A Practical Design Guide for Welded Connections

Part 2

Analysis and Design of Welded Connections

by

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Design Considerations for Welded Connections

General Design Considerations

Part 2 of this course will focus on concepts of the analysis and design of welded connections. Over welding drastically increases welding costs. Therefore, it is very important to understand proper design of welded connections to reduce cost. As you plan to design welded connections, there are some general considerations to make the design more effective.

One major problem associated with welded connections is **distortion**. Distortion occurs due to the thermal expansion and contraction of weld material and adjacent base material during the welding process. Symmetrically located welds will reduce distortion, but sometimes it may not be possible to place welds symmetrically. Over welding also causes distortion, so intermittent welding can limit distortion if continuous welds are not required.

This section will cover details for determining a required weld size to carry the subjected loading. When possible, try to place welds in low stress areas in order to reduce the loading on the welded joint and reduce the required weld size. It is also best to avoid stress changes in a weld; The weld's cross-section ideally should be completely loaded in tension, compression, or shear when possible.

LRFD Requirements

The welded connection design procedures presented here will be based on the Load and Resistance Factor Design (LRFD) method. A full description of the method is beyond the scope of this course, but below is a list of some important requirements for welded connections.

Minimum Weld Length: The minimum length of the fillet weld is four times the weld's leg dimension. When longitudinal fillet welds are used to connect plates (see Figure 2), the weld length may not be less than the perpendicular distance between the welds.

Minimum Weld Size: The minimum leg dimension of a fillet weld is determined from Table 1.

Maximum Weld Size: For materials of less than ¼" inch in thickness the maximum weld size is equal to the material thickness. For materials thicker than ¼" inch the maximum weld is equal to 1/16" less than the material thickness.

Table 1   Minimum leg dimension for fillet welds

Material thickness [thicker part] (inches)	Minimum weld size (inches)
$t \le \dfrac{1}{4}$	$\dfrac{1}{8}$
$\dfrac{1}{4} < t \le \dfrac{1}{2}$	$\dfrac{3}{16}$
$\dfrac{1}{2} < t \le \dfrac{3}{4}$	$\dfrac{1}{4}$
$t > \dfrac{3}{4}$	$\dfrac{5}{16}$

Concepts for Fillet Weld Analysis and Design

Introduction

Most mechanical and structural welded connections are fillet welds (around 80%). As an engineer it is very important to have a strong understanding of fillet weld design. They are mostly used to connect plates when the joint forms a 90-degree angle, such as tee joints and corner joints.

When possible, fillet welds should be designed so they are only subjected to shearing stress. Failure tests of welded connections loaded parallel to the direction of the weld fail by shear at a 45° angle. Therefore, weld strength is based on the assumption of the weld area at the theoretical throat shown in Figure 1. For an equal leg fillet weld the throat dimension is equal to 0.707 times the leg dimension. This gives the weld area equal to the throat dimension (0.707 times the leg dimension) times the length of the weld.
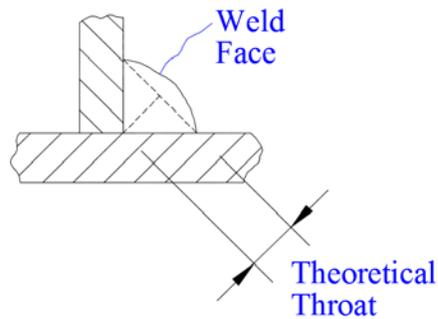
Figure 1   Theoretical throat of a fillet weld

Weld orientation with respect to the load direction can be transverse or longitudinal, as shown in Figure 2. Transverse fillet welds are stronger than longitudinal fillet welds because they are more uniformly stressed. Longitudinal fillet welds will have varying stress due to deformation along the length. Though transverse welds are stronger, the common practice (and more conservative approach) is to design them the same as longitudinal welds.
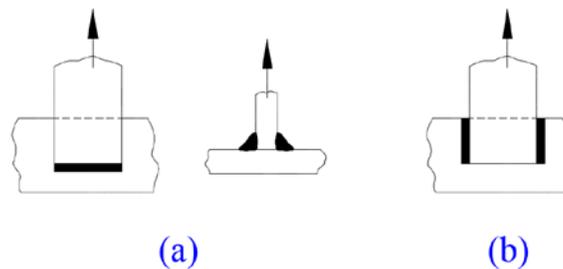

Figure 2   (a) Transverse fillet weld and (b) longitudinal (parallel) fillet weld

Quick Estimate for Determining Required Weld Size

It is important as an engineer to be able to develop a quick 'rule of thumb' type of estimate on weld size. This will allow for a starting point on design and will help determine if a calculated weld size seems correct. If a fillet weld is on both sides and the full length of the plate, the approximate fillet weld size (leg dimension) will be 75% of the thickness of the thinner plate. This assumption will give an approximate weld size required to develop the full strength of the plate. This should not be used in place of calculated weld size, but it can provide a good starting point or a quick check.

Fillet Welds in Direct Loading

Resistance Factor

The design strength of a weld will be determined using the Load and Resistant Factor Design (LRFD) method. **Resistance factors** are used in the LRFD method to account for uncertainties in material strength. Theoretical ultimate strength values are reduced by multiplying the ultimate strength and a resistance factor ϕ. For fillet welds with shear on the effective area, which is the case for longitudinal fillet welds in direct loading, the resistance factor is equal to 0.75.

Fillet Weld Design Strength

Using LRFD code, the design strength of a fillet weld with shear on the effective area is equal to the resistance factor times the nominal strength of the weld (defined by 0.6 times the electrode yield strength in ksi) times the weld throat dimension times the length of the weld. The strength per unit length of weld is given in Equation 1 where t is the weld's throat dimension in inches.

Design strength of weld per unit length	$\phi(0.6F_{EXX})(t)$	Equation 1

Using a resistance factor of 0.75 and a throat dimension of 0.707 times the leg dimension, Table 2 gives values of the design strength per unit length for different leg dimensions and electrodes.

For example, using a E70 electrode, a ¼" weld has a design strength of 5.57 kips per inch of weld length. The calculation for that would be

$$\phi(0.6F_{EXX})(t) = 0.75(0.6 \cdot 70)(0.707 \cdot 0.25) = 5.57$$

Table 2   Design strength (in kips) per unit length (in inches) for direct loaded equal leg fillet welds

Leg Size	Electrode Strength (EXX) in ksi					
(in)	60	70	80	90	100	110
1/16	1.19	1.39	1.59	1.79	1.99	2.19
1/8	2.39	2.78	3.18	3.58	3.98	4.37
3/16	3.58	4.18	4.77	5.37	5.97	6.56
1/4	4.77	5.57	6.36	7.16	7.95	8.75
5/16	5.97	6.96	7.95	8.95	9.94	10.94
3/8	7.16	8.35	9.54	10.74	11.93	13.12
7/16	8.35	9.74	11.14	12.53	13.92	15.31
1/2	9.54	11.14	12.73	14.32	15.91	17.50
9/16	10.74	12.53	14.32	16.11	17.90	19.69
5/8	11.93	13.92	15.91	17.90	19.88	21.87
11/16	13.12	15.31	17.50	19.69	21.87	24.06
3/4	14.32	16.70	19.09	21.48	23.86	26.25
13/16	15.51	18.09	20.68	23.26	25.85	28.43
7/8	16.70	19.49	22.27	25.05	27.84	30.62
15/16	17.90	20.88	23.86	26.84	29.83	32.81
1	19.09	22.27	25.45	28.63	31.82	35.00

It should be noted that the values in Table 2 are based on using the shielded arc wielding method. Submerged arc welding methods provides a deeper penetration which results in a slightly higher strength.

Full analysis of a directly loaded welded connection also requires determining the design strength of the plate, which can be calculated using the following equation.

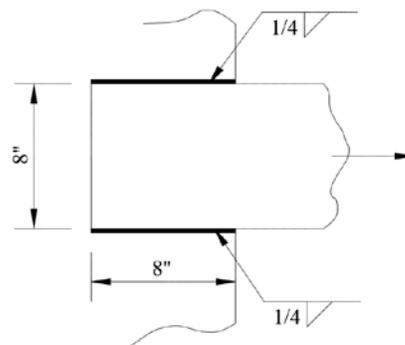**Design strength of plate**

$$\phi F_y A_g$$

Equation 2

Theoretical ultimate strength value is again reduced by multiplying by a resistance factor ϕ. For tensile failure of a plate the resistance factor value is 0.9. In Equation 2, F_y is the material's yield strength in kips per square inch (ksi) and A_g is the cross-sectional area of the plate in square inches.

Example Problem 1

Determine the design strength of the welded connection shown. Both plates are ½" thick and have a yield strength of 36 ksi. The electrode is E60.

Effective throat thickness	(0.707)(0.25) = 0.177 in
Weld capacity per inch (Table 2)	4.77 kips/in
Total capacity of weld	4.77 kips/in (16 in) = 76.32 kips

Design capacity of the plate $\phi F_y A_g$ = (0.90)(36 ksi)(0.5 in)(8 in) = 129.6 kips

The final design capacity is the minimum of that of the weld and plate.

Design capacity   **76.32 kips**

Example Problem 2

Determine the new design strength for the connection in Example Problem 1 if the weld size is increased to 3/8", the electrode was changed to E70, and the plate material strength was increased to 50ksi.

Effective throat thickness	(0.707)(0.375) = 0.265 in
Weld capacity per inch (Table 2)	8.35 kips/in
Total capacity of weld	8.35 kips/in (16 in) = 133.6 kips
Design capacity of the plate	$\phi F_y A_g$ = (0.90)(50 ksi)(0.5 in)(8 in) = 180 kips

The final design capacity is the minimum of that of the weld and plate.

Design capacity	**133.6 kips**

Circular Fillet Weld

Consider the very common mechanical and structural application of a fillet weld connecting a circular shaft or pipe to a plate. Circular fillet welds are commonly loaded in torsion, with a typical application shown in Figure 3. For this loading application, the weld is loaded in shear just like the longitudinal weld loaded in direct tension. The design process is identical to that presented in the previous examples with the weld length now based on the circumference of the pipe.
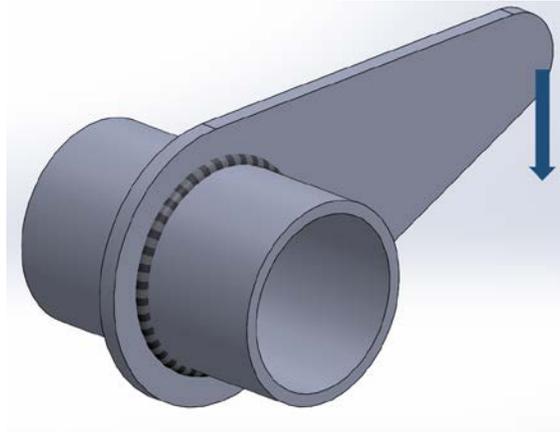
Figure 3   Circular fillet weld with torsional loading

Figure 4 shows the application when an axial load is placed on the shaft or pipe. For this loading condition the weld is loaded the same as the transverse weld shown in Figure 2 (a). As mentioned, the transverse weld is stronger than the longitudinal weld. However, it is common practice to design the transverse weld following the same procedure as the longitudinal weld.
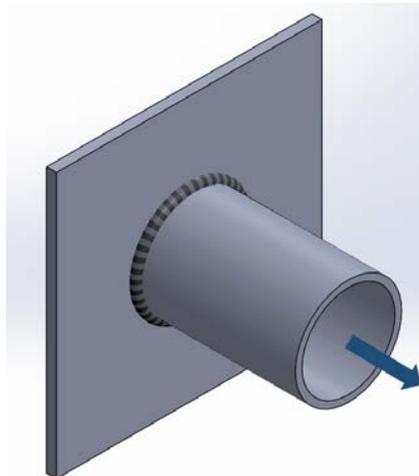

Figure 4   Circular fillet weld with axial loading

Example Problem 3

A round mechanical pipe has an outside diameter of 3" and has a wall thickness of 1/4". The pipe is welded to a flat plate and axially loaded similar to that shown in Figure 4. The yield strength of the pipe is 36 ksi. Determine the fillet weld size required (E70 electrode) as an all-around weld to develop the full strength of the pipe (based on yield strength of the pipe).

Pipe cross-sectional area	2.16 in^2
Yield strength of pipe	(36)(2.16) = 77.76 kips
Length of weld	(3.14)(3) = 9.425 in
Load per inch of weld	(77.76 kips) / (9.425 in) = 8.25 kips/in

From Table 2 using E70 the required weld size is 3/8"

Eccentrically Loaded Fillet Welds

The previous section covered directly loaded welds where the load passes through the centroid of the weld and the entire weld was loaded in shear. It is common to have welded connections which are eccentrically loaded, where the load does not pass through the centroid of the weld. Such loading will result in either welds loaded in shear and torsion or shear and bending as illustrated in Figure 5. For eccentrically loaded welded connections, the loading is resolved into a force and moment couple placed at the centroid of the weld. The effects of both the force and couple are determined separately and superimposed to get the final results.
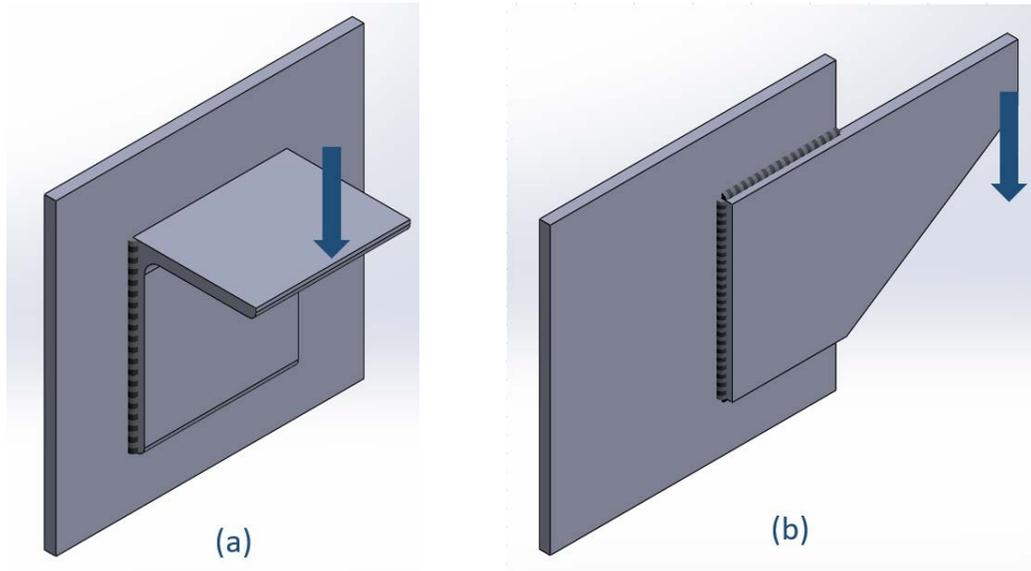
Figure 5   Types of eccentrically loaded connections (a) weld subjected to shear and bending (b) weld subjected to shear and torsion

Shear and Bending Loading

The first type of eccentrically loaded connection discussed is one that results in the combination of shear and bending, such as the case shown in Figure 6 (a). Common practice is to assume that the shear stress is uniformly distributed along the length of the weld. Assuming a fillet weld on both sides of the angle plate (giving a total weld length of 2L), the shear force per unit length of weld is given by

Shear force per unit length of weld
$$f_s = \frac{F}{2L}$$
Equation 3

Figure 6   (a) Eccentrically loaded connection with weld subjected to shear and bending (b) bending stress distribution

The bending stress will vary linearly along the length as illustrated in figure 6 (b). Testing shows that the upper portion of the weld carries more of the bending load compared to the bottom portion. Therefore, the neutral axis is assumed to be located a distance equal to 2/3L from the top. From that assumption, the bending force per unit length is equal to

Bending force per unit length of weld

$$f_b = \frac{2.25(F)(e)}{L^2}$$

Equation 4

Design of the weld is then determined by combining the values of shear and bending vectorially using maximum values.

Resultant force per unit length of weld

$$f_r = \sqrt{f_s^2 + f_b^2}$$

Equation 5

Example Problem 4

Determine the required weld size for the eccentric connection shown using E70 electrode.

Shear Force
$$f_s = \frac{F}{2L} = \frac{30k}{2(6in)} = 2.5\frac{k}{in}$$

Bending Force
$$f_b = \frac{2.25(F)(e)}{L^2} = \frac{2.25(30k)(2.5in)}{(6in)^2} = 4.688\frac{k}{in}$$

Resultant Force
$$f_r = \sqrt{f_s^2 + f_b^2} = \sqrt{\left(2.5\frac{k}{in}\right)^2 + \left(4.688\frac{k}{in}\right)^2} = 5.313\frac{k}{in}$$

Required Weld Size
$$w = \frac{f_r}{0.707\phi(0.6F_{Exx})} = \frac{5.313\frac{k}{in}}{(0.707)(0.75)(0.6)(70ksi)} = 0.239in$$

Use 1/4 inch welds

Shear and Torsion Loading

Next we consider the case of shear and torsion loading, which is shown in Figure 7 (a). Weld capacity for these joints can be determined using the elastic method or the ultimate strength method; the elastic method is more conservative and will be the method used for this section.

For calculations we will need to know some properties of the weld group, which are determined by treating the weld as a line as shown in Figure 7 (b).
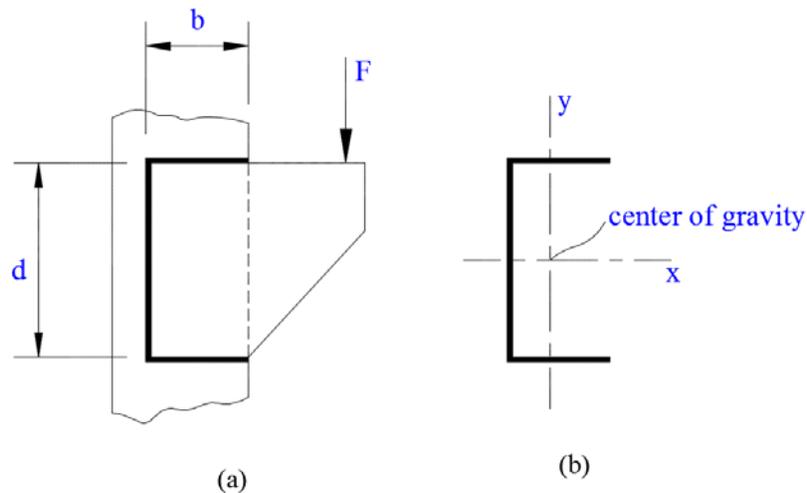

Figure 7   (a) Eccentrically loaded connection with weld subjected to shear and torsion (b) weld treated as line

As with the case for shear and bending, common practice is to assume that the shear stress is uniformly distributed along the length of the weld. For a torque T, the torsional force is calculated using the following equation.

Torsional force per unit length of weld

$$f = \frac{Td}{J}$$

Equation 6

In equation 6, the distance from the weld center of gravity to the point of interest is give as d and J is the polar moment of inertia of the weld. For convenience, the torsional force is generally expressed in terms of horizontal and vertical components using the horizontal and vertical distances h and v.
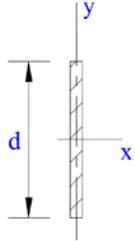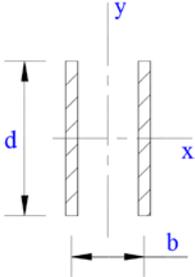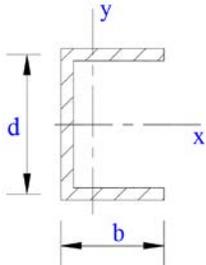
Horizontal
$$f_h = \frac{Tv}{J}$$
Equation 7

Vertical
$$f_v = \frac{Th}{J}$$
Equation 8

Table 3　Properties of common weld patterns

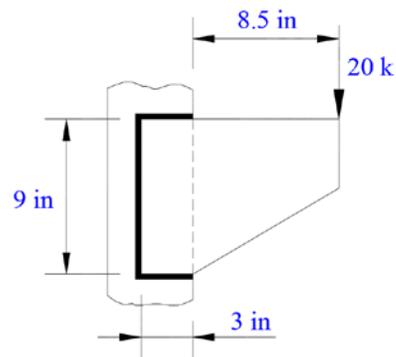| Weld Pattern	Center of Gravity (in)	Polar Moment of Inertia (in³)
	$\bar{x} = 0$ $\bar{y} = \dfrac{d}{2}$	$J = \dfrac{d^3}{12}$
	$\bar{x} = 0$ $\bar{y} = 0$	$J = \dfrac{d\left(3b^2 + d^2\right)}{6}$
	$\bar{x} = \dfrac{b^2}{2b + d}$ $\bar{y} = \dfrac{d}{2}$	$J = \dfrac{(2b + d)^3}{12} - \dfrac{b^2(b + d)^2}{2b + d}$

In order to calculate forces on the weld we must first determine two properties of the weld group: center of gravity location and polar moment of inertia. Table 3 gives these properties for some common weld patterns, but they can be calculated for any pattern.

Example Problem 5

Determine the weld size required for the ½ inch plate bracket shown using E70 electrode.

Properties of the weld pattern:

Length of Weld

$$L_w = 2b + d = 2(3) + 9 = 15in$$

Centroid Location

$$\bar{x} = \frac{b^2}{2b+d} = \frac{3^2}{2(3)+9} = 0.60in$$

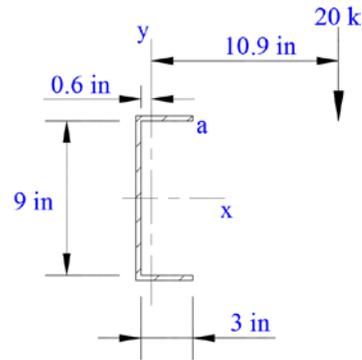$$\bar{y} = \frac{d}{2} = \frac{9}{2} = 4.5in$$

Polar Moment of Inertia

$$J = \frac{(2b+d)^3}{12} - \frac{b^2(b+d)^2}{2b+d}$$

$$J = \frac{(2(3)+9)^3}{12} - \frac{3^2(3+9)^2}{2(3)+9} = 194.85in^3$$

The weld pattern is shown in the figure to the right. The maximum stress will occur at the location farthest from the center of gravity, which would point a on the figure.

Shear Force

$$f_s = \frac{F}{L_w} = \frac{20k}{15in} = 1.33\frac{k}{in}$$

Torsional Force - Horizontal Component

$$f_h = \frac{Tv}{J} = \frac{20k(10.9in)(4.5in)}{194.85in^3} = 5.03\frac{k}{in}$$

Torsional Force - Vertical Component

$$f_v = \frac{Th}{J} = \frac{20k(10.9in)(3-0.6)in}{194.85in^3} = 2.69\frac{k}{in}$$

Next we can determine the resultant force on the weld at location a.

$$f_r = \sqrt{f_h^2 + (f_v + f_s)^2}$$

$$f_r = \sqrt{5.03^2 + (2.69+1.33)^2} = 6.44\frac{k}{in}$$

Determine the required weld size.

$$w = \frac{f_r}{0.707\phi(0.6F_{Exx})} = \frac{6.44\frac{k}{in}}{(0.707)(0.75)(0.6)(70ksi)} = 0.289in$$

Use 5/16 inch weld

Groove Welds

Introduction

In general groove welds are more expensive than fillet welds due to the preparation of the workpiece (cutting the channel discussed in Part 1 of the course). A major disadvantage of groove welds compared to fillet welds is the difficulty of fitting pieces together for welding, especially if it is field welded. Therefore, field groove welds are rarely used unless parts are fabricated over length and cut in the field to fit.

A groove weld will have equal or better strength than the plate, but must be full penetration (all the way through the plate) for strength connections. For complete penetration groove welds subjected to axial loading (tension or compression), the weld stress is assumed to be the load divided by the net area. If plates of different thickness are joined with a full penetration groove weld, the strength is based on the weaker plate. If the welded connection is not required to carry large loads, partial penetration groove welds are often more economical.

Reinforcement

Groove welds can have reinforcement, as shown in Figure 8. Reinforcement increases the thickness of the weld material. For joints subjected to static loading, the increased thickness of weld material will increase the strength of the joint. Reinforcement is not good for fatigue loading conditions (repeated loading, vibrating loading, etc.) due to the stress concentration, which will cause earlier fatigue failure. Therefore, if the load will be subjected to any type of fatigue loading conditions the joint should have reinforcement and then grind smooth.
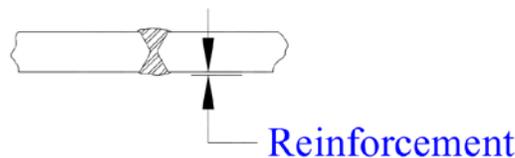

Figure 8   Groove weld reinforcement

Design Strength of Groove Welds

The design strength of a groove weld is determined from
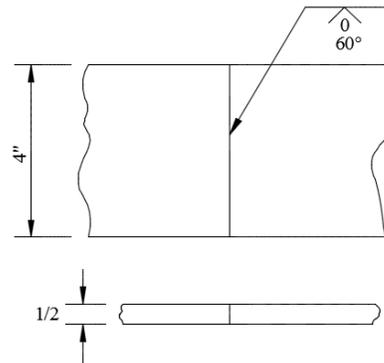
Design strength of a groove weld
$$\phi(0.6F_{EXX})(A)$$
Equation 9

Where $\phi = 0.8$ and A is the area of the weld

Example Problem 6

Determine the maximum tensile load that can be applied for the full depth groove weld for the plates shown. The plates have a yield strength of 50 ksi and the electrode is E70. What would be the maximum tensile load if the weld was a partial depth of ½ the plate thickness?

The first part of the problem is for a full penetration weld. Because the weld strength (70 ksi) is larger than the plate strength (50 ksi) the design strength would be based on the plate strength (the weaker of the two).

Full Penetration Weld
$$F_{max} = \phi F_y A = 0.9(50ksi)[(4in)(0.5in)] = 90k$$

The second part of the problem is for a partial penetration weld. The strength of the weld must be examined and compared to the strength of the plate.

Partial Penetration Weld
$$F_{max} = \phi(0.6F_{EXX})(A) = 0.8(0.6)(70ksi)(4in)(0.25in)$$
$$F_{max} = 33.6k$$

Additional Topics

Welding Structural Angle

Another common application for welding is a connection between structural angle and a flat surface such as a plate. A typical example of that type of connection is illustrated in Figure 9. The connection can have parallel welds, transverse welds, or both as illustrated.
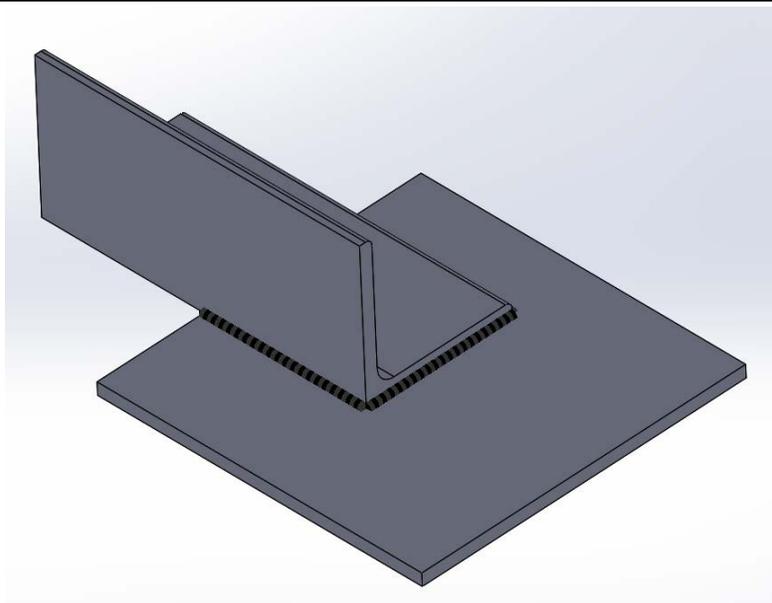

Figure 9   Structural angle welded to plate

When the structural angle is axially loaded in tension or compression, the load is treated as if it passes through the center of gravity of the angle. This is illustrated in Figure 10. Because the load if offset to one side, the required weld length on each side will not be equal. The process for determining the required weld lengths L_1 and L_2 is best illustrated in an example.
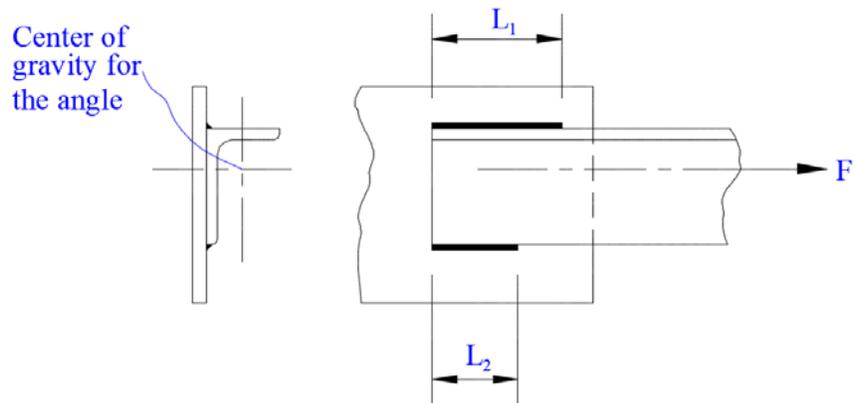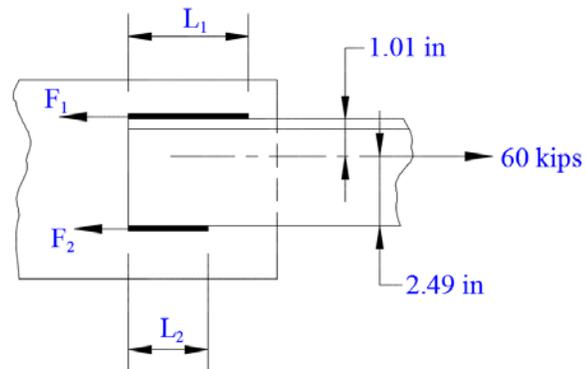
Figure 10   Load passing through the center of gravity of the angle

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Example Problem 7

A L 3 ½ x 3 ½ x 3/8 angle is to be welded to the plate as shown. Determine the lengths L_1 and L_2 if 1/4 inch fillet welds are used with E 70 electrode.

The forces acting on each weld can be determined using summation of moments and summation of forces.

$$\sum M_{F2} = 0$$
$$F_1(3.5in) = 60k(2.49in)$$

$$F_1 = 42.7k$$
$$F_2 = 60k - 42.7k = 17.3k$$

From Table 2, a ¼ inch weld with E70 has a capacity of 5.57 kips per inch. The weld lengths required are

$$L_1 = \frac{F_1}{5.57} = \frac{42.7k}{5.57k/in} = 7.67in$$

$$L_2 = \frac{F_2}{5.57} = \frac{17.3k}{5.57k/in} = 3.11in$$