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Fatigue life assessment of welded joints by the equivalent crack length method

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Abstract

The fatigue life of welded structures is often dominated by crack initiation and growth from the weld toes, where the notch or an initial crack like flaw determines the fatigue endurance of the structure. In the present paper, the equivalent crack length method is proposed for predicting the crack propagation life of a welded joint from this initial flaw of length $a_0$ to a final crack at fracture $l_c$. The geometrical configuration of a welded structure with stress concentration is assumed approximately equivalent to an initial crack in an unwelded plate. The equivalent crack length $a_0$ depends on the joint geometry and is determined from a single experimental data point under the low cycle fatigue region, where most of the fatigue life is spent on crack propagation and the crack initiation cycle can be ignored. Once a Paris law type equation is determined by the single experimental data point, the fatigue life of the same type welded joint can be calculated for other applied stress ranges. The critical crack propagation length $l_c$ for final fracture depends on the applied stress level in terms of $\Delta K_{ic}$; with higher stress levels the crack propagation length may be very short, whereas with very low stress levels the maximum propagation length is longer but it is limited for unstable fatigue crack growth. In this way, the final crack length is related to the critical stress intensity factor $\Delta K_{ic}$. The method gives conservative results in the high cycle fatigue region as only the fatigue crack propagation phase is taken into account in the fatigue life calculation. The proposed approach has been successfully applied to experimental data. The extension of the proposed method for fatigue under variable amplitude loading will be also discussed.

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Keywords: Fatigue life; welded joints; crack propagation; equivalent crack length

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1. Introduction

The fatigue strength of welded joints is typically determined by fatigue crack initiation and propagation from points of high stress concentration, such as the weld toes. These local stress concentrations are due to welding defects, such as lack of penetration and undercuts, localized stress peaks due to uneven toe shapes and welding residual stresses created during the welding process. Thus, the configuration of a welded joint includes many influential factors from the viewpoint of fatigue. Consideration of all these factors separately may give the reliable information for fatigue design but requires a lot of experimental work. In addition, this kind of an approach cannot be applied flexibly to other cases than the studied one. In this paper, the equivalent crack length method is proposed to predict the fatigue life of welded joints by a simple method based on single fatigue test.

In the low cycle fatigue (LCF) region, the crack initiation phase is typically short compared to the crack propagation phase. In the high cycle fatigue (HCF) regime, however, the number of cycles required to initiate a crack increases. Therefore calculating only the fatigue crack propagation life should give reasonably accurate results for LCF and conservative results for HCF, if the initiation life is not critically decreased e.g. due to stress concentrations. Linear elastic fracture mechanics and the Paris law are used for predicting the fatigue crack propagation life. The Paris law states that there is an exponential relationship between the stress intensity factor range $\Delta K$ and the crack growth rate $da/dN$ for a stress ratio $R = \sigma_{min}/\sigma_{max} = 0$:

$$\frac{da}{dN} = C \Delta K^m,$$

where $C$ is the Paris law constant, $m$ is the Paris law exponent and $\Delta K$ is given by the relationship

$$\Delta K = F(a)\Delta \sigma \sqrt{a}.$$

In Eq. (2) $a$ is the crack length, $\Delta \sigma$ is the applied stress range and $F$ represents all geometrical correction factors needed for taking into account the effects of joint geometry and dimensions as well as the crack shape and size, as these influence the applied stress distribution at the crack path.

Determining $F$ is often difficult, especially for complicated structures such as welded joints, where also the local weld geometry need to be taken into account. In the International Institute of Welding (IIW) recommendations by Hobbacher (2009) the applied loading is first divided into membrane and bending stresses as the applied stress distribution has an effect on the geometrical correction factors $F$. The correction factor $F$ is then divided into correction for joint geometry and dimensions $M_k$, and crack shape and size $Y$. Hobbacher (2009) gives approximate equations for $M_k$ and $Y$ for a few simple joint geometries as well as a list of references with other correction factors.

The aim of this paper is to propose a simple method to evaluate the fatigue life of various types of welded joints. It is assumed that an initial flaw of size $a_0$ in a single unwelded plate is approximately equivalent to an initial flaw or stress concentration effect in a welded structure. In this way, the geometrical effects of the function $F$ can be included in a single equivalent crack with length $a_0$. This is shown schematically in Figure 1. A single experimental data point is used to determine the value of $a_0$ for the joint geometry in question. With this information, the S-N curve can be estimated. In this paper, the proposed approach is applied to four experimental data sets.

![Schematic view of notches or initial flaws at the weld toes of some typical welded joints that are approximately equivalent to an initial crack in an unwelded plate.](image)

Fig. 1. Schematic view of notches or initial flaws at the weld toes of some typical welded joints that are approximately equivalent to an initial crack in an unwelded plate.
2. The equivalent crack

The equivalent crack is defined by a crack which reflects the effect of the geometrical factor $F$ and the length of a real crack $a$ after crack initiation at weld toe. Thus, the crack with length $a_0$ is an initial imaginary crack in an unwelded structure including $F$ and $a$, and the value of $a_0$ depends on the weld joint geometry and dimensions. The stress intensity factor range $\Delta K$ is then given by

$$\Delta K = F \Delta \sigma \sqrt{\pi a} = \Delta \sigma \sqrt{\pi a^*}, \quad (3)$$

where $a^*$ is the crack length with values between the initial equivalent crack length $a_0$ and the critical crack length $l_c = a_0 + l$. $l$ is the crack propagation length. The crack propagation life for constant amplitude loading can now be calculated by integration from Eqs. (1) and (2).

$$N_f = \left[ \left( \frac{1}{C} \int_{a_0}^{a_{0/f}} \left( \frac{1}{\Delta \sigma \sqrt{\pi a^*}} \right)^{2-m} da^* \right)^{2-2m} \right]$$

$$= \left[ \frac{1}{C} \left( \frac{1}{\Delta \sigma \sqrt{\pi a^*}} \right)^{2-m} \right]^{2-2m} \left[ \frac{1}{(a_0 + l)^{2-m}} - \frac{1}{a_{0}^{2-m}} \right] \quad (4)$$

In Eq. (4), the crack propagation length has to be positive, $l \geq 0$, and the critical crack length $l_c$ has to be smaller than the plate thickness $t$, i.e. $(a_0 + l) < t$. The calculated fatigue life $N_f$ in Eq. (4) is a function of the Paris law constant $C$ and exponent $m$, the equivalent crack length $a_0$, the crack propagation length $l$, and the applied stress range $\Delta \sigma: N_f = N_f(C, m, \Delta \sigma, a_0, l)$. Values for $C$ and $m$ depend on the material and can be found in literature. $a_0$ and $l$ are calculated based on a single experimental data point, where the values of $N_{f, \text{ref}}$ and $\Delta \sigma_{\text{ref}}$ are known, and the critical crack length defined by the critical stress intensity factor $\Delta K_{fc}$ and limited by the plate thickness.

The Paris law is limited by the critical stress intensity factor, here denoted $\Delta K_{fc}$, and the threshold stress intensity factor $\Delta K_{th}$. $\Delta K_{th}$ gives a lower limit below which no crack growth is assumed. This is actually not correct as below this limit there is the short crack growth region, where the crack propagation does not follow Paris law. However, for conservativeness, it can be assumed, that no crack growth takes place below this limit, which is here defined by the threshold stress $\Delta \sigma_{th}$ and the initial crack length $a_0$

$$\Delta K_{th} = \Delta \sigma_{th} \sqrt{\pi a_0} . \quad (5)$$
\( \Delta K_{fc} \) on the other hand gives the upper boundary for stable crack growth. The maximum crack length for unstable crack growth is given by the critical crack length \( l_c = a_0 + l < t \), where \( l \) depends on the applied stress level \( \Delta \sigma \) and is limited by the plate thickness \( t \).

\[
\Delta K_{fc} = \Delta \sigma \sqrt{\pi (a_0 + l)}
\]  \hfill (6)

The Paris law region is shown in Figure 2(b), where the linear part is limited by the threshold and critical stress intensity factor ranges. Figure 2 illustrates also the effect of different applied stress ranges. With low applied stress ranges \( \Delta \sigma_3 \) close to the threshold value, the crack growth rate is initially lower and fatigue life longer than with higher applied stress ranges \( \Delta \sigma_2 \) and \( \Delta \sigma_1 \). As \( \Delta K_{fc} \) is constant, higher applied stress ranges lead to shorter crack propagation lengths \( l \) and lower applied stress ranges lead to longer crack propagation lengths. The crack propagation length for different applied stress levels can be determined from Eq. (6) when \( a_0 \) is known

\[
l = \left[ \left( \frac{\Delta \sigma_{th}}{\Delta \sigma} \right)^2 - 1 \right] a_0 + \left( \frac{\Delta \sigma_{th}}{\Delta \sigma} \right)^2 l_{th}. \]  \hfill (7)

Once the equivalent crack length \( a_0 \) has been determined, the S-N curve can be calculated using Eqs. (4) and (7). Finally, the threshold stress range \( \Delta \sigma_{th} \) can be estimated from Eq. (5) when \( \Delta K_{th} \) is known. For more precise fatigue life estimation, the effect of \( \Delta K_{th} \) on crack growth rate near the threshold can be introduced through Eq. (4).

3. Results

The proposed method is applied to constant amplitude loading experimental data from Kihara and Yoshii (1991), Marquis (1996), and Haagensen and Alnes (2005). Kihara and Yoshii studied cruciform non-load-carrying joints of HT60 steel with a yield strength of 540 MPa. The 6 mm thick specimens were tested axially under a stress ratio of \( R = 0.05 \). Marquis as well as Haagensen and Alnes studied longitudinal non-load-carrying attachments. In Marquis (1996), the specimens were made of AISI 304 and S420 steels with yield strengths of 328 MPa and 420 MPa, respectively. Plate thickness was 10 mm and the specimens were tested with axial loading under \( R = 0 \). It was estimated that the endurance limits were 105 MPa for AISI 304 and 110 MPa for S420. In Haagensen and Alnes (2005), the specimens were made of S700 steel with yield strength of 700 MPa. The applied stress ratio was \( R = 0.1 \) and the specimens were tested also under axial loading. Plate thickness was 8 mm. Table 1 gives the used material parameters for the different specimens, the calculation steps and the determined values for \( a_0 \) and \( \Delta \sigma_{th} \). Figure 3 shows the experimental data and the estimated S-N curves for the longitudinal attachments and cruciform joints. Run-outs are indicated with arrows.
Table 1. Calculation of the equivalent crack length and the corresponding S-N curves

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<tbody>
<tr>
<td></td>
<td>Cruciform HT60</td>
<td>Longitudinal S700</td>
<td>Longitudinal S420</td>
<td>Longitudinal AISI 304</td>
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<td>C</td>
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<td>1.25·10^{-11} \textsuperscript{2)}</td>
<td>5.7·10^{-12} \textsuperscript{1)}</td>
<td>5.7·10^{-12} \textsuperscript{1)}</td>
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<td>m</td>
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<td>2.84 \textsuperscript{2)}</td>
<td>3.11 \textsuperscript{1)}</td>
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<td>(\Delta K_f) [MPa(\sqrt{m})]</td>
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<td>90 \textsuperscript{2)}</td>
<td>80 \textsuperscript{1)}</td>
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<td>(\Delta K_{th}) [MPa(\sqrt{m})]</td>
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<td>4 \textsuperscript{2)}</td>
<td>4 \textsuperscript{1)}</td>
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<td>(N_{f,ref}) [cycles]</td>
<td>9 691</td>
<td>40 274</td>
<td>92 591</td>
<td>21 681</td>
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<tr>
<td>(\Delta \sigma_{ref}) [MPa]</td>
<td>309</td>
<td>300</td>
<td>267</td>
<td>373</td>
</tr>
<tr>
<td>(l_c) [mm]</td>
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<td>&lt; 8</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
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<td>II. Calculation of (a_0) using Eqs. (4) and (6) and the limit (l_c = a_0 + l &lt; t)</td>
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<td>(a_0) [mm]</td>
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<td>0.84</td>
<td>0.42</td>
<td>0.75</td>
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<td>III. Calculation of (\Delta \sigma_{th}) using Eq. (5) and the S-N curve using Eqs. (4) and (7)</td>
<td></td>
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<td>(\Delta \sigma_{th}) [MPa]</td>
<td>46</td>
<td>78</td>
<td>110</td>
<td>83</td>
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</table>

\textsuperscript{1)} NRIM fatigue data sheet no. 21 (1980) \textsuperscript{2)} NRIM fatigue data sheet no. 31 (1982)

Fig. 3. Comparison of the experimental results and the calculated curves for a) longitudinal non-load-carrying attachments and b) cruciform non-load-carrying attachments.

4. Discussion

The equivalent crack lengths and the resulting S-N curves were calculated for four different experimental data sets shown in Figure 3a) and b). The calculated curves represent the mean S-N curve and the characteristic curves for design purposes (e.g. 95% survival probability) need to be calculated separately. In two cases, S420 and HT60, the calculated S-N curves were in good agreement with the experimental data. For AISI 304 the calculated fatigue lives were slightly on the conservative side whereas for S700 the calculated S-N curve was clearly conservative, especially under lower applied stress ranges, with respect to the data. For S700 the conservativeness is due to the difference in the assumed \((m = 3.11)\) and the observed \((m > 5)\) S-N curve slopes. The calculated threshold stresses varied between 46 MPa and 110 MPa. The \(\Delta \sigma_{th}\) value for S420 was the same as estimated in Marquis (1996),
whereas the $\Delta \sigma_{th}$ value for AISI 304 was on the conservative side. For AISI 304, S420 and S700 the estimated $a_0$ values were less than 1 mm. For HT60, the initial equivalent crack length was, however, $a_0 > 2$ mm. This is due to the difference in the reference fatigue lives: for HT60 the value of $N_{f,ref}$ was clearly lower than for S700 even though the applied stress ranges were almost the same.

The proposed approach has two main benefits. First, only one data point is needed for the determination of the mean S-N curve. In this way, the fatigue life can be estimated even when there is very limited data available. In addition, the method could be used, together with experimental data, to estimate scatter in fatigue life. Secondly, the behaviour under very high applied stresses close to the critical stress intensity factor and also very low applied stress close to the threshold stress intensity factor can be taken into account through Eqs. (4-6). Verifying the behavior in these regions is however often problematic as most of the experimental data on welded joints is for fatigue lives between $1 \cdot 10^4$ and $1 \cdot 10^7$ cycles where the S-N curve slope is close to constant.

The calculated fatigue life in Eq. (4) is for stress ratios of $R = 0$. For welded joints in the as-welded state, when no post-weld improvement methods have been used, it can be assumed that there are tensile residual stresses at the weld toes, which increase the local mean stresses experienced by the structure. Because of this, possible beneficial crack closure effects at these locations can be ignored at least as an initial assumption. This is also a conservative approach. In addition, as the local $R > 0$, it is often assumed that the applied stress ratio has little effect on the fatigue strength of welded structures [Hobbacher (2009)]. Therefore it is assumed here that at least cases with $R$ is close to zero can be analyzed with Eq. (4). However, all these complex influential factors are implicitly included in the determination of the equivalent crack $a_0$ and the calculation based on one experimental data point. This is the advantage of the proposed method. This method will be applied to the fatigue life prediction under variable amplitude loadings as it is expected that the sequence effect found in VAL could be taken into account with this approach.

5. Conclusions

The equivalent crack length method for determining the fatigue life of welded structures was proposed. One experimental data point is needed to determine the equivalent crack length after which, the mean S-N curve for the joint in question can be estimated. The method was applied to four data sets including non-load-carrying longitudinal and cruciform joints. All of the data was from axial constant amplitude loading tests with stress ratios close to zero. The calculated S-N curves were either in good agreement or conservative with respect to the experimental results. In this study, only constant amplitude loading cases were considered. However, the method can be extended to variable amplitude loading cases, where the sequence effect of varying stress cycles could be taken into account.

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