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PFM Analysis for Pre-Existing Cracks on Alloy 182 Weld in PWR Primary Water Environment using Monte Carlo Simulation

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1. Introduction

Probabilistic Fracture Mechanics (PFM) analysis was generally used to consider the scatter and uncertainty of parameters in complex phenomenon. Weld defects could be present in weld regions of Pressurized Water Reactors (PWRs), which cannot be considered by the typical fracture mechanics analysis. It is necessary to evaluate the effects of the pre-existing cracks in welds for the integrity of the welds. In this paper, PFM analysis for pre-existing cracks on Alloy 182 weld in PWR primary water environment was carried out using a Monte Carlo simulation.

2. Models and Methods

A number of pre-existing cracks were sampled in the beginning of the simulation. All of the sampled cracks were propagated by Primary Water Stress Corrosion Cracking (PWSCC) mechanism. If a sampled crack becomes Through-Wall Crack (TWC) or satisfies the failure criteria, the crack will be counted as a 'failed' crack and the failure probability will be calculated like Eq. 1.

$$P_{fail} = \frac{the\ number\ of\ failed\ crack\ samples}{the\ number\ of\ total\ crack\ samples} \quad (1)$$

2.1 Initial distribution of pre-existing crack

Only axial oriented cracks which located in the inner surface of a butt weld were considered in this simulation. Circumferential cracks will be treated in later research. Semi-elliptical cracks were assumed as shown in Fig.1.

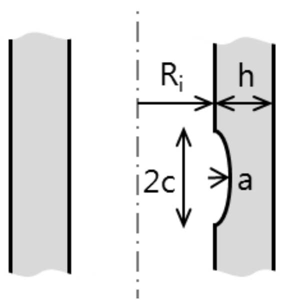

Fig. 1. Geometry of a sampled crack

The depth and aspect ratio(a/c) of sampled cracks were randomly selected from the distribution of each parameter. Log-normal distribution form was chosen for both two parameters from the NRC (Nuclear Regulatory Commission) reports [1, 2]. These distributions were influenced by the pipe thickness, material and welding process.

Possible geometry range of sampled crack was divided and expressed in the 2nd order matrix as shown in Fig. 2. This matrix was named 'Cell Probability Matrix (CPM)' because each cell of this matrix contains the probability of sampled crack geometry which was determined from the distribution of depth and aspect ratio.

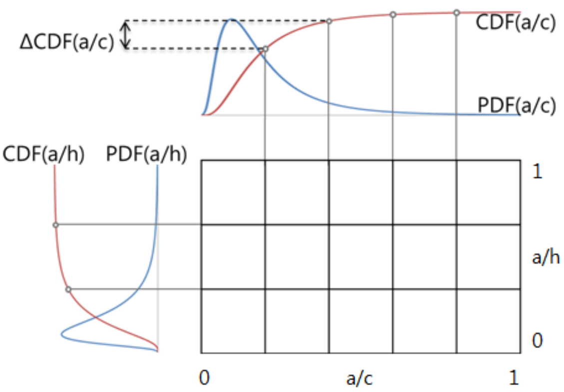

Fig. 2. Schematic diagram of CPM. (CDF means Cumulative Distribution Function and PDF means Probability Density Function.)

2.2 Stress

Operation stress caused by internal pressure and residual stress in the weld were considered. Lame's equation was used to calculate general distribution of operating stress. Residual stress distribution was derived from the report of EPRI (Electric Power Research Institute) [3]. Stresses caused by dead weight and thermal expansion were neglected in this paper.

2.3 K-solution

K is the stress intensity factor at the crack surface point (K_{length}) or deepest point (K_{depth}). The value of K is determined from various variables (e.g. geometry of crack, stress distribution in the weld). K-solution in Zahoor's Handbook [4] was used to calculate K.

2.4 Crack growth rate

Crack growth rate equation in xLPR 1.0 [5] was used, which was originally introduced from MRP-263 report [6]. This growth equation can consider dissolved hydrogen (DH) effect which related to the difference of electrochemical potential between Ni/NiO transition and current DH. Temperature and stress intensity factor were considered also but zinc addition effect was not developed quantitatively.

2.5 Inspection

2 parameter logistic POD (Probability of Detection) model was used. Parameter values were taken from the PINC report [7]. When a crack is detected from the inspection, that crack will be repaired and eliminated from the simulation.

2.6 J-solution

J means J-integral value which represents the stress filed near the crack tip in a plastic deformation state. J-solution was fitted from the tabulated data of Zahoor's Handbook [4]

2.7 Failure criteria

Tearing modulus criteria was used. If a sampled crack reaches critical crack size which was determined from the J and tearing modulus, the crack will grow unstably and the pipe will be failed. Load controlled system was assumed for conservative analysis results.

2.8 Failure Probability Matrix (FPM)

This matrix contains the information of cumulative failure probability of each cell as a function of Effective Full Power Year (EFPY). The cumulative failure probability of each cell can be calculated from the Eq. 1.

3. Results and discussion

Typical geometry and operating conditions of Reactor Pressure Vessel (RPV) outlet nozzle were selected from the EPRI report [3] and PINEP-PWSCC code [8]. Used inputs for PFM analysis in this paper is summarized in Table I.

Table I: Inputs for PFM analysis

Material properties (Alloy 182)
Young's modulus : 197200 MPa
n (strain hardening exponent) : 4.18
Poisson's ratio : 0.32
Yield strength : 372.37 MPa
Ultimate strength : 583.3 MPa
J_{IC} : 459 kJ/m^2
Tearing modulus of material : 245
Operation condition (RPV outlet nozzle)
Plant life : 80 year
Capacity factor : 80 %
Operation pressure : 15.51 MPa
Operation temperature : 596.89 K
Dissolved hydrogen : 30 cc/kg
Pipe inner radius : 381 mm
Pipe thickness : 58.42 mm
Residual stress (hoop direction, z is the distance from the inner surface of the pipe, in unit of MPa) : $119 + 1028\left(\frac{z}{h}\right) - 1223\left(\frac{z}{h}\right)^2 + 417.1\left(\frac{z}{h}\right)^3$
Other conditions
The number of cells: 20 × 20
Crack samples per each cell : 1000
Manual Metal Arc Welding (MMAW) process
Radiographic inspection is applied
Pre-service inspection : ultrasonic
In-service inspection : ultrasonic (10-year interval)

The cumulative failure probability caused by pre-existing cracks can be obtained from the Eq. 2.

$$P_{pre}(EFPY) = P_1 \times CPM(X,Y) \times FPM(X,Y,EFPY) \quad (2)$$

Where, P_1 is the probability of having at least one crack in the welding joint [9]. In this input conditions, the value of P_1 is calculated as 0.04. X and Y are the index of matrix in CPM or FPM.

CPM can be calculated and expressed like Fig. 3. The contoured value means existence probability of each cell.

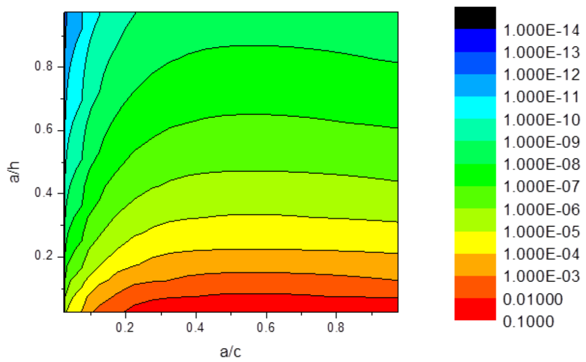

Fig. 3. CPM result from the reference inputs

FPM is a function of EFPY. In this paper, operation times of 1, 2, 10 and 64 EFPY results are shown in Fig. 4. Contoured value means failure probability of each cell. After 10 EFPY of operation, values of each cell in FPM reached almost steady state.

Cumulative failure probability due to the pre-existing cracks was expressed in Fig. 5 as a function of EFPY. When the EFPY was 0 and every after 8 EFPY, inspection was carried out and as a result, gradient of failure probability was significantly decreased. After 15 EFPY of operation, failure probability reached almost steady state similar to the results of FPM analysis. At the end of the simulation time (64 EFPY), cumulative failure probability was approximately reached to 0.023.

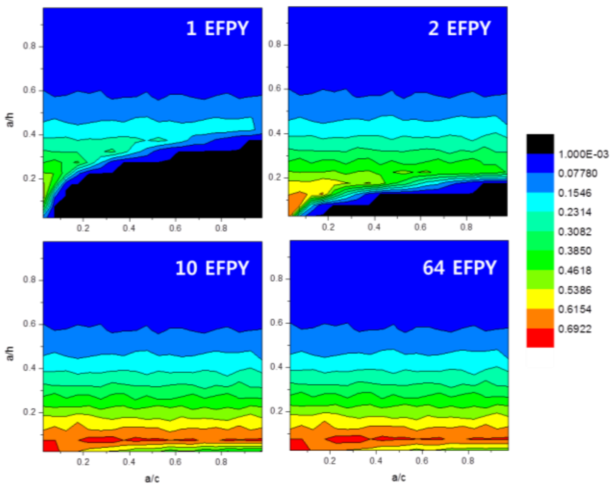

Fig. 4. FPM results from the reference inputs. Operation times of 1, 2, 10 and 64 EFPY.

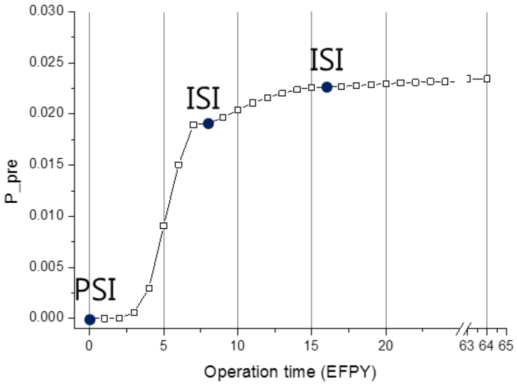

Fig. 5. Cumulative failure probability due to the pre-existing cracks as a function of EFPY. (PSI means pre-service inspection and ISI means in-service inspection)

Population tracing of sampled crack was carried out additionally. In this paper, operation times of 0 to 3 EFPY results are shown in Fig. 6. It seems that the depth of sampled cracks propagated more rapidly than the length of those. If the aspect ratio of a sampled crack is larger than unity, K and J solution of this simulation will not be applicable. This problem will be reviewed in later research.

4. Conclusions

PFM analysis for pre-existing cracks on Alloy 182 weld in PWR primary water environment was carried out. It was shown that inspection decreases the gradient of the failure probability. And failure probability caused by the pre-existing cracks was stabilized after 15 years of operation time in this input condition.

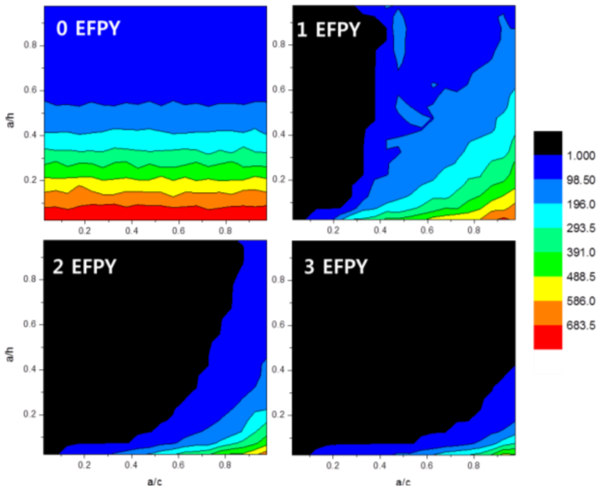

Fig. 6. Population tracing results of sampled cracks. Operation times of 0 to 3 EFPY.

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