Probabilistic Fracture Mechanics Analysis for Pipe Considering Dispersion of Seismic Loading

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ABSTRACT

Studies on probabilistic fracture mechanics, PFM, have been performed for the quantitative integrity assessment for the pipes, which are used in nuclear power plants. The seismic load is one of the dominant loads in the failure assessment of the pipes. Its probabilistic variation, however, was not taken into account in the past PFM analysis. Authors have been developed PFM analysis code, which accommodates the variation of the seismic loading. This paper describes the outlook of the code and the results of the parametric failure assessment of the pipe.

1. INTRODUCTION

Design and structural integrity evaluation of the components of nuclear power plant are performed using deterministic evaluation method. In this evaluation, the result includes excessive margin, because the safety factors are taken into account for every evaluation process, and that causes increase of plant construction cost. The probabilistic evaluation method is one of the candidates to reduce the excessive margin. For example, in the probabilistic structural integrity evaluation, the dominant factors concerning with failure are expressed by mathematical models, taking into account the variation, and the failure probability is calculated. The structural integrity is assessed by comparison of this failure probability and its limitation. The fracture mechanics, in which the probabilistic technique is applied, is called 'probabilistic fracture mechanics', PFM. In PFM, the crack size, material strength, crack growth rate and so on are expressed using probabilistic models, and the leak and break probabilities are calculated. Generally, the loads, which cause break of pipe, are internal pressure, dead weight, thermal expansion and seismic load. The seismic loading has much effect on break probability, because the variation of it is relatively large. This paper describes the results of the study on modeling of seismic load, improvement of PFM code and parametric failure assessment of the pipe by the code.

2. MODELING OF SEISMIC LOADING

2.1 SEISMIC LOAD

The variation of seismic load for the pipe can be classified roughly to two parts. One is the variation of amplitude and frequency of the earthquake acting to the nuclear plant building. These variations are estimated using the seismic hazard curve. Another is the variation of the stress of the pipe, which is caused from the variation of seismic analysis model, material properties, etc. of the building and piping. The variation of the stress is expressed using log-normal distribution, referring past study on seismic response of components in the nuclear power building [1]. These variation models for the earthquake and the stress of the pipe have been integrated into the original PFM code.

2.2 ANALYTICAL CODE

Inelastic PFM code, PFMAC, is applied for this study. PFMAC has been developed in ARTECH (Advanced Reactor Technology Co., Ltd.). It has been improved to take into account the variation of the seismic stress and earthquake. The evaluation procedure of PFMAC is shown in Fig. 1. PFMAC uses stratified Monte Carlo method to reduce the calculation time. The input data options for PFMAC are summarized in Table 1.

3. PFM ANALYSIS

3.1 CONDITION FOR ANALYSIS

Main Steam Pipes of Japanese BWR have been chosen in this study. The portion for analysis is 26B-carbon steel pipe, which is 660.4 mm in diameter and 33.3 mm in thickness.

Material of the pipe is STS410 in JIS Standard. The material properties at 300°C, which are shown in Table 2, are used in this study.

Crack growth loads are summarized in Table 3. These loads have been estimated using the design loads of the BWR plants. S1 and S2 earthquake load is not included for crack growth load.

Fracture mechanics parameter used in the crack growth evaluation is stress intensity factor, which was proposed by Raju and Newman [8]. Crack growth rate is calculated based on the following Paris's law [9].

$$\frac{da}{dn} (m/cycle) = 1.738 \times 10^{-13} \Delta K^{5.95} \quad (\Delta K < 13.2 \text{ MPa}\sqrt{m}) \quad (1)$$

$$\frac{da}{dn} (m/cycle) = 5.325 \times 10^{-9} \Delta K^{1.95} \quad (\Delta K \geq 13.2 \text{ MPa}\sqrt{m}) \quad (2)$$

When the crack depth is over 80% of the pipe thickness, the crack is judged as the penetrated crack. For the penetrated crack, the crack propagation analysis is not performed. If the penetrated crack is stable, its failure mode is judged as leakage, and if it is unstable, its failure mode is judged as break.

The loads shown in Table 3 are only applied for the crack growth analysis. On the other hand for crack stability assessment, the loads shown in Table 4 are applied. The amplitude

of the median of the seismic stress and frequency are decided using seismic hazard curve shown in Fig. 2. The seismic stress, S , is expressed by log-normal distribution as follows.

$$f(S) = \frac{1}{S \sigma \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{\ln(S) - \ln(\mu)}{\sigma} \right)^2 \right\} \quad (3)$$

$$\sigma = 0.95, \quad \mu = S_d \frac{400}{\alpha}, \quad S_d = 11.6 \text{ MPa}$$

where S_d is the seismic stress at S2 earthquake calculated using the deterministic evaluation method, μ is the median of the seismic stress and α is ground acceleration. The ground acceleration of S2 earthquake is assumed 400 gal.

The net-section criterion adopting G factor [10], which is the modification factor considering the effect of tearing instability, is applied to crack stability assessment. The crack stability assessment is performed before crack penetration assessment.

The critical moment, M_{cr} , is given as follows.

$$M_{cr} = M_0 / G \quad (4)$$

$$M_0 = 2 R^2 t \sigma_f (2 - a/t) \sin \beta$$

$$\beta \leq \pi - \theta$$

$$\beta > \pi - \theta$$

$$\beta = \frac{1}{2} \left(\pi - \frac{a}{t} \theta - \frac{P_m}{\sigma_f} \pi \right)$$

$$\beta = \frac{\pi}{2 - a/t} \left(1 - \frac{a}{t} - \frac{P_m}{\sigma_f} \right)$$

$$G = 1$$

$$2 \leq D < 6$$

$$G = 0.692 - \frac{0.0115}{25.4} D + \left(0.188 + \frac{0.0104}{25.4} D \right) \log \left(\frac{\pi}{180} \theta \right)$$

$$6 \leq D \leq 30$$

M_0 : Critical moment calculated using net-section criterion [11]

G : G-factor

σ_f : Flow stress

a : Crack depth

t : Pipe thickness

D : Pipe diameter

θ : Crack angle (rad.)

β : Fully plastic neutral axis angle (rad.)

P_m : Primary membrane stress due to internal pressure

Pre-service inspection, PSI, is taken into account in this analysis. Non-detection probability is given by the following equation [5].

$$P_{ND} = \frac{1}{2} (1 - \varepsilon) \left\{ 1 - \frac{2}{\sqrt{\pi}} \int_0^{\sqrt{\ln(A/A^*)}} e^{-t^2} dt \right\} + \varepsilon \quad (5)$$

$$A = \begin{cases} \frac{\pi}{2} ac & (2c \leq D_B) \\ \frac{\pi}{4} a D_B & (2c > D_B) \end{cases}$$

$$A^* = \frac{\pi}{4} a^* D_B$$

$$\varepsilon = 0.005, \quad D_B = 25.4 \text{ mm}, \quad V = 1.33, \quad a^* = 6.35 \text{ mm}$$

3.2 PARAMETER FOR ANALYSIS

Parameters for analysis are summarized in Table 5. In the reference case, the seismic load is not taken into account. In Case-A, the variation of seismic stress, expresses by Equation (3), is taken into account, and the ground acceleration of 400 gal is applied continuously. In Case-B, the seismic hazard curve of "Tohoku" [12] shown in Fig.2 is used. The variation of the median of seismic stress is estimated as shown in Fig. 3. In Case-C, the effect of seismic hazard curve difference is evaluated. Seismic hazard curves for "Tsuruga", "Mito" and "Kakegawa" [13] shown in Fig. 2 and Fig. 3 are used. In Case-D, the effect of median stress is evaluated. Crack propagation due to seismic load is not taken into account aforementioned reference case and Case-A to Case-D. In Case-E, 300 cycles of seismic load per each earthquake is applied as the crack growth evaluation. The crack growth load is equal to the median of the stress for the crack stability assessment.

3.3 RESULT OF ANALYSIS

Figure 4 shows the results of reference case and Case-A. The break probability of Case-A increases with operational time and it is six figures larger than that of reference case after 80 years operation. This difference is caused by ignoring the frequency of the earthquake. It is necessary to consider both of variation of seismic stress and frequency of earthquake.

The results of Case-B are shown in Fig. 5. In the case, taking into account the variation of seismic stress and the frequency of earthquake, the break probability increases with operational time. The cumulative probability of break is two figures larger than the reference case after 80 years operation. This trend is quite different from the case without seismic load, whose break probability does not increase after around 10 years.

The comparison of break probability using the seismic hazard curves for "Tohoku", "Tsuruga", "Mito" and "Kakegawa" is summarized in Fig. 6. Generally, the hazard, whose probability of occurrence is high, gives high probability of break. The region of extreme low and high ground acceleration of seismic hazard curve shown in Fig. 2 is not much effective for failure probability. Because the failure of pipe does not occur due to low seismic load and high acceleration has low probability of occurrence. The break probability, therefore, is sensitive to the amplitude of seismic acceleration, whose probability of occurrence is around $10^{-2} \sim 10^{-3}$ per year.

The break probability for the case that the median of the seismic stress are 2/3 and 4/3 times of the reference case ($\mu=11.6\text{Mpa}$), is shown in Fig. 7. The probability of occurrence remarkably changes as the seismic load increases and it causes the deference of break probability.

Deference for the seismic load cycle per earthquake is shown in Fig. 8. The variation of crack growth load is not considered in this analysis. This figure shows that the seismic load has little effect for crack growth.

4. CONCLUSION

The probabilistic fracture mechanics code, which can take into account the variation of

seismic loading and its frequency, is established. Using this analysis code, the effects of earthquake are assessed. The variation of seismic stress and amplitude and frequency of earthquake have much effect for the break probability, but not for the leak probability. The assumption of seismic hazard curve and variation of the stress due to earthquake, therefore, are important matter for the PFM analysis.

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Table 1 Options for input data of PFMAC code

Input quantity	Options
Crack depth	Log-normal, exponential
Aspect ratio	Log-normal, exponential
Exponent of crack growth rate	Uniform, log-normal
Flow stress	Uniform, normal
Non-detection probability of PSI and ISI	Nakatsujii[2], Marshal[3], PISC[4], LLNL[5], PNL[6, 7]
Crack stability assessment	Net-section criterion, G-factor, Hp-factor
Fracture Mechanics Parameter	ΔK , ΔK_{eff} , ΔJ , $\Delta J'$
ISI period	User option
Amplitude of stress for crack growth evaluation	Uniform
Frequency of stress for crack growth evaluation	Uniform, Poisson
Amplitude of stress for crack stability evaluation	Uniform, normal, log-normal, exponential
Frequency of stress for crack stability evaluation	Uniform, Poisson

Table 2 Material constant of pipe

Material	STS 410
Operation temperature	300 °C
Design stress intensity	122.6 MPa
Design yield strength	183.4 MPa
Design ultimate strength	404.0 MPa
Flow Stress	293.7 MPa
Young's Modulus	178.5 GPa
Poisson's ratio	0.3

Table 3 Crack growth loads w/o seismic load

Frequency (cycles/year)	Membrane Stress (MPa)		Bending Stress (MPa)	
	Min.	Max.	Min.	Max.
7	0	122.6	0	0
18	49.0	183.9	0	0
320	92.0	122.6	0	0
8	0	0	-122.6	122.6
16	0	0	-61.3	61.3
330	0	0	-12.3	12.3

Table 4 Crack stability assessment loads w/o seismic load

	Stress (MPa)
Membrane Stress	61.3
Bending Stress (M/Z)	91.1

Table 5 Parameter for analysis

	Crack Growth Load	Variation of Seismic Stress	Variation of Earthquake	Hazard Curve
Ref.	Table 3	w/o earthquake	w/o earthquake	—
Case-A	Table 3	Eq.(3)	400gal(const.)	—
Case-B	Table 3	Eq.(3)	Fig. 2 ¹⁾	Tohoku
Case-C1	Table 3	Eq.(3)	Fig. 2 ¹⁾	Tsuruga
Case-C2	Table 3	Eq.(3)	Fig. 2 ¹⁾	Mito
Case-C3	Table 3	Eq.(3)	Fig. 2 ¹⁾	Kakegawa
Case-D1	Table 3	2/3 of Case-B	Fig. 2 ¹⁾	Tohoku
Case-D2	Table 3	4/3 of Case-B	Fig. 2 ¹⁾	Tohoku
Case-E	Table 3 & 300 cycles of seismic load / earthquake	Eq.(3)	Fig. 2 ¹⁾	Tohoku

1) : Relationship between ground acceleration and frequency is defined by hazard curve.

Fig. 1 Calculation flowchart of PFMAC

Fig. 2 Seismic hazard curves

Fig. 3 Probabilistic distribution of seismic stress

Fig. 4 Failure probability considering variation of seismic stress

Fig. 5 Failure probability considering variation of seismic stress and earthquake

Fig. 6 Effect of difference of seismic hazard curve

Fig. 7 Effect of median of stress due to seismic load

Fig. 8 Effect of seismic load to crack growth