FLAW GROWTH EVALUATION FOR DEEP SURFACE FLAW
BASED ON FFS CODE PROCEDURE

F. Iwamatsu, K. Miyazaki, Hitachi Research Laboratory, Hitachi, Japan
M. Mochizuki, Osaka University, Japan

ABSTRACT
Rational and applicable flaw evaluation based on a fitness-for-service code is required due to ongoing developments in NDT techniques. In this study, SCC growth evaluation under several stress distributions was conducted using a conventional code procedure, a proposed code procedure, and a detailed finite element analysis method.

In-service inspection including evaluation for nuclear power plants was conducted on the basis of a fitness-for-service code, such as the ASME Boiler and Pressure Vessel Code Section XI. In flaw evaluation based on ASME Section XI, an aspect ratio of a detected surface flaw is defined by $a/\ell$, where $a$ is the flaw depth and $\ell$ is the flaw length, and the aspect ratio $a/\ell$ is limited up to 0.5. Therefore, a deep surface flaw, which has an aspect ratio $a/\ell$ greater than 0.5, is characterized as a semicircle with $\ell$ equal to $2a$. Meanwhile, deep surface flaws caused by stress corrosion cracking (SCC) were detected in Ni based alloy weld metal by the NDT technique. Since the limit of the flaw characterization rule seems to lead to conservative evaluation results for a deep surface flaw, more rational and applicable flaw evaluation is required to eliminate surplus conservatism. Therefore, in this study, flaw growth evaluation was conducted using a conventional code procedure, a proposed code procedure to deal with a deep surface flaw shape, and a detailed finite element analysis method. Since detection of deep surface flaws are assumed in Ni based alloy weld metal, a deep initial flaw caused by SCC and anisotropic SCC growth rates was considered in flaw growth evaluation. Membrane, bending, and residual stress distributions were assumed. Comparisons of these results show the applicability and effectiveness of flaw growth evaluation beyond current code limits.

INTRODUCTION
SCC has been detected in welded components of nuclear power plants\(^1\). The detected surface flaw is characterized by a semi-ellipse for analytical evaluation in Fitness-for-Service (FFS) Code, such as ASME Section XI\(^2\), to calculate flaw growth until the next inspection or the end of service lifetime of the component. In the flaw evaluation based on ASME Section XI, an aspect ratio of a surface flaw is represented by $a/\ell$, where $a$ is the flaw depth and $\ell$ is the flaw length. To calculate stress intensity factors (SIFs), which are parameters affecting flaw growth evaluation, influence coefficients are prescribed for $a/\ell$ is from 0.0 to 0.5. Therefore, the aspect ratio of the characterized surface flaw shall not exceed 0.5. Some FFS Code prescribes a flaw evaluation procedure similar to that in ASME Section XI. API 579-1/ASME FFS-1—Fitness-for-Service\(^3\) (API/ASME) prescribes equations to calculate SIFs up to $a/\ell$ equal to 1.0 for a surface flaw in a plate under membrane or bending stresses.
Therefore, a deep surface flaw, which has aspect ratios \( a/\ell \) greater than 0.5, is characterized in accordance with a limit of each flaw characterization rule. Meanwhile, deep surface flaws beyond these limits caused by SCC have been detected in the Ni based alloy weld metal by a NDT technique, such as an ultrasonic test. Therefore, more rational and applicable flaw evaluation is required for a deep surface flaw. The authors have proposed influence coefficients to calculate SIFs for surface flaws and summarized them as a tabular form on the basis of equations prescribed in ASME Section XI.

In this study, to verify applicability and effectiveness of proposed coefficients, flaw growth evaluation was conducted on the basis of ASME Section XI, API/ASME, proposed coefficients, and a detailed FEA method. Since detection of deep surface flaws is assumed in Ni based alloy weld metal, a deep initial flaw caused by SCC and anisotropic SCC growth rates was considered in flaw growth evaluation. Membrane, bending and residual stress distributions were assumed. Comparisons of these results show the applicability and effectiveness of flaw growth evaluation beyond current code limits.

**SIF SOLUTIONS BASED ON CODES**

Generally, since flaw growth rates due to SCC or fatigue are represented as a function of SIF, flaw growth evaluation requires calculation of SIFs. In accordance with the ASME Section XI procedure, a detected surface flaw with an aspect ratio \( a/\ell \) over 0.5 is characterized as a semicircle flaw with \( \ell = 2a \) as shown in Fig. 1.

Stress distribution \( \sigma \) on the surface flaw as driving force is represented by the third order polynomial.

\[
\sigma = A_0 + A_1 \left( \frac{x}{a} \right) + A_2 \left( \frac{x}{a} \right)^2 + A_3 \left( \frac{x}{a} \right)^3
\]

where \( x \) is distance in the flaw depth direction from flawed surface as shown in Fig. 2, and \( A_0 \) through \( A_3 \) are constants depending on stress distribution. SIFs at the deepest and surface points (points 1 and 2 in Fig. 2, respectively) are calculated in accordance with the following equation for a characterized surface flaw.

\[
K = [\left( A_0 + A_p \right)G_0 + A_1G_1 + A_2G_2 + A_3G_3]\sqrt{a/\ell}/Q
\]

where \( A_p \) is internal pressure loading on the flaw surface and \( G_0 \) through \( G_3 \) are influence coefficients depending on \( a/t \) and \( a/\ell \) (Coefficients G). Coefficients G are can be obtained from Tables A-3320-1 and A-3320-2 in the ASME code for a surface flaw with an aspect ratio \( a/\ell \) between 0.0 and 0.5. The flaw shape parameter \( Q \) is calculated in accordance with the following equation.

\[
Q = 1 + 4.593 \left( \frac{a}{\ell} \right)^{1.65}
\]

Eqs. (1) through (3) enable calculation of SIFs for an arbitrary semi-elliptical flaw shape with an aspect ratio \( a/\ell \) between 0.0 and 0.5. To evaluate flaw growth behavior of a deep surface flaw, the application range of coefficients G should be extended to an aspect ratio over 0.5. Also, the flaw shape parameter \( Q \) should be converted into the following equations.
To extend flaw growth evaluation for a deep flaw, coefficients G should be evaluated by a series of FEA depending on flaw sizes \(a/t\) and \(a/\ell\). Therefore, the authors have proposed coefficients G to calculate SIFs for surface flaws with an aspect ratio \(a/\ell\) up to 4.0 and summarized them as a tabular form on the basis of equations prescribed in ASME Section XI. Several example problems are required to verify the applicability and effectiveness of proposed coefficients G.

API/ASME prescribes the equations to calculate SIFs for a surface flaw in a plate under membrane and bending stresses with an aspect ratio \(a/\ell\) between 0.0 and 1.0. Stress distribution \(\sigma\) on the surface flaw as driving force is represented by the fourth order polynomial.

\[
\sigma = A_0 + A_1 \left(\frac{x}{t}\right) + A_2 \left(\frac{x}{t}\right)^2 + A_3 \left(\frac{x}{t}\right)^3 + A_4 \left(\frac{x}{t}\right)^4
\]  

(5)

where \(t\) is thickness of a plate. Equivalent membrane and bending stress distribution, \(\sigma_m\) and \(\sigma_b\), respectively, are in accordance with the following equation.

\[
\sigma_m = A_0 + \frac{A_1}{2} + \frac{A_2}{3} + \frac{A_3}{4} + \frac{A_4}{5}
\]  

(6)

\[
\sigma_b = -\frac{A_1}{2} - \frac{A_2}{3} - \frac{9}{20} A_3 - \frac{6}{15} A_4
\]  

(7)

SIFs on the flaw tip are calculated in accordance with the following equation.

\[
K = \left[ M_m (\sigma_m + p_c) + M_b \sigma_b \right] \sqrt{m/Q}
\]  

(8)

where \(p_c\) is internal pressure loading on the flaw surface and the same as \(A_p\) in Eq. (2). \(M_m\) and \(M_b\) can be determined using equations. \(Q\) is the same as Eq. (4).

**FLAW GROWTH EVALUATION USING FEA**

Since it is difficult to conduct fatigue or SCC growth tests while maintaining a deep flaw shape up to the end of a test, flaw evaluation using FEA that enables flaw growth behavior to represent an arbitrary flaw shape was conducted for comparison with flaw growth evaluation based on code procedures. Flaw evaluation using FEA required repeated calculation considering flaw growth behavior, which means that an FE model considering a flaw shape has to be generated for each analytical step. Moreover, hundreds of analytical steps are needed to obtain accurate results. Therefore, the authors have proposed automatic flaw growth evaluation using the developed program and commercial software (FEA method). In evaluations using the FEA method, three-dimensional FE models considering the arbitrary planer flaw shape are automatically generated using the program in Visual Basic. SIFs are calculated using a commercial FEA program ABAQUS for generated FE models. The FEA method enables SIFs to be calculated on each flaw tip node and arbitrary planer flaw shapes to be estimated under
complicated stress distribution as shown in Fig. 3. Therefore, accurate SIFs calculated for a flaw with an aspect ratio \( a/\ell \) over code limits.

**ANALYTICAL CONDITIONS OF FALW GROWTH EVALUATION**

To verify applicability and effectiveness of proposed coefficients G to flaw growth evaluation, SCC growth behaviors under membrane, bending, and residual stress distributions were evaluated on the basis of ASME Section XI, API/ASME, proposed coefficients G, and a detailed FEA method. Analytical conditions are as follows.

Initial flaw: A flaw model assumed a semi-elliptical flaw in a plate as shown in Fig. 2. Initial flaw depth \( a_0 \) was 1.0 mm, initial flaw length \( \ell_0 \) was 0.2 mm, and thickness of a plate \( t \) was 10.0 mm. The initial aspect ratio \( a_0/\ell_0 \) is 5.0 and flaw deep ratio \( a_0/t \) is 0.1. The initial aspect ratio \( a_0/\ell_0 \) exceeds the limits of procedures, which are 0.5 in ASME Section XI, 1.0 in API/ASME, and 4.0 in proposed coefficients G. Therefore, the initial flaw length is expanded on the basis of each aspect ratio limit except the FEA method. In evaluation using the procedures except the FEA method, a semi-elliptical flaw shape is applied during flaw growth evaluation in accordance with the flaw characterization rule. In an evaluation using the FEA method, an arbitrary flaw shape is defined on the basis of flaw extension at each flaw tip node as shown in Fig. 3.

Stress distribution: Membrane, bending, and residual stress fields were assumed for flaw growth evaluation. Each stress distribution is represented as follows and shown in Fig. 4.

\[
\sigma = 300 \quad \text{(Membrane)}
\]
\[
\sigma = 300 - 300(x/t) \quad \text{(Bending)}
\]
\[
\sigma = 470.0 - 3512.1(x/t) + 7182.7(x/t)^2 - 4018.3(x/t)^3 \quad \text{(Residual stress)}
\]

Note that the bending stress field is not exactly pure bending but includes membrane stress. Residual stress field was considered with 100 MPa membrane stress as applied stresses from all forms of loading.

Calculation of SIFs: SIF, \( K \), is calculated using coefficients G, equations, and the FEA method as described above.

Flaw growth rate: In consideration of deep surface flaws in the Ni based alloy weld metal caused by SCC, a SCC growth rate was applied for a Ni base alloy in a BWR environment with normal water chemistry \(^2\). The applied SCC growth rate in a flaw depth direction is represented as follows and shown in Fig. 5.

\[
\frac{da}{dt} = \begin{cases} 
8.92 \times 10^{-14} K^{2.5} & \text{for } K \leq 27.5 \\
3.53 \times 10^{-10} & \text{for } K > 27.5
\end{cases}
\]  

(9)

where \( t \) is time. A unit of \( da/dt \) is m/s. The 1/10 SCC growth rate in Eq. (5) was assumed in a flaw length direction. Anisotropic SCC growth rates are assumed to maintain a deep flaw shape for as long as possible during flaw growth evaluation. Time increments \( \Delta t \) were set to 0.01 years for evaluation using G values and within 0.1 years for evaluation using the FEA method to calculate flaw extension \( \Delta a \) for a step.
RESULTS OF FLAW GROWTH EVALUATION

Flaw growth evaluation was conducted on the basis of ASME Section XI, API/ASME, proposed coefficients G, and a detailed FEA method. Flaw growth behaviors until flaw depth $a$ reached 8 mm, which means that flaw depth ratio $a/t$ reaches 0.8, were obtained from each evaluation. Results of flaw growth evaluation for a deep surface flaw under membrane, bending, and residual stress distributions are shown in Tables 1 through 3 and Figs. 6 through 8. These figures compare flaw depth versus time and SIF versus flaw depth ratio. As described above, the FEA method enables flaw growth evaluation to represent arbitrary planer flaw shapes. Therefore, flaw depth and length should be defined for an arbitrary planer flaw shape. In this study, flaw depth was defined as the distance from the flawed surface at the deepest node and flaw length as the length on the flawed surface.

Evaluation results for membrane stress distribution are shown in Table 1 and Fig. 6. Evaluated times differ depending on evaluation procedures, especially the time evaluated by the FEA method, which is over 10 times that evaluated by the ASME Section XI procedure. Since an aspect ratio $a/\ell$ is limited up to 0.5 in the ASME Section XI procedure, a flaw length with an aspect ratio $a/\ell$ exceeding 0.5 is expanded into $2a$. The initial SIF at the deepest point by the ASME Section XI procedure is over seven times that by the FEA procedure. In addition, flaw growth rate is represented as a function of the 2.5th power of SIF as shown in Eq. (9) in this evaluation. An aspect ratio limit has a significant effect on flaw growth evaluation in this case. SIFs at the end of evaluation calculated by the API/ASME procedure are approximately 20% different in regard to the FEA method, which caused over 10 years difference in evaluated times. Although SIFs by proposed coefficients G roughly correspond with those by the FEA method as shown in Fig. 6(b), evaluated times are about four years different.

Evaluation results for bending stress distribution are shown in Table 2 and Fig. 7. Evaluated times also differ depending on evaluation procedures, especially the time evaluated by the FEA method, which is over six times that evaluated by the ASME Section XI procedure. Although tendencies of SIFs calculated using API/ASME, proposed G, and FEA seem to correspond totally, differences in SIFs while the flaw is small remarkably affect the evaluated times. Because the evaluated time until the flaw depth reaches 2 mm was more than half the total time until the flaw depth reaches 8 mm in the cases of proposed G and FEA, the flaw characterization for the initial flaw is primarily of importance.

Evaluation results for bending stress distribution are shown in Table 3 and Fig. 8. The flaw depth evaluated by API/ASME did not propagate to 8 mm in 60 years. From Eqs. (6) and (7), equivalent membrane and bending stresses, $\sigma_m$ and $\sigma_b$, are approximately 104 MPa and -27 MPa, respectively. These equivalent stresses seem to be underestimated for the assumed residual stress distribution. In this case, the polynomial approximation of the stress distribution would be appropriate and API/ASME also specifies the evaluation procedure using the polynomial approximation. Note that the aspect ratio limit for the polynomial approximation in API/ASME is the same as that in ASME Section XI: $a/\ell$ is limited up to 0.5. The evaluated results obtained by ASME Section XI, proposed G, and FEA were compared as described below. Evaluated time until the flaw depth reaches 8 mm relatively corresponds to results for membrane and bending stresses.
Since the residual stress is sharply decreased adjacent to the flawed surface as shown in Fig. 4, the flaw growth rate at the surface point while the small flaw is relatively higher. Therefore, the aspect ratio is sharply changed into the semicircle flaw, and the effect of deference of SIFs for the small flaw is not significant.

Although it is difficult to conduct fatigue or SCC flaw growth tests while maintaining a deep flaw shape up to the end of a test, the detailed FEA method obtained the most accurate results for the flaw growth evaluation. Therefore, it is verified that the code procedure including the application range is expanded into the deep flaw shape generally obtaining the conservative results for the flaw growth evaluation. From the comparison evaluation results between conventional code and proposed G to deal with a deep surface flaw shape, the expansion of the application range of the aspect ratio enables rational and applicable flaw evaluation.

SUMMARY AND CONCLUSIONS

Rational and applicable flaw evaluation based on a fitness-for-service code is required due to the ongoing developments in NDT techniques. SCC growth evaluation under several stress distributions was conducted using a conventional code procedure, a proposed code procedure, and a detailed finite element analysis method. The results are summarized as follows:

(a) It is verified that the code procedure including the application range is expanded into the deep flaw shape generally obtaining conservative results for the flaw growth evaluation.

(b) The expansion of the application range of the aspect ratio enables rational and applicable flaw evaluation.

(a) \( a/t \leq 0.5 \)

(b) \( a/t > 0.5 \)

Figure 1 Flaw characterization in ASME Section XI

Figure 2 Schematic of characterized surface flaw
**Figure 3** Renewal of flaw shape using FEA method

- $\Delta a_i$: flaw extension at point $i$ ($i = 1, 2, \ldots, n$)
- Propagated flaw (Arbitrary planar shape)
- FE mesh for previous flaw
- Point $n$
- Point $2$
- Point $1$

**Figure 4** Assumed stress distributions for flaw growth evaluation

**Figure 5** SCC growth rate for Ni base alloy in BWR environment

\[ K, \text{ MPa(m)}^{0.5} \]

- Stress intensity factor $K$
- SCC growth rate $d\Delta a/dt$, m/s
Table 1 Results of flaw growth evaluation for membrane stress distribution

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<th>Results of evaluation</th>
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<td>(\ell_0, \text{mm})</td>
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Figure 6 Transition of flaw growth under membrane stress distribution

Table 2 Results of flaw growth evaluation for bending stress distribution

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Figure 7 Transition of flaw growth under bending stress distribution
Table 3 Results of flaw growth evaluation for residual stress distribution

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<td>FEA</td>
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* Flaw did not propagate to 8 mm in 60 years

Figure 8 Transition of flaw growth under residual stress distribution

REFERENCES