Analysis and Determination of the Stress Intensity Factor of Load-Carrying Cruciform Fillet Welded Joints

Nabil Mahmoud, Ahmed Badr, Fikry Salim and Amro Elhossainy

Structure Engineering Department, Faculty of Engineering, Mansourah University, Egypt.
drfikry_salem@yahoo.com

Abstract: Fracture mechanics is the field of mechanics concerned with the study of the formation of cracks in materials. The determination of stress intensity factor (SIF) plays an important role in fracture analysis. This stress intensity factor (SIF) can be determined by experimental, numerical or analytical methods. However, with complicated component and crack geometry or under complex loading only numerical procedures are applicable. In this study, SIF of load-carrying cruciform welded joints has been evaluated using finite element method (FEM). 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/L [1] program. Moreover, the effects of the crack position (toe, root or cold lab crack) have been considered. The objective of this paper is to study analytically the effects of variation of crack position as well as the effect of mesh fineness and crack increment on the stress intensity factor (K_I) under a constant load for load-carrying cruciform fillet welded joints.
[Nabil Mahmoud, Ahmed Badr, Fikry Salim and Amro Elhossainy. **Analysis and Determination of the Stress Intensity Factor of Load-Carrying Cruciform Fillet Welded Joints.** *J Am Sci* 2014;10(1):30-36]. (ISSN: 1545-1003). http://www.jofamericanscience.org. 7

Keywords: Fracture mechanics, stress intensity factor, cruciform joint and fillet weld

1. Introduction

The most important requirement for ensuring the structural reliability is the prevention of brittle fractures that can cause failure. To prevent the brittle fracture in structures, it is very important to perform correct welding works under consistent process controls, and to avoid weld defects that can become the source of brittle fractures. Particular attention needs to be paid to the quality of the welded joints of the strength construction, which is subject to considerable stresses [2].

A major achievement in the theoretical foundation of LEFM was the introduction of the stress intensity factor K (the demand) as a parameter for the intensity of stresses close to the crack tip and related to the energy release rate [3]. Stress intensity factor tightly knit with fracture mechanics which assumes that cracks already exist in welded joints. This factor define the stress field close to the crack tip of a crack and provide fundamental information on how the crack is going to propagate. In linear elastic fracture problem, the prediction of the crack growth and the crack direction are determined by the stress intensity factor [4]. The stress intensity factor (SIF) for flat crack propagation (usually referred to as opening mode), having units of $\mathrm{Mpa}\sqrt{\mathrm{mm}}$. This single parameter K_I is related to both: the stress level, σ, and the flaw size, a. The fracture toughness for a particular material (K_{Ic} or K_c) is constant value. When the particular combination value of σ and a leads to a critical value of K_I; unstable crack growth occurs and crack extension happened [5].

With fillet welded joints, stress concentrations occur at the weld toe and at the weld root, which make these regions the points from which cracks may initiate [[6, 7]. Therefore Shen and Clayton [8] stated that all the cracks were found to be initiated at the weld end toe, the maximum stress concentration site. In this work Load-carrying cruciform welded joints with isosceles triangles and non-isosceles triangle fillet weld shapes were considered and have been analyzed by the finite element method based simulator FRANC2D/L program. The stress intensity factors during the crack propagation phase were calculated by using the software FRANC2D/L, which is shown to be highly accurate, with the direction of crack propagation being predicted by using the maximum normal stress criterion.

2. Material Properties.

The material used in the present study for base material and weld metal was high strength hot rolled steel with the yield strength Fy was taken equal to 355 MPa and fracture toughness K_{IC} was taken equal to 2000 $\mathrm{Mpa.}\sqrt{\mathrm{mm}}$ [9]. Values of Poisson's ratio (υ) and the modulus of elasticity (E) were taken equal to 0.3 and 206000 MPa respectively. The material has been assumed to be isotropic, linear elastic.

3. Mesh Description and Boundary Conditions.

The boundary conditions of load-carrying cruciform fillet welded joints model are shown in Figure (1). Boundary conditions were shown as the hinged in x-direction and y-direction for the bottom side of the lower attached plate that was used in this study. Uniform distributed stresses (F_{app}) were applied at the upper edge of the upper attached plate.

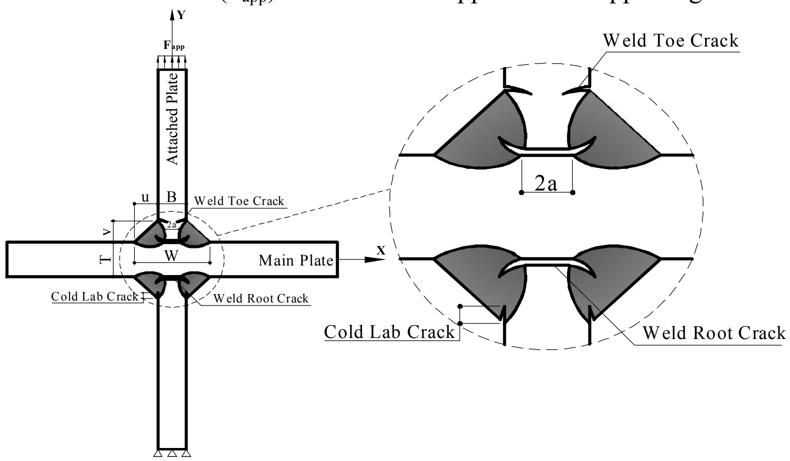
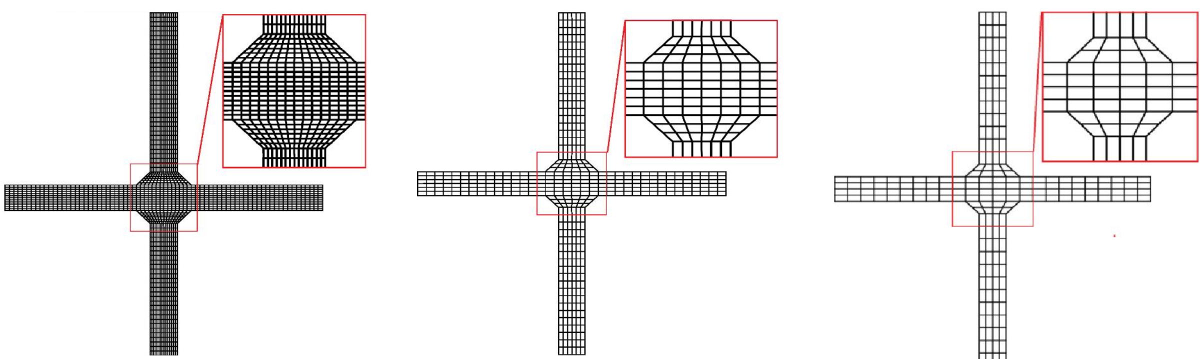


Figure (1): Model Description and Boundary Conditions of Load-Carrying Cruciform Welded Joint.

4. Effect of Mesh Size on SIF, K_I.

To investigate the convergence in results, finite element method analyses were performed on models with different mesh sizes as shown in Figure (2). An existing crack has to be assumed in welded toe joint and grows to its final length under the applied load. Figure (3) shows the results of mesh sizes density. It was noticed that there are no effects on the stability of results and the very close agreements between the three types of mesh sizes indicate that these effects on the SIF are negligible.



(a) Fine Mesh Size **(b) Medium Mesh Size** **(c) Coarse Mesh Size**

Figure (2): Different Mesh Size Description of Cruciform Welded Joint.

5. Effect of Crack Increment Steps on SIF.

In order to study the simulation of crack growth, an initial non-cohesive edge crack was placed on fillet weld toe, perpendicular to the direction of the applied stress, where it was predicted that critical tensile stresses would occur. Having specified the location of the crack, the program was able to predict the direction in which the crack would propagate. Prior to performing the analysis, it was necessary to specify the magnitude of crack increment and also the number of steps over which the crack would propagate.

In the present study, a crack increment step (Δa) was taken as variable to study the effect of crack increment step on the stress intensity factor and evaluate the suitable crack increment step (Δa) for loaded cruciform welded joints with different geometries. The crack growth was simulated over a suitable step of increment according to welded plate thickness. Moreover, in this study, the crack path was not pre-selected, but crack direction was allowed to change according to the maximum tangential stress criterion [1]. Moreover, the auto-mesh was carried out automatically. An existing crack has to be assumed in welded toe joint and grows to its final length under the applied load. Figure (4) shows the results of a crack increment step (Δa). It was noticed that there are no effects on the stability of results and the very close agreements between the three types of a crack increment step (fine, medium and coarse increment) indicate that these effects on the SIF are negligible.

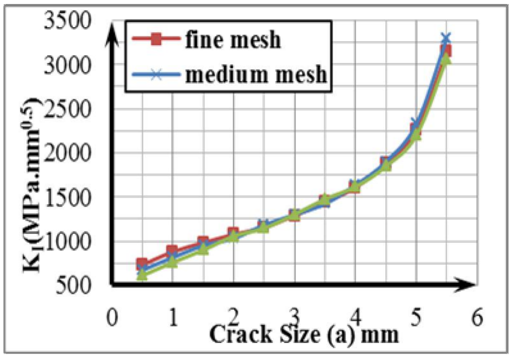


Figure (3): Convergence Results for the Effect of Mesh Size Density on SIF, Toe Crack.

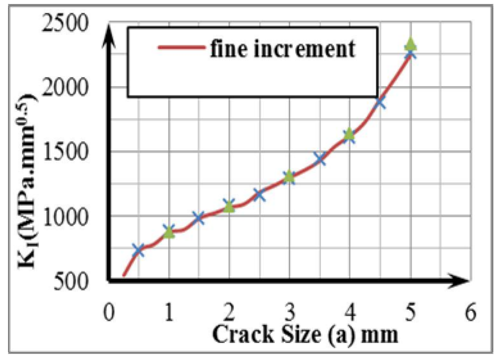


Figure (4): Convergence Results for the Effect of Crack Increment on SIF, Toe Crack.

6. Effect of Crack Position (Toe, Root or Cold-Lab) on SIF, K_I.

In this case the cruciform welded joint models shown in table (1) were analyzed to study the effect of variation of crack position (toe, root or cold lab crack) on the stress intensity factor (K_I) under a constant load. The applied edge stress for the model was based on the development of the yield stress over the net cross-section.

Table (1): The Details of Geometries for Cruciform Welded Joints.

Model	Model Description	B (mm)	T (mm)	v (mm)	u (mm)
1	Isosceles triangles weld, equal thickness	16	16	6	6
2	Non-isosceles triangles weld, equal thickness	16	16	10	10
3	Non -isosceles triangles weld, equal thickness	16	16	6	10
4	Non -isosceles triangles weld, equal thickness	16	16	10	6
5	Non -isosceles triangles weld, unequal thickness	12	16	6	10
6	Non -isosceles triangles weld, unequal thickness	12	16	10	6
7	Isosceles triangles weld, unequal thickness	12	16	10	10
8	Isosceles triangles weld, unequal thickness	12	16	6	6

6.1 Results and Discussion.

6.1.1 Stress Analysis.

The stress analysis was carried out under given load condition with plane strain state. With fillet welded joints, stress concentrations occur at the weld toe and at the weld root, which make these regions the points from which cracks may initiate [6, 7]. Figures (5 to 8) show stress distribution contour in y-direction for one of the models under analysis (model 2). It was observed that for fillet welded joints, stress concentrations occur at the weld toe or at the weld root, which make these regions the points from which cracks may initiate.

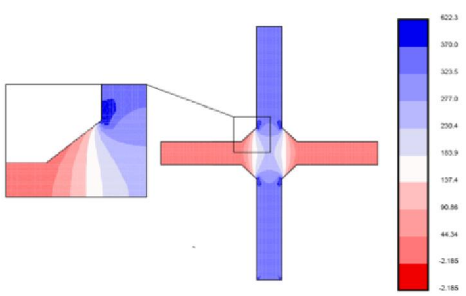


Figure (5): Stress Distribution Contour in Y-Direction, Non-Cracked Model

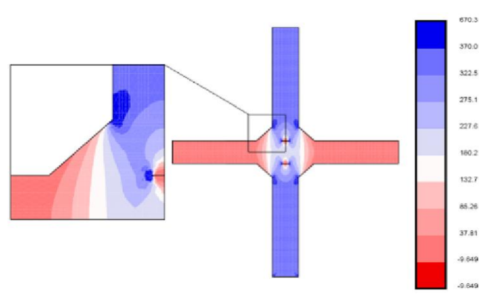


Figure (6): Stress Distribution Contour in Y-Direction, Root-Crack Model.

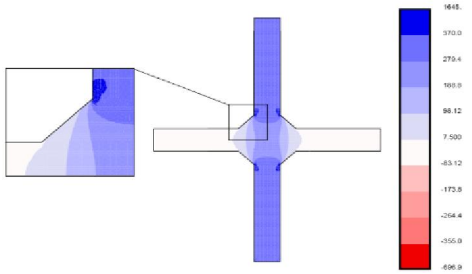


Figure (7): Stress Distribution Contour in Y-Direction, Cold-Lab Crack Model.

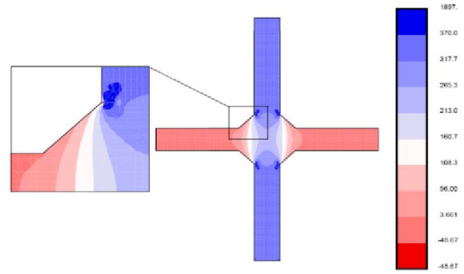


Figure (8): Stress Distribution Contour in Y-Direction, Toe Crack Model.

The values of maximum stress in y-direction for analyzed models with different crack positions are shown in Figure (9). It was observed that for all analyzed models maximum tensile stress for toe crack is higher than that for cold lab crack higher than that for root crack higher than that for non-cracked model. This result indicates that the crack initiation may occur at toe or at root. Toe cracks and lack of penetration are frequently encountered defects. Toe cracks occur because of the stress concentration in the weld toe region, while lack of penetration defects result from inaccessibility of the root region during welding.

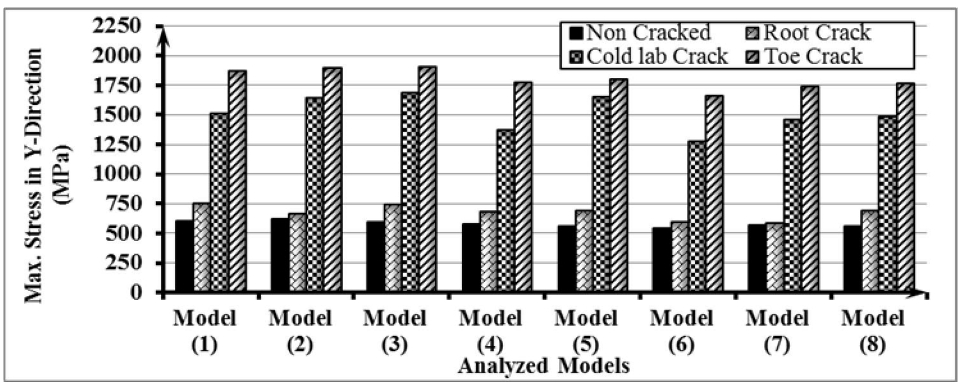


Figure (9): Values of Maximum Stress in Y-Direction for Analyzed Models.

6.1.2 Crack Propagation Analysis.

The finite element method in addition to the J-integral method was considered to calculate the stress intensity factors. This method is appropriate for numerical solutions based on the finite element method, and is one of the most popular techniques used to calculate the stress intensity factors in numerical studies of fractures [10]. The site and curved crack growth paths of continuous root, cold-lab and toe cracks were taken into account as shown in Figures (10 to 12) which show the deformed shape for one of the models under analysis (model 5) at final crack propagation.

6.1.3 Calculation of the Stress Intensity Factors.

When a propagating crack is considered, the stress intensity factors and crack growth direction must be calculated for each increasing crack length. The sign of the K_{II} is important for determining the crack growth direction. Paris and Erdogan [11] have shown that a crack continues to advance in its own plane when it is subjected only to mode I. The presence of positive K_{II} at the crack tip means a turn of the direction to clockwise while negative K_{II} means a counterclockwise turn. Firstly, K_I is calculated for the initial crack length, and then a crack increment (Δa) is added to original crack length to obtain the new crack condition by taking the effect of crack front growing direction. That procedure is repeated until the desired crack length.

Figures (13 to 20) show the variations of stress intensity factor, K_I, with the systematic increase in the crack size for the different three crack position (toe, root and cold-lab). It was observed that for all analyzed models values of stress intensity factor (K_I) increased with the increase in crack size. The path of crack propagation in case of root crack is longer than that in cases of toe and cold-lab cracks. Values of stress intensity factor (K_I) in cases of toe and cold-lab cracks are higher than that in case of root crack for the same crack size which means that the failure by unstable fracture in the elastic load range is more likely to occur in case of toe and cold-lab cracks than in case of root crack.

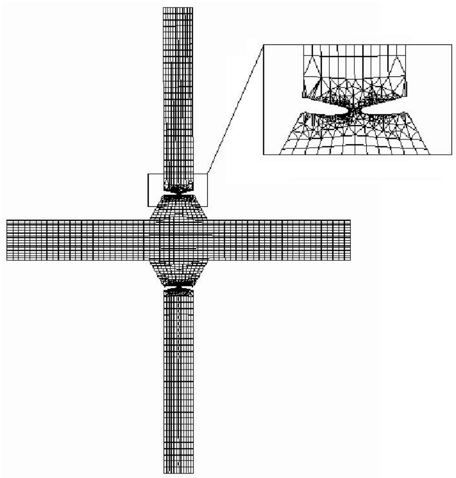


Figure (10): Deformed Shape of the Model with Toe Crack.

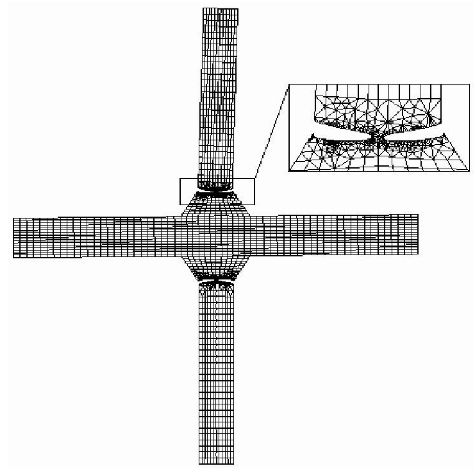


Figure (11): Deformed Shape of the Model with Cold-Lab Crack.

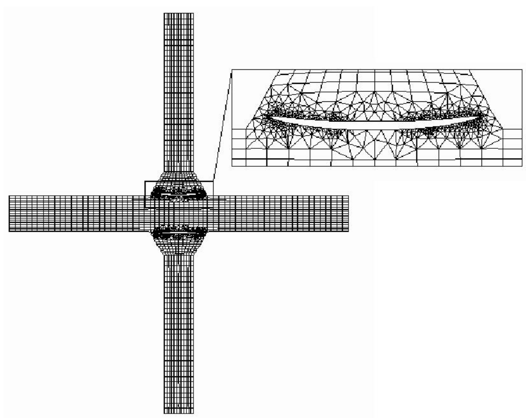


Figure (12): Deformed Shape of the Model with Root Crack.

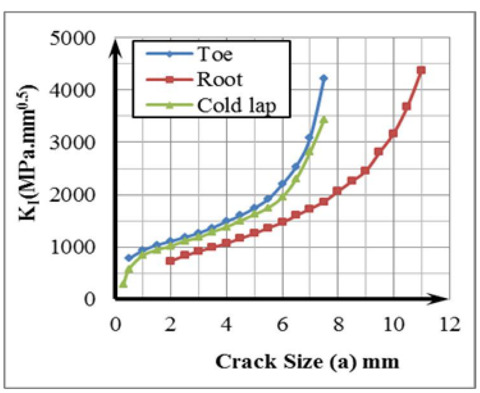


Figure (13): Relationship between SIF, (K_I) and Crack Size (a) for Model (1).

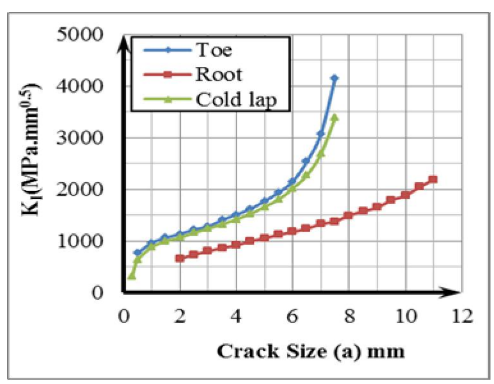


Figure (14): Relationship between SIF, (K_I) and Crack Size (a) for Model (2).

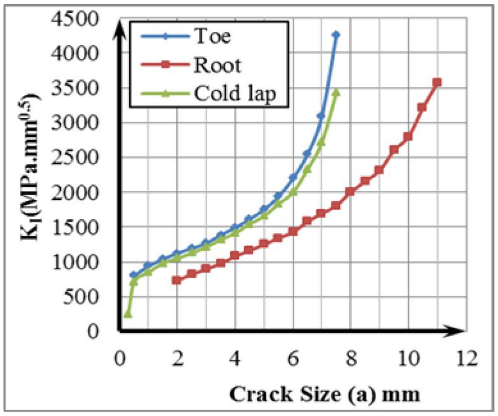


Figure (15): Relationship between SIF, (K_I) and Crack Size (a) for Model (3).

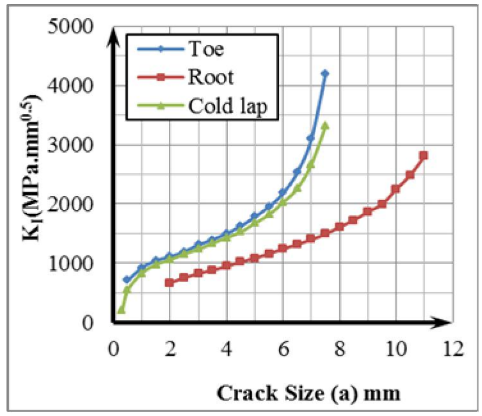


Figure (16): Relationship between SIF, (K_I) and Crack Size (a) for Model (4).

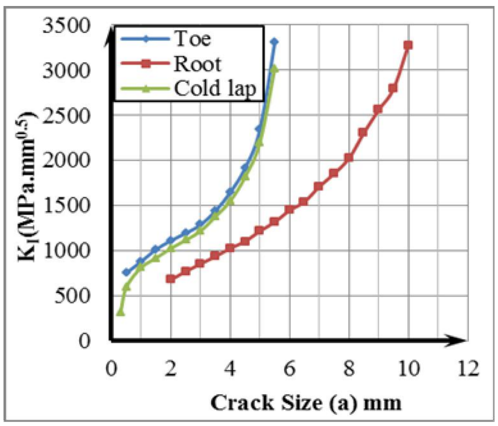


Figure (17): Relationship between SIF, (K_I) and Crack Size (a) for Model (5).

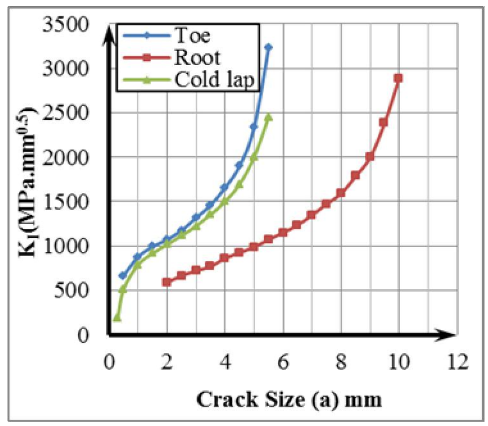


Figure (18): Relationship between SIF, (K_I) and Crack Size (a) for Model (6).

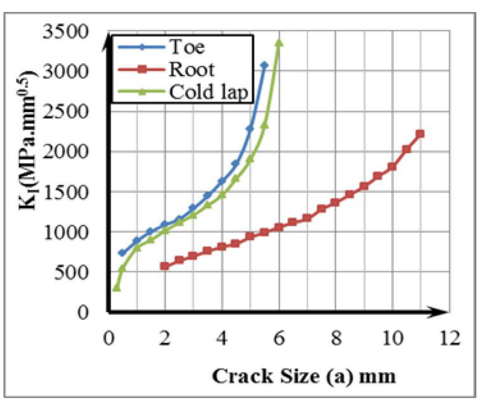


Figure (19): Relationship between SIF, (K_I) and Crack Size (a) for Model (7).

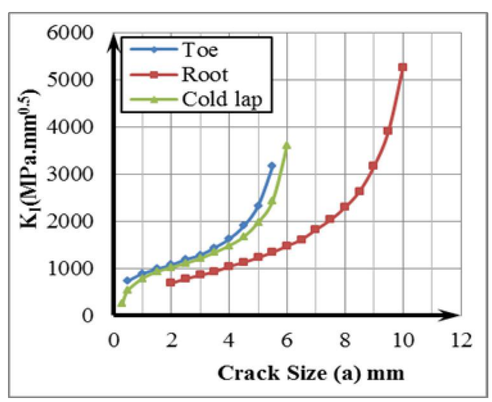


Figure (20): Relationship between SIF, (K_I) and Crack Size (a) for Model (8).

Conclusions

- For fillet welded joints, stress concentrations occur at the weld toe or at the weld root, which make these regions the points from which cracks may initiate.
- The values of stress intensity factor (K_I) for the weld root, weld toe or cold-lab cracks increased with the increase in crack size.
- The path of crack propagation in case of root crack is longer than that in cases of toe and cold-lab cracks.

- Values of stress intensity factor (K_I) in cases of toe and cold-lab cracks are higher than that in case of root crack for the same crack size which means that the failure by unstable fracture in the elastic load range is more likely to occur in case of toe and cold-lab cracks than in case of root crack.

References

1. Iesulauro, E.: FRANC2D/L: A Crack Propagation Simulator for Plane Layered Structures, Version 1.5, User's Guide, Cornell University. Ithaca, New York.
2. Ishikawa, T., Inoue, T., Shimanuki, H., Imai, S., Otani, J., Hirota, K., Tada, M., Yamaguchi, Y., Matsumoto, T. and Yajima, H.: Fracture toughness in welded joints of high strength shipbuilding steel plates with heavy-thickness. Proceedings of the Sixteenth (2007) International Offshore and Polar Engineering Conference, Lisbon, Portugal, July 1-6, 2007.
3. Bazant, Z. P. and J. Planas. 1998. Fracture and size effect in concrete and other quasibrittle materials. Boca Raton, FL: CRC Press.
4. Alshoaibi Abdulnaser, M., Hadi, M.S.A. and Ariffin A.K.: An adaptive finite element procedure for crack propagation analysis. Journal of Zhejiang University Science A 2007 8(2):228-236
5. ROLFE, S. T.: Fracture and Fatigue Control in Steel Structures. Engineering Journal, American Institute of Steel Construction, First Quarter (1977).
6. Motarjemi, K., Kokabi, A. H., Ziaie, A. A., Manteghi, S. and Burdekin, F. M.: Comparison of stress intensity factor for cruciform and T welded joints with different attachment and main plate thickness. Engng Fract Mech, Vol. 65, No.1 (2000), pp: 55–66.
7. Al-Mukhtar, A. M., Henkel, S., Biermann, H. and Hübner, P.: A Finite Element Calculation of Stress Intensity Factors of Cruciform and Butt Welded Joints for Some Geometrical Parameters. Jordan Journal of Mechanical and Industrial Engineering. Vol. 3, Number 4 (2009), pp: 236-245.
8. Shen, W. Y. and Clayton, P.: Fatigue of fillet welded A515 steel. Engineering fracture mechanics, Vol. 53. No.6 (1996), pp: 1007-1016.
9. Haldimann-Sturm, S. C. and Nussbaumer, A.: Fatigue design of cast steel nodes in tubular bridge structures. International Journal of Fatigue vol. 30 (2008), pp: 528–537.
10. Aslantaş, K. and Taşgetiren, S.: Modeling of Spall Formation in a Plate Made of Austempered Ductile Iron Having a Subsurface-Edge Crack. Computational Materials Science, Vol. 29 (2004), p: 29-36.
11. Nykänen, T., Marquis, G. and Björk, T.: Fatigue analysis of non- load carrying fillet welded cruciform joints. Engineering fracture mechanics. Vol. 74, No.3 (2007), pp: 399-415.

1/5/2014