POTENTIAL FOR WELD GROUP FAILURE IN DESIGN BY BS5950-1:2000

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Abstract

In the year 2000, BS5950 introduced a revised method of weld design for planar weld groups, incorporating the greater resistance of transverse welds compared to longitudinal welds. The "Strength Enhancement Factor" K depends on the angle θ between the transverse resultant force and the plane through the throat line. For welds along two parallel edges of a plate, θ may differ by a much as 45 degrees. This difference will result in a large variation of the K factor. As the smaller value will control, any benefit gained on one side will be lost on the other. A similar paradox exists when a weld turns a corner in a group. At the common point of two perpendicular segments, two different values of K can occur, again with the smaller critical value nullifying the extra benefit. More critical than such loss of benefit is the possibility that a designer checks weld capacity only at the extreme fibres as the worst stressed according to conventional theory; or checks it in one direction and not both at a corner; thus missing the likelihood that a closer fibre or the other leg at a corner might fail the Code.

Keywords: Structural Failure, Steel Connections, Welding Design, BS5950

Introduction

In its year 2000 version, the British Standard Code BS5950-1:2000 (British Standards Institution, 2000) offered to weld designers the benefit of the higher resistance of transverse welds compared to longitudinal welds.

Thus, the design resistance per unit length of fillet weld may be determined by either (a) "Simple Method", or (b) "Directional Method". The Directional Method offers transverse weld capacities of 8% to 53% higher than the Simple Method.

This paper presents the essential features of an anomaly with the directional method, by which the benefit intended to be given to the transverse welds may be reduced or completed eliminated simply by strict adherence to the Code.

Fillet Weld Design Methods by BS Code

According to the Code, the stress components f_x, f_y, and f_z at a given point in a weld group shall be determined from the applied forces and moments, using its elastic section properties. The capacity of the weld shall be checked by one of the following two methods:

(a) Simple Method

In this method, the resultant stress f at any point in the weld group, determined as the vector sum of the three component stresses, namely:

$$f = \sqrt{(f_x^2+f_y^2+f_z^2)} \qquad \text{. . . (1)}$$

shall not exceed the design strength p_w (*vide* Table 37 of the Code).

That is, $f \leq p_w$. . . . (2)

(b) Directional Method

Figure 1 depicts a fillet weld with a resultant force F per unit length of a weld.

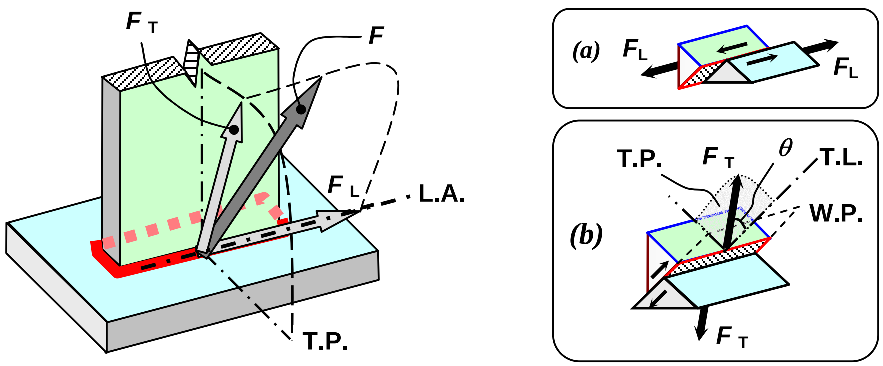

Figure 1. Longitudinal and Transverse Load Components on Weld
F - Weld force per unit length; F_L - Longitudinal Component; F_T - Transverse Component; L.A. - Longitudinal Axis; T.P. - Transverse Plane; W.P. - Weld

This force may be resolved into:

(a) A longitudinal (or “parallel”) component F_L along the weld, with shear actions as shown in Figure 1(a); and,

(b) A transverse component F_T in the plane perpendicular to the weld axis, with shear actions as shown in Figure 1(b).

The forces F are simply the corresponding stresses f times the throat width w_t.

Welds under transverse loading are stronger than those under parallel loading. Figure 2, from Butler *et al.* (1972), depicts typical stress-strain curves for longitudinal and transverse fillet welds. They illustrate the higher strength of transverse welds, and the higher ductility of longitudinal welds.

The “Directional Method” takes into account the strength difference in the parallel and transverse directions of the applied forces and consequent stresses.

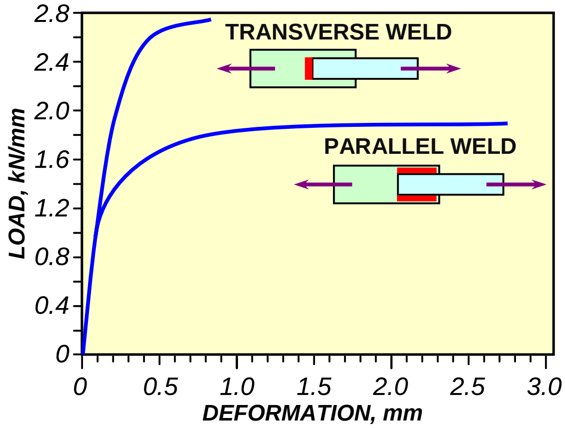

Figure 2. Load-Deformation Behaviour of Welds under Longitudinal and Transverse Loads (Butler *et al.*, 1972)

The design resistance per unit length of the parallel weld is given by:

$$P_L = w_t.p_w \qquad \text{. . . (3a)}$$

The design resistance per unit length of the transverse weld is given by:

$$P_T = K.P_L \quad \text{with} \quad K = 1.25\sqrt{\frac{1.5}{2+\cos^2\theta}} \qquad \text{. . . (3b)}$$

where, K is the "Strength Enhancement Factor", and θ is the angle between the weld throat line and the line of action of the resultant force F_T in the transverse plane, as shown in Figure 1(b).

Figure 3 depicts various orientations of transverse loading F_T, and the variation of the K factor with θ.

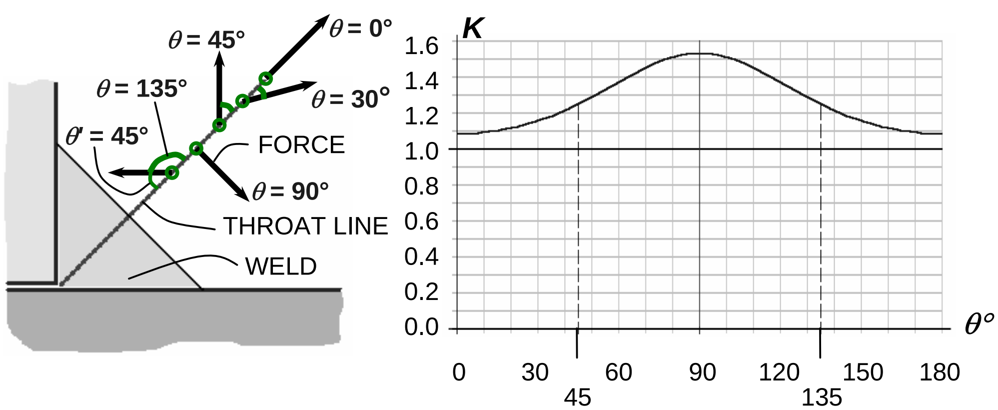

Figure 3. Measurement of θ, and Variation of K

The following points may be noted regarding the K factor:

1. As $\cos(180–\theta) = –\cos\theta$ and the cosine term in Eq. (3b) is squared, we may simply take θ as the acute angle between F_T and the throat line. This is also obvious from the fact that the θ - K curve in Figure 3 is symmetric about the vertical line at $\theta = 90°$.

2. Factor K varies from 1.083 for $\theta = 0°$, to 1.531 for $\theta = 90°$. For the specific case of the resultant acting in the plane of the weld group or perpendicular to it, $\theta = 45°$, for which $K = 1.25$.

BS5950-1:2000 states that for a combination of transverse and longitudinal forces on the weld, the design criterion to be satisfied is the interaction equation:

$$\left(\frac{F_L}{P_L}\right)^2 + \left(\frac{F_T}{P_T}\right)^2 \leq 1 \qquad \text{. . . (4a)}$$

where, F_L = Force applied parallel to the weld per unit length $= f_L.w_t$

F_T = Resultant force applied transverse to weld per unit length $= f_T.w_t$

P_L = Longitudinal strength of the weld per unit length $= p_w.w_t$

and, P_T = Transverse strength of the weld per unit length $= K.p_w.w_t$

For weld groups with a single size of fillet weld, when the common factor w_t is removed, the interaction equation (4a) reduces to:

$$\left(\frac{f_L}{p_w}\right)^2 + \left(\frac{f_T}{K.p_w}\right)^2 \leq 1 \qquad \text{. . . 4(b)}$$

where, f_L and f_T are simply the longitudinal and transverse stresses at the point.

Sharp Variations in Enhancement Factor

As depicted in Figure 4, there are three common situations in which sharp variations in the Enhancement Factor K occur:

(a) Parallel welds around a plate as at ‘a’ and ‘b’ of a beam flange;

(b) Welds at right angles as at ‘c’ and ‘d’ of a channel web and flange; and,

(c) Weld group for in-plane forces, as at ‘e’ and ‘f’ of a lap joint.

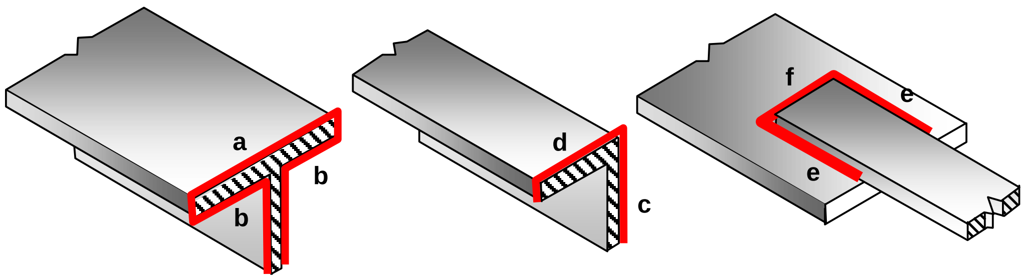

Figure 4. Weld Segments Subject to Variations of Enhancement Factor, K
a – Beam flange outside, **b** – Beam flange inside, **c** – Channel web,
d – Channel flange, **e** – Longitudinal lap weld, **f** – Transverse lap weld

Each of these three situations will be discussed separately.

Parallel Welds around a Plate

Consider the I-beam shown in Figure 5(a), fillet welded (*a* = 14 mm) all around at its support and subjected to the force and bending moment indicated in Figure 5(b).

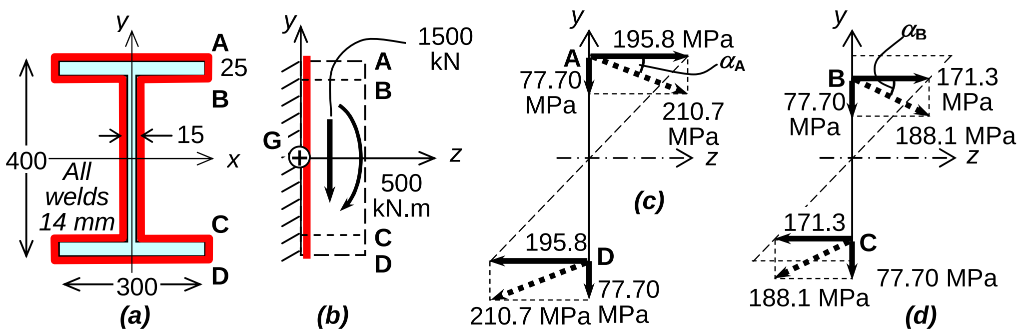

Figure 5. 'I' Beam Parallel Welds Example

The example is taken from Krishnamurthy *et al.*, 2002, in which the properties of the section and the stress computations for the extreme fibres A and D have been computed.

The resulting stresses at the extreme fibres due to the applied shear and bending moment may be computed (Krishnamurthy *et al.*, 2002) to be as shown in Figs. 5(c) and (d). All stresses are transverse to the welds. Hence the interaction equations (4) reduce to the simple check:

$$F_T \le P_T, \quad \text{or,} \quad f \le K.p_w \qquad \text{. . . (5)}$$

The longitudinal section of the upper flange AB is shown in Figure 6, and the resultant stresses at A and B are marked, together with the throat lines at 45°.

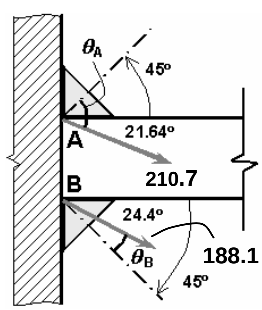

Figure 6. Angles θ at A and B

The resultant stress f_A at A (or D) is 210.7 MPa at α_A of 21.64° to the horizontal.

The resultant stress f_B at B (or C) is 188.1 MPa at α_B of 24.40° to the horizontal.

Considering unit length of weld, these stress magnitudes f are also the forces F per unit length.

Then the values of θ may be computed as follows:

θ_A = 45+21.64 = 66.64°

and, θ_B = 45–24.40 = 20.60°

From Eq. (3b), the corresponding K factors at A and B are found to be 1.42 and 1.12. In other words, if the transverse weld on the outside of the flange can be considered to be stronger than longitudinal welds by 42%, the transverse weld on the inside can be considered to be stronger only by 12%, a loss of benefit of 30% between the two parallel welds, in the utilisation of the extra capacity of transverse welds.

Application of the modified interaction equation for this case, namely Eq.(5) gives:

$210.7 \le 1.42\, p_w$ at A, and, $188.1 \le 1.12\, p_w$ at B

i.e., $p_w \ge 148.3$ MPa at A, and, $p_w \ge 167.9$ MPa at B

This has been an analysis exercise, but it demonstrates that although the stress at B is less than that at A, the Code design criterion demands more capacity at B than at A.

However, most present day designers will focus on the extreme fibre at A, and not at an inner fibre such as B.

In the worst case scenario of a uniform force at 45° to the horizontal acting on the I-beam, both α_A and α_B will be 45°. Then, θ_A will be (45+45) or 90° with K = 1.531. But θ_B will be (45–45) or 0° with K = 1.083.

In this case, the benefit provided by BS5950 for transverse welds is reduced from 53% to 8%!

Welds at Corner of Channel Web and Flange

Consider the weld group BACD around a channel section as shown in Figure 7.

To illustrate the argument with simple numbers, let the forces per unit length of weld at the corner A be: F_x = 100 kN, F_y = 100 kN, and F_z = 100 kN.

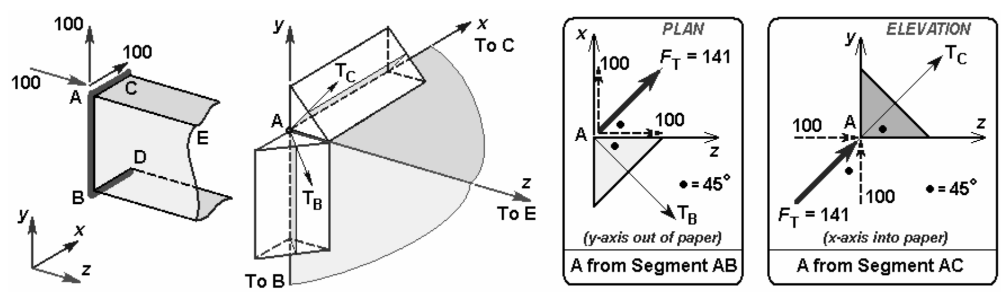

Figure 7. Channel Section Perpendicular Welds Example.

In the enlarged view of the corner A in the figure, the throat lines for the two segments AB and AC are indicated as T_B and T_C, with the corresponding throat planes being shown lightly shaded.

Note that for both the segments AB and AC, the angle made with the *z*-axis by the respective throat lines T_B in the *zx* plane and T_C in the *yz* plane, is 45°.

The transverse forces in the planes of the web and top flange of the channel are shown within boxed areas at the right of Figure 7.

(a) A from Segment AB:

For segment AB, F_y of 100 kN becomes the longitudinal force F_L. The transverse force F_T is the resultant of F_x and F_z, namely $\sqrt{(100^2 + 100^2)}$, that is 141 kN, inclined at 45° to the *z*-axis, in a sense opposite to that of the throat line.

Hence, the included angle θ between the throat line and transverse resultant F_T = 45 + 45 = 90°, for which, K = 1.531.

(b) A from Segment AC:

For segment AC, F_x of 100 kN becomes the longitudinal force F_L. The transverse force F_T is the resultant of F_y and F_z, namely $\sqrt{(100^2 + 100^2)}$, that is 141 kN, also inclined at 45° to the *z*-axis, but in the same sense as the throat line.

Hence, the included angle θ between the throat line and transverse resultant F_T = 45–45 = 0°, for which, K = 1.083.

Obviously, the segment with the smaller K, namely AC, will control the design. The benefit received along the segment AB has been eliminated by just turning the corner!

If for instance, P_L = 150 kN, with $P_T = K.P_L$, the interaction equation (4a) gives, at A:

From AB, $(100/150)^2 + [141/(1.531\times150)]^2 = 0.444+0.379 = 0.823 < 1$

From AC, $(100/150)^2 + [141/(1.083\times150)]^2 = 0.444+0.754 = 1.198 > 1$

This implies that apart from checking a weld at closer points, in order to detect non-satisfaction of the Code provision, one would have to check all the segments meeting at a point, to find out the worst case!

If a designer or checker evaluates the design at A from the segment AB and does not check it from AC, he will miss the increase of the transverse term by 100% in this case. In the general case, the difference may be more or less, but unpredictable.

Extreme Case: Welded Lap Joint

The anomaly pointed out in the case of the channel corner may be extended to the particular case of a force in the plane of a weld group, with very adverse results.

Consider the fillet welded lap joint of Figure 8 under a (factored) tensile force, F'. A constant weld size of throat thickness w_t is assumed. This example is taken from Krishnamurthy *et al.*, 2002, and also cited in Liew and Krishnamurthy, 2002.

The total length of weld L is (a+2b). Weld area A is $w_t.L$. The applied force consists only of $F_x = F'$, so that $f_x = F'/A$.

As f_y and f_z are zero, the resultant stress $f = f_x$.

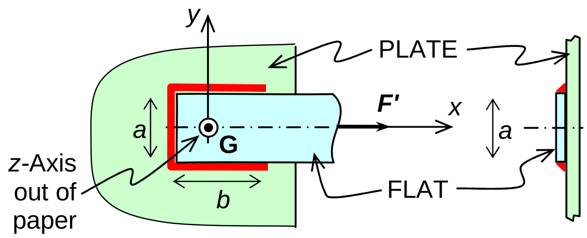

Figure 8. Lap Joint in Tension

(a) Simple Method:

$$f_x = F_x'/A \leq p_w \qquad \ldots (6)$$

from which, assuming b, w_t may be found, or assuming w_t, b may be found.

(b) Directional Method:

Longitudinal capacity $P_L = p_w.w_t$

For the two longitudinal welds, $F_L = w_t.f_L = w_t.f_x$, and, $F_T = 0$. Hence the interaction equations (4) reduce to:

$$F_L \leq P_L, \qquad \text{or,} \qquad f_x \leq p_w \qquad \ldots (7a)$$

For transverse capacity, as indicated in Figure 9, $\theta = 45°$, for which K= 1.25, and hence, $P_T = 1.25 p_w.w_t$

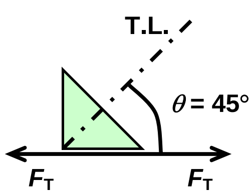

Figure 9. Transverse Load (F_T), and Throat Line (T.L.)

For the transverse end weld, $F_L = 0$, and, $F_T = w_t.f_T = w_t.f_x$. Hence the interaction equations (4) reduce to:

$$F_T \leq P_T, \qquad \text{or,} \qquad f_x \leq 1.25\, p_w \qquad \ldots (7b)$$

To satisfy both conditions (7a) and (7b), the more stringent Eq. (7a) controls. Hence, $f_x \leq p_w$, which is the same criterion as for the Simple Method.

Thus, it is seen that for such joints where a single force acts in the plane of and parallel to one of the weld segments in the group, there is no benefit from the increased capacity of the transverse weld(s) offered by BS5950. Surely this could not have been the intent of the Code framers!

In this particular case, it happens that there is an alternative to BS5950, namely the ultimate strength method offered by Eurocode (2000), according to which, under certain conditions, the capacities of the longitudinal and transverse welds may be added. The authors have dealt with this method in detail in Krishnamurthy *et al.*, 2002, and in Liew and Krishnamurthy, 2002.

Risk of Failure

The fact that by the Directional Method a fibre stressed to less than the maximum may fail the Code is not the problem, All that is needed is to revise the design until the Code interaction equation (4a) is satisfied.

The real problem is that conventionally, weld designers evaluate the stress at the extreme fibres, as critical for design. In the Directional Method using the Interaction Equation, it may be a closer fibre that may decide the minimum weld size.

Further, as has been pointed out, it is necessary to check the situation not only at closer locations, but also along both legs at the same corner to pick the more critical of the two K factors.

Designers and even checkers may overlook these possibilities. As a consequence, failure to provide the larger weld size in either of the two situations presented may well result in the failure of the joint at the limit state.

There is no directive in the Code to require designers to search all over a weld group and in all directions for such critical locations. Until they are universally educated in this new danger, there is real risk that apparent compliance with the Code may hide the potential for structural failure.

To detect and correct such risks of omission, design checkers and approvers will have to do extra work.

During the transition period, delays will occur due to the rejection of incomplete designs and their revision.

Conclusion

It is clear that in many practical instances of parallel welds on both sides of a plate, and at right angular turns in a weld group, strict application of BS5950 to the design of fillet weld groups may result in a considerable reduction, even complete elimination, of the potential advantage of higher strength of transverse welds.

Frequently, it may be worthwhile even to omit certain segments which lead to smaller K values, and increase the size of the remaining ones with larger K values. This increase in size will be relatively smaller than the decrease in length, thus resulting in overall economy.

For instance, reverting to the I-beam example, in the worst case scenario of a uniform force at 45° to the horizontal, with reference to Figure 6, omission of the weld on the underside of the flange (with the lower *K*), will result in an increase of the weld on the upper side by (1.083/1.531), that is, only by 71% rather than 100%, a savings of 29%.

At the same time, it is not recommended that these lower capacity segments be actually be welded, and only their theoretical contributions be omitted during the design computations.

For, to give due credence to the research and investigations underlying the Code clauses, the strength should actually be expected to go down in the controversial segments, and lead to stress concentrations and other adverse consequences by their presence.

European (Eurocode 3, 2000), American (AISC, 1992; AWS, 2000), and other codes also offer benefits based on the higher capacity of transverse loads. However, these do not relate the extra strength to the angle θ between the resultant and the throat plane, and hence do not lead to the kind of self-reduction of benefit that BS5950 can impose.

The authors suggest that pending re-evaluation of the basis of the *K* factor, some alternatives to recognise and moderate the extreme differences such as have been pointed out herein be recommended by the Code authorities.

One possibility of a quick-fix may be to approve an average of the two different values along two parallel sides, or at the common point at a corner. This may cut the wastage by about half.

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