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Determination of Some Parameters for Fatigue Life in Welded Joints Using Fracture Mechanics Method

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In this work, the parameters stress intensity factor (SIF), initial and final crack lengths (a_i and a_f), crack growth parameters (C and m), and fatigue strength (FAT) are investigated. The determination of initial crack length seems to be the most serious factor in fatigue life and strength calculations for welded joints. A fracture mechanics approach was used in these calculations based on SIF which was calculated with the finite element method (FEM). The weld toe crack was determined to be equal to 0.1 mm, whereas the weld root crack's length was varied depending on the degree of the weld penetration. These initial crack length values are applicable for all types of joints which have the same crack phenomenon. As based on the above calculated parameters, the new limits of FAT for new geometries which are not listed yet in recommendations can be calculated according to the current approach.

Keywords FAT-class, fatigue life, fracture mechanics, FRANC2D, initial and final crack lengths, propagation life, welded joints

1. Introduction

In engineering structures even small flaws, cold laps, non-melted line, etc., can eliminate the fatigue crack initiation period. Then, only propagation life plays a significant role in fatigue life of welded joints. The dimensions of these detected defects have a major role in fatigue life. The problem is aggravated because of the undetermined lengths of initial cracks and the complexity of welded joints.

The inevitable parameter, which must be studied and calculated in fracture mechanics methods, is the stress intensity factor range (ΔK). The stress intensity factor provides more information for failure.

In this work, SIFs have been calculated using a Fracture Analyses Code two-dimensional program, FRANC2D (Ref 1). The calculated results have been verified with the available solutions from International Institute of Welding (IIW) (Ref 2), British Standards Institution (BSI) (Ref 3) and from the literature.

Traditionally, the fatigue design of welded joints for structural applications has used the *S-N* curve type of approach based on experimental results for different weld geometries (Ref 4), included for example in Eurocode 3, BS 5400, BS 7608 (Ref 5-7) and IIW (Ref 2) where the initial crack length (a_i) is non-measurable yet and no guidance is found. Therefore, the problem that arises to determine the fatigue life is to choose the appropriate parameters of C, m, a_i and final crack length (a_f).

There is often a considerable amount of scatter in fatigue data even when carefully machined standard specimens out of the same lot of material are used. Therefore, a reduction factor is often applied to the *S-N* curves to provide a conservative value of FAT for the design of components. The FAT class is determined at two million cycles for 95% survival probability (Ref 2). In this work, this value of FAT for some notch cases is calculated. In addition, a_i, C and m have been determined by backward calculations. Recommended values of FAT for a new geometry can be given by using the current approach.

1.1 Fracture Mechanics Method

Between the two conventional approaches that are called, *S-N* and fracture mechanics approach for prediction fatigue life, fracture mechanics is an indispensable method when a crack is detected. The fracture mechanics based method can be used to determine FAT of unknown notch cases of welded joints.

Since for welds in structural metals crack initiation often occupies only a small portion of the life, it can then be assumed negligible. The assumption of existence of an initial crack (Ref 2) makes the fracture mechanics method suitable for assessment of fatigue life and inspection intervals. More details and discussion of various fracture controlled concepts such as safe-life, fail-safe and damage tolerance have been given in Ref 8. In addition, an introduction to the most important damage tolerance issues of safety relevant railway components such as axles, wheels and rails is provided also (Ref 8).

However, because it is not possible to suppose where the first crack will be started and to determine the a_i and a_f depth, the fracture mechanics approach assumes the existence of an initial crack (a_i) and predicts the fatigue life by calculation of the growth of the crack to its final size (a_f). The accurate parameters have not yet been scientifically established. Therefore, Poutiainen et al. (Ref 9) mentioned that the initial cracks used in fatigue analyses are often in the range of

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0.05-0.2 mm (Ref 9). Nevertheless, these values can vary depending on the welding operation parameters, geometry or material properties, respectively.

In this study, the actual weld toe geometry is considered and initial crack lengths are determined by backward calculation.

2. Material Properties

The material used for the base material and weld metal was an extra high strength hot-rolled steel with the minimum yield strength 550 MPa and the tensile strength minimum 600 MPa and maximum 760 MPa, respectively (Ref 10). Fatigue testing was calculated for an applied loading such that the maximum applied stress was maintained constant at 200 MPa and 104 MPa for non-load carrying cruciform and butt weld joints respectively, failing from the weld toe. Values of Poisson's ratio υ and the modulus of elasticity E were chosen as 0.293 and 210 GPa, respectively.

Experimentally, many structures are optimized by the choice of high-strength steel. The reason for this choice is to allow higher stresses and to reduce dimensions taking benefit of the high-strength material with respect to the yield criterion. In fracture mechanics, the FAT of a welded joint is not primarily governed by the strength of the base material of the joining members, hence the governing parameters in fracture mechanics are mainly the local and global geometry of the joint only, i.e., FAT is known to be closely related to the precise geometrical discontinuity of the welded joint (Ref 11). Therefore, the similar material as a single joint between the weld metal and a base metal has been assumed in the simulation.

The same steel was used in case of lack of penetration (LOP) in load-carrying cruciform and butt joints which fail from LOP with a uniform tensile stress range of 96 and 104 MPa, respectively.

It is important to emphasize that the above materials properties were only used for SIF and FAT verifications. Therefore, for experimental comparisons the materials properties and the actual geometrical parameters are similar to those used in the respective literature to make valid comparisons.

2.1 Selection of the Notch Cases

The most conventional joints in engineering structures are butt welded and cruciform fillet welded joints. According to the crack type, location and applied load position, these joints can be classified into load-carrying and non-load carrying joints, see Fig. 1. In the latter, fatigue cracks usually occur at the weld toe, where the load is applied along the x-direction. By contrast, in the former, cracks start from lack of penetration (LOP) where the load is applied along the y-direction (see Fig. 1a and b). Due to symmetry, one quarter of the joint can be modelled. Figure 1 shows the used FE models and the sites of cracking. The high stresses are located at weld toe transition and in addition at the tip of LOP. That explains the reason for crack propagation from these locations.

3. Stress Intensity Factor Determination

SIFs were calculated for two notch cases, namely cruciform and butt welded joints. Results were bench marked with the solutions from IIW (Ref 2), BSI (Ref 3) and literature.

3.1 Cruciform Welded Joints

One of the formulas for SIFs of cruciform welded joints containing LOP (Fig. 1a) was presented first by Frank and Fisher (Ref 12) and then improved by BSI7910 (Ref 3), in case of isosceles fillet weld shape as follows:

$$\Delta K = K_I = M_k \Delta\sigma \left(\pi a Sec \frac{\pi a}{w}\right)^{1/2} \quad \text{(Eq 1)}$$

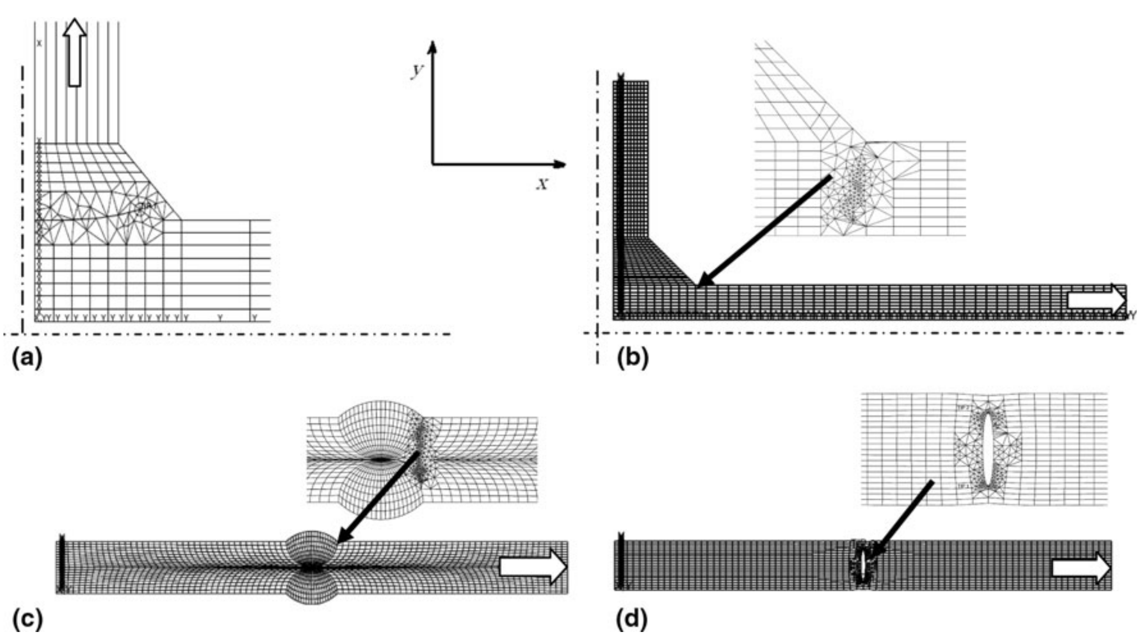


Fig. 1 FE modelling (FRANC2D): (a) LOP crack in load-carrying cruciform joint, (b) toe crack in non-load carrying cruciform joint, (c) toe crack in butt joint, and (d) LOP in butt joint

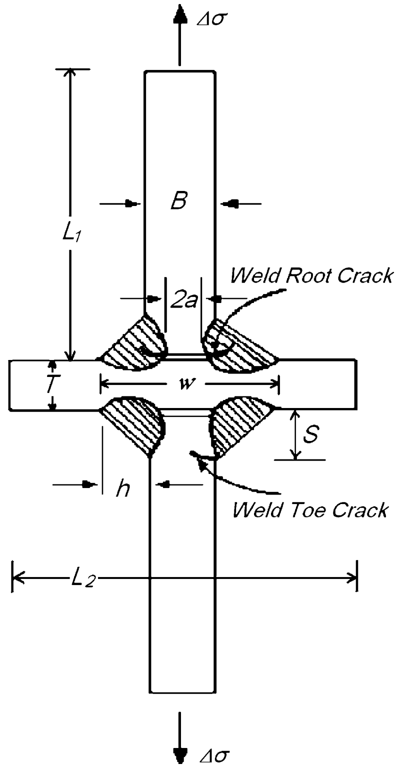


Fig. 2 Load-carrying cruciform fillet welded joint

where M_k is the magnification of SIF:

$$M_k = A_0 + A_1\left(\frac{2a}{w}\right) + A_2\left(\frac{2a}{w}\right)^2 \quad \text{(Eq 2)}$$

All parameters are shown in Fig. 2 in the case of a load-carrying cruciform joint where a_i is the half crack length (i.e., LOP = $2a_i$ for complete geometry). B and T are the attachment and main plate thicknesses, respectively, and $\Delta\sigma$ the applied tensile stress on the attachment plate, h and S are the fillet weld leg length on the main and attached plate, respectively, and h/B is the weld size. L_1 and L_2 are the attached and main plate's lengths, respectively. The width of the fillet weld as shown in Fig. 2 is:

$$w = B + 2h \quad \text{(Eq 3)}$$

The values of A_0, A_1 and A_2 for equal leg length and unity ratio of B/T are used due to Ref 3 as follows:

$$A_0 = 0.956 - 0.343\left(\frac{h}{B}\right) \quad \text{(Eq 4)}$$

$$A_1 = -1.219 + 6.210\left(\frac{h}{B}\right) - 12.220\left(\frac{h}{B}\right)^2 + 9.704\left(\frac{h}{B}\right)^3 - 2.741\left(\frac{h}{B}\right)^4 \quad \text{(Eq 5)}$$

$$A_2 = 1.954 - 7.938\left(\frac{h}{B}\right) + 13.299\left(\frac{h}{B}\right)^2 - 9.541\left(\frac{h}{B}\right)^3 + 2.513\left(\frac{h}{B}\right)^4 \quad \text{(Eq 6)}$$

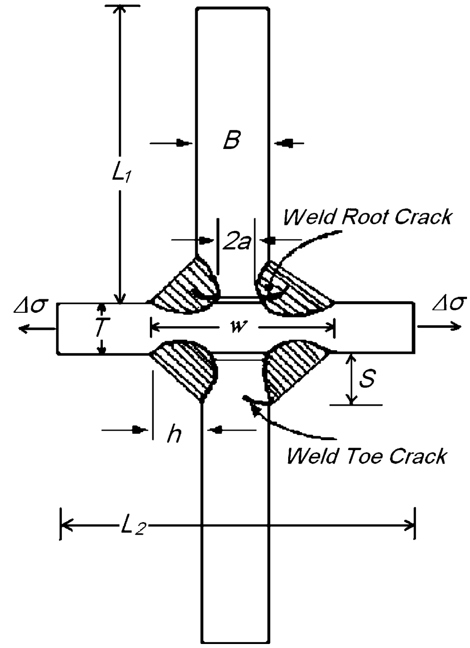


Fig. 3 Non-load carrying cruciform fillet welded joint

The limits of validity for this formula are within the following range:

$$\frac{B}{T} = 1, \quad 0.2\langle\frac{h}{B}\langle 1.2, \quad \text{and } 0.1\langle\frac{2a}{w}\langle 0.7$$

IIW (Ref 2) has used the old Frank and Fisher formulas (for more details see Ref 12) to calculate SIF ranges that are valid for h/B from 0.2 to 1.2 and for $a/w < 0.7$:

$$\Delta K = \frac{\Delta\sigma(A_1 + A_2 a/w)\sqrt{\pi a Sec(\pi a/2w)}}{1 + 2h/B} \quad \text{(Eq 7)}$$

$$A_1 = 0.528 + 3.287(x) - 4.361(x)^2 + 3.696(x)^3 - 1.875(x)^4 + 0.415(x)^5 \quad \text{(Eq 8)}$$

$$A_2 = 0.218 + 2.717(x) - 10.171(x)^2 + 13.122(x)^3 - 7.755(x)^4 + 1.783(x)^5 \quad \text{(Eq 9)}$$

where $x = h/B$.

For an elliptical crack at the toe of non-load carrying fillet welded joints (Fig. 1) where the load is applied at the end of the main plate as shown in Fig. 3, the range of the SIF, (ΔK) can be written as follows (Ref 13):

$$\Delta K = \frac{M_k Y_u}{\phi_0}\Delta\sigma\sqrt{a} \quad \text{(Eq 10)}$$

In this case, $\Delta\sigma$ is the nominal tensile stress range in the main plate and (a) is the crack depth (Ref 11). ϕ_0 is the complete elliptical integral defined as (Ref 13):

$$\phi_0 = \int_0^{\pi/2}\left[1 - \left(1 - \frac{a^2}{c^2}\right)\sin^2\phi\right]^{1/2} d\phi \quad \text{(Eq 11)}$$

where ϕ is the parametric angle of an ellipse.

Hence, the crack aspect ratio is zero, $a/2c = 0$, and $\phi_0 = 1$, where c is half length of the surface crack (Ref 13). The correction term Y_u for a double-edge crack in a plate under tensile loading (Eq 12), given by Brown and Srawley (Ref 14) was applied:

$$Y_u = 1.98 + 0.36\left(\frac{2a}{T}\right) - 2.12\left(\frac{2a}{T}\right)^2 + 3.42\left(\frac{2a}{T}\right)^3, \quad 0\langle\frac{2a}{T}\langle 0.95 \qquad \text{(Eq 12)}$$

The formula of M_k has been used from IIW that introduced a systematic set of formulae for M_k values for different welded joints (Ref 2). The formula for M_k in transverse non-load carrying attachment is:

$$M_k = C\left(\frac{a}{T}\right)^k, \quad M_k \leq 1 \qquad \text{(Eq 13)}$$

$$C = 0.8068 - 0.1554\left(\frac{s}{T}\right) + 0.0429\left(\frac{s}{T}\right)^2 + 0.0794\left(\frac{h}{T}\right) \qquad \text{(Eq 14)}$$

$$k = -0.1993 - 0.1839\left(\frac{s}{T}\right) + 0.0495\left(\frac{s}{T}\right)^2 + 0.0815\left(\frac{h}{T}\right) \qquad \text{(Eq 15)}$$

All parameters are shown in Fig. 3.

From the solution of Eq 12 and 13 in Eq 10, SIFs have been calculated for cruciform joints which fail from their toe.

3.2 Butt Welded Joints

The range of SIF, ΔK for the butt welded specimens was calculated using the following empirical Eq 16 (Ref 15):

$$\Delta K = \Delta\sigma\sqrt{\pi a}\left(1.12 - 0.23\left(\frac{a}{t}\right) + 10.55\left(\frac{a}{t}\right)^2 - 21.72\left(\frac{a}{t}\right)^3 + 30.39\left(\frac{a}{t}\right)^4\right) \qquad \text{(Eq 16)}$$

where $\Delta\sigma$ is the stress range, a the crack length and t the plate thickness. The results have been compared with those obtained by using FRANC2D.

4. Backward Fatigue Life Calculation

The fatigue life parameters which are calculated in this work are FAT, a_i, a_f, C and m. The initial materials' constants used in this calculation for FAT95% (see Fig. 4) are $C = 5E-13$, and $m = 3$. The units are Newton and millimetre as recommended by IIW (Ref 2).

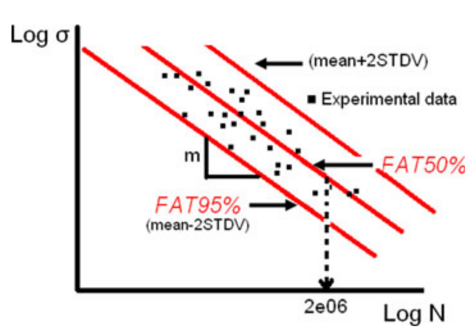


Fig. 4 *S-N* curve

Fatigue life calculation procedures were carried out as based on the fracture mechanics method using a simple form of Paris' law (Eq 17).

The determination of the number of cycles (N) until failure is done by integration of the crack growth relation from a_i up to reaching a final crack length at break-through (a_f) as follows:

$$\frac{da}{dN} = C(\Delta K_I)^m \qquad \text{(Eq 17)}$$

$$dN = \frac{da}{C(\Delta K_I)^m} \Rightarrow \int_0^N dN = \int_{a_i}^{a_f} \frac{da}{C(\Delta K_I)^m} \qquad \text{(Eq 18)}$$

The SIF range inside is:

$$\Delta K_I = Y\Delta\sigma\sqrt{\pi a} \qquad \text{(Eq 19)}$$

where $\Delta\sigma$ is the applied stress range, a is the crack length, and Y is the correction factor as a function of $f(a/t)$, consequently:

$$\int_0^N dN = \frac{1}{C}\int_{a_i}^{a_f} \frac{da}{\left[Y\Delta\sigma(\pi a)^{1/2}\right]^m} \qquad \text{(Eq 20)}$$

Thus, the number of cycles for one increment is determined as follows:

$$N = \frac{1}{CY^m(\Delta\sigma)^m\pi^{m/2}} \frac{\left[a_{i+1}^{\left(1-\frac{m}{2}\right)} - a_i^{\left(1-\frac{m}{2}\right)}\right]}{1-\frac{m}{2}} \qquad \text{(Eq 21)}$$

Through dividing the crack path into (n) increments, between a_i and a_f, then the number of cycles N_j for each increment (between a_j and $a_j + \Delta a$) can be calculated. The crack length vector and calculated SIF are transferred to Excel and integrated numerically according to Eq 22. Then, the total life N can be calculated by summation of the N_j for each increment as:

$$N = \sum_{j=1}^{n} N_j = \sum_{j=1}^{n} \frac{\Delta a}{C(\Delta K_I)_j^m} \qquad \text{(Eq 22)}$$

where j is the step's number. Thus, a numerical integration for a crack growth rate is carried out at various stress levels, and the results of fatigue life are recorded to determine the *S-N* curve.

The repetition of fatigue test many times reflects the statistical nature of fracture event. Therefore, most of the fatigue results are distributed and scattered around the mean value and further away (see Fig. 4). If these data are plotted it will have a bell-shaped curved like a Gauss distribution. The standard deviation (STDV) is given for data that are normally distributed. According to IIW, all FAT data are given as characteristic values, which are assumed to have a survival probability (reliability) of at least 95% (i.e. 5% failure probability) within two standard deviations calculated from the mean value (FAT50%) of a two-sided 75% confidence level (Ref 2), see Fig. 4.

The initial crack length should be considered in the determination of the fatigue life of welded joints. The main objective of this wok is to choose the appropriate growth parameters and a_i. With backward calculations, the initial crack length is determined by the best fit of the calculation to the characteristic FAT95% according to the value of C and m from IIW. In case of FAT50%, a new value of C50% is needed which is equal to C95% + 2STDV beside the calculated a_i. From IIW, STDV is chosen equal to 0.178. Both curves of these FAT values are plotted using the straight line equation with slope m, as follows:

$$\log N = \log C - m \log \mathrm{FAT} \qquad \text{(Eq 23)}$$

Then the characteristic fatigue strength (FAT95%) is calculated by:

$$\log(2 \times 10^6) = \log \mathrm{C95\%} - m \log \mathrm{FAT95\%} \qquad \text{(Eq 23.1)}$$

The mean fatigue strength (FAT50%) is then calculated by:

$$\log(2 \times 10^6) = \log(\mathrm{C95\%} + 2 \times \mathrm{STDV}) - m \log \mathrm{FAT50\%} \qquad \text{(Eq 23.2)}$$

Finally, the *S-N* curves are obtained (see Fig. 4) according to:

$$N = (\mathrm{FAT95\%}/\Delta\sigma)^m \times (2 \times 10^6) \qquad \text{(Eq 24)}$$

$$N = (\mathrm{FAT50\%}/\Delta\sigma)^m \times (2 \times 10^6) \qquad \text{(Eq 25)}$$

The mean values of materials' constants are calculated in this work as C50% = 2.17E-13 and m = 3. This mean value of C is only 8.5% larger than the mean value from BS7910 which is given equal to 2E-13 (Ref 3).

5. Results and Discussion

5.1 Cruciform Welded Joints SIF Calculations

Figure 5(a) shows the solution of Eq 10 and FRANC2D for toe crack with a good agreement. Figure 5(b) shows the comparisons between the FE solution, the solution from IIW and a modified solution from BSI7910 in case of LOP. The solutions from BSI agree better with FEA (FRANC2D) than those from IIW, for more details see Ref 16.

5.2 Butt Welded Joints SIF Calculations

Figure 6 shows a good agreement between the calculated SIF from FRANC2D and an empirical solution from Broek (Ref 15) for the case of a toe crack in a butt welded joint.

5.3 Fatigue Life Calculations

Figures 7-11 show the *S-N* curves of characteristic and mean fatigue lives, FAT95% and FAT50%, respectively. FAT50% refers to experimental values observed during fatigue of steel structures. The numerical integration refers to backward calculations using Paris law.

The initial crack length, (a_i), has been determined which gave the credible coalescence with FAT class from recommendations. The value of a_i was 0.1 mm for the crack initiated from the weld toe, while a_i was equal to the un-penetrated line for the joints having LOP or incomplete melting. The final crack lengths are determined equal to half sheet thickness (Ref 10, 17, 18). For LOP, a relationship has been given in Ref 19. In all cases,

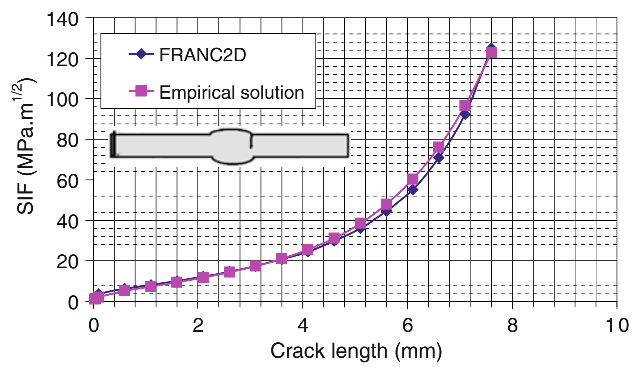


Fig. 6 SIF solution for a butt weld as compared with an empirical solution after Broek (Ref 15)

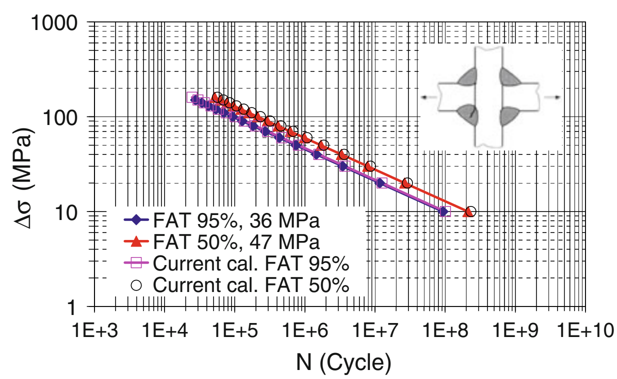


Fig. 7 *S-N* curve for a cruciform joint having LOP, throat thickness > $t/3$, FAT36, type no. 23 (Ref 21)

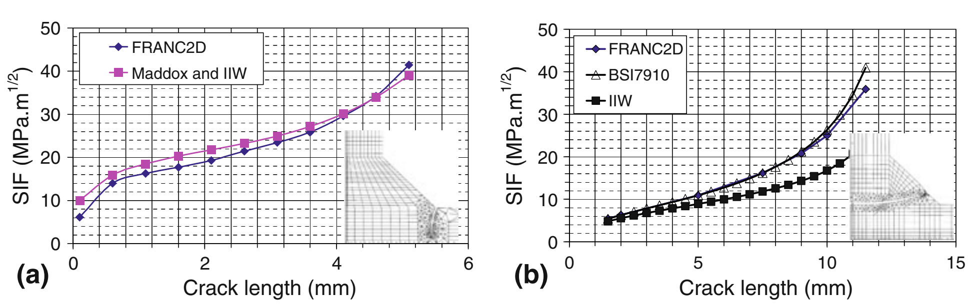


Fig. 5 The SIF as a function of crack length for cruciform welded joints: (a) weld toe and (b) weld root failure

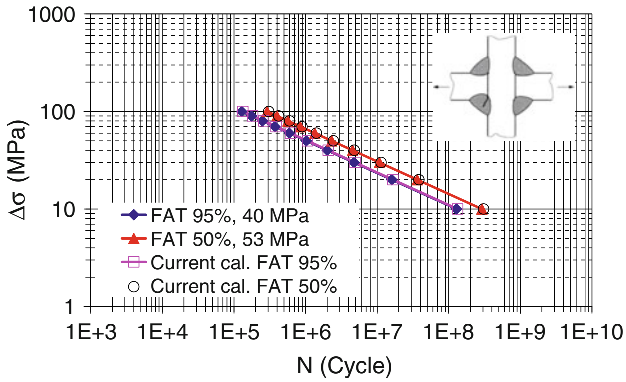


Fig. 8 *S-N* curve for a cruciform joint having LOP, throat thickness < *t*/3, FAT40, type no. 23 (Ref 21)

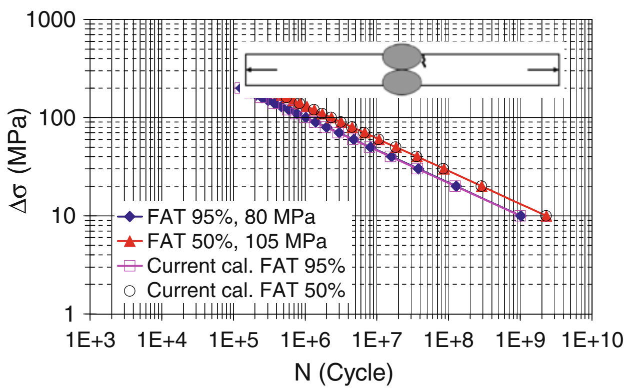


Fig. 9 *S-N* curve for a transverse butt weld having toe crack. FAT80, case 213 (Ref 2)

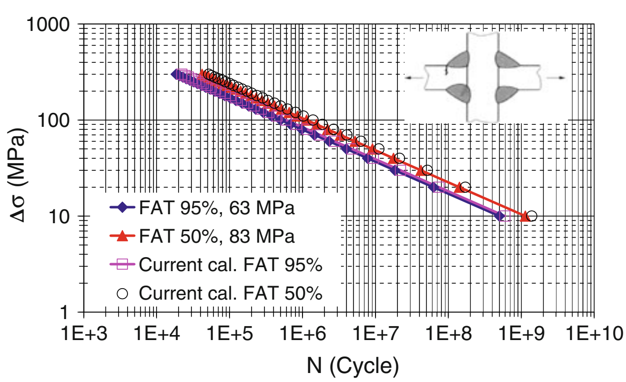


Fig. 10 *S-N* curve for a load-carrying cruciform joint having toe crack. FAT63, case 413 (Ref 2)

the final crack length has a less significant effect on the fatigue life (Ref 10, 20), and its variation can be considered as negligible.

Germanischer Lloyd Aktiengesellschaft (GL) (Ref 21) presented some recommended values of fatigue strength for the welded metal in load-carrying fillet welds at cruciform or T-joint in case of LOP. These values from GL based on the weld throat size and the stress range in weld throat and differ from those in IIW. FAT values for steel were 36 MPa for a throat thickness larger than the ratio (plate thickness/3), and 40 MPa

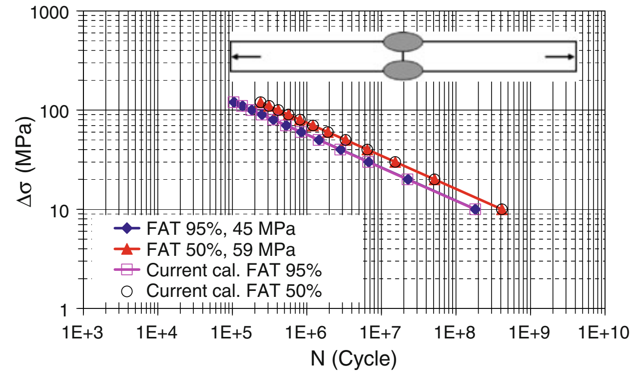


Fig. 11 *S-N* curve for a transverse partial penetration butt weld joint having LOP. FAT45, case 217 (Ref 2)

for a throat thickness smaller than the ratio (plate thickness/3). In contrast, IIW stated that FAT for steel is 45 MPa in LOP case.

The FAT values from GL in case of load-carrying cruciform joints provided more realistic results as compared with IIW and good agreement with the calculated values of this study. Figures 7 and 8 show the comparisons for these FAT values and the current approach.

Also, the toe crack case has been verified as shown in Fig. 9 for butt welded joints. Also in this case, a_i was determined to be equal to 0.1 mm.

The results of the non-load carrying cruciform joint failing from the weld toe are presented in Fig. 10. Although this case differs from butt joints, the same a_i has been adopted.

A butt weld joint with LOP is presented in Fig. 11. A good agreement is obtained when the initial crack length a_i equals to the LOP defect existing at the beginning.

These initial crack lengths of the above mentioned cases are uniform and have confirmed for all types of joints. A final crack was defined in many studies equal to half parts thickness. In case of LOP, a_f was set to be 0.8 × (leg length on cross plate side) + cross plate thickness/2. The coefficient multiplying the leg length was varied between 0.6 and 0.9 (Ref 19). In all cases, the final crack length a_f has a less significant effect on fatigue life (Ref 10), and the variation can be considered as negligible.

5.4 Experimental Verification

From literature (Ref 22-24), it is evident that most of fatigue life predictions of fillet welded joints are based on toe failure. Other studies (Ref 25-28) have considered the fatigue behavior of fillet welded cruciform joints failing from the weld root region.

In spite of relatively high residual stresses which are likely to occur in the welds, several works proposed that residual stress can be neglected or they have relieved (Ref 9, 27). Therefore, residual stresses were not taken into account in the present calculations.

5.4.1 Weld Toe Failure. For fillet welds, the high stress concentration at the weld toe is presented due to the fact that these locations rely to be sound and usually weldment contains flaws and crack-like defects. Therefore, the presence of the weld toe radius inevitably will reduce these concentrations of stresses near the weld toe.

The effect of the toe radius is not included in FAT values from recommendations of IIW and BS7910. This will provide a good example to evaluate the current approach. Lindqvist

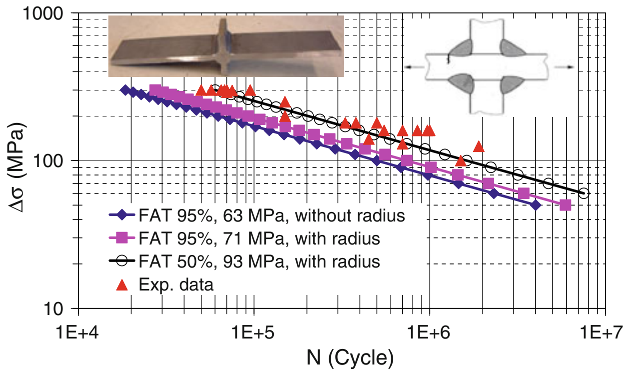


Fig. 12 Calculated fatigue life based on fracture mechanics compared with measured results by Lindqvist (Ref 10). Non-load carrying cruciform joint with toe crack = 0.1 mm, $R = 0$

(Ref 10) conducted fatigue tests for toe cracks in a non-load carrying cruciform weld joint having 0.6 mm toe radius.

These reported results were compared with the current approach from this work for tension mode only.

In this study, the new value of FAT95% for non-load carrying fillet weld having a toe radius was calculated equal to 71 MPa. The new calculated FAT value is higher than that of recommendations (FAT95%, 63 MPa) due to the effect of improved local weld geometries and stress concentration.

To verify the predicted values, the mean and design curves were drawn and are shown in Fig. 12. The mean fatigue life was calculated according to IIW based on FAT95% +2STDV. FAT50% is then compared with reported fatigue lives from Ref 10. The fatigue tests were performed under tension and bending under constant amplitudes. The sheet thickness of 6 mm was used in pure tension at a stress ratio, $R = 0$. The frequency was 10 Hz in both cases. The experimental testing was performed at SSAB Tunnplats laboratory in Borlänge (Ref 10). Figure 12 shows an excellent agreement between the experimental results for tension fatigue ($R = 0$) and the presently calculated fatigue lives for FAT50%.

5.4.2 Weld Root Failure. In case of LOP, the current approach was compared with published test results by Singh et al. (Ref 27). These authors carried out the fatigue life experiments of constant amplitude with a stress ratio $R = 0$ on gas tungsten arc welded load-carrying cruciform joints made of AISI 304L stainless steel in cold rolled form of 6 mm thickness.

The experimental results were reported and identified as propagation and initiation life for LOP equal to 2, 3 and 6 mm, see Fig. 13. The FAT value increases as the LOP decreases. For 2 mm, FAT equals to 74 MPa, where it equals to 34 MPa in case of 6 mm LOP. The decrease FAT strength as LOP increases is due to the difference in SIF and the decrease of the crack path to reach a_f.

The fatigue lives of different LOP (2, 3 and 6 mm) are presented in Fig. 14. The lower curve refers to FAT95% equal to 34 MPa (LOP = 6 mm). According to GL (Ref 21), it can be concluded that LOP equal to 6 mm will be a maximum critical LOP which is allowed according to the size of fillet weld (i.e., throat thickness > plate thickness/3).

As a summary of the present paper, Table 1 gives all used models and the calculated results.

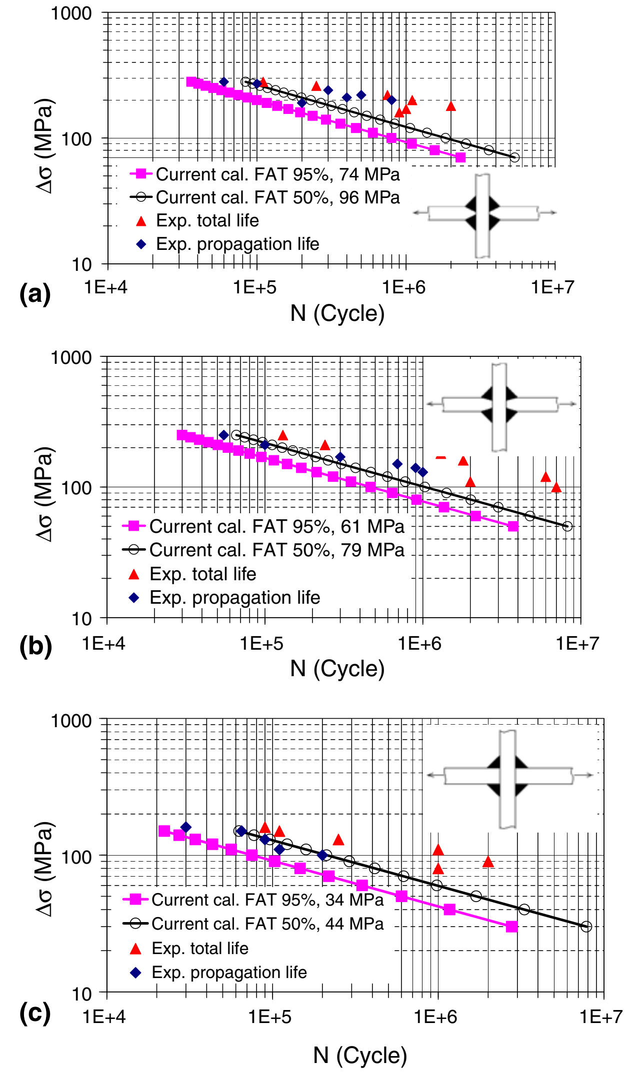


Fig. 13 Calculated fatigue life based on fracture mechanics compared with experimental data reported by Singh et al. (Ref 26): (a) LOP = 2 mm, (b) LOP = 3 mm, and (c) LOP = 6 mm

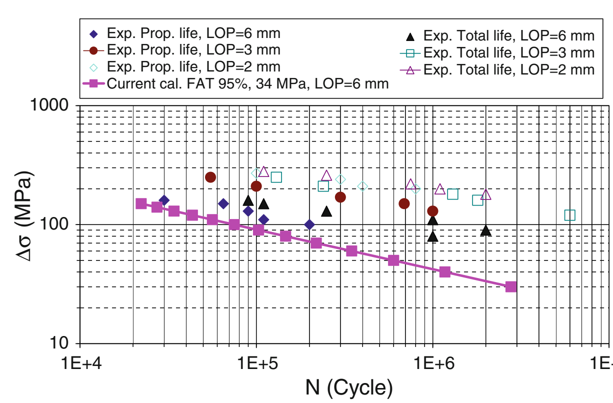


Fig. 14 Fatigue life for different LOP sized published by Singh et al. (Ref 27) compared with calculated lives based on fracture mechanics

Table 1 FE models and descriptions

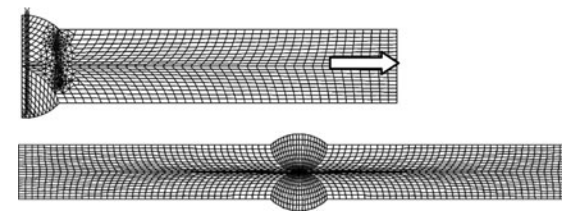
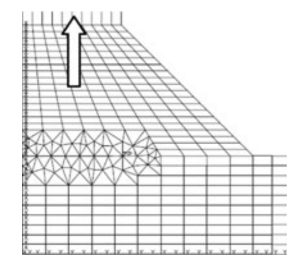
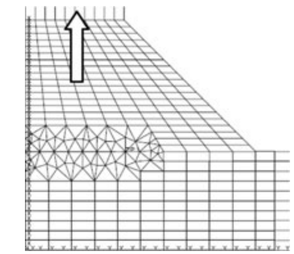
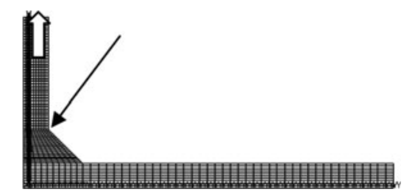
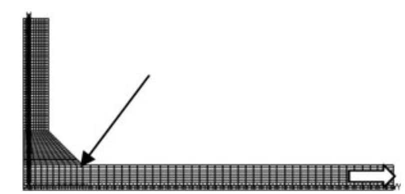
Case FAT95%	Description	FAT50%	Crack growth parameters	Joint type and potentially crack location (FE model)
217 45	Transverses butt weld with partial penetration, analysis based on stress in weld throat sectional area, welds overfill not taken into account *Geometrical conditions* Max LOP $\leq 0.2t$ but max = 2.2 mm	59	$a_i = 1.1$ mm $C = 2.17E\text{-}13$ $m = 3$	 • LOP in transverse butt weld joint • Fix x and at corner FIX xy • Weld reinforcement not taken into account
213 80	Transverse butt weld with weld toe crack and with complete penetration *Geometrical conditions* Toe angle max 30° Weld bead height max = 1 + 0.1 × weld bead width Crack will propagate through the sheet thickness	105	$a_i = 0.1$ mm $C = 2.17E\text{-}13$ $m = 3$	 • Weld toe crack • One side locked in x-direction. At least one point. Fix xy to prevent the model from rotation
414 36	Load-carrying cruciform joint with LOP. Incomplete penetration and un-weld line regarded as initial crack (a_i) $0 < a_i <$ sheet thickness. Throat thickness $> t/3$ *Geometrical conditions* Equal sheets thickness ($B = T$) and leg length. ($S = h$). Throat thickness $> t/3$, $a_f = Y \times$ (leg length + thickness/2). Y: factor varied from 0.6-0.9 and normally $Y = 0.8$	47	$a_i = 7$ mm $C = 2.17E\text{-}13$ $m = 3$	 • LOP in load-carrying cruciform joint • Fix xy at corner • Un-weld line was regarded as a_i

Table 1 continued

Case FAT95%	Description	FAT50%	Crack growth parameters	Joint type and potentially crack location (FE model)
414 40	Load-carrying cruciform joint with LOP Throat thickness < t/3. Equal leg length (Isosceles). LOP propagates through the weld metal perpendicular to the applied load and coincides with the LOP line *Geometrical conditions* Equal sheet thickness ($B = T$) and leg length ($S = h$)	53	$a_i = 4$ mm $C = 2.17E\text{-}13$ $m = 3$	 • LOP in load-carrying cruciform joint • Fix xy at corner • Un-weld line was regarded as a_i
413 63	Numerical analysis of 2-D load-carrying cruciform joints, fatigue crack propagation life is determined automatically for the 2-D models through integration of the Paris equation for $a_i = 0.1 - a_f$ *Geometrical conditions* Equal sheet thickness ($B = T$), leg length $S = h$, throat thickness < t/3	83	$a_i = 0.1$ mm $C = 2.17E\text{-}13$ $m = 3$	 • Weld toe crack • Lop is inactive
412 71	Non-load carrying with toe crack *Geometrical conditions* Equal sheet thickness ($B = T$), leg length $S = h$, throat thickness < t/3. weld toe radius ≥ 0.6 mm	93	$a_i = 0.1$ mm $C = 2.17E\text{-}13$ $m = 3$	 • Weld toe crack • Lop is inactive

6. Conclusions

Fatigue life prediction of welded joints in general is very complex, costly and time consuming. Therefore, fracture mechanics has been used to find the accurate prediction of fatigue life parameters of welded joints. The literature proposed different values of crack lengths and presented them normally as a range which leads to serious results. The solutions of SIFs from FEA have been compared with those from BSI, IIW and literature. In case of LOP, consistent results have been obtained between FEA and the modified solution from BSI which is particularly better than that from IIW. Therefore, it was shown that FRANC2D can be used to simulate various weld shapes in cases, where the use of analytical and empirical solutions is limited. The entire fatigue process in fillet welded joints has been modelled by a pure fracture mechanics approach. The simple version of Paris' law has been adopted. In this work, the initial crack length and growth rate parameters have been determined according to backward calculations to calculate FAT. An initial crack size equal to 0.1 mm was used for joints that have weld toe crack. The conventional crack lengths for joints having LOP or incomplete melting will be equal to the line of LOP. These initial crack length values are applicable for all types of joints which have the same crack type size. The final crack length has little effect as compared with the effect of the initial crack. Therefore, it is defined to be equal to one-half of the sheet thickness in the case of weld toe when the crack path is perpendicular to the applied load. Some other empirical equations were checked for final length in case of LOP. Final crack length assumptions have been verified from the *a*-*N* curve when the number of cycles becomes constant.

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