

GUIDE TO THE USE OF DATA ITEMS ON THE FATIGUE STRENGTH OF WELDED JOINTS IN STEELS

1. INTRODUCTION

This Data Item provides an introduction and guide to the use of existing Data Items concerned with the fatigue strength of welded joints. Included in this guide are some details concerning design of welded joints and principal causes of fatigue failure, together with the reasons for the relatively small influence that parent material strength has on the fatigue strength of welded joints. The fatigue strengths in terms of stress range at 2×10^6 cycles of typical welded joints range from 170 MN/m^2 ($25 \times 10^3 \text{ lbf/in}^2$) for a good quality transverse butt weld down to 55 MN/m^2 ($8 \times 10^3 \text{ lbf/in}^2$) for a partial penetration cruciform butt weld. These values are much lower than the fatigue strength of as-rolled carbon steel unwelded plate which, expressed as stress range for endurance of 2×10^6 cycles, is in the region of 250 MN/m^2 ($36 \times 10^3 \text{ lbf/in}^2$).

2. NOTATION

Both SI and British units are quoted, but any coherent system of units may be used.

a	crack length (for a crack free to extend at one end only)	m	in
C	coefficient in simple crack growth rate law defined by $\frac{da}{dN} = C(\Delta K)^n$	$\text{m} \frac{(\text{m}^{3/2})^n}{\text{N}}$	$\text{in} \frac{(\text{in}^{3/2})^n}{\text{lbf}}$
K_t	elastic stress concentration factor		
ΔK	stress intensity factor range	$\text{N/m}^{3/2}$	$\text{lbf/in}^{3/2}$
M	moment applied to beam section	N m	lbf in
N	number of load cycles		
n	characteristic of slope of crack growth rate curve		
P	applied load	N	lbf
R	$S_{\min}/S_{\max}$		
S	nominal stress in absence of crack	N/m^2	lbf/in^2
$S_{\max}$	maximum value of S in fatigue cycle	N/m^2	lbf/in^2
$S_{\min}$	minimum value of S in fatigue cycle	N/m^2	lbf/in^2
ΔS	nominal stress range in absence of crack	N/m^2	lbf/in^2
s	weld leg length	m	in

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t	nominal thickness of loaded plate	m	in
W	size of scaled component used as a reference	m	in
α	geometrical factor in stress intensity factor		

2.1 Code Designations

In most design codes, welded joints are classified according to type and class, where each type exhibits identifiable features that are known to affect fatigue strength. the fatigue performance of different types can then be compared in terms of allowable stress versus number of cycles to failure data and a particular class designated accordingly. In British Standards the class designations range from A to W representing progressively decreasing fatigue strengths. The complete range of type and class designations is given in Table 17, Reference 5.

3. WELDED JOINT BEHAVIOUR AND FACTORS AFFECTING FATIGUE STRENGTH

The fatigue strength (at long endurances) of a welded joint between similar steels depends upon a number of factors, in particular the geometry of the joint. Other factors include the particular joint design with regard to the final shape of the weld overfill and its configuration relative to the load, welding process, weld defects (particularly if crack-like and normal to the load), and post-weld treatments. The material of the weld is formed at the time of welding and is a mixture of the welding rod material and the parent material. It is therefore inhomogeneous and possesses properties that are difficult to quantify. Additionally the parent plate material local to the weld in the area known as the 'heat affected zone' experiences large variations in temperature during the welding process which can affect material properties, and so lead to a degradation of fatigue properties. In welded joints it is found that tiny intrusion defects associated with the weld and invisible to the naked eye are always present in addition to any other visible defects, and these act as additional initiation regions for fatigue cracks. The intrusion defects are present in welds that would normally be regarded as "sound" and free from significant defects. It may be noted that the fatigue strength of a welded structure is dependent upon the fatigue strength of its individual joints and has little to do with the fatigue strength of the plate material as will be discussed later.

3.1 Methods of Improving Fatigue Strength

For a given design of joint, fatigue crack initiation occurs due to a combination of the varying stress, the residual stresses, and the stress concentration present at the weld toe acting in conjunction with intrusion, or any other, defects present. For both as-welded and stress relieved joints, improvement of the weld overfill profile by grinding or other forms of machining provides an opportunity to reduce stress concentrations and hence improve the fatigue strength. This process would also tend to remove small surface cracks present at the weld toe and hence retard fatigue crack initiation. Other processes such as peening or the provision of a tungsten-inert-gas weld run at the weld toe can also improve fatigue strength.

3.2 Influence of Parent Material Type

For the range of weldable steels the fatigue strength of the parent plate has little influence upon the fatigue strength at long endurances of any welded joint within that parent plate. This can be appreciated by considering the fracture mechanics aspects of welded joint fatigue failure. In the case of fatigue cracking of plain homogeneous material, it has been observed by Paris (see Reference 1) that the increment of fatigue crack extension per cycle is proportional to a power of stress intensity factor range under cyclic loading

(see Data Item No. 80036*), that is,

$$\frac{da}{dN} = C(\Delta K)^n, \quad (3.1)$$

where $\Delta K = \Delta S(\pi a)^{1/2} \alpha.$ (3.2)

Experimental work has shown that this is indeed the case for many materials, provided that the maximum applied K does not approach the material fracture toughness, and also that the range (ΔK) is above a minimum threshold level. It has also been shown that the constants C and n vary little for all weldable steels and most steel weld metals. For welded details it has been found that the inherent tiny intrusion defects associated with a weld act as initiation regions for fatigue cracking, and virtually all of the fatigue life is occupied by propagation of the crack from an initial to a final size. This implies that once a crack has initiated at a weld it will propagate either into the weld or into the parent plate at a rate that is insensitive to the strength of the parent plate material.

3.2.1 Implications of using a higher strength steel

Substitution of a higher strength steel in place of one of lower strength in welded construction to accommodate increased loading is only advantageous if that increased loading is essentially static or deadweight in nature. In welded joints, if the applied stress range is increased in proportion to the increased static material strength the result is an increased ΔK and hence a much greater rate of fatigue crack propagation and shorter fatigue life. Thus the use of high strength steels in welded construction often does not improve the fatigue performance, since if used at higher stress ranges they will fail earlier than low strength steels operating at a lower stress range.

3.3 Size Effect

It is important to appreciate that increasing the absolute size of a welded joint can lead to a significant reduction in fatigue life at a given stress level[†]. Available experimental data suggest that the fatigue strength of a welded joint decreases with increased plate thickness. A specific example of size effect for which data are available can be seen in Data Item No. 78023[‡], Figure 1. This shows toe failure data for transverse fillet welded joints under bending loading for various plate thicknesses. However, the vast majority of tests for fatigue strength of welds have been conducted on specimens of limited size, having thicknesses typically in the range of 8 to 20 mm and having restricted length. These do not show clearly the effects of absolute size. Therefore an over-estimate of fatigue strength can be made if the results obtained from these specimens are assumed to be representative of much larger and thicker section components.

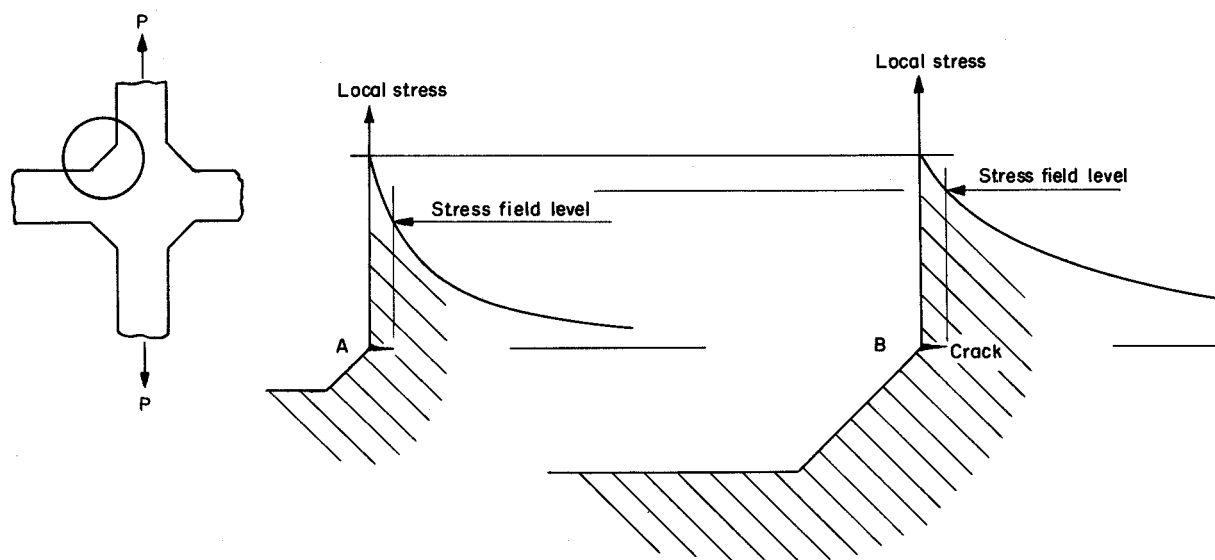
It is often difficult to obtain unambiguous experimental evidence of the influence of plate thickness on the fatigue strength of welded joints. This is because in increasing the plate thickness a number of other relevant variables are often affected, including the detailed joint geometry and the number of weld passes necessary to make the joint, which increases the risk of significant crack-like defects. A higher level of residual stresses is also associated with a larger plate thickness and this in turn increases the likelihood of fabrication cracks and crack propagation in service.

The theoretical reasons for lower crack propagation threshold and higher subsequent crack propagation rate in larger sized joints can be seen by adopting a fracture mechanics viewpoint. Consider two geometrically similar components containing idealised weld shaped features, one being proportionally larger than the other, as shown in Sketch 3.1.

* Data Item No. 80036 "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

† Data Item No. 87016 "Effect of size on fatigue strength of steel components".

‡ Data Item No. 78023 "Fatigue strength of transverse fillet welded joints and attachments in steels under bending loading".



Sketch 3.1

If the loads are appropriately scaled, the respective fields of stress concentration will exhibit the same maximum level, and will be geometrically similar, extending to the same **proportion** of the cross-section of the member. It may well be that for reasons of welding procedure the larger component will contain a larger initial crack and this would certainly be deleterious but, even if the size of initial crack in the two cases is the same, the larger absolute size of the region of stress concentration in the larger component will allow enhanced values of the crack stress intensity factor, $K_t S \alpha \sqrt{a}$, (where α is a function of a/W , the **same** for each case) to control the crack growth rate to a larger absolute value of a for the larger component. It is assumed that the final length that is either acceptable or causes failure is the same fraction of the size W in each case. When Equation (3.1) is integrated to give the total life of a component with a small initial crack, the final crack length has little influence on the total life. (For example, $\frac{3}{4}$ of the life may accrue whilst a crack grows from, say, 0.25 to 1 mm, but in the remaining quarter of its life it will grow to the failure length which could be 20 or 50 mm). Thus the crack in the larger component, which experiences the enhanced stress intensity factor and thus faster fatigue crack growth rate whilst it grows to the larger absolute size in the region of stress concentration, experiences a shorter overall life than does the crack in the small component since at the larger crack size the crack growth rate is much higher, and this is not compensated for by the crack begin able to grow to the longer final size (the same fraction of W) in the larger component.

The foregoing argument has been confirmed by detailed crack growth calculations on several types of joint (see Reference 4).

3.4 The Effect of Residual Stresses

As-welded joints contain a highly localised system of residual stresses resulting from internal constraints arising during cooling of the weld. Experience shows that these stresses in the critical regions at the weld toe and the ends of weld runs are often tensile. Residual stresses in the direction of welding are high, usually of the order of the material yield strength, whereas stresses perpendicular to the direction of welding are not necessarily of this magnitude but depend on plate thickness. In thin plate the temperature during cooling is reasonably uniform through the thickness of the plate and the resulting transverse and through-thickness stresses are likely to be small although stresses along the weld may be high. In thicker plates the temperature differences are more pronounced and the larger the section that remains relatively cool during welding the higher are the residual stresses in the region of the weld. Therefore in very thick joints the transverse and through-thickness stresses may be as high as the material yield strength.

Longitudinal welds are here defined as welds where the maximum stress acts parallel to the weld. Since the residual stress in the weld in this direction is in the region of yield, any applied tensile loading will cause local yielding and a degree of shakedown during the first few load cycles, particularly in the region of the stress concentration at the end of the weld run. Thereafter the stress cycle in the weld will be from the yield level downwards to a level given by the yield stress minus the local stress range. The consequence of this is that the mean level of the local stress cycle will be approximately the same regardless of the externally applied mean stress level. Hence it is customary to ignore external mean stress in the assessment of as-welded fatigue strength, the stress range ΔS being the important factor.

In transverse welds the maximum stress acts perpendicular to the welding direction. The maximum stress developed at the stress concentration at the weld toe is the sum of the residual stress and the applied stress acting at the stress concentration. If this sum exceeds the yield stress, local yielding will occur and, locally, subsequent cycles will range from the yield stress down to the yield stress less the local stress range. In thinner joints the residual stresses tend to be low and hence low applied stresses may not cause local stresses to exceed yield.

3.5 Effect of Applied Mean Stress

If the residual stresses in the direction of loading are low, as in the case of transverse fillet welded joints in thin plate, or can be brought to a low level by post-weld treatment, then the effects of applied mean stress may become evident. If the mean stress is such that, at the stress range applied, the maximum local stress is less than yield the fatigue life will be greater than that found if the same stress had caused local yielding in critical regions. If local yielding does not occur then lowering the mean stress applied will give an increase in endurance; the effect of mean stress will be greater at lower alternating stresses.

3.6 Thermal Stress Relieving

Thermal stress relieving is carried out in order to reduce the residual stresses present as a result of the welding process and hence extend fatigue endurance, although fatigue improvement may not be the primary reason for the treatment. It also has metallurgical benefits and enhances resistance to brittle fracture and stress corrosion. In thermally stress relieved joints the actual stress ratio, R , in the weld will be less than that in an as-welded joint having the same applied stress ratio. This is because in stress relieved welds the actual stress ratio approaches the applied stress ratio, while in as-welded joints the actual stress ratio is given by the yield stress minus the applied stress range divided by the yield stress (due to the presence of residual stresses as stated previously). The lower stress ratio in stress relieved welds gives rise to a higher threshold ΔK for crack propagation and hence a higher fatigue limit. Thermal stress relieving is an expensive operation and often results in some deformation of the assembly, particularly in bigger assemblies. Some local stress relieving is possible at sites subject to particularly high stresses. If effective stress relieving has been carried out, the fatigue strength for a given stress range will then be governed by weld geometry. The most crucial features are built-in crack-like defects or stress concentrations caused by the weld overfill.

It is difficult to quantify the effect that thermal stress relieving has in terms of increased fatigue endurance, since such factors as material yield stress and applied mean stress will affect results. However, thermal stress relieving will have the greatest effect in the following cases:

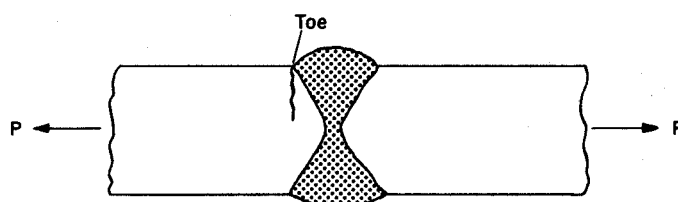
- when the subsequently applied mean stress is low,
 - in the weld Classes having greater fatigue strength, for example B or C,
- and – at the high cycle end of the $S-N$ curve.

4. WELD TYPES

The following sections highlight the main features of various types of welded joints. The types of welded joint for which data are available and provided by Data Items are given in Table 8.1. The relevant Data Item number is indicated in the table together with the corresponding type and class designation according to British Standard BS 5400.

4.1 Transversely Loaded Butt Welds

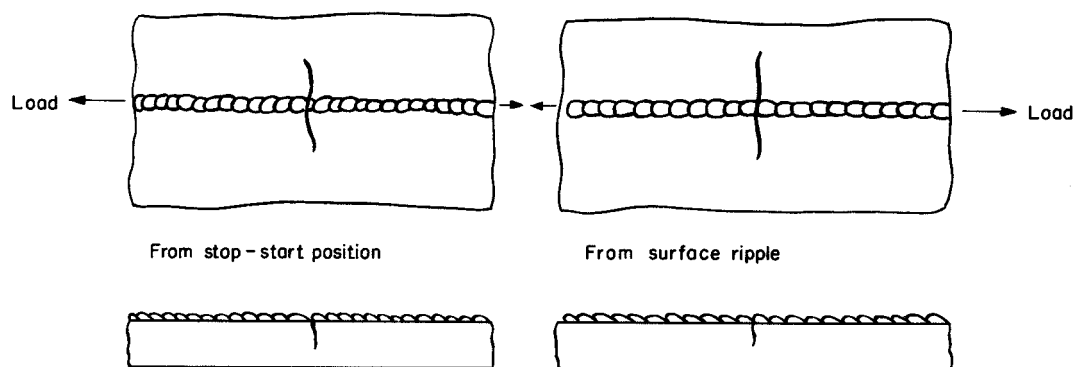
This type of joint consists of a weld normal to the direction of loading. Assuming the weld to be sound and free from significant defects, failure normally initiates from intrusion defects and the stress concentration at the weld toe and propagates through the parent plate in a direction normal to the direction of loading, as shown in Sketch 4.1.



Sketch 4.1

4.2 Longitudinally Loaded Butt Welds

For longitudinally loaded butt welds the change of section caused by the weld overfill profile is parallel to the direction of the applied stress, and therefore the fatigue endurance of these welds is greater and more consistent than is the case for transverse butt welds despite having higher residual stresses. Failure in longitudinal butt welds usually initiates from a stop-start position in manual welding or from a surface ripple on the face of the weld as shown in Sketch 4.2.



Sketch 4.2

The fatigue endurance of longitudinal butt welds is greatly reduced if the welding is made intermittent since the weld ends provide likely crack initiation sites.