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Basis of Fatigue Design for Welded Joints

Principes des règles de calcul des assemblages soudés

Grundlagen der Ermüdungsbemessung geschweisster Verbindungen

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SUMMARY
The paper considers the general form of the S-N curves which should appear in fatigue design rules for welded joints. It is agreed that, for as-welded joints, they should be based on stress range using all available test results from the literature. The curves should be linear on a Log S v. Log N basis, with a slope m = 3, probably with a single band to a shallower (but fictitious) slope at 10 million cycles for cumulative damage calculations. For stress relieved joints the allowable stress range could be increased for partially compressive loading.

RESUME
L'article traite de la forme générale des courbes S-N que l'on doit prendre en considération dans les règles de calcul à la fatigue des assemblages soudés. Il est admis que, pour les assemblages soudés sans traitement ultérieur, les règles doivent être basées sur la différence des contraintes en exploitant tous les résultats d'essais de la littérature. Les courbes doivent être linéaires dans une échelle Log S - Log N avec une pente m = 3, probablement avec un domaine singulier de pente plus faible (mais fictive) au-delà de 10 millions de cycles pour le calcul de dommages cumulés. La différence de contraintes admissible peut être augmentée dans le cas d'assemblages soudés ayant subi un traitement thermique et soumis à des charges partielles de compression.

ZUSAMMENFASSUNG
Der Beitrag behandelt in allgemeiner Form die S-N Kurven, die für die Ermüdungsbemessung geschweisster Verbindungen berücksichtigt werden sollten. Die Bemessungsregeln für Verbindungen ohne Nachbehandlung sollten auf der Spannungsdifferenz fundieren unter Berücksichtigung aller erhältlicher Versuchsresultate aus der Literatur. Die Wöhlerlinie sollte im doppeltlogarithmischen Massstab eine Gerade mit der Neigung m = 3 darstellen. Für Schadenakkumulationsberechnungen kann ab 10 Millionen Lastwechseln eine flachere (fiktive) Neigung angenommen werden. Im Fall von spannungsarm geglühten Schweissverbindungen kann der zulässige Spannungsbereich bei teilweiser Druckbeanspruchung erhöht werden.

1. INTRODUCTION

Fatigue design rules for welded joints have existed in several countries for many years. The majority of them, at least for high cycle fatigue, have tended to relate particularly to bridges, but in the absence of any alternative they have in many cases been used for the design of other types of structure as well. They are therefore of considerable significance.

It so happens that in several countries the fatigue design Standards have been updated comparatively recently, and it is known that others are currently in course of preparation. Also several attempts are now being made on an International basis (e.g. by I.S.O., IIW and ECCS) to produce other fatigue design rules. At first sight one would expect all these rules to be very similar, since the basic data available to the writers of the rules must have been similar, most of it having been published. In fact, however, there are still significant differences between rules prepared in different countries. It is hoped, therefore, that it will prove useful to review some of the variables which should be covered by fatigue design rules.

2. DEFINITION OF BASIC S-N CURVES

As far as welded joints are concerned it is not yet possible to predict, by means of fracture mechanics, the S-N curves for all joint geometries. In theory that is a possibility but in practice it would require knowledge of the stress intensity factor for each type of joint, together with details of the expected pre-existing defects and of the weld shape in the vicinity of those defects. Such information does not, in general, exist. It is therefore inevitable that the basic S-N curves appearing in fatigue design rules must be based on experimental laboratory results, the great majority of which relate to constant amplitude loading.

The first stage in writing fatigue design rules must therefore be the analysis of available experimental data, but it is important only to include relevant data. Thus it is wise to exclude:-

(a) Data obtained a long time ago, since in many cases their accuracy is suspect and in any case welding methods have improved over the years. In the analysis carried out in relation to the British rules [1] any results obtained prior to 1950 were automatically excluded;

(b) Data obtained other than under tensile loading. This restriction relates to the influence of residual stresses and will be considered in more detail later.

On the other hand it has been shown in numerous investigations [2] that the high cycle fatigue strength of welded joints in structural steels is independent of the static strength of the parent material so that results for all such steels can be included.

It is also important to recognize at this stage that fatigue test results inevitably show considerable scatter in life for a given stress, as a result both of variations in overall geometry for a particular type of joint (e.g. attachment size, weld size, etc.) and also because of small variations in weld profile and toe defect geometry. By way of example tests at The Welding Institute on nominally identical non-load-carrying fillet welds made by twenty welders showed a scatter of life of approximately 5:1, while even specimens made by the same welder produced a scatter of about 3.6:1. Clearly, therefore, in order to allow for the variations which will inevitably occur in practice, it is essential to use data from as many sources as possible and not to base design rules on data generated by, for example, a single laboratory.

Most of the data currently available relate to the endurance range 10^5 to 2×10^6 cycles and there now seems to be general agreement that, in that region at least, the curve is a straight line when plotted on the basis of Log S v. Log N. That is also consistent with a fracture mechanics approach [3] assuming that the whole of the life is taken up in crack propagation - i.e. that fatigue cracks develop from small pre-existing defects or 'cracks'. On that basis it is easy to show that the slope, m, of the S-N curve as defined by

$$S^m.N = \text{constant}$$

should be equal to the exponent in the Paris crack propagation equation

$$\frac{da}{dN} = C.(\Delta K)^m$$

In effect this has been confirmed since an analysis of crack propagation data for weldable structural steels [4] has shown that the value of m is typically in the range 2.4 to 3.6 with a mean value of 3.0. Equally an analysis of fatigue test data for welded joints containing high tensile residual stresses and subjected to tensile loading also showed that the average slope was typically about 3.0, at least for the lower strength joints (e.g. joints with longitudinal fillet welds) which are normally critical from the design point of view.

In some instances, notably in Germany, it has been proposed [5] that the slope of S-N curves should be assumed to be considerably flatter with m typically equal to 3.75. Indeed it has been shown that, given a wide enough scatter band increasing in width as stress decreases, several sets of fatigue data can be made to fit such a slope. However in assessing the significance of those results it has to be remembered that S-N curves with shallower than normal slopes can arise for several reasons, among which are the following:-

(a) If the joints are tested in bending (of the plate) rather than axially. In this respect tests on beams are obviously different, and therefore satisfactory, since the stress in the flanges will be essentially axial;

(b) If the mode of failure does not involve cracks originating at pre-existing toe defects, so that it is necessary both to initiate and propagate a crack. This is true of most of the higher strength joints, such as continuous longitudinal welds (e.g. web to flange joints) and joints which have been improved by, for example, dressing the weld toe. Since the initiation period is longer at lower stresses the S-N curve is rotated to a shallower slope;

(c) If the joints have low residual stresses, due either to stress relief or to the fact that the specimens were too small to hold residual stresses. The latter is particularly true of joints with transverse welds and is a very common fault of specimen design. The whole problem of residual stresses is considered in more detail below.

In most structures the stresses are essentially axial, the design is not governed by joints with high fatigue strength and the joints are likely to contain high residual stresses. Consequently one would not expect S-N curves with shallow slopes to be relevant.

For ease of computation there is some benefit both in having m as an integer value and in having as many S-N curves as possible parallel to each other. Thus, in the light of all these considerations it would seem realistic to base the analysis of the experimental data, at least for all joints failing from the weld toe, on an assumed straight line relationship between Log S and Log N with a slope m = 3.0.

3. INFLUENCE OF RESIDUAL STRESSES

It has been noted above that the slope of the S-N curve can be considerably influenced by the presence of residual stresses, and they also influence the choice of stress parameter to be used in design rules.

The majority of welded structures are not stress relieved so that, in them at least, it is realistic to assume that high tensile residual stresses of yield stress magnitude will exist in some places. In general the only sensible assumption which can be made is that such stresses may exist at any point where a fatigue crack could initiate. In simplified terms, assuming the residual stress to be equal to yield stress tension, the actual stress cycle to which the material adjacent to the weld will be subjected under applied cyclic loading will vary from yield stress tension downwards, regardless of the nominal stress cycle. For example, if the nominal stress cycle is $+\sigma_1$ to $-\sigma_2$, giving a total range equal to $(\sigma_1 + \sigma_2)$, the actual stress cycle will vary from $+\sigma_y$ to $\{\sigma_y - (\sigma_1 + \sigma_2)\}$. In other words the fatigue behaviour of a welded joint in a real structure can be expressed in terms of stress range alone, and there is no need to consider the stress ratio $R(= S_{min}/S_{max})$.

It can therefore be argued that cycles which are (nominally) partially or even wholly compressive should be just as damaging as cycles which are fully tensile. To some extent this has been confirmed experimentally. For example Fig. 1 shows some results for specimens with longitudinal non-load-carrying fillet welds tested at R = 0 under compressive loading. All the results lie within the scatter band for tensile loading although within the upper half of it. For comparison some specimens of the same batch were also tested under tensile loading and the results are also shown in Fig. 1; clearly they can be considered as identical to the earlier tensile test results. These, and other similar, data tend to confirm the validity of basing design stresses on stress range alone. However, recent results obtained under compression-to-compression loading suggest that this approach may be unduly conservative for that situation, but further check tests are required before a final conclusion can be reached.

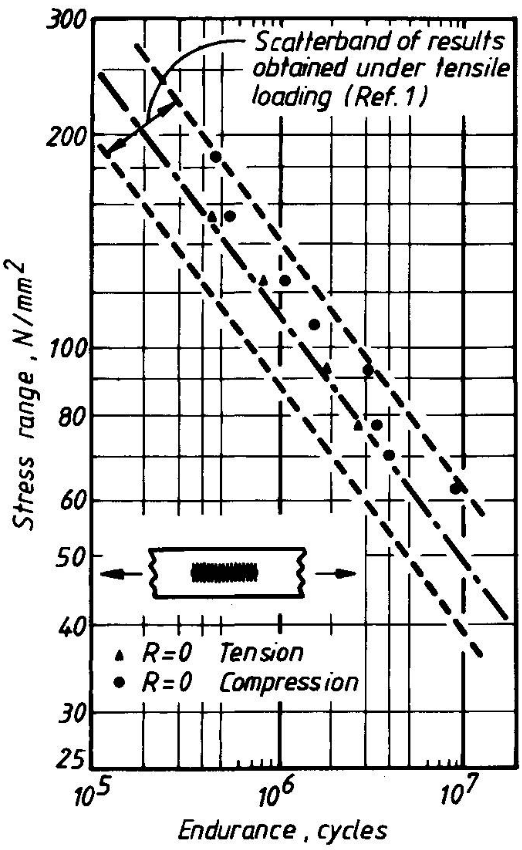

Fig. 1 Comparison of test results for tensile and compressive loading

In contrast to welded structures many welded specimens do not contain high tensile residual stresses because they are too small to provide the necessary restraint; typically such specimens are usually only about 100-150mm wide x 12mm thick, or even less. It is for this reason that it was suggested previously that only results obtained under tensile loading should be used in deriving design rules.

Nevertheless it is reasonable to assume that, in the as-welded condition, specimens with the welds parallel to the loading direction ('longitudinal' welds) are likely to contain high residual stresses, since the heated width during welding will be localized so that residual stresses are able to form. In contrast, with transverse welds a relatively large proportion of the cross section will be heated at one time which will tend to inhibit the formation of residual stresses.

The difference between these two situations has been investigated by carrying out tests under pulsating tension (R = O) loading on specimens with longitudinal non-load-carrying fillet welds, one series being stress relieved (and thereby simulating the situation existing in small specimens with transverse welds) and one being as-welded. These results are shown in Fig. 2, from which it is clear that the as-welded specimens gave the steeper S-N curve, although the difference in fatigue strength is quite small. This is due to the as-welded specimens cycling at a higher mean strain than the stress relieved specimens when both are subjected to the same nominal stress range.

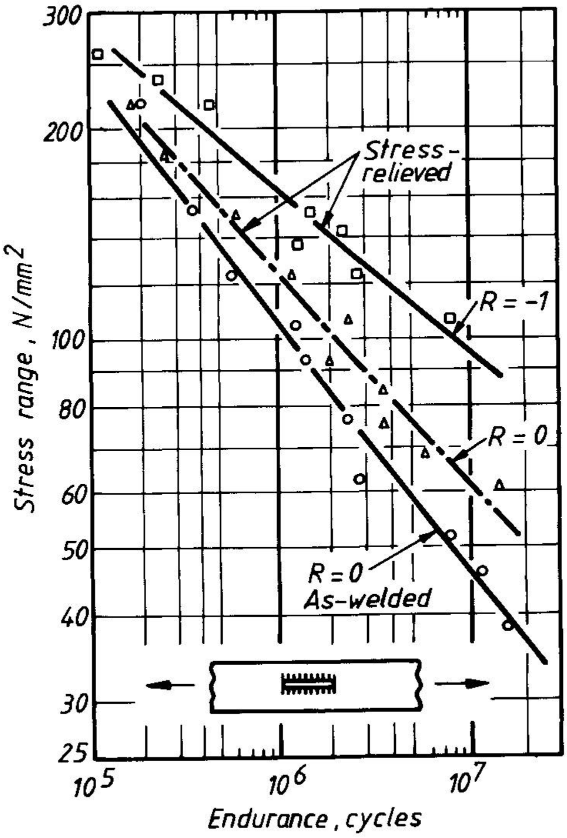

Fig. 2 Influence of stress ratio and stress relief on fatigue strength

Figure 2 also shows some results for stress relieved specimens tested at R = -1. Clearly these show a large increase in stress range and tend to confirm that if a joint contains low residual stresses and is subjected to partly compressive loading fatigue strength is increased. Thus it is obviously unsafe to use such results to define design rules for more severe conditions (i.e. for tensile loading and high residual stresses).

It may therefore be concluded that S-N curves for as-welded joints should be based on stress range and be independent of stress ratio, although there may well be a case for increasing design stresses for joints subjected only to compression-to-compression loading. For stress relieved joints it would certainly be safe to increase the design stress range for joints subjected to partially compressive loading. In this context it has been proposed that the revised British rules for the design of offshore structures should specify that such joints may be designed for a stress range equal to the tensile component of stress plus only sixty per cent of the compressive component.

4. THE S-N CURVE AT SHORT AND LONG ENDURANCES

Given that it is realistic to assume that the S-N curve is linear in the intermediate life region, there is still a need to define its form for design purposes in the low and high life regions.

As far as the short life situation is concerned there is no real problem, since it is known that the Log S v. Log N line can certainly be extrapolated up to a stress at least equal to yield. However it is also true that a design will normally be limited to an upper limit stress which is less than yield stress. Hence in the low life region it seems reasonable merely to extrapolate the design S-N curves back to yield stress.

In the high life region the situation is more complicated. If tests are carried out under constant amplitude loading a fatigue limit will ultimately be found below which failures do not occur. There is some evidence that this limit will occur at different lives for different classes of joint; in effect the lower the joint class the longer the life and the lower the fatigue limit stress. However, for simplicity of design, there is some benefit in defining that the fatigue limit will correspond to a particular life regardless of class. In the British rules 10^7 cycles was the selected life, based on a fracture mechanics analysis, but there are theoretical indications that this may be too short for some types of joint, particularly those in thick plates.

However in most instances the position of the constant amplitude fatigue limit is irrelevant since, in service, a joint will usually be subjected to a stress spectrum with some stresses above, and some below, the fatigue limit. In this situation a conventional cumulative damage calculation by, for example, Miner's rule is fallacious because, if applied literally, the stresses below the fatigue limit will be assumed to do no damage. In fact the higher stresses in the spectrum will propagate a crack and as the crack grows the lower stresses will progressively become effective in helping it to grow.

This problem has been investigated by fracture mechanics and it has been shown, for a wide variety of stress spectra, that a reasonable design solution is to lower the 'cut-off' to the stress corresponding to 2×10^7 [6]. An alternative solution, originally proposed by Haibach, which was subsequently adopted in the new British design rules, is to introduce a fictitious bend in the S-N curve to a shallower slope (m = 5). The advantage of the latter approach is that it avoids the anomaly which can occur when using the Miner summation method in conjunction with an S-N curve with a sharp cut-off. That produces a step change in the value of $\Sigma \frac{n}{N}$ depending on whether a particular stress level is just above or just below the cut-off stress.

It will be seen, therefore, that in design rules it is really necessary to have two 'cut-off' stresses (see Fig. 3), one corresponding to the constant amplitude fatigue limit (say 10^7 cycles) and one being relevant to cumulative damage calculations. The former may be applicable both under constant amplitude loading or if the expected number of cycles is very large, in which case it may be necessary to keep all stress ranges below the limit. The latter may either consist of a fictitious cut-off at (say) 2×10^7 cycles, which has the merit of simplicity but can lead to difficulties of interpretation for stresses close to the cut-off stress, or may take the form of a bent S-N curve; this avoids problems of interpretation but is more difficult to justify theoretically. Nevertheless for design purposes it is probably the better solution.

An interesting implication of this approach is that, except for very special applications or purely for research purposes,

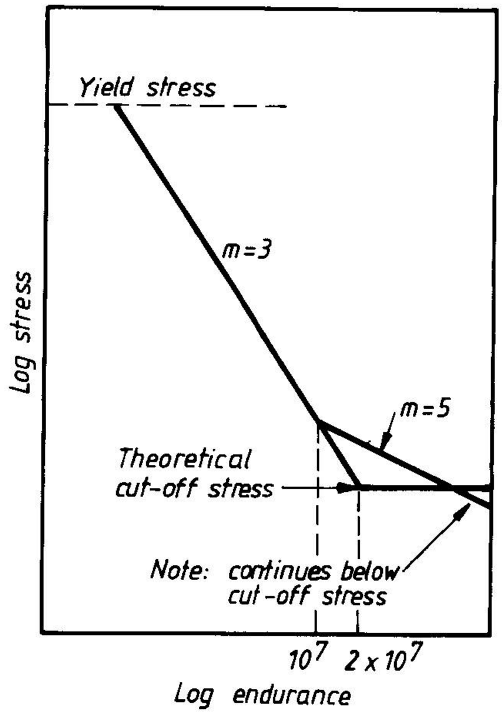

Fig. 3 Possible forms of S-N curve at long life

there is no point in continuing fatigue tests to long lives. As far as defining the design stress for a particular joint type is concerned all that is required is the S-N curve in the intermediate life (10^5 - 2×10^6 cycles) region. This can greatly reduce the cost of fatigue testing since testing machines are expensive. Looked at from a different angle, supposing that one does carry out tests to longer lives and obtains some unbroken specimens, what can one do with those results; surely they are more or less useless.

5. JOINT CLASSIFICATION

Having defined the general form of the S-N curves the main problem which remains is to fix their positions for each type of joint. As far as is known, in all the Standards produced to date, the curves have been arranged to fit the test results usually by amalgamating several types of joint into a simple 'class' and allocating a curve to the class. Recently it has been proposed that the process should be reversed and that there should be a standard set of parallel S-N curves, arranged in approximately geometrical progression of stress. The joint classification would then consist of fitting the test results to the set of curves and selecting the one which seemed most appropriate.

This certainly seems to be the better procedure, provided that the gradation of curves is reasonable. If one were to assume a spacing between curves of about ten per cent, and a need to cover a range of fatigue strengths from about 40 to 200 N/mm^2 at 2×10^6 cycles, approximately fifteen curves would be needed. This is more than in most National Standards at the moment, but having a fine gradation considerably eases the problem of compromise between different Standards by reducing the severity of the changes that may be necessary.

An important point which arises, however, is to decide whether the curves represent the mean of the data or the design stress and, if the latter, what 'factor of safety' should be introduced. This is complicated by the fact that some joints give far more scatter than others. For example Fig. 4 shows a comparison between the scatter bands (mean ± 2 standard deviations) for transverse and longitudinal non-load-carrying fillet welds [1]. It will be seen that although the mean strength of the longitudinal welds is lower than that of the transverse, the lower limit stresses are reversed in order because of the lower scatter of the longitudinal welds. In view of this problem it is believed that the curves in a design standard should be the design curves and not the mean curves, and that they should be assumed to represent the mean - two standard deviations stress. That should be suitable for most types of structure.

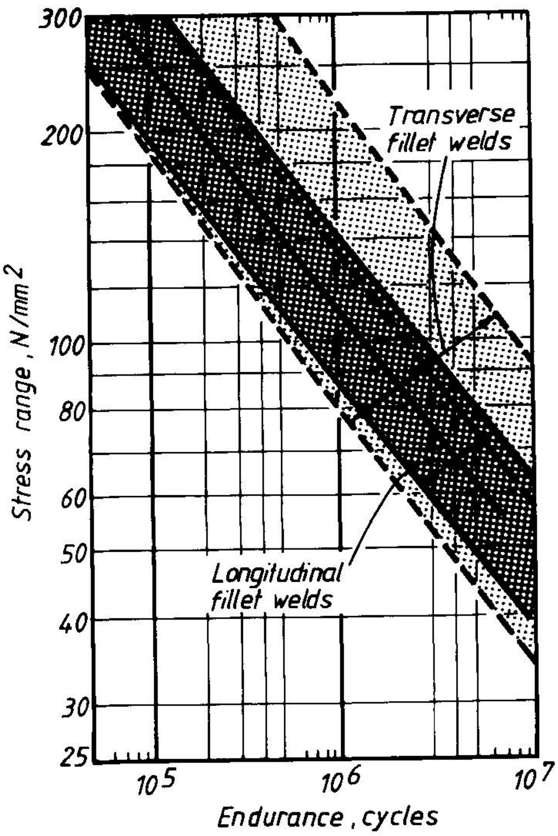

Fig. 4 Comparison of scatter for two types of fillet welded joint

6. CONCLUDING REMARKS

In summary, therefore, the following suggestions can be made regarding the form of fatigue design rules for welded joints:-

(1) For as-welded joints the design stresses should be based on stress range, regardless of stress ratio. For joints subjected to fully compressive loading there may be a case to relax that requirement but further research is still required on that problem. For stress relieved joints an increase in stress range can be permitted if the stress cycle is partly compressive; it is suggested that this would involve only taking into account sixty per cent of the compressive half cycle.

(2) It is important to base design stresses on as wide a range of available results as possible and not to base them on results obtained in a single laboratory or even a single country if that can be avoided.

(3) To simplify the designer's work and to ensure consistency with the fracture mechanics approach it seems reasonable to make all S-N curves (at least those for joints involving failure from the weld toe) parallel with a slope $m = 3.0$.

(4) Although it can be shown by fracture mechanics methods that reasonable design stresses are produced, for variable amplitude loading situations, by introducing a 'fatigue limit' at 2×10^7 cycles, it is probably more practical to bend the curve to a shallower slope (see Fig. 3). This avoids difficulties of interpretation for stresses in the region of the 'fatigue limit'.

However, regardless of the fact that fatigue design rules must inevitably cover several different aspects of the problem, there is no doubt that the most important part is the joint classification system and the associated S-N curves. In effect this represents an enforced educational exercise for the designer because it will inevitably tend to encourage him to avoid using joints with high stress concentrations and low fatigue strengths. By that means alone designs can be greatly improved. In other words good fatigue design must start with GOOD DETAILS.

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