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Evaluation of the J-R Curve of Welded Pipe with a Circumferential Through Wall Crack in Four Point Bending

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ABSTRACT

To evaluate the fracture toughness characteristics of the nuclear piping, it is ideal to perform the J-R tests using real pipes. However, the J-R test using a real pipe is not only difficult to perform but also expensive. For these reasons, J-R test has usually performed using standard CT (compact tension) specimen. However, the evaluation of fracture toughness characteristics using the CT specimen has been known to be very conservative than that of the real pipe. Thus, the J-R test using a real pipe is essential to assess the fracture toughness properties accurately. In this study, FE analyses for welded pipes were performed to get the plastic limit load solution for circumferential through-wall cracks under bending moment. Also, the fracture toughness tests using welded pipes were performed to determine the J-R characteristics and identify additional safety margins of a real pipe.

INTRODUCTION

Since the Fukushima nuclear accidents, the evaluation of safety for nuclear power plants has become more important. To guarantee the safety of a nuclear power plant during operation and to maintain primary piping system integrity during its life time, evaluation of the pipe integrity is necessary [1]. The welded part in the primary piping system consists of base metal, deposited weld metal, fusion zone and weld junction. In the welded part, various shapes of the welding root, crown, and grinding are part of the stress concentration. Various types of welded part failures in a primary pipe have been well known in previous researches [2-4]. Thus, residual stresses and welding flaws in the welded part is very important to evaluate the integrity of a pipe. The majority of the J-R curves have been obtained using standard CT specimens with a deep crack according to ASTM E 1820[5] instead of a real pipe. So, many researchers have performed J-R tests using non-standard specimens.[6,7] However J-R curves using standard specimens are known to be conservative due to the difference in the constraint effect between real pipes and standard specimens [8]. Thus, the J-R test using a real pipe is essential to assess the fracture toughness properties and to identify additional safety margin of a pipe accurately.

In this study, FE analyses for welded pipes were performed to get the plastic limit load solution for circumferential through wall cracks under bending moment. Also, the relationship between normalized compliance and normalized crack length was obtained to measure the crack length of a welded pipe using the load-ratio method. Fracture toughness tests were performed to get J-R curves for circumferential through-wall cracked welded pipes. And then, J-R curves of welded pipes were compared with those of standard specimens to determine the fracture toughness and to identify additional safety margins.

DEFINITION OF J-INTEGRAL

The J-integral by ASTM E1820 can be determined by superposing the elastic component J_{el} and the plastic component J_{pl} as follows;

$$J = J_{el} + J_{pl} \tag{1}$$

The elastic component of J-integral can be expressed as follows;

$$J_{el} = \frac{K^2}{E'} \tag{2}$$

Where K and E' denote the linear elastic stress intensity factor and the elastic modulus. In a condition of plane stress, $E' = E$ and in a condition of plane strain, $E' = E/\left(1-\nu^2\right)$.

J_{el} of a welded pipe could be calculated from the solution proposed in ASTM E 1820[5]. However, J_{pl} of a welded pipe could not be obtained, because the material properties of a welded pipe were non-homogenous. Thus, FE analysis for a welded pipe was performed to obtain J_{pl} using the plastic limit load method. The plastic component of the J-integral, J_{pl}, can be expressed as follows;

$$J_{pl} = \int_0^{\Delta_d} \eta_{pl} P d\Delta_{pl} + \int_{\theta_0}^{\theta} \gamma J_p d\theta \tag{3}$$

η_{pl} and γ of a pipe under bending can be obtained from the plastic limit moment, M_L.

FEA MODEL

Half of the analysis model considering its symmetric condition was constructed for a four point bending test. Pipe dimensions of finite element model are shown in Table 1. The constraint for a real pipe model was determined as a 1-direction rotation at the support point. Fig. 1 shows FE analysis model.

The material of FE analysis model was assumed to be an elastic-perfectly plastic material. Finite element analysis was performed using commercial code of ABAQUS 6.10. The C3D20R elements were used, and the whole model consisted of 31,200 elements. FE analysis of a real pipe was performed according to various circumferential through-wall crack lengths (2θ).

LIMIT LOAD SOLUTION OF A WELDED PART

The relationship between the limit moment and circumferential through-wall crack angle of a welded pipe was obtained using FE analysis. Fig. 2 shows the comparison of the plastic limit moments using FE analysis and the solution of Zahoor [10] and Miller [11]. From the comparison of the plastic limit moments for circumferential through wall cracked welded pipe under bending moment, the difference of the plastic limit moment increased gradually as the crack length ratio increased.

To get the plastic limit moment of a welded pipe accurately, the solution proposed by Miller [11] was modified using the correction factor of a welded part. The correction factor of a welded pipe was obtained using the strength mismatch factor proposed by Kim et al. [12].

$$CF_{weldedpipe} = 1 + \left\{ \frac{3h}{R_m(\pi-\theta)} \left(\frac{\sigma_{Y,weldment}}{\sigma_{Y,basemetal}} \right) \left(\frac{\theta}{\pi} \right) \right\} \tag{4}$$

where CF is the correction factor of a welded pipe, σ_{YW} and σ_{YB} are the yield strength of the weldment and the base metal. R_m is average of a pipe diameter, θ is half angle of a crack and h is half width of a welded part.

$$M_{L,weldedpipe} = CF \times M_{L,Miller} \tag{5}$$

Thus, the plastic limit moment of a welded pipe can be calculated using the correction factor of a welded pipe. And then, the coefficient function of plastic J component (η_{pl}) and the correction function of crack propagation (γ) were obtained as follows (for $0.17 \leq \theta/\pi \leq 0.5$);

$$\eta_{pl} = \frac{1}{2R_m t}\left(\frac{-1.372 - 2.052x + 4.857x^2}{1 - 1.372x - 1.026x^2 + 1.619x^3}\right), \quad x = \frac{\theta}{\pi} \tag{6}$$

$$\gamma = \frac{1}{R_m}\left(\frac{2.052 - 9.714x}{1.372 + 2.052x - 4.857x^2}\right), \quad x = \frac{\theta}{\pi} \tag{7}$$

CRACK LENGTH EQUATION OF A WELDED PART

To calculate the crack length of a welded pipe using the load-ratio method proposed by Landes [13], the relationship between normalized compliance and normalized crack length of a welded pipe was obtained by FE analysis. The relationship between normalized compliance and normalized crack length of a welded pipe was similar to the base metal proposed by Park et al. [14]. The normalized crack length equation of a welded pipe can be represented as follows;

$$(\theta / \pi)_{weldedpipe} = 0.93 - 4.02u + 8.69u^2 - 17.1u^3 + 20.9u^4 \tag{8}$$

where θ/π is crack length ratio, u is normalized compliance, E is elastic modulus, C is compliance obtai ned from FE analysis, n is hardening exponent. Fig. 3 shows the relationship between normalized crack le ngths and normalized compliance in accordance with hardness exponent (n) of a welded part.

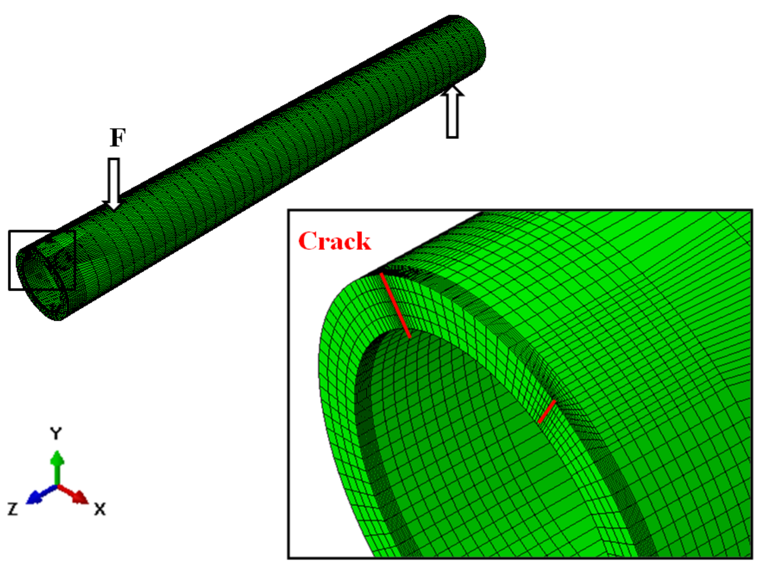


Figure 1. Finite element model for a welded pipe

Table 1. Pipe dimensions of FE model

O.D. (mm)	168.3
I.D. (mm)	131.7
Thickness (mm)	18.3
Length (mm)	3,000
Width of welded part (mm)	12.0
Circumferential through-wall crack angle (deg.)	2θ = 60, 90, 120, 150 and 180

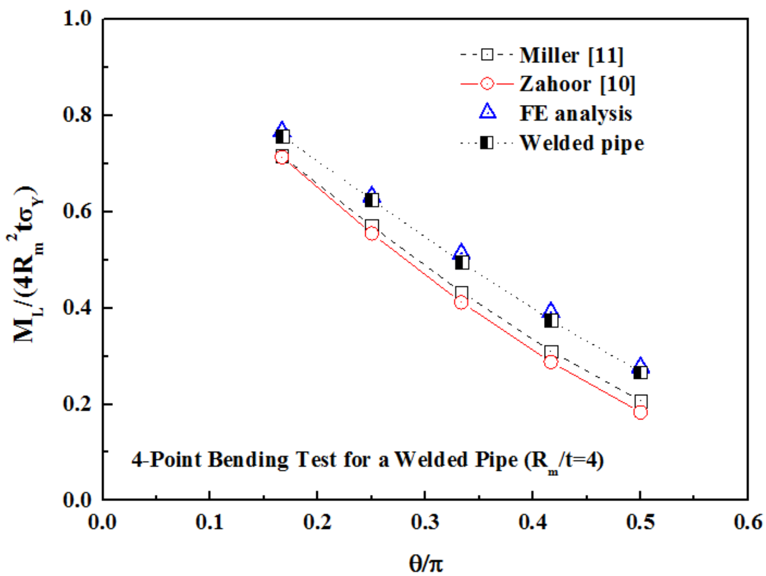


Figure 2. Comparison of limit moments for welded pipes under bending moment

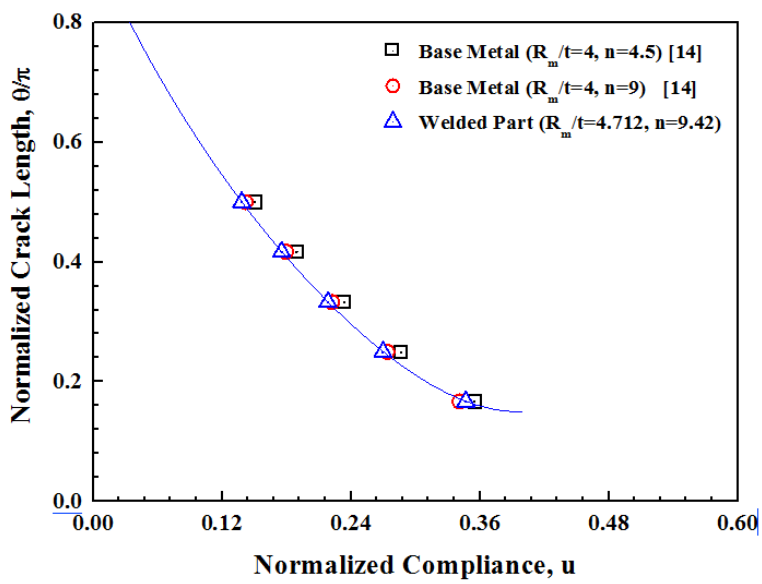


Figure 3. Normalized crack length versus compliance in accordance with hardening exponent (n)

J-R TEST FOR A WELDED PIPE

To obtain the engineering stress-strain curve of the base metal and the welded part, tensile tests were performed at room temperature, and the test speed was 1mm/min as specified in ASTM E8[9]. From tensile test, material properties of the base metal and the welded part were obtained, as shown in Table 2.

To perform the J-R test, two safety injection pipes were butt welded. Table 3 shows the chemical composition of pipe materials. The J-R tests of welded pipes were performed with various circumferential through-wall crack angles using the four-point bending test system. The four-point bending test system was consisted of an electrical capacity of 250kN on a hydraulic universal testing machine (INSTRON model 8802), data acquirement device (DAQ) and crack opening displacement (COD) gage, as shown in Fig. 4.

Table 2. Results of tensile tests and relevant R-O constants

Material	σ_Y (MPa)	σ_{UTS} (MPa)	R-O constant	
			α	n
SA312 TP304L	268.4	582.6	4.61	4.31
Welded Part	493.6	611.4	2.79	9.42

Table 3. Chemical composition of the pipe materials (wt. %)

C	Mn	Si	P	S	Ni	Cr	Fe
0.023	1.44	0.32	0.03	0.006	10.1	18.3	Bal.

Figure 4. Four-point bending testing system

THE RESULT OF J-R TESTS

Fig. 5 shows the comparison of the load-load line displacement curves of welded pipes in accordance with the circumferential through-wall crack angle. Fig. 6 shows the crack propagation and fractured appearances of welded pipes. The length of the crack propagation was calculated by nine point method, as shown in Fig. 7. The J-R curves of welded pipes were calculated using the crack length equation and the J-integral solution.

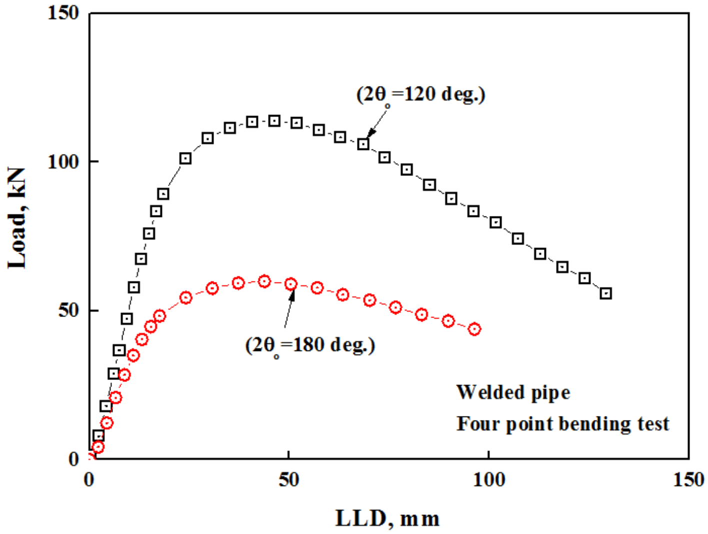
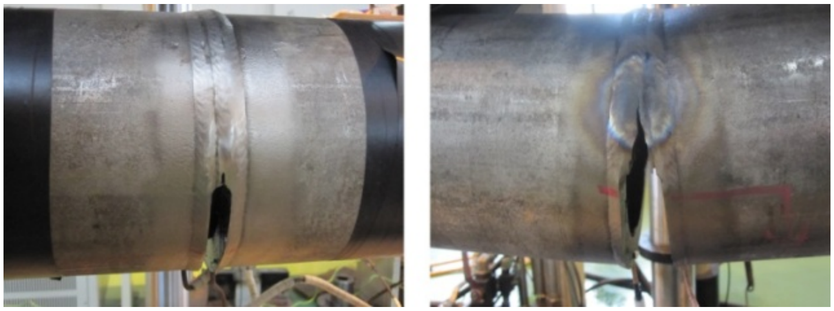
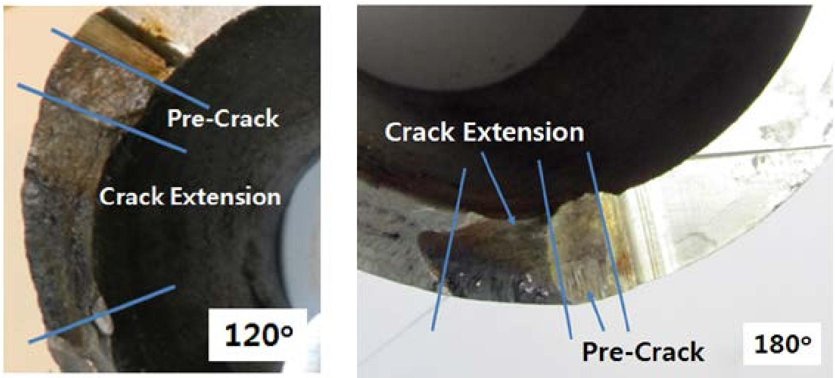


Figure 5. Load versus displacement curves of welded pipes



(a) (b)

Figure 6. Crack propagation for a welded pipe ($2\theta = 120^o$)



(a) (b)

Figure 7. Fracture appearances of welded pipes after J-R tests

COMPARISON OF J-R CURVES

Fig. 8 shows the comparison of the J-R curves for the base metal and a welded part using real pipe. The slope of the J-R curve for the base metal was higher than the welded part. The value of the fracture toughness for the welded part was lower about 15 % than for the base metal.

The comparison of J-R curves for CT specimens and real pipes was performed to determine the fracture toughness characteristics of a pipe, as shown in Fig. 9. From the result of the comparison, J-R curves for specimens were lower than real pipes in the region of initial crack extension. It seems that the geometry parameter, as a curvature of pipes, have affected to both of fracture toughness and the slope of J-R curve.

The fracture toughness, J_{IC}, for a welded pipe was compared to identify additional safety margins with specimens. From the comparison, the value of fracture toughness, J_{IC} for a welded pipe was higher than specimens and the conservation of the J-R curves for specimens were evaluated accurately.

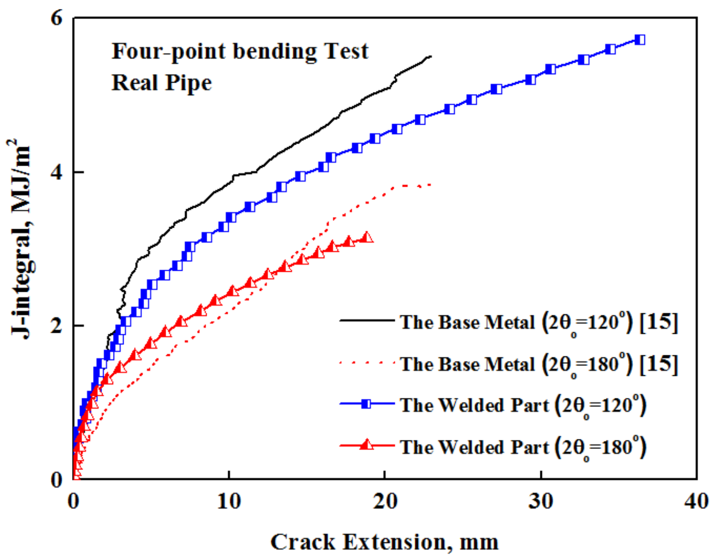


Figure 8. Comparison of J-R curves of the welded part in accordance with the crack angle of a pipe

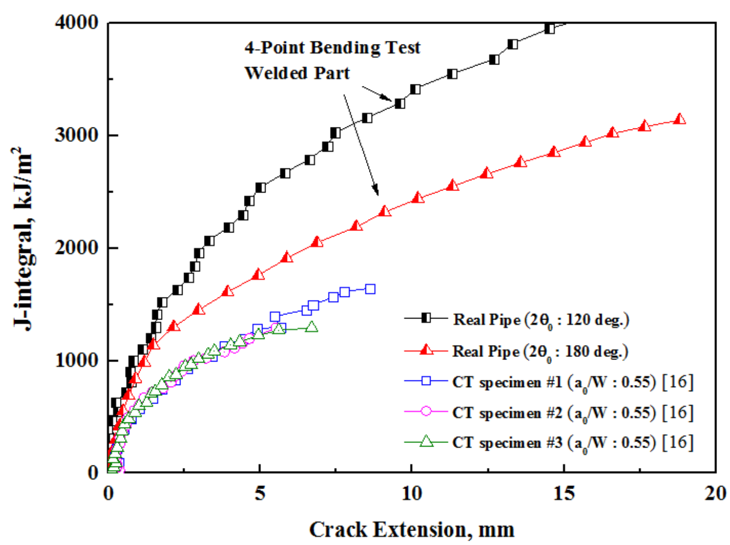


Figure 9. Comparison of J-R curves of a welded part using specimens and pipes

CONCLUSION

In this study, J-R tests using real pipes were performed to evaluate the fracture toughness characteristics of the nuclear piping. FE analysis was performed to obtain the J-integral equation of a circumferential through-wall cracked welded pipe. J-R tests using CT specimen and real pipes were performed to identify additional safety margins. The following conclusions were obtained from this study.

(1) The slope of the J-R curve for the base metal was higher than the welded part. Also, the value of the fracture toughness for the welded part was lower about 15 % than for the base metal.

(2) From the comparison, the value of fracture toughness, J_{IC} for a welded pipe was higher than specimens and the conservation of the J-R curves for specimens were evaluated accurately.

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