**Anchor Bolts**

| (a) Headed Anchor Bolts | (b) Bent-Bar Anchor Bolts |

TMS 602 Article 2.4 D
- Plate and bent-bar anchors: ASTM A36
- Headed anchor bolts: ASTM A307, Grade A
  - ASTM A307 does not have a 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
- ASTM F1554 anchor bolts
  - Not included in TMS 602
  - Three specified yield strengths: 36, 55, and 105 ksi
  - 36 ksi is usually sufficient for masonry

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**Anchor Bolt Requirements**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Provision</th>
<th>TMS 402 Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Placement</td>
<td>Placed in grout; Exception: 1/4 in. anchor bolts may be placed in 1/2 in. mortar joints.</td>
<td>6.3.1</td>
</tr>
<tr>
<td></td>
<td>Thickness of grout between reinforcement and anchor bolt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coarse grout: 1/2 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine grout: 1/4 in.</td>
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</tr>
<tr>
<td></td>
<td>Anchor bolts in drilled holes of face shell permitted to contact face shell</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clear distance between bars ≤ max{d_b, 1 in.}</td>
<td></td>
</tr>
<tr>
<td>Embedment length, l_p</td>
<td>Headed bolts: masonry surface to compression bearing surface of head</td>
<td>6.3.4</td>
</tr>
<tr>
<td></td>
<td>Bent-bar bolts: masonry surface to the compression bearing surface of the bent end, minus one anchor bolt diameter.</td>
<td>6.3.5</td>
</tr>
<tr>
<td></td>
<td>Minimum l_p = max{4d_w, 2 in.}</td>
<td></td>
</tr>
<tr>
<td>Projected area for axial tension</td>
<td>A_{pt} = \pi t_b^2</td>
<td>6.3.2</td>
</tr>
<tr>
<td>Projected area for shear</td>
<td>A_{pv} = \frac{\pi t_w^2}{2}</td>
<td>6.3.3</td>
</tr>
<tr>
<td></td>
<td>l_{be} = edge of masonry to center of bolt in direction of load</td>
<td>6.3.7</td>
</tr>
</tbody>
</table>
Anchor Bolts: Projected Tension Area (6.3.2)

- Projected area reduced by that falling 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.

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

Anchor Bolts: Groups

\[
X = \sqrt{(l_b)^2 - \left(\frac{t}{2}\right)^2} = \frac{1}{2} \sqrt{4(l_b)^2 - t^2}
\]

\[
Y = l_b - X
\]

\[
A_{pt} = (2X + Z)t + l_b^2 \left(\frac{\pi \theta}{180} - \sin \theta\right)
\]

\[
\theta = 2 \arcsin \left(\frac{t/2}{l_b}\right)\text{ degrees}
\]
### Anchor Bolts: Bolt Area

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

- \( A_b \) = effective tensile stress area
- \( d_0 \) = nominal anchor diameter
- \( n_t \) = number of threads per inch

<table>
<thead>
<tr>
<th>Bolt</th>
<th>( A ) (in(^2))</th>
<th>( A_b ) (in(^2))</th>
<th>( A_b / A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 - 13</td>
<td>0.196</td>
<td>0.142</td>
<td>0.723</td>
</tr>
<tr>
<td>5/8 - 11</td>
<td>0.307</td>
<td>0.226</td>
<td>0.737</td>
</tr>
<tr>
<td>3/4 - 10</td>
<td>0.442</td>
<td>0.334</td>
<td>0.757</td>
</tr>
<tr>
<td>7/8 - 9</td>
<td>0.601</td>
<td>0.462</td>
<td>0.768</td>
</tr>
<tr>
<td>1 - 8</td>
<td>0.785</td>
<td>0.606</td>
<td>0.771</td>
</tr>
</tbody>
</table>

Suitable approximation: \( A_b = 0.75 \) (nominal area)
Anchor Bolts: Testing

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.

5th-percentile value, assuming a coefficient of variation of 20%

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Anchor Bolts: Tension

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Allowable Stress (8.1.3.3.1)</th>
<th>Strength (9.1.6.3.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry breakout</td>
<td>$B_{ab} = 1.25 A_{pt} \sqrt{f_m'}$</td>
<td>$B_{anb} = 4 A_{pt} \sqrt{f_m'} \phi = 0.5$</td>
</tr>
<tr>
<td>Steel yielding</td>
<td>$B_{as} = 0.6 A_b f_y$</td>
<td>$B_{ans} = A_b f_y \phi = 0.9$</td>
</tr>
<tr>
<td>Anchor pullout (only bent bar)</td>
<td>$B_{ap} = 0.6 f_m' e_b d_b + [120 \pi (l_b + e_b + d_b) d_b]$</td>
<td>$B_{anp} = 1.5 f_m' e_b d_b + [300 \pi (l_b + e_b + d_b) d_b] \phi = 0.65$</td>
</tr>
</tbody>
</table>
Anchor Bolts: Tension Example

**Given:** 1/2 in. headed bolt \((f_y = 36 \text{ ksi})\) embedded in side of 8 in. CMU wall; Type S mortar.

**Required:** Embedment depth to develop tensile capacity of anchor bolt.

**Solution:**

\[ A_b = 0.142 \text{ in}^2 \]

Steel yielding

\[ B_{ans} = A_b f_y = 0.142 \text{ in}^2 (36 \text{ ksi}) = 5.11 \text{kips} \]

\[ \phi B_{ans} = 0.9(5.11 \text{kips}) = 4.60 \text{kips} \]

Req'd breakout strength

\[ B_{anb} = \left( \phi_x B_{ans} \right) / \phi_y = 4.60 \text{kips} / 0.5 = 9.20 \text{kips} \]

Req'd \(A_{pt}\)

\[ B_{anb} = 4A_{pt} \sqrt{f_m'} \quad \Rightarrow \quad 9200 \text{lb} = 4A_{pt} \sqrt{2000 \text{psi}} \quad \Rightarrow \quad A_{pt} = 51.4 \text{in}^2 \]

Embedment depth

\[ A_{pt} = \pi d_b^2 \quad \Rightarrow \quad 51.4 \text{in}^2 = \pi d_b^2 \quad \Rightarrow \quad l_b = 4.05 \text{in} \]

Use 4 in. of embedment to develop strength of bolt

---

Anchor Bolts: Tension Example

**Required:** Embedment depth to develop tensile capacity of anchor if anchor bolt embedded in top of wall.

**Solution:** Cone falls outside edge of masonry

\[ A_{pt} = (2X) t + l_b^2 \left( \frac{\pi \theta}{180} - \sin \theta \right) \]

\[ X = \sqrt{(l_b)^2 - \left( \frac{t}{2} \right)^2} = \frac{1}{2} \sqrt{4(l_b)^2 - t^2} \]

\[ \theta = 2 \arcsin \left( \frac{t/2}{l_b} \right) \text{ degrees} \]

Solve for \(l_b\) such that \(A_{pt} = 51.4 \text{ in}^2\)

\[ l_b = 4.09 \text{ in.} \]

Use 4-1/4 in. of embedment to develop strength of bolt

Embedment depth for other bolt sizes to develop strength of bolt \((f_y = 36 \text{ ksi})\):

<table>
<thead>
<tr>
<th>(d_o) (in)</th>
<th>(l_b) (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/8</td>
<td>6 (5.82)</td>
</tr>
<tr>
<td>3/4</td>
<td>8-1/4 (8.24)</td>
</tr>
<tr>
<td>7/8</td>
<td>11-1/4 (11.19)</td>
</tr>
<tr>
<td>1</td>
<td>14-1/2 (14.56)</td>
</tr>
</tbody>
</table>
Anchor Bolts: Tension Example

**Required:** Determine required embedment for J- or L-bolt with $e_b = 2.0\text{in.}$

**Solution:**

Req’d pullout strength

$$B_{anp} = \left( \phi_s B_{ans} \right) / \phi_p = 5.11\text{kips}/0.65 = 7.86\text{kips}$$

**Pullout**

$$B_{anp} = 1.5 f'_m e_b d_b + \left[ 300 \pi \left( l_b + e_b + d_b \right) d_b \right]$$

$$7.86k = 1.5 \left( 2.0\text{ksi} \right) \left( 2.0\text{in} \right) \left( 0.50\text{in} \right) + \left[ 0.3 \pi \left( l_b + 2.0\text{in} + 0.50\text{in} \right) 0.50\text{in} \right]$$

$$l_b = 7.82\text{in}$$

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**Forget using L- or J- bolts in tension**

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Anchor Bolts: Shear

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Allowable Stress (8.1.3.2)</th>
<th>Strength (9.1.6.3.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry breakout</td>
<td>$B_{vb} = 1.25 A_{pv} \sqrt{f'_m}$</td>
<td>$B_{vnb} = 4 A_{pv} \sqrt{f'_m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi = 0.5$</td>
</tr>
<tr>
<td>Masonry crushing</td>
<td>$B_{vc} = 580 A_{pm} \sqrt{f'_m}$</td>
<td>$B_{vnc} = 1750 A_{pm} \sqrt{f'_m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi = 0.5$</td>
</tr>
<tr>
<td>Anchor bolt pryout</td>
<td>$B_{vpry} = 2.0 B_{ab} = 2.5 A_{pt} \sqrt{f'_m}$</td>
<td>$B_{vpry} = 2.0 B_{anb} = 8 A_{pt} \sqrt{f'_m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi = 0.5$</td>
</tr>
<tr>
<td>Steel yielding</td>
<td>$B_{vs} = 0.36 A_{b} f'_y$</td>
<td>$B_{vns} = 0.6 A_{b} f'_y$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\phi = 0.9$</td>
</tr>
</tbody>
</table>
Anchor Bolts: Shear Example

Given: 1/2 in. bolt \( (f_y = 36 \text{ksi}) \) embedded 6 inch in top center of 8 in. CMU wall; threads excluded from shear plane; Type S mortar.
Required: Shear strength of anchor bolt for out-of-plane loads.
Solution:

Masonry breakout:

\[
A_{pv} = \frac{\pi l_{be}^2}{2} = \frac{\pi (3.81 \text{in.})^2}{2} = 22.8 \text{in}^2
\]

\[
B_{vn} = 4A_{pv}\sqrt{f'_m} = 4(22.8 \text{in}^2)\sqrt{2000 \text{ psi} \left(\frac{1 \text{kip}}{1000 \text{lb}}\right)} = 4.08 \text{kips}
\]

\[
\phi B_{vn} = 0.5(4.08 \text{kips}) = 2.04 \text{kips}
\]

Masonry crushing:

\[
B_{vnc} = 1750\sqrt{f'_m A_b} = 1750\sqrt{(2000 \text{ psi})(0.20 \text{in}^2)\left(\frac{1 \text{kip}}{1000 \text{lb}}\right)} = 7.83 \text{kips}
\]

\[
\phi B_{vnc} = 0.5(7.83 \text{kips}) = 3.91 \text{kips}
\]

Anchor Bolts: Shear Example, cont.

Anchor bolt pryout:

\[
\theta = 2 \arcsin \left( \frac{t/2}{l_b} \right) = 2 \arcsin \left( \frac{7.625 \text{in.}/2}{6 \text{in.}} \right) = 78.9^\circ
\]

\[
X = \frac{1}{2} \sqrt{4l_b^2 - t^2} = \frac{1}{2} \sqrt{4(6 \text{in.})^2 - (7.625 \text{in.})^2} = 4.63 \text{in.}
\]

\[
A_{pt} = (2X)\sqrt{\frac{\pi \theta}{180} - \sin \theta} = (2(4.63 \text{in.})(7.625 \text{in.})) + (6.0 \text{in.})\left(\frac{\pi (78.9^\circ)}{180} - \sin 78.9^\circ\right) = 84.9 \text{in}^2
\]

\[
B_{vnpry} = 8A_{pt}\sqrt{f'_m} = 8(84.9 \text{in}^2)\sqrt{2000 \text{ psi} \left(\frac{1 \text{kip}}{1000 \text{lb}}\right)} = 30.37 \text{kip}
\]

\[
\phi B_{vnpry} = 0.5(30.4 \text{kips}) = 15.19 \text{kips}
\]

Steel yielding:

\[
B_{vs} = 0.6A_{b}f_y = 0.6(0.20 \text{in}^2)(36 \text{ksi}) = 4.32 \text{kips}
\]

\[
\phi B_{vs} = 0.9(7.2 \text{kips}) = 6.48 \text{kips}
\]

Design Shear Load = 2.04 kips

What is the design shear load for an in-plane shear load?
Anchor Bolts: Combined Shear and Tension

Allowable Stress: (8.1.3.3.3)  
Strength: (9.1.6.3.3)  

\[
\left( \frac{b_a}{B_a} \right)^{5/3} + \left( \frac{b_v}{B_v} \right)^{5/3} \leq 1 \\
\left( \frac{b_{au}}{\phi B_{au}} \right)^{5/3} + \left( \frac{b_{vm}}{\phi B_{vm}} \right)^{5/3} \leq 1
\]

Anchor Bolts: 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

Anchor Bolts Embedded in Grout.

- Design so that anchor strength is governed by steel tensile or shear yielding.
- Alternatively, if governed by masonry breakout or anchor pullout, design to resist not less than 2.0 times the factored forces transmitted by the assembly.

ASCE 7-16 12.11.2:
Anchorage of Structural Walls and Transfer of Design Forces into Diaphragms.
Structural walls shall be designed to resist bending between anchors where the anchor spacing exceeds 4 ft.
Example: Anchor Bolts


Given: 8 in. normal weight (125 pcf) CMU wall; Grade 60 steel; Type S PCL mortar (special reinforced wall); $f'_{m}=2000$psi; roof forces act at 7.32in. eccentricity; $S_{DS}=1.43$, I=1.0, bars at 24 in. ($w_w = 56$psf),

Required: Anchor bolts for out-of-plane loading

Solution: ASCE 7-16, 12.11.2.1 Wall Anchorage Forces

$$F_p = 0.4S_{DS}k_aIeW_p > 0.2k_aIeW_p$$

$$k_a = 1.0 + \frac{L_f}{100} \leq 2.0 \quad L_f = 200$\text{ft}$, so \ k_a = 2$$

$$F_p = 0.4(1.43)(2.0)(1.0)(0.056ksf)(2\text{ ft} + 14\text{ ft}) = 1.02$\text{ k/ft}$$

Vertical Shear Load = $(1.2+0.2S_{DS})D = 1.486(0.2k/\text{ft}) = 0.30$\text{k/ft}$
Example: Anchor Bolts, cont.

Try ¾ in. A 307 Anchor Bolt. Assume $f_y = 36$ ksi
• Max length of bolt in block
  • $7.62 - 1.25 - 0.5 = 5.88$ in. Use 5.75 in.
• Embedment length, $l_b$
  • $5.75 - 0.5 = 5.25$ in.

\[ A_{pt} = \pi l_b^2 = \pi (5.25\text{in})^2 = 86.6\text{in}^2 \]

Tensile breakout of anchor: $\phi = 0.5$

\[ \phi B_{asb} = \phi \left( 4 A_{pt} \sqrt{f_y} \right) = 0.5(4)(86.6\text{in}^2)\sqrt{2000\text{psi}} = 7.74\text{kips} \]

Tensile yield of anchor: $\phi = 0.9$

\[ \phi B_{ass} = \phi A_b f_y = 0.9(0.334\text{in}^2)(36\text{ksi}) = 10.8\text{kip} \]

Tensile breakout controls; divide by 2.0 to meet ASCE 7
• $7.74/2.0 = 3.87$ kips

Use $\phi B_{an} = 3.87$ kips

Example: Anchor Bolts, cont.

Shear yield of anchor: $\phi = 0.9$

\[ \phi B_{vns} = \phi (0.6 A_b f_y) \]
\[ = 0.9(0.6)(0.44\text{in}^2)(36\text{ksi}) = 8.55\text{kip} \]

Shear breakout of anchor: $\phi = 0.5$

\[ \phi B_{vnb} = \phi \left( 4 A_{pv} \sqrt{f_m} \right) \]

Shear crushing of masonry: $\phi = 0.5$

\[ \phi B_{vac} = \phi \left( 1750 \sqrt{f_m A_b} \right) \]
\[ = 0.5(1750)^{0.5}(2000\text{psi})(0.44\text{in}^2) = 4.76\text{kips} \]
Example: Anchor Bolts, cont.

Shear pryout of anchor: $\phi=0.5$

$$\phi B_{\text{v pry}} = \phi (2.0 B_{\text{amb}}) = \phi (8 A_p t \sqrt{f_m})$$

$$= 0.5 (8) (86.6i \text{ in}^2) / 2000 \text{ psi} = 15.5 \text{ kips}$$

- Shear crushing controls
- Divide by 2.0 to meet ASCE 7
  - $4.76/2.0 = 2.38 \text{ kips}$
  
  Use $\phi B_{\text{vn}} = 2.38 \text{ kips}$

Combined tension and shear

Determine required spacing of bolts, $s$

$$\left( \frac{b_{af}}{\phi B_{an}} \right)^{5/3} + \left( \frac{b_{vf}}{\phi B_{vn}} \right)^{5/3} \leq 1$$

$$\left( \frac{1.02 \frac{k}{ft}}{3.87k} \right)^{5/3} + \left( \frac{0.30 \frac{k}{ft}}{2.38k} \right)^{5/3} \leq 1$$

$s = 3.25 \text{ ft} = 39 \text{ in.}$
Use ¾ in. A307 bolt @ 32 in.

With 2013 TMS 402 and ASCE 7-10
$s = 1.70 \text{ ft} = 20.4 \text{ in.}$
Use ¾ in. A307 bolt @ 16 in.

Seismic Requirements

Seismic Design Category A (7.4.1)
Empirical design is acceptable

Seismic Design Category B (7.4.2)
Empirical design not allowed for lateral force resisting system

Seismic Design Category C (7.4.3)
Non-participating elements (partitions, screen walls, etc.)
Isolated from the structure
Reinforced either in the horizontal or vertical direction
  - Horizontal: 2-W1.7 wires every 16 in. or #4 at 48 in.
  - Vertical: #4 at 120 in.; bar within 16 in. of end of wall
Shear walls reinforced (ordinary, intermediate, or special)
Seismic Requirements

Seismic Design Category C
7.4.3.2.4 Lateral stiffness — At each story level, at least 80 percent of the lateral stiffness shall be provided by lateral-force-resisting walls. Along each line of lateral resistance at a particular story level, at least 80 percent of the lateral stiffness shall be provided by lateral-force-resisting walls.

7.4.3.2.5 Design of columns, pilasters, and beams supporting discontinuous elements — Columns and pilasters that are part of the seismic force-resisting system and that support reactions from discontinuous stiff elements shall be provided with transverse reinforcement spaced at no more than one-fourth of the least nominal dimension of the column or pilaster. The minimum transverse reinforcement ratio shall be 0.0015. Beams supporting reactions from discontinuous walls shall be provided with transverse reinforcement spaced at no more than one-half of the nominal depth of the beam. The minimum transverse reinforcement ratio shall be 0.0015.

Seismic Design Category D (7.4.4)
Non-participating elements (partitions, screen walls, etc.):
Isolated from the structure
Reinforced either in the horizontal or vertical direction; spacing of vertical reinforcing in non-participating elements reduced to 48 in.
Only special reinforced shear walls allowed
Mortar
Fully grouted walls: Type S or M mortar; any kind
Partially grouted walls: Type S or M cement-lime or mortar cement

Seismic Design Category E an F (7.4.5)
Additional requirements for stack bond masonry
Seismic Observations

Parapets: Quite vulnerable to earthquakes. One of earliest and most successful retrofit programs was to brace parapets.

Anchorage of walls to diaphragms: Primary cause of failure of older masonry construction is inadequate anchorage of masonry walls to roof and floors. Successful retrofit has been to attach the walls at the diaphragm.

Pictures from Nisqually earthquake, 2001

Seismic Observations

Chimneys:
• Quite vulnerable in earthquakes. Fail by overturning or breaking at roof line.
• Successful reinforcing has been:
  o 4-#4 vertical bars in chimneys up to 40 in. wide; add 2-#4 for additional 40 in. or additional flue
  o 1/4 in. ties at 18 in.; two ties at each bend in vertical steel
  o 2 anchorage straps at each floor or roof level
Non-isolated infills

- Tight infill will function structurally.
- Can be primary load resisting system for older buildings.
- Buildings in downtown LA had shaking on order of 0.15-0.20g during Northridge earthquake. Older buildings with unreinforced infills experienced some damage, but remained open and usable after the earthquake.

Out-of-Plane Loading

- Typical erroneous assumption is unreinforced masonry infills are vulnerable to out-of-plane failure due to
  - Inadequate anchorage
  - Cracking of masonry
- Resistance mechanism is arching; thus, significant strength after cracking.
- No anchors are needed; anchors can reduce capacity by causing localized damage and compromising the integrity of the boundary.
- Infills with height/thickness < 25 should have adequate out-of-plane strength.
SERF Infill Details

**SECTION B-B**
- Dovetail Anchor
- Concrete
- Column CMU Wall

**SECTION A-A**
- Embedded Plate
- Concrete Beam
- Angle welded to plate and anchored to bond beam
- Bond Beam
- Concrete Column
- CMU Wall
- Dovetail Anchor