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Comparison of the Stress Intensity Factor of Load-Carrying Cruciform Welded Joints with Different Geometries

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The investigation of fatigue strength needs an accurate solution and reliable values of the stress intensity factor (SIF). In this study, SIF of load-carrying cruciform welded joints has been evaluated using finite element method (FEM), and compared with the available solutions from literature. Load-carrying cruciform welded joints with isosceles triangles and non-isosceles triangle fillet weld shapes were considered and have been analyzed by the FEM-based simulator FRANC2D program. Moreover, the effects of plate thickness and penetration depth have been considered. The aim of this work was to study the effects of these geometrical variables on fatigue SIF of the load-carrying welded joints with lack of penetration. The ability of FRANC2D to find an appropriate SIF solution is shown and compared with available solutions.

Keywords cruciform joint, fillet weld, lack of penetration, stress intensity factor, toe length, welded joint

1. Introduction

The inevitable parameter in fracture mechanics is the stress intensity factor (SIF), which is used in fatigue life calculation. SIF tightly knit with fracture mechanics which assumes that cracks already exist in welded joints.

An accurate determination of the SIF for the case under analysis is necessary in order to use the *Paris*' equation to calculate the fatigue life of welded joints (Ref 1).

With welded joints, high stress concentrations occur at the weld toe and at the weld root, which make these regions the points from which fatigue cracks may initiate. Nykänen et al. (Ref 2) mentioned that in parallel joints, toe cracks and lack of penetration (LOP) are frequently encountered defects. Toe cracks occur because of the stress concentration in the weld toe region, while LOP defects result from inaccessibility of the root region during welding. For load-carrying cruciform welded joints, LOP is considered the initial crack and plays an important role in fatigue life of these joints.

The effects of geometry on SIF solution have not yet been sufficiently investigated. Moreover, some geometrical parameters like weld toe leg length have not yet been investigated. Recent researches (Ref 3, 4) have investigated the effect of weld geometry configurations. The configurations included weld flank angle, weld toe radius and weld throat thickness with equal leg length on both sides of plates (cross and main plate) of non-load-carrying cruciform joints. Therefore, the plate thicknesses and weld leg length effects have been discussed in this study.

From literature (Ref 5-7), it is evident that most of the investigations on fatigue life prediction and SIF calculations of the fillet welded joints are based on toe failure. Some other studies have considered the fatigue behavior of fillet welded cruciform joints failing from the root region.

Motarjemi et al. (Ref 1), Usami and Kusumoto (Ref 8), Frank and Fisher (Ref 9), Balasubramanian and Guha (Ref 10), Knight (Ref 11) and Maddox (Ref 12) have studied the fatigue behavior and SIF of cruciform and T-welded joints of carbon steels failing from the LOP.

Singh et al. (Ref 13) carried out the fatigue life evaluations on gas tungsten arc welded load-carrying cruciform joints of AISI 304L stainless steel with a LOP. The predicted lives were compared with the experimental values for different LOP sizes.

These calculations need reliable SIF solutions. Unfortunately, there are limited SIF solutions due to the complexity and variety of welded geometries even for one joint. Also, these available limited solutions are even not yet validated.

In this study, fracture analysis code (FRANC2D) (Ref 14) has been used to calculate SIFs for cruciform welded joints. The comparisons between current FE solutions and available analytical solutions show a good agreement and the ability to calculate SIF for new geometrical limits is shown.

Therefore, it can be concluded that the proposed model can be used to find SIFs for other geometries which have unknown SIF solutions.

2. Stress Intensity Factor of Load-Carrying Cruciform Joint

For fillet welds and partial penetration T-butt welds, the unpenetrated region may be considered to act as an initial crack

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(Ref 1). The SIF resulting from the unpenetrated region will depend on the detailed geometry and hence a significant effect on fatigue behavior is to be expected.

Frank and Fisher (Ref 9) derived an empirical formula for obtaining the SIF of fatigue cracks that originate from weld roots based on the results of FEA. They performed a fatigue crack propagation analysis using their empirical formula and proposed a stress range calculation formula to evaluate fatigue strength. However, their study examined only joints with isosceles-triangle-shaped fillet welds (Ref 13, 15).

The polynomial expression for SIF range (ΔK), for a crack at the weld root in the case of an isosceles weld shape of a load-carrying cruciform joint developed by Frank and Fisher, is given as:

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

where h and S are the fillet weld leg length on main and attached plate, respectively, and h/B is the weld size, B is the attachment plate thickness and a is the crack length ($2a$ = LOP). The tensile stress range, $\Delta\sigma$, is applied to attachment plate as shown in Fig. 1. The width of the fillet weld is:

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

A_1 and A_2 are functions of weld size (h/B) given by:

$$A_1 = 0.528 + 3.286(h/B) - 4.361(h/B)^2 + 3.696(h/B)^3 - 1.874(h/B)^4 + 0.415(h/B)^5 \quad \text{(Eq 3)}$$

$$A_2 = 0.218 + 2.7717(h/B) - 10.171(h/B)^2 + 13.122(h/B)^3 - 7.775(h/B)^4 + 1.785(h/B)^5 \quad \text{(Eq 4)}$$

The International Institute of Welding (IIW) (Ref 16, 17) adopted Frank and Fisher formulas for the SIF which is valid for h/B from 0.2 to 1.2 and for $a/w < 0.7$ (Ref 9).

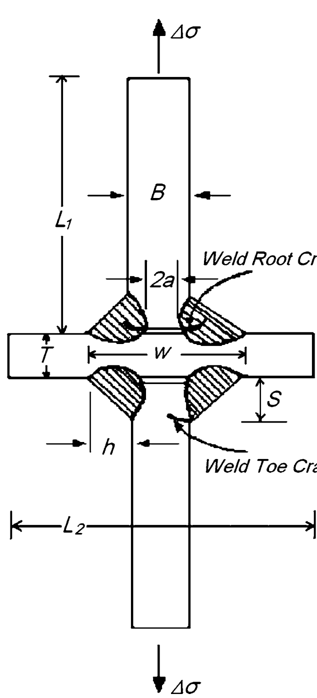

Fig. 1 Geometry of load-carrying cruciform welded joint

This formula was then improved by the British Standards Institution BSI PD6493 (Ref 18) and BSI 7910 (Ref 19), respectively. The range of the SIF can be written as:

$$\Delta K_I = M_k \Delta\sigma \left(\pi a Sec\frac{\pi a}{w}\right)^{1/2} \quad \text{(Eq 5)}$$

The parameter ΔK_I is known as the opening mode-I SIF and represents the strength of the stress surrounding the crack tip. M_k is the stress concentration magnification factor which is defined as the ratio of the SIF of a cracked plate with a stress concentration to the SIF with the same cracked plate without the stress concentration (Ref 20).

Maddox (Ref 21) introduced the concept of M_k as a magnification of the SIF, which would be the case for a crack of the same geometry but without the presence of the weld. Lie (Ref 22), Thurlbeck (Ref 23) and Bowness and Lee (Ref 24) have carried out further work on M_k values for cracks at weld toes as:

$$M_k = A_0 + A_1\left(\frac{2a}{w}\right) + A_2\left(\frac{2a}{w}\right)^2 \quad \text{(Eq 6)}$$

The values of A_0, A_1 and A_2 for equal leg length fillet welds ($h = S$) and unity ratio of main plate to attachment plate thickness ($B = T$) are as follows (Ref 1):

$$A_0 = 0.956 - 0.343\left(\frac{h}{B}\right) \quad \text{(Eq 7)}$$

$$A_1 = -1.219 + 6.210\left(\frac{h}{B}\right) - 12.220\left(\frac{h}{B}\right)^2 + 9.704\left(\frac{h}{B}\right)^3 - 2.741\left(\frac{h}{B}\right)^4 \quad \text{(Eq 8)}$$

$$A_2 = 1.954 - 7.938\left(\frac{h}{B}\right) + 13.299\left(\frac{h}{B}\right)^2 - 9.541\left(\frac{h}{B}\right)^3 + 2.513\left(\frac{h}{B}\right)^4 \quad \text{(Eq 9)}$$

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

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

In all above formulas, the unity leg lengths have been assumed ($h = S$). Motarjemi et al. (Ref 1) calculated the SIFs for cruciform and T-steel welded joints numerically.

SIF results of the cruciform joint were firstly compared with the above formulas for the case of equal attachment and main plate thickness ratio ($B/T = 1$). Results were then calculated for welded joints with $B/T < 1$, where the above formula is no longer valid. No analysis was carried out for $B/T > 1$, as this is not a recommended design. Moreover, the effect of different leg length has not yet been studied.

The effect of residual stresses on SIF and fatigue life have assumed negligible in small sheet thicknesses lower than 20 mm. However, some literature have assumed that residual stresses are relieved (Ref 13).

The other assumption was used that in the as-welded condition the crack remains open (mode-I) during the loading cycle due to the tensile residual stresses caused by welding are high enough (Ref 2, 20). Therefore, the SIFs range corresponding to the nominal stress range is effective and independent of the *R*-ratio of nominal stresses.

3. FE Simulations of Crack Growth and SIF Calculation

The fracture analysis code 2-dimensions (FRANC2D) is a FE-based simulator for curvilinear crack propagation in planar structures (plane stress, plane strain, and axisymmetric). CASCA, which is used for the creation of the meshes (see Fig. 2), is a preprocessor for generating initial input files for FRANC2D. This program has the ability to analyze a cracked body using special isoparametric crack tip elements to describe the singularity ahead of the crack tip.

If the loading and the cracks are not considered, the cruciform joint is symmetrical about both *x*- and *y*-axes. In the case of crack initiation from LOP, the joint is always symmetrical unless the weld penetrations have different lengths from each side, e.g., one side has complete penetration and the other side has incomplete penetration. Therefore, the joint can be simplified to a half or quarter model. In current calculations, only a quarter of cruciform specimen is modeled in FE analysis because of symmetry.

The material type used in this study for base material and weld metal was steel, so values of v and E were chosen as 0.293 and 203 GPa, respectively, and the materials have been assumed to be isotropic, linear elastic.

The effects of mesh density, crack growth increments and the symmetry have been benchmarked. Figure 2 shows one FE mesh with 8-noded, plane strain elements and the boundary conditions that are used in this work.

The main purpose of this work is to show the validity of the FRANC2D program to calculate accurate SIF in welded joints which will be used to calculate fatigue life. Hence, with knowledge of the SIF at different crack depths (a), it is possible to make curve fits for $K_I(a)$ for different loadings due to the linear relation between SIF and load.

Table 1 lists different geometrical parameters that were used including the attachment plate thickness and main plate thickness, weld size, shape, and toe leg length. Moreover, the unpenetrate line, LOP, was treated as an initial crack ($2a$).

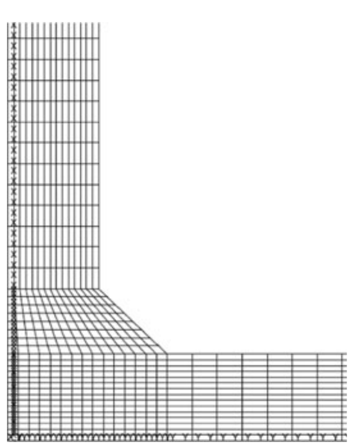

Fig. 2 Mesh and boundary conditions

A uniform tensile stress range of 96 MPa was applied to the end of the attachment plate to consider the crack growth propagation from LOP.

Results of the FE analysis were processed using analytical methods and these data were used to estimate the relative change in SIF due to the geometry of the fillet.

In this study, first the SIFs calculated for $B/T = 1$ using FRANC2D are compared with those calculated from BSI, IIW and Frank and Fisher's formula. Then, the calculated results are obtained for $B/T < 1$, where no empirical or analytical solutions are available and Frank and Fisher formulas are no longer valid.

FRANC provides higher time saving because it is better than other available FEM program at mesh generation and automatic crack propagation. There is other choice in the simulation by FRANC2D that is based on step-by-step FE procedure with continuous re-meshing to the surrounding region of the propagating crack tip. Therefore, this program has advantages over other FE software in calculations of SIFs.

The crack path direction coincides with LOP. After some millimeters, the path will be inclined toward the applied load as shown in Fig. 3. The trend of the current model agrees with the experimental test results carried out by Kainuma and Mori (Ref 15). They showed that the fatigue crack originated from the weld root of load-carrying cruciform joint and propagated into the weld metal in a direction roughly perpendicular to the applied load. This direction coincided with that of the unwelded line. A failure line leaning approximately 45° toward the unwelded line was generated by the final and static failures (Ref 15). In the elastic analysis the SIFs at the tip of LOP are calculated.

The FEM simulation by FRANC2D shows that the maximum stress intensities develop when the plane of the crack is normal to the direction of the primary tensile stress. However, as the plane of the crack tilts further away from the mode-I tensile loading, the structural member, in the form of plate or similar configuration, will lose its ability to support the external load. At this point, fatigue failure will occur.

Fatigue failure is assumed to occur in the case of weld toe cracks when the depth of propagation reaches 40% of the plate thickness. It has been shown that after this depth, the residual fatigue life is insignificant (Ref 25), although some researchers have used 50% of the plate thickness (Ref 26-28). In cases of LOP, the above limits are not more valid in load-carrying cruciform joint, rather than the critical crack length was set to be $(0.8 \times S) + B/2$. The coefficient multiplying the leg length was varied between 0.6 and 0.9 and the difference in the calculated lives remained within a few percentage points of the values obtained when a coefficient of 0.8 was used (Ref 15). Whatever the value of final crack, it has such little effect on fatigue life that it can be considered as negligible.

The simulation procedure is validated by comparing with experimental and numerical data that are founded in the literature when the LOP is equal to the plate thickness, as

Table 1 The details of geometries for cruciform welded joint

***B*, mm**	***T*, mm**	**2*a*, mm**	***h*, mm**	***S*, mm**	**L_1, mm**	**L_2, mm**
15	15,25	3	6,10	6,10	150	150

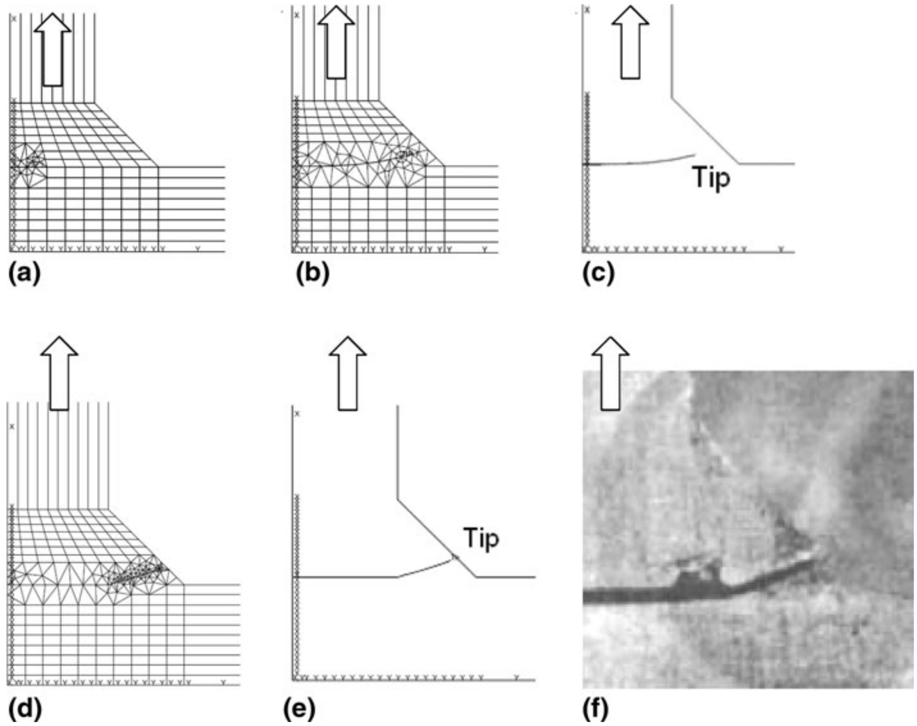

Fig. 3 (a) Crack initiation (LOP = *B*/3), (b) crack growth steps, (c) the boundary condition of root crack joint, (d, e) current simulation, and (f) real propagation path (LOP = *B*) (Ref 29)

shown in Fig. 3(d)-(f). In this case, the crack will suddenly curve toward final failure.

In this analysis, the cracks were considered to be grown under mode-I type, and the results were acceptable.

4. Results and Discussion

At cruciform joints with fillet welds two loci of crack initiation exist, the weld transition toe at the surface of the main plate and at the weld root. The first crack propagates through the main plate, whereas the second one propagates through the weld throat (Ref 15, 30, 31).

The initial numerical study was to find the SIFs versus crack length. The maximum hoop stress theory was exploited in FRANC2D to predict the direction of the crack growth when it was perpendicular to the nominal applied load.

The LOP size will influence the fatigue life of cruciform joints because it considers as initial crack. As the LOP increases, the fatigue life decreases (Ref 32), because the larger LOP will need a shorter path before reaching final failure.

In welded cruciform joints, the LOP occurs in the joint due to the lack of access to the root. The structures in which such joints are used are often subjected to fatigue loading. This may result in the initiation of fatigue cracks at the LOP tip as well as from the weld toe region, which depends on the LOP size, fillet geometry and leg length.

Usami and Kusumoto (Ref 8) determined a solution for the maximum principal SIF by considering both K_{I} and K_{II} in the case of cruciform joints with root crack. The SIFs K_{I} and K_{II} of cruciform joints were calculated by FEM (Ref 33). The fatigue limit and the direction of crack propagation under mixed load loading are well expressed by the maximum principal stress criterion.

5. Results Convergence

5.1 Influence of Mesh Size

To investigate the convergence in results, FEM analyses were performed on models with different meshes and crack increment steps. The meshes generated for the quarter model of the specimen are shown in Fig. 2. The SIFs were obtained by applying the fracture mechanics method to the FEM where an existing crack has to be assumed in welded joint and grows to its final length under the fatigue loading. Figure 4 shows that the results of crack length increments (Δa) and mesh size density have converged respectively. There are no influences on the stability of results.

As well as providing confidence in the analysis, the very close agreements between the two types of mesh and increments indicate that these effects on the SIF are negligible.

5.2 Influence of Symmetry

Taking into account symmetry, only a quarter of the complete geometry was simulated. Mashiri et al. (Ref 34, 35) found that the percentage difference in the number of cycles for fatigue crack propagation life between the simplified half model and a full model is 0.3% using the boundary element analysis system software (BEASY). The complete cruciform joint model with the four crack tips and the boundary conditions is shown in Fig. 5.

The FRANC2D FE-based simulation shows that no difference occurs between quarter and complete models as shown in Fig. 6. Therefore, the quarter models are a reasonable approximation of the cruciform joints and can be used to estimate SIF and the fatigue crack propagation life of these joints.

5.3 Stress Intensity Factor Solutions

The influence of the weld geometry was incorporated into the solution using FRANC analysis. Existing SIF solutions are mostly derived from 2-D plane strain models containing edge cracks (Ref 36), where the maximum stress intensities develop when the plane of the crack path is normal to the direction of the primary tensile stress. The SIFs for cruciform joints were calculated using FRANC2D and were compared with solutions from Frank and Fisher (Ref 9), BSI 7910 (Ref 18, 19) and IIW (Ref 16, 17). The comparisons are shown in Fig. 7.

To study the effect of curved crack path and convergence of results, two FE solutions have been used. In the first solution, the SIFs are calculated for only initial crack step, i.e., $a_i = 1.5$, 2, 5, 7.5, 9, 10, and 11.5 mm. In the second solution, the initial LOP growing to final crack (from $2a_i$ = LOP to failure) was

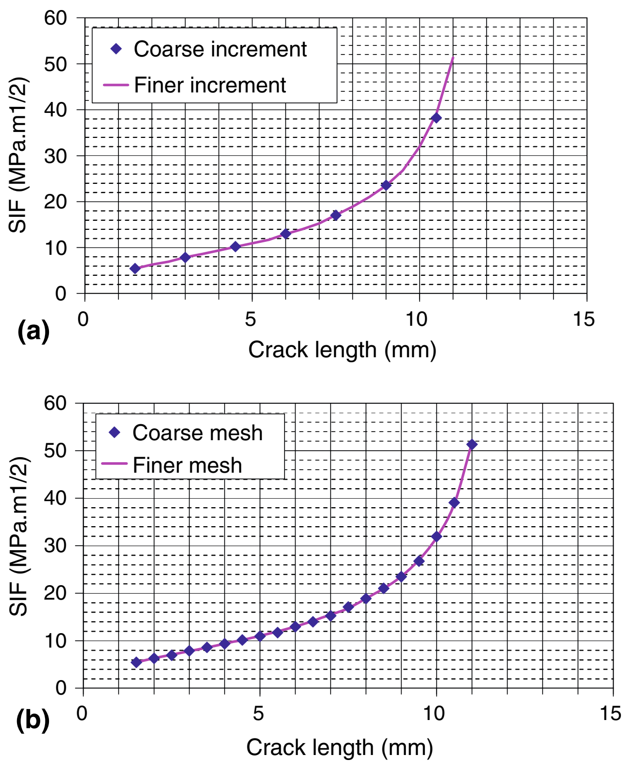

Fig. 4 Convergence results for the effect of (a) crack increment and (b) mesh size and density, $\Delta\sigma$ = 96 MPa

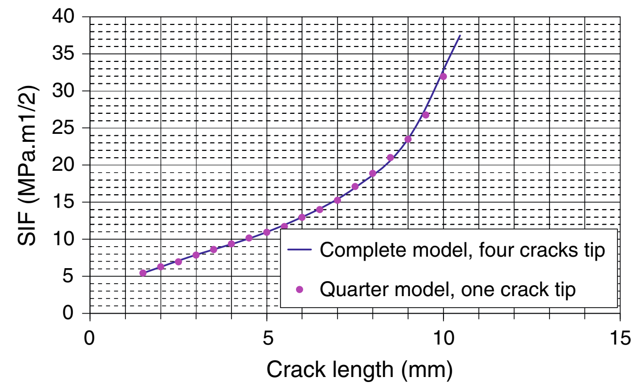

Fig. 6 SIF comparisons between complete cruciform model and quarter model (FRANC2D), $\Delta\sigma$ = 96 MPa

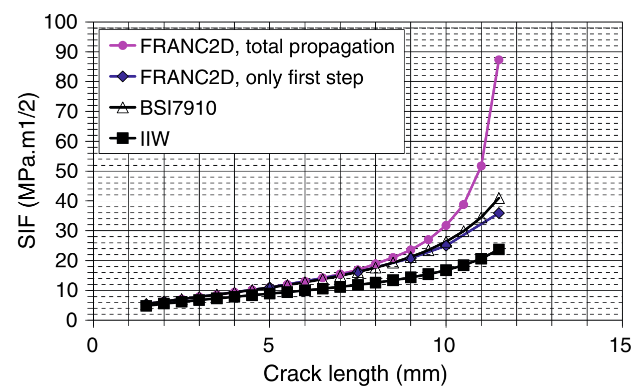

Fig. 7 Comparisons between different SIF solutions, $\Delta\sigma$ = 96 MPa

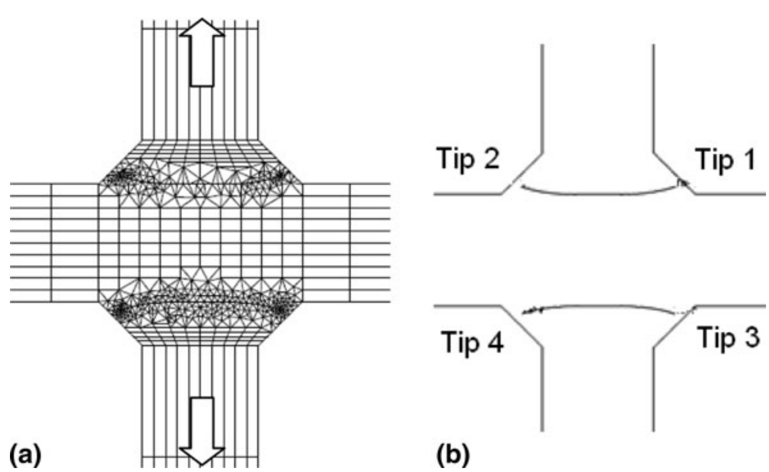

Fig. 5 Simulation of load-carrying cruciform joint (FRANC2D): (a) FE model and (b) crack growth boundary

calculated. The comparison of both solutions shows that the solutions from BSI 7910 are more realistic and have quite good agreement with FEA, more than IIW solution. This is because the latter solution has used the none-modified SIFs equation.

The first FRANC calculation is more consistent with those from BSI up to the final calculated crack length; however, the first FRANC solution assumed a straight line crack path normal to applied load.

The second calculation from FRANC shows a good fit with BSI up to crack length equal to plate thickness ($a = B/2$) where the crack is normal to the applied load and has a straight path. Over this length, the comparison has a little bit diverged because the crack will be inclined with respect to the original crack path.

Since the authors found negligible variation between the two FRANC2D solutions and the modified SIF solution from BSI 7910, it is proposed to use FE for calculating the SIF range in various shapes failing from the root gap.

The most important results are that the solutions from BSI and IIW have ignored the real effect of crack path inclination as shown in comparison between second FRANC solution and those from BSI and IIW as shown in Fig. 7.

Therefore, another advantage is recorded for FRANC even rather than the most modified SIF solutions.

5.4 Effect of Weld Shape and Leg Length

Due to the variation of the weld throat thickness, the leg length h and S will be varied. According to Örjasäter (Ref 37), the fatigue strength increases with leg length. In this case, the influence of the leg length is difficult to quantify.

The weld shape usually depends on the welding position and welding conditions, which cause difference in weld geometrical parameters. Sometimes, the weld is shaped like a scalene triangle or an isosceles triangle or it has a concave or convex curvature. Hence, the applications of available solutions are limited.

Motarjemi (Ref 1), Singh et al. (Ref 13), and Thurlbeck (Ref 23) referred to use Frank and Fisher equation for equal leg length case (i.e., $h = S$) and unity thicknesses ratio (B/T). Therefore, according to the above literature, the present study will investigate the effect of weld toe length of main and attached plate (h and S) on SIF. Moreover, the ability to use FRANC has been shown.

Figures 8 and 9 show the comparisons between SIF that are calculated by FRANC2D and those calculated from BSI (modified Frank and Fisher formula) for isosceles triangles shape fillet weld ($S = h$) and plate thickness ratio (B/T) of unity. It can be seen that the calculated results have very good agreement with BSI as discussed in the previous section. It shows that the increasing of weld size will decrease the SIF as shown in Fig. 8(a) and (b).

The current simulation showed that the empirical formulas are unable to find appropriate SIF solutions in the case of unequal leg length ($h \neq S$); however, with the ratio of h/B and S/B being within (0.2-1.2), as shown in Fig. 9. Hence, the FE solutions are considered.

It can be concluded that the leg length on the main plate side, h, has a significant effect on SIF in the case of load-carrying cruciform joint more than that of the attached leg length, S. The SIF increases as leg length on main plate increases as shown in Fig. 9. The same results of leg length effects have been obtained in case of $B \neq T$ as shown in Fig. 10 and 11.

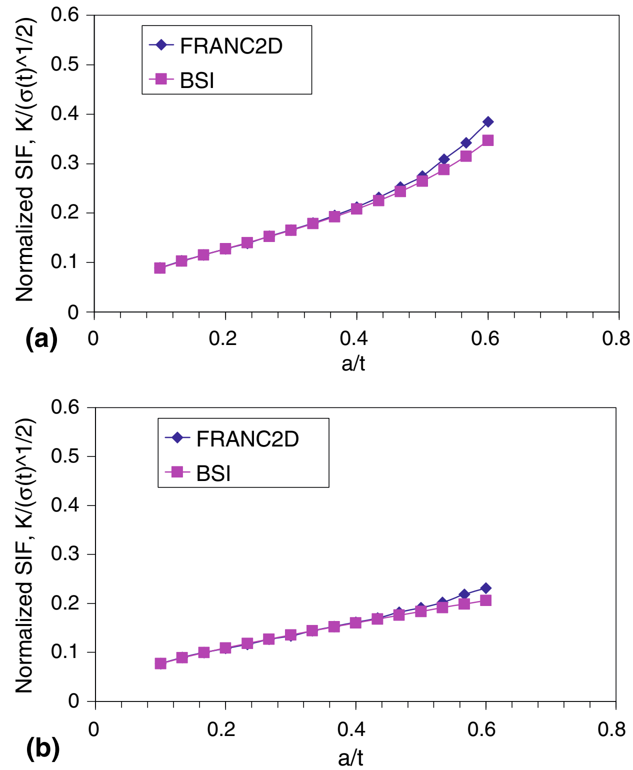

Fig. 8 Calculated SIF for $B = T = 15$ mm, $2a = 3$ mm, isosceles triangles weld shape, $\Delta\sigma = 96$ MPa: (a) $h = S = 6$ mm and (b) $h = S = 10$ mm

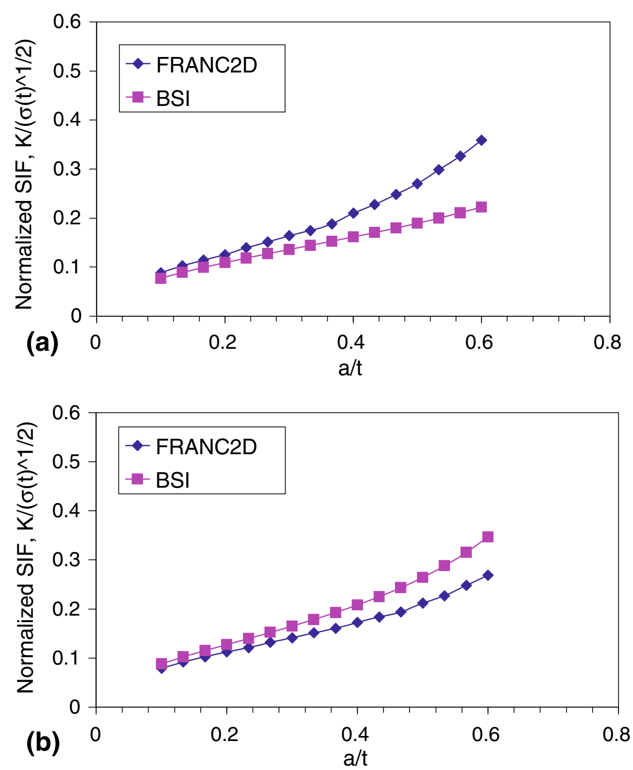

Fig. 9 Calculated SIF for $B = T = 15$ mm, $2a = 3$ mm, non-isosceles triangles weld shape, $\Delta\sigma = 96$ MPa: (a) $h = 10$ mm, $S = 6$ mm and (b) $h = 6$ mm, $S = 10$ mm

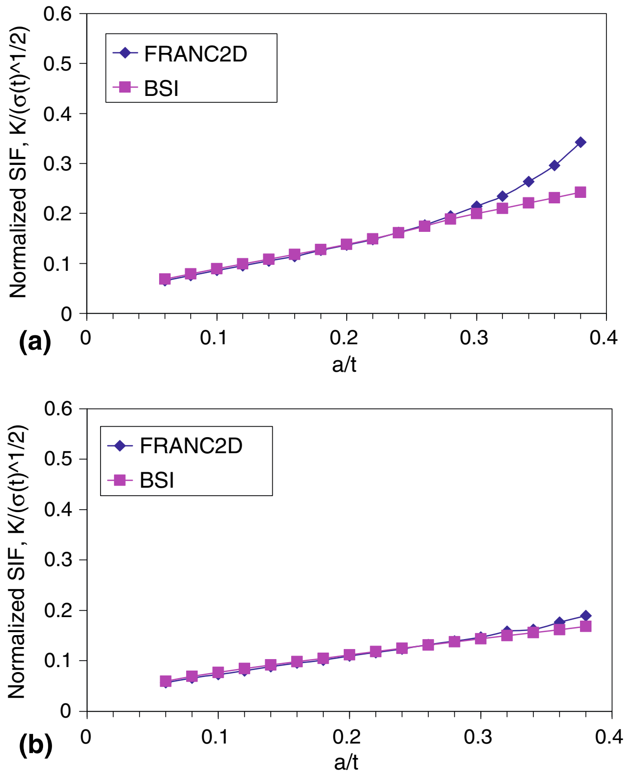

Fig. 10 Calculated SIF for $B = 15$ mm, $T = 25$ mm, $2a = 3$ mm, isosceles triangles weld shape, $\Delta\sigma = 96$ MPa: (a) $h = S = 6$ mm and (b) $h = S = 10$ mm

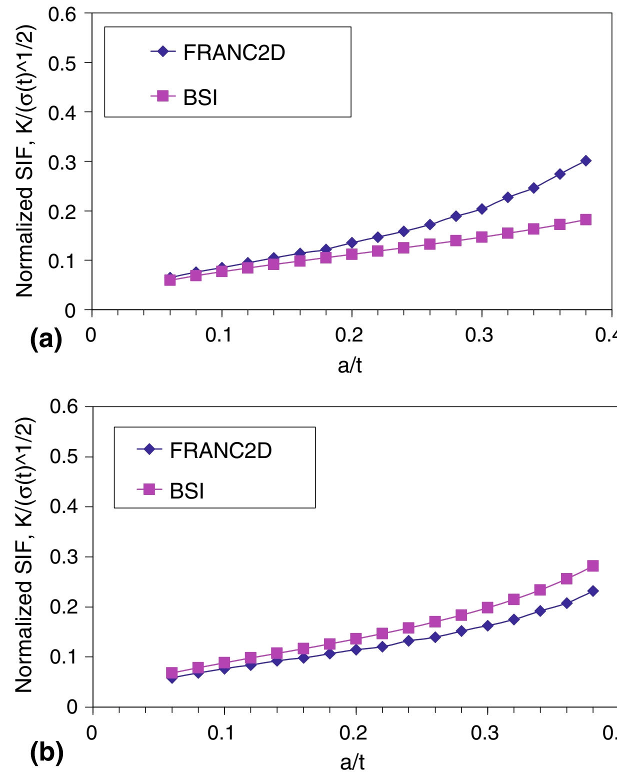

Fig. 11 Calculated SIF for $B = 15$ mm, $T = 25$ mm, 2a = 3 mm, non-isosceles triangles weld shape, $\Delta\sigma = 96$ MPa: (a) $h = 10$ mm, $S = 6$ mm and (b) $h = 6$ mm, $S = 10$ mm

5.5 Effect of Plate Thickness Ratio

The analytical formula from BSI and IIW are no longer able to find SIF solutions when $B \neq T$ and $S \neq h$. The comparison with FEM for plate thickness ratio $B/T < 1$ is shown in Fig. 10. In isosceles triangles fillet weld shape there are no big differences between equal plate thicknesses $B/T = 1$ (Fig. 8) and non-equal plate thickness $B/T < 1$ (Fig. 10). For design reasons, usually the ratio $B/T > 1$ is not considered (Ref 1).

It can be concluded that the effect of plate thickness on SIF and fatigue strength is less significant as compared with the effect of leg length. This is because the thickness affects different mechanisms in fillet welded joints in both cracking cases, weld toe crack and weld root crack. When fatigue cracks originate from a weld toe, the thickness affects the stress concentration at the weld toe. In contrast, only the thickness affects the initial crack size (LOP) when crack originates from a weld root. Therefore, assuming constant crack length (constant LOP), the effects of thicknesses are less. Unless the increase in B will increase LOP, then the fatigue life will decrease.

No specific studies deal with the calculations and comparisons of SIF as based on FE, IIW and BSI to investigate the reliability of proposed solutions to use in fatigue life laws. Moreover, in knowledge of authors, FRANC was not used in fillet welded joints cracking until now.

6. Conclusions

The comparisons between different SIF solutions have been discussed. Once the reliable SIF solution is constructed, it can easily be used by local approach to calculate fatigue life. Several formulas were used to calculate SIF via crack length.

The different methods for obtaining accurate SIF solutions are discussed. Benchmarks were created by modifying SIF at the crack tip and comparing between different solutions. The LOP forms the root cracks and recommendations are given to use the modified solution from BSI 7910 instead of IIW. The reason for the difference between these two solutions (BSI and IIW) is that IIW uses the old Frank and Fisher formula, whereas recently BSI modified this formula.

The new modified solution from BSI is compared with those from FRANC2D and good agreements have been shown. However, FRANC2D has advantages over both solutions because it provides good crack path descriptions and considers the curved crack path. Hence, a more accurate SIF solution has been obtained. The crack path orientation angle has been investigated by using two crack propagation manners.

In the case of other geometries, the current solution will be adequate to use due to limits in the use of analytical and empirical solutions. The effect of weld toe length on main plate and cross plate was not sufficiently investigated and explained. Therefore, this is another purpose of the present study which shows the effect of leg length on the fracture toughness of fillet welded joints.

The main findings of the weld geometry effect are as follows:

1. The increase of weld size in isosceles triangles fillet weld shape will decrease the SIF.
2. The weld leg length, h and S, have a major effect on SIF. The new ratio (S/h) was presented for SIF calculation in

root crack of cruciform joints. The conclusions showed that the value of SIF is strongly affected by the leg length on main plate side. The increasing h will significantly increase SIF.

3. The effects of unequal plate thicknesses ($B/T < 1$) were studied, and there are no effects of plate thickness ratio on SIF solutions for load-carrying cruciform joints.

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References

1. A.K. Motarjemi, A.H. Kokabi, A.A. Ziaie, S. Manteghi, and F.M. Burdekin, Comparison of the Stress Intensity Factor of T and Cruciform Welded Joints with Different Main and Attachment Plate Thickness, *Eng. Fract. Mech.*, 2000, **65**(1), p 55–66
2. T. Nykänen, X. Li, T. Björk, and G. Marquis, A Parametric Fracture Mechanics Study of Welded Joints with Toe Cracks, *Eng. Fract. Mech.*, 2005, **72**(10), p 1580–1609
3. C.-H. Lee, K.-H. Chang, G.-C. Jang, and C.-Y. Lee, Effect of Weld Geometry on the Fatigue Life of Non-Load-Carrying Fillet Welded Cruciform Joints, *Eng. Fail. Anal.*, 2009, **16**(3), p 849–855
4. J. Lindqvist, "Fatigue Strengths Thickness Dependence in Welded Construction," M.Sc. Thesis, Borlänge University, 2002
5. I.F.C. Smith and R.A. Smith, Fatigue Crack Growth in a Fillet Welded Joint, *Eng. Fract. Mech.*, 1983, **18**(4), p 861–869
6. R.A. Testin, J.Y. Yung, F.V. Lawrence, and R.C. Rice, Predicting the Fatigue Resistance of Steel Weldments, *Weld. Res. Suppl.*, 1987, **4**, p 93s–98s
7. J.M. Ferreira and C.M. Branco, Influence of Fillet Weld Joint Geometry on Fatigue Crack Growth, *Theor. Appl. Fract. Mech.*, 1991, **15**(2), p 131–142
8. S. Usami and S. Kusumoto, Fatigue Strength at Roots of Cruciform, Tee and Lap Joints, *Trans. Japan Weld. Soc.*, 1979, **9**(1), p 1–10
9. K.H. Frank and J.W. Fisher, Fatigue Strength of Fillet Welded Cruciform Joints, *J. Struct. Div.*, 1979, **105**, p 1727–1740
10. V. Balasubramanian and B. Guha, Fatigue Life Predication of Welded Cruciform Joints Using Strain Energy Density Factor Approach, *Theor. Appl. Fract. Mech.*, 2000, **34**(1), p 85–92
11. J.W. Knight, "Some Basic Fatigue Data for Various Types of Fillet Welded Joints in Structured Steel," Welding Institute Members Report 9/1976/E, 1976
12. S.J. Maddox, Assessing the Significance of Flaws in Welds Subjects to Fatigue, *Weld. J. Res. Suppl.*, 1974, **53**(9), p 401–409
13. P.J. Singh, D.R.G. Achar, B. Guha, and H. Nordberg, Fatigue Life Predication of Gas Tungsten Arc Welded AISI, 304L Cruciform Joints with Different LOP Sizes, *Int. J. Fatigue*, 2003, **25**(1), p 1–7
14. Cornell Fracture Group, http://www.cfg.cornell.edu, 2007
15. S. Kainuma and T. Mori, A Fatigue Strength Evaluation Method For Load-Carrying Fillet Welded Cruciform Joints, *Int. J. Fatigue*, 2006, **28**(8), p 864–872
16. A. Hobbacher, "Recommendations for Fatigue Design of Welded Joints and Components," IIW Doc., No XIII-1965r14-03/XV-1127r14-03, International Institute of Welding, 2006
17. A. Hobbacher, "Recommendations for Fatigue Design of Welded Joints and Components," IIW Doc., No XIII-2151-07/XV-1254-07, International Institute of Welding, 2007
18. British Standard Institution, London, PD 6493, Appendix J, 1997, p 29
19. British Standards Institution, "Guidance on Methods for the Acceptance of Flaws in Structure," PD 6493, BS 7910, Appendix J, 2001
20. T. Nykänen, G. Marquis, and T. Björk, Fatigue Analysis of Non-Load Carrying Fillet Welded Cruciform Joints, *Eng. Fract. Mech.*, 2007, **74**(3), p 399–415
21. S.J. Maddox, An Analysis of Fatigue Cracks in Fillet Welded Joints, *Int. J. Fract.*, 1975, **11**(2), p 221–243
22. S.T. Lie, "The Influence of Geometrical Parameters on the Fatigue Strength of Fillet Welds Using Boundary Element and Fracture Mechanics Methods," Ph.D. Thesis, University of Manchester, Institute of Science and Technology (UMIST), 1983
23. S.D. Thurlbeck, "A Fracture Mechanics Based Methodology for the Assessment of Weld Toe Cracks in Tubular Offshore Joints," Ph.D. Thesis, University of Manchester, Institute of Science and Technology (UMIST), 1991
24. D. Bowness and M.M.K. Lee, Stress Intensity Factor Solutions for Semi-Elliptical Weld-Toe Cracks in T-Butt Geometries, *Fatigue Fract. Eng. Mater. Struct.*, 1996, **19**(6), p 787–797
25. T. Mori, X.L. Zhao, and P. Grundy, Fatigue Strength of Transverse Single-Sided Fillet Welded Joints, *Aust. Civil/Struct. Trans.*, 1997, **C39**(2–3), p 95–105
26. T.N. Nguyen and M.A. Wahab, A Theoretical Study of the Effect of Weld Geometry Parameters on Fatigue Crack Propagation Life, *Eng. Fract. Mech.*, 1995, **51**(1), p 1–18
27. R.O. Bell, O. Vosikovsky, and S.A. Bain, The Significance of Weld Toe Undercuts in the Fatigue of Steel Plate T-Joints, *Int. J. Fatigue*, 1989, **11**(1), p 3–11
28. A.S.J. Swamidas, P.J. Cheema, and D.B. Muggeridge, Fatigue Strength of Fillet Welded Cruciform Joints, *Can. J. Civil Eng.*, 1989, **16**(2), p 162–171
29. V. Balasubramanian and B. Guha, Establishing Criteria for Root and Toe Cracking of Load Carrying Cruciform Joints of Pressure Vessel Grade Steel, *Eng. Fail. Anal.*, 2004, **11**(6), p 967–974
30. H. Yokota and K. Anami, *Local Stress Approach for Fatigue Assessment*, Kochi University of Technology, 2006
31. A. Hobbacher, Stress Intensity Factor of Welded Joint, *Eng. Fract. Mech.*, 1993, **46**(2), p 173–182
32. A. Al-Mukhtar, P. Hübner, S. Henkel, and H. Biermann, Lebensdauerberechnung Von Schweissverbindungen Mit Bruchmechanischen Methoden (Fatigue Life Calculation of Welded Joints with Fracture Mechanics Methods), *The German Association for Materials Research and Testing (DVM), 41 Conference*, 17-18 February, Wuppertal, Germany, 2009, p 63–72 (in German)
33. H. Miyata, S. Shida, and S. Kusumoto, The Simple Method of Evaluation of Stress Intensity Factor Using the Finite Element Method, *Proceedings of the Symposium on Mechanical Behaviour of Materials*, 1974, p 63–81
34. F.R. Mashiri, X.L. Zhao, and P. Grundy, Effect of Weld Profile and Undercut on Fatigue Crack Propagation Life of Thin Walled Cruciform Joint, *Thin Walled Struct.*, 2001, **39**(3), p 261–285
35. F.R. Mashiri, X.L. Zhao, and P. Grundy, Crack Propagation Analysis of Welded Thin-Walled Cruciform Joint Using Boundary Element Method, *Materials Research Forum 1997 Conference Proceedings,* Institute of Metals and Materials Australasia Ltd, Australia, 20–21 Nov, 1997
36. M.S. Alam, "Structural Integrity and Fatigue Crack Propagation Life Assessment of Welded and Weld-Repaired Structures," Ph.D. Thesis, Louisiana State University and Agricultural and Mechanical College, 2005
37. O. Örjasäter, Effect of Plate Thickness on Fatigue of Welded Components, *SINTEF, Materials Technology Trondheim*, IIW–XIII-1582-95, Norway, May 1995