Effect of Crack Interval on Multiple Crack Propagation Behavior*

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Abstract
In the authors’ previous study, fatigue crack propagation tests were performed using four-point bending specimens with multiple parallel edge notches at regular intervals of 10mm. In this study, similar tests were carried out using the specimens with crack intervals of 5mm or 2.5mm. It was found that multiple crack propagation behavior was affected by the crack interval. A small number of cracks grew selectively in the specimen with narrow crack intervals while many cracks grew to long lengths in the specimens with broad crack intervals. Experimental results were first simulated by a previously proposed method using stress intensity factor solution for multiple cracks with alternately different lengths. Simulation results showed a good agreement with experimental results in case of specimens with broad crack intervals but showed different tendency from test results in case of specimens with narrow crack intervals. To simulate the experimental results a new method was proposed, in which the stress intensity factor solution was modified to include an effect of cracks outside the neighboring two cracks. The method gave a good simulation result for the specimens with narrow crack intervals but gave higher propagation rate than experiment for the specimens with broad crack intervals, resulting in a conservative evaluation.

Key words: Multiple Cracks, Stress Intensity Factor, Influence Coefficient, Crack Propagation, Fatigue, Finite Element Method, Crack Interval, Four-Point Bending, Eccentric Tension-Compression

1. Introduction

The first stage of blades (buckets) of gas turbine experience a complex thermal and mechanical history during an operation cycle (1). This loading history sometimes causes multiple parallel cracks on the surface of the blade (2)(3). Several stress intensity factor (SIF) solutions were proposed for the multiple parallel cracks under remote tensile stress (4)(5) but they could not be applied to the blade surface because the stress distribution was very complicated there. A SIF solution under complex stress distribution was newly developed by some of the present authors for multiple parallel edge (MPE) cracks of uniform length at regular intervals (6). Crack propagation behavior on the blade surface was evaluated by using this solution. As a result, evaluated MPE crack propagation behavior was approximately consistent with the observed crack depth on the blade surface if the crack
interval of MPE cracks was suitably selected in the evaluation (6).

The authors next developed a SIF solution for MPE cracks whose lengths were alternately different (7). They performed fatigue crack propagation tests using four-point bending specimens with MPE notches at regular intervals of 10mm. The test results were simulated using this SIF solution with a help of some simple assumptions. As a result, the simulated results showed a good agreement with experimental results when the crack lengths were relatively short but showed different tendency from the experiment when the crack lengths became long.

In this study, fatigue crack propagation tests were carried out using four-point bending specimens with MPE notches at regular intervals of 5mm or 2.5mm. Specimens with narrower crack intervals were used in order to investigate stronger interaction among MPE cracks. New methods for simulating MPE crack propagation behavior were proposed.

Nomenclature

\[
a, a': \text{crack lengths of MPE cracks of alternately different lengths}
\]
\[
F_i(\xi) : \text{influence factor of MPE cracks in four-point bending specimen}
\]
\[
H : \text{crack interval}
\]
\[
h_i(\xi, \eta, \zeta) : \text{factor describing an effect that crack length are different alternately}
\]
\[
r : \text{parameter defined in Eq. (5)}
\]
\[
W : \text{plate width}
\]
\[
x : \text{distance from a mouth of a crack}
\]
\[
\zeta : \text{parameter defined as } \zeta = \ln(a/a')
\]
\[
\eta : \text{relative crack interval defined as } \eta = H/W
\]
\[
\xi : \text{relative crack length defined as } \xi = a/W
\]
\[
\sigma_i : \text{coefficient in polynomial stress distribution equation}
\]

Subscripts

\[
e : \text{experiment}
\]
\[
ma : \text{multiple cracks of alternately different lengths}
\]
\[
mu : \text{multiple cracks of uniform length}
\]
\[
s : \text{single crack}
\]

2. MPE Crack Propagation Tests

2.1 Test Method

MPE crack propagation tests were performed using three specimens. Each specimen was first machined in the shape shown in Fig. 1(a). Specimen thickness is 20mm. Number of notches \(M\), notch interval \(H\), notch length \(a_0\) and distance \(D\) in each specimen are shown in Table 1. Fatigue pre-cracking from MPE notches was carried out by applying eccentric tension-compression cyclic loading shown in Table 1 through pins inserted in two holes in the specimen. Fatigue pre-cracks for each specimen were successfully introduced in the majority of notches except for a several notches near two end notches. Pre-cracking for each specimen was continued till an average length of pre-cracks became about 1mm or longer.

After pre-cracking, the specimens were machined again in the shape shown in Fig. 1(b) and the MPE crack propagation tests were performed under four-point bending cyclic loading. Four-point bending loading conditions are shown in Table 2. An inner span was 110mm and a width \(W\) was 40mm for all the specimens. Loading frequency was 1Hz. The MPE crack propagation test was interrupted several times and crack lengths were measured on both surfaces of the specimen by means of a traveling microscope.

All specimens are made of 800MPa class high strength steel plate. The following equation shows fatigue crack propagation property of the tested steel plate which was
obtained using a standard compact specimen with 50mm width at room temperature under stress ratio of nearly zero.

\[
da/dN = 8.76 \times 10^{-8} (\Delta K)^{6.69}
\]

In the equation, \(a\) is a crack length (mm), \(N\) is a number of cycles and \(\Delta K\) is a SIF range (MPa\(\sqrt{m}\)), respectively.

\[
K_d = -69.29 + 10.76D
\]

(a) Specimen used for pre-cracking

(b) Specimen used for crack propagation test

Fig.1 Geometry of specimens used

Table 1 Loading conditions for pre-cracking

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>(M)</th>
<th>(H) (mm)</th>
<th>(a_0) (mm)</th>
<th>(D) (mm)</th>
<th>Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>41</td>
<td>5</td>
<td>3</td>
<td>60</td>
<td>-27~53</td>
</tr>
<tr>
<td>F</td>
<td>38</td>
<td>5</td>
<td>3</td>
<td>40</td>
<td>-133~49</td>
</tr>
<tr>
<td>G</td>
<td>81</td>
<td>2.5</td>
<td>2</td>
<td>60</td>
<td>-71~24</td>
</tr>
</tbody>
</table>

Table 2 Fatigue loading conditions

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>(S) (mm)</th>
<th>Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>210</td>
<td>-74~0</td>
</tr>
<tr>
<td>F</td>
<td>190</td>
<td>-74~0</td>
</tr>
<tr>
<td>G</td>
<td>210</td>
<td>-98~0</td>
</tr>
</tbody>
</table>

2.2 Test Results

The results of MPE crack propagation tests are shown in Fig. 2. In each graph, the ordinate corresponds to crack length including notch length and the abscissa to the crack number counted from the left end crack in the specimen. The cracks No.1~10 and No.72~81 of specimen G are omitted in the figure. White round symbols in each graph show distributions of pre-crack lengths and the other symbols show distributions of fatigue crack lengths measured at the number of cycles shown in each graph.

In the authors' previous study (7), the MPE crack propagation tests were performed using four specimens with MPE notches at regular intervals of \(H=10\)mm. In these specimens, cracks within the inner span propagated uniformly till their extension from pre-cracks became 1mm or longer. In the present study, the specimens with narrower notch intervals did not showed such uniform crack propagation behavior. In the specimens E and F with notch intervals of \(H=5\)mm, about a half of cracks hardly propagated and the cracks tended to propagate in such a way that the lengths were different alternately. In the specimen G with \(H=2.5\)mm, a few cracks propagated very fast and remaining majority of the cracks hardly propagated.

In order to investigate the effect of the crack interval on the MPE crack propagation
behavior, an average value and a standard deviation of relative crack length distribution were calculated. The relative crack length $\xi$ was defined as $\xi = a/W$. A relation between the average value $\mu(\xi)$ and the standard deviation $\sigma(\xi)$ are shown in Fig. 3. The results of four specimens with $H=10$mm (Specimen No. A~D) are also shown in the figure. The left end (the lowest) point of each plot in Fig. 3 corresponds to the average value and the standard deviation of pre-crack length distribution in each specimen. The relation between $\mu(\xi)$ and $\sigma(\xi)$ in each specimen can be approximated as an exponential function with an exponent $m$ as shown by a solid line in Fig. 3. Figure 4 shows a relation between the

![Graph](image)

(a) Specimen E (Cracks from No. 10 to No. 32 are located inside the inner span)

![Graph](image)

(b) Specimen F (Cracks from No. 9 to No.30 are located inside the inner span)

![Graph](image)

(c) Specimen G (Cracks from No. 20 to No. 64 are located inside the inner span)

Fig. 2 Experimental results of MPE crack propagation tests

![Graph](image)

Fig. 3 Relation between standard deviation and average value of relative crack length

![Graph](image)

Fig. 4 Relation between exponent $m$ and relative crack interval $\eta$
exponent \( m \) and a relative crack interval \( \eta = H/W \). The exponent \( m \) decreases with an increase in the relative crack interval \( \eta \) in the range of \( 0.06 \leq \eta \leq 0.25 \). This tendency is consistent with an experimental result that the specimen with broad crack interval shows relatively uniform MPE crack propagation behavior compared with the specimen with narrow crack interval.

3. Propagation behavior of the longest crack in each specimen

When the four point bending specimen with MPE cracks of uniform length (Fig. 1(b)) is subjected to a linear stress distribution

\[
\sigma = \sigma_0 + \sigma_1 (x/W)
\]

the stress intensity factor (SIF) \( K_{mu} \) can be described as

\[
K_{mu} = \left\{ F_0(\xi) \sigma_0 + F_1(\xi) \sigma_1 \xi \right\} \sqrt{\pi a}
\]

where \( x \) is a distance from a mouth of a crack. Finite element elastic analyses were performed for specimen with \( H=5\)mm and for specimen with \( H=2.5\)mm, and influence factors \( F_0(\xi) \) and \( F_1(\xi) \) for \( \xi = 0.1, 0.2, 0.3, 0.4 \) and \( 0.5 \) were calculated for each specimen. The relations between influence factors and \( \xi \) were approximated by polynomial expressions as follows:

\[
F = A_0 + A_1 \xi + A_2 \xi^2 + A_3 \xi^3 + A_4 \xi^4
\]

The coefficients \( A_0 \sim A_4 \) are listed in Table 3. Similar equations for specimens with \( H=10\)mm are shown in ref. (7).

Table 3 Coefficients of approximation equations of \( F_0 \) and \( F_1 \) for four-point bending specimens

<table>
<thead>
<tr>
<th>( H )</th>
<th>( F_0 ) or ( F_1 )</th>
<th>( A_0 )</th>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_3 )</th>
<th>( A_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5mm</td>
<td>( F_0 )</td>
<td>1.119</td>
<td>-8.937</td>
<td>51.32</td>
<td>-112.1</td>
<td>96.64</td>
</tr>
<tr>
<td>5mm</td>
<td>( F_1 )</td>
<td>0.6819</td>
<td>-3.294</td>
<td>15.04</td>
<td>-28.27</td>
<td>23.51</td>
</tr>
<tr>
<td>2.5mm</td>
<td>( F_0 )</td>
<td>1.118</td>
<td>-12.12</td>
<td>71.13</td>
<td>-162.7</td>
<td>137.6</td>
</tr>
<tr>
<td>2.5mm</td>
<td>( F_1 )</td>
<td>0.6814</td>
<td>-5.361</td>
<td>27.28</td>
<td>-57.89</td>
<td>47.09</td>
</tr>
</tbody>
</table>

The crack growth rate of the longest crack in each specimen was calculated by three different methods and defined as \( (da/dN)_{e} \), \( (da/dN)_{s} \) and \( (da/dN)_{mu} \), respectively. The rate \( (da/dN)_{e} \), was calculated by means of a seven-point incremental polynomial method using all experimental data points. A five-point incremental polynomial method was used for specimens A and G because data points were limited in these specimens. The rate \( (da/dN)_{e} \) was calculated using Eq. (1) and a SIF equation of single crack in a four-point bending specimen \(^8\). The calculation was done for every crack length for which the rate \( (da/dN)_{e} \) was evaluated. The rate \( (da/dN)_{mu} \) was calculated using Eqs. (1) and (3). Using these three crack growth rate, the following parameter was calculated:

\[
\frac{(da/dN)_e - (da/dN)_{mu}}{(da/dN)_e - (da/dN)_{mu}}
\]

The parameter \( r \) becomes zero when \( (da/dN)_{e} \) is equal to \( (da/dN)_{mu} \) while \( r \) becomes unity when \( (da/dN)_{e} = (da/dN)_{s} \).
The relation between parameter $r$ and relative crack length $\xi$ is shown in Fig. 5. Every specimen shows increase of $r$ with an increase in $\xi$ after the start of crack propagation test. In specimens D and F, the parameter $r$ keeps constant value after $r$ attains unity. The first (the lowest) point of each plot is shown by a solid symbol in Fig. 5. Denote this point by $(\xi_0, r_0)$. The point $(\xi_0, r_0)$ is affected by pre-crack length distribution in each specimen and the location in $r-\xi$ plot is different from each other. On the other hand, the slope of $r-\xi$ relation of each specimen shows roughly the same value of three. Figure 6 shows a relation between $r$ and $\xi'$ where $\xi'$ is defined as $\xi' = \xi - (\xi_0 - r_0/3)$. The new axis $\xi'$ was introduced to arrange all first points of specimens A~G on a single line in $r-\xi'$ plot. All data points of specimens A~G are plotted along a black kinked line shown in Fig. 6. It can be seen from Fig. 6 that the crack growth rate of the longest crack in each specimen tends to shift from the growth rate calculated assuming MPE cracks of uniform length ($r=0$) to that calculated assuming a single crack ($r=1$).

Figure 7 shows comparison between crack propagation behavior obtained by experiment (plots) and that calculated using the black kinked line in Fig. 6 and Eq. (5) (lines). The calculation in Fig. 7 is not a simulation of crack propagation behavior but only a rearrangement of the experimental data. The simulation methods are proposed in the next section.

![Fig. 5 Relation between parameter $r$ and relative crack length $\xi$.](image1)

![Fig. 6 Relation between $r$ and $\xi'$.](image2)

![Fig. 7 Comparison between calculated results by Eq. (5) (lines) and experimental results (symbols) of propagation behavior of the longest crack in each specimen.](image3)

### 4. Simulation of MPE crack propagation behavior

#### 4.1 Simulation using SIF solution for MPE cracks of alternately different lengths

It was shown in ref. (7) that the SIF of MPE cracks of alternately different lengths ($a$...
and \(a'\) can be evaluated by multiplying the SIF of MPE cracks of uniform length \((a)\) by a parameter \(h\). It was also shown that the parameter \(h\) is a function of relative crack length \(\xi\), relative crack interval \(\eta\) and a parameter \(\zeta\) defined as \(\zeta = \ln(a/a')\). Approximation equations of function \(h_i(\xi, \eta, \zeta)\) were proposed for constant stress distribution \(\sigma = \sigma_0\) \((i=0)\) and for linear stress distribution \(\sigma = \sigma_0(x/W)\) \((i=1)\), respectively \((7)\). By using the function \(h_i(\xi, \eta, \zeta)\), the SIF \(K_{ma}\) for cracks of length \(a\) in the four-point bending specimen (Fig. 1(b)) with MPE cracks of alternately different lengths \((a\) and \(a'\)) can be described as in the followings:

\[
K_{ma} = [F_0(\xi)h_0(\xi, \eta, \zeta)\sigma_0 + F_1(\xi)h_1(\xi, \eta, \zeta)\sigma_1]\sqrt{\pi a}
\]

\((6)\)

\(F_0(\xi)\) and \(F_1(\xi)\) in Eq. (6) are given in Eq. (4).

In ref. \((7)\), the MPE crack propagation behavior in the four-point bending specimen was simulated using the following three assumptions:

(a) SIF value of a crack number \(j\) in considering MPE cracks with arbitrary crack length distribution is the same as that of MPE cracks with alternately different lengths \(a_j\) and \((a_j+1+a_{j+1})/2\), where \(a_j\) is a crack length of the crack number \(j\) and \(a_{j-1}\), \(a_{j+1}\) are those of the neighboring two cracks.

(b) The SIF of MPE cracks with alternately different lengths \(a_j\) and \((a_j+1+a_{j+1})/2\) under bending stress \(\sigma_b\) is calculated by the following equation:

\[
K = [F_0(\xi)h_0(\xi, \eta, \zeta_{j+1}) - 2F_1(\xi)h_1(\xi, \eta, \zeta_{j+1})]\sqrt{\pi a}
\]

\((7)\)

where \(\xi = a/W\) and \(\zeta_{j+1} = \ln(2a/(a_j+a_{j+1}))\).

(c) The left end crack (crack number 1) and the right end crack in the specimen do not propagate at all. The other cracks in the specimen propagate according to the SIF values calculated with bending stress at their locations.

MPE crack propagation behavior in specimens \(E \sim G\) were simulated using the same assumptions \((a) \sim (c)\). The results are shown in Fig. 8. The symbols in Fig. 8 are the experimental results which are quite the same as those in Fig. 2. Each line in Fig. 8 corresponds to the simulated result at the number of cycles shown in the figure. This cycle was determined as the cycle when the simulated crack length of the longest crack became the same as that obtained in the experiment. In the simulation of each specimen, the pre-crack length distribution shown by white round symbols was used as the initial crack condition.

The crack propagation behavior of specimen \(E\) was simulated as long cracks and short cracks were arranged alternately. This tendency was similar to the experimental result except that some cracks among the long cracks elongated very long in the experiment as can be seen in the cracks No. 11, No. 16, No. 22 and No. 26 while all long cracks tended to elongate uniformly in the simulation. Simulated crack propagation behavior of specimen \(F\) showed similar tendency to that of specimen \(E\). In a figure of specimen \(G\), crack length distributions from No. 11 to No. 71 are shown. In the experiment of specimen \(G\), a few cracks propagated very fast and remaining majority of the cracks hardly propagated. On the other hand, the crack propagation behavior of specimen \(G\) was simulated as long cracks and short cracks were arranged alternately.

Figure 9 shows relation between a crack length of the longest crack in the specimen and number of cycles. The symbols in Fig. 9 are the experimental results while lines correspond to the simulated results. The results of four specimens with \(H=10\)mm (Specimen No. \(A \sim D\)) \((7)\) are also shown in the figure. Simulated results of crack propagation behavior in specimens \(A \sim D\) agree well with those obtained in the experiments. On the other hand, simulated crack growth rates in specimens \(E \sim G\) with narrower crack intervals were lower.
Fig. 8 Comparison between simulated results by Eq. (7) (lines) and experimental results (symbols) of MPE crack propagation behavior

Fig. 9 Comparison between simulated results by Eq. (7) (lines) and experimental results (symbols) of propagation behavior of the longest cracks
than those in the experiments. The discrepancy between simulation and experiment was largest in specimen G with the narrowest crack interval of $H=2.5\text{mm}$. The longest crack in specimen G propagated to 15mm long during 19,000 cycles in experiment while 86,000 cycles was necessary for propagating to the same length in simulation.

4.2 Simulation considering an effect of cracks outside the neighboring two cracks

In the method described in section 4.1, SIF value of a certain crack is evaluated simply considering crack lengths of this crack and the neighboring two cracks. This assumption gave appropriate simulation results of MPE crack propagation behavior for specimens with crack interval of $H=10\text{mm}$ however gave lower crack growth rate for specimens with $H\leq 5\text{mm}$. This discrepancy between simulation and experiment in the later case seems to be caused by an effect of cracks outside the neighboring two cracks.

Consider SIF value of crack No. $j$ in MPE cracks with relative crack interval $\eta$ and with arbitrary crack length distribution. The method described in section 4.1 assumes $\bar{\xi}_{j+2} = \xi_j$ where $\bar{\xi}_{j+2}$ is an average of relative crack length of crack No. $j+2$ and that of crack No. $j+2$. The method also assumes $\bar{\xi}_{j+3}=\xi_{j+1}$, $\bar{\xi}_{j+4}=\xi_j$ and so on but we don't take them into account here. Assume that the error introduced by assuming $\bar{\xi}_{j+2} = \xi_j$ can be approximately evaluated by a ratio of the SIF of MPE cracks of uniform relative crack length $\xi_j$ with relative crack interval $2\eta$ to the SIF of MPE cracks of alternately different relative crack lengths $\xi_j$ and $\xi_{j+2}$ with relative crack interval $2\eta$. This ratio can be described as $h(\xi_j, 2\eta, \zeta_j)$ where $\zeta_j = \ln(\xi_j/\xi_{j+2})$. Then the SIF of crack No. $j$ can be evaluated by the following equation:

$$K_{ma} = \left\{ \frac{F_0(\bar{\xi}_j, h_0(\xi_j, \eta, \zeta_j)) h_0(\xi_j, 2\eta, \zeta_j) - 2F_1(\bar{\xi}_j, h_1(\xi_j, \eta, \zeta_j)) h_1(\xi_j, 2\eta, \zeta_{j+2}) h_j(\xi_j, \xi_j)}{2F_1(\bar{\xi}_j, h_1(\xi_j, \eta, \zeta_j)) h_1(\xi_j, 2\eta, \zeta_{j+2}) h_j(\xi_j, \xi_j)} \right\} \sigma_b \sqrt{\pi a} \quad (8)$$

where $\zeta_j = \ln(\xi_j/\xi_{j+1})$.

Figure 10 shows MPE crack propagation behavior of specimens E ~ G simulated according to the method described in section 4.1 except that Eq. (8) is used instead of Eq. (7) and two left end cracks and two right end cracks in the specimen are assumed not to propagate at all. The symbols in Fig. 10 are the experimental results while lines correspond to the simulated results. The simulated results by Eq. (8) gave a good agreement with the experiments for specimens E and F with $H=5\text{mm}$. In specimen G with $H=2.5\text{mm}$, much more cracks elongated to long length in the simulation than the experiment although the discrepancy between the simulation and the experiment became smaller compared with Fig. 8(c). Simulation results of specimens A ~ D are not shown in Fig. 10 for the lack of space. In the simulation of these specimens, a few cracks selectively propagated very fast though many cracks propagated to long lengths in the experiment.

Figure 11 shows relation between a crack length of the longest crack in the specimen and number of cycles. The symbols in Fig. 11 show the experimental results while lines correspond to the results simulated by using Eq. (8). Simulated results of crack propagation behavior in specimens E and F with $H=5\text{mm}$ agree well with those obtained in the experiments. Simulated crack growth rates in specimens A ~ D with $H=10\text{mm}$ are higher than those in the experiments while simulated crack growth rate in specimen G with $H=2.5\text{mm}$ is lower than those in the experiment.

Consider a following equation:

$$K_{ma} = \left\{ \frac{F_0(\bar{\xi}_j, h_0(\xi_j, \eta, \zeta_j)) h_0(\xi_j, 2\eta, \zeta_j) h_0(\xi_j, 3\eta, \zeta_{j+3}) - 2F_1(\bar{\xi}_j, h_1(\xi_j, \eta, \zeta_j)) h_1(\xi_j, 2\eta, \zeta_{j+2}) h_1(\xi_j, 3\eta, \zeta_{j+3}) h_j(\xi_j, \xi_j)}{2F_1(\bar{\xi}_j, h_1(\xi_j, \eta, \zeta_j)) h_1(\xi_j, 2\eta, \zeta_{j+2}) h_1(\xi_j, 3\eta, \zeta_{j+3}) h_j(\xi_j, \xi_j)} \right\} \sigma_b \sqrt{\pi a} \quad (9)$$
Fig. 10 Comparison between simulated results by Eq. (8) (lines) and experimental results (symbols) of MPE crack propagation behavior.

Fig. 11 Comparison between simulated results by Eq. (8) (lines) and experimental results (symbols) of propagation behavior of the longest cracks.
Equation (9) was introduced on the analogy of Eq. (8). Figure 12 shows MPE crack propagation behavior of specimen G simulated by using Eq. (9) and by assuming three left end cracks and three right end cracks in the specimen do not propagate at all. The simulated results by Eq. (9) show a good agreement with the experiments for specimen G. In the simulation of specimens A~F, a fewer cracks selectively propagated very fast unlike the experimental results. Figure 13 shows relation between a crack length of the longest crack in the specimen and number of cycles. The lines in Fig. 13 correspond to the results simulated by using Eq. (9). Simulated results of crack propagation behavior in specimen G with $H=2.5\text{mm}$ agree well with those obtained in the experiments. On the other hand, simulated crack growth rates in specimens A~F with narrower crack intervals are higher than those in the experiments.

5. Conclusions

Fatigue crack propagation tests were performed using four-point bending specimens with multiple parallel edge (MPE) cracks at regular intervals. The results obtained are summarized as follows:

(1) The MPE crack propagation behavior was affected by the crack interval. A small number of cracks grew selectively in the specimens with narrow crack intervals while many cracks grew to long lengths in the specimens with broad crack intervals.

(2) The crack growth rate of the longest crack in each specimen tends to shift from a growth rate calculated assuming MPE cracks of uniform length to that calculated assuming a single crack.
(3) The MPE crack propagation behavior was first simulated using stress intensity factor (SIF) solution for MPE cracks of alternately different lengths (simply considering crack lengths of the concerning crack and the neighboring two cracks). As a result, simulated crack propagation behavior showed a good agreement with the experiment for specimens with broad crack interval (relative crack interval $\eta = 0.25$) but gave lower crack growth rate for specimens with narrow crack interval ($0.0625 \leq \eta \leq 0.125$).

(4) The MPE crack propagation behavior was next simulated using SIF solution considering an effect of cracks outside the neighboring two cracks. This method gave good simulation results for the specimens with narrow crack intervals but gave higher crack growth rate than experiment for the specimens with broad crack intervals, resulting in a conservative evaluation.

(5) The present simulation methods are applicable to any MPE crack problems if the SIF solution of the MPE cracks of uniform length is available. Required data for the simulation is initial crack length distribution only. From these points of view, it is considered to be a practical method. However, an accuracy of the simulation needs to be improved in a future study.

References


