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A study on convergence using the probabilistic fracture mechanics code xLPR

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1. Introduction

The structural integrity of primary system piping in nuclear power plants has traditionally been assessed using deterministic methodologies based on the double-ended guillotine break (DEGB) assumption and the leak-before-break (LBB) concept. However, deterministic approaches have an inherent limitation in that they cannot explicitly quantify the uncertainties associated with material properties, weld residual stresses, flaw geometry, and crack initiation and growth behavior. Accordingly, risk-informed assessments based on probabilistic fracture mechanics (PFM), which quantify these uncertainties as random variables to directly calculate the probability of pipe rupture, have been actively studied by both regulatory bodies and industry in recent years.

The xLPR (Extremely Low Probability of Rupture) code, jointly developed by the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI), is a representative PFM analysis code reflecting this trend. xLPR evaluates the entire process of crack initiation, growth, through-wall penetration, and rupture caused by primary water stress corrosion cracking (PWSCC) and fatigue using probabilistic input variables, and it has been employed to estimate pipe rupture probabilities and loss-of-coolant accident (LOCA) frequencies.

Pipe rupture is a rare event with an extremely low probability of occurrence. If the number of samples is insufficient, no rupture may be observed among the realizations, resulting in a rupture probability estimated as zero and thus an underestimation of the actual risk. Therefore, for PFM analysis results to be accepted as a basis for regulatory decision-making, a convergence assessment is essential to demonstrate that the estimated probabilities converge stably with respect to the number of samples. This requirement is also specified in U.S. NRC Regulatory Guide 1.245 through indicators such as the stability of output statistics, sensitivity to sample size, and quantification of confidence intervals [1]. Nevertheless, research on concrete and standardized convergence acceptance criteria applicable to practical analyses remains limited.

In this study, prior to establishing a standardized convergence assessment method, probabilistic analysis results obtained using xLPR were compiled, and the number of samples required to achieve converged results was investigated.

2. Model

In this study, a probabilistic fracture mechanics assessment was performed for a dissimilar metal weld (DMW) in nuclear power plant piping. Since the detailed geometry and material property data of the target piping cannot be disclosed for security reasons, only the minimum information required for the analysis is presented in this paper. xLPR supports probabilistic analyses of straight pipe sections and is applicable to both similar and dissimilar metal welds

2.1 Surge Line

The analysis target is the pressurizer surge line of a nuclear power plant. The outer diameter of the pipe is approximately 13inch, and the dissimilar metal weld consists of a carbon steel nozzle and an austenitic stainless steel pipe joined with Alloy 82/182 weld metal. Primary water stress corrosion cracking (PWSCC) and fatigue were considered as the degradation mechanisms, and the plant operating period was assumed to be 80 years. Both axial and circumferential crack orientations were considered.

2.2 Material properties

The materials considered in the analysis are carbon steel, Alloy 82/182, and austenitic stainless steel, and their material properties were applied with reference to ASME Code Section II, Part D[2] and the xLPR Material Library.

2.3 Weld Residual Stress

In probabilistic fracture mechanics, the weld residual stress is reflected in the surface stress used for the crack initiation criterion and in the calculation of the stress intensity factor used for crack growth. Since it affects both crack initiation and growth, it is an important input

parameter governing the analysis results. In this study, the residual stress distribution of the Alloy 82/182 weld was applied based on the equations provided in ASME Code Case N-899 [3].

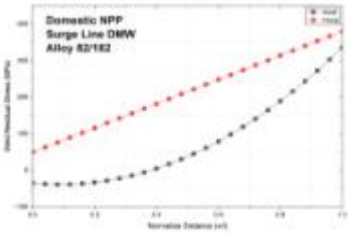


Figure .Distribution of weld residual stress for surge line

3. Probability of Rupture

The EPRI methodology [4] proposes an approach in which the probability of crack initiation and the probability of rupture in the presence of an initial flaw are evaluated separately and then combined; in Korea, Yoon et al. conducted a study utilizing this approach [5]. In this study, the same probabilistic calculation method from the previous studies was employed, and the rupture probability is calculated as shown in Equation (2). The calculated rupture probability was divided by the evaluation period (80 years) to convert it into an annual rupture frequency.

$$P(\text{Rupture}) = P(\text{Crack Initiation}) \times P(\text{Rupture} \mid \text{nitial Flaw}) \quad (2)$$

4. Results

Table 1 summarizes the crack initiation probability for the dissimilar metal weld without any initial flaw and the pipe rupture probability under the initial flaw condition, for both axial and circumferential cracks. For circumferential cracks, crack initiation was observed, but no rupture occurred in the analysis assuming an initial flaw. In contrast, for axial cracks, no crack initiation was observed, whereas the crack grew to rupture in the analysis assuming an initial flaw.

Figure 2 presents the relative errors calculated by accumulating the number of realizations in increments of 5,000 and comparing the result at each accumulation step with that of the previous step. For the two cases in which meaningful probabilities were observed the initiation probability of circumferential cracks and the rupture probability of axial cracks starting from an initial flaw the maximum relative error was approximately 4% in both cases.

Table . Probabilistic Analysis Results of Surge Line

	Crack Orientation	Probability of Crack Initation	Probability of (Ruptrue/Initail flaw)	Probability of Rupture
Surge Line (Alloy82/182)	Circumferencial	8.79E-02	Less than 2.0E-06	Less than 1.76E-07
	Axial	Less than 2.0E-05	2.0E-02	Less than 4.0E-07

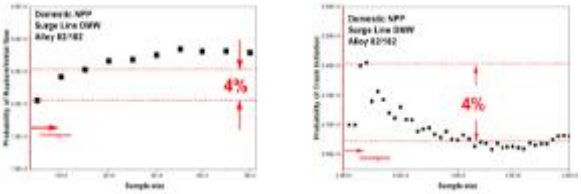


Figure 2. Convergence Results of surge line

5. Conclusions

In this study, a probabilistic fracture mechanics assessment was performed for a pressurizer surge line with an Alloy 82/182 dissimilar metal weld to derive the pipe rupture probability, and the convergence of the results with respect to the accumulated number of realizations was investigated. For the circumferential crack initiation and the axial crack rupture from an initial flaw, in which meaningful probabilities were obtained, the relative error with respect to the previous accumulated result was examined while accumulating realizations in increments of 5,000. In both cases, the relative error remained within approximately 4% for more than 10,000 realizations, confirming the convergence trend of the results. Meanwhile, since this study applied the conservative residual stress distribution of ASME Code Case N-899 and did not consider mitigation measures such as stress improvement, lower probabilities are expected if these are taken into account. These results are expected to serve as fundamental data for the future development of standardized convergence acceptance criteria.

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