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Evaluation of Dynamic J-R Curve for Leak Before Break Design of Nuclear Reactor Coolant Piping System

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1. Introduction

Because safety is of paramount importance in the nuclear industry, numerous efforts have been made to guarantee structural integrity against sudden accidents. In the past, design against a Double Ended Guillotine Break (DEGB) was accomplished through the construction of massive pipe whip restraints and jet impingement shields to minimize the secondary damage to other structures in close proximity to ruptured piping. However, through long-term operating experience, the commercial nuclear industry has recognized that, for most damaged piping, fluid leakage from through-wall cracks occurs prior to a DEGB accident. Hence, if the leakage can be detected reliably at an early stage of fracture, a DEGB accident can be prevented by shutting down the reactor prior to the DEGB. Leak-Before-Break (LBB) design is based on this concept. For a piping system where LBB design is applied, a leak detection monitoring system must be installed to detect crack initiation while construction of massive pipe whip restraints and jet impingement shields become unnecessary. Thus, LBB design focuses on the ability to detect cracks for structural integrity while DEGB design focuses on preventing secondary damage. Since the mid-1980s, the LBB design concept has been widely applied on nuclear high energy piping systems. In Korea, the LBB design concept based on U.S. nuclear regulatory commission (USNRC) standard review plan 3.6.3 and NUREG-1061 has been applied to reactor coolant piping systems ever since the Yong-Gwang units 3 & 4 nuclear power plants were approved in 1994 (J.B.Lee & Choi, 1999).

The LBB design applied to nuclear piping systems is based on the premise that a piping break accident can be prevented by detecting leakage from a through-wall crack by leak detection instrumentation prior to a DEGB accident. To meet LBB design criteria, the nuclear piping material must have excellent fracture toughness characteristics so that a sudden break will not occur even if the piping has a large through-wall crack that corresponds to a detectable leakage rate. For LBB design, material properties for stress – strain curves and J-R curves as a function of resistance to stable crack extension at service temperatures are needed. The stress – strain curve is for use in the determination of detectable leakage crack length and the elastic-plastic finite element analysis of the piping with a through-wall crack. The J-R curve is for use in the crack stability evaluation of piping under normal operating loads and safe shutdown earthquake loads. In the Korean standard nuclear power plant, shown in Fig. 1, carbon steel with stainless steel cladding is used for the hot leg pipe and the cold leg pipe of the reactor coolant piping system. For carbon steel, it is reported that fracture toughness is dependent on loading speed due to dynamic strain aging (J.W.Kim & I.S.Kim, 1997). In addition to static J-R curve testing, the dynamic J-R curve, which is a part of facture toughness data, is also required to verify satisfaction of LBB when applying seismic loading for carbon steel nuclear piping. However, until now it has been difficult to obtain a reliable dynamic J-R curve for ferritic steel due to the fast loading condition. In this paper, the measurement method for obtaining a reliable dynamic J-R curve for integrity analysis of nuclear piping systems is proposed and discussed.

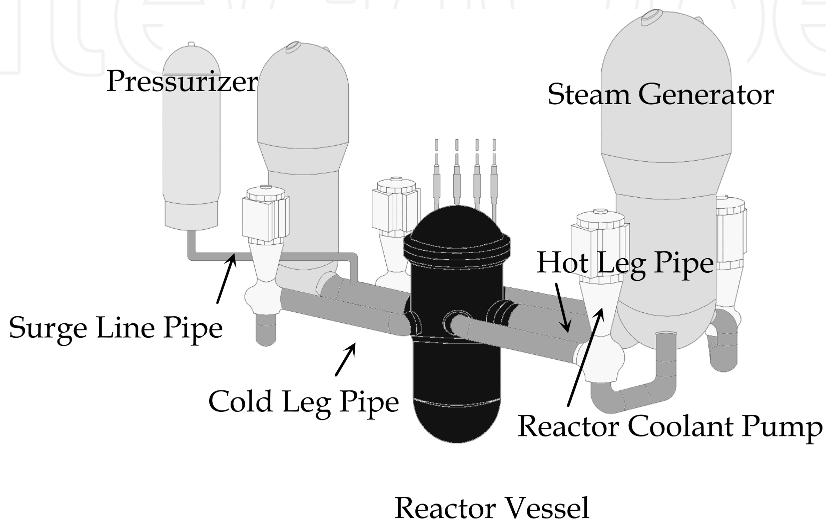


Fig. 1. Reactor coolant piping system

2. Dynamic J-R curve using DCPD and normalization methods

A dynamic J-R curve can be obtained by two different test methods; direct current potential drop (DCPD) (Joyce, 1996) and the Normalization method (Landes et al., 1991; ASTM, 2001). With DCPD on ferritic steel, a pulse drop phenomenon of output voltage occurs due to its ferromagnetic characteristics, making it difficult to determine a reliable J-R curve. On the other hand, the Normalization method, which was recently designated by the American Society for Testing and Materials (ASTM) code, has its strong point in that the J-R curve can be obtained by load - displacement curve without additional crack length measurement instrumentation such as needed by DCPD. In Korea, dynamic J-R curves have been obtained for piping materials in several nuclear power plants, and a database has been developed for dynamic J-R curves on each material based on these test results. According to the ASTM code at the time, the dynamic J-R curves were obtained by DCPD, but more recently, they are obtained by the Normalization method for newly constructed power plant projects. To utilize previous dynamic J-R curve data obtained by DCPD for piping material, the effect of test methods was investigated.

2.1 Experimental procedure

To compare the dynamic J-R curves between the DCPD and normalization methods, dynamic J-R curve testing was performed for base and weld metals of reactor coolant piping systems. Test specimens were 1 inch compact tension specimens. A test speed of 1,000 mm/min for dynamic J-R testing was determined on the basis of the natural frequency method proposed at Battelle (Scott et al., 2002) according to Eq. (1)

$$V_{LL} = 4 \times \text{natural frequency (mode 1)} \times D_i \quad (1)$$

where D_i is the load line displacement at crack initiation of the static J-R curve testing. This test speed also satisfies the criterion of ASTM E1820 A14 (Nakamura et al., 1986; ASTM, 2009) in which test time t_Q should be longer than minimum test time t_w

$$t_w = \frac{2\pi}{\sqrt{k_s/M_{eff}}} \quad (2)$$

where k_s is specimen load line stiffness in N/m, M_{eff} is effective mass of the specimen, taken here to be half of the specimen mass in kg.

Table 1 represents tested materials for each pipe and number of tests. Each hot leg is a 42 inch inner diameter pipe of SA508 Cl.1a material with a 3-½ inch nominal wall thickness. The cold leg is a 30 inch inner diameter pipe of SA508 Cl.1a material with a 3 inch nominal wall thickness. The elbow is SA516 Gr.70. The straight pipe and elbow are welded by submerged arc welding (SAW) and shielded metal arc welding (SMAW). Table 2 shows the chemical composition of the tested material and weld deposit. The comparison between DCPD and the Normalization method is summarized in Table 3. For DCPD, potential drop instrumentation was used for crack length measurement during the experiment but for the Normalization method, J-R curve was estimated only by the load – displacement curve without any crack length measurement device during the test. Therefore, in this study, dynamic J-R curve testing was performed using DCPD and analyzed by both DCPD and Normalization methods for each specimen with the test results compared between the two methods. Comparison tests were performed on two power plants, Shin-Kori units 3 & 4 and Shin-Wolsung units 1 & 2. For Shin-Kori, physical crack extension length did not exceed the lesser of 4mm or 15% of the initial uncracked ligament in accordance with normalization method. For Shin-Wolsung, tests were performed until full coverage of crack opening displacement (COD) gage, 10mm in accordance with previous DCPD method as performed at our test laboratory. Test temperature was 316°C; same as the operating temperature of the piping system. Additionally, in the case of Shin-Wolsung, tests were performed at hot standby temperature, 177°C. Table 1 shows the number of test specimens and test temperatures for dynamic J-R curve testing.

Item			Material	Dynamic J-R curve testing		
				Shin-Kori units 3 & 4	Shin-Wolsung units 1 & 2	
				316°C	177°C	316°C
Base metal	Main loop piping	Hot leg	SA508 Cl. 1a	1	1	1
		Cold leg	SA508 Cl. 1a	1	1	1
		Elbow	SA516 Gr. 70	1	1	1
Weld metal	Main loop piping segments		SMAW	1	1	1
			SAW	1	1	1
Total				15		

Table 1. Fracture toughness test conditions of the coolant piping

Pipe	C	Si	Mn	Cu	Mo	V	Ni
Hot leg & cold leg	<0.30	0.15~0.40	0.70~1.35	<0.2	<0.1	<0.03	<0.4
Elbow	<0.30	0.15~0.40	0.85~1.20	<0.4	<0.12	<0.03	<0.4
SMAW	<0.17	<0.75	<1.60	-	<0.30	<0.08	<0.30
SAW	<0.15	<0.80	1.25~2.10	<0.06	0.40~0.65	<0.03	<0.20

Table 2. Chemical composition of base materials and weld joints for reactor coolant piping (%, wt)

Item	DCPD method	Normalization method
Crack length measurement device	DCPD	N/A
Crack length estimation method during the test	By variation of output voltage when constant current is applied to specimen	By only load-displacement record
Effective crack extension length	Not more than 4mm or 15% of the initial uncracked ligament, whichever is less as physical crack extension length	Not more than 25% of the initial uncracked ligament as effective data region at data analysis

Table 3. Comparison of dynamic J-R curve testing method

2.1.1 DCPD method

The schematic diagram of the dynamic J-R curve testing apparatus is shown in Fig. 2. The specimen was isolated from the load frame by inserting Bakelite plates between the connecting rods, and constant current was applied to the specimen using a power supply in order to measure crack growth length during the test. A sufficiently high current of 100 amperes was used to minimize error due to ferromagnetic phenomenon. (Landow & Marschall, 1991; B.S.Lee et al., 1999) Current input wires were mechanically fastened to both sides of the specimen with screws at points A and B in Fig. 3, and voltage measurement wires, 0.7mm in diameter were spot welded at the points C and D. Using high-speed data acquisition, the variation of load, crack opening displacement (COD) value and output voltage were acquired digitally during the test. Prior to the dynamic J-R curve testing at high temperature, to compensate for the thermal effect, the reference voltage was measured from the specimen with current off at the test temperature. Voltage measurement was normalized by subtracting the reference voltage from measured voltage during the dynamic J-R tests. The variation of crack length was calculated based on Johnson's equation, Eq. (3) (Johnson, 1965).

$$\frac{a}{W} = \frac{2}{\pi}\cos^{-1}\left[\frac{\cosh(\pi y/2W)}{\cosh\left[(U/U_0)\cosh^{-1}\left[\cosh(\pi y/2W)/\cos(\pi a_0/2W)\right]\right]}\right] \tag{3}$$

where U_0 and a_0 are initial output voltage and initial crack length, respectively. According to the ASTM code (ASTM, 2009), as shown in Fig. 4(a), crack initiation point is determined as the intersection point of the measured DCPD curve and the 5% offset line based on a linear best-fit line of the data over the range from 0.1~0.5 P_{max}. However, as shown in Fig. 4(b), in the case of the tested ferritic steel, pulse drop phenomenon in the early loading stage of testing occurs due to the sudden reorientation of ferromagnetic domain nearby the crack tip (Hackett et al., 1986).

This pulse drop phenomenon makes it difficult to determine the crack initiation point. To resolve this problem, a backtracking technique proposed by Oh (Oh et al., 2002) was selected.

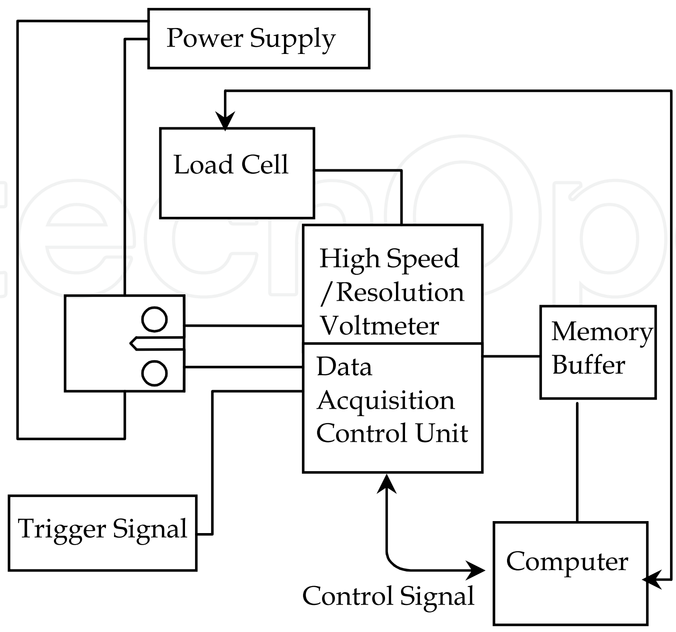


Fig. 2. Data acquisition system for dynamic J-R curve testing

In the backtracking technique, the crack initiation point is estimated by using final crack length measured in the fractured specimen. The backtracking technique is as follow; First, prior to crack initiation, it is assumed that crack extension length is in accordance with the standard blunting relation of $\Delta a=J/(2\sigma_Y)$, namely, a_0 in Eq. (3) is substituted for $a_0+J_B/(2\sigma_Y)$ where J_B=J at crack initiation. Next, with changing U_0, the variation of crack length for each loading point can be obtained. Through this iterative process, U_0 is obtained such that the calculated final crack length is in agreement with the measured final crack length. Finally, the J-R curve is calculated using U_0.

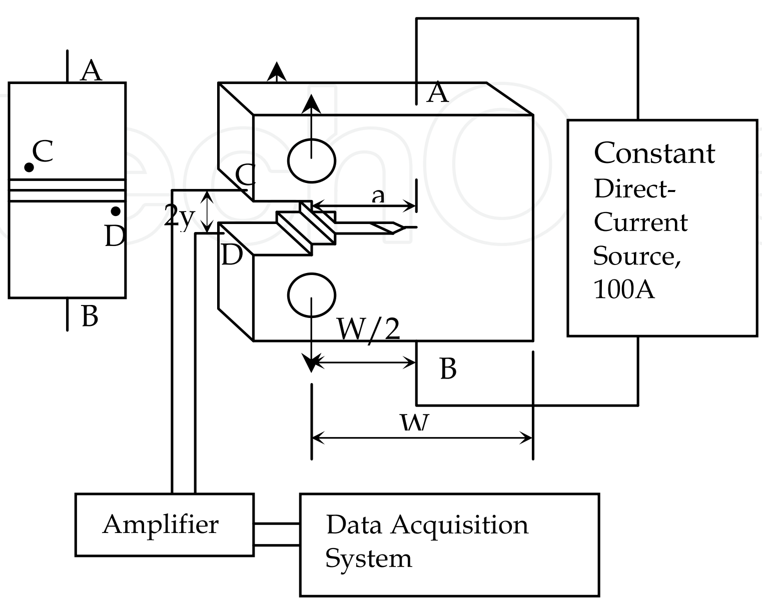
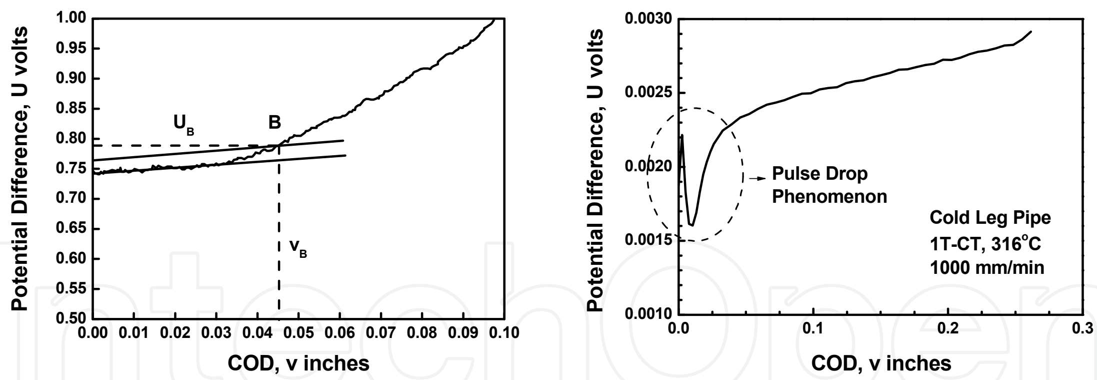


Fig. 3. Specimen geometry for dynamic J-R curve testing



(a) HY130 steel (Joyce, 1996) (b) SA508 Gr.1a steel

Fig. 4. Potential rise versus crack opening displacement

2.1.2 Normalization method

In the Normalization method (ASTM, 2009), dynamic J-R curve can be estimated using load - displacement data pairs. At first, load - displacement data is normalized by considering specimen size and crack length per Eqs. (4) and (5)

$$P_{Ni} = \frac{P_i}{WB\left[\frac{W - a_{bi}}{W}\right]^{\eta_{pl}}} \tag{4}$$

$$v'_{pli} = \frac{v_{pli}}{W} = \frac{v_i - P_i C_i}{W} \tag{5}$$

where $a_{bi}=a_0+J_i/(2\sigma_Y)$, P_{Ni} is normalized load, P_i is load, W is specimen width, B is specimen thickness, η_{pl} is plastic η factor, v'_{pli} is normalized displacement, v is load line displacement, and C_i is compliance. Using final crack length measured at the broken specimen surface, final normalized load displacement pair can be obtained from Eqs (4) and (5). Fitting coefficients a, b, c, d are obtained by curve fitting with Eq. (6) for effective data pair (P_{Ni}, v'_{pli}) including final normalized load displacement pair designated in ASTM E1820 A15.

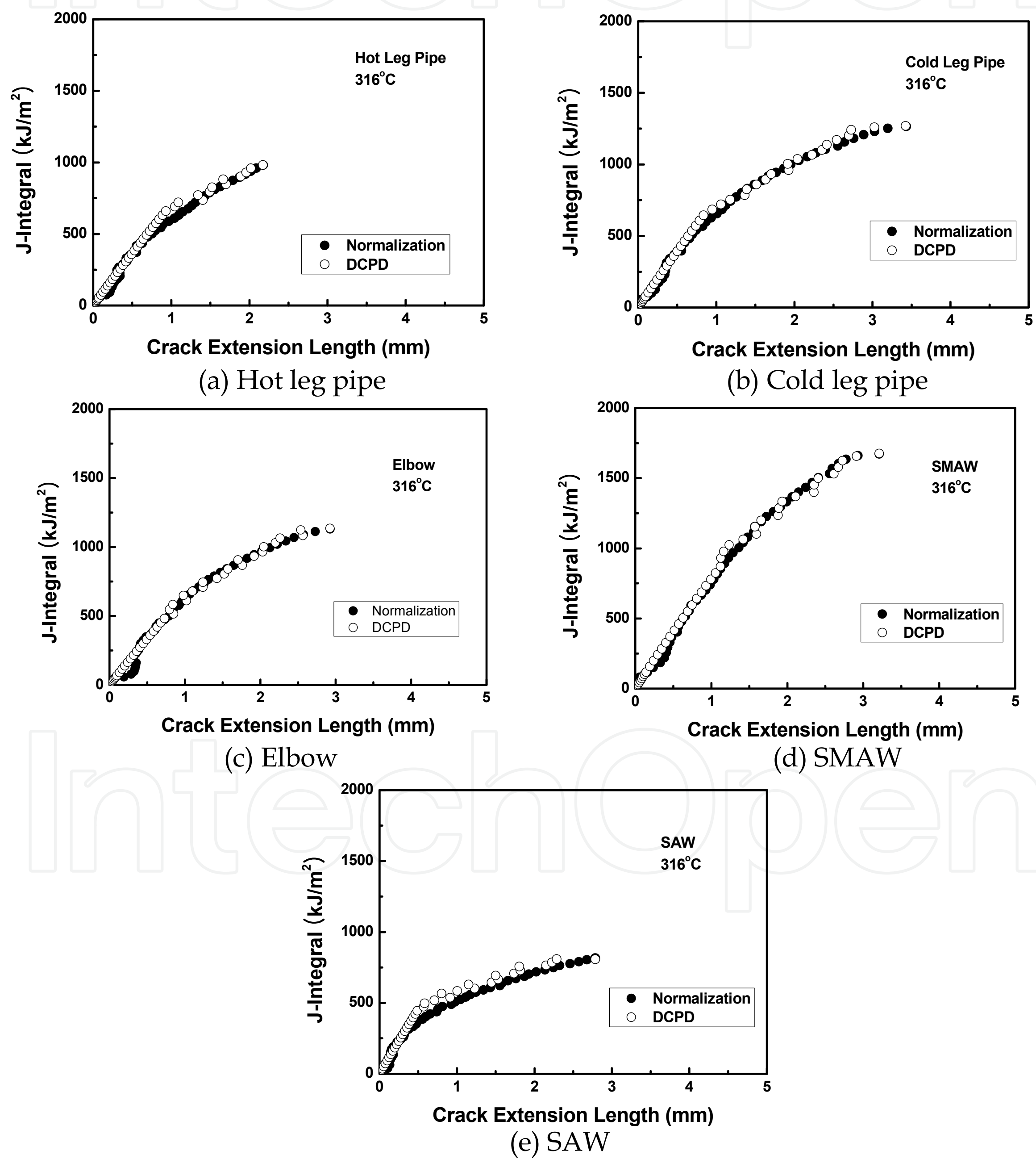
$$P_N = \frac{a + bv'_{pl} + cv'^{2}_{pl}}{d + v'_{pl}} \tag{6}$$

The crack length a_i coinciding with P_{Ni} in Eq.(4) and with P_N in Eq.(6) is calculated for each v'_{pli} by checking with slightly increasing crack lengths from initial crack length a_0. Finally, using load, load line displacement and the calculated crack length data, the J-R curve can then be calculated.

2.2 Test results and discussion

Figure 5 shows the comparison of dynamic J-R curve between DCPD and the Normalization method for Shin-Kori units 3 & 4 when testing in accordance with crack extension criteria of the Normalization method. The dynamic J-R value at given crack extension length is well within the deviation range of ±5%. In the case of hot leg pipe and SAW, the dynamic J-R data using DCPD method tend to be 10% higher at the crack initiation point compared to that using the Normalization method. However, in the case of other materials, the dynamic

J-R curves are coincident with each other. Figure 6 shows the comparison of dynamic J-R curve between DCPD method and normalization method for Shin-Wolsung when testing until load line displacement of 10mm is reached. Note: hereafter short crack extension means the crack extension length is not more than 4mm or 15% of the initial uncracked ligament, whichever is less, and long crack extension means the crack extension length is over 4mm and 15% of the initial uncracked ligament. Except cold leg pipe material at 177°C and 316°C and elbow material at 316°C with long crack extension, the dynamic J-R curve is coincident for different test methods. Therefore we know that for short crack extension, the dynamic J-R curve is coincident for different test methods, but for long crackextension, the J-R curve using DCPD is estimated to 10~30% higher than that using normalization method.

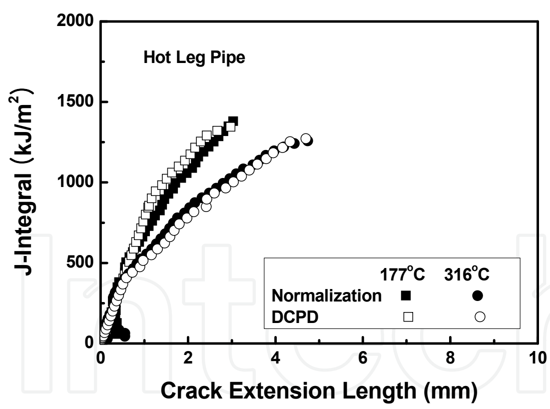


(a) Hot leg pipe (b) Cold leg pipe

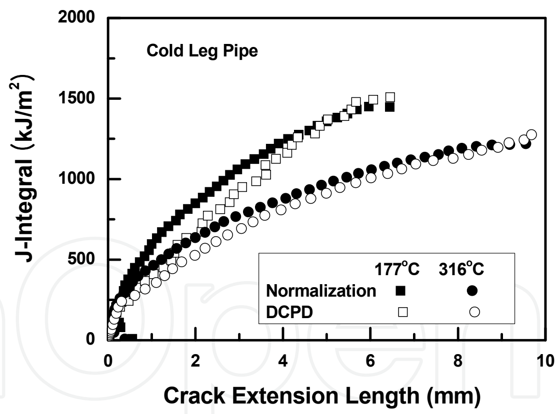
(c) Elbow (d) SMAW

(e) SAW

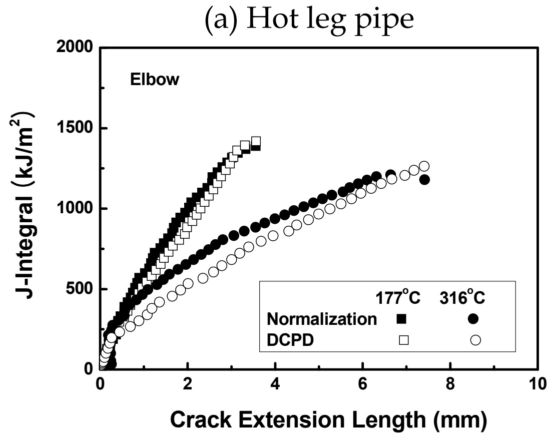
Fig. 5. Comparison of dynamic J-R curve between DCPD and normalization method when testing in accordance with crack extension criteria of normalization method



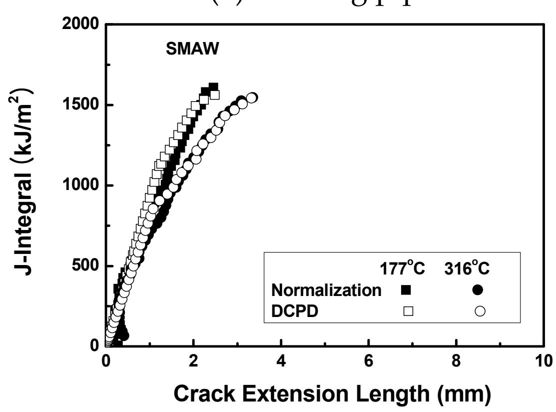
(a) Hot leg pipe



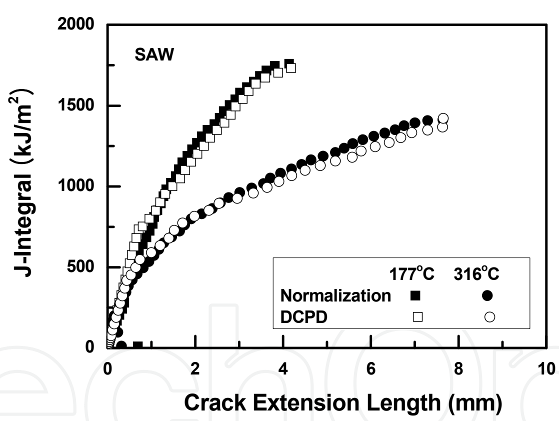
(b) Cold leg pipe



(c) Elbow



(d) SMAW



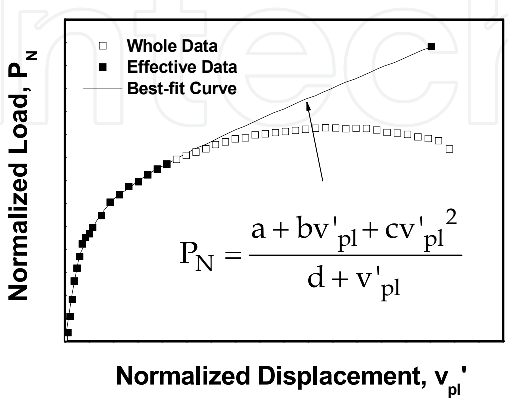
(e) SAW

Fig. 6. Comparison of dynamic J-R curve between DCPD and normalization method when testing until load line displacement of 10mm

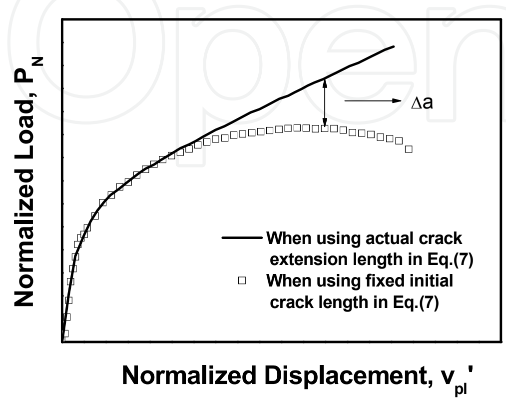
When applying DCPD, the pulse drop phenomenon on the displacement versus DCPD output voltage relationship makes it difficult to determine an accurate dynamic J-R curve. The output voltage increases slightly, decreases sharply and then recovers in a early loading stage for this ferritic steel as shown in Fig.4(b) by superimposition of the induced voltage due to sudden reorientation of ferromagnetic domain nearby the crack tip. Since Johnson's equation, Eq.(3), considers only the variation of output voltage with specimen geometry including crack length, some errors for estimation of crack length can occur in this case where output voltage includes the induced voltage. Despite this problem with DCPD, for short crack extension, dynamic J-R curve using DCPD is similar to that using normalization. On the other hand, at long crack extension a difference in dynamic J-R curve between two test methods appears. However, in this case, normalization method is also not effective since a crack extension criterion is violated according to ASTM code. The difficulty of obtaining reliable J-R curve for long crack extension can be explained as follow; For normalization method, the normalization is based on the principle of load separation following Eq.(7) (Sharobeam & Landes, 1991; Landes et al., 1991)

$$P_N = \frac{P}{G(a/W)} = H\left(v_{pl}/W\right) \tag{7}$$

where P_N is normalized load, P is load, a is crack length, v_{pl} is plastic displacement and W is specimen width. In Eq.(7), if crack length is fixed, normalized load P_N value is easily calculated. However, to obtain J-R curve, normalized load in accordance with normalized function of Eq.(3) should be calculated based on actual crack length variation instead of fixed initial crack length. When load - displacement curve is normalized as fixed specimen geometry and crack length, the normalized curve is described by the open symbols in Fig. 7(a). According to ASTM code, to obtain the normalized load - displacement curve considering the variation of actual crack length, final data pairs estimated from measured final crack length and effective data pairs prior to crack initiation point in accordance with the method designated in ASTM E1820 code were selected. By performing a best fit for selected data pairs using Eq.(6), the normalized load - displacement curve can be estimated reflecting crack length variation. Crack extension length is estimated from the difference of two normalized curves as shown in Fig. 7(b), so for estimation of dynamic J-R curve, it is important to estimate reliable normalized load - displacement curve. In normalization method, normalized load - displacement curve at crack propagation region is estimated by interpolation using Eq.(6). In the case of small crack extension, this interpolation is reasonable because the region to be interpolated is narrow but in the case of long crack extension, interpolation errors can occur. If the position of normalized data pairs at the middle point between crack initiation point and final point is incorrectly estimated, the final estimated J-R curve is also in error from the actual J-R curve. It is therefore important to estimate the middle point exactly between crack initiation point and final point in the long crack extension case. If the position of middle point can be measured exactly through experiment, the reliable J-R curve will be able to evaluate for long crack extension beyond the crack extension length designated at ASTM code.



(a)



(b)

Fig. 7. J-R curve estimation concept on normalization method (a) Optimal best-fit for effective data pair (b) Crack extension length estimation from normalized curve

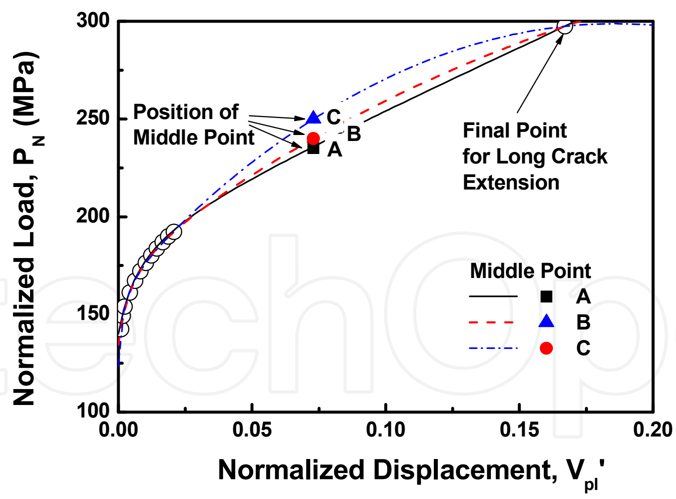


Fig. 8. The illustration diagram for the variation of the normalized load - displacement curve with the position of middle point

3. Proposal of modified normalization method for measurement of dynamic J-R curve with long crack extension

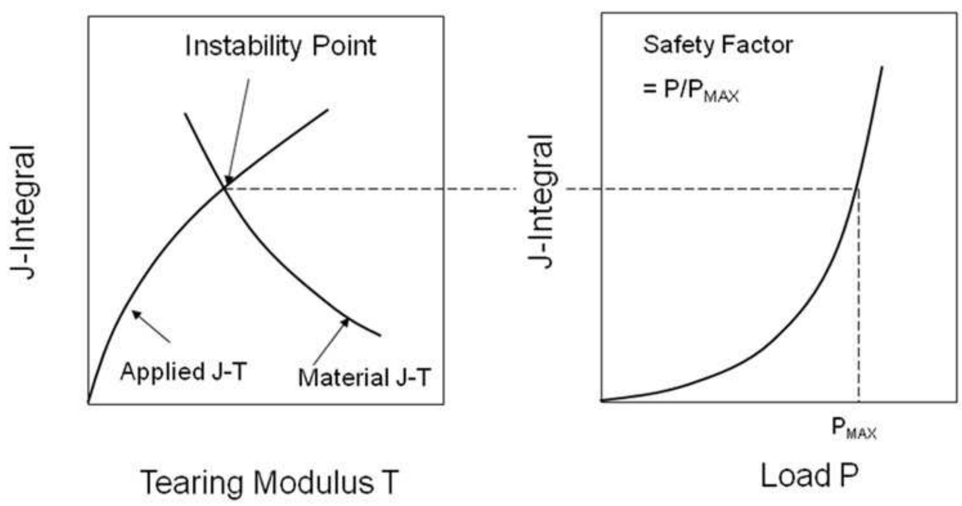
3.1 Importance of J-R curve for long crack extension

In LBB analysis, as an integrity analysis method against instability fracture of cracked piping, J-integral, tearing modulus (J/T) method (Ernst et al., 1979, 1981) and the limit load method were used. While the limit load method is appropriate for the analysis of stainless steel piping, J/T method is appropriate for the analysis of both carbon and stainless steel piping. For ductile material, final instability rupture occurs after stable crack extension with increasing load value. This instability point where piping rupture occurs can be determined using J/T method based on J-integral parameter. The stable growth criterion is

$$T_{app}\left(=\frac{E}{\sigma_f^2}\frac{dJ}{da}\right) < T_{mat}\left(=\frac{E}{\sigma_f^2}\frac{dJ_R}{da}\right) \tag{8}$$

where T_{app} is applied tearing modulus, T_{mat} is material tearing modulus, E is elastic modulus, σ_f is effective yield strength as defined by the average value of tensile strength and yield strength, J is J-integral value to be calculated from finite element analysis for the cracked piping and J_R is J-integral value to be obtained from J-R curve testing.

As shown in Fig. 9, tearing instability point is determined from intersection point of two J/T curves. From this instability point, critical load P_{max} value is determined, and the safety factor is defined as the ratio between the critical load P_{max} and applied load P. If the safety factor is larger than 1, the structural integrity can be verified by Eq. (8). For reliable stability analysis, T_{mat} curve should be evaluated experimentally to determine the intersection point between T_{app} curve and T_{mat} curve. However, when testing using normalization method for the dynamic J-R curve, T_{mat} curve can not sufficiently be measured due to the restriction of crack extension length. In this case, T_{mat} curve corresponding to long crack extension should be estimated from the limited T_{mat} curve with short crack extension by extrapolation as shown in Fig. 9. As an analytical approach of extrapolation, Wallen, K (Wallen, 2009) suggested additional two applicable best-fit methods from limited T_{mat} curve in addition to conventional fitting method for tearing modulus curve. However, analytical approach has uncertainty basically by fitting. In this paper, to evaluate reliable T_{mat} curve at long crack extension region experimentally, we have researched the method for measurement of dynamic J-R curve with crack extension as long as possible.



Material J/T : $T_{mat} = \frac{E}{\sigma_0^2}\frac{dJ_R}{da}$ **Applied J/T :** $T_{app} = \frac{E}{\sigma_0^2}\frac{dJ}{da}$

Fig. 9. Graphical illustration of J/T method

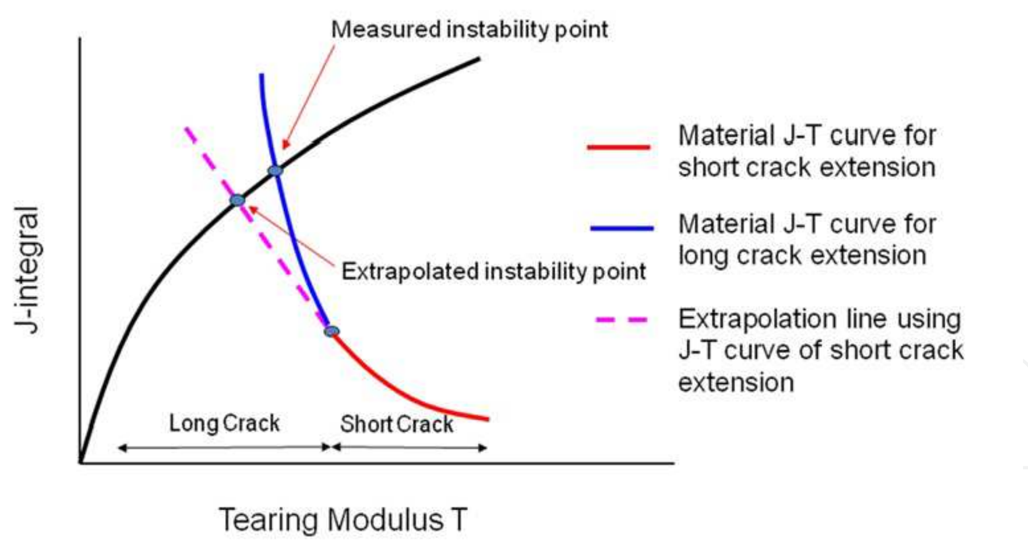


Fig. 10. The illustration diagram for estimation of crack instability point for J/T method

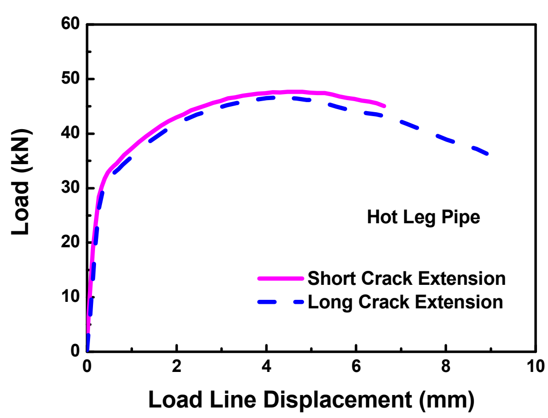
3.2 Dynamic J-R curve testing for long crack extension

To obtain the effective J-R curve under the condition of long crack extension, two specimens were used where one is for short crack extension and the other is for long crack extension. By using two test data, the dynamic J-R curve was evaluated over the crack extension length range according to ASTM code. Table 1 shows test matrix for reactor coolant piping base metal for Shin-Wolsung.

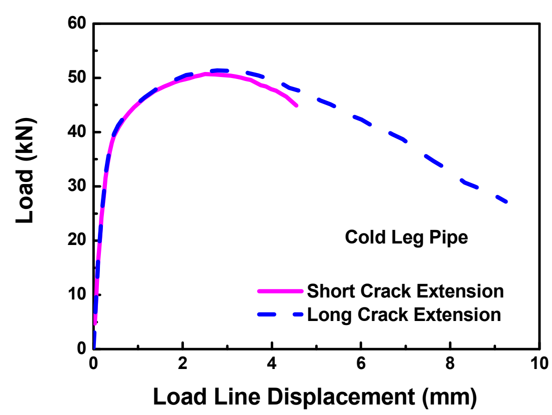
Item		Material	Pipe size (Inner Dia.)	Number of test	
				Short crack extension	Long crack extension
Main Loop Piping	Hot Leg	SA508 Gr. 1a	42 in.	1	1
	Cold Leg	SA508 Gr. 1a	30 in.	1	1
	Elbow	SA516 Gr. 70		1	1

Table 4. Dynamic J-R test conditions for short and long crack extension conditions

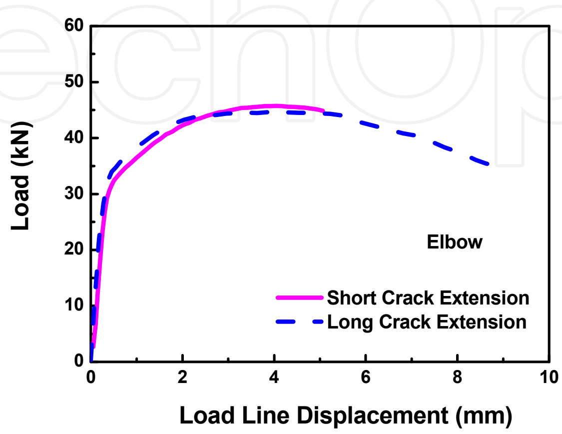
The load - displacement curve for each piping material is shown in Fig 11. In the dynamic J-R curves obtained by normalization method, for hot leg pipe and elbow materials, dynamic J-R curves were similar regardless of crack extension length; whereas for cold leg piping material, J-R curve for short crack extension length was lower than that for long crack extension length as shown in Fig.12. To analyze the reason for the difference between short and long crack extension for cold leg pipe, normalized load-displacement curve is described in Fig. 13. Normalized load-displacement curve, P_N - v'_{pl} curve shows different shape between two tests with different crack extension length. In general, normalized load – displacement curve should maintain a constant shape regardless of crack extension size. Therefore, optimal normalized P_N - v'_{pl} curve should be calculated by considering both P_{Ni} - v'_{pli} data pair for short and long crack extension.



(a) Hot leg pipe

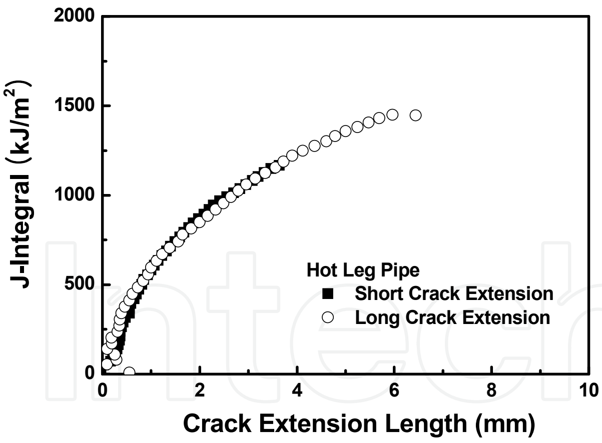


b) Cold leg pipe

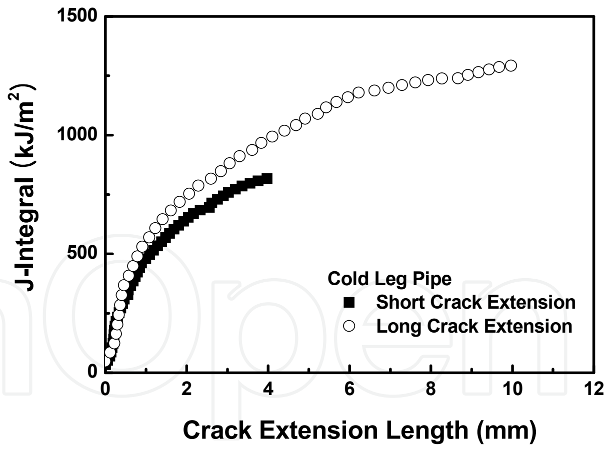


(c) Elbow

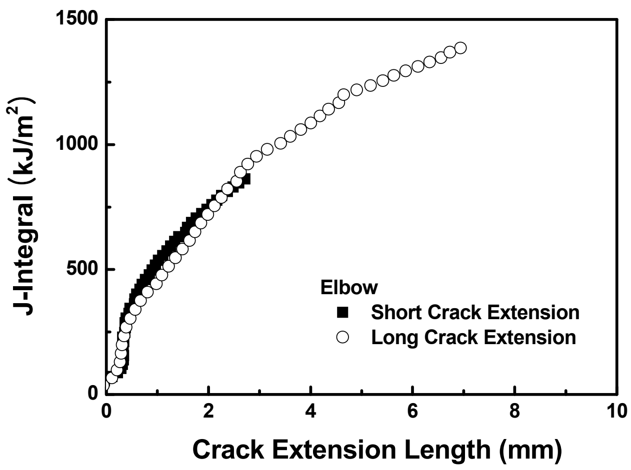
Fig. 11. The load versus load line displacement curves for each material



(a) Hot leg pipe



(b) Cold leg pipe



(c) Elbow

Fig. 12. The comparison of dynamic J-R curve by normalization method between the tests for short and long crack extension

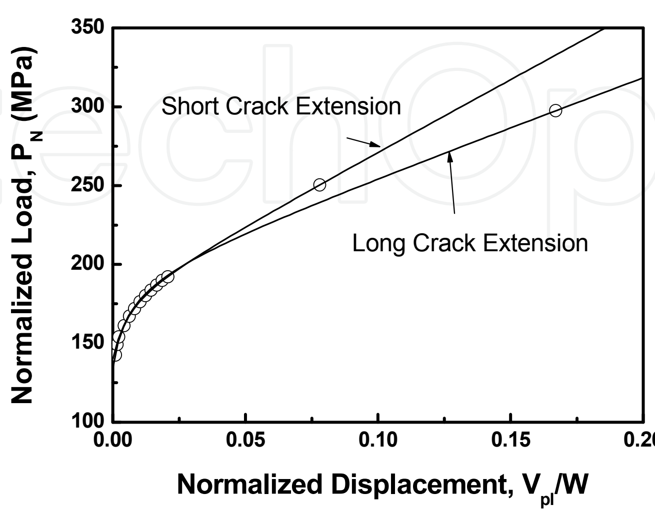


Fig. 13. Normalized load, displacement data pair and its each fitting curve for short and long crack extension of cold leg piping material

3.3 Combined analysis

Based on this concept, combined analysis is proposed as the evaluation method of J-R curve to long crack extension using the test results with two different crack extensions. The procedure is as follows; At first, the P_{Ni} - v'_{pli} data pair is obtained by using load – load line displacement curve for long crack extension length in accordance with Eqs.(9) and (10), and final P_{Ni} - v'_{pli} data pair is obtained for two specimens respectively, where final P_{Ni} - v'_{pli} values are

$$\text{Final } P_{Ni} = \frac{P_f}{WB\left[\frac{W-a_f}{W}\right]^{\eta_{pl}}} \tag{9}$$

$$\text{Final } v'_{pli} = \frac{v_f - P_f C_f}{W} \tag{10}$$

A line is drawn from the final P_{Ni} - v'_{pli} data pair of short crack extension tangent to the P_N - v'_{pl} curve of long crack extension. The right side data to the tangent point and data with v'_{pli} <0.001 are excluded from effective P_{Ni} - v'_{pli} data pair. The coefficients of the fitting function of Eq.(11) instead of Eq.(6) are calculated for two final P_{Ni} - v'_{pli} values and the effective P_{Ni} - v'_{pli} data pair.

$$P_N = \frac{a + bv'_{pl} + cv'^{2}_{pl} + dv'^{3}_{pl}}{e + v'_{pl}} \tag{11}$$

The following least square method is used for curve fitting of the function of Eq.(11).

$$z = \sum\left\{P_N\left(e + v'_{pl}\right) - \left(a + bv'_{pl} + cv'^{2}_{pl} + dv'^{3}_{pl}\right)\right\}^2 = \min. \tag{12}$$

The coefficient values, a, b, c, d, e can be calculated directly by Eq.(13).

$$\begin{bmatrix} n & \sum v'_{pl} & \sum v'^{2}_{pl} & \sum v'^{3}_{pl} & -\sum P_N \\ \sum v'_{pl} & \sum v'^{2}_{pl} & \sum v'^{3}_{pl} & \sum v'^{4}_{pl} & -\sum v'_{pl} P_N \\ \sum v'^{2}_{pl} & \sum v'^{3}_{pl} & \sum v'^{4}_{pl} & \sum v'^{5}_{pl} & -\sum v'^{2}_{pl} P_N \\ \sum v'^{3}_{pl} & \sum v'^{4}_{pl} & \sum v'^{5}_{pl} & \sum v'^{6}_{pl} & -\sum v'^{3}_{pl} P_N \\ \sum P_N & \sum v'_{pl} P_N & \sum v'^{2}_{pl} P_N & \sum v'^{3}_{pl} P_N & -\sum P_N^2 \end{bmatrix} \begin{Bmatrix} a \\ b \\ c \\ d \\ e \end{Bmatrix} = \begin{Bmatrix} \sum v'_{pl} P_N \\ \sum v'^{2}_{pl} P_N \\ \sum v'^{3}_{pl} P_N \\ \sum v'^{4}_{pl} P_N \\ \sum v'_{pl} P_N^2 \end{Bmatrix} \tag{13}$$

Figure 14 shows normalized load - displacement curve best-fit by Eq.(11) for two final points of short and long crack extension cases and the effective P_{Ni} - v'_{pli} data pair. Next, the crack length a_i coinciding with P_{Ni} in Eq.(4) and with P_N in Eq.(11) is calculated for each v'_{pli} by checking with slightly increasing crack lengths from initial crack length a_0, where load - displacement curve for long crack extension length is used. However, J-R curve obtained using combined analysis was deviated from individual J-R curve for short and long crack extension respectively in the case of hot leg pipe material as shown in Fig. 14. This reason is that load - displacement curve between short and long crack extension have slightly different shape as shown in Fig. 11. Therefore, it is needed to adjust the position of middle point by reflecting the characteristics of J-R curves for short and long crack extension. To do so, the coincidence level is evaluated by comparing the J-R curves between normalization analysis by only short crack extension and combined analysis. As a method of evaluation for coincidence, best fit curve of Eq.(14) for the J-R curve of short crack extension is used.

$$J = C(\Delta a)^m \quad (14)$$

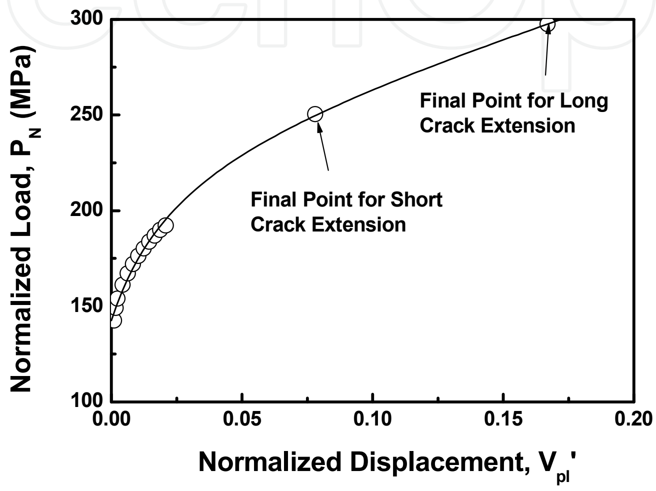


Fig. 14. The best fit curve by Equation (11) on effective data pair for combined analysis

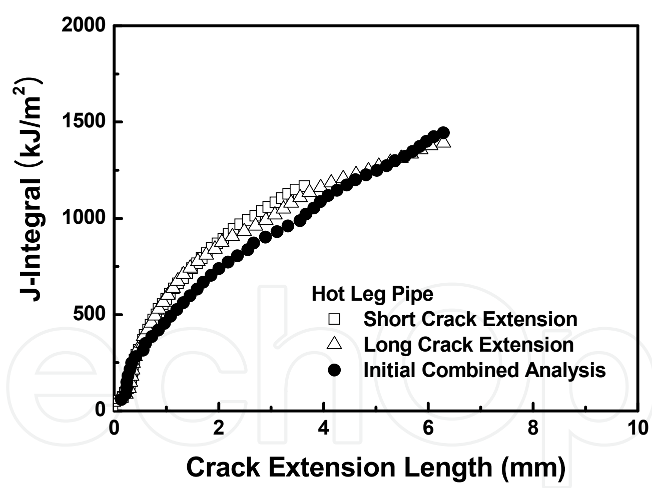
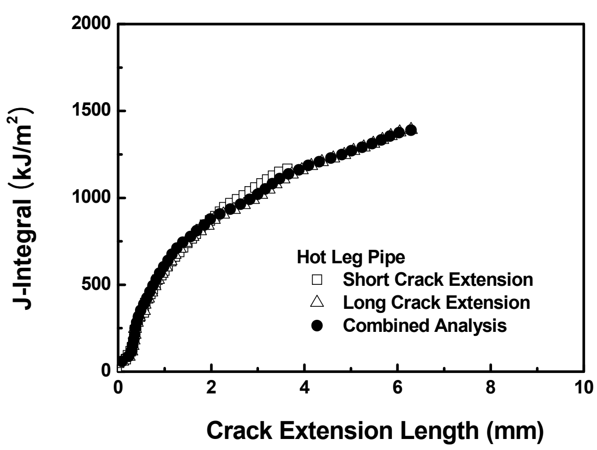


Fig. 15. Dynamic J-R curve for hot leg pipe material prior to adjustment of middle point on normalized load versus displacement curve in combined analysis

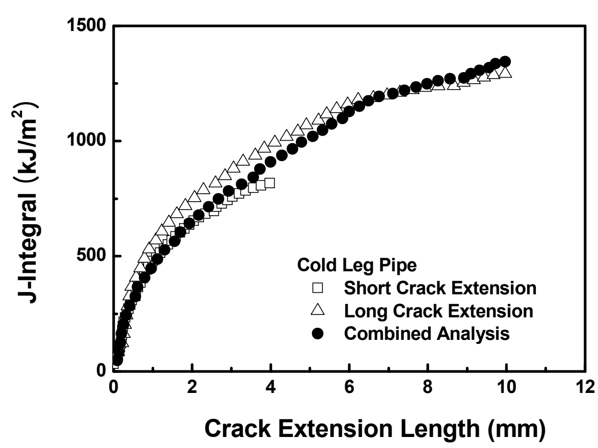
Next, the standard deviation σ of Eq.(15) is calculated from J value by combined analysis and J value obtained by J-R curve of Eq.(14). Such that, the data of combined analysis to short crack extension are used in calculating σ

$$\sigma = \sqrt{\frac{\sum (J_{fit} - J_{combined})^2}{n-1}} \quad (15)$$

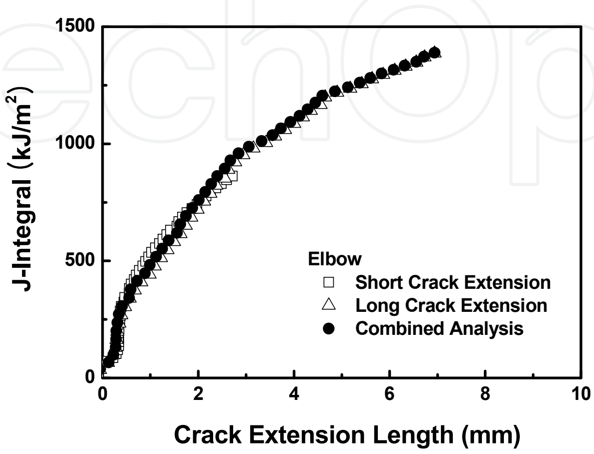
where J_{fit} is J value obtained by fitting function of Eq.(14) $J_{combined}$ is J value obtained by combined analysis and n is the number of effective J-R data to short crack extension. Optimal middle point on the normalized load-displacement relationship is determined as a point when standard deviation σ value of Eq.(15) is reached to minimize by adjusting P_N value at v'_{pl} value at final point of short crack extension. Using the optimal middle point, final P_{Ni} - v'_{pli} data pair of long crack extension and effective P_{Ni} - v'_{pli} data pairs, J-R curve can be estimated. Figure 9 shows the comparison of dynamic J-R curve among the combined method and normalization method of short and long crack extension. For all three kinds of piping, dynamic J-R curve by combined analysis is well described with the behavior of that for two different crack extensions. From this combined analysis, we could obtain reasonable dynamic J-R curve until long crack extension for nuclear piping materials. In combined analysis, one J-R curve is obtained using two specimens. Therefore, the scatter of material properties with the position of taking specimen is required not to be large. In LBB analysis, the lowest material property is used among three test results for material property scatter. In this approach, the J-R curve tends to be estimated as an average J-R data for two test results. Further investigation is therefore needed for low bound curve of J-R curve with long crack extension effectively based on the statistical concept.



(a) Hot leg pipe



(b) Cold leg pipe



(c) Elbow

Fig. 16. The dynamic J-R curve by combined analysis for each material

4. Conclusion

From the comparison test results between DCPD and normalization method as a dynamic J-R curve testing method, short crack extension, dynamic J-R curves were similar but, for long crack extension, J-R curve estimated by normalization was higher by 10~30% at the initial loading stage than that by DCPD. For reliable J/T analysis for LBB design of nuclear piping, material J-R curve for long crack extension is needed. However, normalization method is applicable for only short crack extension. To overcome this problem, combined analysis based on normalized method was proposed. In combined analysis, dynamic J-R curve with long crack extension is estimated by two dynamic J-R curve tests with different crack extension length. The dynamic J-R curve beyond the crack extension length range designated by ASTM code could be estimated using the combined analysis.

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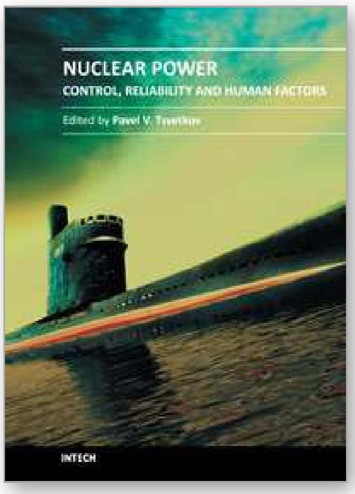

Nuclear Power - Control, Reliability and Human Factors
Edited by Dr. Pavel Tsvetkov

ISBN 978-953-307-599-0
Hard cover, 428 pages
Publisher InTech
Published online 26, September, 2011
Published in print edition September, 2011

Advances in reactor designs, materials and human-machine interfaces guarantee safety and reliability of emerging reactor technologies, eliminating possibilities for high-consequence human errors as those which have occurred in the past. New instrumentation and control technologies based in digital systems, novel sensors and measurement approaches facilitate safety, reliability and economic competitiveness of nuclear power options. Autonomous operation scenarios are becoming increasingly popular to consider for small modular systems. This book belongs to a series of books on nuclear power published by InTech. It consists of four major sections and contains twenty-one chapters on topics from key subject areas pertinent to instrumentation and control, operation reliability, system aging and human-machine interfaces. The book targets a broad potential readership group - students, researchers and specialists in the field - who are interested in learning about nuclear power.