ICM11

Surface crack growth simulation under mixed mode cyclic loading condition

Masanori Kikuchi\textsuperscript{a*}, Yoshitaka Wada\textsuperscript{b} and Kazuhiro Suga\textsuperscript{a}

\textsuperscript{a} Tokyo University of Science, 2641 Yamazaki, Noda, Chiba, 278-8510, Japan
\textsuperscript{b} Tokyo University of Science, Suwa, 5000-1, Toyohira, Chino, 391-0292, Japan

Abstract

Surface crack growth process by fatigue is simulated using S-version FEM. Complicated crack growth process in 3-dimensional field under mixed mode loading condition can be modelled easily by this method. Simulation results are compared with experimental ones, and it is pointed out that several factors should be taken into account for the accurate prediction of surface crack growth under mixed mode cyclic loading condition. One of them is plasticity induced crack closure effect, which becomes significant near free surface of the specimen and delays crack growth rate. Another factor is the effect of $K_{II}$ at the deepest point of surface crack, which results factory roof on the fracture surface and affects crack growth rate, too. Effects of these 2 factors are studied by numerical simulation and they are considered in the crack growth analysis. It is shown that accurate and conservative predictions of surface crack growth processes are conducted well.

© 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of ICM11

Keywords: Surface crack, Fatigue, Plasticity induced crack closure, Factory roof, S-version FEM

1. Introduction

It is well known that final fracture of structure is mainly due to fatigue of materials by long-term cyclic loading. It is important to evaluate fatigue damage for the integrity of structures. For this purpose, estimation of residual fatigue life is a key technology after a small crack is detected. For the evaluation of residual fatigue life, FEM (Finite Element Method) plays an important role with some crack growth criteria. In the 2-dimensional field, comparisons of fatigue test results with those of numerical simulation

\textsuperscript{*} Corresponding author. Tel.:+4-7122-9586; fax:+4-7124-5372.
E-mail address:kik@rs.noda.tus.ac.jp.
have been done by many authors. The estimation of crack growth rate by fatigue is conducted using Paris’ law[1], and crack growth direction is evaluated by MTS (Maximum Tangential Stress) criterion[2]. Availabilities of these criteria have been verified by many studies [3,4]. In the 3-dimensional field, comparison of experiments with numerical simulation has been done in some literatures [5,6]. But these comparisons have not been done well. It is because of problems on numerical simulation techniques. In 3-dimensional field, modelling of 3-dimensional crack shape for FEM analysis is not easy when it changes it’s shape continuously. Especially under mixed mode loading conditions, configuration of 3-d fatigue crack becomes very complicated, and it is very time consuming work to model its shape precisely. Recently, some new techniques solved this problem. Kikuchi et al.[7,8] simulated fatigue crack growth automatically using S-FEM[9] in 2- and 3-dimensional fields. Maitiretimu et al.[10] also carried out fatigue test under Mode I+II+III condition, and results are compared with numerical simulation.

In this paper, results of fatigue crack growth simulation using S-version FEM is briefly introduced at first. Numerical results are compared with experimental ones, and it is pointed out that two factors, plasticity induced crack closure and effect of K_{III}, are important to predict crack growth behaviour correctly. These two factors are studied experimentally and numerically and their effects on fatigue crack growth are discussed.

2. Fatigue crack growth simulation of two surface cracks using S-FEM

Interaction of multiple surface crack is an important problem for the structural integrity of nuclear power plant. In Fig.1, two parallel cracks are assumed to exist on different levels. Distance between two crack tips is expressed by S and H, horizontal and vertical distances, respectively. S_0, initial S value, is set to 3 mm and H_0, initial H value, is assumed to be 1 mm. Size and aspect ratio of two cracks are assumed to be same with each other. Initial crack size is 2c_0=2 mm, and initial aspect ratio is 0.5. Pure mode I tensile load is subjected to this plate, but stress state at the inner crack tip is not under pure mode I loading by the effect of another crack tip.

For the crack growth simulation, criteria proposed by Richard et al. [11] are employed in this study. The crack growth angle, shown in Fig.2, is determined by equation (1).

\[
\phi_0 = \left[ 140^\circ - \frac{|K_{II}|}{K_j + |K_{II}| + |K_{III}|} - 70^\circ \left( \frac{|K_{II}|}{K_j + |K_{II}| + |K_{III}|} \right)^2 \right]
\]

where \( \phi_0 < 0^\circ \) for \( K_{II} > 0 \) and \( \phi_0 > 0^\circ \) for \( K_{II} < 0 \).

Equivalent stress intensity factor is defined by the following equation.

\[
\Delta K_{eq} = \frac{\Delta K_j}{2} + \frac{1}{2} \sqrt{\Delta K_j^2 + 4(1.115\Delta K_{II})^2 + 4(\Delta K_{III})^2}
\]

Fig.3 shows changes of crack shapes by fatigue crack growth simulation. Two parallel cracks grow in flat plane at first. After inner crack tips overlap, interaction effect appears
clearly, and inner crack tip changes growing direction. Both crack tips tend to go nearer to each other after S value becomes minus. These phenomena are very similar to numerical simulation of two parallel cracks in 2-dimensional field, which agrees with experimental observation. Then this simulation result seems reasonable.

It is shown that complicated crack growth behaviours are simulated well by using S-version FEM. Through comparisons of these numerical results with experimental ones, it becomes possible to verify conventional crack growth criteria.

3. Effect of plasticity induced crack closure of surface crack

Aluminum alloy A2017-T3 is used as test specimen. Similar specimen shown in Fig. 1 is made and tested. Cyclic load is subjected by three-point bending. Stress ratio R=0.1, and R is changed to 0.8 for the marking of crack shape by introducing beach marks. During fatigue test, interaction of two surface cracks occurs, and crack changes growing direction similar to results in Fig.3. Fracture surface after test is shown in Fig. 4. Beach marks are clearly observed, and crack growth rate is measured easily. By one of authors’ previous paper[10], it is pointed out that plasticity induced crack closure affects largely on crack growth rate especially near surface of the specimen. Plasticity induced crack closure rate, U, is defined by equation (3) and is calculated by the similar way of ref.[10].

\[ U = \frac{P_{\text{max}} - P_{\text{close}}}{P_{\text{max}} - P_{\text{min}}} \quad (3) \]

where \( P_{\text{close}} \) is a load at closure. U value changes along crack front, and distribution of this value is obtained as shown in Fig.5. In this figure, abscissa is eccentric angle which is defined as shown in Fig.6. U becomes the minimum value at specimen surface, and increases rapidly to \( \theta = 40^\circ \), and gradually decreases to the deepest point of surface crack. Using this U value, effective stress intensity factor range, \( \Delta K_{\text{eff}} \), is defined by Eq.(4), and Paris’ law is expressed by Eq.(5).

\[ \Delta K_{\text{eff}} = \Delta K \times U \quad (4) \]

\[ \frac{da}{dN} = C' (\Delta K_{\text{eff}})^n = C' (U\Delta K)^n \quad (5) \]
Fatigue crack growth simulation is conducted using eq.(5), and crack shapes are compared with experimental ones. Figure 7(a) and (b) show crack shapes after 150000 cyclic stresses are subjected. Figure 7(a) shows two cracks by considering U effect. Inner cracks overlap a little. But for the same cycles, two cracks are estimated largely if U effect is neglected, as shown in Fig. 7(b), where crack overlapping occurs largely, and crack size is much larger than that of Fig 7(a).

In Fig.8, changes of right side surface crack are shown. In this figure, three results are compared with each other. It is noticed that results without using U are largely different from those of experiment, and results with U value become nearer to experimental ones. Fig.9 shows comparisons of crack growth rate. The abscissa is crack length at specimen surface. By considering U effect, prediction of crack length becomes much nearer to that of experiment. If U effect is neglected, it overestimates crack length too much. Though it is conservative evaluation, it is too much conservative. It is important to evaluate U effect properly.

4. Effect of factory roof due to $K_{III}$

Slant surface crack is introduced in flat plate with $45^\circ$ slant angle. Initial crack size is $2c=9$ mm, and aspect ratio $a/c=0.7$. Fatigue test is conducted by 4-point bending test. As shown in Fig.10, span of loading points is 70 mm, and cracked area is subjected to uniform bending moment. By this loading, $K_I$ and $K_{III}$ exist near specimen surface, and $K_I$ and $K_{III}$ exist at the deepest point of surface crack. Stress ratio is 0.1 and it is changed to 0.8 for beach marks.

Figure 11 shows fracture surface after the test. Crack growth behaviour is observed clearly by beach marks. At the deepest point of crack surface, special area is observed, where beach marks are not recognized, and crack grows with twisting. This area shows factory roof. Factory roof is generated by the existence of $K_I$ and $K_{III}$ stress intensity factors. It is observed that crack growth behaviour is largely different from other area, where $K_I$ and $K_{III}$ are dominant.
This specimen is modeled for S-FEM analysis, and crack growth behavior is simulated. Simulation results are compared with experimental ones. Figure 12 shows final crack shape by S-version FEM. By numerical simulation, crack shape is smooth along the crack front, and factory roof is not observed. Figure 13 is comparison of surface crack shapes between experiment and simulation. Numerical simulation predicts crack growth shape nearly semi-elliptical. But experimental results show that beach marks are not recognized at the deepest point of surface crack, in factory roof area. It is also noticed that crack growth rate is lower than numerical prediction in this area. Near the surface of the specimen, numerical simulation predicts crack growth shape well. The main difference between experiment and numerical simulation is the existence of factory roof. To predict crack growth behavior with high accuracy, it is necessary to evaluate the effect of factory roof on crack growth process. In factory roof, crack surface twists sharply and generate non-continuous surface. By this reason, contact of crack surfaces occurs and stress intensity factor decreases. It decreases crack growth rate.

To model factory roof for FEM analysis, discontinuous shape of factory roof should be modeled, and growth of factory roof should be simulated under cyclic loading and contact between crack surfaces. It is too much complicated. In the following, crack growth criterion to express the effect of factory roof is considered, instead of exact modeling of it.

By Eq.(2), it is noticed that equivalent stress intensity factor increases due to the increase of $K_{III}$ value. It means that fatigue crack growth rate also increases with the increase of $K_{III}$. It is contrary to the experimental results shown in this study. A new criterion is considered which agree with experimental results. It should satisfy following conditions.

(a) For larger $K_{III}$ value, $K_{eq}$ becomes small.
(b) For $K_I = 0$, $K_{eq}$ is equal to $K_{III}$
(c) For $K_{III} = 0$, $K_{eq}$ becomes equal to $K_I$

To satisfy these conditions, equivalent stress intensity factor for $K_I$ and $K_{III}$ is proposed by the next equation.

$$
\Delta K_{eq(I,III)} = \frac{\sqrt{|\Delta K_I - \sqrt{2} |\Delta K_{III}|^2 + \Delta K_{I}'^2}}{\sqrt{2}}
$$

(6)

By combining with $K_{II}$, following equation is obtained to determine equivalent stress intensity factor, where coefficients on $K_{II}$ term are same as Eq.(2).

$$
\Delta K_{eq(I,II,III)} = \frac{\Delta K_{eq(I,III)} + \frac{1}{2} \sqrt{\Delta K_{eq(I,III)}^2 + 4(1.155\Delta K_{II})^2}}{2}
$$

(7)

Equation (7) is used for fatigue crack growth simulation and results are obtained. Beach marks are compared with new results, and they are shown in Fig.14. New results become very similar to experimental ones. It is obvious that new criterion is available to predict change of crack shapes during fatigue under mixed mode loading condition including $K_{III}$.

Crack growth rate is also evaluated and result is shown in Fig.15. The abscissa of these figures is crack length at specimen surface, 2c, and the ordinate is number of cycles. It is noticed that prediction by new criterion is nearer to experimental result than by Richard’s
criterion. It means generation of factory roof at deepest point of surface crack affects crack growth rate at specimen surface, though $K_{II}$ is zero at specimen surface. In this meaning, factory roof should be considered to estimate the residual fatigue life of structures.

5. Concluding remarks

By using S-FEM, it became possible to predict crack growth process for arbitrary 3-dimenisonal crack problem. To estimate crack shape and crack growth process, it is important to evaluate crack closure effect and the effect of $K_{II}$ for precise estimation of shape and fatigue life of surface cracked specimen. More comparisons between experiments and numerical simulation are needed for detailed discussion on fatigue crack growth criteria.

References

[1] P Paris and F Erdogan, “A critical analysis of crack propagation laws”, Journal of .Basic Engineering Transactions ASME, December (1963) pp.528-534

[2] Erdoga, F. and Sih, G.C., “On the Crack Extension in Plates Under Plane Loading and Transverse Shear”, Journal of .Basic Engineering Transactions ASME, Vol.85, (1963), pp.519-527

[3] D. Lebaillif and N. Recho, Brittle and ductile crack propagation using automatic finite element crack box technique, Engineering Fracture Mechanics, vol. 74, (2007), pp. 1810-1824

[4] T. N. Bittencourt, Quasi-automatic of crack propagation for 2D lefm problems, Engineering Fracture Mechanics, vol. 55, No. 2(1996), pp. 321-334

[5] D. N. dell’Erba, M. H. Aliabadi, On the solution of three-dimensional thermo-elastic mixed-mode edge crack problems by the dual boundary element method, Engineering Fracture Mechanics, vol. 66, (2000), pp. 269-285

[6] R. Citarella and F.-G. Buchholz, comparison of crack growth simulation by DBEM and FEM for SEN-specimens undergoing torsion or bending loading, Engineering Fracture Mechanics, vol. 75, (2008), pp.489-509

[7] Kikuchi, M., Wada, Y., Takahashi, M. and Li Y., “Fatigue crack growth simulation using S-FEM”, ASME PVP2008-61900, Proc. ASME PVP2008, (2008)

[8] Kikuchi, M., Wada, Suyama, H. and Li Y., “Interaction Effect Analysis of Two Surface Cracks Using S-Version FEM”, ASME PVP2009-77103, Proc. ASME PVP2009 (2009)

[9] J. Fish, S. Markolefas, R. Guittal, P. Nayak, On adaptive multilevel superposition of finite element meshes, Applied Numerical Mathematics, vol. 14, (1994), pp. 135-164.

[10] Maitiretimu, M., Kikuchi, M. and Geni M., “Comparison of Experimental and Numerically Simulated Fatigue Crack Propagation”, Transactions of the Japan Society of Mechanical Engineers, Series A, Vol.3, No.7(2009) pp.952-967

[11] H. A. Richard, M. Fulland, and M. Sander, Theoretical crack path prediction, Fatigue & Fracture of Engineering Materials & Structures, vol. 28, (2005), pp. 3-12.