level < anchor design load. OR
2. Design strength of the anchors at least **2.5** times the factored forces transmitted by the component.

ASCE 7-16

13.4.2.2 Anchors in Masonry.

- Designed by TMS 402.
- Designed to be governed by tensile or shear yielding.

EXCEPTION:

1. Support or component that is being anchored undergoes ductile yielding at a load level < anchor design load. OR
2. Anchors designed to resist the load combinations in Section 12.4.3 with Ω_0 as in Tables 13.5-1 and 13.6-1.

ASCE 7-16 Modifications

Table 13.5-1 Coefficients for Architectural Components

Ω_0 = 2 for most things

Ω_0 = 1.5 for a few things

Ω_0 = 2.5 for

- Other flexible components with high-deformability or limited deformability elements and attachments
  - Low-deformability elements and attachments have Ω_0 = 1.5
- Egress stairs and ramp fasteners and attachments

Table 13.6-1 Seismic Coefficients for Mechanical and Electrical Components

Ω_0 = 2, except Ω_0 = 1.5 for mechanical components elevated on integral structural steel or sheet metal supports

ASCE 7-16 Modifications

14.4.5 Modifications to Chapter 9 of TMS 402

Anchorage assemblies connecting masonry elements that are part of the seismic force-resisting system to diaphragms and chords shall be designed so that the strength of the anchor is governed by steel tensile or shear yielding.

Alternatively, the anchorage assembly is permitted to be designed so that it is governed by masonry breakout or anchor pullout provided that the anchorage assembly is designed to resist not less than **2.0** times the factored forces transmitted by the assembly.

was 2.5 in ASCE 7-10

IBC Section 1613 excludes Chapter 14 of ASCE 7

ASCE 7-16 Modifications

15.4 Nonbuilding Structural Design Requirements

ASCE 7-10

15.4.9.2 Anchors in Masonry.

- Designed by TMS 402.
- Designed to be governed by tensile or shear yielding.

EXCEPTION:

1. Attachment that the anchor is connecting to the structure undergoes ductile yielding at a load level < anchor design load. OR
2. Design strength of the anchors at least **2.5** times the factored forces transmitted by the component.

ASCE 7-16

15.4.9.2 Anchors in Masonry.

- Designed by TMS 402.
- Designed to be governed by tensile or shear yielding.

EXCEPTION:

1. Attachment that the anchor is connecting to the structure undergoes ductile yielding at a load level < anchor design load. OR
2. Anchors designed to resist the load combinations in Section 12.4.3 with Ω_0 as in Tables 15.4-1 and 15.4-2.

ASCE 7-16 Modifications

Table 15.4-1 Seismic Coefficients for Nonbuilding Structures Similar to Buildings

No masonry system listed in Table 15.4-1.

Section 15.4-1: Design basis is a seismic force-resisting system selected from Table 12.2-1 or Table 15.4-1.

Masonry bearing walls systems in Table 12.2-1: $\Omega_0 = 2.5$

Table 15.4-2 Seismic Coefficients for Nonbuilding Structures Not Similar to Buildings:

All other reinforced masonry structures not similar to buildings

- Detailed as intermediate reinforced masonry shear walls: $\Omega_0 = 2$
- Detailed as ordinary reinforced masonry shear walls: $\Omega_0 = 2.5$

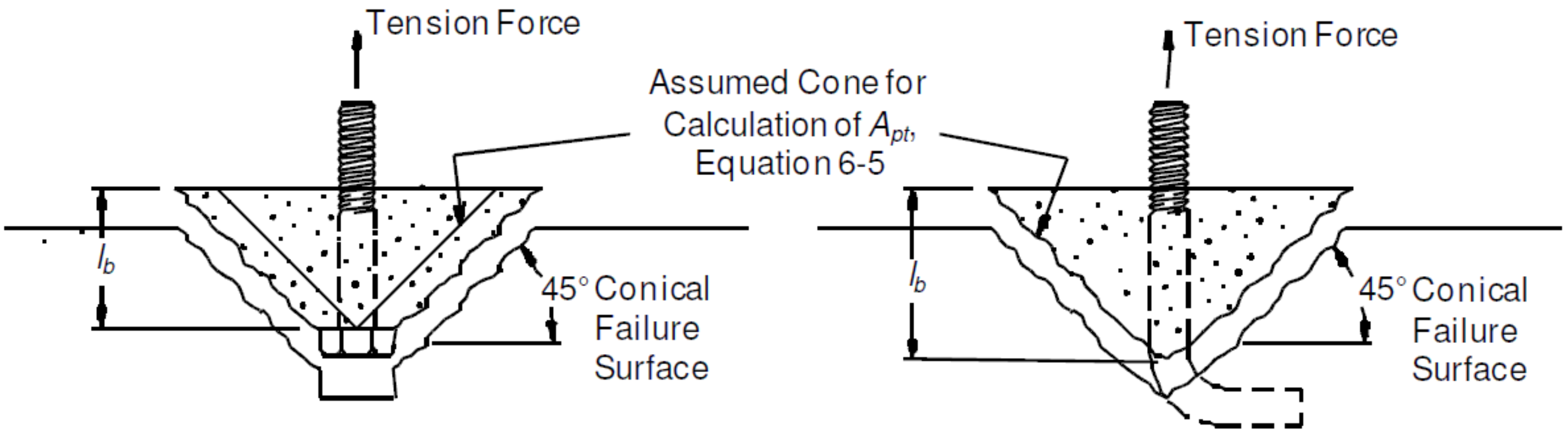
All other nonreinforced masonry structures not similar to buildings: $\Omega_0 = 2$

Anchor Bolts In Tension

Tension Strength

Failure Mode	Allowable Stress Design (8.1.3.3.1)	Strength Design (9.1.6.3.1)
Masonry breakout	$B_{ab} = 1.25 A_{pt} \sqrt{f'_m}$	$B_{anb} = 4 A_{pt} \sqrt{f'_\mathrm{m}}$ $\phi = 0.5$
Steel yielding	$B_{as} = 0.60 A_b f_y$	$B_{ans} = A_b f_y$ $\phi = 0.9$
Anchor pullout (0nly bent bar)	$B_{ap} = 0.6 f'_\mathrm{m} e_b d_b + [120\pi(l_b + e_b + d_b)d_b]$	$B_{anp} = 1.5 f'_\mathrm{m} e_b d_b + [300\pi(l_b + e_b + d_b)d_b]$ $\phi = 0.65$

Tensile Breakout Cone



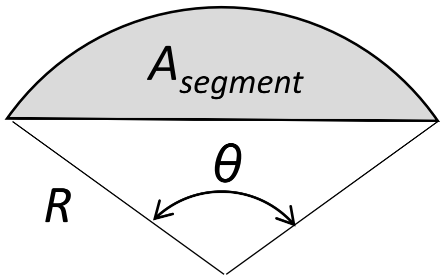
TMS 402 *Figure CC-6.3-3*

$$A_{pt} = \pi l_b^2$$ TMS 402 Equation 6-5

- Projected area reduced by that in an open cell, core, or outside the wall.
- When projected areas overlap, projected area reduced so no portion of the masonry included more than once.

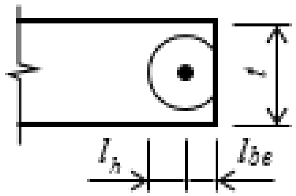
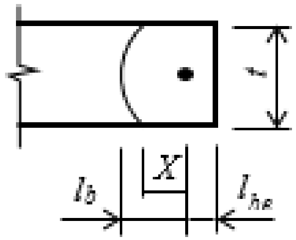
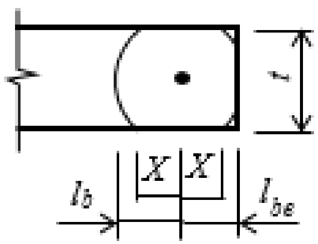
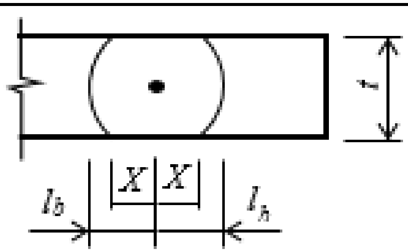
Geometry

$$A_{segment} = \frac{R^2}{2}\left(\frac{\pi\theta}{180} - \sin\theta\right)$$



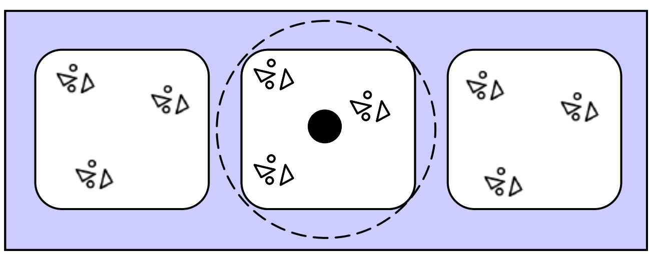
Following table can be developed

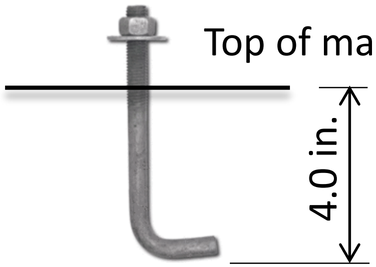
1. θ and θ_1 in degrees
2. $X = \sqrt{l_b^2 - (t/2)^2}$
3. The table can be used for multiple bolts by setting $l_{be} = s_1/2$, where s_1 is the spacing of the bolts, finding A_{pt} for each bolt, and then adding to get the total projected tension area.

Anchor bolt configuration	Geometry	Projected tension area, A_{pt}
	$l_b \le \frac{t}{2}$ $l_{be} \le l_b$	$A_{pt} = \pi l_b^2 - \frac{l_b^2}{2}\left(\frac{\pi\theta}{180} - \sin\,\theta\right)$ $\theta = 2\arccos\left(\frac{l_{be}}{l_b}\right)$
	$l_b > \frac{t}{2}$ $l_{be} \le l_b$ $l_{be} \le X$	$A_{pt} = (X + l_{be})t + \frac{l_b^2}{2}\left(\frac{\pi\theta}{180} - \sin\,\theta\right)$ $\theta = 2\arcsin\left(\frac{t/2}{l_b}\right)$
	$l_b > \frac{t}{2}$ $l_{be} \le l_b$ $l_{be} > X$	$A_{pt} = 2Xt + \frac{l_b^2}{2}\left(\frac{\pi(\theta - \theta_1)}{180} - \sin\,\theta + \sin\,\theta_1\right)$ $\theta = 2\arcsin\left(\frac{t/2}{l_b}\right)$ $\theta_1 = 2\arccos\left(\frac{l_{be}}{l_b}\right)$
	$l_b > \frac{t}{2}$ $l_{be} > l_b$	$A_{pt} = 2Xt + l_b^2\left(\frac{\pi\theta}{180} - \sin\,\theta\right)$ $\theta = 2\arcsin\left(\frac{t/2}{l_b}\right)$

Example: Bent-Bar Anchor

- 1/2-in. diameter, A36 bent-bar anchor with a 1-in. hook
- embedded vertically in a grouted bond beam of an 8-in. CMU wall
- bottom of the anchor hook is embedded a distance of 4.0 in.
- f'_m = 2,000 psi
- Use strength design to determine design tensile strength





Effective embedment $l_b = 4.0in. - d_b - d_b = 4.0in. - 2(0.5in.) = 3.0in.$

Projected tensile area $A_{pt} = \pi l_b^2 = \pi(3.0in.)^2 = 28.3in.^2$

Design Strength:

Masonry breakout: $\phi B_{anb} = \phi 4 A_{pt}\sqrt{f'_m} = 0.5(4)(28.3in.^2)\sqrt{2000psi} = 2530\ lb$

Steel yielding: $\phi B_{ans} = \phi A_b f_y = 0.9(0.142in.^2)(36{,}000psi) = 4600\ lb$

Anchor pullout:

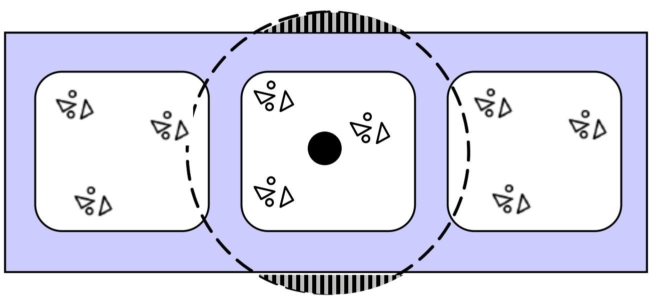
$$\phi B_{anp} = \phi[1.5 f'_m e_b d_b + 300\pi(l_b + e_b + d_b)d_b]$$
$$= 0.65[1.5(2000psi)(1.0in.)(0.5in.)$$
$$+300\pi(3.0\ in. + 1.0in. + 0.5in.)(0.5in.)$$
$$= 2350\ lb$$

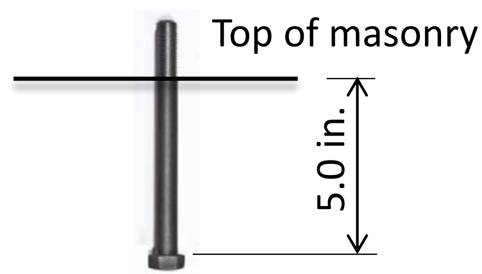
Design strength = 2350 lb

Typically pullout controls with bent-bar anchor bolts and headed bolts are recommended.

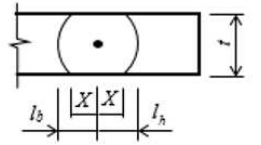
Example: Headed Anchor

- 1/2-in. diameter, A307 headed anchor bolt
- embedded vertically in a grouted bond beam of an 8-in. CMU wall
- embedment is 5.0 in.
- f'_m = 2,000 psi
- Use strength design to determine design tensile strength





Projected Tensile Area:

	$l_b > \frac{t}{2}$ $l_{be} > l_b$	$A_{pt} = 2Xt + l_b^2\left(\frac{\pi\theta}{180} - \sin\theta\right)$ $\theta = 2\arcsin\left(\frac{t/2}{l_b}\right)$

$$X = \sqrt{l_b^2 - (t/2)^2} = \sqrt{(5.0in.)^2 - (7.625in./2)^2} = 3.235in.$$

$$\theta = 2\arcsin\left(\frac{t/2}{l_b}\right) = 2\arcsin\left(\frac{7.625in./2}{5.0in.}\right) = 99.4^\circ$$

$$A_{pt} = 2Xt + l_b^2\left(\frac{\pi\theta}{180} - sin\theta\right)$$

$$= 2(3.235in.)(7.625in.) + (5.0in.)^2\left(\frac{\pi(99.4^\circ)}{180} - sin99.4^\circ\right) = 68.0\text{in.}^2$$

Design Strength:

Masonry breakout: $\phi B_{anb} = \phi 4 A_{pt}\sqrt{f'_m} = 0.5(4)(68.0in.^2)\sqrt{2000psi} = 6080\ lb$

Steel yielding: $\phi B_{ans} = \phi A_b f_y = 0.9(0.142in.^2)(36{,}000psi) = 4600\ lb$

Design strength = 4600 lb

Solve for minimum embedment to develop yield strength of anchor:

Set masonry breakout design strength to 4600 lb:

$$\phi B_{anb} = \phi 4 A_{pt}\sqrt{f'_m}$$
$$4600lb = 0.5(4)\left(A_{pt}\right)\sqrt{2000psi}$$
$$A_{pt} = 51.4\ in.^2$$

Solve numerically:

$$l_b = 4.09\ in.$$

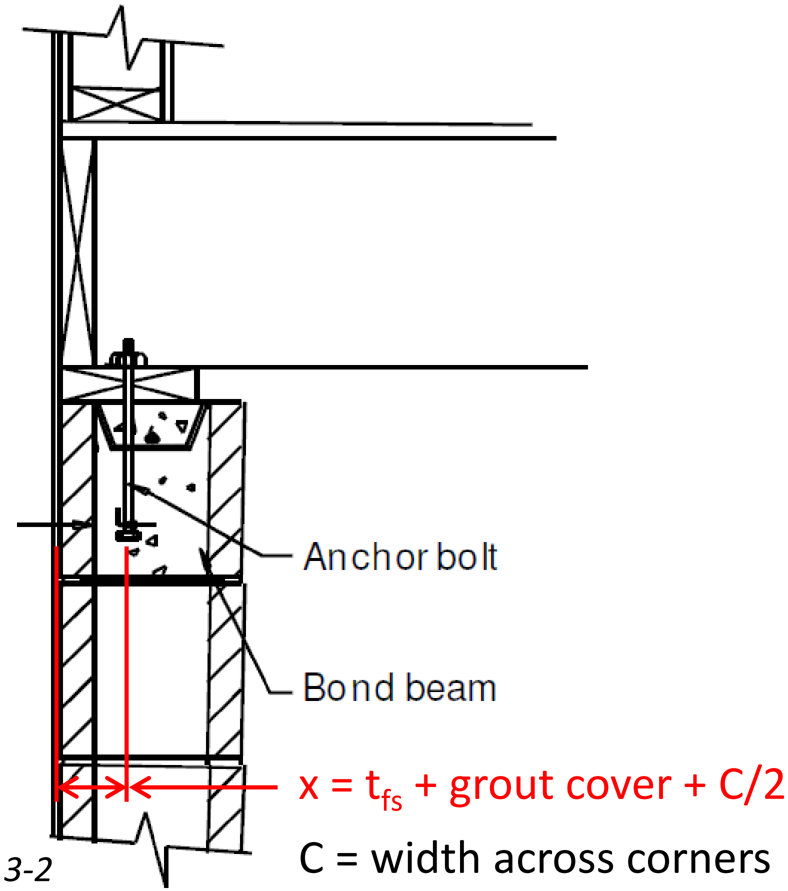
Use embedment depth of 4.25 inch for yield to control

Design Table: Tension

Minimum embedment length (inch) for yielding to control headed bolt strength
Bolt embedded at mid-thickness of top of CMU wall

Bolt diam.	8 inch CMU			12 inch CMU		
	f'_m = 2 ksi	f'_m = 2.5 ksi	f'_m = 3 ksi	f'_m = 2 ksi	f'_m = 2.5 ksi	f'_m = 3 ksi
1/2	4-1/4 (4.09)	4 (3.83)	3-3/4 (3.66)	4-1/4 (4.05)	4 (3.83)	3-3/4 (3.66)
5/8	6 (5.82)	5-1/2 (5.30)	5 (4.93)	5-1/4 (5.10)	5 (4.83)	4-3/4 (4.61)
3/4	8-1/4 (8.24)	7-1/2 (7.44)	7 (6.85)	6-1/2 (6.28)	6 (5.87)	5-3/4 (5.61)
7/8	11-1/4 (11.19)	10-1/4 (10.06)	9-1/4 (9.23)	8 (7.98)	7-1/2 (7.31)	7 (6.83)
1	14-3/4 (14.56)	13-1/4 (13.06)	12 (11.96)	10-1/4 (10.04)	9-1/4 (9.11)	8-1/2 (8.44)

Headed Anchor: Placement



TMS 402 *Figure CC-6.3-2*

C = width across corners

Bolt	x (in.)
1/2	2-1/4 (2.18)
5/8	2-1/2 (2.29)
3/4	2-1/2 (2.40)
7/8	2-1/2 (2.51)
1	2-3/4 (2.62)

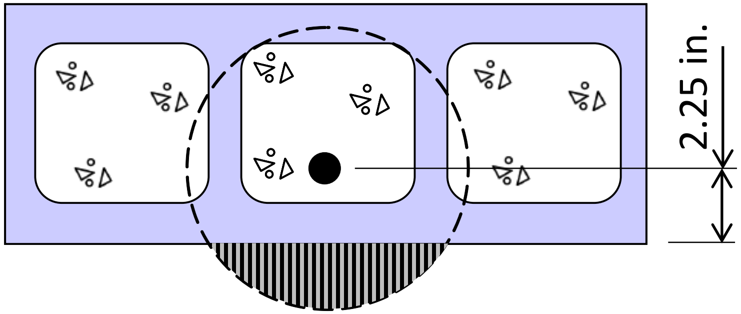
x = closest centerline of bolt can be to edge of masonry

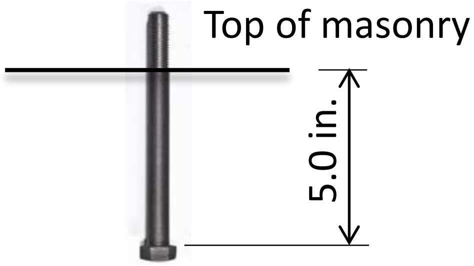
Example: 1/2 in bolt, coarse grout

x = 1.25 in. + 0.5 in. + (0.866 in.)/2 = 2.18 in.

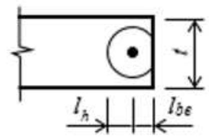
Example: Headed Anchor

- 1/2-in. diameter, A307 headed anchor bolt
- embedded vertically in a grouted bond beam of an 8-in. CMU wall
- embedment is 5.0 in.
- 2.25 in. from edge of wall
- f'_m = 2,000 psi
- Use strength design to determine design tensile strength





Projected Tensile Area:

	$l_b \le \frac{t}{2}$ $l_{be} \le l_b$	$A_{pt} = \pi l_b^2 - \frac{l_b^2}{2}\left(\frac{\pi \theta}{180} - \sin\theta\right)$ $\theta = 2\arccos\left(\frac{l_{be}}{l_b}\right)$

$$\theta = 2\arccos\left(\frac{l_{be}}{l_b}\right) = 2\arccos\left(\frac{2.25in.}{5.0in.}\right) = 126.5\,°$$

$$A_{pt} = \pi l_b^2 - \frac{l_b^2}{2}\left(\frac{\pi\theta}{180} - sin\theta\right)$$

$$= \pi(5.0in.)^2 - \frac{(5.0in.)^2}{2}\left(\frac{\pi(126.5°)}{180} - sin126.5°\right) = 61.0\text{in.}^2$$

Design Strength:

Masonry breakout: $\phi B_{anb} = \phi 4 A_{pt}\sqrt{f'_m} = 0.5(4)(61.0in.^2)\sqrt{2000psi} = 5460\ lb$

Steel yielding: $\phi B_{ans} = \phi A_b f_y = 0.9(0.142in.^2)(36{,}000psi) = 4600\ lb$

Design strength = 4600 lb

Solve for minimum embedment to develop yield strength of anchor:

Set masonry breakout design strength to 4600 lb:

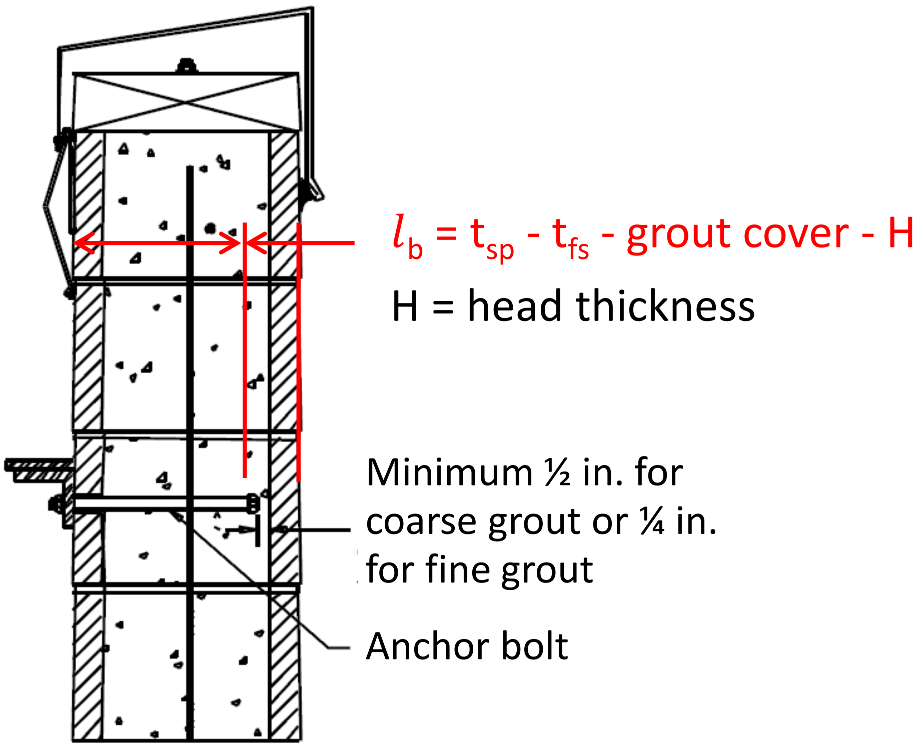
$$\phi B_{anb} = \phi 4 A_{pt} \sqrt{f'_m}$$
$$4600 lb = 0.5(4)\left(A_{pt}\right)\sqrt{2000 psi}$$
$$A_{pt} = 51.4\ in.^2$$

Solve numerically:

$$l_b = 4.51\ in.$$

Use embedment depth of 4.5 inch for yield to control

Headed Anchor: Placement



TMS 402 *Figure CC-6.3-2*

Bolt	l_b (in.)	Design strength
1/2	5-1/2 (5.53)	4600 lb (yield)
5/8	5-1/4 (5.45)	7320 lb (yield)
3/4	5-1/4 (5.38)	7740 lb (breakout)
7/8	5-1/4 (5.30)	7740 lb (breakout)
1	5 (5.20)	7020 lb (breakout)

l_b = maximum embedment depth

f'_m = 2000 psi

<u>Example:</u> 1/2 in bolt, coarse grout

l_b = 7.625 in. - 1.25 in. - 0.5 in. - 11/32 = 5.53 in.

Tensile Strength of Bolt: ???

TMS 402 Section 2.1 Notation
A_b = cross-sectional area of an anchor bolt

Commentary 9.1.6.3.1.1 *Axial tensile strength of headed anchor bolts* — Steel strength is calculated using the effective tensile stress area of the anchor (that is, including the reduction in area of the anchor shank due to threads).

Commentary 9.1.6.3 *Nominal strength determined by calculation for headed and bent-bar anchor bolts* — Use of a yield strength of 37 ksi in the Code design equations for A307 anchors will result in anchor capacities similar to those obtained using the American Institute of Steel Construction provisions.

Tensile Strength of Bolt: ???

Allowable Tensile Strength of A307 Anchor Bolts

<u>TMS 402</u>

$0.6A_b f_y$ where A_b= effective area $\approx 0.75(A_{nominal})$

$0.6(0.75)A_{nominal}(37ksi) = 16.6ksi(A_{nominal})$

<u>AISC 360</u>

Allowable tensile strength: $\frac{F_{nt}A_b}{\Omega}$

A_b = nominal unthreaded area of bolt

F_{nt} = 45 ksi for A307 bolts

$\frac{F_{nt}A_b}{\Omega} = \frac{45ksi(A_{nominal})}{2} = 22.5ksi(A_{nominal})$

Using $0.6A_{nominal}(37ksi) = 22.2ksi(A_{nominal})$

Tensile Strength of Bolt: ???

Design Tensile Strength of A307 Anchor Bolts

<u>TMS 402</u>

$\phi A_b f_y$ where A_b= effective area $\approx 0.75(A_{nominal})$

$0.9(0.75)A_{nominal}(37ksi) = 25.0ksi(A_{nominal})$

Using $0.9A_{nominal}(37ksi) = 33.3ksi(A_{nominal})$

<u>AISC 360</u>

Design tensile strength: $\phi F_{nt} A_b$

$\phi F_{nt} A_b = 0.75(45ksi)A_b = 33.8ksi(A_{nominal})$

<u>ACI 318</u>

$\phi A_{se,N} f_{uta} = 0.75[0.75A_{nominal}](60ksi) = 33.8ksi(A_{nominal})$

Anchor Bolts In Shear

Shear Strength

Failure Mode	Allowable Stress (8.1.3.3.2)	Strength (9.1.6.3.2)
Masonry breakout	$B_{vb} = 1.25 A_{pv} \sqrt{f'_m}$ Errata: Listed as B_{av} in 2016 TMS 402	$B_{vnb} = 4 A_{pv} \sqrt{f'_m}$ $\phi = 0.5$
Masonry crushing (changed in 2016)	$B_{vc} = 580 \sqrt[4]{f'_m A_b}$	$B_{vnc} = 1750 \sqrt[4]{f'_m A_b}$ $\phi = 0.5$
Anchor bolt pryout	$B_{vpry} = 2.0 B_{ab} = 2.5 A_{pt} \sqrt{f'_m}$	$B_{vnpry} = 2.0 B_{anb} = 8 A_{pt} \sqrt{f'_m}$ $\phi = 0.5$
Steel yielding	$B_{vs} = 0.36 A_b f_y$	$B_{vns} = 0.6 A_b f_y$ $\phi = 0.9$

Masonry Crushing: 2013

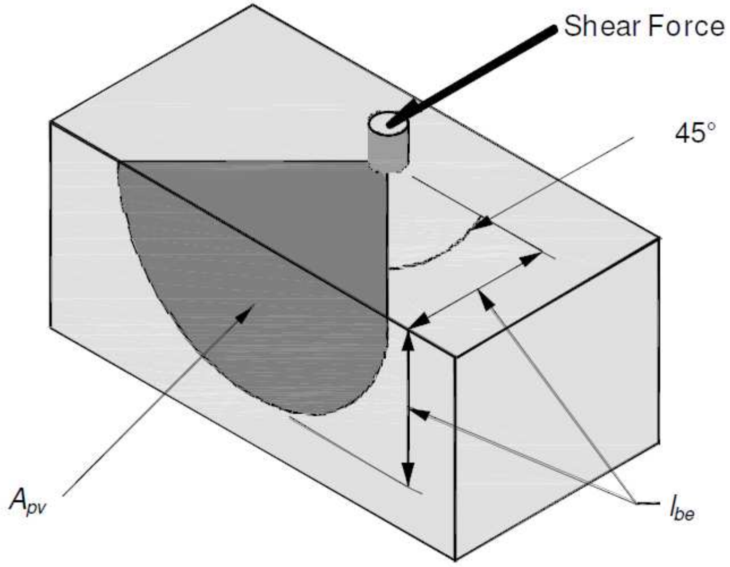
	TMS 402-13 Governing Equation		
	Breakout	Crushing	Yielding
Design Strength	$4A_{pv}\sqrt{f'_m}$	$1050\sqrt[4]{f'_m A_b}$	$0.6A_b f_y$
Number of Tests	95	188	62
Average of Test/Calculated	1.23	2.33	1.45
Standard Deviation of Ratio	0.14	0.73	0.20
Coefficient of Variation	0.11	0.31	0.14

- Several alternate equations for shear crushing were examined
- FEMA 369 equation chosen: $1750\sqrt[4]{f'_m A_b}$.

Masonry Crushing: 2016

	TMS 402-16 Governing Equation		
	Breakout	Crushing	Yielding
Design Strength	$4A_{pv}\sqrt{f'_m}$	$1750\sqrt[4]{f'_m A_b}$	$0.6A_b f_y$
Number of Tests	95	131	119
Average of Test/Calculated	1.23	1.49	1.44
Standard Deviation of Ratio	0.14	0.44	0.35
Coefficient of Variation	0.11	0.29	0.24

Shear Breakout



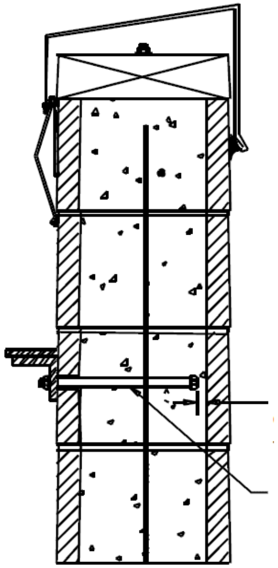
TMS 402 *Figure CC-6.3-6*

$$A_{pv} = \frac{\pi l_{be}^2}{2}$$

l_{be} = edge of masonry to center of bolt in direction of load

Example: Shear

- 1/2-in. diameter, A307 headed anchor
- embedded horizontally in the side of an 8-in. CMU wall
- embedment depth of 5.0 in.
- f'_m = 2,000 psi
- Use strength design to determine design shear strength
- anchor is located far from free edges in the direction of applied shear



Design Strength:

Masonry crushing:

$$\phi B_{vnc} = \phi(1750)\sqrt[4]{f'_m A_b}$$
$$= 0.5(1750)\sqrt[4]{(2000psi)(0.142in.^2)} = 3592\ lb$$

effective bolt area used for masonry crushing; entire area of the bolt will bear against the masonry but A_b used for consistency and effective bolt area was basis on analysis for code change. Only makes 7% difference.

Masonry pryout:

$$\phi B_{vnpry} = \phi 8 A_{pt}\sqrt{f'_m} =$$
$$= 0.5(8)(78.5in.^2)\sqrt{2000psi} = 14,040lb$$
$$A_{pt} = \pi l_b^2 = \pi(5.0in.)^2 = 78.5\text{in.}^2$$

Steel yielding:

$$\phi B_{vns} = \phi 0.6 A_b f_y = 0.9(0.6)(0.142in.^2)(36{,}000psi) = 2760\ lb$$

Commentary 9.1.6.3.2 Steel strength is calculated using the effective tensile stress area (that is, threads are conservatively assumed to lie in the critical shear plane).

Design strength = 2760 lb

Determine the minimum edge distance so masonry breakout will not control:

Set masonry breakout design strength to 2760 lb:

$$\phi B_{vnb} = \phi 4 A_{pv}\sqrt{f'_m}$$
$$2760lb = 0.5(4)\left(A_{pv}\right)\sqrt{2000psi}$$
$$A_{pv} = 30.9\ in.^2$$

Solve for l_{be}:

$$A_{pv} = \frac{\pi l_{be}^2}{2}$$
$$30.9in.^2 = \frac{\pi l_{be}^2}{2}$$
$$l_{be} = 4.43\ in.$$

As long as the edge distance is greater than 4.4 in., shear breakout will not control for this problem.

Determine the minimum embedment so anchor bolt pryout will not control:

Set pryout design strength to 2760 lb:

$$\phi B_{vnpry} = \phi 8 A_{pt} \sqrt{f'_m}$$
$$2760lb = 0.5(8)\left(A_{pt}\right)\sqrt{2000psi}$$
$$A_{pv} = 15.4\ in.^2$$

Solve for l_b:

$$A_{pv} = \pi l_b^2$$
$$15.4in.^2 = \pi l_b^2$$
$$l_b = 2.22\ in.$$

As long as the embedment is greater than 2-1/4 in., anchor bolt pryout will not control for this problem.

Anchor bolt		**Design shear strength** and minimum required edge distance and effective embedment depth		
Diameter		f'_m = 2000 psi	f'_m = 2500 psi	f'_m = 3000 psi
f_y = 36000 psi				
1/2 in.	Design strength	2760 lb	2760 lb	2760 lb
	Minimum l_{be}	4.4 in.	4.2 in.	4.0 in.
	Minimum l_b	2.2 in.	2.1 in.	2.0 in.
5/8 in.	Design strength	4030 lb	4270 lb	4390 lb
	Minimum l_{be}	5.4 in.	5.2 in.	5.1 in.
	Minimum l_b	2.8 in.	2.6 in.	2.5 in.
3/4 in.	Design strength	4450 lb	4700 lb	4920 lb
	Minimum l_{be}	5.6 in.	5.5 in.	5.3 in.
	Minimum l_b	3.0 in.	3.0 in.	3.0 in.
7/8 in.	Design strength	4820 lb	5450 lb	5340 lb
	Minimum l_{be}	5.9 in.	5.7 in.	5.6 in.
	Minimum l_b	3.5 in.	3.5 in.	3.5 in.
1 in.	Design strength	5160 lb	5820 lb	5710 lb
	Minimum l_{be}	6.1 in.	5.9 in.	5.8 in.
	Minimum l_b	4.0 in.	4.0 in.	4.0 in.

Design strengths controlled by steel yielding are in green.

Minimum embedment depths controlled by $4d_b$ are in gold.

Anchor bolt		**Allowable shear strength** and minimum required edge distance and effective embedment depth		
Diameter		f'_m = 2000 psi	f'_m = 2500 psi	f'_m = 3000 psi
f_y = 36000 psi				
1/2 in.	Design strength	1840 lb	1840 lb	1840 lb
	Minimum l_{be}	4.6 in.	4.3 in.	4.1 in.
	Minimum l_b	2.3 in.	2.2 in.	2.1 in.
5/8 in.	Design strength	2670 lb	2830 lb	2930 lb
	Minimum l_{be}	5.5 in.	5.4 in.	5.2 in.
	Minimum l_b	2.8 in.	2.7 in.	2.6 in.
3/4 in.	Design strength	2950 lb	3120 lb	3260 lb
	Minimum l_{be}	5.8 in.	5.6 in.	5.5 in.
	Minimum l_b	3.0 in.	3.0 in.	3.0 in.
7/8 in.	Design strength	3200 lb	3380 lb	3540 lb
	Minimum l_{be}	6.0 in.	5.9 in.	5.7 in.
	Minimum l_b	3.5 in.	3.5 in.	3.5 in.
1 in.	Design strength	3420 lb	3620 lb	3790 lb
	Minimum l_{be}	6.2 in.	6.1 in.	5.9 in.
	Minimum l_b	4.0 in.	4.0 in.	4.0 in.

Design strengths controlled by steel yielding are in green.

Minimum embedment depths controlled by $4d_b$ are in gold.

Shear Strength of Bolt: ???

Design Shear Strength of A307 Anchor Bolts

<u>TMS 402</u>

$\phi 0.6 A_b f_y$ where A_b= effective area $\approx 0.75(A_{nominal})$

$0.9(0.6)(0.75)A_{nominal}(37ksi) = 15.0ksi(A_{nominal})$

Using $0.9(0.6)A_{nominal}(37ksi)$
$= 20.0ksi(A_{nominal})$

<u>AISC 360</u>

Design shear strength: $\phi F_{nt} A_b$

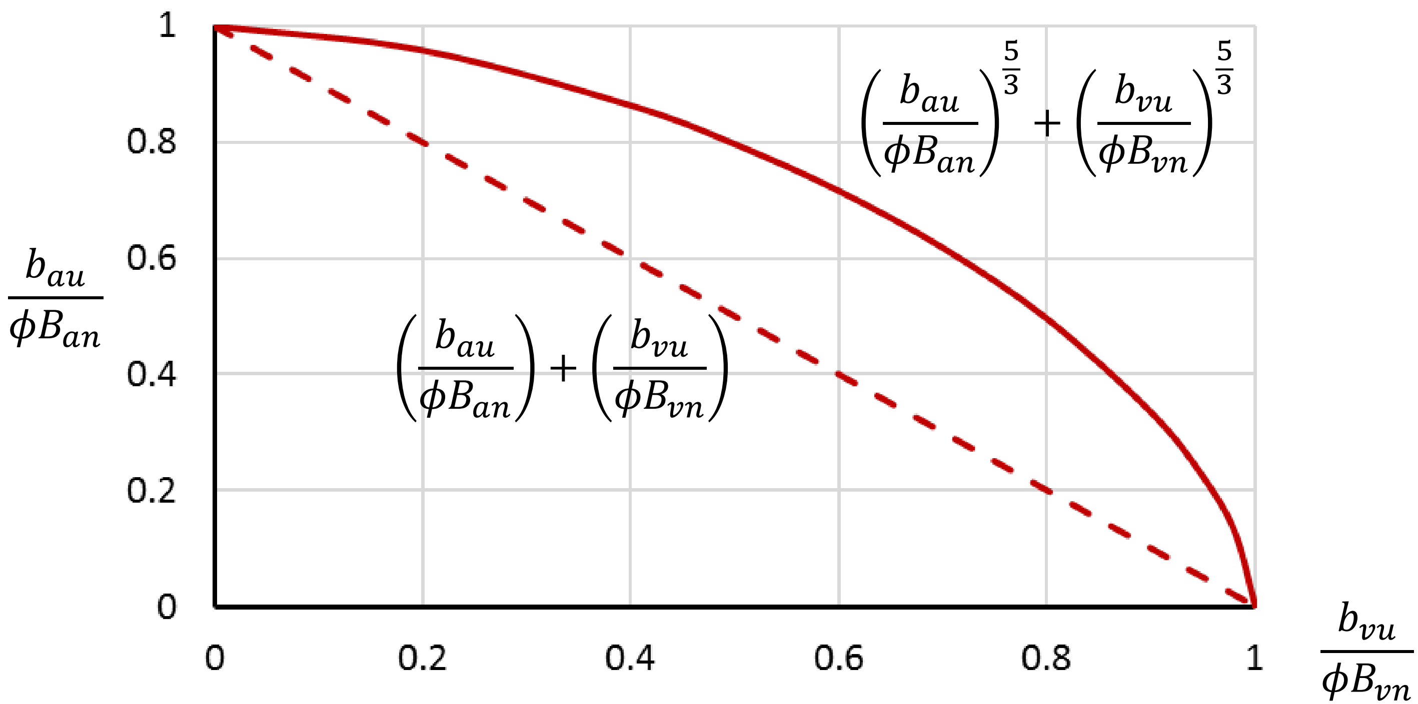
$\phi F_{nt} A_b = 0.75(27ksi)A_b = 20.2ksi(A_{nominal})$

<u>ACI 318</u>

$\phi 0.6 A_{se,V} f_{uta} = 0.75(0.6)[0.75A_{nominal}](60ksi) =$
$20.2ksi(A_{nominal})$

Anchor Bolts In Combined Tension and Shear

Interaction



$\frac{b_{au}}{\phi B_{an}}$	$b_{vu}/\phi B_{vn}$	
	n = 1 (linear)	n = 5/3
0.25	0.75	0.94
0.5	0.50	0.80
0.75	0.25	0.56

Justification for 5/3 Exponent

Fabrello-Streufert et al (2003)

Fabrello-Streufert, A.M., Pollock, D.G., and McLean, D.I. (2003). "Anchor Bolts in Masonry Under Combined Tension and Shear Loading," *TMS Journal*, The Masonry Society, 21(1), 13-28.

- examined a linear equation, a 4/3 exponent, a 5/3 exponent, and circular interaction equation (an exponent of 2).
- Elliptical interaction equation with a 5/3 exponent had the smallest amount of average error and provides a more consistent factor of safety.

McGinley (2003b, 2004)

McGinley, W.M. (2003b). *Capacity of Anchor Bolts in Concrete Masonry*, Phase 3, Report to NCMA.
McGinley, W.M. (2004). *Capacity of Anchor Bolts in Concrete Masonry*, Phase 4, Report to NCMA.

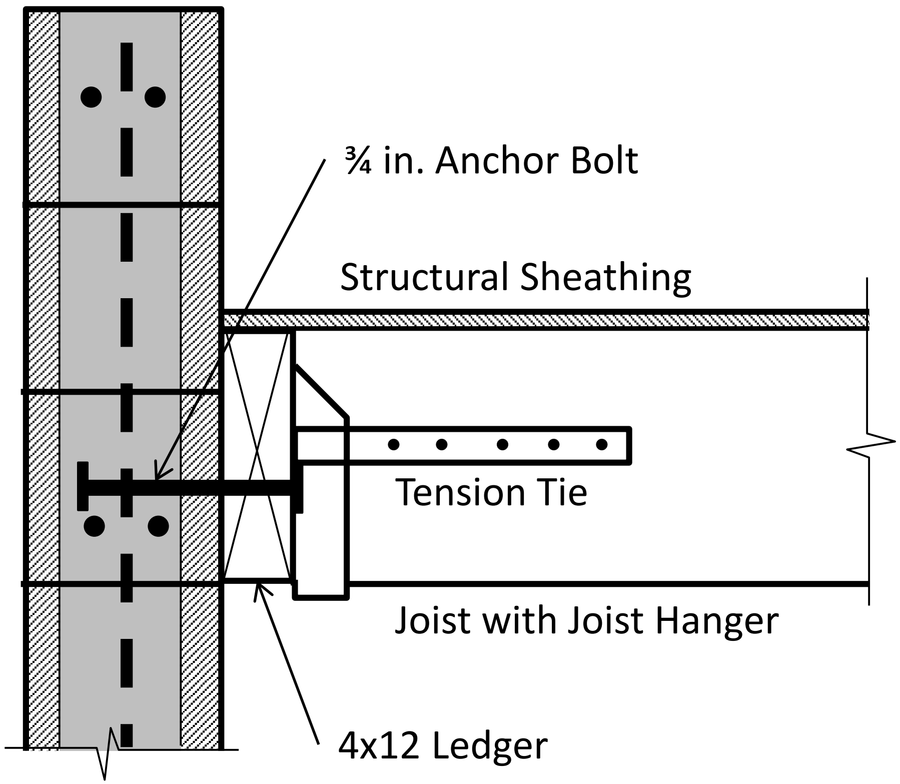
- initially suggested an exponent of between 1.4 and 1.5. He later stated that a higher exponent "may be more appropriate and may be closer to the 5/3 values suggested by others."

ICC Evaluation Service Reports

- exponent of 5/3 is permitted to be used when the strength of the anchors is determined by test using the ICC Evaluation Services Reports for adhesive anchors (ICC-ES 2012a), expansion anchors (ICC-ES 2012b), and screw anchors (ICC-ES 2012c) in masonry.

Example: Combined Loading

- 3/4-in. diameter, A307 headed anchor
- embedded 5-1/4 inch in the side of an 8-in. CMU wall
- tension force of 1.19 kip/ft and shear force of 0.30 kip/ft
- anchors not near edge
- f'_m = 2,000 psi
- Use strength design, determine the required anchor bolt spacing



2015 NEHRP Recommended Seismic Provisions: Design Examples, FEMA P-1051, prepared for the Federal Emergency Management Agency by the Building Seismic Safety Council.

Tension Strength

Projected tensile area $A_{pt} = \pi l_b^2 = \pi(5.25 in.)^2 = 86.6 in.^2$

Design Strength:

Masonry breakout: $\phi B_{anb} = \phi 4 A_{pt}\sqrt{f'_m} = 0.5(4)(86.6 in.^2)\sqrt{2000 psi} = 7745\ lb$

Steel yielding: $\phi B_{ans} = \phi A_b f_y = 0.9(0.334 in.^2)(36{,}000 psi) = 10{,}822\ lb$

Masonry breakout controls

Use ϕB_{an} = 7.74 kips

Shear Strength

Design Strength:

Masonry crushing:

$$\phi B_{vnc} = \phi(1750)\sqrt[4]{f'_m A_b}$$
$$= 0.5(1750)\sqrt[4]{(2000psi)(0.334in.^2)} = 4448\ lb$$

Masonry pryout:

$$\phi B_{vnpry} = \phi 8 A_{pt}\sqrt{f'_m} =$$
$$= 0.5(8)(86.6in.^2)\sqrt{2000psi} = 15{,}491lb$$

Steel yielding:

$$\phi B_{vns} = \phi 0.6 A_b f_y$$
$$= 0.9(0.6)(0.334in.^2)(36{,}000psi) = 6493\ lb$$

Masonry crushing controls

Use ϕB_{vn} = 4.45 kips

Determine spacing

Since masonry breakout and masonry crushing controls, ASCE 7 requires both the tensile and the shear load to be doubled.

Interaction equation:

$$\left(\frac{b_{au}}{\phi B_{an}}\right)^{5/3} + \left(\frac{b_{vu}}{\phi B_{vn}}\right)^{5/3} = 1.0$$

Solve for spacing, *s*:

$$\left(\frac{2\left(1.19\,\frac{k}{ft}\right)s}{7.74\ kip}\right)^{5/3} + \left(\frac{2\left(0.30\,\frac{k}{ft}\right)s}{4.45\ kip}\right)^{5/3} = 1.0$$

s = 2.84 ft = 34.0 inch

Use *s* = 32 inch

Examine effect of code changes

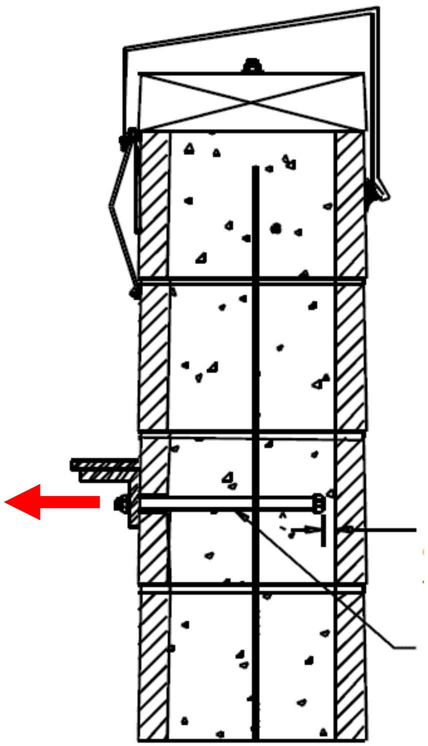
Design Basis	Required spacing, s
TMS 402-16	34.5 inch
TMS 402-13 and ASCE 7-10	18.0 inch
TMS 402-13 with new shear crushing equation	21.7 inch
TMS 402-13 with 5/3 exponent for interaction	23.6 inch
TMS 402-13 with ASCE 7-16 load increase	22.5 inch

In this problem:

- each of the three changes had approximately the same effect on the spacing
- overall effect was almost doubling the required spacing of the anchor bolts

Anchor Bolts: Seismic Loads

Effect of Bolt Size



TMS 402 *Figure CC-6.3-2*

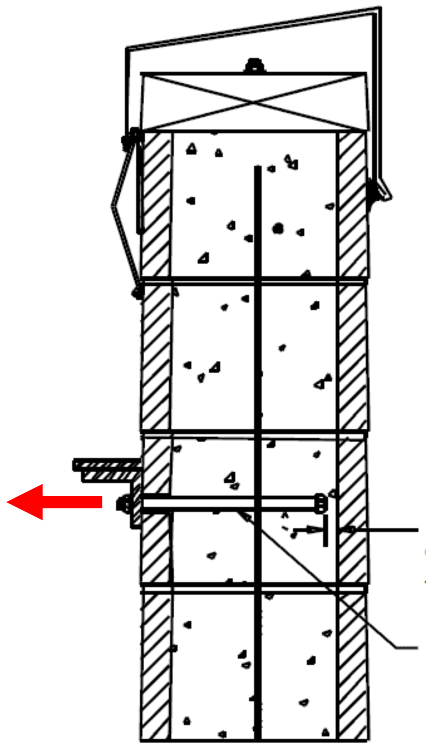
A307 Headed anchor bolt

l_b = 5.0 in.; f'_m = 2000 psi

Bolt	Design Tensile Strength (kip)		Seismic Strength ($\Omega_0 = 2.0$)
	Yield	Masonry Breakout	
1/2	4.60	7.02	4.60
5/8	7.32	7.02	3.51

Increasing the bolt diameter lowered the seismic strength due to Masonry Breakout controlling

Effect of Tensile Strength



TMS 402 *Figure CC-6.3-2*

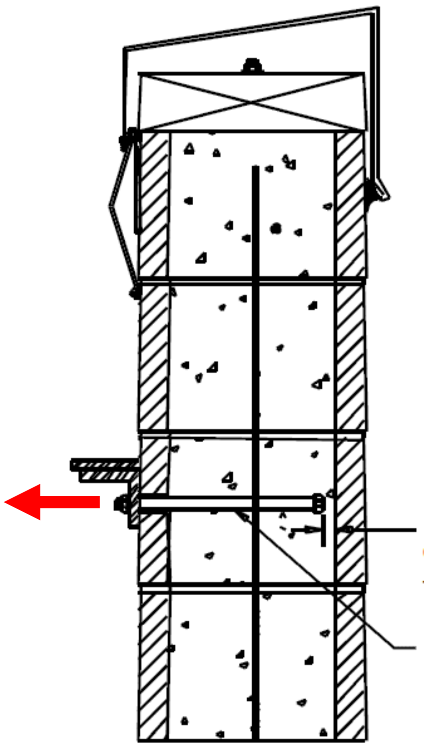
A307 1/2 in. headed anchor bolt

l_b = 4.5 in.; f'_m = 2000 psi

Tensile Strength	Design Tensile Strength (kip)		Seismic Strength $(\Omega_0 = 2.0)$
	Yield	Masonry Breakout	
TMS 402	4.60	5.69	4.60
AISC 360	6.61	5.69	2.84

TMS 402 is not necessarily conservative.
Using lower tensile strength changes failure mode.

Effect of f'_m



TMS 402 *Figure CC-6.3-2*

A307 1/2 in. headed anchor bolt
l_b = 4 in.

f'_m	Design Strength (kip)		Seismic Strength ($\Omega_0 = 2.0$)
	Yield	Masonry Breakout	
2000 psi	4.60	4.50	2.25
2100 psi	4.60	4.61	4.60

$f'_m = 2100\ psi$ requires Type S mortar and a CMU unit strength of 2250 psi.

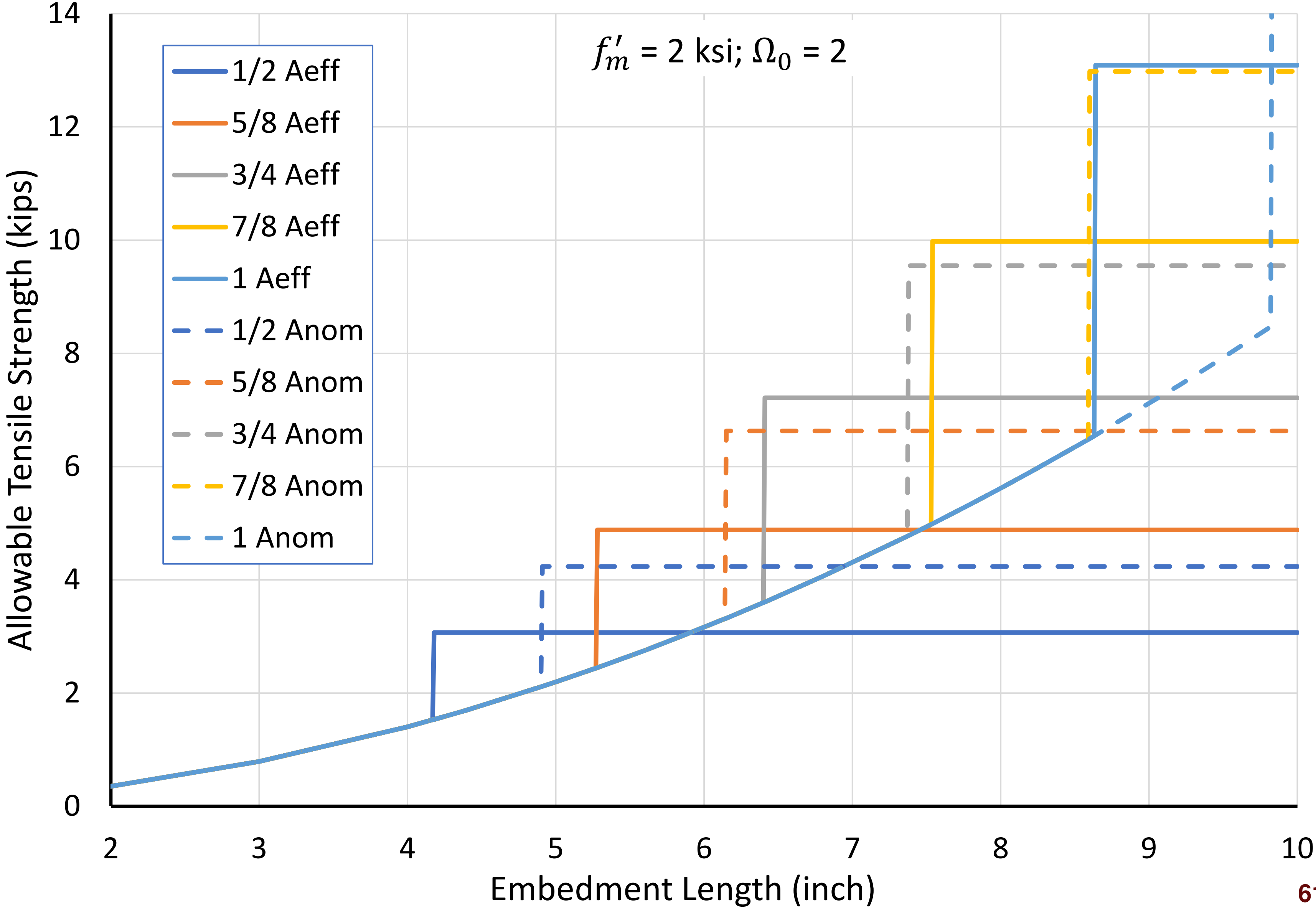
Most manufacturers provide around 2600 psi blocks, which results in $f'_m = 2250\ psi$

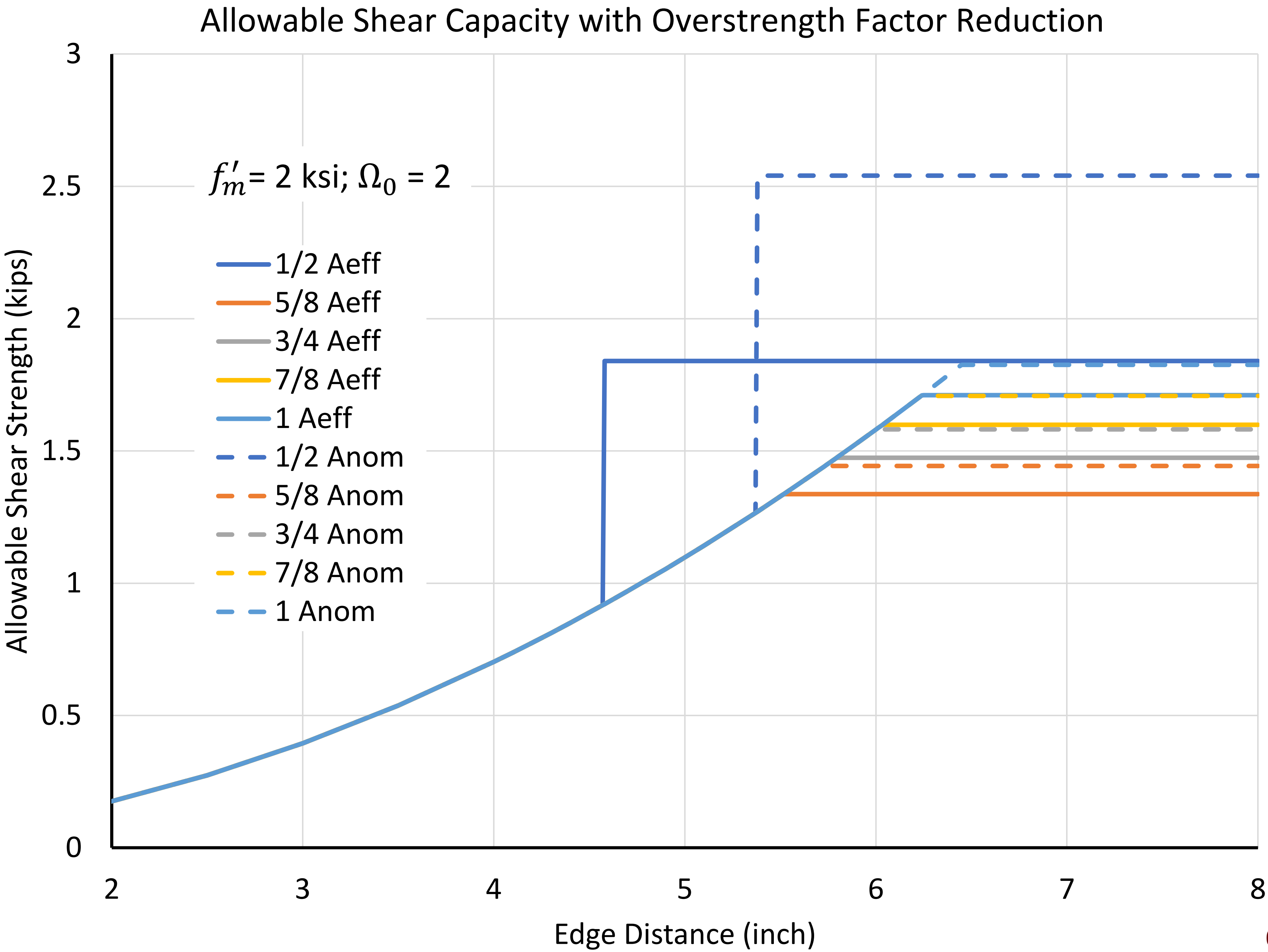
Graphs of Anchor Bolt Strength

- Allowable tensile capacity vs. embedment length
- Allowable shear capacity vs. edge distance
- Considers reduction of capacity for non-yielding seismic condition
  - Valid for pure seismic loading only
  - Overstrength factor is intended to be applied only to seismic load

  - Anom = nominal bolt area
  - Aeff = effective bolt area

Allowable Tensile Capacity with Overstrength Factor Reduction




Allowable Shear Capacity with Overstrength Factor Reduction
f'_m= 2 ksi; Ω_0 = 2
1/2 Aeff
5/8 Aeff
3/4 Aeff
7/8 Aeff
1 Aeff
1/2 Anom
5/8 Anom
3/4 Anom
7/8 Anom
1 Anom
Allowable Shear Strength (kips)
Edge Distance (inch)
0
0.5
1
1.5
2
2.5
3
2
3
4
5
6
7
8

This concludes The American Institute of Architects Continuing Education Systems Course

The Masonry Society

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