Effect of Combined Loading Due to Bending and Internal Pressure on Pipe Flaw Evaluation Criteria*

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Abstract

Considering a rule for the rationalization of maintenance of Light Water Reactor piping, reliable flaw evaluation criteria are essential for determining how a detected flaw will be detrimental to continuous plant operation. Ductile fracture is one of the dominant failure modes that must be considered for carbon steel piping and can be analyzed by elastic-plastic fracture mechanics. Some analytical efforts have provided various flaw evaluation criteria using load correction factors, such as the Z-factors in the JSME codes on fitness-for-service for nuclear power plants and the section XI of the ASME boiler and pressure vessel code. The present Z-factors were conventionally determined, taking conservativity and simplicity into account; however, the effect of internal pressure, which is an important factor under actual plant conditions, was not adequately considered. Recently, a J-estimation scheme, LBB.ENG C for the ductile fracture analysis of circumferentially through-wall-cracked pipes subjected to combined loading was developed for more accurate prediction under more realistic conditions. This method explicitly incorporates the contributions of both bending and tension due to internal pressure by means of a scheme that is compatible with an arbitrary combined-loading history. In this study, the effect of internal pressure on the flaw evaluation criteria was investigated using the new J-estimation scheme. The Z-factor obtained in this study was compared with the presently used Z-factors, and the predictability of the current flaw evaluation criteria was quantitatively evaluated in consideration of the internal pressure.

Key words: Fracture Criterion, Ductile Fracture, J-Integral, Fracture Mechanics, Pipe Flaw Evaluation, Fitness-For-Service, Z-Factor

1. Introduction

As the number of aged nuclear power plants is increasing, the substantiation of reliability as well as the assessment of the possible extensions of plant life is becoming important in Japan. Thus, the importance of appropriate and rationalized management of the plant life has been widely recognized. The Japan Society of Mechanical Engineers (JSME) has established a code for nuclear power generation facilities⁽¹⁾, which provides the rules on the fitness-for-service for operating nuclear power plants. The concept of flaw evaluation forms the basis of the fitness-for-service rules, in which the crack propagation

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from detected flaws up to the end of the plant life or the next inspection period is predicted to determine the necessity of repairing or replacing the components of concern. Focusing on the piping typical of component elements, the flaw evaluation addresses acceptance criteria to predict the load and mode at the final failure status by the use of elastic-plastic fracture analysis.

Since piping is essentially used for the transportation of fluid, it is subjected to tensile load due to internal pressure under normal operating conditions. Considering seismic force as an external load, piping is additionally subjected to a bending load as a critical loading mode. Therefore, combined loading consisting of tension and bending is the basic loading condition to be considered for pipe failure. However, pipe fracture behavior under combined loading has not been adequately examined. The effect of combined loading is not addressed in the present flaw evaluation criteria, but is treated in a conventional manner. The authors recently developed a J-estimation scheme, LBB.ENG, for the ductile fracture analysis of circumferentially through-wall-cracked pipes subjected to combined loading⁽²⁾⁻⁽⁴⁾. This method incorporates the contributions of both tension and bending using explicit expressions. The effectivity of the method was validated through a comparison with the results of large-scale fracture experiments on cracked pipes under a combined loading condition⁽⁴⁾.

In the present study, the effect of combined loading on the flaw evaluation criteria for a common carbon steel piping material was quantitatively investigated using LBB.ENG. More accurate flaw evaluation criteria taking combined loading into account were derived, and the possible rationalization of maintenance by using new methods was investigated by a comparison with the flaw evaluation criteria in the presently used codes.

2. Outline of Ductile Fracture Evaluation

Figure 1 shows the schematic of a cracked pipe of concern. R is the mean radius, t is the pipe thickness, and 2θ is the total crack angle. The circumferentially through-wall-cracked pipe is subjected to bending moment M and tensile load T due to internal pressure, and these loadings are represented by bending stress $\sigma_b (= M/(\pi R^2 t))$ and tensile stress $\sigma_t (= T/(2\pi R t))$, respectively. The parameter s is defined as σ_t normalized by the material flow stress σ_f and is used for simplicity hereinafter.

The rotation ϕ , due to the crack may be written as the sum of its elastic and plastic components ϕ_{EL} and ϕ_{PL} :

$$\phi = \phi_{EL} + \phi_{PL}. \quad (1)$$

ϕ_{EL} is related to the strain energy using Castigliano's theorem, and is expressed as

$$\phi_{EL} = \frac{\sigma_b}{E} I_b(\theta) + \frac{\sigma_t}{E} I_t(\theta) \quad (2)$$

$$I_b(\theta) = 4 \int_0^{\theta} \theta F_b^2(\theta) d\theta \quad (3)$$

$$I_t(\theta) = 4 \int_0^{\theta} \theta F_b(\theta) F_t(\theta) d\theta. \quad (4)$$

where E is Young's modulus, and $F_b(\theta)$ and $F_t(\theta)$ are the compliance functions of stress

Fig. 1 Circumferentially through-wall-cracked pipe subjected to combined tension and bending

intensity factors K_b and K_t for bending and tension, respectively, which are defined as functions of θ by

$$F_b(\theta) = \frac{K_b}{\sigma_b \sqrt{\pi R \theta}}, \quad F_t(\theta) = \frac{K_t}{\sigma_t \sqrt{\pi R \theta}}. \quad (5)$$

The solutions of K_b and K_t are obtained by Klecker et al.⁽⁵⁾ as an example.

For the evaluation of ϕ_{EL} , beam theory can be applied to a pipe of nonlinear elastic material on the basis of the deformation theory of plasticity. The relation between stress σ and strain ε is defined by the following power law:

$$\varepsilon / \varepsilon_0 = \alpha (\sigma / \sigma_0)^n, \quad \varepsilon_0 = \sigma_0 / E. \quad (6)$$

Furthermore, assuming that the existence of a crack can be replaced with a pipe section with reduced thickness t_e and that the pipe section can be used to simulate the reduction of the compliance due to the existence of the crack, the following evaluation equations are derived⁽⁴⁾:

$$\phi_{PL} = \left(\frac{t}{t_e} \right)^{n-1} \left(\frac{\pi}{4 \hat{K}_M} \right)^n \alpha \frac{\kappa^n}{\kappa(n=1)} \left(\frac{\sigma_b}{\sigma_0} \right)^{n-1} \phi_{EL} \quad (7)$$

$$\frac{t}{t_e} = \begin{cases} \left[1 - \left(1 - \frac{\pi}{4} \right) \sin 2\theta \right] \frac{\cos\left(\frac{\pi}{2}s\right)}{\cos\frac{\theta}{2} - \frac{1}{2}\sin\theta}, & \text{for } \theta < \frac{\pi}{4} \\ \frac{\pi}{4} \frac{\cos\left(\frac{\pi}{2}s\right)}{\cos\frac{\theta}{2} - \frac{1}{2}\sin\theta}, & \text{for } \theta \geq \frac{\pi}{4} \end{cases} \quad (8)$$

$$\kappa = \frac{1}{2} \left\{ 1 + \left[1 + \frac{16 \hat{K}_M (\hat{K}_T g_T - \hat{K}_M g_M) (\sigma_t / \sigma_b)^2}{\hat{K}_T^2 g_T^2} \right]^{1/2} \right\} \quad (9)$$

$$\hat{K}_M = \frac{\sqrt{\pi}}{2} \frac{\Gamma\left(\frac{1}{2n} + 1\right)}{\Gamma\left(\frac{1}{2n} + \frac{3}{2}\right)}, \quad \hat{K}_T = \frac{\sqrt{\pi}}{2} \frac{\Gamma\left(\frac{1}{2n} + \frac{1}{2}\right)}{\Gamma\left(\frac{1}{2n} + 1\right)} \quad (10)$$

$$g_M = \frac{n+1}{n} \frac{2}{\pi}, \quad g_T = \frac{1}{n} + \frac{2}{\pi}. \quad (11)$$

where Γ is the Gamma function.

The J-integral, J , is also divided into its elastic and plastic components J_{EL} and J_{PL} .

$$J = J_{EL} + J_{PL} \quad (12)$$

J_{EL} is directly obtained from the stress intensity factor K_I under a plane stress condition:

$$J_{EL} = K_I^2 / E. \quad (13)$$

On the basis of the fact that J is equivalent to the release rate of potential energy for a nonlinear elastic material and the assumption that the plastic deformation is a function of

only the net-section stress, J_{PL} can be calculated by the following equations⁽²⁾:

$$J_{PL} = \int_0^{\phi_{PL}} \eta_p M d\phi_{PL} + 2 \int_{\theta_0}^{\theta} \gamma_p J_{PL} d\theta + 2 \int_{s_0}^s \mu_p J_{PL} ds \quad (14)$$

$$\eta_p = -\frac{\partial h_p / \partial \theta}{2Rth_p} \quad (15)$$

$$\gamma_p = \frac{\partial^2 h_p / \partial \theta^2}{2\partial h_p / \partial \theta} \quad (16)$$

$$\mu_p = \frac{\partial^2 h_p / \partial s \partial \theta}{2\partial h_p / \partial \theta} \quad (17)$$

$$h_p = \cos\left(\frac{\theta}{2} + \frac{\pi}{2}s\right) - \frac{1}{2}\sin\theta. \quad (18)$$

The second term on the right side of Eq. (14) corresponds to the contribution of the crack growth to J_{PL} and is 0 for a stationary crack. The third term on the right side of the equation corresponds to the contribution of the tensile load variation to J_{PL} and is 0 under constant tensile loading.

By integrating the load-rotation relation given by Eqs. (1), (2), and (7), the J-integral provided by Eqs. (12) to (14), and the J-resistance curve,

$$J = J_R(\Delta a) \quad (19)$$

which is introduced as an additional criterion of ductile crack extension, then the loads, rotation, J-integral, and crack extension are uniquely related to each other, which means that the prediction of fracture behavior in consideration of both combined loading and crack extension can be achieved.

3. Derivation of Pipe Flaw Evaluation Criteria

3.1 Basic Concept

Figure 2 shows a flowchart of pipe flaw evaluation. In the first step of evaluation, characterized flaws detected by nondestructive tests are compared with the allowable flaw sizes in the acceptance standards. If the characterized flaws are smaller than the allowable flaw sizes, they are acceptable for continued service. Otherwise, the flaws must be repaired or evaluated by the second step of evaluation. In this step, the extent of crack

Fig. 2 Flowchart of pipe flaw evaluation

growth up to the next inspection or the end of the service lifetime is determined, and failure analysis is subsequently conducted. The predicted propagated flaws are compared with the critical flaw sizes in the acceptance criteria. If they are smaller than the critical flaw sizes, they are acceptable for continued service during the evaluated time period. Otherwise the flaws must be removed or repaired.

In the above evaluation procedure, critical flaw sizes in the acceptance criteria must be determined in accordance with the expected failure mode under the specific conditions. When a pipe material exhibits a relatively high J-resistance, final failure is due by plastic collapse⁽⁶⁾. The failure load is then identical to the plastic collapse load, which can be predicted by limit load analysis based on the net-section collapse criterion. The net-section collapse load is obtained from the equilibrium condition of the admissible stress distribution on the cracked section. Thus, it can be easily evaluated once the lower limit of the flow stress is identified.

In contrast, the J-resistance is often lower than the driving force of crack growth for carbon steel piping, and the failure occurs after a certain amount of stable crack growth. In such a case, the failure load is evaluated by elastic-plastic fracture analysis using the J-estimation scheme.

3.2 Significance of Z-factor and Consideration of Combined Loading

In the present flaw evaluation criteria, the Z-factor (Z) is used to determine the critical flaw sizes for ductile fracture. Z is defined as the ratio of the net-section collapse load to the failure load. It is equal to unity for plastic collapse and larger than unity for ductile fracture. Z indicates the degree of the reduction of the load-carrying capacity from the net-section collapse load. If Z is previously identified, the failure load for ductile fracture can be easily evaluated as the net-section collapse load divided by Z . Alternatively, a critical crack size for a certain load under the plastic collapse condition can be directly converted into the same critical crack size for the load multiplied by Z under the ductile fracture condition.

The concept of the Z-factor was first introduced in the Section XI of the ASME Boiler and Pressure Vessel Code⁽⁷⁾. Z was formulated as a function of the nominal diameter OD (in inches) and the radius-to-thickness ratio R/t ⁽⁶⁾⁽⁸⁾. The Z-factor in the ASME Code, Z_{ASME} , for a ferritic steel base metal pipe is

$$Z_{ASME} = 1.20[1 + 0.021A(OD - 4)] \quad (20)$$

$$A = \begin{cases} [0.125(R/t) - 0.25]^{0.25}, & \text{for } 5 \leq R/t \leq 10 \\ [0.4(R/t) - 3.0]^{0.25}, & \text{for } 10 < R/t \leq 20 \end{cases} \quad (21)$$

The above equations are applicable when OD is between 4 and 37 inches. Another Z-factor is given in the JSME Code⁽¹⁾ taking the properties of materials used in Japan into account. The Z-factor in the JSME Code, Z_{JSME} , for a ferritic steel base metal pipe is

$$Z_{JSME} = 0.2885 \log_{10} OD + 0.9573. \quad (22)$$

The above equations are applicable when $6 \text{ inches} \leq OD \leq 30 \text{ inches}$. The applicable range of R/t is not obvious; however, it is approximately between 4 and 9. Note that both Eqs. (20) and (22) consider pure bending load only, and the effect of combined loading is not considered.

It is expected that a new Z-factor taking the effect of combined loading into account can be derived using LBB.ENG. The Z-factor under combined loading Z_C is defined as

$$Z_C = \text{Max}[1, M_{NSC} / M_{max}]. \quad (23)$$

where M_{NSC} is the net-section collapse moment given by

$$M_{NSC} = 4\sigma_f R^2 t h_p(\theta, s) \quad (24)$$

and h_p is given in Eq. (18). M_{max} in Eq. (23) is the maximum moment predicted using LBB.ENG.ENG.

4. Analysis of Z-factor

4.1 Conditions of Analysis

LBB.ENG.ENG was applied to analyze the Z-factor under combined loading, Z_C . The material properties used for the analysis were determined on the basis of the Japanese carbon steel pipe database⁽⁹⁾⁽¹⁰⁾. The stress-strain relation for STS480 carbon steel at 300°C, and the J-R curve for STS410 carbon steel at 300°C were selected to give the most conservative values of Z_C . Table 1 shows the material properties used for the analysis.

θ_0 , OD , the nominal thickness (or the radius-to-thickness ratio R/t), and the normalized membrane stress P_m/S_m (where P_m is the membrane stress due to internal pressure and S_m is the design stress intensity) were considered as the parameters affecting Z_C . The range of θ_0 was 5 to 90°, and the range of OD was 2.5 to 30 inches. The nominal thickness is fixed to Sch 80 but is sometimes increased to Sch 160. P_m/S_m was set to 0 (no internal pressure), 0.34 (maximum value obtained from actual plant surveys⁽⁹⁾⁽¹⁰⁾), and 0.5 (maximum allowable value under normal operating conditions). A finer subdivision was also applied as necessary to observe the effect of P_m/S_m on Z_C .

4.2 Results of Analysis

Figures 3(a) and (b) show typical predicted relations between moment and rotation for 6- and 26-inch-diameter pipes, respectively. These relations have a similar configuration, and the maximum moment decreases with increasing P_m/S_m .

Figures 4(a) to (c) show the effect of OD on Z_C for the three values of P_m/S_m . As defined in Eq. (23), Z_C is effective only in the case of $Z_C > 1$; however, the ratio of the net-section collapse moment to the predicted maximum moment obtained from LBB.ENG.ENG is regarded here as the conventional Z-factor. θ_0 was fixed at 15, 30, ..., 90° and OD was

Table 1 Material properties used for analysis

Young's modulus	Flow stress	Stress-strain relation*			J-R curve**			Design stress intensity
		σ_0	α	n	J_{in}	C	m	
196 GPa	389 MPa	244 MPa	4.412	3.389	0.119 MN/m	136.3	0.9234	139 MPa

*: Stress-strain relation provided as $\varepsilon/\varepsilon_0 = \alpha(\sigma/\sigma_0)^n$, $\varepsilon_0 = \sigma_0/E$

**: J-R curve provided as $J = J_{in} + C(\Delta\sigma)^m$

(a) 6-inch-diameter, Sch 80 pipes

(b) 26-inch-diameter, Sch 80 pipes

Fig. 3 Examples of predicted relations between moment and rotation

varied from 2.5 to 30-inches. The case when $P_m/S_m = 0.50$ and $\theta_0 = 90^\circ$ was excluded because these values result in plastic collapse due to pure tension. The nominal thickness was Sch 80. These figures show that a larger OD generally gives a larger Z_C regardless of the value of P_m/S_m or θ_0 . The dependence of OD on Z_C seems to be more significant when θ_0 is larger. OD, as well as P_m/S_m and θ_0 , determines whether or not Z_C is larger than unity. The change in the slope at a diameter of 30-inches is caused by the larger value of R/t for this diameter.

Figures 5(a) to (c) show the effect of θ_0 on Z_C for the three values of P_m/S_m . OD was fixed at 2.5, 6, 16, and 26 inches and θ_0 was varied from 5 to 90° . The case when $P_m/S_m = 0.50$ and $\theta_0 = 90^\circ$ was also excluded. The nominal thickness was Sch 80. These figures show that Z_C increases monotonically with increasing θ_0 when $P_m/S_m = 0.00$, however, Z_C attains its maximum value at a certain value of θ_0 in the case of positive P_m/S_m . This value of θ_0 ranges between 55 to 70° and depends on both P_m/S_m and OD.

Figure 6 shows the effect of R/t on Z_C for the three different values of P_m/S_m . OD and θ_0 were fixed at 26 inches and 60° , respectively. The nominal thickness was varied from Sch 80 to 160. R/t was 9.2 for Sch 80 and 4.6 for Sch 160. It can be seen from the figure that Z_C increases almost linearly with increasing R/t .

Figure 7 shows the effect of P_m/S_m on Z_C . OD was fixed at 6, 16, and 26 inches and θ_0 was fixed at 60° . P_m/S_m was varied from 0.00 to 0.50. The figure also shows that Z_C has

Fig. 4 Effect of nominal diameter on Z-factor

Fig. 5 Effect of initial half crack angle on Z-factor

Fig. 6 Effect of R/t on Z-factor

Fig. 7 Effect of P_m/S_m on Z-factor

a linear relationship with P_m/S_m . It can be ascertained that a similar relationship is also satisfied for different OD , θ_0 , and R/t values. In previous studies⁽⁹⁾⁽¹⁰⁾, an increase in P_m/S_m due to internal pressure was shown to slightly reduce the load-correction factor. This is because the R6 procedure option 2⁽¹¹⁾ was applied to conveniently identify the Z-factor under combined loading, although the accuracy of evaluation using this method has not been adequately confirmed. Therefore, the R6 procedure may give a too conservative prediction under a combined loading condition.

4.3 Formulation of Z-Factor

On the basis of the results of the analysis, an approximate expression for Z_C under combined loading was formulated. Z_C can be generally expressed as a function of OD , θ_0 , R/t , and P_m/S_m :

$$Z_C = Z_C(OD, \theta_0, R/t, P_m/S_m). \quad (25)$$

However, it would not be appropriate to consider all the parameters in Eq. (25) from the viewpoint of codification. In this study, the contributions of the parameters to Z_C are addressed as follows. The dominant parameter affecting Z_C is assumed to be OD . Since the effect of θ_0 is difficult to incorporate in the expression in a consistent manner, Z_C is conservatively replaced with its maximum value for arbitrary values of θ_0 . The effects of both R/t and P_m/S_m seem to be independent of other factors according to Figs. 6 and 7, respectively. Consequently, Eq. (25) can be rewritten as

$$Z_C = f_1(P_m/S_m) f_2(R/t) f_3(OD). \quad (26)$$

In the above equation, functions f_1 and f_2 were obtained by the linear approximations by the least-squares method using the result of the analysis, and function f_3 was determined by assuring a linear relation of Z_C with $\log_{10}(OD)$ excluding the contributions of both P_m/S_m and R/t . Thus, the formula used to evaluate Z_C under combined loading is given by the following equation:

$$Z_C = \left[1.00 - 0.226 \frac{P_m}{S_m} \right] \left[0.826 + 0.0189 \frac{R}{t} \right] \left[0.977 + 0.0707 \log_{10} OD \right]. \quad (27)$$

Again note that Z_C should be unity in the case of $Z_C < 1$. The applicable range of this equation is limited to the range of the parameters in the analysis, that is, 2.5 to 30 inches for OD , Sch 80 to 160 for nominal thickness, $\theta_0 \leq 60^\circ$, and $P_m/S_m \leq 0.5$.

Figure 8 shows a comparison of the values of Z_C predicted using Eq. (27) and the calculated values for each analysis condition. Results when $Z_C < 1$ are also plotted for comparison. The predicted values of Z_C are in good agreement with the calculated values for a wide range of OD and P_m/S_m , and the difference is less than 3%.

Fig. 8 Comparison between calculated and predicted Z-factors

4.4 Comparison with Present Z-Factors

The proposed formula for Z_C under combined loading in Eq. (27) was compared with the present Z-factors, Z_{ASME} in Eq. (20) and Z_{JSME} in Eq. (22), as shown in Figs. 9(a) and (b). Results for $Z_C < 1$ are also plotted. When $R/t = 5$ and 10, the values of Z_C are always less than the other Z-factors independently of OD or P_m/S_m . Since the material properties used to develop Z_{JSME} and Z_C are essentially the same, the difference between Z_{JSME} and Z_C when $P_m/S_m = 0$ results from the accuracy and conservativity of the evaluation methods. In other words, the R6 procedure option 2⁽¹¹⁾ used to develop Z_{JSME} gives conservative predictions of failure loads, while LBB.ENGCG, used to develop Z_C , may predict more accurate failure loads.

As a result, it was ascertained that the presently used Z-factors, which do not take combined loading into consideration, were still conservative under a combined loading condition, and the new Z-factor under combined loading promises more reliable flaw evaluation.

Fig. 9 Comparison between proposed and present Z-factors

5. Conclusions

In this study, a Z-factor for carbon steel pipes taking combined loading into account was investigated. The J-estimation scheme, LBB.ENGCG, developed to evaluate the ductile fracture behavior of circumferentially through-wall-cracked pipes subjected to combined loading, was used to analyze the Z-factor. The effect of internal pressure as well as other factors on the Z-factor was quantitatively examined. It was found that the Z-factor was generally larger for a larger diameter, larger crack angle, smaller thickness, and lower pressure. A formula to evaluate the Z-factor under combined loading was developed on the basis of the results of the analysis, and was compared with the present Z-factors. As a result, it was ascertained that the presently used Z-factors, which do not take combined loading into consideration, were still conservative under a combined loading condition. The new Z-factor under combined loading promises more reliable flaw evaluation.

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References

- (1) The Japan Society of Mechanical Engineers, Codes for Nuclear Power Generation Facilities -Rules of Fitness-for-Service for Nuclear Power Plants-, JSME S NA1-2004 (2004).
- (2) Miura, N. and Wilkowski, G., J-R Curves from Circumferentially Through-Wall-Cracked Pipe Tests Subjected to Combined Bending and Tension -Part I: Theory and Numerical Simulation, *Transactions of the ASME, Journal of Pressure Vessel Technology*, Vol. 120 (1998), pp. 406-411.

- (3) Miura, N. and Wilkowski, G., J-R Curves from Circumferentially Through-Wall-Cracked Pipe Tests Subjected to Combined Bending and Tension -Part II: Experimental and Analytical Validation, *Transactions of the ASME, Journal of Pressure Vessel Technology*, Vol. 120 (1998), pp. 412-417.
- (4) Miura, N., Approximate Evaluation Method for Ductile Fracture Analysis of Circumferentially Through-Wall-Cracked Pipe Subjected to Combined Bending and Tension, *Nuclear Engineering and Design*, Vol. 191 (1999), pp. 177-194.
- (5) Klecker, R. et al., NRC Leak-Before-Break (LBB.NRC) Analysis Method for Circumferentially Through-Wall Cracked Pipes Under Axial Plus Bending Loads, NUREG/CR-4572 (1986).
- (6) Novetech Corporation, Evaluation of Flaws in Ferritic Piping, EPRI NP-6045, Final Report (1988).
- (7) ASME Boiler and Pressure Vessel Code: Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components (2004).
- (8) Section XI Task Group for Piping Flaw Evaluation, Evaluation of Flaws in Austenitic Steel Piping, EPRI NP-4690-SR, Special Report (1986).
- (9) Nuclear Power Engineering Test Center, Proving Test on the Integrity of Carbon Steel Piping in LWRs, Summary Report of Proving Tests on the Reliability for Nuclear Power Plant (1989).
- (10) Asada, Y. et al., Leak-Before-Break Verification Test and Evaluations of Crack Growth and Fracture Criterion for Carbon Steel Piping, *International Journal of Pressure Vessel and Piping*, Vol. 43 (1990), pp. 379-397.
- (11) Milne, I. et al., Assessment of the Integrity of Structures Containing Defects, CEGB R/H/R6 -Revision 3 (1987).