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Estimations of C^* and COD for Non-Idealized Circumferential Through-Wall Crack in Cylinders under Creep Conditions

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1. Introduction

On actual crack growth behavior of cylinders, internal surface crack develops through the wall thickness and may partially penetrate the wall thickness at its deepest point. So, the through-wall crack is formed with different crack lengths on inner and outer surface of cylinders during penetration process. These transition cracks are typically referred to as non-idealized through-wall crack (TWC). Therefore, to assess crack growth or leak rate more accurately, estimation of fracture mechanics parameter for non-idealized TWC in cylinders is necessary. In this context, some numerical works have been conducted to derive elastic and plastic fracture mechanics parameters such as stress intensity factor, *J*-integral and COD under elastic or plastic material behavior [1~4].

In this study, estimations of C^* and COD for non-idealized circumferential TWC in cylinders under creep condition were addressed through elastic-creep finite element(FE) analyses.

2. C^* and COD Estimation Methods

2.1 GE/EPRI method

Under creep condition, creep-deformation properties can be characterized as the power law (Norton's law) relation as follow:

$$\dot{\varepsilon}_c = A\sigma^n \tag{1}$$

where, $\dot{\varepsilon}_c$ denotes the creep strain rate and A denotes material constant, respectively. Due to the analogy between plasticity and creep which are idealized in power law, the C^* and COD rate estimation schemes for non-idealized TWC in cylinders can be expressed based GE/EPRI J and COD estimation methods as follow:

$$C^{*\ non-idealized} = AR_m(\pi-\theta_1)h_1(n)^{non-idealized}\left(\frac{Q\sigma_o}{Q_o}\right)^{n+1} \tag{2}$$

$$\dot{\delta}^{non-idealized} = AR_m\pi h_2(n)^{non-idealized}\left(\frac{Q\sigma_o}{Q_o}\right)^{n} \tag{3}$$

where, σ_o is yield strength, h_1 and h_2 are plastic influence functions, Q is the generalized load and Q_o is a generalized reference load for non-idealized TWC in cylinder. The plastic influence functions along the crack front for non-idealized TWC are given in Ref. [4].

Since the creep-deformation relation was idealized in power law, employment of GE/EPRI method is limited to only power law creep model.

2.2 Enhanced Reference Stress Method

Using analogy between plasticity and creep, the steady-state $C(t)$-integral (C^*) and COD rate for creep can be estimated as follow:

$$\frac{C^{*\ non-idealized}}{J_e^{\ non-idealized}} = \frac{E\dot{\varepsilon}_c}{\sigma_{ref}}\ ;\ \sigma_{ref} = \frac{Q}{Q_{oR}}\sigma_o \tag{4}$$

$$\frac{\dot{\delta}_c^{\ non-idealized}}{J_e^{\ non-idealized}} = \frac{E\dot{\varepsilon}_c}{\sigma_{ref}}\ ;\ \sigma_{ref} = \frac{Q}{Q_{oR}}\sigma_o \tag{5}$$

where, σ_{ref} is the reference stress(RS), $\dot{\varepsilon}_c$ is the creep strain rate at $\sigma = \sigma_{ref}$ determined from creep-deformation relation and Q_{oR} is optimized reference load defined to provide best estimates. Q_{oR} should be appropriately defined to minimize the influence of h_1 and h_2. Jang et al. proposed Q_{oR} for non-idealized circumferential TWC in cylinders as follow [3]:

$$Q_{oR} = S_{i,circ} \times Q_L \tag{6}$$

where '*i*' denotes the loading condition such as axial tension, global bending and internal pressure. S is modification factor for optimized reference load and Q_L is the generalized plastic limit load of idealized TWC.

ERS method has advantages against the GE/EPRI method because it is not restricted to idealized power law creep materials. Moreover, it is quite simple to use since it is formulated from plastic limit load solutions.

3. Elastic-Creep Finite Element Analyses

2.1Geometry

In this study, non-idealized circumferential TWC in cylinders subjected to axial tension (T), global bending moment (M) and internal pressure (P) was considered. The circumferential non-idealized TWC in the pipe is characterized by a half crack length (defined by half crack angle θ_1 and θ_2) on the inner and the outer surface of the pipe where $\theta_1>\theta_2$. In the present study, three parameters, i.e., θ_1/θ_2 (=1.5, 2), θ_1/π (=0.125, 0.250) and R_m/t (=5) are systematically considered.

2.2 Creep Law

In this study, three creep laws were considered, i.e., power law creep, primary-secondary creep and θ-projection creep which are described by Eq. (1), (7) and (8), respectively.

$$\varepsilon_c = \begin{cases} B\sigma^m t^p & \text{for} \quad t \le t_{fp} \\ B\sigma^m t_{fp}^p + A\sigma^n (t - t_{fp}) & \text{for} \quad t > t_{fp} \end{cases} \tag{7}$$

$$\begin{aligned} &\varepsilon_c = \theta_1(1-e^{-3600\theta_2 t}) + \theta_3(e^{3600\theta_4 t} - 1) \\ &\log\theta_i = a_i + b_i T + c_i\sigma + d_i\sigma T \quad ; \quad i = 1 \sim 4 \end{aligned} \tag{8}$$

where, Eq. (7) is for creep-deformation of typical TP316 stainless steels at 565°C and Eq. (8) is for that of typical Cr-Mo-V ferritic steels at 565°C. Detailed material constants of Eq. (7) and (8) are summarized in Ref. [5, 6].

2.3 Elastic-Creep FE analyses

Elastic-creep FE analyses for non-idealized TWC in cylinders were performed using the ABAQUS. In order to avoid problems associated with incompressibility, reduced integration 20 node elements (C3D30R in ABAQUS element library) were used. For power law creep, ABAQUS built-in routine was utilized to calculate the $C(t)$-integral, while for the other two creep laws considered in this study, the user subroutines were utilized.

4. Results

Figure 1 and Fig. 2 show the representative FE $C(t)$-integral and COD results on outer surface of non-idealized TWC under power law creep, respectively. FE results are compared with C^* at steady state ($t>t_{red}$) estimated from GE/EPRI method and ERS method. As expected, the GE/EPRI method gives overall accurate results, which in turn show the accuracy of the plastic influence functions for the plastic J-integral. ERS method shows good agreement with FE results in principle under the other creep laws as well as power law creep.

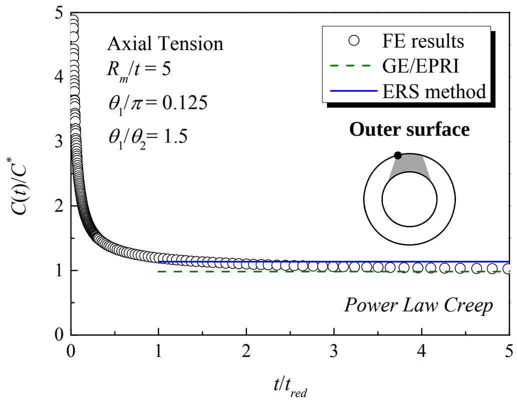

Fig. 1. Comparison of the FE $C(t)$-integral results under the power law creep with GE/EPRI and ERS methods.

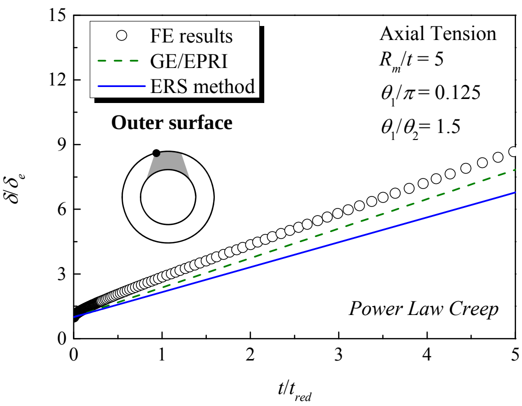

Fig. 2. Comparison of the FE COD results under the power law creep with GE/EPRI and ERS methods.

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