Weldment Design and Simplifications

1 Introduction - The Line Method

The sizing of weld beads is a well documented engineering calculation and it is quite easy to find many references. My favourite method for sizing welds is one called the line method. This method calculates the geometric properties of a weld group by first representing it as a series of zero thickness lines. A force per unit length requirement is then calculated for each critical weld location and from this a weld size can be chosen to suit. There is no need for trial weld geometries or iterations.

The line method is a conservative approach in that it does not account for the changes in the weld group's geometry as the throat thickness of the weld increases beyond that of a line. Because of this, the approach becomes more and more conservative as the throat thickness of a weld bead is increased. For quick design calculations though where the strength of a weld group need not be determined to such a fine detail (almost all calculations will fit into this category), this method works perfectly.

2 Weld Group Geometry

The line method represents each weld in a group as a line of zero thickness. The positioning of this line representation should always be at the root of the welded joint no matter what type of weld is used.

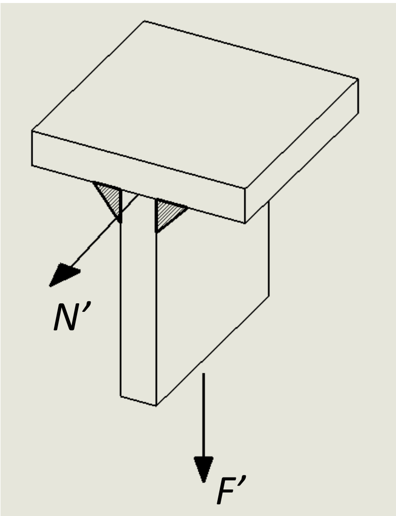
Intermittent welds should be first calculated as continuous and later sized based on their intermittency. I.e. if a 1m joint requires 200N/mm of weld strength, a 75-150mm weld stagger will equate to a 0.5m effective joint requiring:

$$\frac{1m}{0.5m} \times 200\ N/mm = 400\ N/mm\ of\ weld\ strength$$

2.1 Types of Weld Group Formulae

Below are a number of weld group formulae intended to help quantify the stresses found within a weld group. Many weld applications can have their stresses broken down into constituent components capable of being solved using these formulae. The results of these formulae can be later combined to provide an overall analysis of almost any weld.

2.2 Axial or Direct Shear



In this instance the weld or weld group is loaded either axially or in shear. There are no torsional or moment affects acting upon the weld group.

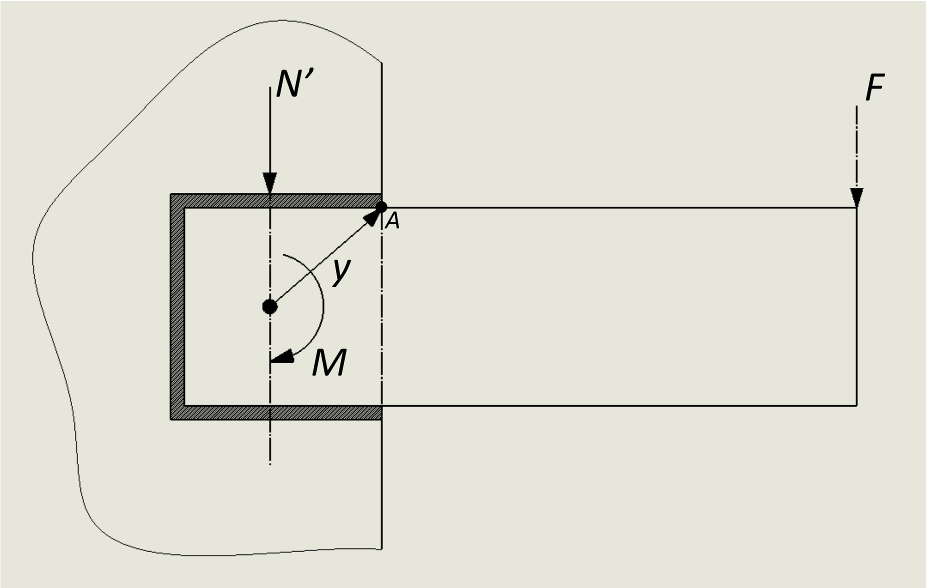
$$\boldsymbol{V_w = \frac{F'}{l}\ (axial)\ or\ V_w = \frac{N'}{l}\ \ (in\ shear)}$$

$Where$:

$V_w\ = the\ design\ force\ per\ unit\ length\ of\ weld\ (N/mm)$
$N'or\ F' = the\ design\ force\ (N)$
$l = the\ total\ weld\ length\ (mm)$

The resultant vector V_w is orientated in the direction of the design force F' or N'.

2.3 In-Plane Torsion



In this instance a weld group is loaded in plane and under torsion by the force F. This force is resolved into two components: N' and M acting through the weld group's centroid. N' is solved using the Direct Shear method while M is solved using the equation below:

$$\boldsymbol{V_w} = \frac{\boldsymbol{M \times y}}{\boldsymbol{J_w}}$$

$Where:$

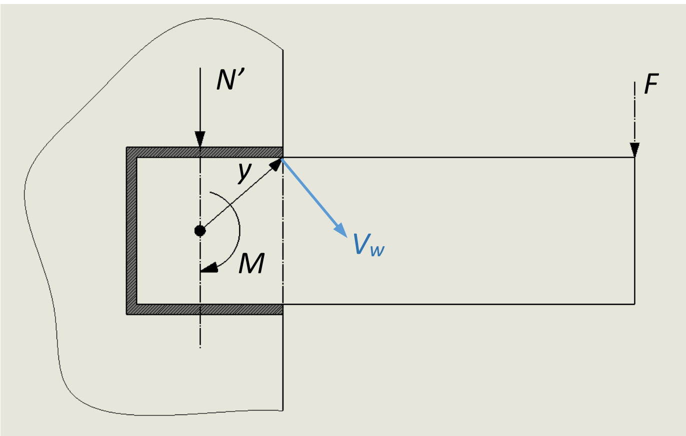
V_w $= the\ maximum\ design\ force\ per\ unit\ length\ of\ the\ weld, located\ at\ point\ A\ (N/mm)$

$M = the\ moment\ generated\ by\ F\ about\ the\ weld\ centroid\ (Nmm)$

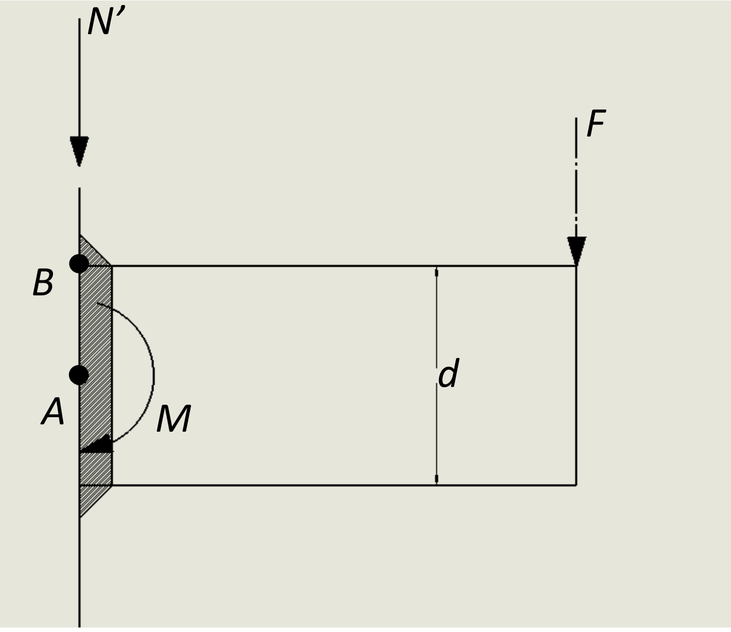
$y = the\ distance\ from\ the\ centroid\ of\ the\ weld\ group\ to\ point\ A\ (mm)$

$J_w = polar\ line\ moment\ of\ inertia\ of\ the\ weld\ group\ (mm^3) - Reference\ Table\ 1.$

The resultant vector V_w is located at point A and orientated perpendicular to the dimension *y*. The vector acts in the direction of the moment M as shown.



2.4 Out of Plane Bending



The load application for this type of analysis is out of plane, placing the welded item into bending under the influence of the force F. As shown, the force F is resolved into two components again acting through the weld centroid. The direct shear load N' is solved using the Direct Shear method while the bending moment M is calculated as follows:

$$\boldsymbol{V_w} = \frac{\boldsymbol{M}}{\boldsymbol{Z_w}}$$

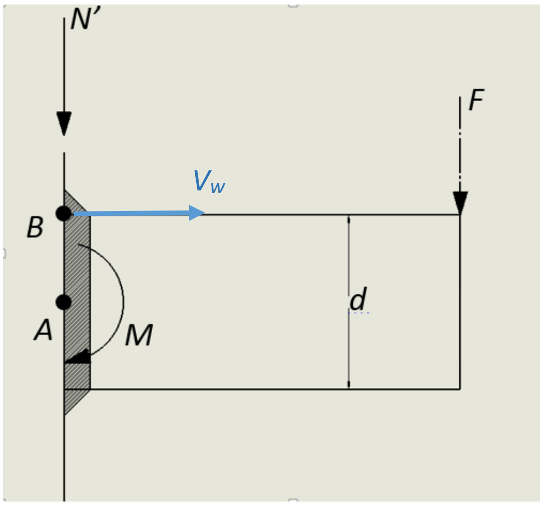
$Where:$

$V_w \ = design\ force\ per\ unit\ length\ at\ point\ B\ (N/mm)$

$M = the\ moment\ generated\ about\ the\ weld\ centroid\ by\ F\ (Nmm)$

$Z_w = line\ modulus\ for\ bending\ of\ the\ weld\ group\ (mm^2) - Reference\ Table\ 1.$

The resultant vector V_w acts through point B, perpendicular to the weld group as shown below.



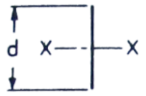
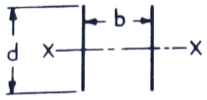
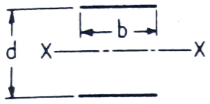
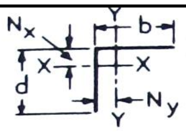
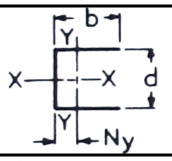
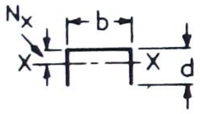
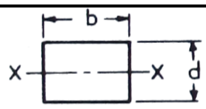
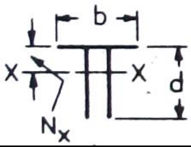
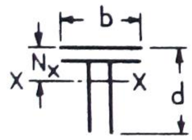
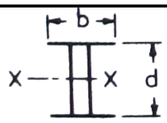
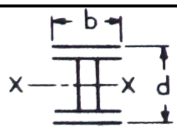
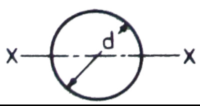
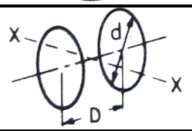
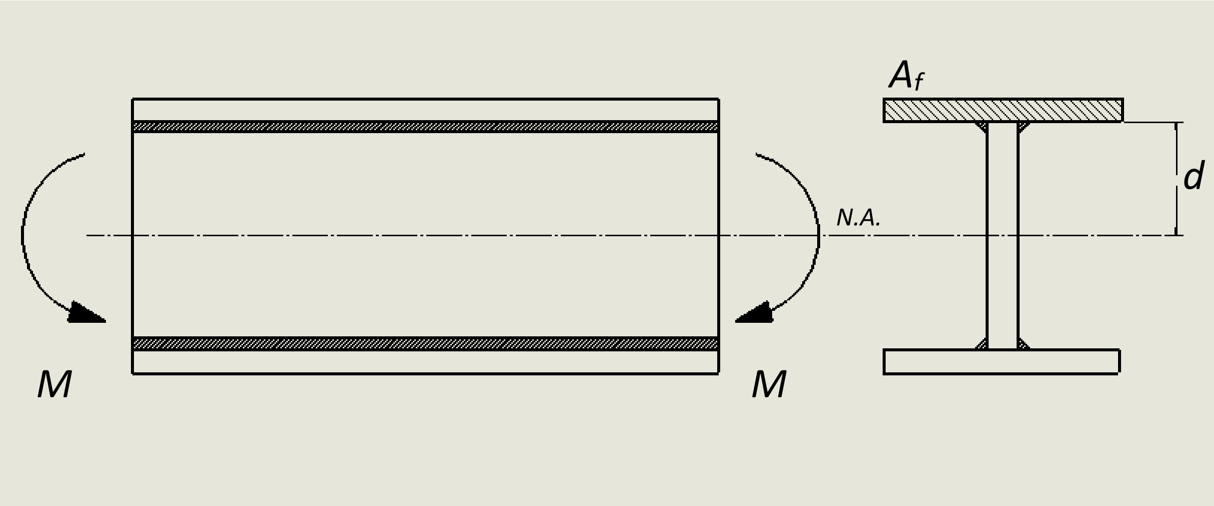
Outline of welded joint b = width, d = depth	Bending – about the horizontal axis X-X	Twisting
	$Z_w = \frac{d^2}{6}$	$J_w = \frac{d^3}{12}$
	$Z_w = \frac{d^2}{3}$	$J_w = \frac{d(3b^2 + d^2)}{6}$
	$Z_w = bd$	$J_w = \frac{b^3 + 3bd^2}{6}$
 $N_x = \frac{d^2}{2(b+d)}$ $N_y = \frac{b^2}{2(b+d)}$	$Z_w = \frac{4bd + d^2}{6}$ top $= \frac{d^2(4b+d)}{6(2b+d)}$ bottom	$J_w = \frac{(b+d)^4 - 6b^2d^2}{12(b+d)}$
 $N_y = \frac{b^2}{2b+d}$	$Z_w = bd + \frac{d^2}{6}$	$J_w = \frac{(2b+d)^3}{12} - \frac{b^2(b+d)^2}{(2b+d)}$
 $N_x = \frac{d^2}{b+2d}$	$Z_w = \frac{2bd + d^2}{3}$ top $= \frac{d^2(2b+d)}{3(b+d)}$ bottom	$J_w = \frac{(b+2d)^3}{12} - \frac{d^2(b+d)^2}{(b+2d)}$
	$Z_w = bd + \frac{d^2}{3}$	$J_w = \frac{(b+d)^3}{6}$
 $N_x = \frac{d^2}{b+2d}$	$Z_w = \frac{2bd + d^2}{3}$ top $= \frac{d^2(2b+d)}{3(b+d)}$ bottom	$J_w = \frac{(b+2d)^3}{12} - \frac{d^2(b+d)^2}{(b+2d)}$
 $N_x = \frac{d^2}{2(b+d)}$	$Z_w = \frac{4bd + d^2}{3}$ top $= \frac{4bd^2 + d^3}{6b + 3d}$ bottom	$J_w = \frac{d^3(4b+d)}{6(b+d)} + \frac{b^3}{6}$
	$Z_w = bd + \frac{d^2}{3}$	$J_w = \frac{b^3 + 3bd^2 + d^3}{6}$
	$Z_w = 2bd + \frac{d^2}{3}$	$J_w = \frac{2b^3 + 6bd^2 + d^3}{6}$
	$Z_w = \frac{\pi d^2}{4}$	$J_w = \frac{\pi d^3}{4}$
	$Z_w = \frac{\pi d^2}{2} + \pi D^2$	

Table 1 – Properties of welds treated as a line

2.5 Shear Flow – Beam Bending



For a composite member in bending as illustrated above, the following shear flow calculation can be used to size a flange weld group.

$$\boldsymbol{f = \frac{VQ}{I}}$$

$Where:$

$f = shear\ flow\ or\ design\ force\ per\ unit\ lenght\ to\ attach\ the\ flange\ to\ the\ web\ (N/mm)$

$V = shear\ force, usually\ obtained\ from\ a\ Shear\ Force\ Diagram\ (SFD)(N)$

$Q = A_f \times d\ (mm^3)$

$A_f = area\ of\ the\ jointed\ flange\ (mm^2)$

$d = distance\ from\ the\ neutral\ axis\ of\ the\ beam\ to\ the\ weld\ root\ (mm)$

$I = second\ moment\ of\ area\ of\ the\ entire\ section\ (mm^4)$

The shear flow vector *f* is orientated along the length of the weld bead.

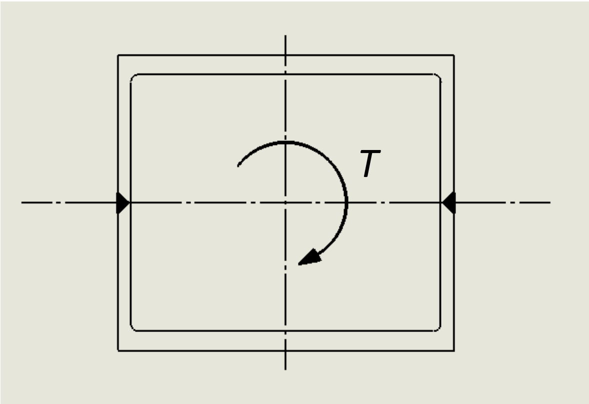
The shear flow (*f*) represents the internal shear between the flange and web elements comprising the beam. Intermittent welds can be used at this interface as long as they are compliant with the requirements of AS3990, Section 9.8 or AS4100 Section 9.7, depending on the code you have selected to use.

Size intermittent welds as follows:

$$\boldsymbol{f'\ (N/mm) = \frac{joint\ length\ (mm)}{effective\ stitch\ weld\ length\ (mm) \times number\ of\ stitches} \times f(N/mm)}$$

$Where\ f'is\ the\ required\ design\ capacity\ of\ the\ stitch\ weld\ bead$

2.6 Shear Flow – Beam Torsion



Composite beams under torsional loading as illustrated above can also have their weld requirements assessed using the shear flow method.

For a closed section beam as shown, the welds connecting the two members can be sized as follows:

$$\boldsymbol{f} = \frac{\boldsymbol{T}}{\boldsymbol{2A}}$$

$Where$:

$f = shear\ flow\ or\ design\ force\ per\ unit\ length\ to\ attach\ the\ component\ sections\ (N/mm)$

$T = torsion\ about\ the\ beam\ centroid\ (Nmm)$

$A = the\ area\ contained\ within\ the\ weld\ root\ perimeter\ (mm^2)$

The shear flow vector acts along the length of the weld.

For open sectioned beams calculating the shear stress along a weld plane becomes more complicated. In these situations and to save time I usually refer to an FEA package to output such results.

2.7 Combining Weld Calculations

Any load application acting upon a weld group can be broken down into a constituent set of force/moment applications and solved using the methods demonstrated. Vector addition is then used to combine these components to yield the overall design capacity of that weld group. From this point you can either size a weld from code using the formulas provided or make use of a table such as those found in Tables 2 and 3.

2.7.1 Fillet Welds – Limit States Design to AS4100-1998

AS4100 – Limit States Design						
Design Capacity per unit length (N/mm)						
Electrode Type	**Weld Quality**	**Weld Leg Length (mm)**				
		5	**6**	**8**	**10**	**12**
E41/W40	GP	530	620	830	1,040	1,250
	SP	700	830	1,110	1,390	1,670
E48/W50	GP	610	740	980	1,220	1,470
	SP	810	980	1,300	1,630	1,960

Table 2 – Limit States fillet weld design capacities

The design capacities tabulated above are based upon the following formulae (ref. HB48, Appendix D1 and AS4100, Clause 9.7.3.10):

$$\boldsymbol{GP\ Welds - \ 0.36 f_{uw} t_t k_r}$$

$$\boldsymbol{SP\ Welds - \ 0.48 f_{uw} t_t k_r}$$

$f_{uw} = nominal\ tensile\ stress\ of\ the\ weld\ material$

$410MPa\ for\ \ E41xx/W40x\ electrodes$

$480MPa\ for\ \ E48xx/W50x\ electrodes$

$t_t = weld\ design\ throat\ thickness\ (mm)$

$Weld\ leg\ lengths\ are\ calculated\ as\ 0.707 \times t_t (mm)$

$k_r = A\ reduction\ factor\ for\ lap\ connections.$

$For\ connections < 1.7m, \qquad k_r = 1.0.\ \ For\ others\ consult\ AS4100\ Clause\ 9.7.3.10$

2.7.2 Fillet Welds – Allowable Stress Design to AS3990-1993

AS3990 – Allowable Stress Design						
Design Capacity per unit length (N/mm)						
Electrode Type	**Weld Quality**	**Weld Leg Length (mm)**				
		5	**6**	**8**	**10**	**12**
E41/W40	GP	348	417	557	696	835
	SP	464	557	742	928	1,113
E48/W50	GP	407	489	652	814	977
	SP	543	652	869	1,086	1,303

Table 3 – Allowable Stress fillet weld design capacities

The design capacities tabulated above are based upon the same formulae as Table 2 with the addition of a safety factor to account for the differences between the Limit States and Allowable Stress design methods.

To equate the Limit States method with the Allowable Stress method in this instance, a load factor of 0.67 is introduced.

Since the Limit States method uses two forms of design factor, a Load and a Capacity Factor, this had to be related to the Allowable Stress method which employs only a Capacity Factor. The Limit States weld size calculation from Table 2 takes into account only the Capacity Factor, so the two methods were equated as follows:

$$Allowable\ Stress\ Weld\ Size = \frac{Limit\ States\ Weld\ Size}{Load\ Factor}$$

AS4100 derives its Load Factors predominantly from AS1170.0. The largest of these factors and often the most used is 1.5. Hence the Load Factor applied to the Limit State Weld Size result is:

$$Allowable\ Stress\ Weld\ Size = \frac{Limit\ States\ Weld\ Size}{1.5} = 0.67 \times Limit\ States\ Weld\ Size$$

Note this is a conservative approach but provides a much more workable solution to the method employed by AS3990-1993.

2.7.3 Butt Welds – Limit States Design to AS4100-1998

Note that in accordance with AS4100 Section 9.7.2, no analysis is required for category SP complete penetration butt welds. The design capacity of the joint is equal to the weaker component being jointed. For category GP butt welds a 2/3 Capacity Factor should to be introduced.

Incomplete penetration butt welds can be assessed in the same manner as for fillet welds provided the design throat thickness used is in accordance with AS1554.1 Table E2.

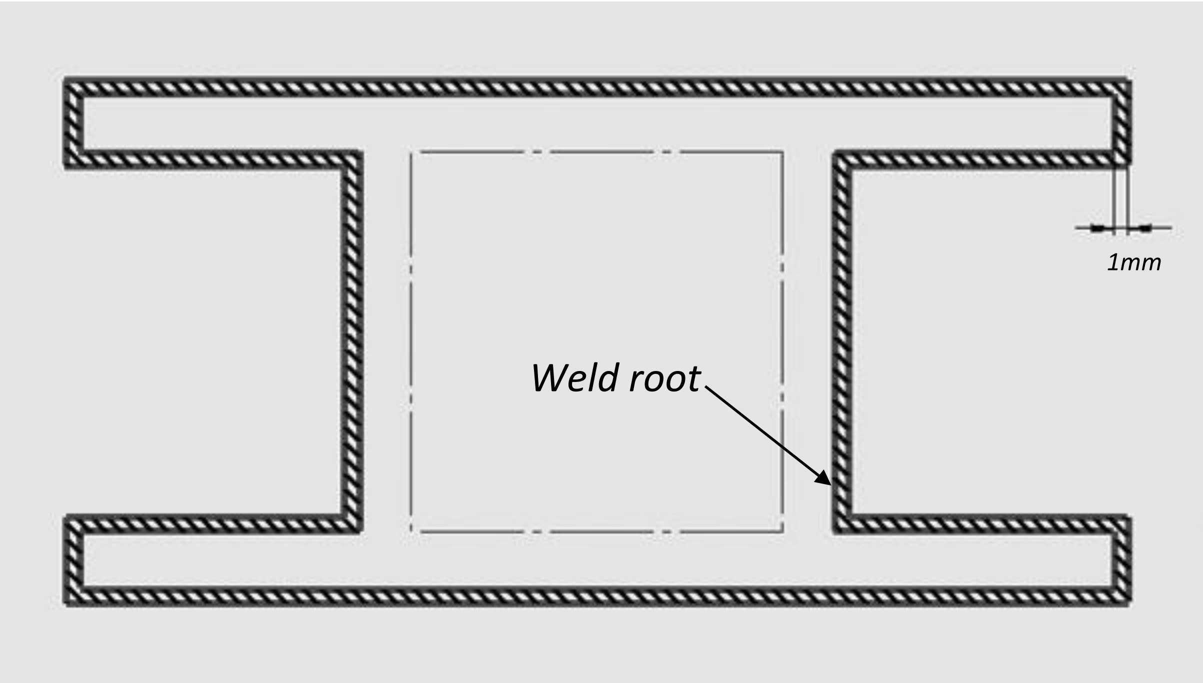
2.7.4 Butt Welds – Allowable Stress Design to AS3990-1993

Note that in accordance with AS3990 Section 9.8.2(a), no analysis is required for complete penetration butt welds. The design capacity of the joint is equal to the weaker component being jointed.

Incomplete penetration butt welds can be assessed in the same manner as for fillet welds provided the design throat thickness used is in accordance with AS1554.1 Table E2 and a Reduction Factor of 0.5 is applied to the ultimate strength of the weld material. This is a more conservative approach to that stipulated by the Limit States method.

2.8 Non-Standard Weld Group Profiles – A Simple Approach

What happens when Table 1 doesn't cover the weld group geometry you are analysing? A simple means of circumventing this issue is to use the computational power of a CAD program. By sketching the weld group in 2D and using a unit (1mm) thickness for each weld, an analysis can be done to output the geometric data required. An example sketch is shown below. Most programs will allow you to evaluate the bounded region for such properties as the polar moment of inertia and section modulus. This is a quick and easy method of analysing complex weld group arrangements using the line method and it is more accurate than simplifying the weld group geometry to suit Table 1.



3 Notes

The methods described in this document cover the vast majority of instances you will face when performing simple weld calculations. You need to be aware of how these calculations tie in with the necessary codes by which you need to comply. Such codes include but are not limited to:

- AS1554 Part 1 for the general purpose welding of steels
- AS1664 Part 1 for limit states aluminium design work
- AS1664 Part 2 for limit stress aluminium design work
- AS 1665 for the welding of aluminium
- AS3990 for allowable stress steel design work
- AS4100 for limit states steel design work