Design of fillet welds and partial penetration butt welds

Richard Henderson of the SCI discusses the directional method for the design of fillet welds and partial penetration butt welds and shows how the combined stress formula is related to Von Mises' failure criterion. The weld design rules can be applied in all cases.

Introduction

A simple rule of thumb approach to sizing partial penetration butt welds carrying longitudinal shear has sometimes been used where the resistance is based on the average shear stress used for checking the shear resistance of beam webs: $0.6p_y$ in BS 5950 or $f_y/\sqrt{3}$ in EN 1993-1-1. This confusingly led to a lower shear resistance than that found when sizing the weld using the specified design strength. In what follows, the directional method in EN 1993-1-8 is discussed and examples of weld design are presented, showing the rule of thumb approach to be conservative and inappropriate.

Directional method

The directional method for design of fillet welds and partial penetration butt welds in EN 1993-1-8 clause 4.5.3.2 involves checks of 1) combined stress and 2) direct stress on the weld throat and compares each with a different limiting stress denoted here by the general term σ_L. The limiting stresses are based on the ultimate strengths of the material (which are constant for most thicknesses up to 100 mm) and the values for different steel grades are given in the table below. The stresses are in MPa. A material factor of 1.25 (for bridges) has been used.

Steel grade		S235	S275[1,2]	S355[1]	S420[1]	S460[1]
	β_w	0.8	0.85	0.9	1.0	1.0
Ultimate strength	f_u	360	410	470	520	540
Limiting combined stress	$f_u/(\beta_w \gamma_{M2})$	360	386	418	416	432
Limiting direct stress	$0.9f_u/\gamma_{M2}$	259	295	338	374	389

1 Subgrade M has minimum tensile strengths which vary with thicknesses below 100 mm
2 Subgrades M and N have a minimum tensile strength of 370 MPa

Table 1 Limiting stresses in fillet welds in EN 1993-1-8

In the directional method for the design of fillet welds, direct stresses perpendicular and parallel to the weld throat are denoted in clause 4.5.3.2(4) and so are shear stresses in the plane of the weld throat. Direct stresses parallel to the axis of the weld are not considered further. The orientations of the stresses are shown in Figure 1.

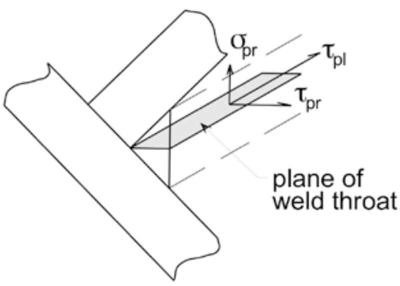

Figure 1 Stresses on the weld throat

The formula in EN 1993-1-8 is

$$\left(\sigma^2_{pr} + 3(\tau^2_{pr} + \tau^2_{pl})\right)^{0.5} \leq \sigma_L \quad (1)$$

where the direct stress is perpendicular to the weld throat and the shear stresses are in the perpendicular (transverse) and parallel (longitudinal) directions. In equation (1), the subscript "pr" has been used instead of the EN 1993-1-8 symbol "⊥" and "pl" instead of "||".

In designing partial penetration butt welds, the designer determines the penetration required and the fabricator chooses the weld preparation to achieve the penetration specified, based on his welding processes and the corresponding weld procedures.

Von Mises' failure criterion

The EC3 formula for the combined stress on a weld is based on the Von Mises failure criterion which is usually expressed in terms of principal stresses (orientated such that there are no coincident shear stresses). The standard expression is:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \leq 2\sigma_L^2$$

where σ_1, σ_2 and σ_3 are the principal stresses in three orthogonal directions and σ_L is a limiting stress. In the design of joints with essentially linear welds between plates, the stress in the through thickness direction is zero (see figure 2) so for the biaxial stress state, the equation becomes:

$$(\sigma_1 - \sigma_2)^2 + \sigma_2^2 + (-\sigma_1)^2 \leq 2\sigma_L^2 \quad (2)$$

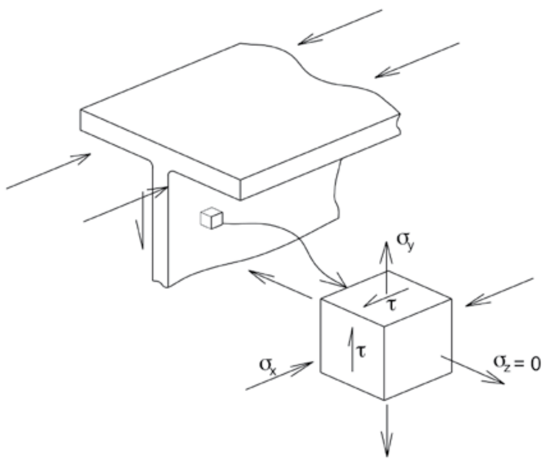

Figure 2: Stresses in plate elements

The failure criterion in equation (2) is expressed in terms of principal stresses which are related to coincident direct and shear stresses using the transformation equations illustrated by Mohr's circle of stress.

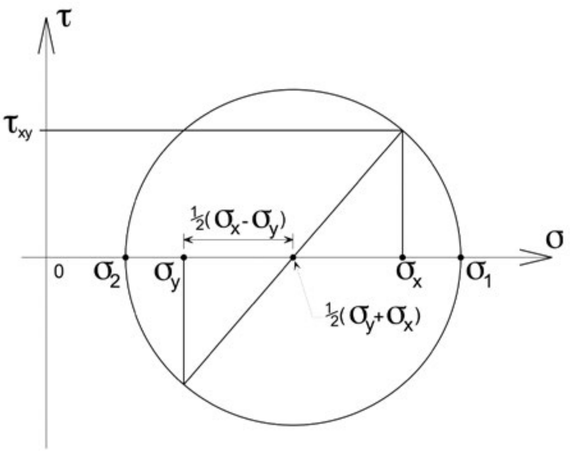

Figure 3: Mohr's circle of stress

In general, orthogonal stresses σ_x and σ_y and coincident shear stress τ_{xy} are present and principal stresses are given by:

$$\sigma_1 = \frac{\sigma_x+\sigma_y}{2} + \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + \tau^2_{xy}}$$

$$\sigma_2 = \frac{\sigma_x+\sigma_y}{2} - \sqrt{\left(\frac{\sigma_x-\sigma_y}{2}\right)^2 + \tau^2_{xy}}$$

where the square root term is the radius of the Mohr's circle and its centre is at $\frac{1}{2}(\sigma_x + \sigma_y)$.

If the transformations are made, the formulae in equations (1) and (2) are algebraically identical when σ_y equals zero.

Steel grade		S235	S275	S355	S420	S460
Limiting combined stress	$f_u/(\beta_w \gamma_{M2})$	360	386	418	416	432
Combined stress (shear only)	$f_L/\sqrt{3}$	208	223	241	240	249
Limiting shear stress: BS 5950: 1990	$0.7f_y$	165	193	249	294	322
Design Strength[1]: BS 5950: 2000	–	–	220	250	200	–

1 Matching electrodes

Table 2: Comparison of Limiting shear stresses EC3 and BS 5950: 1990

Limiting stresses

The Von Mises failure criterion is often expressed in terms of the yield strength of the material. However, in the Eurocode, in the design of fillet welds and partial penetration butt welds, as we have seen in Table 1, for lower steel grades, the limiting strength is allowed to be a higher value, between the yield strength and the ultimate strength of the material. Interestingly, for higher strength steels, the inclusion of the material factor of 1.25 means that the limiting stress is less than the yield strength of the material. For S355 steel, the limiting direct stress is less than the yield strength for material 40 mm thick or less.

Engineers who remember designing to BS 5950-1: 1990 will recall the requirement to check the stress on the fusion line of partial penetration butt welds and limit it to $0.7p_y$ in shear or $1.0p_y$ in tension. This check was no longer a requirement in the 2000 update of the code. Comparisons of the limiting shear stress with the values for combined stress assuming pure shear (ie σ_{pr} in equation (1) is zero) in Table 2 show that the limiting stresses in the Eurocode are higher for the lower strength grades and lower for the higher strength grades.

Examples

(1) A weld in pure shear is carrying a force of 1.27 kN/mm in grade S355 material. A partial penetration Vee butt weld is to be used. What depth of weld penetration is required? The shear stress on the weld of 250 MPa gives a weld throat to BS 5950 of 5.1 mm. Design to BS 5950: 1990 used a design strength p_w of 255 MPa on the weld throat. However the shear stress on the fusion line was also limited to $0.7p_y$ = 249 MPa resulting in the same weld size.

Using the directional method in EC3, all the components of stress are zero except for the shear stress parallel to the axis of the weld (τ_{pl}) so substituting in equation (1), the design shear stress is 418/√3 MPa (241 MPa) and the weld size is 5.3 mm. If the principal stresses are calculated in each case, we find the following for the weld to BS 5950: 2000. The shear stress is 250 MPa and the direct stresses σ_x and σ_y are both zero. The principal stresses are therefore equal to ± 250 MPa.

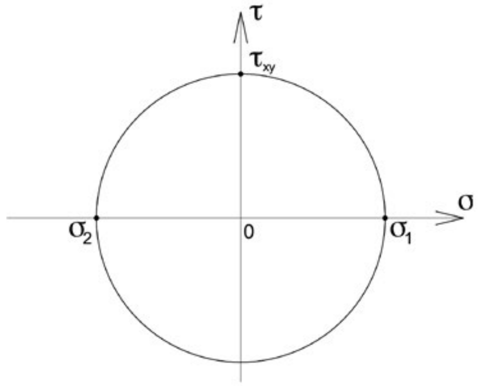

Figure 4: Principal stresses for pure shear

Substituting in equation (2) for the failure criterion, the limiting stress is 250 x √3 = 433 MPa. This is higher than 418 MPa, the limiting stress to EC3, where the principal stresses are ± 241 MPa.

(2) A second example of welds in pure shear is a lap joint transferring tension between plates in S355 material 20 mm thick, through longitudinal welds. It will be assumed that the edges of the plate are to be prepared for a partial penetration Vee butt weld. The thickness of the plates and length of the welds is such that it is assumed the direct stresses due to the eccentricity moment can be neglected.

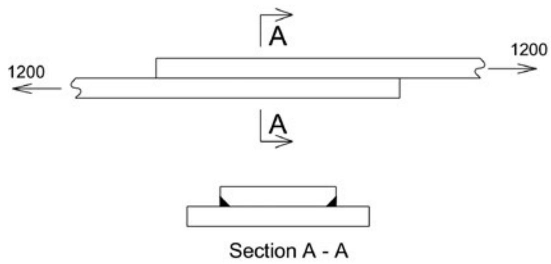

Figure 5: Connection assuming pure shear

1200 kN is to be transferred through welds on each edge of the plate with an effective length of 400 mm. The longitudinal shear stress per mm of weld is 1200 / (2 x 400) = 1.5 kN/mm. The penetration required is 1.5 × 10^3 × √3/418 = 6.2 mm.

The size of weld throat to BS 5950: 2000 would be 1.5 x 10^3 / 250 = 6.0 mm.

(3) Consider a similar example to (2) where the eccentricity is not negligible. The force to be transferred is 500 kN and the eccentricity is 100 mm so the eccentricity moment is 50 kNm.

Figure 6: Connection with shear and moment

The effective length of weld is 400 mm. A plastic distribution of stress will be assumed (EN 1993-1-8 clause 4.9(1)) so the modulus of the weld group is 2 × (1 × 400^2/4) = 8 × 104 mm^3/mm.

The shear stress on the weld is 500 / (2 × 400) = 0.625 kN/mm and the direct stress on the weld is 50 × 10^3 / (8 × 10^4) = 0.625 kN/mm. Weld penetration a is given by:

$$a = \sqrt{\frac{0.625^2 + 3 \times 0.625^2}{0.418^2}} = 3.0 \text{ mm}$$

For interest, principal stresses are -129 MPa and 337 MPa.

Were fillet welds to be used instead of partial penetration butt welds, the forces/mm of weld would be as follows, assuming a 45° throat: transverse shear = 0.625/√2 = 0.442 kN/mm; direct stress = 0.442 kN/mm; longitudinal shear = 0.625 kN/mm. The weld size is:

$$a = \sqrt{\frac{0.442^2 + 3 \times (0.442^2 + 0.625^2)}{0.418^2}} = 3.4 \text{ mm}$$

The corresponding principal stresses are -169 MPa and 301 MPa.

Examples 1 and 2 illustrate that in the case of pure shear, the weld sizes resulting from design to EN 1993-1-8 are little different from those to BS 5950. When sizing welds to EN 1993-1-8, use the limiting weld strengths for direct stress and combined stress on the weld throat. There is no requirement for a separate check on the fusion faces. The limiting shear stress (f_y/√3) for the determination of shear resistance of webs in EC3 (equivalent to 0.6p_y in BS5950) is not used in weld design.