Calculation of Stress Intensity Factor of Stress Corrosion Cracking in the Weldment of Core Shroud of Boiling Water Reactor

Yongkui Li  
Japan Atomic Energy Agency  
Yoshiyuki Kaji  
Japan Atomic Energy Agency  
Takahiro Igarashi  
Japan Atomic Energy Agency

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ABSTRACT

Stress corrosion cracking is recently observed in the heat affected zone of welded joint of the core shroud of boiling water reactors. Stress intensity factor is essential for evaluation of crack growth behavior in stress corrosion cracking. In this study, stress intensity factor of surface crack under residual stress field was calculated using two experienced equations in API RP579 with the aids of finite element method. The feasibility and reliability of the used methods were discussed.

1. INTRODUCTION

Stress corrosion cracking (SCC) is normally found in the core shroud of the boiling water reactor of a nuclear power plant after it has serviced several decades. Stress intensity factor estimated by using an appropriate modeling of components is essential for evaluation of crack growth behavior in stress corrosion cracking. For the appropriate modeling of welded components with a surface crack, it is important to understand the effects of residual stress distribution on the stress intensity factor of the crack.

In this study, the stress intensity factor of the SCC was estimated using the methods of semi-elliptical shape surface crack in API RP579 [1]. The guide of API provides two methods to calculate the stress intensity factor. The results of tension-compression-tension axial weld residual stress in weldment H6a of a core shroud by ABAQUS were used [2-4]. On the basis of the axial stress at the crack tip, we calculated the stress intensity factor, and made comparison of the estimated results by the two methods.

2. SIMULATION RESULTS OF WELD RESIDUAL AXIAL STRESS

As shown in Fig. 1, the core shroud is an open cylinder without inner pressure, and the global model containing girth seam H6a was cut from the core shroud. The global model is composed of 12 weld beads and base metal part, and composed of 9207 elements with type of 8-node trilinear displacement [2-3]. The weld beads were heated one by one with defining heat DFLUX in subroutine in ABAQUS. The maximum temperature of bead was no more than 1200°C, and the layer temperature was controlled smaller than 180°C. After the final beads cooling to the room temperature, the distribution of weld residual stress was obtained.

Ring part is the base metal region below the girth seam H6a. Weld residual stress only distributes partially in the ring part below the girth seam H6a in the path shown Fig. 2. The path is 6mm to weld line of H6a in distance, at which the axial stress of outer surface is largest. Therefore, we assumed that the crack grew up along the path from outside of the core shroud. The curve of axial residual stress in the path through the wall appears like a "V" shape, and the compression stress is produced in the center region of the measurement path in the model. More details of the simulation on the axial stress can be found in Ref. 3.

3. CALCULATION METHODS FOR STRESS INTENSITY FACTOR

The SCC was assumed to initiate from the outer surface in
the ring part under the weld line of H6a seam. In views of convenience for constructing a surface crack, the ring part in the global model was cut in sub-model technology in ABAQUS. After that a semi-elliptical surface crack was introduced into the ring part as shown in Fig. 3, and the ratio of depth to half length \((a/c)\) of crack was fixed by 0.5 with the growth of the crack. \(a\) and \(2c\) are the depth and length of the introduced static crack in elliptical shape. Using the cracks with different depths, the stress intensity factor was calculated by two methods in the guide of API RP579.

![Fig. 3 Surface crack constructed in the model of ring part](image)

3.1 Method 1

The method to calculate the stress intensity factor considering the changing of applied loads calculated by Eq. (1).

\[
K_I = \frac{G_0 \sigma_0 + G_1 \sigma_1 \left(\frac{a}{c}\right) + G_2 \sigma_2 \left(\frac{a}{c}\right)^2 + G_3 \sigma_3 \left(\frac{a}{c}\right)^3}{E} \sqrt{\pi a} \quad (1)
\]

\[
Q = 1.0 + 4.593 \left(\frac{a}{c}\right)^{1.65} \quad \text{for } a/c \leq 1 \quad (2)
\]

where, \(K_I\) is the stress intensity factor of fracture model, \(G_0\), \(G_1\), \(G_2\), \(G_3\) and \(G_4\) are the factors depending on the sizes and shapes of a surface crack, and among those factors, \(G_2\), \(G_3\) and \(G_4\) are different at deepest with surface point of a surface crack. \(t\) is the thickness of ring wall. \(\sigma_0\), \(\sigma_1\), \(\sigma_2\), \(\sigma_3\) and \(\sigma_4\) are the coefficients depending on Eq. (3). By fitting Eq. (3) to the axial stress within half length of the measured path by simulated as shown in Fig. 4, the coefficients of \(\sigma_0\), \(\sigma_1\), \(\sigma_2\), \(\sigma_3\) and \(\sigma_4\) were obtained.

\[
\sigma(x) = \sigma_0 + \sigma_1 \left(\frac{x}{c}\right) + \sigma_2 \left(\frac{x}{c}\right)^2 + \sigma_3 \left(\frac{x}{c}\right)^3 + \sigma_4 \left(\frac{x}{c}\right)^4 \quad (3)
\]

![Fig. 4 Fitting load curve for solution of the coefficients of \(\sigma_{0-4}\)](image)

3.2 Method 2

The other fitness-for-service method is using the experienced equations as shown in Eqs. (4-7), and can use the

stress distribution at the tip of crack to calculate the stress intensity factor.

\[
K_I = G_0 \sigma \sqrt{\frac{a}{c}} \quad (4)
\]

\[
G_0 = A_0 + A_1 \beta + A_2 \beta^2 + A_3 \beta^3 + A_4 \beta^4 + A_5 \beta^5 + A_6 \beta^6
\]

\[
\beta = \frac{2a}{c} \quad (6)
\]

\[
Q = 1.0 + 1.464 \left(\frac{a}{c}\right)^{1.65} \quad \text{for } a/c \leq 1 \quad (7)
\]

where, \(\sigma\) is the axial stress at crack tip obtained by simulation after introducing a static surface crack. \(G_0\) and \(A_0-6\) are the coefficients and dependent of ratios of \(a/t\), \(c/a\) and depth of crack to thickness of cylinder. \(\theta\) is the angle defined in Ref. 1, and \(\theta = 0^\circ\) at the surface point of the crack and \(\theta = 90^\circ\) at the deepest point.

4. RESULTS AND DISCUSSION

By the two methods, we calculated the stress intensity factor at the deepest point and surface point of the cracks, and the results were plotted in Figs. 5 and 6, respectively.

![Fig. 5 Stress intensity factor at the deepest point of the surface crack with the propagation of crack](image)

At the deepest point of the surface crack, the stress intensity factor with method 1 increases to 17.3 MPam\(^{1/2}\) at crack depth of 6mm, and decreases to 0 MPam\(^{1/2}\) at about 15mm. It decreases to -20 MPam\(^{1/2}\) until 20mm in crack depth. The calculated results at deepest point of the surface crack indicate that the propagation of
the surface crack is suspended at 15mm in the depth direction. Correspondingly, stress intensity factor by method 2 is an enlarged calculation result of stress intensity factor. Stress intensity factor increases with increase of crack depth and saturates in about 15mm in depth at the surface point in method 1 as shown in Fig. 6. As for the method 2, the same tendency is observed. This means that the surface crack propagates continuously in length direction with increasing crack length, which is well agreement with the results stress intensity factor in pipe and plate by Miyazaki et al [5].

However, the stress intensity factor at deepest point of crack by method 2 had much difference to that by method 1. From the comparison of the results using two polynomial equations (Eqs. (1) and (4)), the different estimated results were caused by the stress term at crack tip by the two methods as shown in Fig. 7. At surface point of the crack, the stress term is almost same for the two methods while it is enlarged in method 2 comparing with method 1. The current data of two methods surface point of the crack, the stress term is almost same for the two methods while it is enlarged in method 2 comparing with method 1. The current data of two methods were caused by the enlarged axial stress at crack tip in method 2.

Two calculation methods to stress intensity factor in API RP579 were used. Method 1 can be used for evaluation on the crack propagation behavior in present model with continuous testifying its reliability. Method 2 is not suitable for the estimation of the components under the residual stress.

REFERENCE

[3] Li, Y., Kaji, Y. and Igarashi, T., Study of Weld Residual Stress Field in the Girth Seam H6a of Core Shroud of Boiling Water Reactor, Proceeding of the 18th International Conference on Nuclear Engineering, Xi’an, China (2010).