A Study on Development of Probabilistic Crack Initiation Model for Alloy 182 Weld

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1. Introduction

To assure the integrity of nuclear power plants, it is essential to evaluate the precise lifetime of Alloy 182 weld, which was usually used for welding materials of pressure boundary components in nuclear reactors [1]. The lifetime of Alloy 182 weld is directly related to the Primary Water Stress Corrosion Cracking (PWSCC) initiation time [2]. However, because of the large time scatters in most crack initiation tests [3], the probabilistic crack initiation models have been mainly adopted in order to consider the cracking time scatters [4, 5]. In this study, we considered a method of estimating the parameters of the probabilistic crack initiation model and evaluating the uncertainty of the estimators when the PWSCC data is given.

2. PWSCC Data

The development team of eXtremely Low Probability of Rupture (xLPR), which is a Probabilistic Fracture Mechanics (PFM) code being co-developed by Nuclear Regulatory Commission (NRC) and Electric Power Research Institute (EPRI), published the summarized results of PWSCC initiation experiments for Alloy 182 weld [3].

In order to quantify the applied stress level to the specimens, only the results of constant tensile load tests or pressurized capsule tests were collected. The selected cracking tests were performed in the simulated Pressurized Water Reactor (PWR) primary water environments [3]. The various temperature conditions in the data were normalized at 325℃ by the Arrhenius equation with an activation energy of 185 kJ/mol [3]. The yield strength measured in the room temperature was corrected to the test temperature (i.e., 325℃) yield strength, and the measured engineering stress was also corrected to the true stress [3]. Then, it is possible to represent the crack initiation time according to the stress ratio r (≡Applied true stress/Test temperature yield strength) as shown in Fig. 1 [3].

The data described above are considered to be the most reliable crack initiation test results for Alloy 182 up to now. Thus, we obtained the PWSCC data from Fig. 1 using the graph digitizer program *GetData 2.26*. The data consists of '59 of PWSCC cracking time data' (see red squares in Fig. 1) and '55 of NO PWSCC suspended time data' (see blue diamonds in Fig. 1).

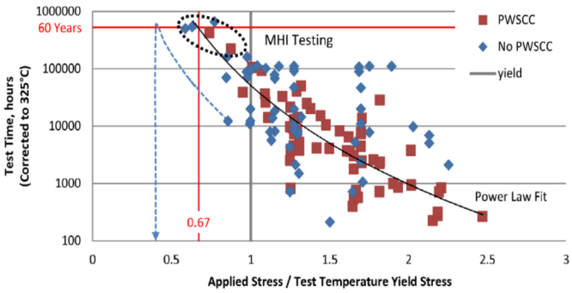

Fig. 1. Crack initiation time according to the stress ratio r; PWSCC cracking time (red squares) and NO PWSCC suspended time (blue diamonds) [3].

3. Model Parameter Estimation

Based on the Weibull distribution [6], which was widely adopted as a crack initiation time model, the following relationship is presumed:

$$F(t;\beta,\eta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad (1)$$

$$\eta = \eta_y r^n, \ \ (n < 0). \quad (2)$$

Where $F(\cdot)$ is the cumulative probability function of crack initiation, t is the time, r is the stress ratio, β is the Weibull shape parameter, η_y is the Weibull scale parameter when the stress ratio $r = 1$, and n is the stress exponent. Since the data in Fig. 1 includes a covariate (i.e., stress ratio r), β, η_y and n can be estimated by the 3-parameter Maximum Likelihood Estimation (MLE) method [6] after substituting Eq. 2 into Eq. 1. The estimated parameter values with a numerical approach are as follows:

- $\hat{\beta}$ = 0.6153
- $\hat{\eta}_y$ = 32528 hr
- $\hat{n}$ = 5.4583.

It is shown that the value of β estimate (i.e., $\hat{\beta} =$ 0.6153) is much lower than the value of Weibull shape parameter ($= 3$) suggested in the preliminary study for Alloy 182 crack initiation [4], which is due to the under-estimation effect of the Weibull shape parameter caused by the data aggregation [7]. Therefore, it is desirable to presume $\beta = 3$ [4] instead of using the β estimate (i.e., 0.6153) at this stage.

Whereas, with respect to the estimates of η_y and n, it is acceptable to use those values. In particular, the estimate of the stress exponent n can be meaningful, because it is estimated through a statistically rigorous procedure with more data (i.e., NO PWSCC data) than that estimated by the xLPR development team [3].

4. Uncertainty of Estimator

As a next step, it is possible to quantitatively evaluate the uncertainty of the estimated parameters by using the bootstrapping [8]. We normalized the stress ratio variation in the PWSCC data based on the estimated stress exponent n. This data reprocessing is needed for the bootstrap procedure, which requires no covariate in the right-censored data. Figure 2 shows the schematic illustration of the bootstrapping.

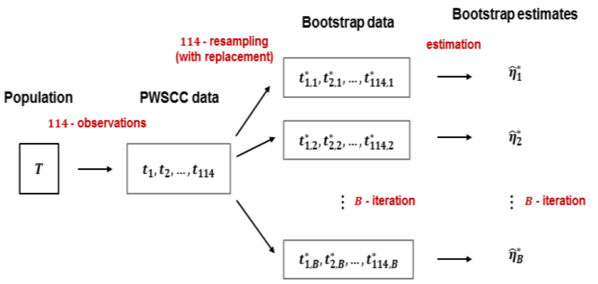

Fig. 2. Schematic illustration of the bootstrapping.

After the stress ratio normalization, it is necessary to obtain an empirical cumulative distribution function (CDF) by Kaplan-Meier method [9]. Then the bootstrap re-sampling procedure can be performed with the obtained empirical CDF for right-censored data [10]. Figure 3 shows the 90% confidence interval (black dotted lines in Fig. 3) for the η estimate curve (black solid line in Fig. 3) over the range of $0.75 < r \le 2.5$ using the bootstrap method.

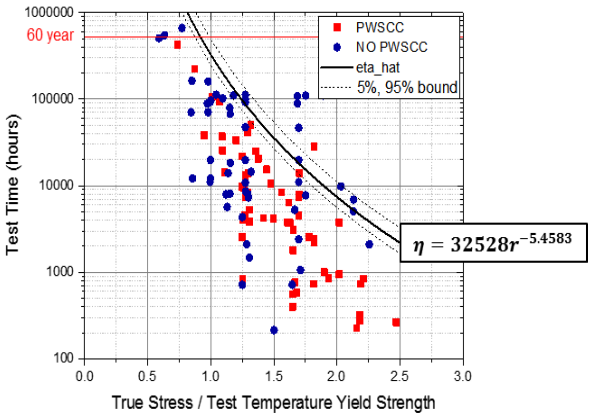

Fig. 3. The 90% bootstrap confidence interval (black dotted line) for the η estimate curve (black solid line) over the range of $0.75 < r \le 2.5$; PWSCC data (red dots) and NO PWSCC data (blue dots) were obtained from Fig. 1..

5. Conclusion

The Weibull distribution is presumed as a basic form of the probabilistic crack initiation model. The stress exponent, the Weibull parameter and confidence interval were estimated from the best available Alloy 182 PWSCC test data. We suggested a methodology for estimating the parameters of the probabilistic crack initiation model when there is a covariate in the given data, and evaluating the uncertainty of estimated parameter, especially when the data is right-censored.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1403006) and was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20164010201000).

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