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EFFECT OF PROBABILISTIC DISTRIBUTION OF SCC GROWTH RATE FOR WORK-HARDENED STAINLESS STEEL ON PFM ANALYSIS RESULTS

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ABSTRACT

The probabilistic distribution of stress corrosion cracking (SCC) growth rate is required for probabilistic fracture mechanics (PFM) analysis of SCC failure, it remains unclear whether it has a significant impact on the PFM results. To investigate the influence of the SCC growth rate distribution on PFM results, probabilistic distributions obtained from different SCC growth rate datasets were used for PFM analysis. The PFM results were strongly influenced by the standard deviation of SCC growth rate, suggesting that it is important to consider the SCC growth rate distribution in reliable assessment based on PFM.

INTRODUCTION

Probabilistic fracture mechanics (PFM) is a structural integrity assessment methodology that quantifies the failure probability of components in nuclear power plants. In PFM analysis, probability distributions expressed as probability density functions are given to random variables such as crack initiation time and material properties. The probability distribution of stress corrosion cracking (SCC) growth rate is one of the issues considered when assessing SCC failures. In general, the probability distribution of SCC growth rate has been evaluated from experimental data reported in several studies performed by different laboratories and may vary depending on the datasets, which could result in differences in PFM results. However, it is not clear whether these differences have a significant impact on PFM results. In this study, different SCC growth rate datasets were used to evaluate the probability distributions of the SCC growth rate in order to investigate their influence on PFM analysis. This study focused on assessing SCC propagation in work-hardened stainless steels under BWR conditions.

PFM analysis conditions

In this study, PFM assessments were performed using the PFM code PEDESTRIAN developed by Nagai et al (2016). Details of this code are available in the literature (Nagai et al (2016)). Table 1 shows the PFM analysis conditions. PFM analyses were carried out assuming a SCC propagation in a weld heat-affected zone (HAZ) of a 600A piping made of Type 316L. An initial crack was assumed which depth and half-length were set as 5.16 mm and 11.82 mm respectively. The applied stress was set in consideration of the stress under normal operation and the welding residual stress as shown in the literature (Nagai et al (2017)). To investigate the influence of the probability distribution of SCC growth rate on PFM analysis, only the SCC growth rate was given as a random variable and all the other input parameters were set as fixed values. Probability of failure was assumed to be the probability of crack propagation up to 75% of the plate thickness. The number of trials in the Monte Carlo simulation was set to 10^6.

Table 1 PFM analysis conditions

Material	SUS316L
Temperature	288 °C
Nominal diameter	600 A
Inner radius	274.2 mm
Thickness	38.5 mm
Crack geometry	Circumferentially semi-elliptical surface crack
initial crack depth	5.16 mm
initial crack half length	11.82 mm
Applied stress	$\sigma\left(\frac{x}{t}\right) = 391.99 - 3644.5\left(\frac{x}{t}\right) + 6945.7\left(\frac{x}{t}\right)^2 - 3540.6\left(\frac{x}{t}\right)^3$
Number of sampling	10^6

RESULT AND DISCUSSION

SCC data for evaluating probability distributions

To obtain the probability distribution of SCC growth rate of work-hardened stainless steel, SCC growth rate data for cold-worked 316L stainless steel (SS) were taken from the literature (Andresen et al. (2000), Andresen et al. (2001), Andresen (2002), Saito et al. (2013), Sumiya et al. (2013), Shoji et al. (2003), Masuoka et al. (2007), Koshiishi et al. (2023)). The yield stress σ_y and hardness of materials vary with the degree of cold work, and these are known to affect the SCC growth rate (Andresen et al. (2001), Shoji et al. (2003)). Considering the weld HAZ of pipe, Vickers hardness has been found to be around 200-260 HV (Suzuki et al. (2009)), which is equivalent to σ_y = 344-573 MPa according to the following equation (Shoji (2008)):

$$\sigma_y = 3.81\,HV - 417 \quad (1)$$

Therefore, the probability distributions were determined from SCC data for cold-worked 316L with hardness below 260 HV, corresponding to σ_y below 573 MPa. Two groups of data were evaluated in this study: previously reported data for cold-worked 316L SS (hereinafter "previous data") (Andresen et al. (2000), Andresen et al. (2001), Andresen (2002), Saito et al. (2013), Sumiya et al. (2013), Shoji et al. (2003), Masuoka et al. (2007)) and experimental data for 15% cold-worked 316L SS, obtained by CRIEPI with an emphasis on test uniformity (hereinafter "CRIEPI data") (Koshiishi et al. (2023)). The value of σ_y for the previous data was 340-571 MPa and that for the CRIPEI data was 478 MPa. The average σ_y and hardness of the previous data were comparable to those of CRIEPI data. Figure 1 shows the SCC growth rate data for the previous data and CRIEPI data. SCC growth rates *da/dt* (m/s) are generally expressed as following equation:

$$da/dt = \mathrm{C}\,K^{\mathrm{m}} \quad (2)$$

where *K* is stress intensity factor, C and m are the coefficients determined experimentally. The equations of SCC growth rate are shown below for each dataset. In this study, C was assumed to be random variable expressed as lognormal distribution and its probabilistic density functions, i.e., median μ and standard deviation σ, are also shown below.

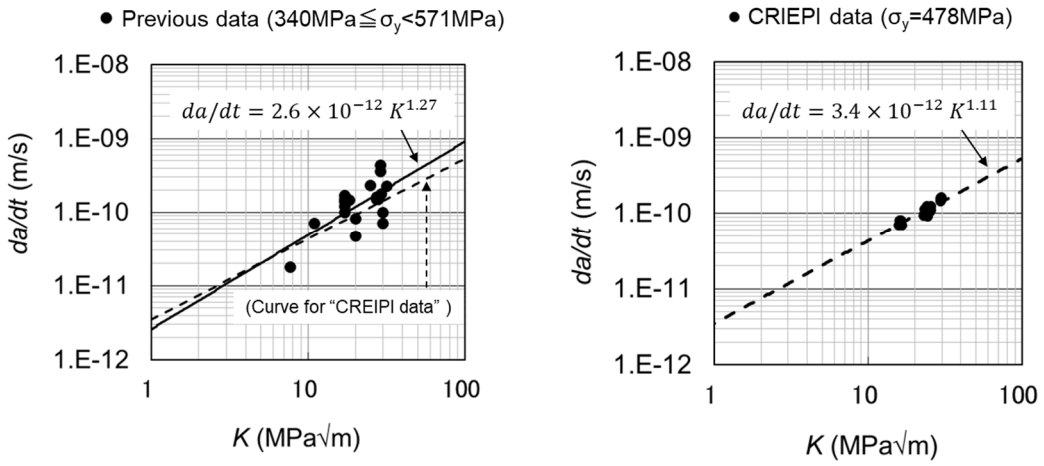
Previous data : $da/dt = \mathrm{C}\,K^{1.27}$

$$\mu = 2.6 \times 10^{-12},\ \sigma = 0.523 \quad (3)$$

CRIEPI data : $da/dt = \mathrm{C}\,K^{1.11}$

$$\mu = 3.4 \times 10^{-12},\ \sigma = 0.102 \quad (4)$$

There was a slight difference in the *K* dependency of SCC growth rate and a large difference in the standard deviations between the previous data and CRIEPI data. The difference in standard deviations between these data may be due to the wide range of σ_y values in the previous data. Figure 2 shows the relationship between σ_y and SCC growth rates of the previous data. The SCC growth rates were normalized to the same *K* (*K* = 22 MPa√m, which is the average *K* of SCC data) using the dependency of *K* in Equation (3). Figure 2 shows that the SCC growth rates tend to increase with increasing σ_y, which is consistent with previous reports (Andresen et al. (2001), Shoji et al. (2003)). This suggests that a wide range of σ_y results in a large standard deviation of SCC growth rates. Since the CRIEPI data were obtained under the same σ_y condition, variations due to differences in the test conditions were smaller than those for the previous data and thus more likely to reflect the variation in the given material.



(a) Previous data (b) CRIEPI data

Figure 1 SCC growth rate datasets

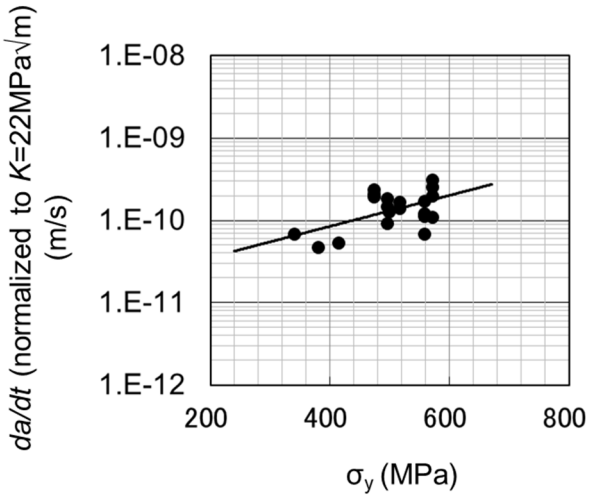


Figure 2 Relationship between σy and SCC growth rates of the previous data

Effect of probability distribution of SCC growth rate on PFM results

PFM analysis of the previous data and CRIEPI data was carried out giving the standard deviations of σ = 0.523 and σ = 0.102 and the SCC growth rate shown in Equations (3) and (4), respectively, and figure 3 shows the PFM results. There were clear differences in the results for the previous data and CRIEPI data, largely due to the difference in standard deviation. Compared with the CRIEPI data, the previous data took a shorter time to reach a given probability of failure (10^{-1}, 10^{-2}, … , 10^{-6}) because its larger standard deviation sampled a higher SCC growth rate during the PFM analysis. PFM results can quantify the time to reach a given probability of failure which could contribute to, for example, optimization of inspection intervals. Figure 4 shows the time to reach probability of failure of 10^{-3}, 10^{-4}, and 10^{-5} for the previous data and the CRIEPI data obtained from the PFM results (Figure 3). The results show that the time to reach the given probability of failure using the CRIEPI data was about 5 times as long as when using the previous data. This could have a significant effect on the structural integrity assessment.

The standard deviations of probability distributions were found to vary depending on the SCC growth rate datasets, which significantly influenced the PFM results. This suggests that appropriate SCC growth rate data for evaluating probability distributions is needed for PFM analysis.

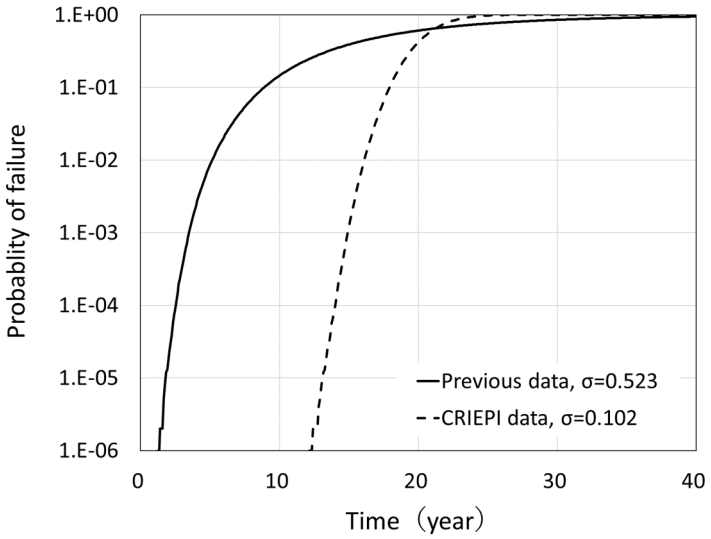


Figure 3 PFM results of the previous data and CRIEPI data

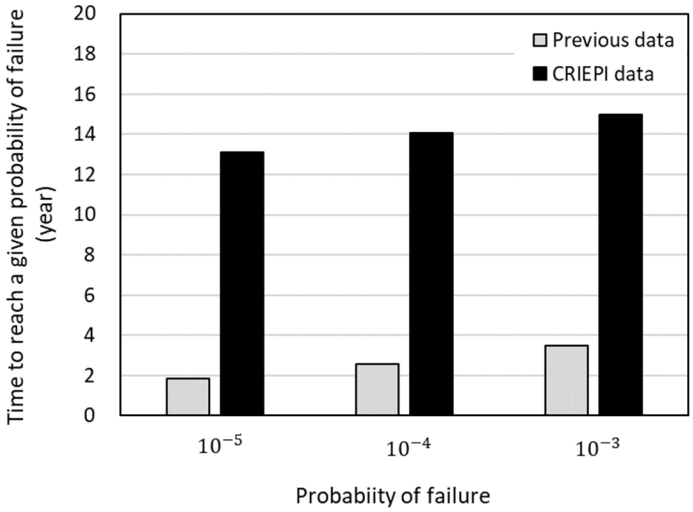


Figure 4 Time to reach a given probability of failure for the previous data and the CRIEPI data obtained from the PFM results in figure 3

CONCLUSION

In this study, probability distributions obtained from different SCC growth rate datasets were used for PFM analysis to investigate the influence of the SCC growth rate distribution on PFM results. The standard deviations of SCC growth rate were found to vary largely depending on the SCC growth rate datasets, which significantly influenced the PFM results. This suggests that appropriate SCC growth rate data for evaluating probability distributions is needed for PFM analysis.

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