Failure Probability Estimation for Axial Through-Wall Cracked Steam Generator Tubes

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1. Introduction

Steam generator tubes in pressurized water reactor (PWR) are exposed to various types of degradation and aging processes which might significantly decrease its structural reliability[1]. Up to now, integrity evaluations are performed by using conventional deterministic approaches. However, there are lots of uncertainties to perform a rational evaluation of lifetime. In this respect, a probabilistic safety assessment method is more appropriate for the assessment of overall steam generator tube safety.

The objective of this study is to estimate the failure probability of steam generator tubes containing a single through-wall cracks. Major input variables such as crack length, yield strength and ultimate tensile strength are considered as probabilistic variables. A limit load solution is used to constitute a limit state function. In the analyses, failure probabilities are calculated by using the FORM (First Order Reliability Method), SORM (Second Order Reliability Method), and MC (Monte Carlo) simulation method.

2. Failure Probability Estimation Method

Probabilistic fracture mechanics deals with the determination of failure probabilities (P_f) of structure components from the scatter of the applied loads and structural resistance properties[2]. The failure behavior of the structure is described by a limit state function ($g(x)$) depending on basic random variables $x=(x_1, x_2, \cdots, x_n)$ which denote applied load and structural resistance parameters such dimensions and material properties. By definition, $g(x) < 0$ implies failure, whereas no failure occurs for $g(x) > 0$. $g(x) = 0$ defines the failure surface. The failure probability can be calculated as the probability content of the failure domain F:

$$P_f = \int_F f_1(x_1)\ldots f_n(x_n)dx_1\ldots dx_n \quad (1)$$

where $f_i(x_i)$ represent the probability densities of respective basic variables x_i, which are for the sake of simplicity assumed to be stochastically independent. The analytical solutions of Eq. (1) are limited to a few of very special cases.

In order to estimate failure probability, two kinds of methods are generally used: the one uses reliability index and the other uses simulation technique. FORM and SORM use the reliability index. In the FORM, a linearization of the limit state function at the design point provides an approximate value of the failure probability as follows:

$$P_f \approx \Phi(-\beta) \quad (2)$$

where Φ is the cumulative standard normal distribution and β is the reliability index, which represents the distance between the origin of the space of basic variables and the design point on the failure surface. In the SORM, the failure surface approximates with quadratic hyper-surface. The main curvatures κ_i of the quadratic hyper-surface at the design point are equal to those of the failure surface. A simple closed-form solution for the probability computation using second-order approximation is given as follows:

$$P_f \approx \Phi(-\beta)\prod_{i=1}^{n-1}(1+\beta\kappa_i)^{-1/2} \quad (3)$$

The MC simulation can be also used to estimate the failure probability. MC simulation requires generating sets of random variables according to the given probability distributions of the basic random variables and putting them into the limit state function. The failure probability can be estimated by Eq. (4).

$$P_f \approx \frac{N_f}{N} \quad (4)$$

where N_f is the number of simulation cycles when the failure occurred and N is the total number of simulation cycles.

3. Failure Probability Estimation of Steam Generator Tubes

In this study, the FORM, SORM and MC simulation were used to estimate the failure probability of steam generator under internal pressure. For this, the limit state function was constituted and the probabilistic variables and the distributions were determined.

The unstable failure loads of steam generator tubes with a single through-wall crack (P_{cr}) were calculated by using Eq. (5)[3,4].

$$P_{cr} = \frac{\sigma_f t}{M_T R} \quad (5)$$

where σ_f is the flow stress defined as the average of the sum of yield strength and ultimate tensile strength, R is the mean radius, t is the thickness, and M_T is the bulging factor proposed by Erodgan[3]. The limit state function of steam generator tubes containing a single through-wall cracks was constituted as follows:

$$g(x_i) = P_{cr} - P_{op} \quad (6)$$

where, P_{op} is the operating pressure difference between inner wall and outer wall of the tubes.

The probabilistic distributions of the input variables were summarized in Table 1[5] where μ is average and σ is standard deviation. The distributions of crack length were used the data from reference[5] and assumed data. The normal distribution was used for all probabilistic variables and the deterministic variable R and t were considered as 9.525 and 1.09 mm, respectively.

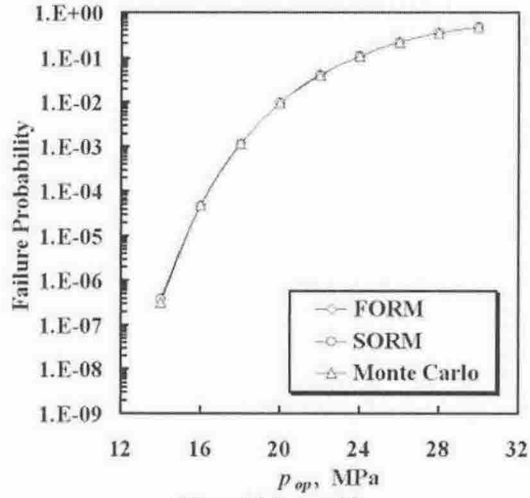
Failure probability of steam generator tubes was predicted with increase of P_{op} from 14 MPa to 30 MPa and the estimated results were presented in Fig. 1. The failure probability indicated somewhat low value below 10^{-6} in the operating condition but showed a big discrepancy according to the input distributions of crack length. And the failure probability obtained by using FORM, SORM and MC simulation showed a good agreement with each other. Therefore, it can be said that the failure probability estimation modules programmed in this study was verified and these can be applied to estimate the failure probability of steam generator tube after considering the effects of degradation type, plugging criterion, crack growth, POD and so on.

4. Conclusion

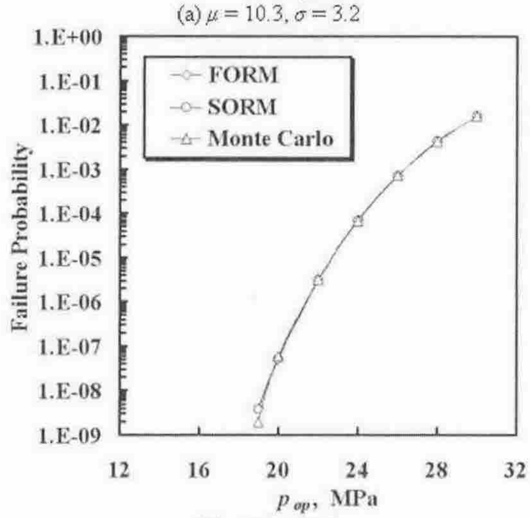
In this study, the FORM, SORM and MC simulation were carried out to estimate the failure probability of steam generator tubes containing a single through-wall crack under internal pressure. The limit state function was constituted and the probabilistic variables and the distributions were selected. The failure probability obtained by using failure probability estimation module programmed in this study showed a good agreement with each other. Therefore, it can be used to estimate the failure probability of steam generator tubes after considering the effect of degradation type, plugging criterion, crack growth, POD and so on.

Table 1 Input data for probabilistic variables

Variable	μ	σ
Yield strength σ_y(MPa)	362	38
Ultimate tensile strength σ_u (MPa)	718	38
Crack length	10.3	3.2
$2c$ (mm)	6	2



(a) $\mu = 10.3, \sigma = 3.2$



(b) $\mu = 6, \sigma = 2$

Fig. 1 Failure probability under internal pressure

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