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Generation of plastic influence functions for J-integral and crack opening displacement of thin-walled pipes with a short circumferential through-wall crack

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ABSTRACT

Fracture mechanics parameters such as the *J*-integral and crack opening displacement (COD), are necessary for Leak-Before-Break (LBB) evaluation. The famous two estimation methods, the GE/EPRI and the Reference Stress Method (RSM), have their applicability limit with regard to the ratio of a pipe mean radius to thickness (R_m/t). In order to extend their applicability limit to a thin walled pipe, several finite element analyses are performed for the *J*-integral and COD, and then new plastic influence functions are developed for thin-walled pipes with a short circumferential through-wall crack. With the newly generated plastic influence functions, the GE/EPRI and the RSM give closer results with those obtained from detailed finite element analyses. In addition, C^*-integral and COD rate are estimated by using the new plastic influence functions and they are well matched with elastic–creep finite element analysis results under the power-law creep condition. Since the LBB concept can be applied to a piping system in a Korean Sodium-cooled Fast Reactor (SFR) which is designed to have thin-walled pipes and to operate in high temperature enough to cause creep, this paper can be applied for the LBB assessment of thin-walled pipes with a short through-wall crack in the SFR.

1. Introduction

Leak-Before-Break (LBB) concept is aimed at demonstrating that leakage through a crack in the wall of a pipe can be detected before the crack becomes unstable and guillotine break occurs. The nuclear industry has performed LBB analyses for circumferential through-wall cracked pipes to justify elimination of design requirements to account for dynamic effects due to pipe rupture. Application of LBB concept allows elimination of preventive measures against dynamic effects, such as pipe whip restraints and jet impingement barrier, and thus provides cost and safety benefit in the pressurized water reactors (PWRs).

Korean Sodium-cooled Fast Reactor (SFR), which is now under design stage, also considers the application of LBB concept to its piping system. One of the major reasons for applying LBB concept is to reduce fire protection facilities against large-scale fire which might occur when sodium coolant is exposed to air. Since SFR will operate in different conditions with different geometries from those of PWRs, the applicability of current LBB evaluation method should be studied in order to apply the LBB concept to SFR pipes.

In the fracture mechanics point of view, the current LBB evaluation procedure [1] is mainly composed of two steps, determination of leakage size crack and crack stability evaluation. First, the crack size corresponding to detectable leakage rate should be determined based on plant's leak detection capability and normal operating condition. For this step, an accurate estimation method is needed to predict crack opening displacement (COD) for subsequent leak-rate evaluations. The second step is to verify that the crack will remain stable at normal operating load plus safe shutdown earthquake loads. When the elastic–plastic fracture mechanics (EPFM) technique is introduced for this step, an accurate *J*-integral estimation method is needed to determine crack stability.

Since the LBB concept has been widely applied for PWRs, there are a number of estimation methods for COD and *J*-integral for an idealized circumferential through-wall cracked pipe, including a finite element analysis (FEA) and engineering approximation equations [2,3]. Instead of using cumbersome FEA, engineering

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approximation equations are preferred in LBB evaluation due to their relatively simple application. Among those, two of the popular approximation equations include the GE/EPRI method [4] and the reference stress method (RSM). The GE/EPRI method was developed based on FEA solutions for through-wall cracked pipes and provides tabulated elastic and plastic influence functions for various geometric and material parameters. The RSM utilizes reference stress concept which is defined using plastic limit load. Kim and Budden [5] proposed the enhanced reference stress method that redefines the reference stress using optimized reference load to reduce excessive conservatism.

In order to apply the LBB concept to SFR pipes, it needs to be checked whether COD and J-integral estimation equations can be applied to them. The GE/EPRI method and the reference stress method have their applicability limit in terms of pipe mean radius to thickness ratio (R_m/t). They can be applied to pipes with R_m/t less than or equal to 20. As SFR is designed to have thin-walled pipes with R_m/t ranged 30–40, application of those might result in inaccurate estimation of COD and J-integral. In addition to COD and J-integral estimation in EPFM regime, estimation methods considering creep effects are also needed for COD and an appropriate fracture mechanics parameter in creep regime since design temperature of SFR is high enough to induce creep. Thus, improvement on current estimation equations is necessary to extend their applicability.

For this purpose, several three-dimensional finite element analyses for short circumferential through-wall cracked pipes are performed with the variation of R_m/t and a loading condition to examine those effects on the estimation equations under EPFM and elastic creep conditions. Then, new elastic and plastic influence functions, and optimized reference loads are suggested for the estimation equations to improve the current applicability limit of R_m/t up to 50. Finally, newly suggested values are also applied to the estimation equations for the COD rate and C^*-integral to extend their applicable regime from the EPFM to the elastic creep condition.

2. Estimation methods for fracture mechanics parameters

There are a number of estimation equations for COD and J-integral under various loading conditions. This section provides a short summary of two of popular estimation methods, the GE/EPRI method and reference stress method for a pipe with a circumferential through-wall crack.

2.1. Elastic plastic fracture mechanics model

The GE/EPRI type estimation equations including the Zahoor solutions [6] were developed based on finite element results using deformation plasticity theory. The GE/EPRI solutions provide elastic and plastic influence functions as tabulated forms for various geometries and loading. In order to use the GE/EPRI estimation equations, a tensile curve of a material should be represented by the Ramberg-Osgood model:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n, \tag{1}$$

in which σ_o is a reference stress usually assumed to be the yield stress, $\varepsilon_o = \sigma_o/E$ the associated strain, E the modulus of elasticity, and α and n strain-hardening parameters. The J-integral and COD (δ) for pipes with circumferentially through-wall cracks under axial tension (P), as defined by the GE/EPRI method, are

$$\begin{aligned} J &= J_e + J_p = \frac{K_I^2(a_e)}{E'} + \alpha\sigma_o\varepsilon_o R_m(\pi-\theta)\frac{\theta}{\pi}\cdot h_1\cdot\left[\frac{P}{P_o}\right]^{n+1} \\ K_I &= \sigma\sqrt{\pi a}F\left(\frac{\theta}{\pi},\frac{R_m}{t}\right) \end{aligned} \tag{2}$$

$$\delta = \delta_e + \delta_p = \frac{2a_eP}{\pi R_m tE}\cdot V_1(a_e) + \alpha\varepsilon_o a\cdot h_2\cdot\left[\frac{P}{P_o}\right]^n \tag{3}$$

In Eqs. (2) and (3), K_I denotes the stress intensity factor for mode I, while $a = R_m\theta$ is half of the crack length with the mean radius R_m and crack half angle θ, and a_e is an effective crack length with the plasticity correction. Furthermore, t is pipe wall thickness, and F, V_1, h_1, and h_2 are the elastic and plastic influence functions, respectively. The plastic limit tension P_o for a through-wall cracked pipe is given as

$$P_o = 2\sigma_o R_m t\left[\pi - \theta - 2\sin^{-1}\left(\frac{1}{2}\sin\theta\right)\right] \tag{4}$$

Similar formulation can be written for the bending case and the combined tension and bending case with the corresponding tabulated influence functions. The GE/EPRI estimation method is applicable to the range of $5 \le R_m/t \le 20$ due to its origin.

The RSM is adopted in many defect assessment methods including R6. Kim and Budden [5] proposed the enhanced reference stress method in which the reference stress is redefined by using the optimized reference load, instead of plastic limit load. In this paper, the RSM means the enhanced reference stress method. Unlike the GE/EPRI method, experimental stress-strain data can be directly used with the RSM. For axial tension case, the J-integral and COD can be estimated by

$$\frac{J}{J_e} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\frac{L_r^2\sigma_{ref}}{E\varepsilon_{ref}} \tag{5}$$

$$\frac{\delta}{\delta_e} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\frac{L_r^2\sigma_{ref}}{E\varepsilon_{ref}} \text{ for } 0 \le L_r < 1 \tag{6}$$

where the reference stress σ_{ref} and the proximity parameter for plastic collapse, L_r, are defined by

$$L_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{P}{P_o^*} \tag{7}$$

In Eqs. (5) and (6), J_e and δ_e denote elastic J-integral and COD, and ε_{ref} is strain at the reference stress. The optimized reference load, P_o^* is determined from the plastic limit tension as

$$\begin{aligned} P_o^* &= \gamma(\theta)P_o; \\ \gamma &= 0.82 + 0.75\left(\frac{\theta}{\pi}\right) + 0.42\left(\frac{\theta}{\pi}\right)^2 \text{ for } \theta/\pi \le 0.5 \end{aligned} \tag{8}$$

Since γ was developed from h_1 and h_2 from the GE/EPRI method, the RSM is also applicable in the range of $5 \le R_m/t \le 20$.

2.2. Elastic–creep fracture mechanics model

For materials following power-law creep as Eq. (9), the steady state creep fracture parameters, C^*-integral and COD rate ($\dot{\delta}$), can be represented by Eqs. (10) and (11) with the use of plastic influence function h_1 and h_2. This is due to the fact that the governing equilibrium and compatibility equations in the power-law type creeping body are identical to those in the plastic body with the