Estimating the fatigue behaviour of welded joints

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Abstract

The present work is concerned with an attempt to predict the fatigue strength of welded joints by means of a fracture mechanics approach that takes into account the fatigue behaviour of short cracks. The methodology estimates the fatigue crack propagation rate as a function of the difference between the applied driving force and the material threshold for crack propagation, a function of crack length.

The fatigue strength of butt-welded specimens stressed transversely was analyzed. Experimental results from the literature were used for comparisons. Good estimations are obtained by using only the fatigue limit and the fatigue propagation threshold for long cracks corresponding to the base metal, and the applied stress distribution along the crack path obtained from simple FE models. The influence of plate thickness, initial crack length and reinforcement angle on fatigue strength of butt-welded joints was analyzed and results show good agreement with experimental trends.

In order to verify the ability of the methodology to estimate the fatigue behaviour of welded joints, a dedicated experimental methodology have to be implemented for the detection and monitoring of the development of surface small cracks initiated at weld toes. Some initial results of a multi-strain gauges technique implemented for those purposes are also shown.

1. Introduction

To ensure that the full effect of the three key features dominating the fatigue life of welded joints (geometric stress concentrations, welding flaws and residual stresses) is allowed for in design, most fatigue design rules consist of series of $\Delta\sigma$-N curves based on data obtained from constant amplitude fatigue test on actual weldments [1-3], in which use is usually made of the commonly used classification method of specifying design curves in terms of the fatigue strength at a given number of cycles (e.g. $2x10^6$ or 10^7). Since the stress concentration effect of the welded joint geometry is included, $\Delta\sigma$ refers to the nominal stress adjacent to the weld detail.

If the fatigue life of the welded joint consists mainly of crack growth, the $\Delta\sigma$-N curve can be calculated by integrating a fatigue crack growth law and the resulting

$\Delta\sigma$-N curve for a given stress ratio *R* (minimum to maximum applied stress), is predicted to be:

$$\Delta\sigma^m N = A \quad (1)$$

where *m*, *A* and *C* are environmentally sensitive material-constants obtained from long crack fatigue behavior and *N* is the total cycle number to failure (fatigue life). According to this expression, the $\Delta\sigma$-N curve is linear on a log-log basis with a slope *m* equal to that of the Paris law. As a consequence of this, most design $\Delta\sigma$ -N curves for welded joints are taken to be parallel with a slope compatible with the fatigue crack law for the material. Since *m* is approximately 3 for most materials, $\Delta\sigma$-N curves with slops of 3 are widely adopted.

However, the above approach disregards the existence of a threshold for crack propagation and that short cracks usually show lower threshold levels and higher propagation rates than long cracks, when considering the same applied driving force (ΔK). The short crack effect can be observed till a crack length in the range 0.2-1 mm for structural steels [4-6]. Previous works on fatigue of welded joints have observed initial crack-like defect depth of about 10-120 μm [7], 20-150 μm [8] or 10-400 μm [9], according to the welding conditions and applied quality control. Radaj and Sonsino have recommended initial crack size a_i = 0.1-0.25 mm in welded structures for life predictions [10]. These defect depths clearly fall on the short crack regime.

The present work is concerned with an attempt to predict the fatigue strength of welded joints by means of a fracture mechanics approach that disregards the fatigue crack initiation life and includes the fatigue crack propagation threshold for both short and long cracks. The methodology [11], previously developed to analyse the short crack behaviour, estimates the threshold for fatigue crack propagation as a function of crack length, ΔK_{th}, and the fatigue crack propagation rate as the difference between the applied driving force, ΔK, and ΔK_{th}, as follow:

$$\frac{da}{dN} = C\left(\Delta K^m - \Delta K_{th}{}^m\right) \quad (2)$$

In expression (2) the threshold for crack propagation is a function of crack length. Details of the fracture mechanics approach can be found in reference [11], where a model to estimate the threshold for fatigue crack propagation can be found.

2. Estimation of the fatigue strength of butt-welded joints

Experimental results of fatigue strength of butt welds obtained by Taylor et al [12] were used for comparison. In Taylor’s work simple butt welds with 12.5 mm thickness were made using conventional manual metal arc welding, and tested in four-point bending. The material used was a low-carbon steel En2b (0.2 wt% C, 0.8 wt% Mn, yield strength 309 MPa). All specimens were fully stress-relieved at 600^{o}C immediately before testing, and fatigue tests were carried out at a frequency of 50

Hz and R = 0.1. Experimental results for the influence of the reinforcement angle on fatigue strength of butt-welds from reference [1] were also used.

2.1. Estimation of the applied driving force

The applied driving force, ΔK, was estimated by using the following solution based on the weight function method for a through thickness crack in a finite plate [13]:

$$\Delta K = \frac{2}{\sqrt{\pi}} \int_0^a \left\{ \frac{\Delta\sigma_{yy}(x)}{\sqrt{a}} \left[\frac{3.52\left(1-\frac{x}{a}\right)}{\left(1-\frac{a}{t}\right)^{3/2}} - \frac{\left(4.35-5.28\frac{x}{a}\right)}{\left(1-\frac{a}{t}\right)^{1/2}} + \left(\frac{1.3-0.3\left(\frac{x}{a}\right)^{3/2}}{\sqrt{1-\left(\frac{x}{a}\right)^2}} + 0.83 - 1.76\frac{x}{a} \right) \left(1-\left(1-\frac{x}{a}\right)\frac{a}{t}\right) \right] \right\} dx \quad (3)$$

Where t is the plate thickness and $\sigma_{yy}(x)$ is the non-uniform stress field calculated along the notch bisector, without considering the presence of the crack. $\sigma_{yy}(x)$ was estimated using finite element models constructed by using LUSAS and FINAS softwares. Eight-node quadratic elements were used in a static, elastic analysis.

2.2. Estimation of the fatigue crack propagation threshold

As a first approximation the fatigue threshold for crack propagation is estimated by using the material properties of the base plate. In this work the fatigue properties determined experimentally for a C-Mn steel and shown in Table 1 are used and supposed to be similar to those of the C-Mn steel used by Taylor in his joints.

C-Mn Steel						
0.11 wt% C, 0.38 wt% Mn, 0.2 wt% Si, 0.013 wt% P, 0.018 wt% S						
σ_{ys} [MPa]	σ_u [MPa]	d [mm]	$\Delta\sigma_{e\ R=0.1}$ [MPa]	ΔK_{thR} [MPa $m^{1/2}$]	C [mm/cycle]	m
286	472	0.028	360	7.6 - 5.7 R	$1.526\ 10^{-9}$	3.15

Table 1.Chemical composition and mechanical properties used for the models.

2.3. Estimation of fatigue strengths

The fatigue crack propagation life is estimated integrating expression (5) between a given crack length range. The initial crack length a_i is defined by the greater defect present at the weld toe. Failure was assumed to occur at a crack depth, a_c, defined as half the plate thickness. If the initiation period is disregarded, the procedure outlined above results in total fatigue lives.

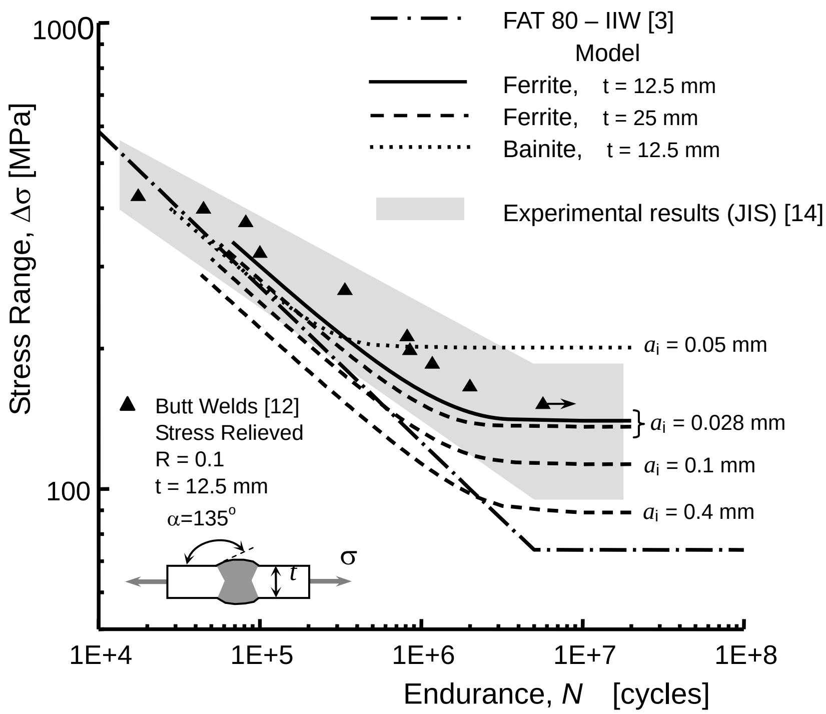

Fig. 1 *Fatigue lives for butt-welds.*

Figure 1 shows the experimental results from reference [12], some estimated $\Delta\sigma$-N curves, IIW design curve for similar weld joints with the worst quality (FAT 80) [3], and a region where experimental results are usually observed for the same type of joint [14]. Among the estimated results is the $\Delta\sigma$-N curve for the base material (ferrite-perlite microstructure, see Table 1), t = 12.5 mm, and $a_i = d$ = 0.028 mm (average grain size). Good agreement can be observed with the experimental results obtained by Taylor [12]. Estimated values are below experimentally ones for any fatigue life. Dashed lines correspond to a $\Delta\sigma$-N curve estimated for t = 25 mm, and different initial crack lengths: a_i = 0.028 mm, 0.1 mm and 0.4 mm. Finally, the dotted line corresponds to a $\Delta\sigma$-N curve estimated using the material parameters of a bainite-martensite microstructure: $\Delta\sigma_{e0.1}$ = 520 MPa, $\Delta K_{th0.1}$ = 9 MP $m^{1/2}$ and d = 0.05 mm. Because toe cracks usually nucleates at heat affected zones, where the microstructure have higher fatigue properties, this curve can be considered as an estimation of the upper limit of the possible results for the analysed joint. A small thickness was chosen with that purpose. On the other hand, the dashed $\Delta\sigma$-N curve estimated with the base material properties, t = 25 mm and a_i = 0.4 mm can be considered as a lower limit. It can be seen that both limit includes the total region within experimental results are usually observed. The lower limit is also very close to the IIW design curve, which represents the lower limit for experimental fatigue live data observed for a given type of joint.

3. Influence of plate thickness in butt-welds

It was well established, both theoretically and experimentally, that fatigue strength of welded joints decreases with increasing plate thickness. Traditionally the thickness effect has been used so that the fatigue strength is reduced after a certain thickness limit upward, usually 25 mm, according to the following expression:

$$\Delta\sigma_t = \Delta\sigma_{t0}\left(\frac{t_0}{t}\right)^n \tag{4}$$

Where $\Delta\sigma_t$ is the fatigue strength for a thickness *t*, $\Delta\sigma_{t0}$ is the fatigue strength for the reference thickness, t_0, and *n* is based on test results. IIW-recommendation [3] suggests t_0 = 25 mm and n = 0.25.

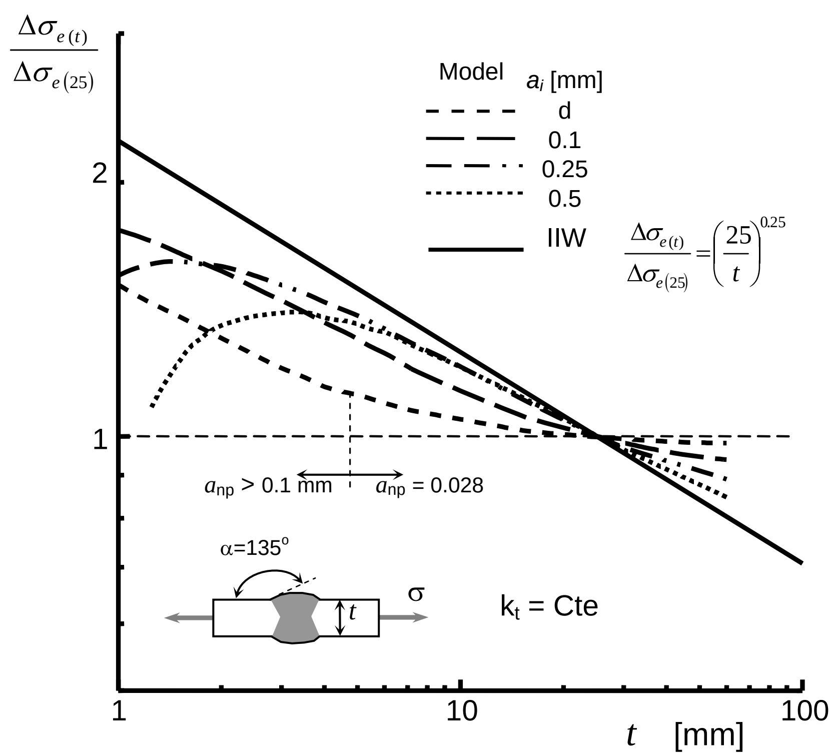

Fig. 2. *Influence of plate thickness on fatigue strength of butt-welds.*

Fig. 2 shows estimated results of the fatigue strength defined at 10^7 cycles as a function of the plate thickness for different initial crack lengths. Correction recommended by IIW for butt joint is also shown, extrapolated to thickness smaller than 25 mm. Even though the results show the same general trend in both figures, that is to say the fatigue limit decreases with thickness as it is usually observed, results shows notable differences in the influence of the initial crack length on fatigue limit of thin plates (t < 10 mm). Fig.2 also shows that an opposite trend could be found for thin plates (t < 6 mm) in the relation between fatigue limit and thickness when initial crack length are longer than about 0.3 mm. This opposite effect was recently observed experimentally by, for instance, Gustafsson [15] for non-load carrying attachments with 3 and 6 mm plate thickness.

For initial crack length smaller than 0.1, as the case of a_i = 0.028 mm, a smaller exponent appear from a given thickness (about 6 mm for Fig. 2). This is attributed to the fact that the influence of the stress gradient on fatigue limit decreases as the crack length that defines that fatigue limit decreases. The relative position between the applied driving force distribution and the material crack propagation threshold curve seems to define a thickness range below which the fatigue limit is given by a non-propagating crack. An initial crack length smaller than 0.1 mm is rear in the case of welded joints, so that this case could be difficult to be actually observed. However, this effect can be also observed for initial crack length as long as 0.1 mm, as it can be seen in Fig. 2.

4. Influence of reinforcement angle in butt-welds

Gurney [1] have point out that the range of values of the fatigue strength of butt welds varied widely, from 100 MPa to 180 MPa for the fatigue strength at $2x10^6$ cycles for R values close to zero.

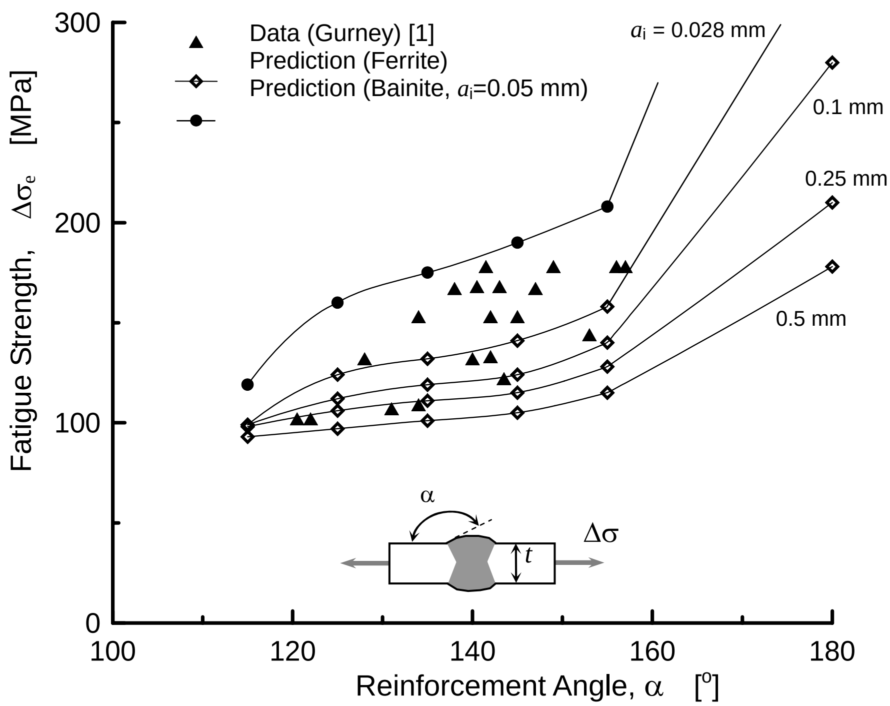

Fig. 3. *Influence of reinforcement angle in fatigue strength of butt-welds.*

Fig. 3 shows the well known experimental results presented by Gurson, together with results of the estimated fatigue limit as a function of the reinforcement angle for different initial crack length. It is worth noting that the model can explain not only the experimental trend, but also the reduction in the scatter observed as the reinforcement angle decreases. This effect is due to the fact that as the reinforcement angle decreases, the stress gradient near the weld toe increases and from a given value non-propagating cracks defines the fatigue limit. Those non-propagating crack are in the range of 0.1-0.2 mm, so that the fatigue limit would be similar for the cases of a_i = 0.028, 0.1 mm and 0.2, as can be observed for α = 115^o. Fig. 3 also shows results obtained with the material data corresponding to a bainite-martensite microstructure and an initial crack length a_i = 0.05 mm. It can be observed that estimated value falls near the upper limit of experimental results.

5. Experimental methodology for the detection and monitoring of surface small cracks

In order to verify the ability of the methodology to estimate the fatigue behavior of welded joints, a dedicated experimental methodology have to be implemented for the detection and monitoring of the development of surface small cracks initiated at weld toes. A multiple strain gauge technique was implemented for this purpose. Details of this technique and experimental setup can be found elsewhere [16,17].

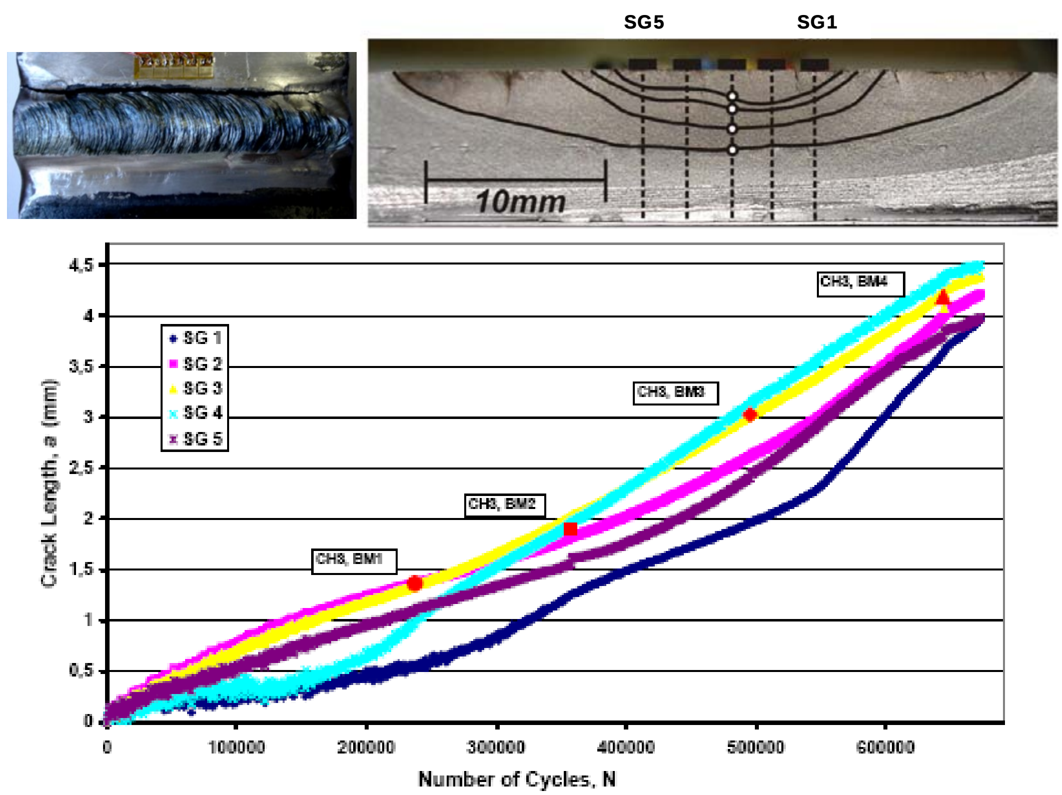

Fig. 4. *Fatigue crack length for each strain gauge position. In the upper-left position a photograph shows the analyzed fatigued welded specimen and details of the attached strain gauges. On the right, a pothograph shows the fracture surface and indications of five ink-marked fatigue crack positions.*

The strain gauge monitoring system, implemented with five gauges, gave very reasonable predictions of crack sizes and shapes, and allowed to detect and monitor the surface crack growth from a depth of about 0.1-0.2 mm. Then, the fatigue crack propagation rate can be measured in a given configuration and therefore estimations obtained form the approach for a given joint configuration can be contrasted.

Fig. 4 shows the measured fatigue crack length for each of the five strain gauge position. In the upper-left position a photograph shows the analyzed fatigued welded specimen and details of the attached strain gauges. On the right, a photograph shows the fracture surface and indications of five ink-marked fatigue crack positions. Very good agreement could be found between the crack depth and shape given by the five ink-marks and the indications of the implemented technique

6. Concluding remarks

Modern technology has improved the quality of welded joints and maximum initial crack-like defect lengths of about 0.1 mm can be obtained. However, much effort should be done in order to analyse the influence of short crack effect in the definition of fatigue strength. The influence of short crack effect depends on the applied stress ratio and only can be neglected when the transition from short to long crack regime become similar to the initial crack length. It is necessary to keep in mind when estimating fatigue strength that the smaller the initial crack length is, the greater the over-prediction of fatigue strength will be if the short crack effect is not taken into account.

Besides, even though more detailed experimental results should be obtained and extensive parametric studies should be carried out in order to reach important conclusions about the influence of the geometrical, microstructural and mechanical parameters involved in the definition of the fatigue behaviour of welded joint, the analysis showed that the present model could be able to describe most of their interactions and to provide a powerful tool to estimate the fatigue strength of different weld configurations.

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