A parametric numerical analysis of stress intensity factors on multiple interacting surface cracks in T-butt joints using FRANCE3D

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Abstract

Under the action of repeated loading, fatigue cracks often initiated in stress concentration areas of aging ship structures. Multiple surface cracks are among the most typical cracks in the vicinity of weld toe of T-butts. It is well known that the existence of multiple cracks may lead to the failure of structures more easily than a single crack. Therefore, the interaction between multiple surface cracks should be taken into account rationally as a basis of fatigue life analysis. In this paper, a parametric analysis of stress intensity factor of a lead crack with disturbing crack in the vicinity of its crack tips is conducted taking the disturbing crack shape and position as the influential parameters. The boundary element analyses are performed to calculate the SIFs at each position along the crack front using FRANC3D. And the disturbing factor in terms of the SIF increment was accordingly discussed and quantified by comparing the SIFs with respect to the existence of disturbing cracks.

Keywords: Stress intensity factor; Multiple interacting surface cracks; Fatigue life; Disturbing factor; Boundary element analyses.

1. Introduction

Fatigue cracks are among the most typical damage or defect forms in aging ship structures, which would be mainly initiated in the concentration areas under the action of repeated loading. And multiple surface cracks are the most typical crack defects in the vicinity of weld toe of T-butts. It is well known that the existence of multiple cracks may lead to the failure of structures more easily than a single crack. However, the current unified fatigue life prediction method was mainly established based on single crack, so the problem for its application arises on fatigue life prediction of ship structures with multiple cracks. Therefore, the fatigue life prediction of ship structures with multiple cracks should be further highlighted and studied with the aging of ships and the widely application of high strength steel in ship structures.

Three typical stages of fatigue growth of two adjacent surface cracks can be observed from experiments, i.e. pre-coalescence, coalescence and post-coalescence [1-2]. At the pre- coalescence stage, adjacent cracks have not contacted and usually behave as isolated cracks, but interaction between them may exist when their neighboring crack tips approach closely. A single concave crack forms when the inner tips of the adjacent cracks tips approach closely. The crack subsequently grows more rapidly at the concave position than elsewhere, leading to the disappearance of the concave front. This stage of growth is usually defined as coalescence. After that, the non-concave single crack continues its growth like a usual surface crack [3, 4].

Some efforts have been made to investigate the interaction of static adjacent cracks. The cracks were usually assumed to be semi-elliptical or elliptical and the stress intensity factors along the crack front were estimated using various numerical methods [5], such as the finite element [6], the finite element alternating [7-9], the body force [10-12], the line-spring [13], the integral equation [14], and the coupled line-spring and boundary element methods [15]. The term 'interaction' was introduced to represent the influence of SIFs around each crack due to the presence of other cracks. It has been widely indicated by these nu-

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merical investigations that the interaction does exist, but its degree mainly depends on the multiple crack configurations (dimension, aspect ratio and separation distance). The maximum SIF at the nearest crack tips between neighboring cracks will be increased due to the interaction between them. Obviously, it is difficult to reuse these SIF results obtained from limited static adjacent cracks in the fatigue growth analysis at the pre-coalescence stage.

Therefore, the purpose of this paper will be mainly on further studying the interaction effect of multiple surface cracks in T-butts on their individual stress intensity factors. A parametric study by boundary element analyses (BEA) in FRANC3D will be made on the stress intensity factor of a lead crack with disturbing crack in the vicinity of its crack tips taking the disturbing crack shape and position as the influential parameters. The interaction effect of multiple surface cracks would be expressed by parameter λ, namely,

$$\lambda = \frac{K - K_0}{K_0} \times 100\% \tag{1}$$

2. Scope of the parametric numerical study

The choice of parameters covered in this study was based on findings from previous work conducted by Bowness and Lee [17]. The overall T-butt joint dimensions would be chosen to minimize finite width effects. However, the finite width effect will be briefly discussed in behind.

The crack depth ratio (a/T) is fixed at 0.5. The considered crack aspect ratios are 0.2, 0.4, 0.6, 0.8 and 1.0. The normalized horizontal distances between crack tips (divided by crack half length) (S/c) are 0.33, 0.67, 1.00, 1.33, 1.67, 2.00. The influence of normalized horizontal distance over 2.00 will be neglected [2, 3].

The attachment thickness ratio (T/t) is fixed at 1.5. The weld toe length ratios (L/T) under study here are 0.33, 0.67, 1.00, considering the practice in real engineering structures. The weld angles (θ) of 30°, 45°, 60° and the ratio ρ/T of 0.0 representing a sharp weld toe will be chosen for the analyses.

3. Model validation

In this part, the finite width effect will be briefly discussed first on an isolated plate to investigate its effects on the following parametric studies. And the convergence analysis of element size will be conducted accordingly to validate the boundary element analysis model.

3.1. Finite width effect

The effect of the boundaries parallel to the crack on the SIFs in plate was analyzed by Xiao and Yan [18]. As h/c is large enough (i.e., $h/c \geq 4$), the effect of the boundaries parallel to the crack on the SIFs can be ignored.

The effect of the boundaries perpendicular to the crack on the SIFs on the plate was calculated here. The models with the following geometrical dimensions were adopted for this purpose, h/c =16.67, a/T=0.5, b/c=1, 2, 3, 4, 5, 6, 7, 8, 9.

Fig. 2 gives the variation of K with b/c. it can be seen that K increase with the decrease of b/c. As b/c is large enough (i.e., $b/c \geq 5$), the effect of the boundaries parallel to the crack on the SIFs can be ignored.

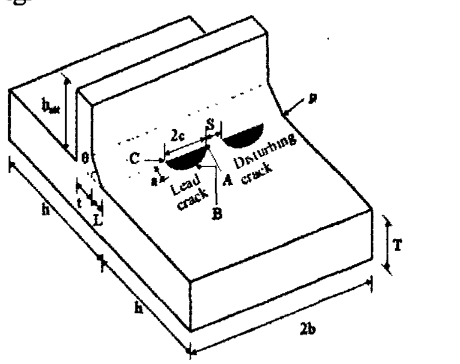


Fig. 1. Nomenclature for T-butt.

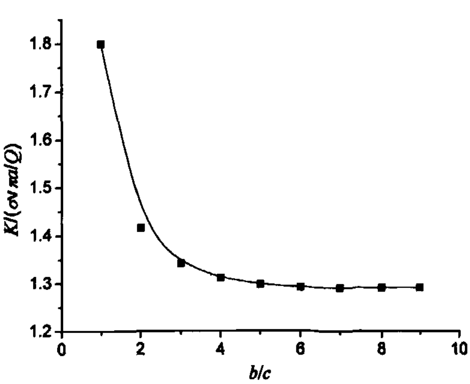
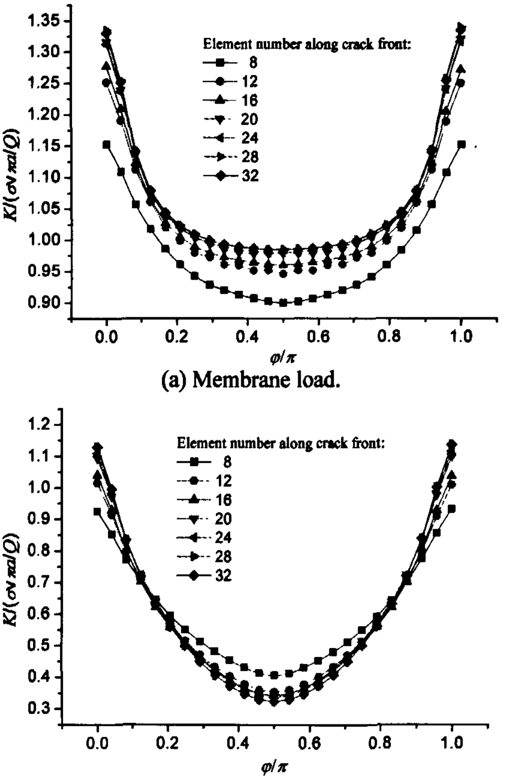


Fig. 2. Variation of K with b/c.



(a) Membrane load.

(b) Bending load.

Fig. 3. Convergence analysis considering membrane and bending load respectively.

3.2. Convergence analysis of element size

It is certain that the BEA results may be quite dependent on mesh density. The rationality of the mesh discretization should be validated first for precise results. The refinement lever from 8 to 32 elements along the crack front will be considered here. The results are shown in Fig.3. It is easily concluded that if the element number is greater than 20, the SIFs will almost independent on the increase of mesh density. Element number of 24 along the crack front will be used in the following calculation.

4. Results and discussion

The large amount of data generated means that only a selection of typical results can be shown here to illustrate the behavior and the main effects.

4.1. Effects of the horizontal distance between crack tips and aspect ratio

A series of BEA have been done on the models with different weld angles and weld toe lengths in this part. But the model with the weld angle of 45°and the normalized weld toe length L/T of 0.67 is taken as a special case for illustrating the effects of the horizontal distance between crack tips and aspect ratio here, as similar tendency has be observed for different cases.

Fig. 4 and Fig. 5 illustrate the effects of the horizontal distance between crack tips and aspect ratio under membrane load and bending load respectively. It could be observed that with increase of a/c, the disturbing factor λ increase. Under membrane loading, λ increases linearly. And under bending load, it increase porabolically. When a/c approaches to 0.2, the effect becomes very small. With increase of S, the disturbing factor λ decrease. And when S/c approaches to 2.00, the effect can be neglected. Under both membrane and bending loads, λ at the inner crack tip point A is the larger than deepest point B and outer crack tip C. Under membrane load, λ at deepest point B is smaller than outer crack tip C, but the difference between them is not significant. Under bending load, λ at deepest point B is 2 times greater than outer crack tip C.

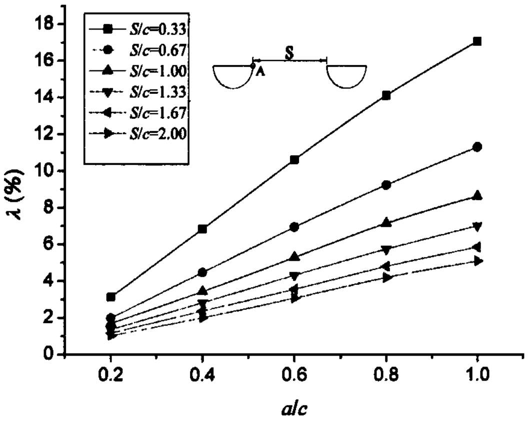
Moreover, λ under membrane load is slightly greater than that under bending load at the inner crack tip point A and outer crack tip point C. And at the deepest point B, λ under bending load is almost twice that under tension load.

4.2. Effect of the weld angle

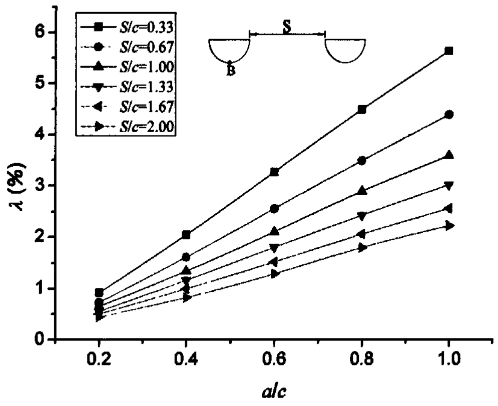
The effect of the weld angle can be shown in Fig. 6. It can be noticed that at the inner crack tip point A under both membrane and bending loads, the increase of weld angle causes the increase of λ. These effects are from the increased stress raising effect of steeper weld angles. λ in T-butt is 2% greater than that in the isolated plate (without attachment). And the same trends could be observed from the weld angle effect on the value of λ in the deepest point B and outer crack tip point C.

4.3. Effect of the weld toe length

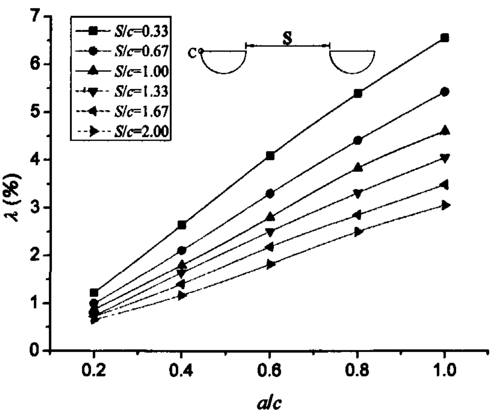
At the inner crack tip point A, the trends under both membrane and bending load are also very similar, as can be shown in Fig. 7. With the increase of L/T, there is little change in λ. Under bending load condition, the effect on L/T is obvious when S/c>1.33.



(a) Inner crack tip.

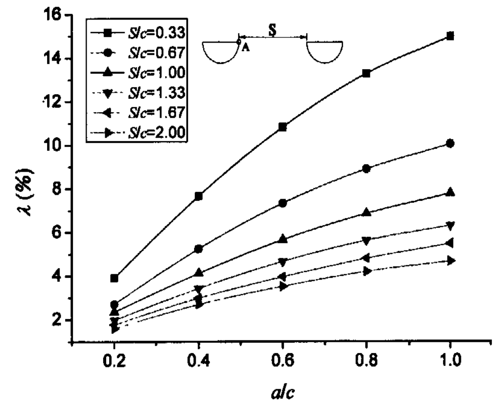


(b) Deepest point.

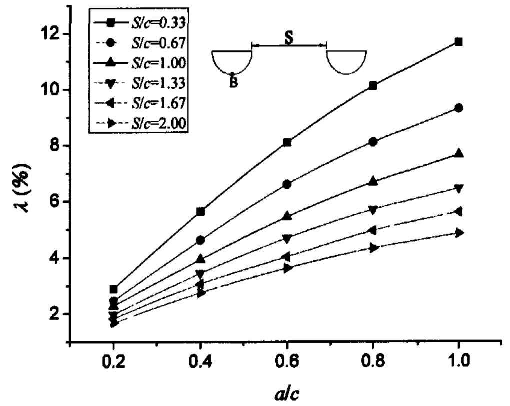


(c) Outer crack tip.

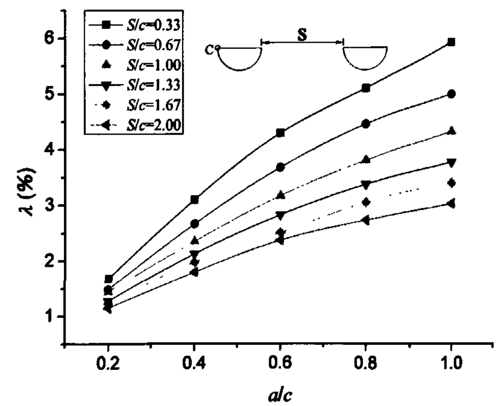
Fig. 4. Effects of horizontal distance between rack tips and aspect ratio under membrane load.



(a) Inner crack tip.

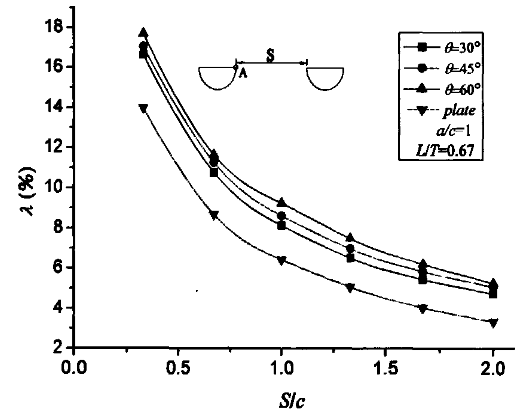


(b) Deepest point.

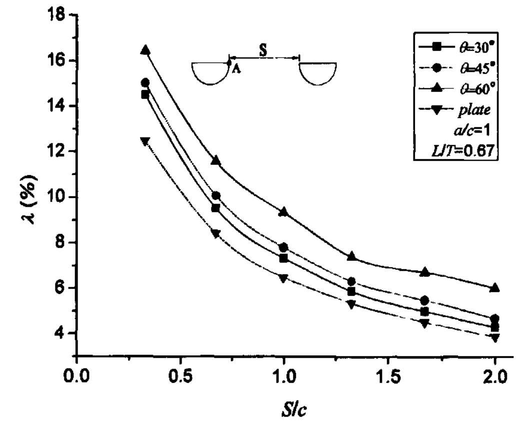


(c) Outer crack tip.

Fig. 5. Effects of horizontal distance between crack tips and aspect ratio under bending load.

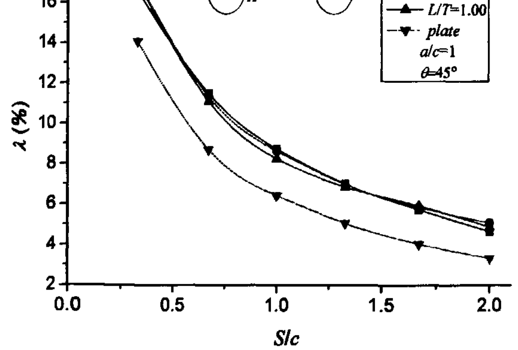


(a) Membrane load.

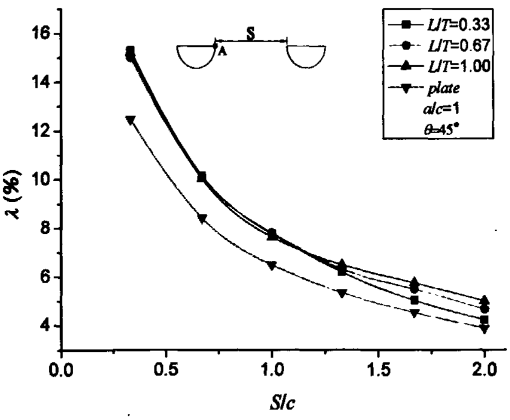


(b) Bending load.

Fig. 6. Effect of weld angle at inner crack tip A.



(a) Membrane load.



(b) Bending load.

Fig. 7. Effect of weld toe length at inner crack tip A.

5. Conclusions

In this study, the SIFs of multiple surface cracks in T-butt joints were evaluated by using FRANCE3D. Based on the analysis results, the relationship between disturbing factor and aspect ratio, horizontal distance between crack tips, weld toe length, weld angle were discussed. The following conclusions were obtained,

(1) When b/c is large enough (i.e., $b/c \geqslant 5$), the effect of the boundaries parallel to the crack on the SIFs can be ignored.

(2) With increase of a/c, the disturbing factor λ increase. When a/c approaches to 0.2, the effect becomes very small.

(3) The increase of weld angle causes the increase of λ. λ in T-butt is 2% greater than that in the isolated plate (without attachment).

(4) With the increase of L/T, there is little change in λ. Under bending load condition, the effect on L/T is obvious when $S/c>1.33$.

Acknowledgements

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Nomenclature

A —inner crack tip;
a —crack depth;
B —deepest point of the crack;
b —plate half width;

C —outer crack tip;
c —crack half length;
h —plate half length;
K —Mode I stress intensity factor of lead crack;
K_0 —Mode I stress intensity factor of independent (no interaction);
L —weld toe length;
Q —shape factor for elliptical crack;
S —horizontal distance between crack tips;
T —main plate thickness;
t —attachment thickness;
θ —weld angle;
λ —disturbing factor;
ρ —weld toe radius;
φ —parametric angle of ellipse, deg.

References

[1] Iida K, Ando K, Hirata T. An evaluation technique for fatigue life of multiple surface cracks. J.S.N.A. 1980; 148. 1983; 153.

[2] Lin XB, Smith RA. Fatigue growth analysis of interacting and coalescing surface defects. International Journal of Fatigue 1997; 85; 283-299.

[3] Kamaya M. Growth evaluation of multiple interacting surface cracks. Part I: Experiments and simulation of coalesced crack. Engineering Fracture Mechanics 2008; 75; 1336-1349.

[4] Kamaya M. Growth evaluation of multiple interacting surface cracks. Part II: growth evaluation of parallel cracks. Engineering Fracture Mechanics 2008; 75: 1350–1366.

[5] Newman Jr JC, Raju IS. An empirical stress intensity factor equation for the surface crack. Eng. Fract. Mech. 1981; 15: 185-92.

[6] Soboyejo WO, Knott JF, Walsh MJ, Cropper KR. Fatigue crack-propagation of coplanar semi-elliptic cracks in pure bending, Engineering Fracture Mechanics 1990; 37; 323-340.

[7] Heath BJ, Grandt AF. Stress intensity factors for coalescing and single corner flaws along a hole bore in plate, Engineering Fracture Mechanics 1984; 19; 665-673.

[8] O'Donoghue PE, Nishioka T, Atluri SN. Multiple surface cracks in pressure vessels, Engineering Fracture Mechanics 1984; 20; 545-560.

[9] O'Donoghue PE, Nishioka T, Atluri SN .Multiple coplanar embedded elliptical cracks in an infinite solid subject to arbitrary crack face tractions. International Journal of Numerical Methods in Engineering 1985; 21: 437-449.

[10] Murakami Y, Nisitani H. Stress intensity factors for interacting two equal semi-elliptical surface cracks in tension, Transactions of Japan Society of Mechanical Engineers Series. A. 1981; 47: 295-303.

[11] Murakami Y, Nemat-Nasser S. Interacting dissimilar semi-elliptical surface flaw under tension and bending. Engineering Fracture Mechanics 1982; 16: 373-386.

[12] Murakami Y, Nemat-Nasser S. Growth and stability of interacting surface flaws of arbitrary shape, Engineering Fracture Mechanics 1983; 17: 193-210.

[13] Kim YJ, Yang WH, Choy YS, Lee JS. An interaction analysis of twin surface cracks by the line-spring model. Nuclear Engineering and Design 1992; 135: 187-196.

[14] Roy A, Chatterjee M. Interaction between coplanar elliptic cracks. 1. Normal loading, International Journal of Solids and Structures 1994; 31: 127-144.

[15] Zeng ZJ, Dai SH, Yang YM. Analysis of surface cracks using the line-spring boundary-element method and the virtual crack extension techniques. International Journal of Fracture 1993; 60: 157-167.

[16] Roy A, Chatterjee M. Interaction between coplanar elliptic cracks. 1. Normal loading, International Journal of Solids and Structures 1994; 31; 127-144.

[17] Bowness D, Lee MMK. Prediction of weld toe magnification factors for semi-elliptical cracks in T–butt joints. International Journal of Fatigue 2000; 22: 369-387.

[18] Xiao XK, Yan XQ. A new numerical analysis for a semi-circular surface crack. Engineering Fracture Mechanics, 2007.

[19] FRANC3D & BES Benchmarking version 2.6. http://www.cfg.cornell.edu/.2003.