Probabilistic Fracture Analysis of Carbon Steel Pipe for LWR Piping

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ABSTRACT

Probabilistic fracture mechanics analysis of carbon steel pipe for light water reactor piping was performed. Effects of influential factors were also investigated. The results showed that those factors, excepting the factors concerning initial crack size distributions, produce little influence on failure probability.

1 INTRODUCTION

Applicability of leak-before-break design to Japanese light water reactor pipings are energetically investigated. For this purpose, several research activities have been carried out by several Japanese investigators. Through their activities include various tests and analyses, proper models which predict pipe failure behaviors simply and conservatively have been proposed. Combining these models with some assumption of initial crack, proper evaluation procedure which assesses piping reliability shall be established.

This paper describes probabilistic fracture mechanics analysis of carbon steel pipe for light water reactor piping employing:

(1) Japanese proposed models for deterministic leak-before-break evaluations
(2) Probabilistic fracture mechanics evaluation method employed in the analyses of American ferritic steel pipes by LLNL (Lo, T. Y., 1986)

Effects of influential factors were also investigated in order to provide information on accuracy of the analysis.

2 EVALUATED PIPE

Carbon steel pipe 26B/S80 was analyzed in this study. The specifications of the pipe are shown in Table 1. The weldment which joints SFVC2B and STS49 is assumed to be contained in this pipe. One initial crack is postulated at the severest loaded point in this weldment.

The mechanical properties of the two materials are shown in Table 2. These are conservative values for design given in Japanese design standard (MITI, Notice No. 501). In this analysis, the properties of SFVC2B are used for the standard conditions (Case S) because the average of the design yield stress, S_y, and the design tensile strength, S_u, is lower than that of STS49.

The properties of STS49 also used for one of the reference cases (Case R1). The reference cases and the parameters for sensitivity study are shown in Table 3.

3 FAILURE EVALUATION MODELS

3.1 Postulated crack

A circumferential surface crack shown in Fig. 1-(a) is postulated on the inner surface of the pipe. After crack depth, a, exceeds pipe wall thickness, t, the crack is treated as a through-wall crack shown in Fig. 1-(b).

Both a and aspect ratio, β, of the initial crack are assumed to be random variables. The probability density function of a is as follows:

$$p_A(a) = \frac{1}{\mu} \cdot \frac{\exp(-\frac{a}{\mu})}{1-\exp(-\frac{t}{\mu})} \qquad (1)$$

where μ is the expectation of a if t is positive infinite. The probabilistic density function of β is as follows:

$$p_B(\beta) = \frac{C_\beta}{\beta\lambda\sqrt{2\pi}} \cdot \exp\left[-\frac{\{\ln(\frac{\beta}{\beta_m})\}^2}{2\lambda^2}\right] \qquad (2)$$

where λ is the standard deviation of $\ln(\beta)$; β_m is the expectation of β. C_β is the coefficient for range of β between 0 and 1. Both Eq. (1) and Eq. (2) were used in the analyses by LLNL. The mean values of μ, λ and β_m are given in Table 4.

3.2 Inspections

The weldment is assumed to be inspected before the plant operation and detected cracks must be repaired (PSI). The probability of missing crack is evaluated by equations employed in the analyses by LLNL.

In this analysis, neither in-service inspections (ISI) nor hydrostatic proof tests are assumed to obtain conservative failure probability.

In one of the reference cases (Case R2), PSI is not assumed.

3.3 Crack growth law

The postulated crack is assumed to grow by fatigue only. The following bilinear curve is employed for the crack growth law:

$$\left(\frac{da}{dN}\right) = \begin{cases} C_1\Delta K^{m_1} & (\ \Delta K \le \Delta K_{tr}\ ) \\ C_2\Delta K^{m_2} & (\ \Delta K > \Delta K_{tr}\ ) \end{cases} \qquad (3)$$

where ΔK is the stress intensity factor range in MPa$\sqrt{m}$; (da/dN) is crack growth rate in mm/cycle; and ΔK_{tr} is the stress intensity factor range at the intersection of the two lines. The mean values of the constants C_1, C_2, m_1 and m_2 (in Table 3) are determined to correspond to the upper bound curve of reference crack growth law for ferritic steels in water of ASME code section XI (ASME, 1983).

For surface cracks, the stress intensity factors are calculated by equation for plates of Newman and Raju (Newman, J. C. and Raju, I. S., 1984). For through-wall cracks, they are calculated by equation for pipes of Tada and Paris (Tada, H., et al, 1985).

Cyclic stress diagram in Fig. 2 is employed for fatigue crack growth evaluations. The diagram is conservatively prepared assuming design load events for the piping.

3.4 Failure criterion

G-factor approach based on plastic collapse criterion is employed as failure criterion (Asada, et al, 1989). In the G-factor approach, the maximum moment, M_{max}, which causes unstable fracture is evaluated by dividing the limit moment, M_L, by the G-factor, G:

$$M_{max} = \frac{M_L}{G} \tag{4}$$

where M_L is evaluated by assuming constant tensile stress, σ_m, which corresponds to the applied tensile load. G is experimentally evaluated as follows:

$$G = \begin{cases} 1 & (2 \le D < 6) \\ (0.692 - 0.0115D) + (0.188 + 0.0104D)\cdot \log_{10}\theta & (6 < D \le 30) \end{cases} \tag{5}$$

where D is the averaged pipe diameter in inches. If the applied moment exceeds M_{max}, the crack is assumed to cause failure (unstable fracture).

The maximum applied loads for the failure evaluation are given as follows:

$$\sigma_m = S_t \times S_m, \quad \sigma_b = S_b \times S_m$$

where S_m is the design stress intensity in Table 2. The mean values of the multipliers S_t and S_b, which are given in Table 4, are determined to be severe including severe seismic loads.

The deterministic value of the flow stress, σ_{fl}, is assumed to be correspond to the average of S_y and S_u in the standard conditions.

Uncertainty of σ_{fl} is taken into consideration in one of the reference cases (Case R3). In the case, the distribution of σ_{fl} is assumed to be normal distribution. And the expectation of σ_{fl} is assumed to be $1.17(S_y+S_u)/2$, the coefficient of variation to be 4.8%.

3.5 Leak rate and leak detections

The crack causes sufficient leakage to be detected is assumed to be repaired. In this analysis, leakage exceeds 3 gpm (gallon/min) is assumed to be detectectable corresponding to the analyses by LLNL.

The evaluation models for leak rate evaluations are corresponded to the models employed in deterministic analysis by Hasegawa (Hasegawa, et al, 1989).

In the reference case (Case R4), leak monitor is assumed to be excluded. If the operation life is "very long", failure probability in this case may be very high (maybe nearly 1). The term of "very long" will be discussed later.

4 RESULTS AND DISCUSSION

4.1 Effects of the change of conditions

Conditional failure probability, P_f (under condition of one crack existence), for each case during double the plant operation life of 40 years are shown in Fig.3. The figure shows that the effects of the changes of conditions on failure probability are little excepting the case of "without PSI".

The effect of excluding leak monitor is unvisibe in this figure. Therefore the term of "very long" is thought to be much longer than (more than double) usual plant operation life.

4.2 Sensitivity indexes

Sensitivity index of the i-th input parameter, X_i, is evaluated by the following equation:

$$\alpha_i = \left(\frac{\partial P_f}{\partial X_i}\right) \cdot \left(\frac{\bar{X}_i}{\bar{P}_f}\right) \tag{6}$$

where $\bar{P}_f$ is the failure probability due to the mean values of the parameters. The uncertain bound of failure probability, V_{P_f}, is approximately estimated using the values of α_i as follows:

$$V_{P_f}{}^2 \approx \sum_{i=1}^{n} \alpha_i{}^2 V_{X_i}{}^2 \tag{7}$$

where V_{X_i} is the uncertainty bound of X_i.

The values of α_i obtained in the sensitivity study are shown in Table 4. From Table 4, the parameters concern initial crack size distributions, μ, λ and β_m are thoug ıt to be important. However uncertainties of the other parameters may produce little influence on failure probability.

5 CONCLUSIONS

A probabilistic analysis of a carbon steel pipe for light water reactor piping was performed. The sensitivities of input parameters and the effects of changes of conditions were also investigated. Major conclusions are as follows:

(1) The effects of input parameters on failure probability are little compared with parameters concerning initial crack size distributions.
(2) The effect of excluding leak monitor is invisible within double of the usual plant operation life.

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Table 1 Specificataions of analysed pipe (26B/S80)

Material	SFVC2B/STS49
Outer Diameter D_{out} (mm)	660.4
Thickness t (mm)	33.3

Table 2 Mechanical properties of pipe materials at 300°C

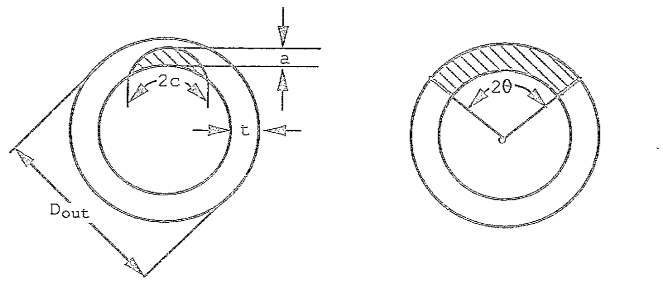
Material	Design stress intensity Sm (MPa)	Design yield strength Sy (MPa)	Design ultimate strength Su (MPa)	Young's modulus E (GPa)
SFVC2B	122.5	183.3	438.1	178.4
STS49	139.2	233.2	438.1	178.4

Table 3 Parameters for sensitivity study

Item	Standard conditions	Conditions for reference cases	Parameter for sensitivity analyses
Mechanical properties	SFVC2B	STS49 (Case R1)	——
Initial crack depth distribution	Eq. (1)	(same as left)	μ
Initial crack aspect ratio distribution	Eq. (2)	(same as left)	β_m , λ
Pre-service inspection	Equations of LLNL	Without PSI (Case R2)	——
Crack growth law	Eq. (7)	(same as left)	C_1, C_2, m_1, m_2
Loads for failure evaluations	$\sigma_m = S_t \times S_m$ $\sigma_b = S_b \times S_m$	(same as left)	S_t , S_b
Flow stress	$\sigma_{f1} = \dfrac{S_y+S_u}{2}$	Distributed flow stress (Case R3) $E[\sigma_{f1}]=1.17\times\{\dfrac{S_y+S_u}{2}\}$ $\dfrac{\sqrt{Var[\sigma_{f1}]}}{E[\sigma_{f1}]} = 0.048$ [Normal distribution]	Deterministic value of σ_{f1}
Leak detection	3 gpm is detectable	Without leak monitor (Case R4)	——

Table 4 Sensitivity indexes obtained in the analysis

Plant operation time (years)			10	20	30	40	80
Failure probability by standard conditions $\bar{P}_f$			1.6×10^{-7}	3.2×10^{-7}	3.6×10^{-7}	4.0×10^{-7}	4.0×10^{-7}
Parameter		Mean value $\bar{X}_i$	Sensitivity index α_i				
Inital crack size	μ	6.248 mm	4.2	4.2	4.1	4.1	4.1
	β_m	0.749	1.6	1.4	1.8	1.8	1.8
	λ	0.534	0.71	0.12	0.37	0.27	0.28
Crack growth law	C_1	1.75×10^{-10}	0.094	0.073	0.091	0.13	0.13
	C_2	5.34×10^{-6}	1.1	0.57	0.40	0.26	0.24
	m_1	5.95	1.15	0.73	0.96	1.8	1.8
	m_2	1.95	8.3	2.6	0.040	-0.78	-3.3
Failure criterion	S_t	0.34	0.12	0.070	0.062	0.058	0.055
	S_b	1.3	0.42	0.24	0.22	0.20	0.20
	σ_{f1}	310.7 MPa	-0.64	-0.37	-0.33	-0.27	-0.30



(a) Part-through crack (b) Through-wall crack

Fig. 1 Configurations of postulated crack

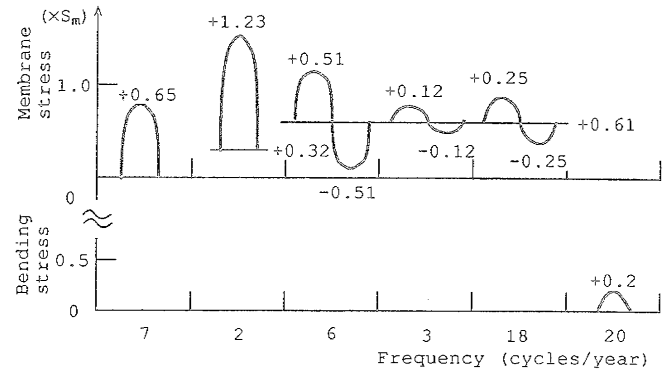


Fig. 2 Cyclic stress diagram for fatigue crack growth evaluations

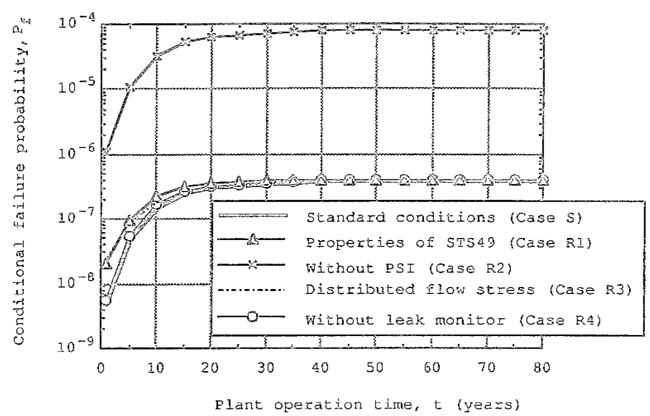


Fig. 3 Conditional failure probabilities of carbon steel pipe