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Variation in Fracture Toughness of Carbon Steel Due to Test Standards and Its Influence on Fracture Load Prediction

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ABSTRACT

This paper describes apparent difference in fracture toughnesses obtained by JSME S001 and ASTM E813 test standards and its influence on fracture load prediction of carbon steel pipes. Fracture toughness tests were conducted in air at room temperature on 1CT specimens prepared from carbon steel pipe STS42(20B, sch. 100) for LWR plants. And using these fracture toughnesses, R6-Rev. 3 approach was applied to estimate fracture load of a carbon steel pipe with a circumferential through-wall crack. It is found that predicted fracture loads for the two pipes with the same geometry are almost the same instead of large difference in apparent fracture toughness.

1 INTRODUCTION

Fracture toughness of carbon steel is not so high to assure that plastic collapse is the unique fracture mode of carbon steel pipes. So it is necessary to develope failure assessment procedure based on elastic-plastic fracture mechanics to find out fracture conditions of carbon steel pipes. J/T approach is effective one and has been extended to develope some engineering application methods such as the R6-Rev. 3[1]. Elastic-plastic fracture toughness J_{IC} and J-R curve play an important role in the application of J/T approach.

As fracture toughness data vary depending on the test methods and specimens, it is very important to make clear the apparent difference in fracture toughness obtained by typical test standards and its influence on a fracture load prediction. In the present work, fracture toughness tests were conducted according to JSME S001 and ASTM E813 standards on carbon steel STS42 used in Light Water Reactor plants. Initiation loads at which crack starts to grow and unstable fracture loads were analyzed and compared with each other, applying the R6-Rev. 3 approach[1] to the fracture analyses of cracked pipes with the same geometry but the different fracture toughness. Details are shown in the following sections.

2 MATERIAL AND TEST PROCEDURE

Material used in the present work is carbon steel STS42 which is equivalent

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to ASTM A333Gr.6 steel. Chemical compositions are shown in Table 1. Mechanical properties and stress-strain curve are shown in Table 2 and Fig. 1 respectively.

1CT specimens with 25 mm thickness were prepared from a carbon steel pipe (20B, sch. 100) so that the crack grows in the circumferential direction of a pipe. All specimens were pre-cracked by fatigue so that a/w was about 0.6, here a,w are the pre-crack length and the width of specimens respectively. Specimens were loaded by the displacement controlled method with the rate of 1 (mm/min.) cross head speed in air at room temperature. Fracture toughness J_{IC} and J-Δa relationships were analyzed by the typical two methods, namely JSME S001 and ASTM E813 standards. The major difference between the two procedures is in the definition of the amount of ductile crack growth Δa.

3 RESULTS AND DISCUSSIONS

3.1 Experiment

Fig. 2 shows J-Δa relationships and trend curves obtained by the two test standards. The trend curves are expressed by the second order polynomials as shown in the following expression.

$$\Delta a = C_1 J + C_2 J^2 \qquad (1)$$

Here, coefficients C_1 and C_2 are summarized with $J_{0.2}$ in Table 3. $J_{0.2}$ is a J-value on a J-R curve at $\Delta a = 0.2$ mm. As shown by Asano et al.[2], the polynomial (1) is good for a curve fitting of J-Δa data over a wide range of Δa. There exists distinct difference between the two J-R curves. The difference is considered to be caused by the difference in Δa for the same value of J-integral. The JSME standard gives a longer Δa than the ASTM standard does, since the former standard defines Δa as the mean value of Δa measured in the midthickness portion of a specimen. Consequently, the lower J-R curve is obtained by the JSME standard.

Figs. 3 and 4 show the blunting lines and the J-R curves for J_{IC} determination by the JSME and the ASTM standards respectively. Table 4 summarizes resulting J_{IC} values with the coefficients A and B of R-curves. R-curve is expressed as a straight line.

$$J = A \cdot \Delta a + B \qquad (2)$$

The value of J_{IC} obtained by the ASTM standard is about three times higher than that obtained by the JSME standard.

Fig. 5 shows J-dJ/da curves obtained by the two test standards. Here, dJ/da is the slope of a J-R curve and obtained by differentiating the eq. (2) with respect to Δa. As higher J-dJ/da curve represents stronger material's resistance against unstable fracture, the ASTM standard tends to give higher toughness than the JSME standard apparently. This trend is also deduced from the fact that the shorter Δa is obtained by the ASTM test standard.

3.2 Analysis

Using the toughness data J_{IC} and J-R curve, the R6-Rev. 3 approach[1] was applied to analyze the crack initiation moment M_{in} and the fracture moment M_{max} of cracked carbon steel pipes subjected to bending moment M as shown in Fig. 6. The carbon steel pipe STS42 (20B, sch. 100) has a circumferential through-wall crack of angle $2\theta_0$ = 120°. The R6-Rev. 3 approach[1] is the structural integrity assessment procedure developed by CEGB, and uses two parameters L_r and K_r corresponding to the coordinates of a cracked pipe on failure assessment diagram. The two parameters can be evaluated by the following equations,

$$L_r = M/M_c(a,\sigma_y),\ K_r = \sqrt{J_e/(a)/J_R(\Delta a)} \qquad (3a,b)$$

where $M_c(a, \sigma_y)$ is a collapse moment and evaluated by the equation (4) for a pipe with a circumferential through-wall crack.

$$M_c(a, \sigma_y) = 4\sigma_y R^2 t\{\cos(\theta_0/2)-\sin\theta_0/2\} \qquad (4)$$

Where R and t are the mean radius and the thickness of a pipe as shown in Fig. 6. σ_y and J_R are material's yield stress and resistance against ductile crack growth respectively. J_e is the elastic component of the applied J-integral and calculated from stress intensity factor given in Ref. [3]. The point specified by the coordinates is compared with a failure assessment curve to judge the fracture of the pipe. In the present study, option 2 Failure Assessment Curve was used in the analyses.

Figures 7 and 8 show the graphical solutions obtained by using the two toughness data. The higher toughness obtained by the ASTM standard resulted in the larger value of L_r at the transition to unstable fracture and the gentle slope of the crack growth loci on the Failure Assessment Diagram.

Table 5 summarizes crack initiation moment M_{in} and fracture moment M_{max} obtained by using the different toughness. It is obvious that the crack initiation moment M_{in} depends on the fracture toughness J_{IC} strongly, while the fracture moment M_{max} is not so sensitive to toughness data. This fact indicates that the analyses using toughness data obtained by the JSME and ASTM standards predict almost the same fracture load.

Sensitivity study was performed to make clear the effect of fracture toughness variation on M_{in} and M_{max} of the pipe shown in Fig. 6. Fig. 9 shows the dependence of M_{in} on J_{IC} values. In the figure, $(J_{IC})_{JSME}$ is the value of J_{IC} obtained by the JSME standard and $(M_{in})_{JSME}$ is the predicted M_{in} by using $(J_{IC})_{JSME}$. The results indicate that M_{in} increases with J_{IC} slightly in the range where J_{IC} is greater than $(J_{IC})_{JSME}$. Fig. 10 shows the effect of the gradient dJ/da of a J-R curve on the value of M_{max}. Where $(dJ/da)_{JSME}$ is the gradient of the J-R curve obtained by the JSME test standard and $(M_{max})_{JSME}$ the fracture moment predicted by using the curve. It can be observed that the increasing rate of M_{max} with dJ/da tends to decrease in the range where dJ/da exceeds $(dJ/da)_{JSME}$.

4. CONCLUSION

Fracture toughness tests were performed on carbon steel STS42 according to the JSME and ASTM test standards. And fracture analyses of cracked pipes were carried out to make clear the effect of the variation in fracture toughness obtained by the two test standards on the fracture load prediction. The following conclusions are summarized.

(1) The ASTM standard gives higher J_{IC} and J-R curve of carbon steel than the JSME standard does. For example, J_{IC} obtained by the ASTM standard is about three times of the value obtained by the JSME standard.

(2) The apparent difference in fracture toughness obtained in (1) does not have much influence on the fracture load prediction of a carbon steel pipe

with a circumferential through-wall crack.
(3) Sensitivity study on fracture toughness shows that the analyses give almost the same fracture load so long as the used toughness data are higher than the values obtained by the JSME test standard.

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(2) Asano, M., Fukakura, J., Kashiwaya, H., Saito, M., Trans. JSME, Vol. 54, No. 499, A(1988), 493. (in Japanese)
(3) Klecker, R., Brust, F., Wilkowski, G.M., NUREG/CR-4572 (1986).

Table 1 Chemical compositions

(wt.%)

C	Si	Mn	P	S
0.22	0.29	1.21	0.026	0.011

Table 2 Mechanical properties of STS42 steel.

	σy (MPa)	σu (MPa)	El. (%)	R.A. (%)
STS42	371.5	546.3	36.0	-

Table 3 J-R curves of carbon steel STS42.

		JSME	ASTM
$J_{0.2}$(kN/m)		173.7	234.4
$\Delta a = C_1 J + C_2 J^2$	C_1	9.991×10^{-4}	7.277×10^{-4}
(mm)	C_2	8.934×10^{-7}	5.361×10^{-7}

Table 4 J_{IC} of carbon steel STS42.

		JSME	ASTM
J_{IC}(kN/m)		263.9	747.6
$J = A \Delta a + B$ (kN/m)	A	439.2	527.6
	B	187.3	317.9

Table 5 M_{in} and M_{max} analyzed by R6-Rev. 3 Approach.

	JSME	ASTM
M_{in} (kN·m)	55.41	67.86
M_{max} (kN·m)	77.98	80.41

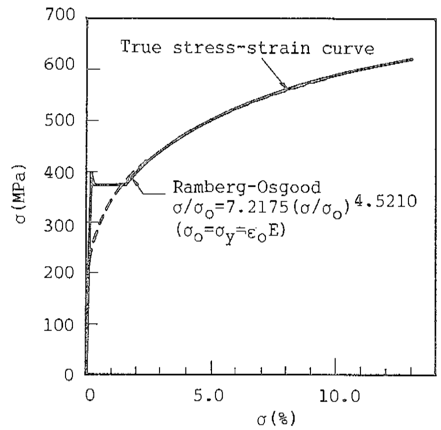

Fig. 1 Stress-strain curve of carbon steel STS42.

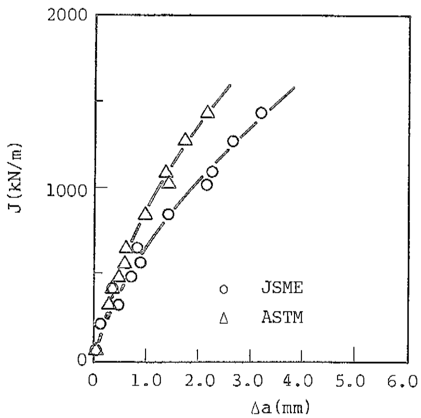

Fig. 2 J-Δa relationships of carbon steel STS42.

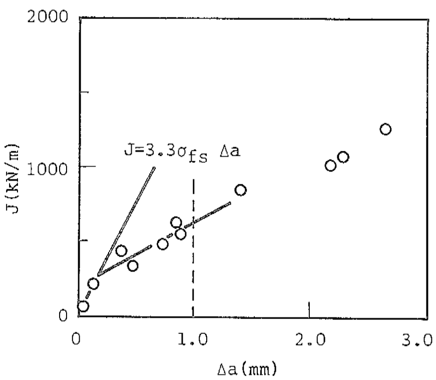

Fig. 3 J_{IC} determination by JSME standard

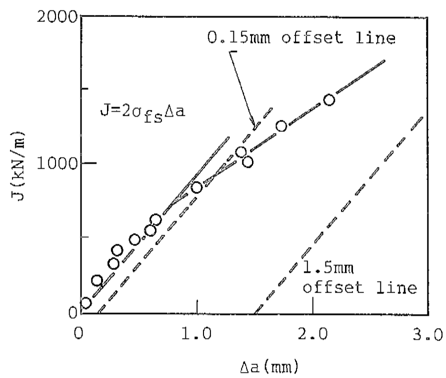

Fig. 4 J_{IC} determination by ASTM standard.

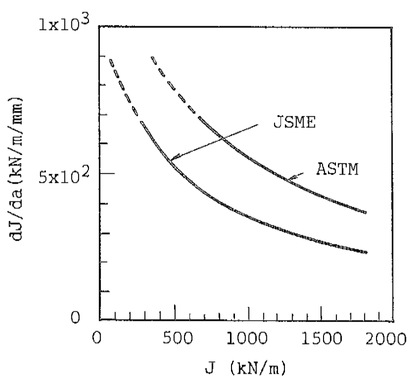

Fig. 5 dJ/da-J curves obtained by JSME and ASTM standards.

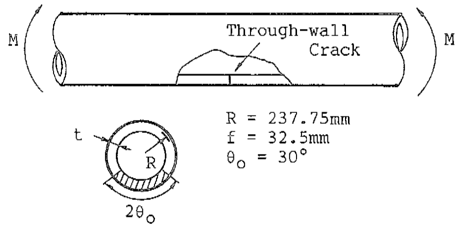

Fig. 6 Through-wall cracked pipe subjected to bending moment.

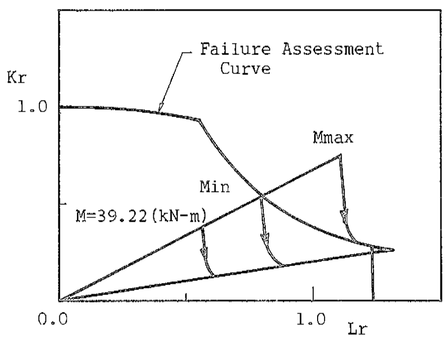

Fig. 7 Fracture analysis on the Failure Assessment Diagram (JSME data).

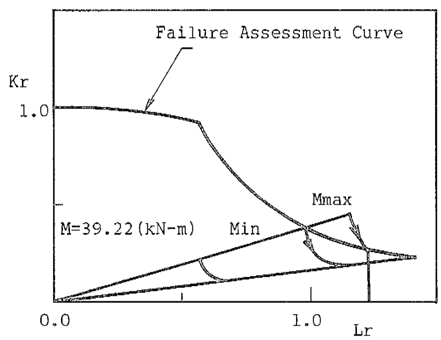

Fig. 8 Fracture analysis on the Failure Assessment Diagram (ASTM data).

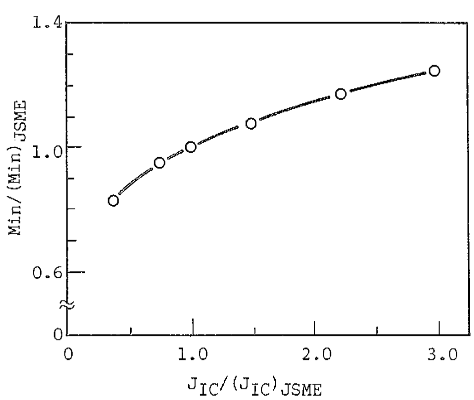

Fig. 9 Influence of J_{IC} on fracture initiation moment M_{in}.

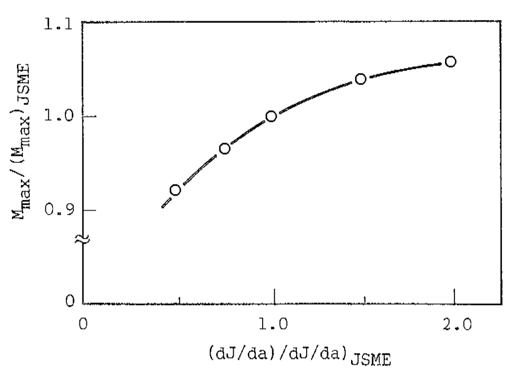

Fig. 10 Influence of dJ/da on unstable fracture moment M_{max}.