7.10 WELDED CONNECTIONS

Structural welding is a process whereby the parts to be connected are heated and fused, with supplementary molten metal added to the joint. For example, the tension member lap joint shown in Figure 7.33 can be constructed by welding across the ends of both connected parts. A relatively small depth of material will become molten, and upon cooling, the structural steel and the weld metal will act as one continuous part where they are joined. The additional metal, sometimes referred to as filler metal, is deposited from a special electrode, which is part of an electrical circuit that includes the connected part, or base metal. In the shielded metal arc welding (SMAW) process, shown schematically in Figure 7.34, current arcs across a gap between the electrode and base metal, heating the connected parts and depositing part of the electrode into the molten base metal. A special coating on the electrode vaporizes and forms a protective gaseous shield, preventing the molten weld metal from oxidizing before it solidifies. The electrode is moved across the joint, and a weld bead is deposited, its size depending on the rate of travel of the electrode. As the weld cools, impurities rise to the surface, forming a coating called slag that must be removed before the member is painted or another pass is made with the electrode.

Shielded metal arc welding is normally done manually and is the process universally used for field welds. For shop welding, an automatic or semiautomatic process is usually used. Foremost among these processes is submerged arc welding (SAW). In this process, the end of the electrode and the arc are submerged in a granular flux that melts and forms a gaseous shield. There is more penetration into the base

FIGURE 7.33

(a)  (b)

FIGURE 7.34

Direction of travel

Coated electrode

Arc

Slag

Gaseous shield

Bead

Molten

Base metal
metal than with shielded metal arc welding, and higher strength results. Other commonly used processes for shop welding include gas shielded metal arc, flux cored arc, and electroslag welding.

Quality control of welded connections is particularly difficult, because defects below the surface, or even minor flaws at the surface, will escape visual detection. Welders must be properly certified, and for critical work, special inspection techniques such as radiography or ultrasonic testing must be used.

The two most common types of welds are the fillet weld and the groove weld. The lap joint illustrated in Figure 7.33a is made with fillet welds, which are defined as those placed in a corner formed by two parts in contact. Fillet welds can also be used in a tee joint, as shown in Figure 7.33b. Groove welds are those deposited in a gap, or groove, between two parts to be connected. They are most frequently used for butt, tee, and corner joints. In most cases, one or both of the connected parts will have beveled edges, called prepared edges, as shown in Figure 7.35a, although relatively thin material can be groove welded with no edge preparation. The welds shown in Figure 7.35a are complete penetration welds and can be made from one side, sometimes with the aid of a backing bar. Partial penetration groove welds can be made from one or both sides, with or without edge preparation (Figure 7.35b).

Figure 7.36 shows the plug or slot weld, which sometimes is used when more weld is needed than length of edge is available. A circular or slotted hole is cut in one of the parts to be connected and is filled with the weld metal.

![Groove Welds]

**FIGURE 7.35**

- Backing bar
- Butt
- Tee
- Corner

(a) Complete penetration groove welds

(b) Partial penetration groove welds

**FIGURE 7.36**
Of the two major types of welds, fillet welds are the most common and are considered here in some detail. The design of complete penetration groove welds is a trivial exercise in that the weld will have the same strength as the base metal and the connected parts can be treated as completely continuous at the joint. The strength of a partial penetration groove weld will depend on the amount of penetration; once that has been determined, the design procedure will be essentially the same as that for a fillet weld.

7.11 FILLET WELDS

The design and analysis of fillet welds is based on the assumption that the cross-section of the weld is a 45° right triangle, as shown in Figure 7.37. Any reinforcement (buildup outside the hypotenuse of the triangle) or penetration is neglected. The size of a fillet weld is denoted \( w \) and is the length of one of the two equal sides of this idealized cross section. Standard weld sizes are specified in increments of \( \frac{1}{16} \) inch. Although a length of weld can be loaded in any direction in shear, compression, or tension, a fillet weld is weakest in shear and is always assumed to fail in this mode. Specifically, failure is assumed to occur in shear on a plane through the throat of the weld. For fillet welds made with the shielded metal arc process, the throat is the perpendicular distance from the corner, or root, of the weld to the hypotenuse and is equal to \( 0.707 \) times the size of the weld. (The effective throat thickness for a weld made with the submerged arc welding process is larger. In this book, we conservatively assume that the shielded metal arc welding process is used.) Thus, for a given length of weld \( L \) subjected to a load of \( P \), the critical shearing stress is

\[
f_v = \frac{P}{0.707wL}\]

where \( w \) is the weld size.

**FIGURE 7.37**

[Diagram of fillet weld showing throat calculation and load distribution]
If the weld ultimate shearing stress, $F_{uw}$, is used in this equation, the nominal load capacity of the weld can be written as

$$R_n = 0.707wLF_{uw}$$

The strength of a fillet weld depends on the weld metal used—that is, it is a function of the type of electrode. The strength of the electrode is defined as its ultimate tensile strength, with strengths of 60, 60, 80, 90, 100, 110, and 120 kips per square inch available for the shielded metal arc welding process. The standard notation for specifying an electrode is the letter $E$ followed by two or three digits indicating the tensile strength in kips per square inch and two digits specifying the type of coating. As strength is the property of primary concern to the design engineer, the last two digits are usually represented by XX, and a typical designation would be E70XX or just E70, indicating an electrode with an ultimate tensile strength of 70 ksi. Electrodes should be selected to match the base metal. For the commonly used grades of steel, only two electrodes need be considered:

- Use E70XX electrodes with steels that have a yield stress less than 60 ksi.
- Use E80XX electrodes with steels that have a yield stress of 60 ksi or 65 ksi.

Most of the AISC Specification provisions for welds have been taken from the *Structural Welding Code* of the American Welding Society (AWS, 2010). Exceptions are listed in AISC J2. The AWS Code should be used for criteria not covered in the AISC Specification.

The design strengths of welds are given in AISC Table J2.5. The ultimate shearing stress $F_{uw}$ in a fillet weld is 0.6 times the tensile strength of the weld metal, denoted $F_{EXX}$. The nominal stress is therefore

$$F_{uw} = 0.60F_{EXX}$$

AISC Section J2.4a presents an alternative fillet weld strength that accounts for the direction of the load. If the angle between the direction of the load and the axis of the weld is denoted $\theta$ (see Figure 7.38), the nominal fillet weld strength is

$$F_{uw} = 0.60F_{EXX} \left(1.0 + 0.50\sin^{1.5} \theta\right)$$

(AISC Equation J2-5)

Table 7.2 shows the strength for several values of $\theta$. As Table 7.2 shows, if the weld axis is parallel to the load, the basic strength given by $F_{uw} = 0.60F_{EXX}$ is correct, but when the weld is perpendicular to the load, the true strength is 50% higher.
### TABLE 7.2

<table>
<thead>
<tr>
<th>Direction of load (θ)</th>
<th>$F_{nw} = 0.60F_{EXX}(1.0 + 0.50 \sin^{1.5}\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>$0.60F_{EXX}(1.0)$</td>
</tr>
<tr>
<td>15°</td>
<td>$0.60F_{EXX}(1.066)$</td>
</tr>
<tr>
<td>30°</td>
<td>$0.60F_{EXX}(1.177)$</td>
</tr>
<tr>
<td>45°</td>
<td>$0.60F_{EXX}(1.297)$</td>
</tr>
<tr>
<td>60°</td>
<td>$0.60F_{EXX}(1.403)$</td>
</tr>
<tr>
<td>75°</td>
<td>$0.60F_{EXX}(1.475)$</td>
</tr>
<tr>
<td>90°</td>
<td>$0.60F_{EXX}(1.5)$</td>
</tr>
</tbody>
</table>

For simple (that is, concentrically loaded) welded connections with both longitudinal and transverse welds, AISC J2.4c specifies that the larger nominal strength from the following two options be used:

1. Use the basic weld strength, $F_{nw} = 0.60F_{EXX}$, for both the longitudinal and the transverse welds:

   $$R_n = R_{nw} + R_{nmt}$$

   where $R_{nw}$ and $R_{nmt}$ are the strengths of the longitudinal and transverse welds, both calculated with $F_{nw} = 0.60F_{EXX}$.

2. Use the 50% increase for the transverse weld, but reduce the basic strength by 15% for the longitudinal welds. That is, use $F_{nw} = 0.85(0.60F_{EXX})$ for the longitudinal welds and $F_{nw} = 1.5(0.60F_{EXX})$ for the transverse weld:

   $$R_n = 0.85R_{nw} + 1.5R_{nmt}$$

   (AISC Equation J2-10b)

Because AISC permits the larger of the two options to be used, it is permissible to use either and be conservative at worst. In this book, however, we will use the AISC specified approach and check both options.

For LRFD, the design strength of a fillet weld is $\phi R_n$, where $\phi = 0.75$. For ASD, the allowable strength is $R_n/\Omega$, where $\Omega = 2.00$.

An additional requirement is that the shear on the base metal cannot exceed the shear strength of the base metal. This means that we cannot use a weld shear strength larger than the base-metal shear strength, so the base-metal shear strength is an upper limit on the weld shear strength. This requirement can be explained by an examination of the welded connection shown in Figure 7.39a. Although both the gusset plate and the tension member plate are subject to shear, we will examine the shear on the gusset plate adjacent to the weld $AB$. The shear would occur along line $AB$ (Figure 7.39b) and subject an area of $tL$ to shear (Figure 7.39c). The shear strength of the weld $AB$ cannot exceed the shear strength of the base metal corresponding to an area $tL$.

The strength of components at connections, including connecting elements such as gusset plates and elements of the members, are covered in AISC J4, "Affected Elements of Members and Connecting Elements." Shear strength is covered in Section J4.2, where the limit states of shear yielding and shear rupture are given. For yielding, the nominal strength is

$$R_n = 0.60F_{av}A_{sv}$$

(AISC Equation J4-3)
For yielding:

\[ R_m = 0.6 F_y \frac{A_{gw}}{F_{yw}} \]

where

- \( 0.6 F_y \) = shear yield stress
- \( A_{gw} \) = gross area of the shear surface = \( tL \)

For LRFD, \( \phi = 1.00 \), and \( R_m = 1.50 \)

For rupture, the nominal strength is

\[ R_n = 0.6 F_u A_{nw} \]

where

- \( 0.6 F_u \) = shear ultimate stress
- \( A_{nw} \) = net area of the shear surface = \( tL \) (for material adjacent to a weld)

For LRFD, \( \phi = 0.75 \), and \( R_n = 1.29 \)

The strength of a fillet weld can now be summarized for both load and resistance factor design in a single equation:

LRFD Equations

Weld shear strength:

\[ R_w \leq 0.75(0.707wL F_{nw}) \]  \hspace{1cm} (7.27)

Base-metal shear strength:

\[ \phi R_n = \min[1.0(0.6F_y tL), 0.75(0.6F_u tL)] \]  \hspace{1cm} (7.28)

It is frequently more convenient to work with the strength per unit length; in which case, \( L = 1 \), and Equation 7.27 and 7.28 become
Gusset

Plate
Gusset

Base Metal
\[ \text{thrust} = 0.707 \, W \]
Weld shear strength:
\[ \phi R_n = 0.75(0.707wF_{mv}) \text{ for a one-inch length} \] (7.29)

Base-metal shear strength:
\[ \phi R_n = \text{min}[1.0(0.6F_yt), 0.75(0.6F_ut)] \text{ for a one-inch length} \] (7.30)

**ASD Equations**

Weld shear strength:
\[ \frac{R_n}{\Omega} = \frac{0.707wLF_{mv}}{2.00} \] (7.31)

Base-metal shear strength:
\[ \frac{R_n}{\Omega} = \text{min} \left[ \frac{0.6F_ytL}{1.50}, \frac{0.6F_utL}{2.00} \right] \] (7.32)

If the strength per unit length is used, \( L = 1 \) and Equations 7.31 and 7.32 become

Weld shear strength:
\[ \frac{R_n}{\Omega} = \frac{0.707wF_{mv}}{2.00} \text{ for a one-inch length} \] (7.33)

Base-metal shear strength:
\[ \frac{R_n}{\Omega} = \text{min} \left[ \frac{0.6F_yt}{1.50}, \frac{0.6F_ut}{2.00} \right] \text{ for a one-inch length} \] (7.34)

**EXAMPLE 7.12**

A plate used as a tension member is connected to a gusset plate, as shown in Figure 7.40. The welds are \( \frac{3}{16} \)-inch fillet welds made with E70XX electrodes. The connected parts are of A36 steel. Assume that the tensile strength of the member is adequate, and determine the available strength of the welded connection.

**SOLUTION**

Because the welds are placed symmetrically about the axis of the member, this connection qualifies as a simple connection, and there is no additional load due to
eccentricity. Since both weld segments are parallel to the applied load, $\theta = 0^\circ$ and the basic strength of the weld is $F_{mv} = 0.60F_{EXX}$. The nominal load capacity per inch of weld is

$$R_n = 0.707wF_{mv} = 0.707\left(\frac{3}{16}\right)(0.6 \times 70) = 5.568 \text{ kips/in.}$$

The design strength of the weld is

$$\phi R_n = 0.75(5.568) = 4.176 \text{ kips/in.}$$

Check the base-metal shear. Since both components are of the same type of steel, the smaller thickness will control. The shear yield strength is

$$\phi R_{n, t} = \phi(0.6F_{y,t}) = 1.00(0.6)(36)\left(\frac{1}{4}\right) = 5.4 \text{ kips/in.}$$

The shear rupture strength is

$$B.M.S., \text{rupture}: \phi R_{n, t} = \phi(0.6F_{y,t}) = 0.75(0.6)(58)\left(\frac{1}{4}\right) = 6.525 \text{ kips/in.}$$

The base-metal shear strength is therefore 5.4 kips/in., and the weld shear strength controls. For the connection,

$$R_n \leq 5.0^\circ < \phi R_{n, t} = 4.176 \text{ kips/in.} \times (4 + 4) \text{ in.} = 33.4 \text{ kips}$$

**ANSWER**

Design strength of the weld is 33.4 kips.

**ASD SOLUTION**

The allowable strength of the weld is

$$R_n = \frac{5.568}{2.00} = 2.784 \text{ kips/in.}$$

Check the base-metal shear. Since both components are of the same type of steel, the smaller thickness will control. The shear yield strength is

$$R_{n, t} = \frac{0.6F_{y,t}}{1.50} = \frac{0.6(36)(1/4)}{1.50} = 3.6 \text{ kips/in.}$$

The shear rupture strength is

$$R_{n, t} = \frac{0.6F_{y,t}}{2.00} = \frac{0.6(58)(1/4)}{2.00} = 4.35 \text{ kips/in.}$$
The base-metal shear strength is therefore 3.6 kips/in., and the weld shear strength controls. For the connection,

\[ \frac{R_a}{\Omega} = 2.784 \text{ kips/in.} \times (4 + 4) \text{ in.} = 22.3 \text{ kips} \]

**ANSWER**

Allowable strength of the weld is 22.3 kips.

---

**EXAMPLE 7.13**

If the connection of Example 7.12 includes both the 4-inch-long longitudinal welds shown in Figure 7.40 and an additional 4-inch-long transverse weld at the end of the member, what is the available strength of the connection?

From Example 7.12, the weld shear design strength is

\[ \phi R_n = 4.176 \text{ kips/in.} \]

Also from Example 7.12, the base-metal shear design strength is

\[ \phi R_n = 5.4 \text{ kips/in.} \]

So the weld strength of 4.176 kips/in. controls.

To determine the strength of the connection, we will investigate the two options given in AISC J2.4c.

1. Use the basic weld strength for both the longitudinal and transverse welds.

\[ \phi R_n = 4.176 (4 + 4 + 4) = 50.1 \text{ kips} \]

2. Use 0.85 times the basic weld strength for the longitudinal welds and 1.5 times the basic weld strength for the transverse weld.

\[ \phi R_n = 0.85 (4.176)(4 + 4) + 1.5(4.176)(4) = 53.5 \text{ kips} \]

The larger value controls.

**ANSWER**

Design strength of the weld is 53.5 kips.

**ASD SOLUTION**

From Example 7.12, the allowable weld shear strength is 2.784 kips/in., and the allowable base metal shear strength is 3.6 kips/in. The weld strength therefore controls.
To determine the strength of the connection, we will investigate the two options given in AISC J2.4c.

1. Use the basic weld strength for both the longitudinal and transverse welds.

\[ \frac{R_n}{\Omega} = 2.784(4 + 4 + 4) = 33.4 \text{ kips} \]

2. Use 0.85 times the basic weld strength for the longitudinal welds and 1.5 times the basic weld strength for the transverse weld.

\[ \frac{R_n}{\Omega} = 0.85(2.784)(4 + 4) + 1.5(2.784)(4) = 35.6 \text{ kips} \]

The larger value controls.

**ANSWER**

Allowable strength of the weld is 35.6 kips.

When E70 electrodes are used, and this will usually be the case, computation of the weld shear strength can be simplified. The strength per unit length can be computed for a \( \frac{1}{16} \)-inch increment of weld size (and fillet welds are specified to the nearest \( \frac{1}{16} \) inch), and then multiplied times the correct \# of 16ths.

**LRFD:** The weld design shear strength from Equation 7.29 is

\[ \phi R_n = 0.75(0.707w_{Fw}) = 0.75(0.707)\left( \frac{1}{16} \right)(0.6 \times 70) = 1.392 \text{ kips/in.} \]

Using this constant, the design shear strength of the \( \frac{1}{16} \)-inch fillet weld in Example 7.12 is

\[ \phi R_n = 1.392 \times 3 \text{ sixteenths} = 4.176 \text{ kips/in.} \]

The base-metal shear strength expression can also be somewhat simplified. The shear yield design strength per unit length is,

\[ \phi R_n = 1.0(0.6F_y) = 0.6F_y \text{ for a one-inch length} \]

and the base-metal shear rupture design strength per unit length is

\[ \phi R_n = 0.75(0.6F_y) = 0.45F_y \text{ for a one-inch length} \]

**ASD:** The weld allowable shear strength from Equation 7.31 is

\[ \frac{R_n}{\Omega} = \frac{0.707w_{Fw}}{2.00} = \frac{0.707(1/16)(0.6 \times 70)}{2.00} = 0.9279 \text{ kips/in.} \]
# Table 2-4

## Applicable ASTM Specifications for Various Structural Shapes

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>$F_y$ Min. Yield Stress (ksi)</th>
<th>$F_u$ Tensile Stress (ksi)</th>
<th>Applicable Shape Series</th>
<th>HSS</th>
<th>Rect.</th>
<th>Round</th>
<th>Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>A36</td>
<td>36</td>
<td>58-80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>W M S HP C MC L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A53 Gr. B</td>
<td>35</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A500 Gr. B</td>
<td>42</td>
<td>58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A500 Gr. C</td>
<td>46</td>
<td>58&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A501 Gr. A</td>
<td>46</td>
<td>62&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A501 Gr. B</td>
<td>50</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A529&lt;sup&gt;f&lt;/sup&gt;</td>
<td>50</td>
<td>65-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A572 Gr. 42</td>
<td>42</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A572 Gr. 50</td>
<td>50</td>
<td>65&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A572 Gr. 55</td>
<td>55</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A618&lt;sup&gt;g&lt;/sup&gt;</td>
<td>60&lt;sup&gt;e&lt;/sup&gt;</td>
<td>70&lt;sup&gt;g&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A992</td>
<td>50&lt;sup&gt;f&lt;/sup&gt;</td>
<td>65&lt;sup&gt;j&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corten</td>
<td>A242</td>
<td>42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>63&lt;sup&gt;k&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistant</td>
<td>A588</td>
<td>50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-Strength Low-Alloy</td>
<td>A847</td>
<td>50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **W** = Preferred material specification
- **M** = Other applicable material specification, the availability of which should be confirmed prior to specification
- **N** = Material specification does not apply

**Notes:**

- <sup>a</sup> Minimum unless a range is shown.
- <sup>b</sup> For shapes over 426 lb/ft, only the minimum of 58 ksi applies.
- <sup>c</sup> For shapes with a flange thickness less than or equal to 1/2 in. only. To improve weldability, a maximum carbon equivalent can be specified (per ASTM Supplementary Requirement S78). If desired, maximum yield stress of 90 ksi can be specified (per ASTM Supplementary Requirement S79).
- <sup>d</sup> If desired, maximum tensile stress of 70 ksi can be specified (per ASTM Supplementary Requirement S91).
- <sup>e</sup> For shapes with a flange thickness less than or equal to 2 in. only.
- <sup>f</sup> ASTM A618 can also be specified as corrosion-resistant; see ASTM A618.
- <sup>g</sup> Minimum applies for walls nominally 3/4 in. thick and under. For walls over 3/4 in., $F_y = 48$ ksi and $F_y = 77$ ksi.
- <sup>h</sup> If desired, maximum yield stress of 65 ksi and maximum yield-to-tensile strength ratio of 0.85 can be specified (per ASTM Supplementary Requirement S79).
- <sup>i</sup> A maximum yield-to-tensile strength ratio of 0.85 and carbon equivalent formula are included as mandatory in ASTM A992.
- <sup>j</sup> For shapes with a flange thickness greater than 2 in. only.
- <sup>k</sup> For shapes with a flange thickness greater than 1 1/2 in. and less than or equal to 2 in. only.
- <sup>l</sup> For shapes with a flange thickness less than or equal to 1 1/2 in. only.
# Table 2-5

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>$F_y$ Min. Yield Stress (ksi)</th>
<th>$F_u$ Tensile Stress (ksi)</th>
<th>Plates and Bars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>A36</td>
<td>32</td>
<td>58-80</td>
<td>58-80</td>
</tr>
<tr>
<td></td>
<td>A529</td>
<td>Gr. 50</td>
<td>50</td>
<td>70-100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gr. 55</td>
<td>55</td>
<td>70-100</td>
</tr>
<tr>
<td>High-</td>
<td>A572</td>
<td>Gr. 42</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td>Gr. 50</td>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>Low-Alloy</td>
<td></td>
<td>Gr. 55</td>
<td>55</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gr. 60</td>
<td>60</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gr. 65</td>
<td>65</td>
<td>80</td>
</tr>
<tr>
<td>Corrosion</td>
<td>A242</td>
<td>42</td>
<td>63</td>
<td>80</td>
</tr>
<tr>
<td>Resistant</td>
<td>A588</td>
<td>46</td>
<td>67</td>
<td>80</td>
</tr>
<tr>
<td>High-</td>
<td></td>
<td>50</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td>42</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Low-Alloy</td>
<td></td>
<td>46</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Quenched</td>
<td>A514e</td>
<td>90</td>
<td>100-130</td>
<td>100-130</td>
</tr>
<tr>
<td>and</td>
<td></td>
<td>100</td>
<td>110-130</td>
<td></td>
</tr>
<tr>
<td>Tempered</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quenched</td>
<td>A652e</td>
<td>70</td>
<td>90-110</td>
<td>90-110</td>
</tr>
<tr>
<td>and</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tempered</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-Alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ■ = Preferred material specification
- FF = Other applicable material specification, the availability of which should be confirmed prior to specification
- □ = Material specification does not apply

* Minimum unless a range is shown.
* Applicable to bars only above 1-in. thickness.
* Available as plates only.
TABLE J2.2
Effective Weld Throats of Flare Groove Welds

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GMAW and FCAW-G</td>
<td>5/8 R</td>
<td>3/4 R</td>
</tr>
<tr>
<td>SMAW and FCAW-S</td>
<td>5/16 R</td>
<td>5/8 R</td>
</tr>
<tr>
<td>SAW</td>
<td>5/16 R</td>
<td>1/2 R</td>
</tr>
</tbody>
</table>

[4] For flare bevel groove with \( R < 3/8 \) in. (10 mm), use only reinforcing fillet weld on filled flush joint. General note: \( R \) = radius of joint surface (can be assumed to be \( 2t \) for HSS), in. (mm).

TABLE J2.3
Minimum Effective Throat of Partial-Joint-Penetration Groove Welds

<table>
<thead>
<tr>
<th>Material Thickness of Thinner Part Joined, in. (mm)</th>
<th>Minimum Effective Throat, [k] in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>To 1/4 (6) inclusive</td>
<td>1/8 (3)</td>
</tr>
<tr>
<td>Over 1/4 (6) to 1/2 (13)</td>
<td>3/16 (5)</td>
</tr>
<tr>
<td>Over 1/2 (13) to 3/4 (19)</td>
<td>1/4 (6)</td>
</tr>
<tr>
<td>Over 3/4 (19) to 1 1/2 (38)</td>
<td>5/16 (8)</td>
</tr>
<tr>
<td>Over 1 1/2 (38) to 2 1/4 (57)</td>
<td>3/8 (10)</td>
</tr>
<tr>
<td>Over 2 1/4 (57) to 6 (150)</td>
<td>1/2 (13)</td>
</tr>
<tr>
<td>Over 6 (150)</td>
<td>5/8 (16)</td>
</tr>
</tbody>
</table>

[k] See Table J2.1.

1b. Limitations

The minimum effective throat of a partial-joint-penetration groove weld shall not be less than the size required to transmit calculated forces nor the size shown in Table J2.3. Minimum weld size is determined by the thinner of the two parts joined.

2. Fillet Welds

2a. Effective Area

The effective area of a fillet weld shall be the effective length multiplied by the effective throat. The effective throat of a fillet weld shall be the shortest distance from the root to the face of the diagrammatic weld. An increase in effective throat
TABLE J2.4
Minimum Size of Fillet Welds

<table>
<thead>
<tr>
<th>Material Thickness of Thinner Part Joined, in. (mm)</th>
<th>Minimum Size of Fillet Weld, ( \text{in. (mm)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>To ( \frac{1}{4} ) (6) inclusive</td>
<td>( \frac{1}{8} ) (3)</td>
</tr>
<tr>
<td>Over ( \frac{1}{4} ) (6) to ( \frac{1}{2} ) (13)</td>
<td>( \frac{3}{16} ) (5)</td>
</tr>
<tr>
<td>Over ( \frac{1}{2} ) (13) to ( \frac{3}{4} ) (19)</td>
<td>( \frac{1}{4} ) (6)</td>
</tr>
<tr>
<td>Over ( \frac{3}{4} ) (19)</td>
<td>( \frac{5}{16} ) (8)</td>
</tr>
</tbody>
</table>

*Note: See Section J2.2b for maximum size of fillet welds.*

is permitted if consistent penetration beyond the root of the diagrammatic weld is demonstrated by tests using the production process and procedure variables.

For fillet welds in holes and slots, the effective length shall be the length of the centerline of the weld along the center of the plane through the throat. In the case of overlapping fillets, the effective area shall not exceed the nominal cross-sectional area of the hole or slot, in the plane of the faying surface.

**2b. Limitations**

The minimum size of fillet welds shall be not less than the size required to transmit calculated forces, nor the size as shown in Table J2.4. These provisions do not apply to fillet weld reinforcements of partial- or complete-joint-penetration groove welds.

The maximum size of fillet welds of connected parts shall be:

(a) Along edges of material less than \( \frac{1}{4} \)-in. (6 mm) thick; not greater than the thickness of the material.

(b) Along edges of material \( \frac{1}{4} \) in. (6 mm) or more in thickness; not greater than the thickness of the material minus \( \frac{1}{16} \) in. (2 mm), unless the weld is especially designated on the drawings to be built out to obtain full-throat thickness. In the as-welded condition, the distance between the edge of the base metal and the toe of the weld is permitted to be less than \( \frac{1}{16} \) in. (2 mm) provided the weld size is clearly verifiable.

The minimum length of fillet welds designed on the basis of strength shall be not less than four times the nominal weld size, or else the effective size of the weld shall be considered not to exceed one quarter of its length. If longitudinal fillet welds are used alone in end connections of flat-bar tension members, the length of each fillet weld shall be not less than the perpendicular distance between them. For the effect of longitudinal fillet weld length in end connections upon the effective area of the connected member, see Section D3.
For end-loaded fillet welds with a length up to 100 times the weld size, it is permitted to take the effective length equal to the actual length. When the length of the end-loaded fillet weld exceeds 100 times the weld size, the effective length shall be determined by multiplying the actual length by the reduction factor, $\beta$, determined as follows:

$$\beta = 1.2 - 0.002(l/w) \leq 1.0$$ (J2-1)

where

$l = \text{actual length of end-loaded weld, in. (mm)}$

$w = \text{size of weld leg, in. (mm)}$

When the length of the weld exceeds 300 times the leg size, $w$, the effective length shall be taken as $180w$.

Intermittent fillet welds are permitted to be used to transfer calculated stress across a joint or faying surfaces and to join components of built-up members. The length of any segment of intermittent fillet welding shall be not less than four times the weld size, with a minimum of $1\frac{1}{2}$ in. (38 mm).

In lap joints, the minimum amount of lap shall be five times the thickness of the thinner part joined, but not less than 1 in. (25 mm). Lap joints joining plates or bars subjected to axial stress that utilize transverse fillet welds only shall be fillet welded along the end of both lapped parts, except where the deflection of the lapped parts is sufficiently restrained to prevent opening of the joint under maximum loading.

Fillet weld terminations are permitted to be stopped short or extend to the ends or sides of parts or be boxed except as limited by the following:

1. For overlapping elements of members in which one connected part extends beyond an edge of another connected part that is subject to calculated tensile stress, fillet welds shall terminate not less than the size of the weld from that edge.

2. For connections where flexibility of the outstanding elements is required, when end returns are used the length of the return shall not exceed four times the nominal size of the weld nor half the width of the part.

3. Fillet welds joining transverse stiffeners to plate girder webs $\frac{3}{4}$-in. (19 mm) thick or less shall end not less than four times nor more than six times the thickness of the web from the web toe of the web-to-flange welds, except where the ends of stiffeners are welded to the flange.

4. Fillet welds that occur on opposite sides of a common plane shall be interrupted at the corner common to both welds.

User Note: Fillet weld terminations should be located approximately one weld size from the edge of the connection to minimize notches in the base metal. Fillet welds terminated at the end of the joint, other than those connecting stiffeners to girder webs, are not a cause for correction.

Fillet welds in holes or slots are permitted to be used to transmit shear and resist loads perpendicular to the faying surface in lap joints or to prevent the buckling or
separation of lapped parts and to join components of built-up members. Such fillet welds may overlap, subject to the provisions of Section J2. Fillet welds in holes or slots are not to be considered plug or slot welds.

3. **Plug and Slot Welds**

3a. **Effective Area**

The effective shearing area of plug and slot welds shall be considered as the nominal cross-sectional area of the hole or slot in the plane of the faying surface.

3b. **Limitations**

Plug or slot welds are permitted to be used to transmit shear in lap joints or to prevent buckling or separation of lapped parts and to join component parts of built-up members.

The diameter of the holes for a plug weld shall not be less than the thickness of the part containing it plus $\frac{5}{16}$ in. (8 mm), rounded to the next larger odd $\frac{1}{16}$ in. (even mm), nor greater than the minimum diameter plus $\frac{1}{8}$ in. (3 mm) or $2\frac{1}{4}$ times the thickness of the weld.

The minimum center-to-center spacing of plug welds shall be four times the diameter of the hole.

The length of slot for a slot weld shall not exceed 10 times the thickness of the weld. The width of the slot shall be not less than the thickness of the part containing it plus $\frac{5}{16}$ in. (8 mm) rounded to the next larger odd $\frac{1}{16}$ in. (even mm), nor shall it be larger than $2\frac{1}{4}$ times the thickness of the weld. The ends of the slot shall be semicircular or shall have the corners rounded to a radius of not less than the thickness of the part containing it, except those ends which extend to the edge of the part.

The minimum spacing of lines of slot welds in a direction transverse to their length shall be four times the width of the slot. The minimum center-to-center spacing in a longitudinal direction on any line shall be two times the length of the slot.

The thickness of plug or slot welds in material $\frac{5}{8}$ in. (16 mm) or less in thickness shall be equal to the thickness of the material. In material over $\frac{5}{8}$-in. (16 mm) thick, the thickness of the weld shall be at least one-half the thickness of the material but not less than $\frac{5}{8}$ in. (16 mm).

4. **Strength**

The design strength, $\sigma_R$, and the allowable strength, $R_n/\Omega$, of welded joints shall be the lower value of the base material strength determined according to the limit states of tensile rupture and shear rupture and the weld metal strength determined according to the limit state of rupture as follows:

For the base metal

$$R_n = \frac{F_{UBM}}{\beta_{BM}}$$  \hspace{1cm} (J2-2)
### TABLE J2.5 (continued)
Available Strength of Welded Joints, ksi (MPa)

<table>
<thead>
<tr>
<th>Load Type and Direction Relative to Weld Axis</th>
<th>Pertinent Metal</th>
<th>Nominal Stress (F_{nBM}) or (F_{nw}) ksi (MPa)</th>
<th>Effective Area (A_{BM}) or (A_{we}) in.(^2) (mm(^2))</th>
<th>Required Filler Metal Strength Level (^{[a][b]})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FILLET WELDS INCLUDING FILLETS IN HOLES AND SLOTS AND SKEWED T-JOINTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear</td>
<td>Base</td>
<td>(\phi = 0.75) (\Omega = 2.00) (0.60F_{EXX})</td>
<td>(\Omega = 2.00) See J2.2a</td>
<td>Filler metal with a strength level equal to or less than matching filler metal is permitted.</td>
</tr>
<tr>
<td></td>
<td>Weld</td>
<td></td>
<td>(0.60F_{EXX})</td>
<td></td>
</tr>
<tr>
<td>Tension or compression in parts joined parallel to a weld need not be considered in design of welds joining the parts.</td>
<td>Parallel to weld axis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PLUG AND SLOT WELDS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear</td>
<td>Base</td>
<td>(\phi = 0.75) (\Omega = 2.00) (0.60F_{EXX})</td>
<td>(\Omega = 2.00) See J2.3a</td>
<td>Filler metal with a strength level equal to or less than matching filler metal is permitted.</td>
</tr>
<tr>
<td></td>
<td>Weld</td>
<td></td>
<td>(0.60F_{EXX})</td>
<td></td>
</tr>
</tbody>
</table>

\(^{[a]}\) For matching weld metal see AWS D1.1/D1.1M, Section 3.3.
\(^{[b]}\) Filler metal with a strength level one strength level greater than matching is permitted.
\(^{[c]}\) Filler metals with a strength level less than matching may be used for groove welds between the webs and flanges of built-up sections transferring shear loads, or in applications where high restraint is a concern. In these applications, the weld joint shall be detailed and the weld shall be designed using the thickness of the material as the effective throat, where \(\phi = 0.80\) \(\Omega = 1.88\) and \(0.60F_{EXX}\) is the nominal strength.

\(^{[d]}\) Alternatively, the provisions of Section J2.4(a) are permitted provided the deformation compatibility of the various weld elements is considered. Sections J2.4(b) and (c) are special applications of Section J2.4(a) that provide for deformation compatibility.

For the weld metal

\[
R_n = F_{nw}A_{we}
\]  

(J2-3)

where

\(F_{nBM}\) = nominal stress of the base metal, ksi (MPa)
\(F_{nw}\) = nominal stress of the weld metal, ksi (MPa)
\(A_{BM}\) = cross-sectional area of the base metal, in.\(^2\) (mm\(^2\))
\(A_{we}\) = effective area of the weld, in.\(^2\) (mm\(^2\))

The values of \(\phi\), \(\Omega\), \(F_{nBM}\) and \(F_{nw}\) and limitations thereon are given in Table J2.5.

Alternatively, for fillet welds the available strength is permitted to be determined as follows:

\[
\phi = 0.75 \text{(LRFD)} \quad \Omega = 2.00 \text{(ASD)}
\]

(J2.4)

(a) For a linear weld group with a uniform leg size, loaded through the center of gravity

\[
R_n = F_{nw}A_{we}
\]

(J2-4)

where

\[
F_{nw} = 0.60F_{EXX}(1.0 + 0.50 \sin^{1.5} \theta)
\]

(J2-5)

---

*Specification for Structural Steel Buildings, June 22, 2010
American Institute of Steel Construction*
and $F_{EXX} = \text{filler metal classification strength, ksi (MPa)}$ (E70 - $F_{EXX} = 70$)

$\theta = \text{angle of loading measured from the weld longitudinal axis, degrees}$

**User Note:** A linear weld group is one in which all elements are in a line or are parallel.

(b) For weld elements within a weld group that are analyzed using an instantaneous center of rotation method, the components of the nominal strength, $R_{nx}$ and $R_{ny}$, and the nominal moment capacity, $M_n$, are permitted to be determined as follows:

$$R_{nx} = \sum F_{nwix}A_{wei} \quad \text{(J2-6a)}$$
$$R_{ny} = \sum F_{nwiy}A_{wei} \quad \text{(J2-6b)}$$
$$M_n = \sum [F_{nwix}A_{wei}(x_i) - F_{nwix}A_{wei}(y_i)] \quad \text{(J2-7)}$$

where

$A_{wei} = \text{effective area of weld throat of the } i\text{th weld element, in.}^2 \text{ (mm}^2\text{)}$

$F_{nwix} = 0.60F_{EXX}(1.0 + 0.50\sin^{1.5} \theta_i) f(p_i) \quad \text{(J2-8)}$

$f(p_i) = [p_i(1.9 - 0.9p_i)]^{0.3} \quad \text{(J2-9)}$

$F_{nwix} = \text{nominal stress in the } i\text{th weld element, ksi (MPa)}$

$F_{nwix} = \text{x-component of nominal stress, } F_{nwix}, \text{ ksi (MPa)}$

$F_{nwiy} = \text{y-component of nominal stress, } F_{nwiy}, \text{ ksi (MPa)}$

$p_i = \Delta_i/\Delta_{mi}, \text{ ratio of element } i \text{ deformation to its deformation at maximum stress}$

$r_{cr} = \text{distance from instantaneous center of rotation to weld element with minimum } \Delta_{ui}/r_i, \text{ ratio, in. (mm)}$

$r_i = \text{distance from instantaneous center of rotation to } i\text{th weld element, in. (mm)}$

$x_i = \text{x component of } r_i$

$y_i = \text{y component of } r_i$

$\Delta_i = r_i\Delta_{u/cr}/r_{cr} = \text{deformation of the } i\text{th weld element at an intermediate stress level, linearly proportioned to the critical deformation based on distance from the instantaneous center of rotation, } r_{cr}, \text{ in. (mm)}$

$\Delta_{mi} = 0.209(\theta_i + 2)^{-0.32} w, \text{ deformation of the } i\text{th weld element at maximum stress, in. (mm)}$

$\Delta_{u/cr} = \text{deformation of the weld element with minimum } \Delta_{ui}/r_i, \text{ ratio at ultimate stress (rupture), usually in the element furthest from instantaneous center of rotation, in. (mm)}$

$\Delta_{ui} = 1.087(\theta_i + 6)^{-0.65} w \leq 0.17w, \text{ deformation of the } i\text{th weld element at ultimate stress (rupture), in. (mm)}$

$\theta_i = \text{angle between the longitudinal axis of } i\text{th weld element and the direction of the resultant force acting on the element, degrees}$

(c) For fillet weld groups concentrically loaded and consisting of elements with a uniform leg size that are oriented both longitudinally and transversely to the direction of applied load, the combined strength, $R_n$, of the fillet weld group shall be determined as the greater of
5. Combination of Welds

If two or more of the general types of welds (groove, fillet, plug, slot) are combined in a single joint, the strength of each shall be separately computed with reference to the axis of the group in order to determine the strength of the combination.

6. Filler Metal Requirements

The choice of filler metal for use with complete-joint-penetration groove welds subject to tension normal to the effective area shall comply with the requirements for matching filler metals given in AWS D1.1/D1.1M.

User Note: The following User Note Table summarizes the AWS D1.1/D1.1M provisions for matching filler metals. Other restrictions exist. For a complete list of base metals and prequalified matching filler metals see AWS D1.1/D1.1M, Table 3.1.

<table>
<thead>
<tr>
<th>Base Metal</th>
<th>Matching Filler Metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>A36 ≤ 3/4 in.</td>
<td>60 &amp; 70 ksi filler metal</td>
</tr>
<tr>
<td>A36 &gt; 3/4 in.</td>
<td>A572 (Gr. 50 &amp; 55)</td>
</tr>
<tr>
<td>A588*</td>
<td>A913 (Gr. 50)</td>
</tr>
<tr>
<td>A1011</td>
<td>A992</td>
</tr>
<tr>
<td></td>
<td>A1018</td>
</tr>
<tr>
<td>A913 (Gr. 60 &amp; 65)</td>
<td>80 ksi filler metal</td>
</tr>
</tbody>
</table>

*For corrosion resistance and color similar to the base metal, see AWS D1.1/D1.1M, subclause 3.7.3.

Notes:
- Filler metals shall meet the requirements of AWS A5.1, A5.5, A5.17, A5.18, A5.20, A5.23, A5.28, or A5.29.
- In joints with base metals of different strengths, use either a filler metal that matches the higher strength base metal or a filler metal that matches the lower strength and produces a low hydrogen deposit.

Filler metal with a specified minimum Charpy V-notch toughness of 20 ft-lb (27 J) at 40 °F (4 °C) or lower shall be used in the following joints:

1. Complete joint-penetration groove welded T- and corner joints with steel backing left in place, subject to tension normal to the effective area, unless the joints