

Chapter 14: Welded joints

Two common types of welds namely butt and fillet welds are shown in Figure 1.

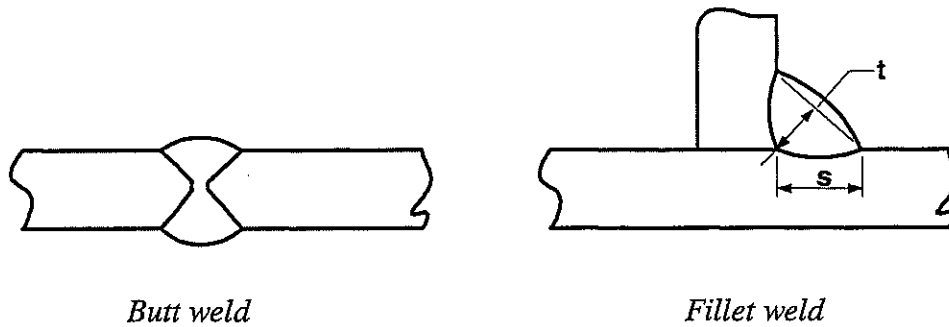


Figure 1 Butt and fillet welds

Butt welds

It is usually assumed that :

- Weld is full penetration, that is of thickness at least equal to the unwelded plate. Also the weld runs for the full width of the unwelded plate.
- A welding rod has been used that has a strength at least equal to the unwelded plate.
- Welding has been carried out by a competent trade welder and is in accordance with correct welding procedures for the material being welded.

Under these conditions, a butt weld can be assumed to have a strength at least equal to that of the unwelded plate. In fact, a butt weld may be tested in a tensile or bend testing machine and if the weld is a good one, the plate should break before the weld.

Design of butt welds

With the above assumptions, it is unnecessary to design a butt weld separately from the plate and the assembly may be considered as a single continuous plate.

Fillet welds

The three assumptions above are also true for a fillet weld except that the size of the weld is not necessarily equal to the size of the plate and may be greater or lesser. Also the weld does not necessarily run the full width of the plate and if long welds are to be made, it is preferable that they be intermittent rather than continuous.

Notes :

- When specifying the length of a fillet weld it may be necessary to include an allowance for starting and stopping the weld. However, this is not a significant factor unless the weld is a very short one and this allowance will be ignored in the examples given.
- For design purposes, if the weld is around a corner or curve, the thickness of the weld is not taken into account when calculating weld length. For example if a fillet weld were made around a 20 mm square bar the length of the weld would be taken as 80 mm.

- The size of a fillet weld is always specified by the leg length s , not the throat thickness t (refer Figure 1). For a standard fillet weld, the angle of the weld is 45° , so:

$$t = 0.707 s$$
- Preferred weld sizes (in mm) are :
 2, 3, 4, 5, 6, 8, 10, 12, 16
- For low carbon and mild steel plates, a commonly used electric welding rod is the E41xx. This rod has a UTS of 410 MPa. For greater strength plates, an E48xx rod (UTS 480 MPa) is also commonly used.
- In Figure 1 a fillet weld has been shown on only one side of the vertical plate. This is not ideal and wherever possible, the weld should be on both sides to minimise the weld stress.

Design of fillet welds

It is customary design practice to design fillet welds on the assumption that the weld will fail in shear across the throat for *any direction* of the applied load. Since the welding rod should have a strength at least equal to the plate, the allowable stress in the weld is the allowable shear stress in the plate material.

Notes :

- Under conditions of *static* or *steady* load, the allowable weld stress is often taken as 0.3 x UTS, so if an E41xx rod is used, the allowable stress would be 0.3×410 or 123 MPa and with an E48xx rod, the allowable stress would be 144 MPa.
- For dynamic or cyclic loads an appropriate design (safety) factor should be applied.
- If the shear stress of the welding rod is not known, a design rule-of-thumb for steel welding is to use 75% of the tensile strength.

Two methods may be used for the design of fillet welds :

Conventional design method

The weld is designed as a separate component, with stress area $A = t L$ where L = length of weld. For applied load F (any direction), the stress in the weld is:

$$f_s = \frac{F}{t L} \quad \text{that is,} \quad t = \frac{F}{f_s L}$$

Weld as a line method

In this method, the weld is considered as a line, that is to have no thickness. Then the line stress f is defined as :

$$f = \frac{F}{L} \quad (\text{units N/mm})$$

Now
$$f_s = \frac{F}{t L} = \frac{f}{t} \quad \text{that is} \quad t = \frac{f}{f_s}$$

Notes :

- Line stress f is not a true stress, rather the force per mm length of weld.
- Both methods are illustrated in Example 1, (page 315) but from then on the line method will be used exclusively.
- The line method has no advantage for the design of simple fillet welds, that is welds with direct loads only. However, it is of great benefit when there are bending or torsion loads on the weld.

Bending loads in fillet welds

Consider a fillet weld in bending as shown in Figure 2.

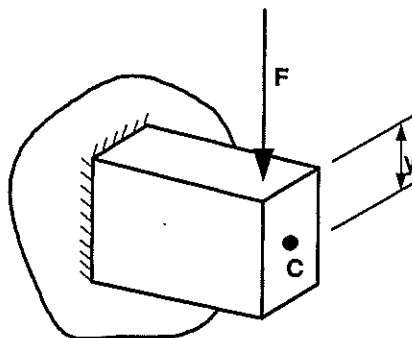


Figure 2 Fillet weld in bending

The conventional bending stress formula (for any bar or beam in bending) is:

$$f_b = \frac{M y}{I} = \frac{M}{Z} \text{ where } Z = \frac{I}{y} \text{ (the section modulus with units mm}^3\text{)}$$

If the weld were not treated as a line, the second moment of area I or the section modulus Z , would be different with each different weld size. If the weld size is unknown, this requires a trial-and-error solution. Using the weld as a line method, a direct solution is possible using a table of formulas for the section modulus of various weld configurations such as in the table given on page 314. The calculated bending stress is then a line stress.

Note : Because the weld is treated as a line, the section modulus listed in the table has units mm^2

For the welded bar shown in Figure 2, there is also a direct line stress due to the applied load F . The direct line stress is :

$$f = \frac{F}{L} \text{ where } L = \text{length of weld (in this case the perimeter of the bar)}$$

Welded Joints

These line stresses do not act in the same direction so they must be combined vectorially to find the resultant. In this case because the stresses are perpendicular to one another, the resultant line stress f_r is :

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

Torsion loads in fillet welds

The conventional torsional stress formula (for any bar or shaft in bending) is:

$$f_t = \frac{T r}{J}$$




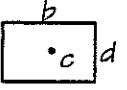
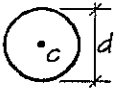
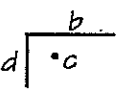
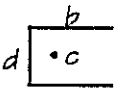
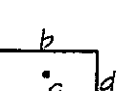




where r = radius or distance from the centroid to the outer fibre
 J = polar second moment of area of the section with units mm^4

If the weld is not treated as a line, then the same problem arises as with bending loads and J would vary with each different weld size. Using the weld as a line method, a direct solution is possible using a table of formulas for the polar moment of various weld configurations such as in the table given on page 314. The calculated torsional stress is then a line stress.

Notes :

- Because the weld is treated as a line, the polar moment listed in the table has units mm^3 .
- If there is a direct stress in the weld this will also need to be combined vectorially with the torsional stress to obtain the resultant line stress.

Bending and torsion line stress formulas (see page 315 for method of locating C)

No	Diagram	Z (about Cx axis)	J (about C)
1		$\frac{d^2}{6}$	$\frac{d^3}{12}$
2		$\frac{d^2}{3}$	$\frac{d(3b^2 + d^2)}{6}$
3		bd	$\frac{b^3 + 3bd^2}{6}$
4		$bd + \frac{d^2}{3}$	$\frac{(b + d)^3}{6}$
5		$\frac{\pi d^2}{4}$	$\frac{\pi d^3}{4}$
6		$\frac{4bd + d^2}{6}$ top $\frac{d^2(4bd + d)}{6(2b + d)}$ bottom	$\frac{(b + d)^4 - 6b^2d^2}{12(b + d)}$
7		$bd + \frac{d^2}{6}$	$\frac{(2b + d)^3}{12} - \frac{b^2(b + d)^2}{(2b + d)}$
8		$\frac{2bd + d^2}{3}$ top $\frac{d^2(2b + d)}{3(b + d)}$ bottom	$\frac{(b + 2d)^3}{12} - \frac{d^2(b + d)^2}{(b + 2d)}$
9		$\frac{2bd + d^2}{3}$ top $\frac{d^2(2b + d)}{3(b + d)}$ bottom	$\frac{(b + 2d)^3}{12} - \frac{d^2(b + d)^2}{(b + 2d)}$
10		$\frac{4bd + d^2}{3}$ top $\frac{4bd^2 + d^3}{6b + 3d}$ bottom	$\frac{d^3(4b + d)}{6(b + d)} + \frac{b^3}{6}$
11		$bd + \frac{d^2}{3}$	$\frac{b^3 + 3bd^2 + d^3}{6}$
12		$2bd + \frac{d^2}{3}$	$\frac{2b^3 + 6bd^2 + d^3}{6}$

Locating the centroid

The position of the centroid of a weld can be calculated in the same way as for any area by breaking the area up into its components and then taking moments of each area about the reference axis and equating this to the total area moment (the total area multiplied by the centroidal distance). That is for a horizontal reference axis (x axis) :

$$A_1 y_1 + A_2 y_2 + \dots = A y_c$$

where y_c is the vertical centroidal distance

Treating the weld as a line, the weld can be considered to be a narrow area of thickness 1 mm with no area moment about the narrow axis. Moments may then be taken as indicated above.

For example, consider the L shaped weld shown in Figure 3 (Number 6 page 314) :

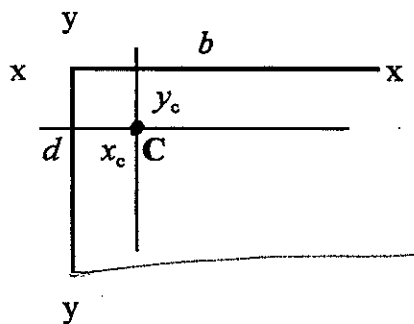


Figure 3

Making the reference x-x axis the weld length b , then y_c is the vertical distance below x-x to the centroid C.

Taking moments about the x-x axis :

$$d \times 1 \times \frac{d}{2} = (b + d) \times 1 \times y_c \quad (\text{weld length } b \text{ has no moment about x-x})$$

$$\therefore y_c = \frac{d^2}{2(b + d)}$$

Similarly taking moments about the y-y axis :

$$b \times 1 \times \frac{b}{2} = (b + d) \times 1 \times x_c \quad (\text{weld length } d \text{ has no moment about y-y})$$

$$\therefore x_c = \frac{b^2}{2(b + d)}$$

For example, if the length of welds are : $b = 50$ mm and $d = 30$ mm :

$$y_c = \frac{d^2}{2(b+d)} = \frac{30^2}{2(50+30)} = 5.625 \text{ mm}$$

$$x_c = \frac{b^2}{2(b+d)} = \frac{50^2}{2(50+30)} = 15.625 \text{ mm}$$

That is, the centroid of the weld is located 5.625 mm down and 15.625 mm to the right.

Example 1 Direct load

The steel bar illustrated in Figure 4 is welded all round to a steel base plate. There is a variable load of maximum value 10 kN acting vertically upward at the centre of the bar. The steel used has a yield point in tension of 220 MPa. A safety factor of 3 is required (on yield). Determine the weld size required using :

(a) conventional stress analysis, (b) weld as a line method.

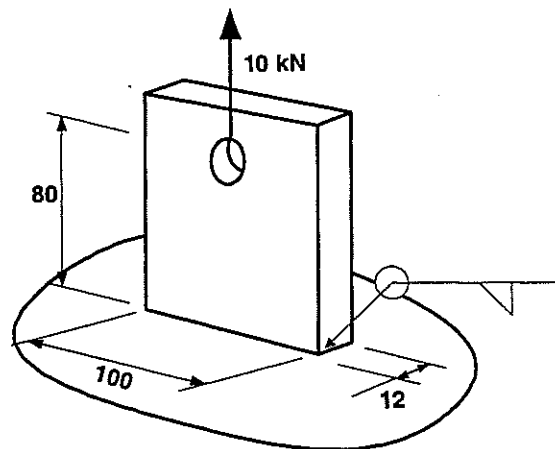


Figure 4

Solution

With a safety factor of 3, the design load is 30 kN. The yield point in shear may be taken as $0.75 \times 220 = 165$ MPa.

(a) Conventional stress analysis

$$f = \frac{F}{A} = \frac{F}{tL}$$

$$\text{Now } L = 100 \times 2 + 2 \times 12 = 224 \text{ mm}$$

$$\therefore 165 = \frac{30000}{t \times 224} \quad \therefore t = 0.812 \text{ mm}$$

$$s = \frac{t}{0.707} = 1.15 \text{ mm}$$

\therefore use 2 mm weld

(b) Weld as a line method

$$\text{The line stress } f = \frac{F}{L} = \frac{30000}{224} = 133.9 \text{ N/mm}$$

$$t = \frac{f}{f_s} = \frac{133.9}{165} = 0.812 \text{ mm (as above)}$$

$$s = \frac{t}{0.707} = 1.15 \text{ mm}$$

∴ use 2 mm weld

Example 2 Weld in bending (+ direct load)

Solve Example 1 by the weld as a line method if the load act upward at 60° to the vertical (that is 30° to the horizontal).

Solution

The design load of 30 kN can be resolved into vertical and horizontal components. They are:

$$F_v = 15 \text{ kN} \quad F_h = 25.98 \text{ kN}$$

The direct line stresses are :

$$f_v = \frac{15000}{224} = 67 \text{ N/mm} \quad f_h = \frac{25980}{224} = 116 \text{ N/mm}$$

The bending moment about the centroid of the weld is :

$$M = 25980 \times 80 = 2078 \times 10^3 \text{ N/mm}$$

From the table page 314, the applicable formula is formula 4 :

$$Z = b d + \frac{d^2}{3} = 12 \times 100 + \frac{100^2}{3} = 4533 \text{ mm}^2$$

The line bending stress is $f_b = \frac{M}{Z} = \frac{2078 \times 10^3}{4533} = 458.4 \text{ N/mm}$ (in a vertical direction)

The most highly stressed section is the bottom left hand corner (the bending stress is a maximum).

The line stresses here are :

$$f_v = 458.4 + 67 = 525.4 \text{ N/mm} \quad f_h = 116 \text{ N/mm}$$

Combining vectorially :

$$f = \sqrt{525.4^2 + 116^2} = 538 \text{ N/mm}$$

$$t = \frac{538}{165} = 3.26 \text{ mm}$$

$$s = \frac{3.26}{0.707} = 4.6 \text{ mm}$$

So use **5 mm** weld

Example 3 Weld in torsion (+ direct load)

A 12 mm thick steel bar is welded to a support plate with a 5 mm fillet weld as shown in Figure 5.

It supports a steel cable acting at an angle of 30° . If the stress in the weld is not to exceed 100 MPa, determine the maximum cable force F .

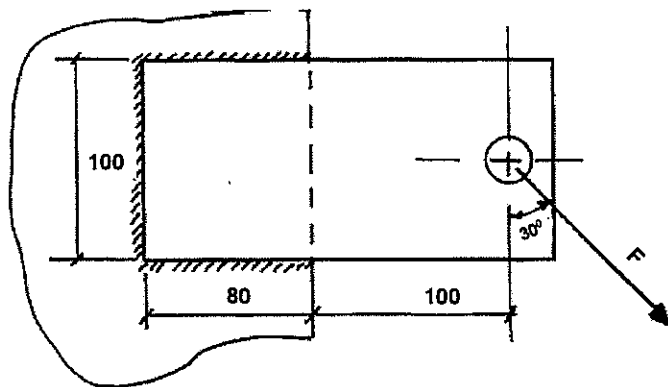


Figure 5

Solution

Rather than writing equations in terms of the force F it is more convenient to assume a value for F . After the stress calculations have been done, the assumed value for F can be multiplied by a factor to increase or decrease its value by comparing the calculated stress to the allowed stress.

So let $F = 1 \text{ kN} = 1000 \text{ N}$ and $F_v = 1000 \cos 60^\circ = 866 \text{ N}$

The length of weld is : $100 + 2 \times 80 = 260 \text{ mm}$

The direct line stress is: $f = \frac{1000}{260} = 3.85 \text{ N/mm}$ (at 60° downward from the horizontal)

To determine the torsional stress, it is first necessary to locate the centroid of the weld.

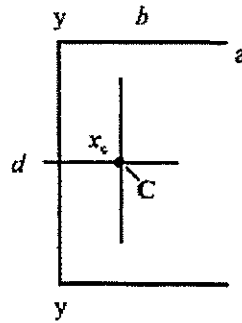


Figure 6

Taking moments about the y-y axis with $b = 80$ mm and $d = 100$ mm:

$$2 \times 80 \times 40 = 260 x_c$$

$$\therefore x_c = 24.62 \text{ mm}$$

That is, the distance from C to the edge of the support plate is : $80 - 24.62 = 55.38$ mm

The torque (turning moment) about C is : $T = 866 \times 155.38 = 134.6 \times 10^3$ N/mm

By inspection, the most highly stressed weld position is at the top RH corner (location "a" in Figure 6)

By trigonometry (see Figure 7) : $R = 74.6$ mm $\theta = 47.9^\circ$

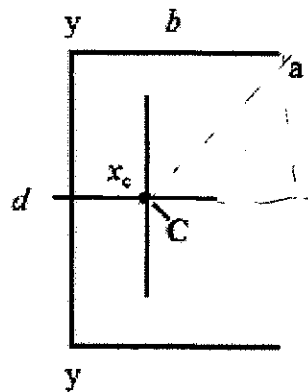


Figure 7

Using Formula 7, page 314 :

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

Now $b = 80 \text{ mm}$ and $d = 100 \text{ mm}$

$$\therefore J = \frac{260^3}{12} - \frac{80^2 \times 180^2}{260} = 667 \times 10^3 \text{ mm}^3$$

The torsional line stress at point "a" is :

$$f_t = \frac{TR}{J} = \frac{134.6 \times 10^3 \times 74.62}{667 \times 10^3} = 15.05 \text{ N/mm}$$

The direct and torsional line stresses may now be combined vectorially :

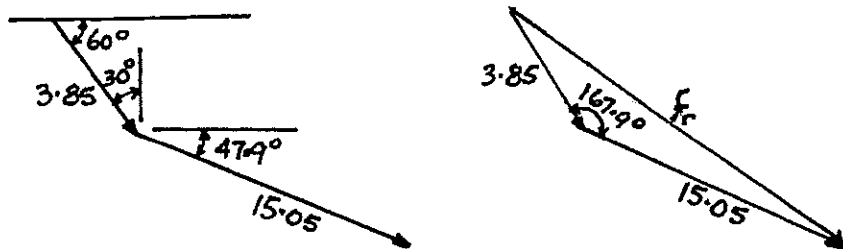


Figure 8

Using the cosine rule :

$$f_r^2 = 3.85^2 + 15.05^2 - 2 \times 3.85 \times 15.05 \cos 167.9^\circ$$

$$\therefore f_r = 18.8 \text{ N/mm}$$

$$\text{Now } f_s = \frac{f}{t} = \frac{18.8}{5 \times 0.707} = 5.327 \text{ MPa}$$

Now the allowable weld stress is 100 MPa

$$\text{Therefore the maximum applied force } F = \frac{100}{5.327} \times 1 = 18.8 \text{ kN}$$