A Comparison of PFM Codes for Analyzing Structural Reliability of Components

Md Nasimul Goni[a], Seung Hyun Kim[a], Yoon-Suk Chang[a,*], Changheui Jang[b]
[a]*Dept. of Nuclear Engineering, Kyung Hee University, 1732 Deokyoungdae-ro, Yongin, Kyunggi, Korea*
[b] *Dept. of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Deahak-ro, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: yschang@khu.ac.kr*

1. Introduction

Most of the nuclear power plants have been operating more than 30 years and during this time some flaws have been detected with in some of these plants piping systems. In this situation, structural reliability evaluation and risk assessment of such aged piping have become increasingly important. Probabilistic fracture mechanics (PFM) is recognized as a rational methodology for evaluating structural reliability and assessing the risk of aged piping because it can take the influence parameters into consideration with their inherent probabilistic distributions.

In this study, we conducted an analysis on computer code pc-PRAISE (Piping Reliability Analysis Including Seismic Events)[1] and PINTIN (Piping INTegrity INner flaws)[2] using their basic functions to verify their reliability and applicability to the failure probability analysis of aged nuclear piping.

2. Probabilistic Fracture Mechanics Model

2.1 Crack initiation

The shape of the surface crack initiated due to SCC is considered to be semi-elliptical and the crack is assumed to be oriented in circumferential direction. In the presence of bending stresses this will give the worst case. Geometry of initiated crack is as shown in Fig. 1. The length of initiated cracks is assumed to be lognormal distributed with a median value (50th percentile value) of 3.225 mm and standard deviation of 0.85. Depth of the initiated crack is taken to be 0.0254 mm[3].

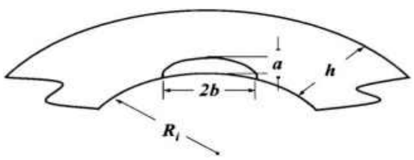

Fig. 1. Geometry of the part-through circumferential crack[1]

2.2 Crack growth

Fatigue crack growth can be expressed as;

$$\frac{da}{dN} = F(\Delta K, R) \quad (1)$$

where a is crack size, N is number of fatigue cycles, $\Delta K = K_{max} - K_{min}$ and $R = K_{max}/K_{min}$, F is some general function of ΔK and R[1].

Crack growth in codes is generally calculated on a cycle by cycle bases or a group of n identical cycle. The crack size is given by;

$$a_{after} = a_{before} + NF(\Delta K_a, R_a) \quad (2)$$

Stress corrosion crack growth is time, rather than cycle, dependent. For a one degree of freedom crack, the crack growth rate can be expressed as;

$$\frac{da}{dt} = G(K) \quad (3)$$

This is generalized to multi-degree-of-freedom cracks, and the stress intensity factor is evaluated at the beginning of a time step. The crack size after a time step is given by;

$$a_{after} = a_{before} + G(\Delta K_a)\Delta t_s \quad (4)$$

where t_s is a time step defined by the user that is often taken to be 0.1 year, and *da/dt* is the growth rate in the depth direction at the beginning of the time step.

Crack growth under fatigue and stress corrosion cracking conditions is treated within pc-PRAISE as simply the sum of the fatigue contribution and the stress corrosion cracking contribution[1,4].

The timing and magnitude of seismic events to be considered are specified by the user. Crack growth is modeled for each seismic event, using the crack size existing before the event. After the seismic event, the crack size is returned to its size before the event. Both pc-PAISE and PINTIN can analyze the effects of seismic events only for materials that follow the growth law;

$$\frac{da}{dN} = c\left[\frac{\Delta k}{(1-R)^{1/2}}\right]^m \quad (5)$$

$$\rightarrow \sum_{i=1}^{N}[\sigma_{max,i}(\sigma_{max,i} - \sigma_{min,i})]^{m/2} = N[(\sigma_{NO} + \Delta\sigma)\Delta\sigma]^{m/2}$$

2.3 Leak detection

A defect that grows to become a through-wall crack leads to a leak. The probability of detecting a leak depends on its size, and pc-PRAISE considers leak to be non-detectable and leaks above that value to be detectable with a probability of unity. So, the equation for the leak rate estimates is

$$\delta = \frac{4\sigma b(1-\nu^2)}{E}$$
$$\frac{\dot{Q}h^{1/2}}{2b} = \begin{cases} 0.25\delta^2 & \delta \le 2 \text{ mils} \\ 0.9375\delta - 0.875 & \delta > 2 \text{ mils} \end{cases} \quad (6)$$

where δ is total crack opening displacement, h is pipe wall thickness, $2b$ is through wall thickness and Q is leak rate(where flow rate is gallon per minute at PWR condition)

2.4 Monte Carlo simulation

Both computer codes of the pc-PRAISE and PINTIN use Monte Carlo simulation techniques to estimate the cumulative distribution of time to first failure for a girth butt in nuclear piping hat is subjected to normal operating conditions, anticipated transients, and seismic events of various magnitudes. The basic equation in the simulation is

$$P(t_F \le t) = \sum_{m=1}^{M} \frac{N_{F,m}(t)}{N_m} P_m \quad (7)$$

where, M is total number cells, N_m is number of samples from m-th cell, P_m is probability of an initial defect having coordinates within the boundaries of m-th cell.

3. Analysis of Pipe Probability

3.1. Analysis conditions

A typical nuclear pipe was analyzed by pc-PRAISE and PINTIN. Table I and Table II summarize analysis conditions and cases.

Table I Analysis conditions[1]

Operating conditions	
Deadweight	14.34 MPa
Deadweight +Thermal expansion	59.16 MPa
Operation pressure	15.51 MPa
Plant life time	40 years
Fatigue crack growth properties for 304SS	
Fatigue constant, C	9.14×10^{-12}
Fatigue exponent, n	4.0
Initial crack size distributions	
Depth distribution	Exponential
Aspect ratio distribution	Lognormal
Water chemistry and conditions that affect SCC	
Oxygen at plant start-up	0.05 ppm
Duration of plant heat-up	5 hrs
Coolant conductivity	0.2 μs/cm

Table II Analysis cases for crack growth mechanism

Case	Crack growth
1	Fatigue
2	Fatigue + Seismic
3	Fatigue + SCC

3.2. Results of probability

By running with the above conditions in use of these two computer programming PFM codes, we can see that, in 3 cases the probabilities of leak are almost same in small leak, big leak and LOCA position. Fig. 2 indicates the probability of Case 2, representatively.

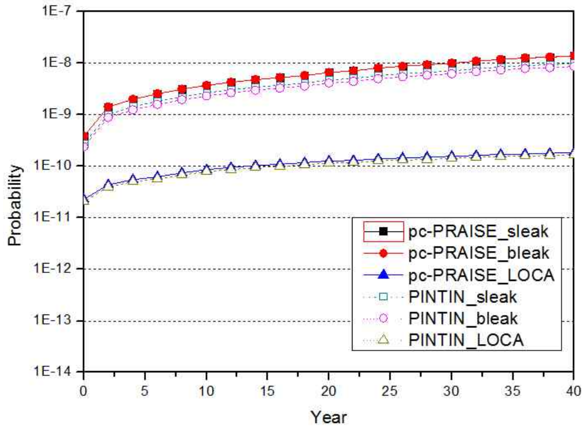

Fig. 2. Comparison of probability (Case 2)

4. Conclusion

For a reference nuclear pipe, the cumulative probabilities of leak were calculated using pc-PRAISE and PINTIN.

(1) In case of result with in PRAISE and PINTIN has no significant difference. However, there is some difference in the big Leak curve. pc-PRAISE includes LOCA in big leak.

(2) Influence of the seismic load and SCC is taking into account in the extreme situation. In case of seismic load, the probability of leaks through the cracks grows larger.

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