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Benchmark analysis on probabilistic fracture mechanics analysis codes concerning fatigue crack growth in aged piping of nuclear power plants

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ABSTRACT

Probabilistic fracture mechanics (PFM) is a rational methodology in structural integrity evaluation and risk assessment of aged piping in nuclear power plants. Several PFM analysis codes have been improved or developed in Japan, such as PRAISE-JNES and PASCAL-SP. Although they were developed for different purposes, some basic functions are almost the same. In this paper, in order to confirm the reliability and applicability of two PFM analysis codes, PRAISE-JNES and PASCAL-SP, a benchmark analysis is carried out using the basic functions in these two codes, considering representative piping systems in nuclear power plants and fatigue as the typical aging mechanisms. We discussed the reliability and applicability of these codes based on a previously proposed criterion to judge quantitatively whether the differences between the analysis results from two PFM analysis codes can be acceptable. Through the benchmark analysis, it is concluded that the analysis results of these two codes are in good agreements quantitatively.

1. Introduction

About one third of nuclear power plants in Japan have been operated more than 30 years and flaws have been detected in some piping systems these years. Therefore, the structural integrity evaluation and risk assessment of the aged piping have been more and more important. Probabilistic fracture mechanics (PFM) is recognized as a rational methodology to evaluate the structural integrity and to assess the risk of aged piping because the probabilistic distributions of influence parameters, such as material properties, initial crack sizes, crack growth rates, crack detection, can be taken into account. Several PFM analysis codes for aged piping have been developed in Japan: one is PRAISE-JNES [1,2] which was improved at JNES (Japan Nuclear Energy Safety Organization) based on the pc-PRAISE [3], and another is PASCAL-SP [4–6] which has been developed at JAEA (Japan Atomic Energy Agency). Although these codes were developed for different purposes, both have same basic functions on failure probability analyses of piping. The reliability and applicability of the PFM analysis codes should be confirmed to apply to a practical matter. However, for a probabilistic analysis code, the standard method for verification and validation (V&V) has not been established yet. In particular, the validation is very difficult to do in a practical way.

In developing the both PFM analysis codes, we have carried out the verification for each probabilistic model carefully, for example scatter of crack growth rate is compared with the experimental data, and so on. However, it is hard to say that analysis results of the PFM analysis codes such as the failure probabilities are validated quantitatively. This is because actual components are considered to have few experiences of failure, and then the values of failure probabilities can be very low. Therefore, it is difficult to compare the numerical solutions with experimental results or examination results. In this context, a benchmark analysis is widely used as an effective method to verify the reliability and accuracy of PFM analysis codes. Several benchmark analyses were carried out for PFM analysis codes [7–9]. International organizations also conducted the benchmark analyses for PFM analysis such as PROSIR in OECD/NEA for reactor pressure vessel integrity, NURBIM in EURATOM for nuclear piping integrity [10], so on. Through those benchmark analyses, analysis results were compared and discussed on some differences. However, a quantitative assessment of the results related to the reliability was not seen.

We have been planning benchmark analyses for PFM analysis codes related to nuclear piping based on a quantitative assessment methodology in order to confirm the reliability and applicability of

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PFM analysis codes. In a previous paper, we conducted a benchmark analysis on an SCC at piping weld, and proposed a criterion to judge whether the differences between analysis results from multiple codes are acceptable [11]. In this paper, as a next step of the benchmark analyses, a benchmark analysis is carried out for PRAISE-JNES and PASCAL-SP using their basic functions. Stainless and carbon steel piping in boiling water plant (BWR) are selected as the analysis example, and fatigue is considered as the typical aging mechanisms. Among input parameters, material properties and the amount of seismic stress are treated as major variables in the case studies. Analysis results on the pipe failure probabilities are compared as a function of operation years. To judge quantitatively whether the difference between the analysis results of the two codes is small enough, the acceptance criterion proposed previously is re-evaluated.

2. PFM analytical codes for benchmark analysis

PRAISE-JNES and PASCAL-SP were used in this benchmark analysis. They were developed to evaluate failure probabilities of aged piping by Monte Carlo methods. Although these codes were developed for different purposes, both have same basic functions on failure probability analysis of piping. Both conform to approaches of Nuclear and Industrial Safety Agency of Japan (NISA) and Codes for Nuclear Power Generation Facilities – Rules on Fitness-for-Service for Nuclear Power Plants – of the Japan Society of Mechanical Engineers (JSME FFS) [12].

PRAISE-JNES and PASCAL-SP have a function of random sampling method based on the stratified Monte Carlo method that consider the weight of probabilistic variables. In both, after sampling of random variables for initial analysis condition with regard to the scatter and uncertainties, plant operation situations including some events such as transient, earthquake and inspection are simulated. During the plant operation, flaw initiation and growth due to SCC (Stress Corrosion Cracking) and fatigue flaw growth caused by seismic stress and transient events are considered. The procedures above are repeated many times to evaluate failure probabilities based on Monte Carlo methods. The purpose and characteristics of each code are as follows.

In this paper, a benchmark analysis is conducted using the nearly identical functions of these two codes. The analysis models or methods such as initial crack size, crack growth rate, failure evaluation or flaw stress of material used in the benchmark analysis will be described in the next chapter in detail. For more information on these codes such as details and differences, existing papers and manuals will provide further details [1,2,4–6,11,13].

2.1. PRAISE-JNES code

PRAISE-JNES [1,2] has been mainly improved to evaluate seismic margin of aged components and provide information of fragilities for seismic PSA (Probabilistic Safety Assessment) or seismic risk assessment related to severe earthquake. Fig. 1 shows evaluation flowchart of PRAISE-JNES. Several analysis models are included considering the response of piping to seismic motion, its uncertainty and the crack growth due to seismic stress. The probabilistic model evaluating realistic seismic capacity which is an important variable in seismic PSA is introduced for aged piping.

2.2. PASCAL-SP code

PASCAL-SP [4–6] has been developed at JAEA as the Japanese original code. The development of the code has been aimed to improve the accuracy and reliability of PFM analysis by introducing new analysis methodologies and algorithms considering the recent development in the fracture mechanics methodologies and computer performance. Fig. 2 shows evaluation flowchart of PASCAL-SP. For the important driving force of SCC, the probabilistic model evaluating residual stress is considered. Parametric finite element method (FEM) analyses varying welding conditions based on experiments of welded pipe joint were conducted [14]. The FEM analyses brought the databases of residual stress distribution including average and scatter values at each point near the piping welds. The probabilistic model where the residual stress at a point is determined by fitting by the least square method using the databases is introduced [15].

3. Benchmark analysis

Some benchmark analysis results on the SCC have already been presented in the previous papers [11,13]. In this study, therefore, the fatigue crack growth is considered as the typical aging mechanisms. As described above, stainless and carbon steel piping in BWR are selected as the representative analysis example. Initial crack size, crack growth rate and flaw stress of material which may have large and direct influences on the failure probability values are taken as probabilistic parameters. Analysis conditions of benchmark analyses are listed as follows.

3.1. Analysis model of crack

A crack initiated via a fatigue mechanism is postulated in the early stages of plant operating. The log-normally distribution of initial crack size at stainless and carbon steel piping is employed. For the crack depth a, the log-normal distribution proposed [16] is expressed as follows:

$$f(a) = \frac{1}{\sqrt{2\pi}a\sigma_a}\exp\left(-\frac{1}{2}\left(\frac{\ln(a/\mu_a)}{\sigma_a}\right)^2\right)$$
$$\mu_a = 0.294\ \text{mm},\ \ \sigma_a = 1.61 \tag{1}$$

where, μ_a is the mean value, σ_a is the standard deviation of crack depth distribution.

For the crack aspect ratio, the log-normal distribution is shown as follows:

$$f(\beta) = \frac{C}{\sqrt{2\pi}\sigma\beta}\exp\left(-\frac{1}{2}\left(\frac{\ln(\beta/\mu)}{\sigma}\right)^2\right)$$
$$\beta = b/a \tag{2}$$
$$\mu = 1.336,\ \ \sigma = 0.538,\ \ C = 1.142$$

where, b is the crack half length, a is the crack depth, β is the crack aspect ratio, μ is the mean value, σ is the standard deviation of crack aspect ratio.

3.2. Crack growth rate

Based on the data provided in JSME FFS rules [12], we have also obtained a probabilistic model of the crack growth rate due to fatigue. For stainless steel used in the BWR water environment, the fatigue crack growth rate with the unit of m/cycle can be expressed as follows:

$$\frac{da}{dN} = \frac{C_f \cdot t_r^{0.5} \cdot \Delta K^{3.0}}{(1-R)^{2.12}} \tag{3}$$

where ΔK is the stress intensity factor range, R is the stress ratio, C_f is evaluated as a probabilistic variable following the log-normal distribution. The median value of C_f is 1.59×10^{-12} and the standard deviation of $\ln(C_f)$ is 0.355. t_r is defined as the load increasing