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FINITE ELEMENT-BASED FATIGUE LIFE PREDICTION OF A LOAD-CARRYING CRUCIFORM JOINT

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ABSTRACT

The aim of this study is to determine the stress intensity factor (SIF) and fatigue lifecycle of load-carrying 6 mm-thick fillet-welded cruciform joints subjected to fatigue loading conditions by means of finite element analysis (FEA). These joints are typical of automotive structures such as the mid-series rear axle of motor trucks which are sensitive to fatigue loading because of their construction and loading conditions. Finite element software was used to develop various cruciform joint models with varying geometrical dimensions, namely the depth of penetration and weld throat length, and simulation and analysis of the crack propagation were performed with 2D and 3D crack simulation software. The effect of the variations in the weld geometry with an induced crack at the weld root and weld toe on fatigue life was determined from the simulation results. The stress intensity factor values and lifecycles determined by the fracture mechanics approach were compared with the simulation results. It was shown that an increase in the depth of weld penetration and the weld size in isosceles triangles fillet weld shape for crack initiated in the weld root can decrease the stress intensity factor (SIF) and intensify the fatigue lifecycle. It was also found that linear misalignment had no significant effect on the SIF and fatigue life of cracks originating from the weld toe.

Keywords: Cruciform welded joint; lack of penetration; SIF; fatigue; FRANC 2D/3D.

INTRODUCTION

The governing parameter for fatigue life estimation by fracture mechanics is the stress intensity factor (SIF), which indicates the stress intensity at the tip of the propagating crack assuming that cracks already exist in welded joints [1]. When the Paris equation is used for calculating the fatigue life of welded joints, precise determination of the SIF is a necessity [1-3]. High stress concentrations normally occur at the vicinity of the weld toe and weld root in typical welded joints, enabling fatigue cracks to originate in these regions. Toe cracks and lack of penetration (LOP) are a common defect in parallel joints. Toe cracks occur because of the stress concentration in the weld toe region, and LOP defects result from the inaccessibility of the root region during welding [2]. For load-carrying cruciform welded joints, LOP is considered the initial crack and plays an important role in the fatigue life of these joints [2, 4].

Fatigue resistance prediction is a major concern in the welded design of mechanical components and engineering structures subjected to cyclic loading. Numerous works have used several approaches to estimate fatigue crack propagation and fatigue life by means of experimentation and FEA [3, 5-7]. Branco et al. [8] applied the adaptive remeshing technique based on the finite element method to evaluate crack shape evolution and fatigue life. The fatigue life of cruciform joints with lack of penetration with different welding process was investigated by Balasubramanian and Guha [9]. A finite element modeling procedure for predicting fatigue crack growth rate in butt welds subjected to mode I loading condition was studied by Lee and Chang [10]. The weld-induced residual stress effect on the fatigue crack growth rate was then modeled by calculating the SIF owed to the residual stress field based on the superposition rule of linear elastic fracture mechanics (LEFM). Investigations on the fatigue fracture behavior of a 30 mm-thick cruciform welded joint with groove indicated a fatigue strength of 80 MPa and the fatigue crack source of the failed specimen originating from the weld toe [11].

Investigations of the effects of varying the geometry of weldment on SIF are scarce. Moreover, certain geometrical parameters such as the leg length ratio and the throat size have not yet been sufficiently investigated. Several researches on the effect of weld geometry have mainly concentrated on the weld flank angle, weld toe radius and weld throat thickness with equal leg length on both sides of plates (cross-plate and main plate) of non-load-carrying cruciform joints [12, 13]. The importance of SIF as a governing factor in fatigue life computation has been further established by numerous investigations focusing on fatigue life prediction and SIF calculations of fillet-welded joints and considering failures in the weld toe and root region [1, 2, 4, 14]. Hence this study focuses on the determination of SIF and fatigue lifecycles for 6 mm-thick load-carrying fillet-welded cruciform joints subjected to fatigue loading conditions by means of FEA using 2D and 3D crack simulation software through variations in the weld geometry with an induced crack at the weld root and weld toe.

METHODS AND MATERIALS

Stress Intensity Factor of Load-Carrying Cruciform Joint

The determination of the fatigue lifecycle of a welded structure is based on SIF computation in accordance with the initial crack caused by cyclic slips or welding flaws. The unpenetrated zone in partially penetrated T-butt welds is regarded as an initial crack. Therefore, the SIF ensuing from this zone is very much influenced by the geometry details and has a substantial effect on fatigue lifecycle behavior [1, 2, 4]. An empirical formula based on the results of finite element analysis (FEA) was introduced by Frank and Fisher [15] to calculate the SIF of fatigue cracks that originate from weld roots. A stress range computation formula was proposed for fatigue crack propagation analysis enabling the determination of the fatigue strength [2].

A polynomial expression for the SIF range (dK) for a crack at the weld root in the case of an isosceles weld shape of a load carrying a cruciform joint developed by Frank and Fisher [15] and is given as:

$$K_1 = \frac{S_R (A_2 + A_2 \frac{a}{w}) \sqrt{\frac{\pi a}{\cos(\pi a / 2w)}}}{1 + 2\left(\frac{H}{t_p}\right)} \tag{1}$$

The International Institute of Welding (IIW) [16] adopted Frank and Fisher's formula for the SIF which is valid for H/t_p from 0.2 to 1.2 and for $\frac{a}{w}$ from 0.0 to 0.7, where H is the leg length, t_p is plate thickness, A_1 and A_2 are function of x and S_R = nominal stress range in the main plate

$$w = H + \frac{t_p}{2} \tag{2}$$

$$x = \frac{H}{t_p} \tag{3}$$

$$A_1 = 0.528 + 3.287x - 4.361x^2 + 3.696x^3 - 1.875x^4 + 0.415x^5 \tag{4}$$

$$A_1 = 0.218 + 2.717x - 10.17x^2 + 13.122x^3 - 7.755x^4 + 1.783x^5 \tag{5}$$

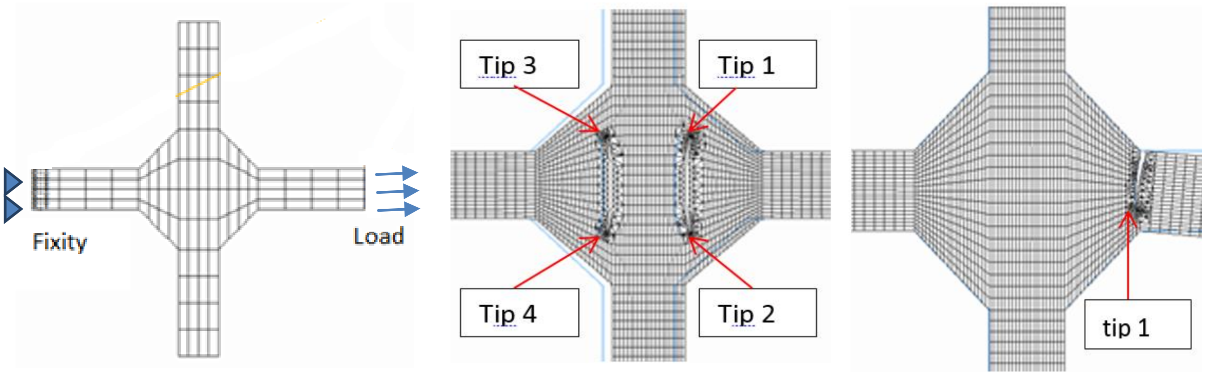
Subsequently the Paris equation was applied to calculate fatigue life. However since the mathematical integration is difficult to solve, fatigue life was determined by the numerical integration method where the stress intensity factor value was calculated from Eq. (1). In sheets with thicknesses less than 20 mm, the influence of residual stresses on SIF and fatigue life has been assumed as negligible although some research supposed that residual stresses are relieved [17]. In addition, the crack was assumed to remain open as in Mode-1 during cyclic loading because of the amount of tensile residual stress caused by welding in as-welded conditions. Therefore, the SIF's range corresponding to the nominal stress range is effective and independent of the R-ratio of nominal stresses.

Finite Element Modeling

In this study, fracture analysis codes (FRANC 2D and FRANC 3D) have been employed to compute the SIFs for load-carrying cruciform welded joints. A further comparison is made between the fracture analysis code computation and analytical calculations. The fracture analysis two-dimensional code (FRANC 2D) is a finite element-based simulator for curvilinear crack propagation in planar structures (plane stress, plane strain, and axisymmetric). The mesh creation was generated by a CASCA preprocessor which is able to analyze a cracked body by defining the singularity ahead of the crack tip and employing distinctive isoperimetric crack tip elements. The base and weld metal used for this study was assumed to be isotropic and linear elastic and the mechanical properties are shown in Table 1. Appropriate benchmarking for the possible influence of crack growth increments, symmetry and mesh density was conducted. All the sub-divided regions in the 2D model were built with rectangular bilinear four-sided meshing and the 3D model was meshed using sweep hexagon meshing and ANSYS APDL FEA software. The developed model was inserted into FRANC 2D and FRANC 3D for preprocessing and the material properties, constraints and loading conditions were defined as depicted in Table 1.

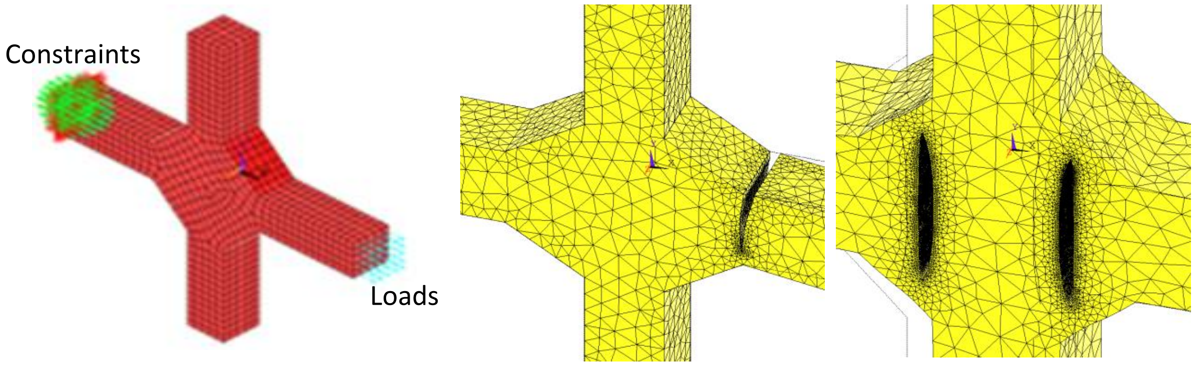
Table 1. Material properties of the base and weld metal.

Properties for cruciform model		Fracture and fatigue data	
Type of material	Steel: DOMEX 550 MC	Nominal stress range, S_R	150 MPa
Yield strength	550 MPa	Material constant, *C*	1.65×10^{-11} (MPa)
Ultimate strength	700 MPa	Material constant, *m*	3
Young modulus	210 GPa	Stress ratio, *R*	0
Plate thickness, t_p	12 mm	Critical fracture toughness, K_{1C}	120 MPa√m



(a) (b) (c)

Figure 1. The 2D FE modeling (a) The bilinear meshing in CASCA; (b) the crack initiation settings for the weld root crack and; (c) the crack initiation settings for the weld toe crack.



(a) (b) (c)

Figure 2. The 3D FE modeling (a) The sweep hexagon meshing in ANSYS; (b) The crack propagation for the weld toe crack; (c) The crack propagation for the weld root crack.

The cruciform model was fixed in the *x* and *y* directions and the nominal stress range was applied on the right end edge. The initial crack with a 1 mm increment was inserted into the cruciform model by coordinates definitions with four crack tips defined at the weld root and one crack initiation at the weld toe. Figure 1 depicts the bilinear meshing in CASCA and the crack initiation definition in FRANC 2D and Figure 2 shows the sweep hexagon meshing with stress distribution used in ANSYS APDL with the initiated weld root cracks designed for preprocessing in FRANC 3D . The geometrical dimensions of the cruciform joint are depicted in Figure 3. The main purpose of this work is to show the validity of the 2D and 3D programs for calculating accurately the SIF in welded joints which is used to calculate fatigue life. Hence, with knowledge of the SIF at different crack depths (a), it is possible to make curve fits for KI (a) for different loadings because of the linear relation between the SIF and load. Table 2 lists different geometrical parameters that were used, including linear misalignment, crack length, weld size, toe-leg length, leg length ratio and assessment methods. Moreover, the unpenetrated line, LOP, was treated as an initial crack (2a) for the crack initiation from the weld root and a 1 mm-deep crack was initiated for all geometrical variations in the weld toe crack. A total of nine geometrical variations were analyzed for the cracks initiating from the weld root and a total of 14 geometrical variations were used to investigate the crack propagation from the weld toe.

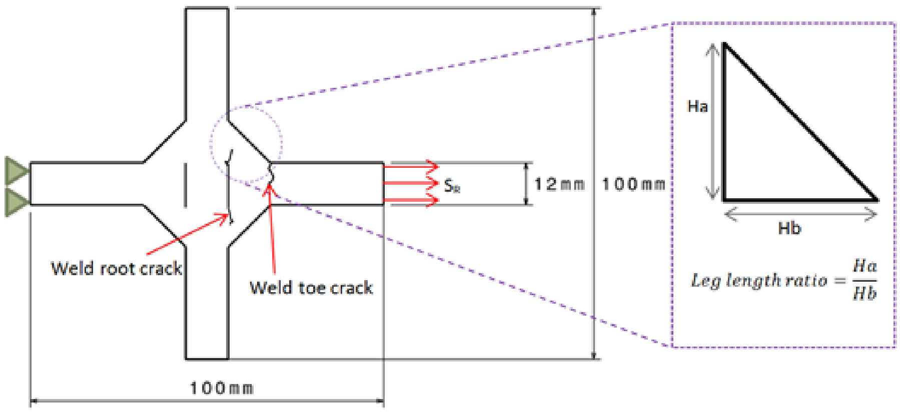


Figure 3. Boundary conditions and cruciform joint dimensions

Table 2. Weld geometry dimensional variations for weld root and weld toe crack initiation.

Total geometries	Crack length (mm)	Leg length, Ha (mm)	Leg length ratio	Misalignment (%)	Assessment methods
9 (root crack)	6, 8, 10	6, 9, 12	1	-	FRANC 2D, FRANC 3D and Analytical
14 (toe crack)	1	7, 9, 10.5, 12	0.58, 0.75, 0.875, 1.0, 1.14, 1.33, 1.7	0, 15	FRANC 2D and FRANC 3D

RESULTS AND DISCUSSION

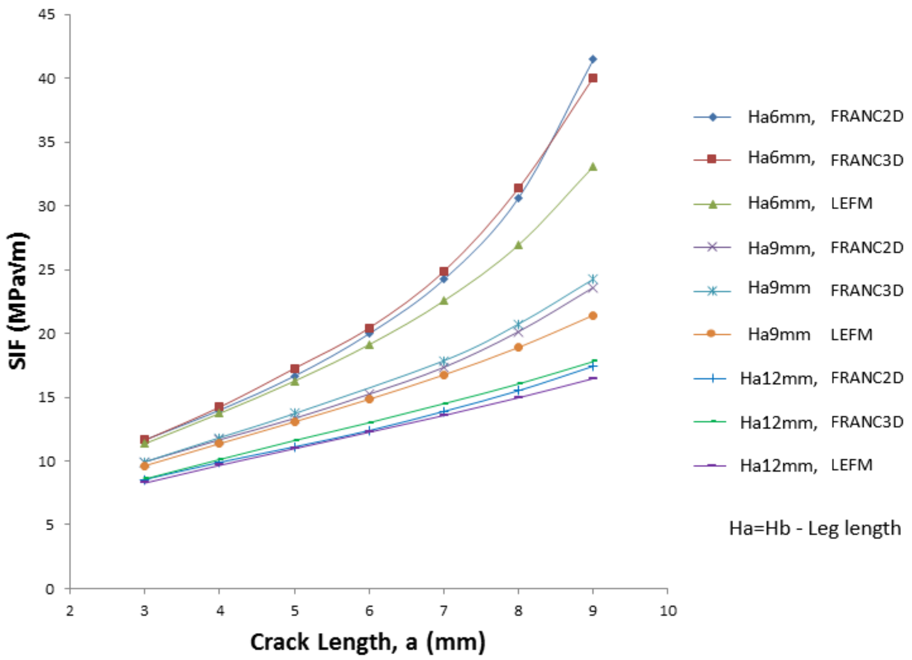
Cracks initiating in a cruciform joint with fillet welds largely exist in the main plate surface in the vicinity of the weld transition toe and at the weld root. The first crack propagates through the main plate, whereas the second one propagates through the weld throat [18]. The maximum hoop stress theory was employed in the 2D and 3D computation during the initial stage of investigating the SIFs versus crack length for crack propagation perpendicular to the nominal load applied. The fatigue life of cruciform joints is influenced by the size of the LOP, which acts as an initial crack with any increase in the LOP causing a decrease in the fatigue life and vice versa, as a bigger LOP needs a shorter route before the final fracture. The FEA was employed to determine the influence of the weld geometry as past research has mostly utilized the 2-D plane strain models containing edge cracks to derive SIF solutions. These models depict a maximum stress intensity development when the direction of the primary tensile stress is normal to the plane of the crack path [17]. The SIFs for cruciform joints were calculated with 2D as well as 3D computation and were compared with solutions from Frank and Fisher. The SIF solutions for cracks initiating from the weld root and weld toe were reached separately under varying geometrical conditions.

Crack Initiation at Weld Root

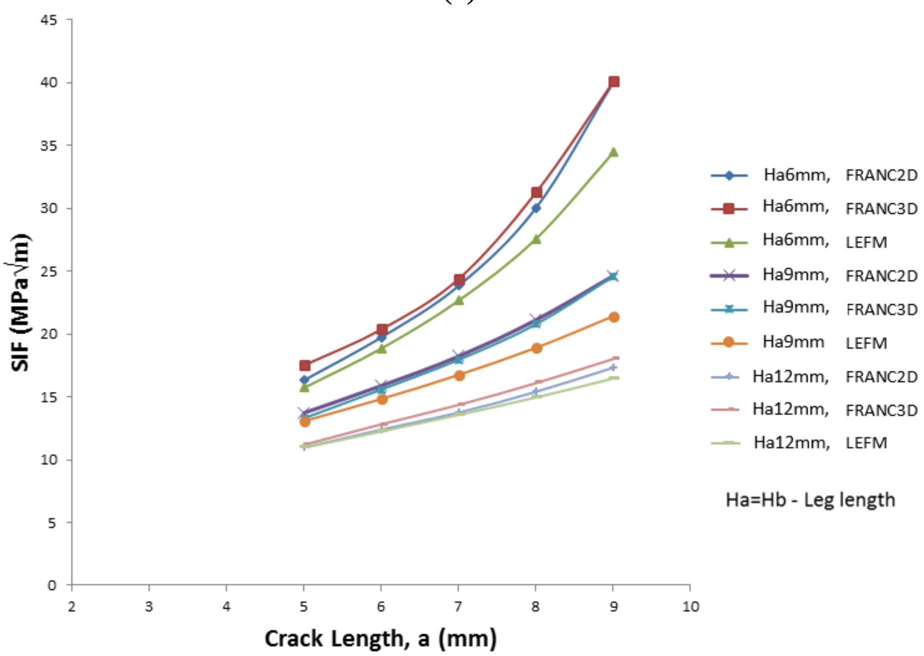
The SIF solutions were determined at each crack tip from the assumed LOP crack initiation to the final crack length with an increment of 1 mm for crack initiation values of 6 mm, 8 mm and 10 mm as well as varied leg lengths of 6 mm, 9 mm and 12 mm. The comparisons for cracks initiating from the weld root are shown in Figure 4. Different SIF solutions from 2D and 3D along with LEFM approach were computed for comparison. The results obtained show that weld geometries with an increased initial crack size but similar leg length contribute to a higher SIF value at the beginning of the propagation. However, equivalent SIF values are depicted as the crack propagates and very similar SIF values are obtained towards the end of the crack for all geometrical variations because of the similarities of the crack propagation path in the simulation [2]. Increments to the leg length size with constant initial crack sizes showed a decrease in the SIF values obtained and good agreement with the findings of [2, 10]. The highest SIF value of 18 MPa√m was obtained with the geometrical variation of 6 mm leg length and 10 mm crack initiation size.

The SIF results obtained from 2D, 3D and LEFM assessment methods are shown in Figure 5. The 2D and 3D computations generate identical SIF solutions along the crack length for all models with similar leg length and initial crack size and SIF values determined by FRANC 3D are seemingly slightly higher than FRANC 2D with a percentage difference of 4.3%, as depicted in Figure 5. The SIF values determined by the LEFM approach minor variations compared with 2D and 3D simulations in the vicinity of the crack initiation, but become more distinct when the crack length increases to the final length. The differences are obvious in geometries with 6 mm and 9 mm leg length. Overall, the SIF value determined with 3D modeling are slightly higher than 2D and LEFM provides the lowest SIF values. The comparable SIF values are owed to the SIF solution techniques employed in each simulation. Three techniques are used in the 2D solution to calculate the stress intensity factor at crack tip, namely the displacement correlation technique, J-integral technique and modified crack closure integral technique; all give similar SIF values. In the 3D modeling, the SIF is calculated with the interaction integral (M-integral) or displacement correlation method; both techniques give similar SIF values as well.

The fatigue life estimation at the final crack length of 9 mm for varied geometrical models of a cruciform joint with root crack initiation using 2D and 3D modeling as well as the LEFM approach is depicted in Figure 5. The geometrical model with leg size of 6 mm and a crack initiation of 10 mm has the lowest fatigue lifecycle with all assessment methods and that with leg size of 12 mm and a crack initiation of 6 mm gave the highest fatigue life estimation in all three assessment methods, with corresponding lifecycle values of 205000, 226000 and 239592 cycles. It is notable that the geometry contributing to the highest fatigue lifecycle has the smallest value of SIF at crack initiation and the geometry with the highest SIF value at the crack initiation resulted in the lowest fatigue lifecycle. Higher SIF contributes to a lower fatigue life [19].



(a)



(b)

Figure 4. Comparison between different SIF solution with varied leg lengths (a) Crack initiation, 2a=6 mm (b) Crack initiation, 2a=10 mm

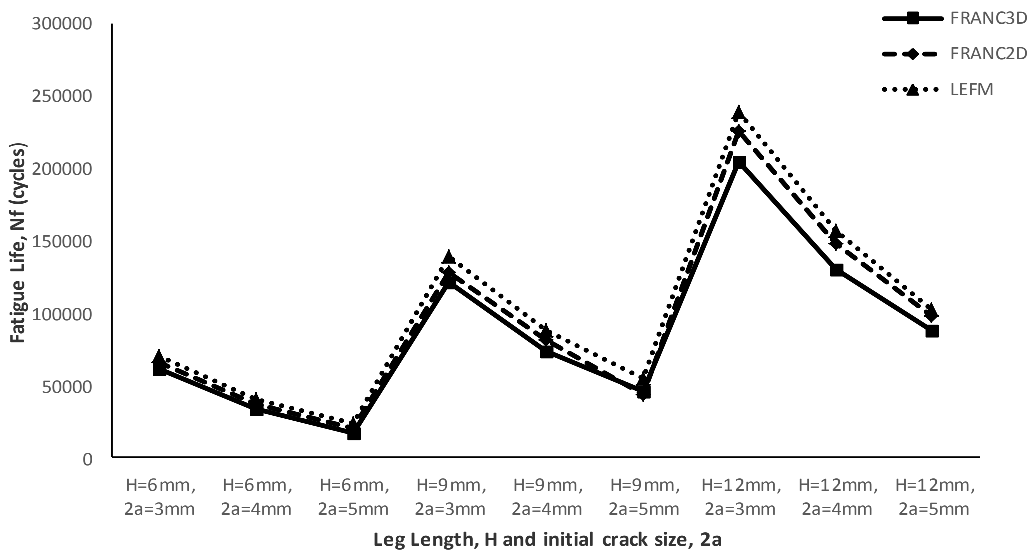
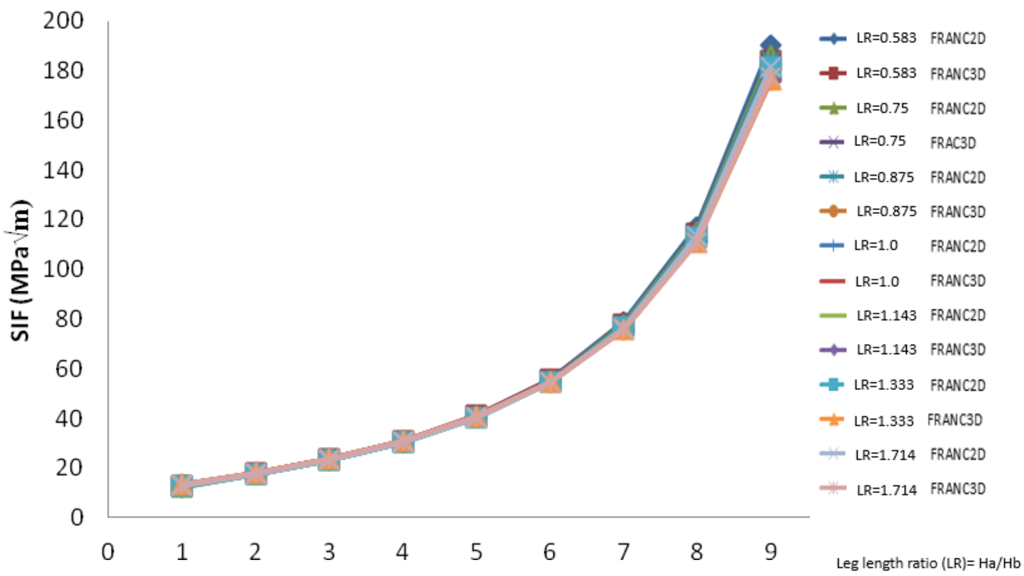


Figure 5. Comparison of fatigue lifecycle for varied geometrical models of a cruciform joint with root crack initiation using FRANC 2D, FRANC 3D and LEFM approaches

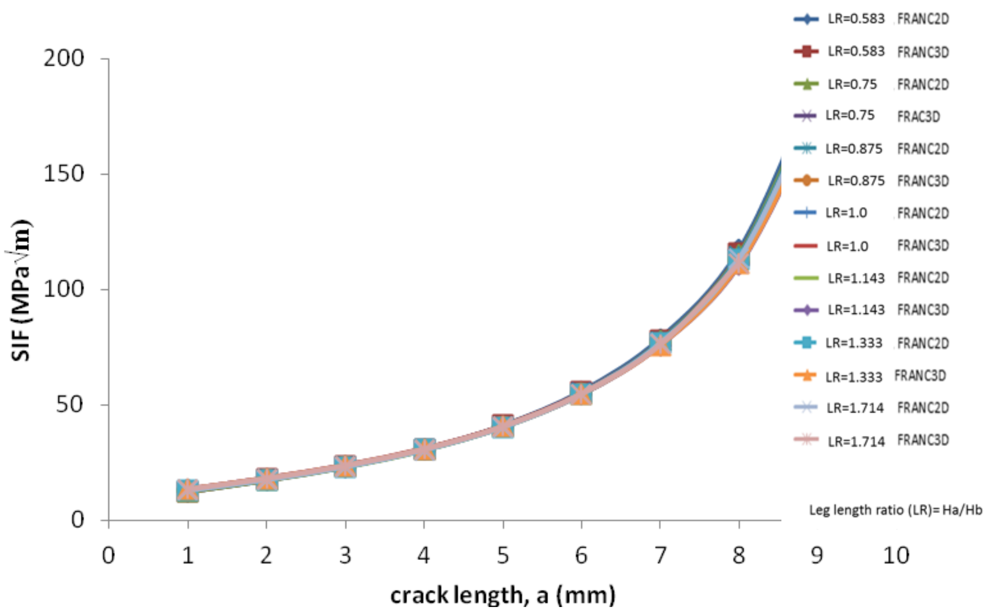
It was observed that for weld geometries with similar leg length, larger initial crack size can cause lower fatigue lifecycles and vice versa; hence an increase in the depth of weld penetration can improve the fatigue life of fillet-weld cruciform joints. In weld geometries with identical LOP, increments in leg length can contribute towards higher fatigue lifecycles and vice versa. Cruciform models with larger initial cracks and small leg length tend to have low fatigue lifecycles because of the shorter distance of crack propagation from the crack origin to the point of final fracture [9]. An increase in this distance contributes towards a higher fatigue life since more load cycles are needed to propagate the crack to final fracture point and hence larger leg lengths with deeper weld penetration result in higher fatigue lifecycles [9, 10]. All fatigue life assessment methods showed similar trends of an escalation in fatigue life with decreasing initial crack size and increasing leg length. Overall, the fatigue lifecycles determined by using different solutions displayed a slight difference when calculated with the LEFM approach, contributing the highest values of fatigue lifecycle regardless of the geometrical variation, whereas the 2D simulations computed the lowest fatigue lifecycles. Fatigue life computation using the 3D simulations displayed lifecycles approximately 17% higher than values from the 2D computations. These are mainly attributed to the different solutions used in the assessment methods whereby the 2D simulations utilized simple analysis based on the Paris model and the 3D simulations employed the Runge-Kutta integration technique to integrate the Paris equation. The determination of fatigue lifecycles for the LEFM approach utilized the numerical integration method.

Crack Initiation at Weld Toe

The SIF solutions were determined with a pre-crack initiation of 1 mm at the weld toe to the final crack length with an increment of 1 mm with different leg length ratio variations of 0.58, 0.75, 0.875, 1.0, 1.14, 1.33, and 1.7 for cruciform models with each leg length ratio subjected to 0% and 15% linear misalignment.



(a)



(b)

Figure 6. Comparison between FRANC 2D and FRANC 3D SIF solutions for cruciform joint with varied leg length ratio (a) With 0% linear misalignment (b) With 15% linear misalignment.

The comparisons for cracks initiating from the weld toe are shown in Figure 6. The stress intensity factor versus crack length for all cruciform models with varied leg length ratios with different linear misalignment was plotted for comparison on the basis of the results obtained from 2D and 3D simulations. Computed SIF values typically grow proportionally to the crack propagation as the crack tip propagates from initial to final crack length. For leg length ratios from 0.583 to 1.0, the leg length at the cross-plate (*Ha*) increased from 7 mm to 12 mm and the leg length at the main plate (*Hb*) was fixed at 12 mm. The crack position on the main plate was not varied. For leg length ratios from 1.0 to 1.714, the leg length at the cross-plate (Ha) remained constant at 12 mm and the leg length at main plate (*Hb*) decreased from 12 mm to 7 mm. The length changes on the main plate (*Hb*) caused the crack initiated at the weld toe to propagate towards the cross-plate. The 2D and 3D analysis shows that the stress intensity values from initial to final crack propagation for all the cruciform joint models with weld toe crack initiation have identical values. The SIF values at initial crack length of 1 mm determined using 2D and 3D solutions are approximately between 12.2MPa√m and 12.9MPa√m and 12.6 MPa√m and 13.4 MPa√m respectively.

The SIF values at final crack length of 9 mm determined using 2D and 3D computations are in the range of 181.3MPa√m to 190.5MPa√m and 175.611MPa√m to 184.788MPa√m respectively. Comparison of the 2D and 3D SIF solutions for cruciform joints with both 0% and 15% misalignment shows a slight difference; the SIF values determined with 2D are constantly less than those of the 3D computations for every crack propagation. From the computed SIF values, fatigue lifecycles for varied leg length ratio models of the cruciform joint with weld toe crack initiation using 2D and 3D simulations for 0% and 15% misalignment were determined and are depicted in Figure 7. The variation of the leg length ratio tends to decrease the fatigue lifecycles as the leg length ratio is increased and upon reaching the value of one onwards, the fatigue lifecycle seemingly increases. However, changes in the fatigue lifecycle are not significant as they are minimal and can be considered approximately identical.

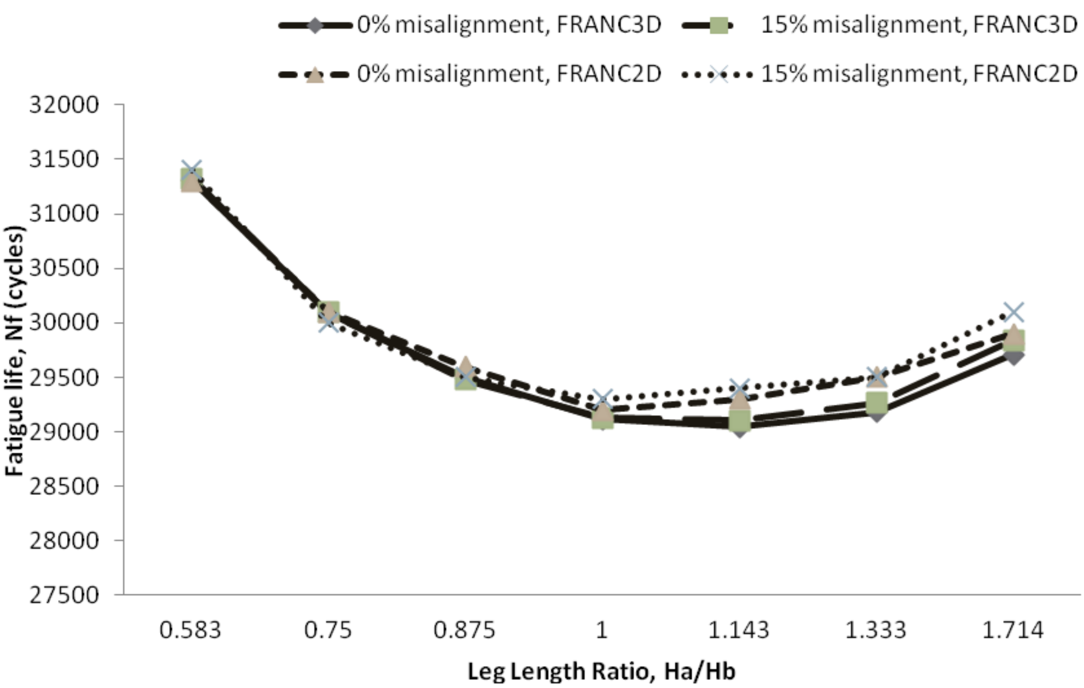


Figure 7. Comparison of fatigue lifecycle for varied leg length ratio models of the cruciform joint with weld toe crack initiation using FRANC 2D and FRANC 3D for 0% and 15% misalignment.

At minimum leg length ratio of 0.583, fatigue life for cruciform models with 0% axial misalignment determined by 2D and 3D simulations is 31300 cycles and 31304 cycles respectively; for the maximum leg length ratio of 1.714, fatigue life for cruciform models with 0% axial misalignment determined by 2D and 3D is 29900 cycles and 29711 cycles respectively. Such identical fatigue lifecycle values are also observed for cruciform models with 15% axial misalignment. With this number of cycles, fatigue life assessment by 2D and 3D simulation yields approximately similar results for the same cruciform model. The overall percentage of difference between the FRANC 2D and FRANC 3D results is less than 3%. Further investigation reveals that a linear misalignment of 15% in the main plate had no significant effect on the fatigue lifecycle for cruciform joint models with varied leg length ratios. According to the simulation analysis, although leg length ratio and linear misalignment varied in the cruciform geometrical model, the identical fatigue lifecycles resulted from the cracks initiated from the weld toe having similar crack paths. The crack was observed to propagate from the weld toe on the upper side to the weld toe on the bottom side of the main plate, a similar propagation distance because there were no changes in the thickness of the plate. The calculation of the fatigue lifecycle was not influenced by leg length changes or linear misalignment as it is primarily governed by the plate thickness.

CONCLUSIONS

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

i) The increase in the depth of weld penetration and the weld size in isosceles triangles fillet-weld shape for crack initiated in the weld root decrease the SIF and increase the fatigue lifecycle.
ii) The weld leg lengths, *Ha* and *Hb*, have a major effect on the SIF. The study showed that the value of the SIF is strongly affected by the leg length on the main plate side. The decreasing *H* significantly increases the SIF.
iii) The effects of leg length ratio and linear misalignment were studied for cracks initiating from the weld toe, and none were found on SIF solutions and fatigue lifecycles for load-carrying cruciform joints.
iv) FRANC 2D and FRANC 3D compute identical SIF and fatigue lifecycle solutions regardless of the different assessment methods used yet the results are comparable to those obtained by employing the LEFM approach.

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