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Fatigue strength of transverse fillet and cruciform butt welds in steels

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The person with overall responsibility for the work in this subject area is Mr M.E. Grayley, Head of Strength Analysis Group.

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FATIGUE STRENGTH OF TRANSVERSE FILLET AND CRUCIFORM BUTT WELDS IN STEELS

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FATIGUE STRENGTH OF TRANSVERSE FILLET AND CRUCIFORM BUTT WELDS IN STEELS

1. NOTATION

a	actual weld throat depth (see Sketches 1.1a, 1.1b and 1.5)	m	in
b	depth of penetration at weld root (see Sketches 1.1a, 1.1b and 3.2)	m	in
K	stress concentration factor at weld toe (based on stress in loaded plate)		
N	endurance		
P	load applied to joint	N	lbf
R	stress ratio $= \dfrac{(S_m - S_a)}{(S_m + S_a)}, = S_{min}/S_{max}$		
S_a	alternating stress (half range) in loaded plate	N/m^2	lbf/in^2
S_m	mean stress in loaded plate	N/m^2	lbf/in^2
S_{min}	minimum stress $(S_m - S_a)$ in loaded plate	N/m^2	lbf/in^2
S_{max}	maximum stress $(S_m + S_a)$ in loaded plate	N/m^2	lbf/in^2
S_y	yield stress	N/m^2	lbf/in^2
s	weld leg length (see Sketches 1.1a, 1.1b and 3.1)	m	in
t	nominal thickness of loaded plate	m	in
θ	weld angle (see Sketches 1.1a, 1.1b and 1.5)	deg	deg

Both SI and British units are quoted.

Tensile stress is considered positive and S_a is considered positive.

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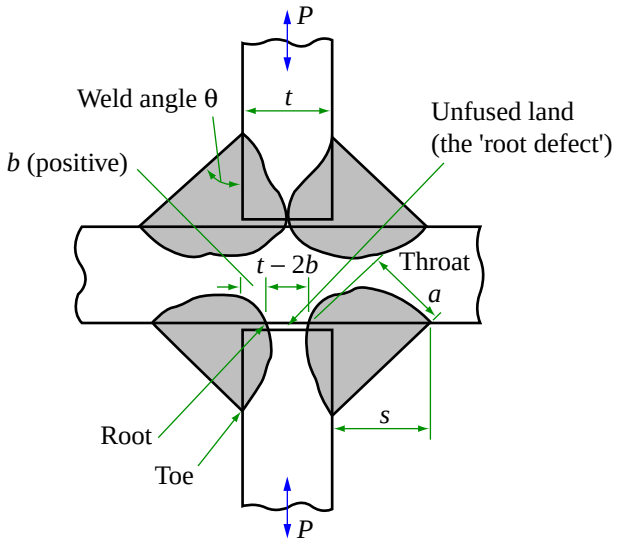
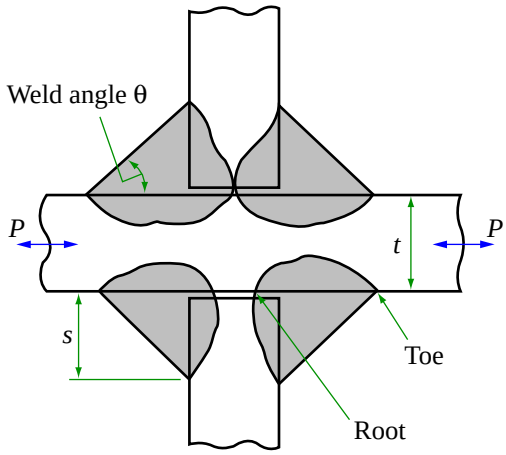
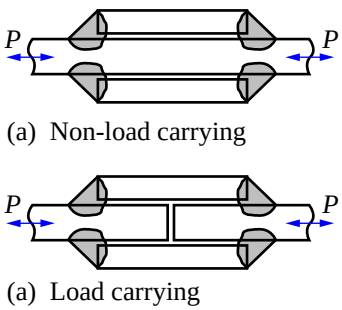


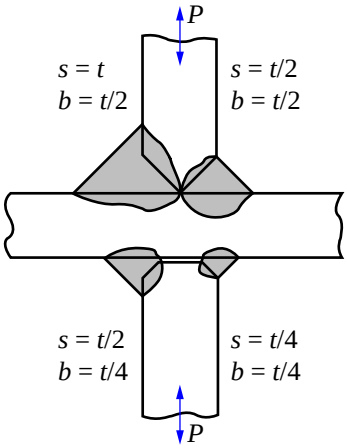
Sketch 1.1a Load-carrying cruciform fillet welded joint showing basic notation



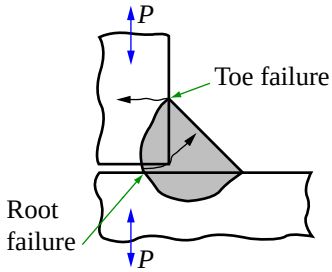
Sketch 1.1b Non-load-carrying cruciform fillet welded joint showing basic notation



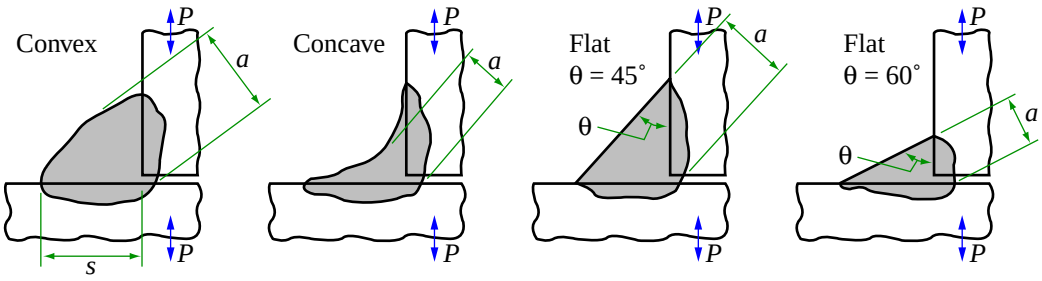
Sketch 1.2 Cover-plate joints. Notation as in Sketches 1.1a and 1.1b. The total loaded cross-sectional area of the cover plate should be equal to or greater than that of the loaded plate.



Sketch 1.3 Partial and full penetration cruciform butt welds (bevel welds). Notation as in Sketches 1.1a and 1.1b.



Sketch 1.4 Illustrating the two modes of failure found in load-carrying fillet welded joints subjected to fatigue



Sketch 1.5 Weld bead profiles (*s* is the same in all four sketches)

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2. PRESENTATION OF DATA

This Item presents experimental data on the as-welded fatigue strength of axially loaded transverse fillet welded joints and cruciform butt welded joints in steels. The types of joint covered by the Item are shown in Sketches 1.1a to 1.3. The data relate to laboratory specimens having weld angles of 45° (see Sketch 1.5).

Provided that the welds are sound and free from severe defects, the fatigue resistance of a joint in the as-welded condition is almost independent of the properties of the plate and weld materials, except in the low cycle region ($N < 10^4$ cycles). The longer endurance of welded joints in fatigue is largely determined by the propagation of either inherent cracks or cracks generated at points of concentration of stress. Fatigue failure can occur in one of two ways: cracks can initiate from small defects, typically up to 0.5 mm in depth, present at the stress concentration at the weld toe and propagate through the plate, or the crack-like defect caused by incomplete penetration of the land, referred to throughout this Item as the "root defect", can grow outwards from the root through the weld metal (see Sketch 1.4). All non-load-carrying joints will fail from the weld toe alone because the "root defect" lies parallel to the stress flow. In load-carrying cruciform and cover plate joints, however, the "root defect" does not lie parallel to the local direction of stress flow and failure may occur from root to toe. The most severe condition is that found in load-carrying cruciform joints where the "root defect" is perpendicular to the local stressing direction. Full penetration of the weld eliminates the "root defect" and so precludes failure from the root.

Results for full penetration cruciform joints at $R = 0$ are given in Figure 1 and compared with results from test pieces of similar shape machined from solid. The figure indicates that the determining factor for fatigue strength is geometry and that a high quality weld in itself does not detract from the fatigue strength. Figures 2 and 3 show, respectively, the reduction in fatigue strength, at $R = 0$, that may be expected for load-carrying cruciform joints from either a weld leg length or penetration that is insufficient to preclude root failure. To a lesser extent the same factors impair the performance of the load-carrying cover plate and non-load-carrying cruciform joints and the results for these are set out in Figures 4 and 5; they show that both have equivalent or lower fatigue strengths than those of Figure 1. Non-load-carrying cruciform joints can be regarded as virtually equivalent to non-load-carrying cover plate joints because they differ only in the width of the attachment, and this is unlikely to have much influence on fatigue strength. The data of the figures refer to loaded cover plates whose width is greater than five times the thickness of the loaded plate. Figure 6 summarises the effect of weld leg length on the fatigue strength of both load-carrying cruciform and cover-plate joints at $N = 2 \times 10^6$ cycles and Figure 7 summarises the effects of both weld leg length and depth of penetration on the location of failure of load-carrying cruciform joints.

The effect of mean stress on the fatigue strength of load-carrying cruciform joints is given in Figure 8 and for non-load-carrying cover plate joints in Figures 9a and 9b for two materials. Figures 10a and 10b give S_a against S_m diagrams for mean lines drawn through the data of Figure 8 and Figures 9a and 9b respectively. The effect of depth of penetration on load-carrying cruciform joints tested at zero mean stress ($R = -1$) is shown in Figure 11 and the results are compared with the zero mean stress line from Figure 8, which is for welds with leg length equal to the plate thickness and zero penetration.

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3. FACTORS AFFECTING FATIGUE STRENGTH

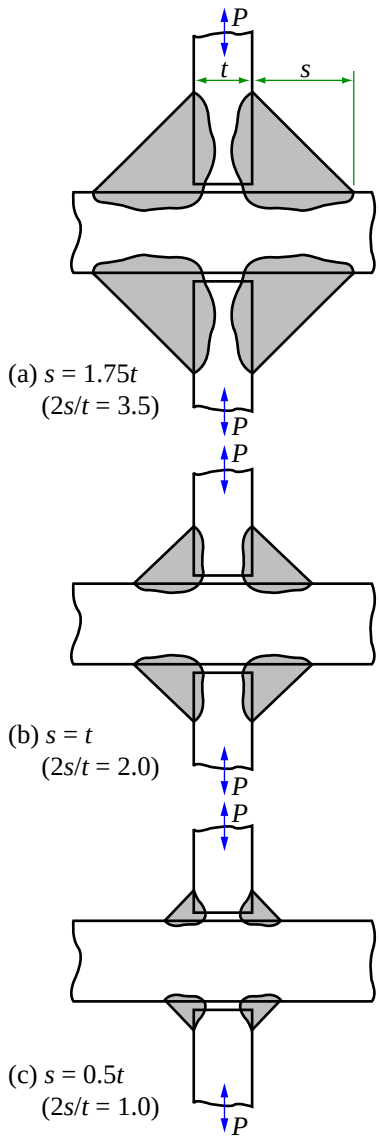
This section discusses the effects of weld geometry and residual stress state on the fatigue performance of the types of joint for which data are provided.

3.1 Weld Leg Length

The value of the stress at the root relative to that at the toe depends on the ratio $2s/t$ and when this ratio is large failure will always occur at the toe of the weld. When $2s/t$ is small, see Figures 6 and 7, stresses at the tip of the "root defect" may be high enough to propagate cracks from that defect so as to cause failure there before failure at the toe. Root cracks propagate through the throat of the weld, the rate of propagation depending largely upon the size of the joint (see Section 3.5). Figure 2 shows the effects of weld leg length on the location of failure and the fatigue strength of load-carrying cruciform joints. This effect is also illustrated for an endurance of 2×10^6 cycles in Figure 6a.

In load-carrying cover plate joints, although the "root defect" is parallel to the direction of loading, failure can occur at either the weld toe or weld root. This is because the "root defect" (see Sketch 1.2) is angled to the direction in which stress is transmitted. The relationship between weld leg length and fatigue strength for this joint is shown in Figure 6b for an endurance of 2×10^6 cycles. The transition from root to toe failure occurs at lower $2s/t$ values than for the cruciform joint.

If a cruciform or cover plate joint is designed such that the weld leg length is large enough to give toe failure alone then further increase in s is unlikely to give a significant increase in fatigue strength.



Sketch 3.1 Showing variation in the parameter 2*s*/*t*

3.2 Depth of Penetration

Depth of penetration at the root of the weld, b, is usually described by the ratio of total penetration to plate thickness $2b/t$. There are two ways in which penetration can be achieved; either by burning in using high penetration electrodes, used on thinner plates, or by contouring the ends of the plates to be welded (see

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Sketch 1.3). In order to eliminate the "root defect" entirely it is necessary to dress the back of the first weld run by backchipping or gouging. All other factors being the same either burning in or contouring results in joints that exhibit similar fatigue properties.

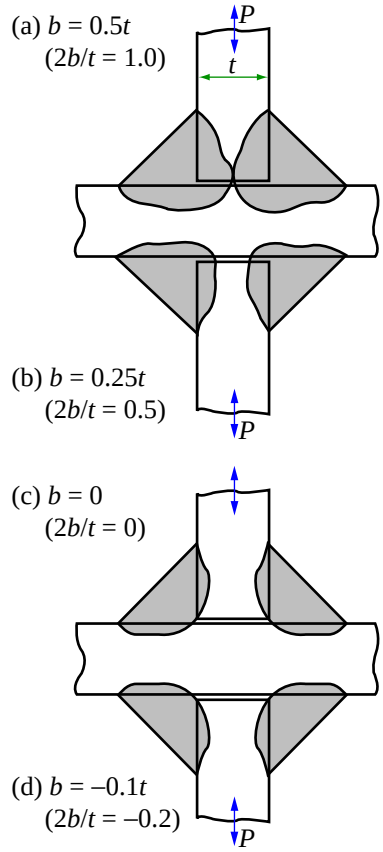
With full penetration, $b = t/2$, no "root defect" exists (see Sketch 3.2) and therefore failure occurs from the weld toe thus achieving maximum fatigue strength. Reducing $2b/t$ below a certain level will cause a reduction in fatigue strength as propagation of the "root defect" significantly affects conditions at the toe. If $2b/t$ is further reduced (that is, if the length, $t - 2b$, of the root defect is large) the stress at the root becomes high due to the decreased load bearing area and failure tends to occur from the root. Negative values of penetration give very low fatigue strengths.

Penetration can modify the effects of weld angle (see Section 3.4).

The effects of $2b/t$ on fatigue strength and location of failure are shown in Figure 3 for cruciform joints tested at $R = 0$ and in Figure 11 for specimens tested at $(R = -1)$.

3.3 Combined Effects of Weld Leg Length and Depth of Penetration

In the case of cruciform joints the highest fatigue strength is normally achieved by keeping the dimensional parameters $2s/t$ and $2b/t$ above certain levels. A joint designed such that $2(s + b)/t$ is greater than about 2.1, as indicated in Figure 7, will exhibit toe failure alone and will therefore have a high fatigue strength.



Sketch 3.2 Showing variation in the parameter $2b/t$

3.4 Weld Bead Shape

The cross-sectional shape of the weld bead can be described as convex, concave or flat, see Sketch 1.5. A concave section produces a lower stress concentration at the toe but a low throat depth, a, and consequently a high throat stress increasing the likelihood of root failure. Conversely a convex weld bead gives a high stress concentration at the toe but a low throat stress. The majority of welds are produced with flat weld beads and almost all of these, including all the joints detailed in the figures, have $\theta = 45°$. The few data available indicate that if weld angle, θ, is increased with weld leg length held constant the fatigue strength is decreased with a greater tendency for root failures to occur. Increasing the depth of penetration reduces the effect of changing weld angle. Defects found in practice such as undercutting, multiple run defects,

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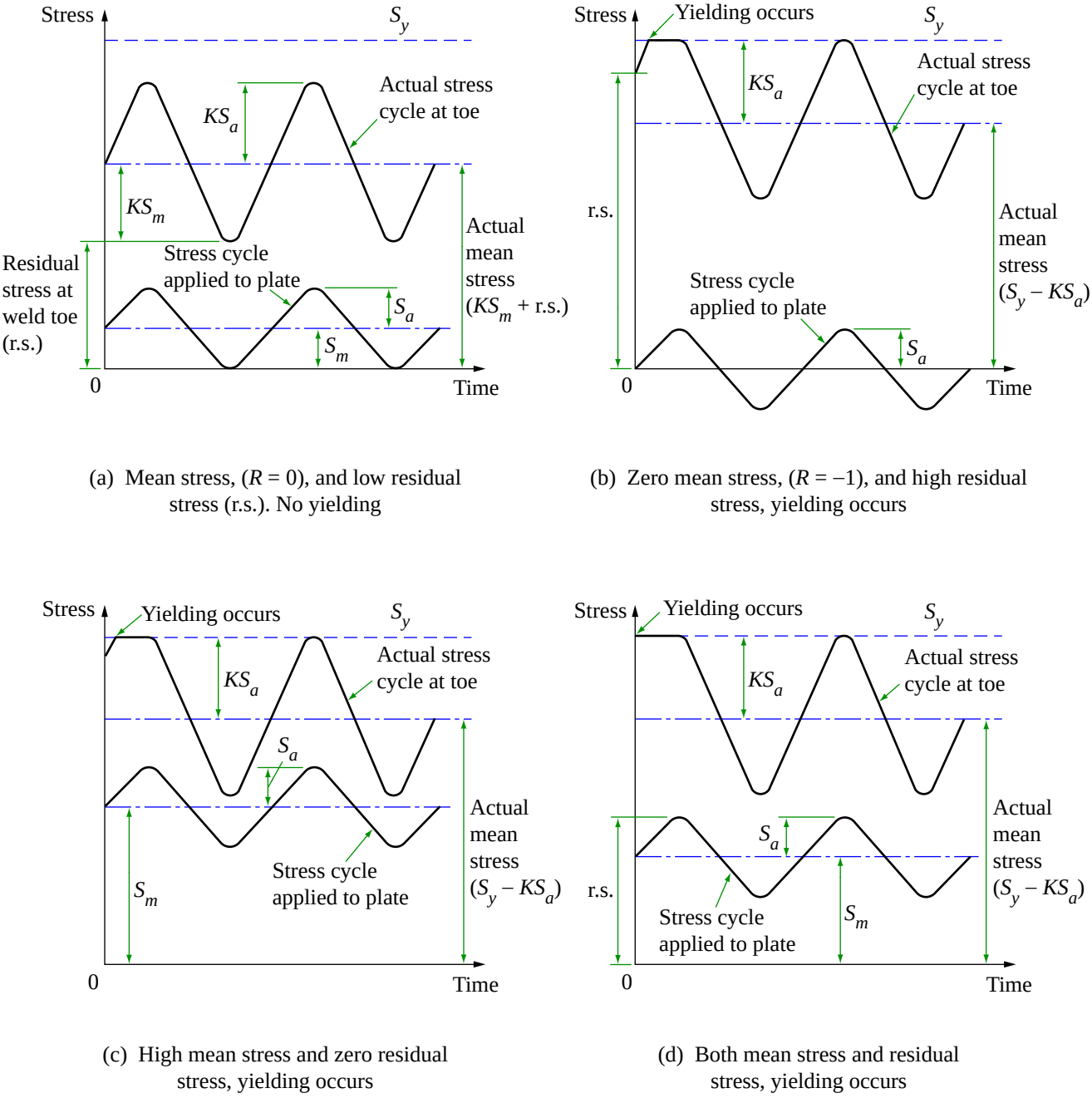
weld ripples and variation in bead shape will lower the fatigue strength below that predicted by the test data shown in the figures. Weld runs ending on the plate surface may lower the strength below that obtained where weld runs are taken beyond the plate edge onto a coupon and then dressed flush.



(a) Mean stress, (R = 0), and low residual stress (r.s.). No yielding

(b) Zero mean stress, (R = −1), and high residual stress, yielding occurs

(c) High mean stress and zero residual stress, yielding occurs

(d) Both mean stress and residual stress, yielding occurs

Sketch 3.3 Showing the actual stress states that exist at the weld toe for four combinations of residual stress at the toe and applied mean stress.
(An arbitrary stress concentration factor, *K*, of two is applied in all four examples.)

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