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Improvement of C*-integral and Crack Opening Displacement Estimation Equations for Thin-walled Pipes with Circumferential Through-wall Cracks

Jeong Soon Park, Myung Jo Jhung
Korea Institute of Nuclear Safety, 19 Guseong-dong, Yuseong-gu, Daejeon
k651pjs@kins.re.kr

1. Introduction

Since the LBB(Leak-Before-Break) concept has been widely applied to high energy piping systems in the pressurized water reactors, a number of engineering estimation methods had been developed for J-integral and COD values. However, those estimation methods were mostly reliable for relatively thick-walled pipes about $R_m/t=5$ or 10.

As the LBB concept might be considered in the design stage of the SFR (Sodium-cooled Fast Reactor) which has relatively thin-walled pipes due to its low design pressure, the applicability of current estimation methods should be investigated for thin-walled pipes. Along with the J-integral and COD, the estimation method for creep fracture mechanics parameters, C*-integral and COD rate, is required because operating temperature of SFR is high enough to induce creep in the structural materials.

In this study, the applicability of the current C*-integral and COD estimation methods to thin-walled pipes is studied for a circumferential through-wall crack using the finite element (FE) method. Based on the FE results, enhancement of the current estimation methods is made.

2. Analysis

2.1 Finite Element Models

For the present work, elastic-creep finite element analyses were performed using the general purpose FEA program, ABAQUS. Pipes with a circumferential through-wall crack ($\theta/\pi=0.125$) is considered with the variation of R_m/t from 5 to 50.

A quarter-model is used by taking advantage of symmetry. Twenty-node reduced-integration elements (C3D20R in ABAQUS) are used forming focused meshes around the crack tip. A typical finite element model is illustrated in Fig. 1.

As a loading condition, two different loadings, axial tension and bending moment, are considered separately. Tension or bending is first applied to the FE model using an elastic calculation at time t=0. The load is then held constant and subsequent time-dependent creep analyses are performed. Load ratio to plastic limit load is set to 0.4 for elastic-creep analyses.

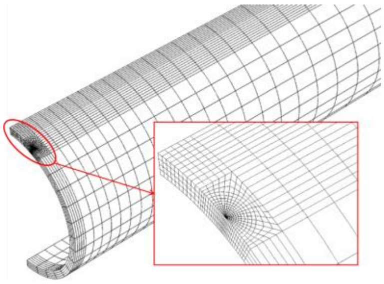

Fig. 1. Typical finite element model for $R_m/t=10$ and $\theta/\pi=0.125$

2.2 Engineering Estimation Method

When the steady-state creep condition is achieved, creep crack tip parameter, C(t)-integral is converged on C*-integral, which is path-independent and constant for power-law creeping materials.

For materials following power-law creep as $\dot{\varepsilon}_c = A\sigma^m$, C*-integral and COD rate($\dot{\delta}$) can be estimated by using the GE/EPRI method [1]:

$$C^* = A \cdot R_m(\pi-\theta)\frac{\theta}{\pi} \cdot h_1 \cdot \left[\frac{P\sigma_o}{P_o}\right]^{n+1}, \quad \dot{\delta} = A \cdot a \cdot h_2 \cdot \left[\frac{P\sigma_o}{P_o}\right]^{n}$$

where, A and m are creep material constants; n is a plastic material constant; σ_o is yield stress; R_m is a mean radius; θ is a crack length; and h_1 and h_2 are plastic influence functions. Furthermore, P denotes applied axial tension, and P_o means plastic limit load for a given geometry.

In the case of the reference stress method (RSM), C*-integral and COD are obtained by

$$\frac{C^*}{J_e} = \frac{E\dot{\varepsilon}_c}{\sigma_{ref}}, \quad \frac{\dot{\delta}_c}{\delta_e} = \frac{\dot{\varepsilon}_c}{(\sigma_{ref}/E)}$$

$$\sigma_{ref} = \frac{P}{P_o^*}\sigma_y, \quad P_o^* = \gamma \cdot P_o, \quad \gamma = \frac{P_o^*}{P_o} = \left(\frac{h_1}{h_1(n=1)}\right)^{1/(1-n)}$$

where P_o^* denotes optimized reference load .

2.3 Elastic-creep Analysis

Elastic-creep FEA C*-integral and COD rate results are shown in Fig. 2 and 3, respectively with comparison of the RSM.

As shown in Fig. 2, the differences between FE results and the estimation methods increase with increasing R_m/t. Similar tendencies can be found in the case of COD rate in Figure 3, in which the maximum difference reaches about 30% at $R_m/t=50$. Therefore, improvement of the estimation methods is needed considering R_m/t effect in order to be applied to thin-walled pipes.

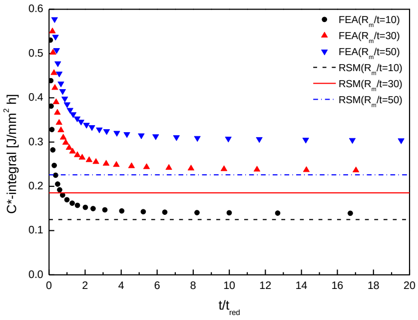

Fig. 2. C*-integral versus time

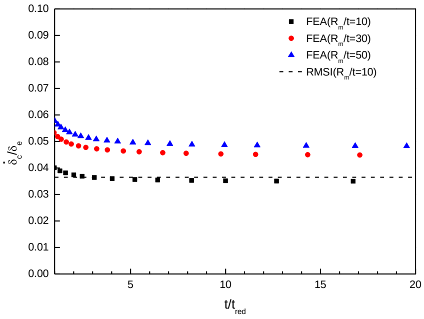

Fig. 3. COD rates versus time

3. Improvement of the estimation method

New plastic influence functions h_1, and h_2 can be determined from the elastic-plastic finite element method, and then, can be used to define γ and new optimized reference load [2].

$$h_1 = \frac{J - J_e}{\alpha\sigma_o\varepsilon_o R_m(\pi-\theta)\dfrac{\theta}{\pi}\cdot(P/P_o)^{n+1}}$$

$$h_2 = \frac{\delta - \delta_e}{\alpha\varepsilon_o a\cdot(P/P_o)^n}$$

In this study, new plastic influence functions and new γ values are developed for $R_m/t=30$ and 50 which are out of the applicability limit of the GE/EPRI method and the RSM.

With newly developed plastic influence functions and γ, differences between the estimation methods and FEA are only about few percent depicted in Fig. 4 and 5.

Therefore, it is predicted that the current estimation methods for C*-integral and COD can be applied to the thin-walled pipes with the proper plastic influence functions developed. However, more analyses will be required for various crack lengths, material properties, and loading conditions to draw the general conclusion since a crack length and material properties used in this study were restricted to one case.

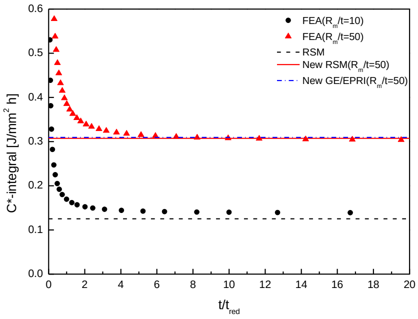

Fig. 4. C*-integral versus time with the new h_1&h_2

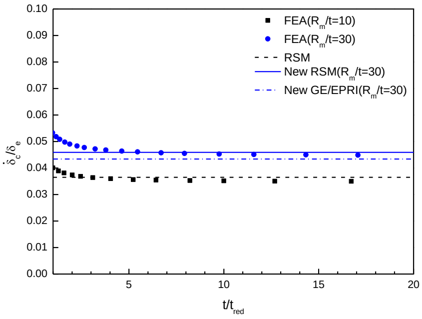

Fig. 5. COD rates versus time with the new h_1&h_2

4. Conclusions

In this paper, the applicability of famous the GE/EPRI method and the RSM method are investigated in the elastic-creep region for the application to thin-walled pipes with R_m/t over 30. As results, The GE/EPRI and the RSM significantly underestimate C*-integral and COD as R_m/t increases over 30. Therefore, extension of the estimation methods is needed considering R_m/t effect.

For extending their applicability, new plastic influence functions are developed and then, γ values are calculated by using new plastic influence functions. With the newly developed values, the GE/EPRI method and the RSM give more reliable COD rate and C*-integral for elastic-creep region. However, more analyses will be required for various crack lengths, material properties, and loading conditions to draw the general conclusion.

REFERENCES

[1] N.S.Huh, Y.-J.Kim, Y.J.Kim, Creep fracture mechanics analysis for through-wall cracked pipes under widespread creep condition, Transactions of the KSME(A), Vol.27, No.6, pp. 890-897, 2003

[2] F.W.Brust et. al., Assessment of short through-wall circumferential cracks in pipes, NUREG/CR-6235, April 1995