Measurement of *J*-Resistance Curve using Full-Size Tubular Specimens

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1. Introduction

To act as an effective barrier against fission product, the steam generator tubes must essentially satisfy structural integrity[1]. The measurement of *J*-resistance curves is necessary when the integrity assessment of steam generator tubes based on elastic-plastic fracture mechanics. However, the standard specimens can not be taken out from steam generator tubes because of the limited thickness and a conservative unstable pressure is obtained by employing the *J*-resistance curves satisfying plane strain condition as suggested in the ASTM standard[2]. The objective of this study is to measure the *J*-resistance curve from the non-standard specimens which have the same size as real steam generator tubes. *J*-resistance test using full-size tubular specimen is performed under tension loading and the results are compared with other organization's[3~5].

2. FAD Analysis

Failure Assessment Diagram (FAD) can be used to determine the failure mode of steam generator tubes. R6[6] approach developed by the Central Electricity Generating Board (CEGB) was used to determine the failure mode of steam generator tubes. This approach uses K_r and L_r as variables. K_r is the ratio of the elastically calculated stress intensity factor to the fracture toughness of the material. L_r is the ratio of the nominal stress in the component to the yield strength of the material. The failure assessment curve for steam generator tubes with an axial through-wall crack is given as follows[7]:

$$K_r = \frac{0.3 + 0.7\exp\left(-0.8L_r^{3.5}\right)}{\left(1 + 0.5L_r^2\right)^{0.5}} \quad (1)$$

The failure assessment curve and the data of applied K_r at burst pressure and L_r were plotted in Fig. 1. Most of the data lay in the region of $K_r/L_r < 0.2$ but some data fell in the region of $K_r/L_r > 0.2$. According to this FAD analyses results, it can be said that the failure mode of steam generator tubes is plastic collapse or elastic-plastic fracture. However, most previous studies[8~10] to estimate the failure behavior of steam generator tube were limited on plastic collapse analysis without considering elastic-plastic fracture.

3. *J*-Resistance Test

3.1 Material and Specimen

The tube specimens were made of Inconel 600 used as a steam generator tube material in pressurized water reactors. The outer diameter and thickness of the specimen were 19.05 mm and 1.09 mm, respectively. The tensile properties were obtained by using the full-size tubular specimens.
J-resistance test was performed using the full-size tubular specimen containing a circumferential through-wall notch with the value of □/□ = 0.45 as shown Fig. 2. The notch were wrought by EDM (Electro-Discharge Machining) method which had a gap width of 0.18 mm.

3.2 Experimental Procedure

J-resistance test of the tubular specimen were carried out by displacement control and the universal testing machine of 25 ton capacity was used. The crack growth behavior according to the increasing load was observed by using a high resolution camera and the crack extension was derived from the images. Also, the load and displacement were continuously stored in a PC. The load-displacement data and load-crack extension data were utilized to determine the *J*-resistance curve.

4. Experimental Result

The total *J*-integral was obtained by the sum of elastic part (J_e) and plastic part (J_p). In this case, the J_e was defined as follows:

$$J_e = \frac{K^2}{E'} \quad (2)$$

where E' is $E/(1-□^2)$ in plane strain condition. Also, K is elastic stress intensity factor and E is Young's modulus.

The plastic part of *J*-integral was calculated as follows:

$$J_p = \eta \frac{U_p}{A_L} \quad (3)$$

where □ is a dimensionless constant, U_p is the plastic area under the load-displacement curve, and A_L is the ligament area. In this study, to calculate the *J*-integral of full-size tubular specimens, elastic *J*-integral equation, □–factor equation, and relationship between crack length and displacement were used. The relevant equations were derived from finite element analyses.

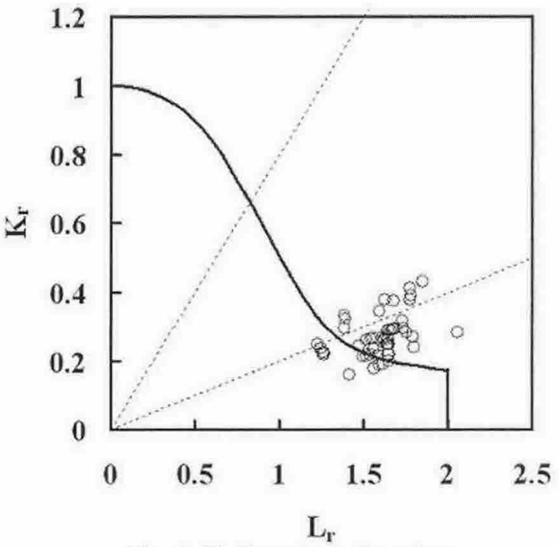

Fig. 1 FAD analysis for tubes

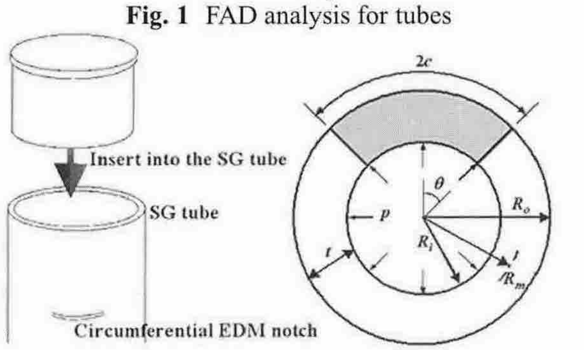

Fig. 2 Circumferential through-wall cracked tube under tension

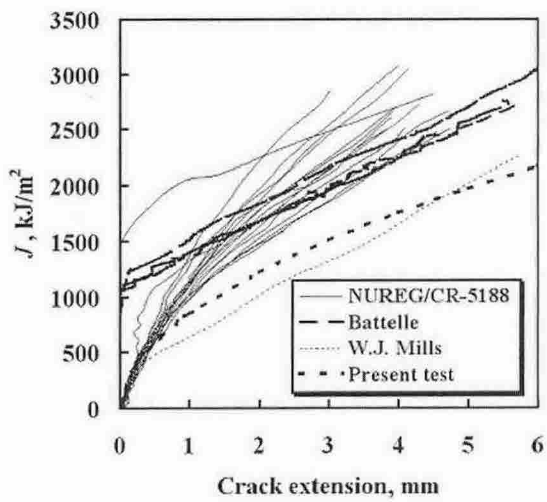

Fig. 3 Comparison of *J*-resistance curve from full-size tubular specimen with other organization's results

The *J*-resistance curve from full-size tubular specimen was depicted in Fig. 3 with Battelle's data etc.[3~5] which were obtained from CT specimens. The *J*-resistance curve from present test was lain in relatively lower region than the other curves and there was a significant disparity among the organization. The differences in fracture toughness may be due to discrepancies in manufacturing, chemical position, orientation, test method, and so on. When $2\square_f\Delta a$ and $4\square_f\Delta a$ were used as the construction line, the corresponding J_{IC} values were 942 kJ/m^2 and 605 kJ/m^2, respectively.

The *J*-resistance curve obtained from full-size tubular specimen in this study can be used for elastic-plastic fracture mechanics analysis of steam generator tubes.

5. Conclusion

In this study, FAD analyses were carried out for steam generator tubes to show the possibility of elastic-plastic fracture. *J*-resistance test was also conducted by using full-size tabular specimens to measure the *J*-resistance curve of steam generator tubes and the curve was compared with other organization's results. Even though there were significant disparities, J_{IC} of 942 kJ/m^2 when $2\square_f\Delta a$ was used as the construction line and *J*-resistance curve can be utilized for elastic-plastic fracture mechanics analysis.

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