Fatigue Crack Propagation Life Calculation in Welded Joints

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ABSTRACT. *The determination of fatigue strength of welded joint across the board has big draw to evaluate fatigue life of welded joints. In spite of considerable fatigue design data which exist for welded joints in the recommendations, the studies for the effect of crack growth parameters C, m and initial crack length determinations of welded structures are still not clear and have not been discussed enough. Therefore, this paper aims to present procedures to find the FAT for welded geometries and determine initial crack depth. The new recommended limits of FAT for new geometries not listed yet in recommendations can be calculated according to backward calculations. Initial crack and crack growth parameter are determined.*

INTRODUCTION

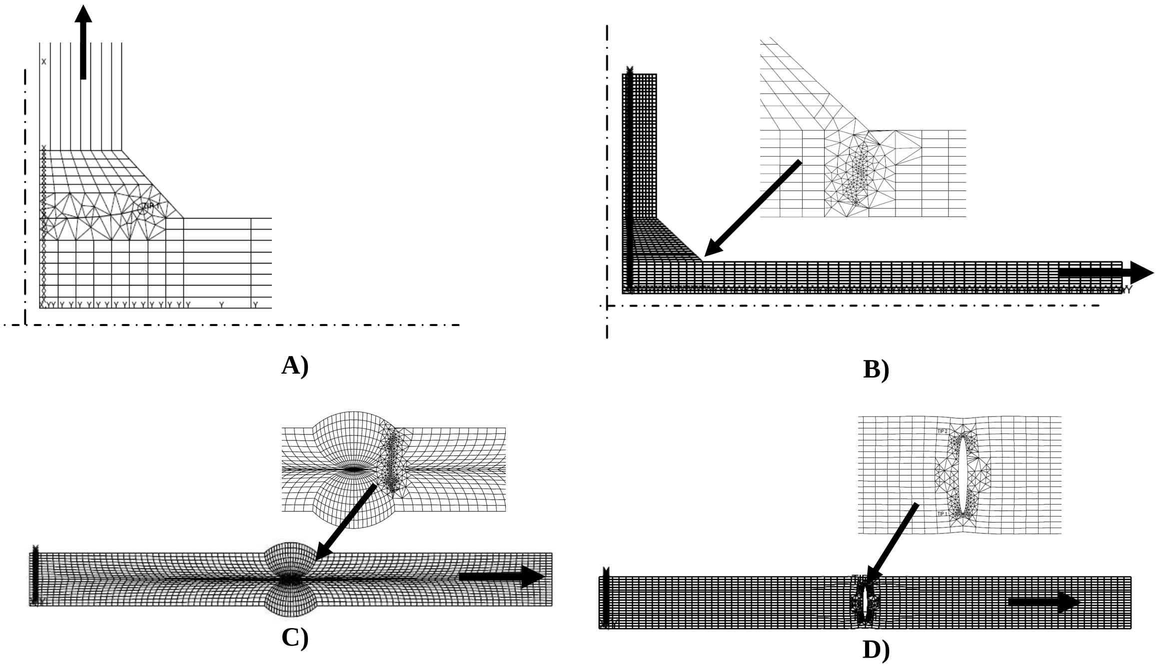
Fatigue life prediction of welded joints in general is very complex, costly and time consuming. In engineering structures even small flaws, cold laps, and non melted line etc., can eliminate the fatigue crack initiation. Only propagation life plays a significant role in fatigue life of welded joints. The length value of these detected defects has a big draw to study. Some literature presented a range of length for these crack like defects in welded joints and they have given conservative value of lives. The reason for this is that the properties of a joint are determined by several parameters, as e.g. complex joint geometry with a number of stresses concentration points, by heterogeneities of weld metal properties and in addition by the effect of residual stresses.

The inevitable parameter, which must be studied and calculated in fracture mechanics methods, is the stress intensity factor (SIF) range ΔK. In this work, SIFs have been calculated using Fracture Analyses Code two-dimensional program, FRANC2D [1]. The calculated results have been verified with available solution from International Institute of Welding (IIW) [2] and British Standards Institution [3] and literature. The problem that arises to determine the fatigue life is to choose the appropriate parameters of C, m, initial crack length a_i and final or critical crack length a_f. 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 [4], included for example in Eurocode 3, BS5400, BS 7608 [5-7] and IIW [2] where the initial crack is non measurable yet and no guidance is found. In this work, a_i, C and m have been calculated by backward calculations.

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 conservative values of fatigue strength for the design of components that are called FAT class, measured at two million cycles. In this work, these values of FAT for some of notch cases are calculated. Recommended values of FAT for a new geometry can be given by using the current approach.

SELECTION OF THE NOTCH CASES

The most conventional joints in engineering structures are butt weld 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 Figure 1. In the latter fatigue cracks usually occur at the weld toe, where the load is applied a long the x-direction. By contrast, in the former, cracks starts from the lack of penetration LOP where the load is applied along the y-direction. Due to symmetry, the quarter modelled joint can be used. 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 crack tip of LOP. That explains the reason for crack propagation from these locations.



A) B) C) D)

Figure 1. Finite element modelling (FRANC2D). A) Root crack in load carrying cruciform joint. B) Toe crack in non-load carrying cruciform joint. C) Toe crack in butt joint. D) LOP in butt joint.

BACKWARD FATIGUE STRENGTH CALCULATION

Fatigue life calculations procedures carried out as based on fracture mechanics method using a simple form of *Paris law*. Materials constants used in this calculation, C=5 E-13, and m=3, where unites are in *N* and *mm* are recommended by IIW [2]. Most of fatigue results are distributed and scattered around the mean value and further away. If these data are graphed it will has a bell-shaped curved. The standard deviation *STDV* is given for data that are normally distributed. According to IIW, all fatigue resistance 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 of a two-sided 75% confidence level [2]. The initial crack length should be considered in determination of fatigue life of welded joints. Emphasis is laid on how to choose growth parameters and a_i. With backward calculations the parameters have been determined which coalescence the FAT95%, according to characteristic value of C and m. In case of FAT50%, a new value of C50% is needed which is equal to C95%±2*STDV*. From IIW, *STDV* is chosen equal to 0.178. Both curves of these FAT values are plotted using the straight line equation with slop m, i.e.

$$LogN = LogC - m.LogFAT \tag{1}$$

The mean value of materials constant are calculated in this work were *C50%*=2.17E-13 and m=3. This mean value of C is only 8.5% larger than the mean value BS7910 which is given equal to 2E-13 [3].

RESULTS AND DISCUSSION

Cruciform welded joints SIF calculations

Figure 2A shows the solution of *Maddox* [8] and FRANC2D with good agreement. Figure 2B shows the comparisons between FE solution, IIW solution and modified solution from BSI7910 in case of LOP. The solutions from BSI agree better with FEA (FRANC2D) more than those from IIW.

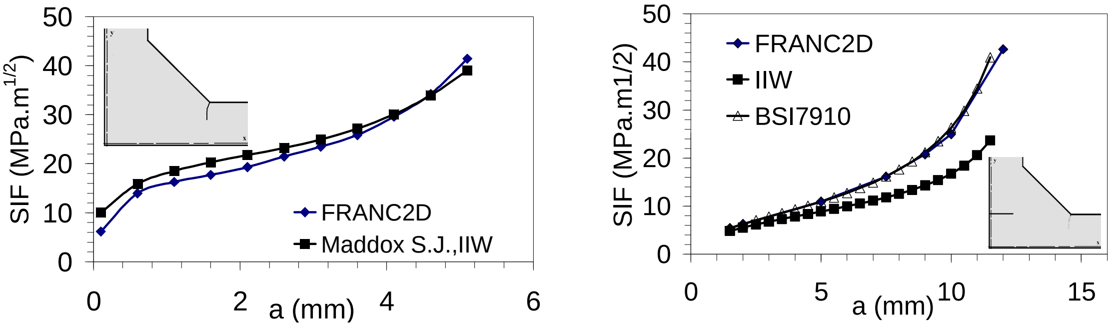


Figure 2. The SIF as a function of crack length for cruciform welded joints failure from: Left) Weld toe and Right) Weld root.

Fatigue life and parameters calculations

The numerical integration refers to backward calculation using *Paris* law. The 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 the a_i equal to un-penetrate line for the joints having LOP or incomplete melting. *Germanischer Lloyd Aktiengesellschaft* GL2007 [9] presented some recommended values of fatigue strength for welded metal in load carrying fillet welds at cruciform or tee joint in case of LOP. FAT values for steel were 36 MPa for throat thickness > (plate thickness/3), and 40 MPa for throat thickness < (plate thickness/3). IIW stated that FAT for steel is 45 MPa. The FAT values from GL in case of load carrying cruciform provided more realistic results as compared with calculated values in this study. Figure 3 show the *S-N* curves of characteristic and mean fatigue life, FAT95% and FAT50%, respectively. FAT50% refers to experimental values applied during the real service time for steel structures. Figure 3 left show the comparisons for FAT95%, 36 MPa value [9] and the current approach. A good agreement is obtained when the a_i equals to the LOP defect which existed from beginning. Toe crack case has been verified as shown in Figure 3, right for butt weld joints, a_i was calculated equal to 0.1 *mm*.

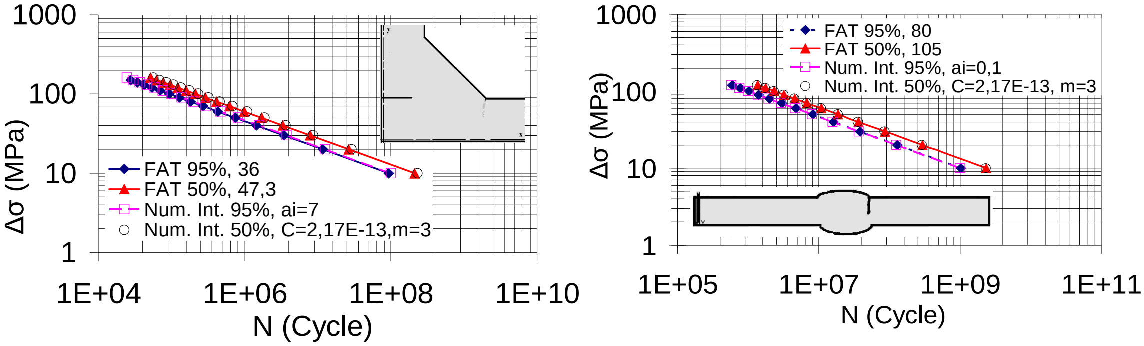


Figure 3. *S-N* curve for: Left) Cruciform joint having LOP. Throat thickness>t/3, FAT36 MPa. Type NO.23 [9]. Right) Transverse butt weld having toe crack. FAT80 MPa, case 213 [2].

The results of the non-load carrying cruciform joint failing from the weld toe is presented in Figure 4 left (FAT95%, 63 MPa). However this case differ than butt joints (FAT95%, 80 MPa), it can be seen that the same a_i has adopted which is equal to 0.1 *mm*. Butt weld joints with LOP are presented in Figure 4 right. A good agreement is obtained when a_i equals to the LOP defect. In mind of authors, these initial cracks length of each case are uniform and have confirmed for all types of joints. Final cracks defined in many researches equal to half parts thickness. In case of LOP, the a_f was set to be 0.8× (leg length on cross plate side) + thickness/2. The coefficient multiplying leg length was varied between 0.6 and 0.9 [10]. In all cases a_f has less significant effect on fatigue life [11], and the variation can be considered as negligible.

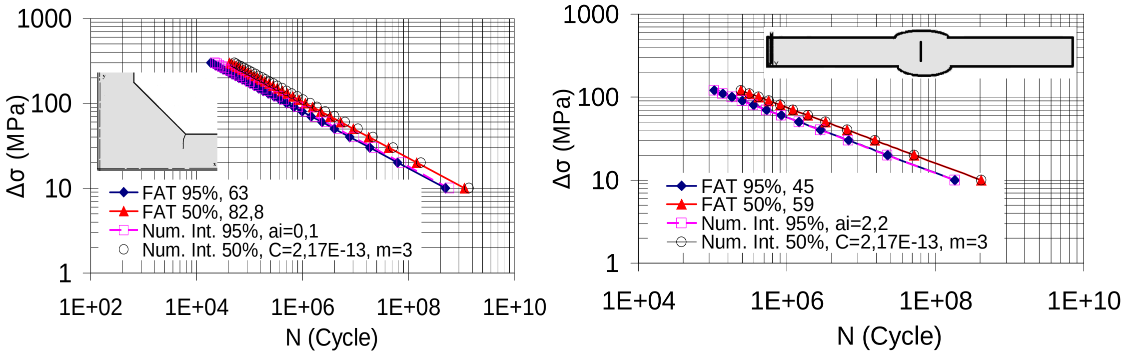


Figure 4. *S-N* curve for: Left) Non-load carrying cruciform joint having toe crack. FAT63 MPa, case 413 [2]. Right) Transverse partial penetration butt weld joint having LOP. FAT45 MPa, case 217 [2].

EXPERIMENTAL VERIFICATION

From literature [12-14], it is evident that most of fatigue life predictions of fillet welded joints are based on toe failure. Studies [15, 16, 17, 18] have considered the fatigue behaviour of fillet welded cruciform failing from the weld root region. 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 toe radius is not included in FAT values from recommendations IIW and BS7910. This will provide a good example to evaluate the current approach from this work. *Lindqvist* [11] conducted the fatigue test for toe crack in a non-load carrying cruciform weld joint having 0.6 *mm* toe radius. These reported results were compared with the current approach which was used in this work for tension mode only. In this study, the new value of FAT95% for non-load carrying fillet weld having 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 Figure 5. The mean fatigue life FAT50%, was calculated equal to 93.3 MPa according to IIW based on FAT95% +2*STDV*. FAT50% is compared with reported test results from *Lindqvist* [11] as shown in Figure 5.

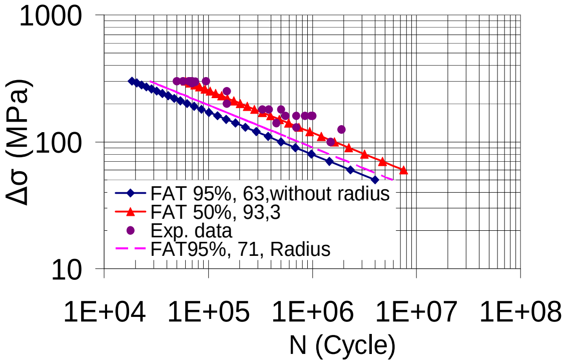


Figure 5. Calculated fatigue life based on fracture mechanics compared with measured results by *Lindqvist* [11].

In case of LOP, the current approach was compared with published test results by *Singh et al.* [17]. They carried out the fatigue life evaluations on gas tungsten arc welded load-carrying cruciform joints made of AISI 304L stainless steel. These experimental results were reported and identified as propagation and initiation life for LOP equal to 2, 3 and 6 *mm*, see Figure 6. The FAT value increase as the LOP decrease. For 2 *mm***,** FAT equals to 74 MPa, where it equals to 34 MPa in case of 6 *mm* LOP. The decreasing in FAT strength as LOP increases owing to decrease the crack path to reach a_f and the fatigue life will decrease. In spite of relatively high residual stresses are likely to occur in the welds, several works proposed that residual stress were neglected or they have relieved [17, 19].

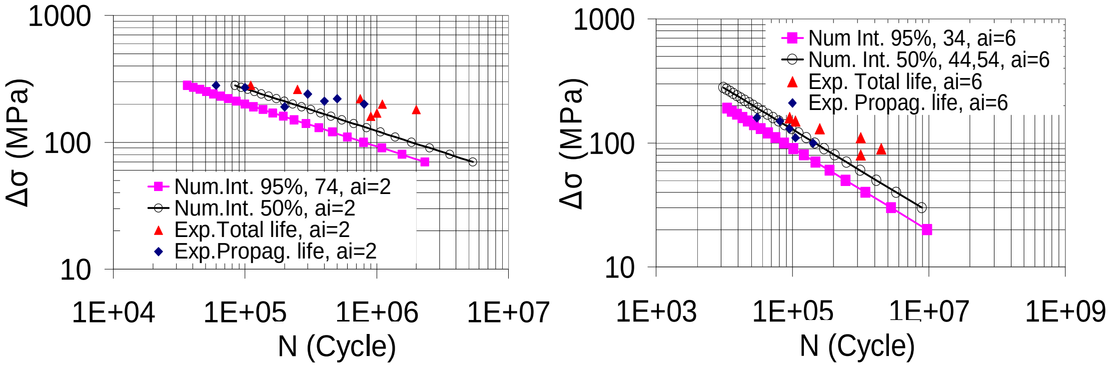


Figure 6. Calculated fatigue life based on fracture mechanics compared with experimental data reported by *Singh et al.* [17]. Left) LOP= 2 *mm*. Right) LOP=6 *mm*.

CONCLUSION

Fracture mechanics has been used to find the accurate prediction of fatigue life of welded joints. Literature proposed different values of cracks length and presented them normally as a range. That was the main motivation for this study to determine the crack length and growth parameters. The solutions of SIFs from FEA have been compared with solutions from BSI, IIW and literature. In case of LOP, good consistent results have been obtained between FEA and modified solution from BSI more than that from IIW. Therefore the ability was shown to use FRANC2D to simulate various weld shapes due to limitation in use of analytical and empirical solutions. The entire fatigue process in fillet welded joint has been modelled by pure fracture mechanics approach. The simple version of *Paris* law has been adopted. In this work, the initial crack depth 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 all joints that have weld toe crack. The conventional crack lengths for joints having LOP or incomplete melting welds metal will be equal to line of LOP. These initial crack length values are applicable for all types of joints which have the same crack type. The final crack length has a little effect as compared with the effect of initial crack. Therefore it is defined equal to half sheet thickness in case of weld toe when the crack path is perpendicular to applied load. Some other empirical equations were used for final length in case of LOP. Final crack length assumptions have been verified from *a*-*N* curve when the number of cycles becomes constant.

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