1. Welding, Bonding, and the Design of Permanent Joints

Form can more readily pursue function with the help of joining processes such as welding, brazing, soldering, cementing, and gluing–processes that are used extensively in manufacturing today. Whenever parts have to be assembled or fabricated, there is usually good cause for considering one of these processes in preliminary design work. Particularly when sections to be joined are thin, one of these methods may lead to significant savings. The elimination of individual fasteners, with their holes and assembly costs, is an important factor. Also, some of the methods allow rapid machine assembly, furthering their attractiveness.

6.1 Welding Symbols

A weldment is fabricated by welding together a collection of metal shapes, cut to particular configurations. During welding, the several parts are held securely together, often by clamping or jigging. The welds must be precisely specified on working drawings, and this is done by using the welding symbol, shown in Fig. (6–1), as standardized by the American Welding Society (AWS). The arrow of this symbol points to the joint to be welded. The body of the symbol contains as many of the following elements as are deemed necessary:

- Reference line
- Arrow
- Basic weld symbols as in Fig. (6–2)
- Dimensions and other data
- Supplementary symbols
- Finish symbols
- Tail
- Specification or process

The *arrow side* of a joint is the line, side, area, or near member to which the arrow points. The side opposite the arrow side is the *other side*.
Figures (6–3 to 6–6) illustrate the types of welds used most frequently by designers. For general machine elements most welds are fillet welds, though butt welds are used a great deal in designing

pressure vessels. Of course, the parts to be joined must be arranged so that there is sufficient clearance for the welding operation. If unusual joints are required because of insufficient clearance or because of the section shape, the design may be a poor one and the designer should begin again and endeavor to synthesize another solution.

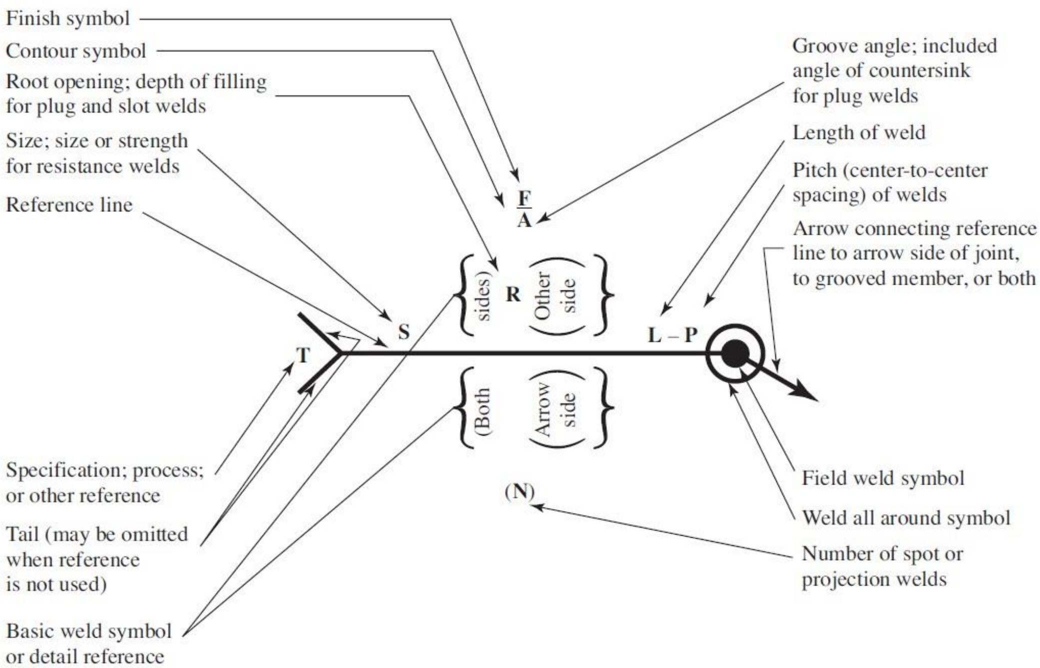


Figure (6–1)

The AWS standard welding symbol showing the location of the symbol elements

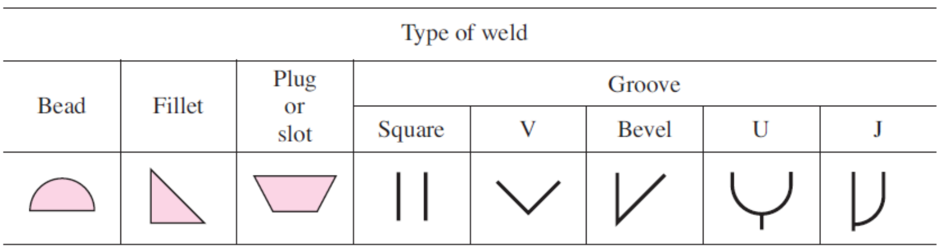


Figure (6–2)

Arc- and gas-weld symbols

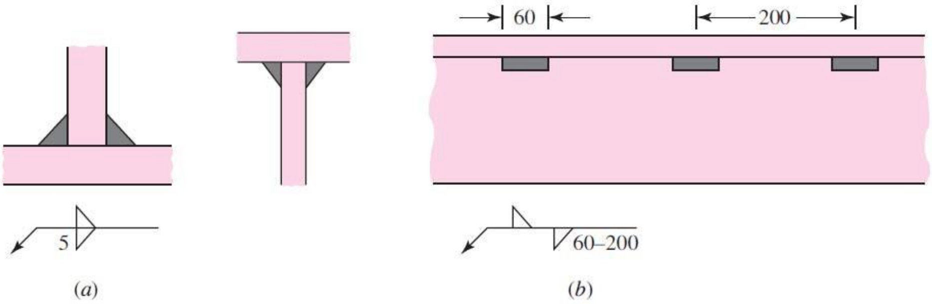
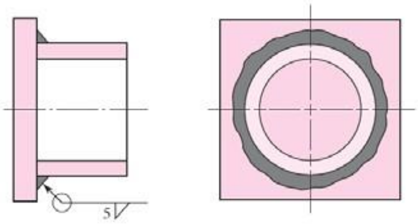


Figure (6–3)

Fillet welds. (*a*) The number indicates the leg size; the arrow should point only to one weld when both sides are the same. (*b*) The symbol indicates that the welds are intermittent and staggered 60 mm along on 200-mm centers

Figure (6–4)

The circle on the weld symbol indicates that the welding is to go all around



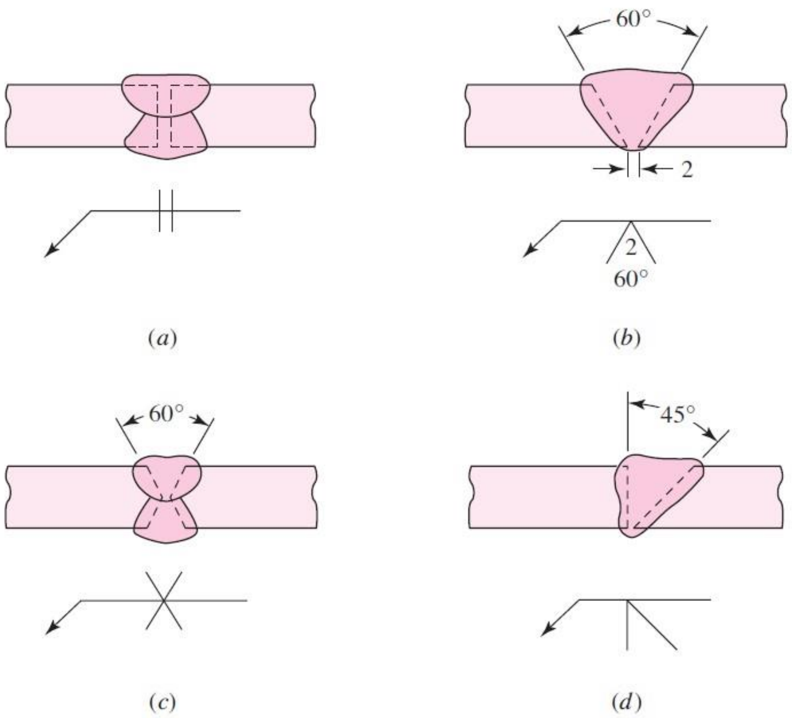


Figure (6–5)

Butt or groove welds: (*a*) square butt-welded on both sides; (*b*) single V with 60° bevel and root opening of 2 mm; (*c*) double V; (*d*) single bevel

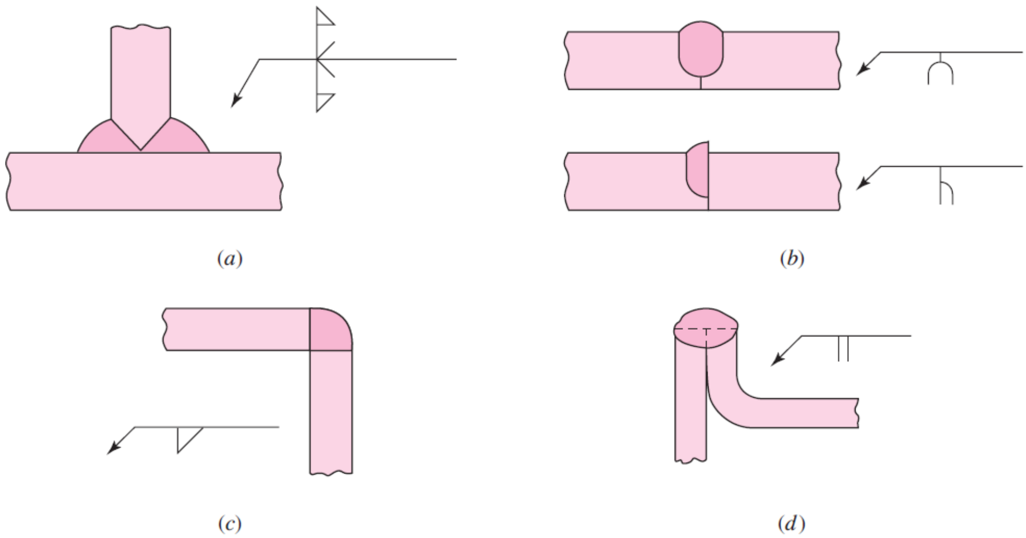


Figure (6–6)

Special groove welds: (*a*) T joint for thick plates; (*b*) U and J welds for thick plates; (*c*) corner weld (may also have a bead weld on inside for greater strength but should not be used for heavy loads); (*d*) edge weld

for sheet metal and light loads

Since heat is used in the welding operation, there are metallurgical changes in the parent metal in the vicinity of the weld. Also, residual stresses may be introduced because of clamping or holding or, sometimes, because of the order of welding. Usually these residual stresses are not severe enough to cause concern; in some cases a light heat treatment after welding has been found helpful in relieving them. When the parts to be welded are thick, a preheating will also be of benefit. If the reliability of the component is to be quite high, a testing program should be established to learn what changes or additions to the operations are necessary to ensure the best quality.

6.2 Butt and Fillet Welds

Figure (6–7*a*) shows a single V-groove weld loaded by the tensile force *F*. For either tension or compression loading, the average normal stress is

$$\sigma = \frac{F}{hl} \qquad \text{6-1}$$

where *h* is the weld throat and *l* is the length of the weld, as shown in the figure. Note that the value of h does not include the reinforcement. The reinforcement can be desirable, but it varies somewhat and does produce stress concentration at point *A* in the figure. If fatigue loads exist, it is good practice to grind or machine off the reinforcement.

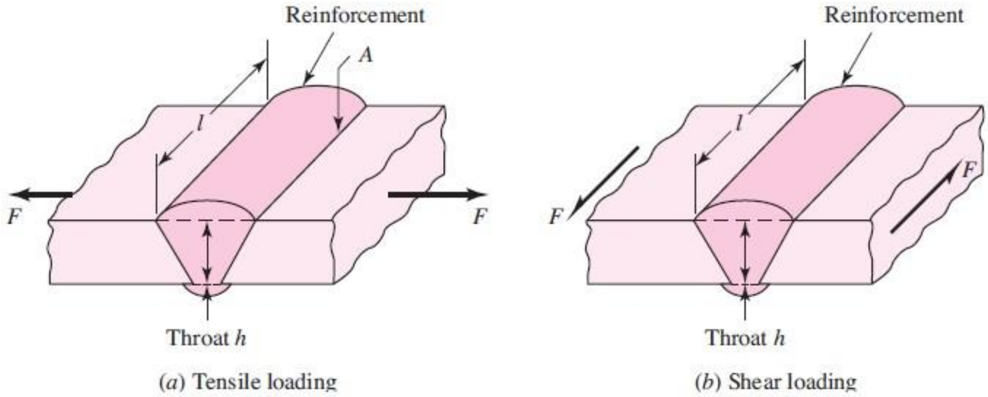


Figure (6–7)
A typical butt joint

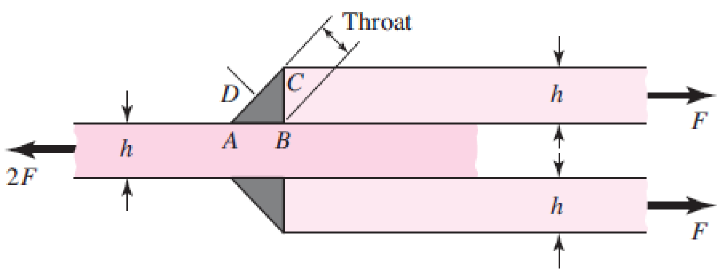


Figure (6–8)
A transverse fillet weld

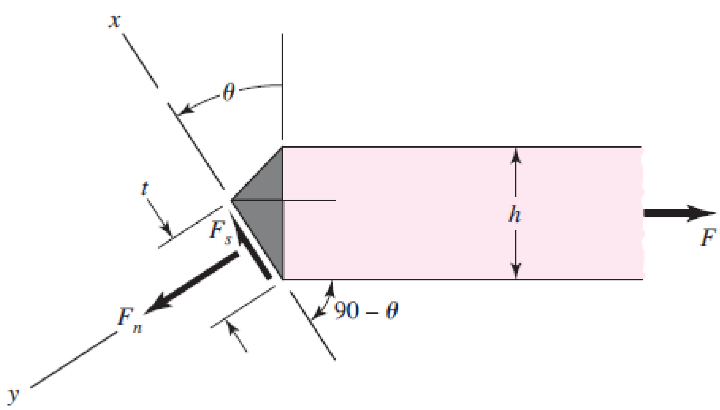


Figure (6–9)
Free body from Fig. (6–8)

The average stress in a butt weld due to shear loading (Fig. 6–7*b*) is

$$\tau = \frac{F}{hl} \qquad 6\text{-}2$$

Figure (6–8) illustrates a typical transverse fillet weld. In Fig. (6–9), a portion of the welded joint has been isolated from Fig. (6–8) as a free body. At angle θ the forces on each weldment consist of a normal force F_n and a shear force F_s . Summing forces in the *x* and *y* directions gives

$$F_s = F \sin \vartheta \qquad a$$

$$F_n = F \cos \vartheta \qquad b$$

Using the law of sines for the triangle in Fig. (6–9) yields

$$\frac{t}{\sin 45^\circ} = \frac{h}{\sin(90^\circ - \theta + 45^\circ)} = \frac{h}{\sin(135^\circ - \theta)} = \frac{\sqrt{2}h}{\cos\theta + \sin\theta}$$

Solving for the throat length *t* gives

$$t = \frac{h}{\cos\theta + \sin\theta} \qquad c$$

The nominal stresses at the angle θ in the weldment, τ and σ, are

$$\tau = \frac{F_s}{A} = \frac{F\sin\theta(\cos\theta + \sin\theta)}{hl} = \frac{F}{hl}(\sin\theta\cos\theta + \sin^2\theta) \qquad d$$

$$\sigma = \frac{F_n}{A} = \frac{F\cos\theta(\cos\theta + \sin\theta)}{hl} = \frac{F}{hl}(\cos^2\theta + \sin\theta\cos\theta) \qquad e$$

The von Mises stress σ′ at angle θ is

$$\sigma' = (\sigma^2 + 3\tau^2)^{1/2} = \frac{F}{hl}[(\cos^2\theta + \sin\theta\cos\theta)^2 + 3(\sin^2\theta + \sin\theta\cos\theta)^2]^{1/2} \qquad f$$

The largest von Mises stress occurs at $\theta = 62.5^\circ$ with a value of $\sigma' = 2.16F/(hl)$. The corresponding values of τ and σ are $\tau = 1.196F/(hl)$ and $\sigma = 0.623F/(hl)$. The maximum shear stress can be found by differentiating Eq. (*d*) with respect to θ and equating to zero. The stationary point occurs at $\theta = 67.5^{o}$ with a corresponding $\tau_{max} = 1.207F/(hl)$ and $\sigma = 0.5F/(hl)$.

There are some experimental and analytical results that are helpful in evaluating Eqs. (*d*) through (*f*) and consequences. A model of the transverse fillet weld of Fig. (6–8) is easily constructed for photoelastic purposes and has the advantage of a balanced loading condition. Norris constructed such a model and reported the stress distribution along the sides *AB* and *BC* of the weld. An approximate graph of the results he obtained is shown as Fig. (6–10*a*). Note that stress concentration exists at *A* and *B* on the horizontal leg and at *B* on the vertical leg. C. H. Norris states that he could not determine the stresses at *A* and *B* with any certainty.

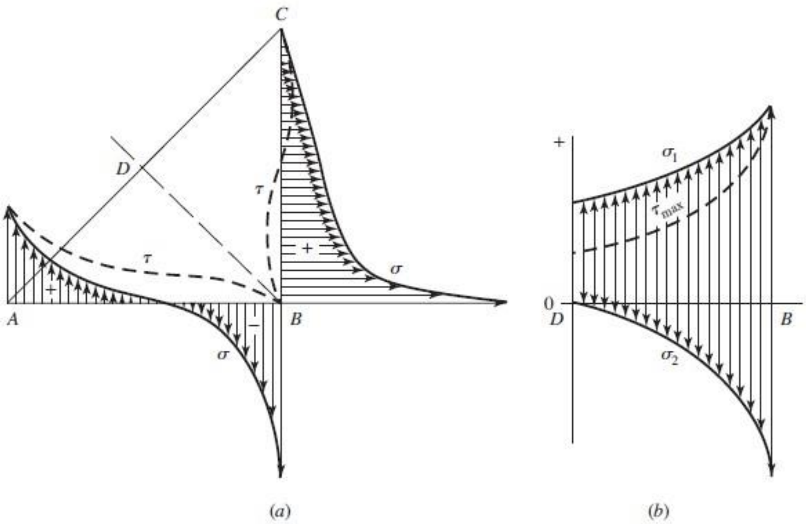


Figure (6–10)
Stress distribution in fillet welds: (*a*) stress distribution on the legs as reported by Norris; (*b*) distribution of principal stresses and maximum

Shear stress as reported by Salakian

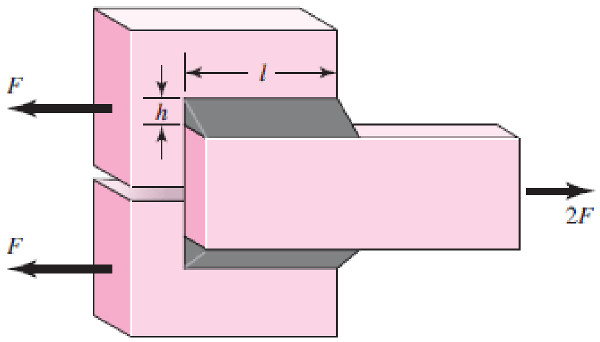


Figure (6–11)
Parallel fillet welds

A. G. Salakian and G. E. Claussen presents data for the stress distribution across the throat of a fillet weld (Fig. 6–10*b*). This graph is of particular interest because we have just learned that it is the throat stresses that are used in design. Again, the figure shows stress concentration at point *B*. Note that Fig. (6–10*a*) applies either to the weld metal or to the parent metal, and that Fig. (6–10*b*) applies only to the weld metal. The most important concept here is that we have *no analytical approach that predicts the existing stresses*. The geometry of the fillet is crude by machinery standards, and even if it were ideal, the macrogeometry is too abrupt and complex for our methods. There are also subtle bending stresses due to eccentricities. Still, in the absence of robust analysis, weldments must be specified and the resulting joints must be safe. The approach has been to use a simple *and conservative* model, verified by testing as conservative. For this model, the basis for weld analysis or design employs

$$\tau = \frac{F}{0.707hl} = \frac{1.414F}{hl} \qquad 66\text{-}3$$

which assumes the entire force *F* is accounted for by a shear stress in the minimum throat area. Note that this inflates the maximum estimated shear stress by a factor of 1.414/1.207 = 1.17. Further, consider the parallel fillet welds shown in Fig. (6–11) where, as in Fig. (6–8), each weld transmits a force *F*. However, in the case of Fig. (6–11), the maximum shear stress *is* at the minimum throat area and corresponds to Eq. (6–3).

6.3 Stresses in Welded Joints in Torsion

Figure (6–12) illustrates a cantilever of length *l* welded to a column by two fillet welds. The reaction at the support of a cantilever always consists of a shear force *V* and a moment *M*. The shear force produces a *primary shear* in the welds of magnitude

$$\tau' = \frac{V}{A} \qquad 6\text{-}4$$

where *A* is the throat area of all the welds.

The moment at the support produces *secondary shear* or *torsion* of the welds, and this stress is given by the equation

$$\tau'' = \frac{Mr}{J} \tag{6-5}$$

where r is the distance from the centroid of the weld group to the point in the weld of interest and J is the second polar moment of area of the weld group about the centroid of the group. When the sizes of the welds are known, these equations can be solved and the results combined to obtain the maximum shear stress. Note that r is usually the farthest distance from the centroid of the weld group.

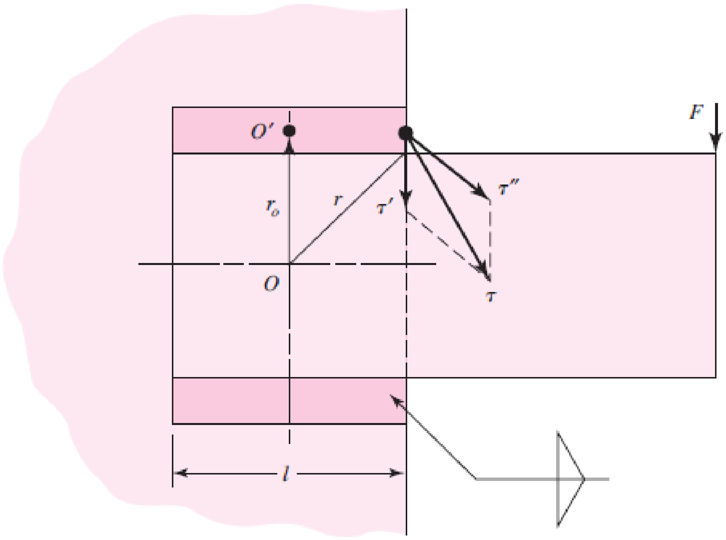


Figure (6–12)

This is a *moment connection;* such a connection

Produces *torsion* in the welds

Figure (6–13) shows two welds in a group. The rectangles represent the throat areas of the welds. Weld 1 has a throat width $b_1 = 0.707h_1$, and weld 2 has a throat width $d_2 = 0.707h_2$. Note that h_1 and h_2 are the respective weld sizes. The throat area of both welds together is

$$A = A_1 + A_2 = b_1 d_1 + b_2 d_2 \tag{a}$$

This is the area that is to be used in Eq. (6–4).

The x axis in Fig. (6–13) passes through the centroid G_1 of

$$I_x = \frac{b_1 d_1^3}{12}$$

weld 1. The second moment of area about this axis is

Similarly, the second moment of area about an axis through G_1 parallel to the y axis is

$$I_y = \frac{d_1 b_1^3}{12}$$

Thus the second polar moment of area of weld 1 about its own centroid is

$$J_{G1} = I_x + I_y = \frac{b_1 d_1^3}{12} + \frac{d_1 b_1^3}{12} \qquad \text{b}$$

In a similar manner, the second polar moment of area of weld 2 about its centroid is

$$J_{G2} = \frac{b_2 d_2^3}{12} + \frac{d_2 b_2^3}{12} \qquad \text{c}$$

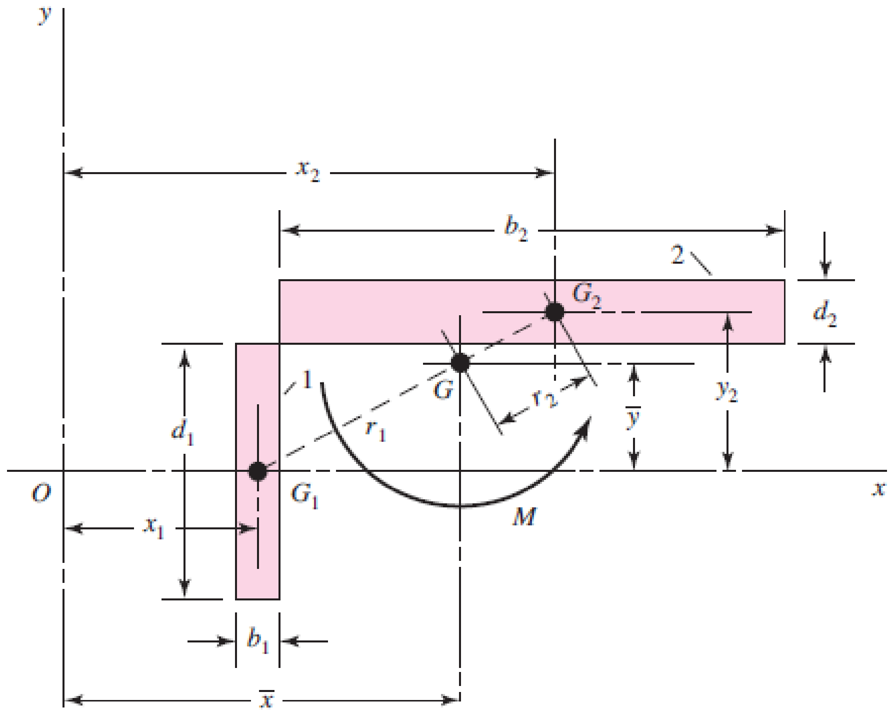


Figure (6–13)

The centroid *G* of the weld group is located at

$$\bar{x} = \frac{A_1x_1 + A_2x_2}{A} \qquad \bar{y} = \frac{A_1y_1 + A_2y_2}{A}$$

Using Fig. (6–13) again, we see that the distances r_1 and r_2 from G_1 and G_2 to G, respectively, are

$$r_1 = [(\bar{x} - x_1)^2 + \bar{y}^2]^{1/2} \qquad r_2 = [(y_2 - \bar{y})^2 + (x_2 - \bar{x})^2]^{1/2}$$

Now, using the parallel-axis theorem, we find the second polar moment of area of the weld group to be

$$J = \left(J_{G1} + A_1r_1^2\right) + \left(J_{G2} + A_2r_2^2\right) \qquad d$$

This is the quantity to be used in Eq. (6–5). The distance r must be measured from G and the moment M computed about G.

The reverse procedure is that in which the allowable shear stress is given and we wish to find the weld size. The usual procedure is to estimate a probable weld size and then to use iteration.

Observe in Eqs. (*b*) and (*c*) the quantities b_1^3 and d_2^3, respectively, which are the cubes of the weld widths. These quantities are small and can be neglected. This leaves the terms $b_1 d_1^3/12$ and $d_2 b_2^3/12$, which make J_{G1} and J_{G2} linear in the weld width. Setting the weld widths b_1 and d_2 to unity leads to the idea of treating each fillet weld as a line. The resulting second moment of area is then a *unit second polar moment of area*. The advantage of treating the weld size as a line is that the value of J_u is the same regardless of the weld size. Since the throat width of a fillet weld is $0.707h$, the relationship between J and the unit value is

$$J = 0.707\, h\, J_u \qquad 6\text{-}6$$

in which J_u is found by conventional methods for an area having unit width. The transfer formula for J_u must be employed when the welds occur in groups, as in Fig. (6–12). Table (6–1) lists the throat areas and the unit second polar moments of area for the most common fillet welds encountered. The example that follows is typical of the calculations normally made.

EXAMPLE 6–1

A 50-kN load is transferred from a welded fitting into a 200-mm steel channel as illustrated in Fig. (6–14). Estimate the maximum stress in the weld.

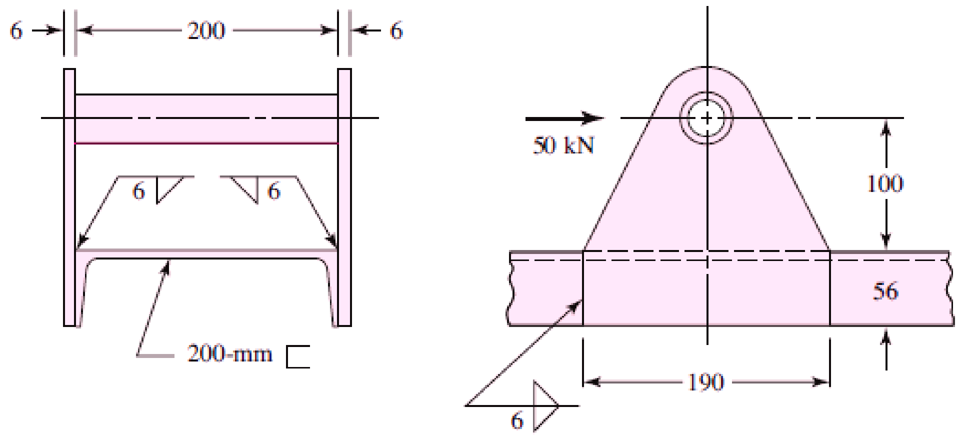


Figure (6–14)
Dimensions in millimeters

Solution

(1) Label the ends and corners of each weld by letter. Sometimes it is desirable to label each weld of a set by number. See Fig. (6–15).
(2) Estimate the primary shear stress τ'. As shown in Fig. (6–14), each plate is welded to the channel by means of three 6-mm fillet welds. Figure (6–15) shows that we have divided the load in half and are considering only a single plate. From case 4 of Table (6–1) we find the throat area as

$$A = 0.707(6)[2(56) + 190] = 1280 \text{ mm}^2$$

Then the primary shear stress is

$$\tau' = \frac{V}{A} = \frac{25(10)^3}{1280} = 19.5 \text{ MPa}$$

(3) Draw the τ' stress, to scale, at each lettered corner or end. See Fig. (9–16).
(4) Locate the centroid of the weld pattern. Using case 4 of Table (6–1), we find

$$\bar{x} = \frac{(56)^2}{2(56) + 190} = 10.4 \text{ mm}$$

This is shown as point *O* on Figs. (6–15) and (6–16).

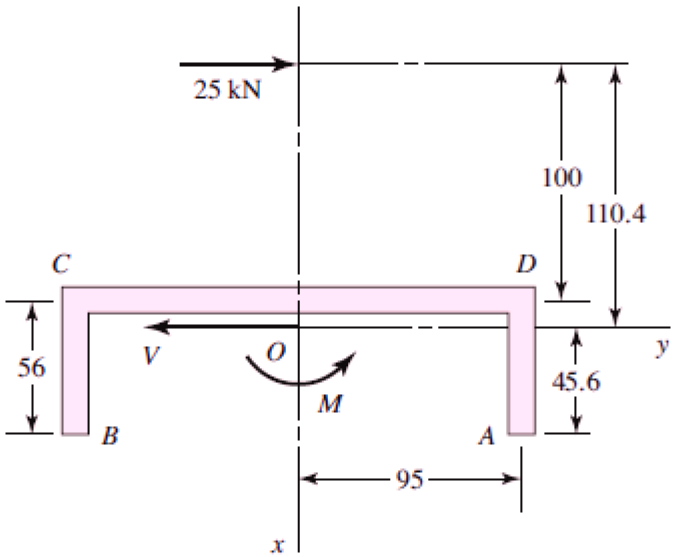


Figure (6–15)
Diagram showing the weld geometry; all dimensions in millimeters. Note that *V* and *M* represent loads applied by the welds *to the plate*

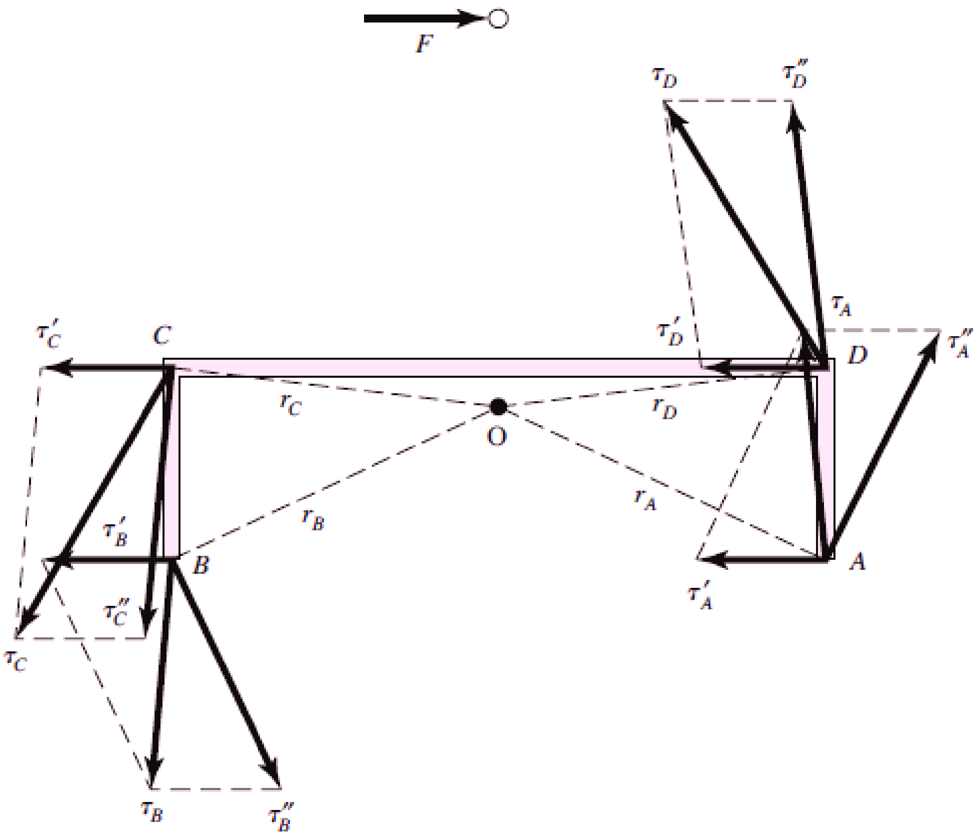


Figure (6–16)
Free-body diagram of one of the side plates

(5) Find the distances r_i (see Fig. 6–16):

$r_A = r_B = [(190/2)^2 + (56 - 10.4)^2]^{1/2} = 105$ mm

$r_C = r_D = [(190/2)^2 + (10.4)^2]^{1/2} = 95.6$ mm

(6) Find J. Using case 4 of Table (6–1) again, we get

$$J = 0.707(6)\left[\frac{8(56)^3 + 6(56)(190)^2 + (190)^3}{12} - \frac{(56)^4}{2(56) + 190}\right]$$
$$= 7.07(10)^6 \text{ mm}^4$$

(7) Find M:

$$M = Fl = 25(100 + 10.4) = 2760 \text{ N·m}$$

(8) Estimate the secondary shear stresses τ'' at each lettered end or corner:

$$\tau''_A = \tau''_B = \frac{Mr}{J} = \frac{2760(10)^3(105)}{7.07(10)^6} = 41.0 \text{ MPa}$$

$$\tau''_C = \tau''_D = \frac{2760(10)^3(95.6)}{7.07(10)^6} = 37.3 \text{ MPa}$$

(9) Draw the τ'' stress, to scale, at each corner and end. See Fig. (6–16). Note that this is a free-body diagram of one of the side plates, and therefore the τ' and τ'' stresses represent what the channel is doing to the plate (through the welds) to hold the plate in equilibrium.

(10) At each letter, combine the two stress components as vectors. This gives

$\tau_A = \tau_B = 37$ MPa

$\tau_C = \tau_D = 44$ MPa

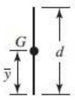
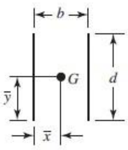
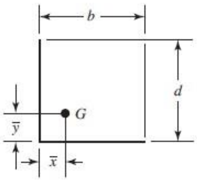
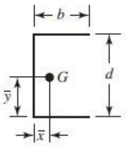
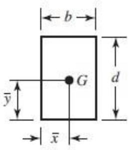
(11) Identify the most highly stressed point:

$\tau_{max} = \tau_C = \tau_D = 44$ MPa

Table (6–1)

Torsional Properties of Fillet Welds

G is centroid of weld group; *h* is weld size; plane of torque couple is in the plane of the paper; all welds are of unit width

Weld	Throat Area	Location of G	Unit Second Polar Moment
	$A = 0.70\,hd$	$\bar{x} = 0$ $\bar{y} = d/2$	$J_u = d^3/12$
	$A = 1.41\,hd$	$\bar{x} = b/2$ $\bar{y} = d/2$	$J_u = \dfrac{d(3b^2 + d^2)}{6}$
	$A = 0.707h(2b + d)$	$\bar{x} = \dfrac{b^2}{2(b+d)}$ $\bar{y} = \dfrac{d^2}{2(b+d)}$	$J_u = \dfrac{(b+d)^4 - 6b^2d^2}{12(b+d)}$
	$A = 0.707h(2b + d)$	$\bar{x} = \dfrac{b^2}{2b+d}$ $\bar{y} = d/2$	$J_u = \dfrac{8b^3 + 6bd^2 + d^3}{12} - \dfrac{b^4}{2b+d}$
	$A = 1.414h(b + d)$	$\bar{x} = b/2$ $\bar{y} = d/2$	$J_u = \dfrac{(b+d)^3}{6}$
	$A = 1.414\,\pi hr$		$J_u = 2\pi r^3$