Elastic-Creep Fracture Analysis for Thin-walled Pipes with Circumferential Through-Wall Crack

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1. Introduction

A 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 breaks occurs. Applying LBB concept to the design stage of nuclear power plants, we can remove preventive measures against the postulated pipe break, thus can improve the piping layout and take economic benefits.

Sodium-cooled Fast Reactor (SFR) also considers LBB concept to reduce fire protection facilities against large-scale fire which might occur when the sodium coolant exposed to air. However, operating temperature of SFR is high enough to induce creep and LBB evaluation method including the effects of creep is not still well established.

Creep fracture mechanics parameters, C(t) and C* and crack opening displacement are crucial to perform high temperature LBB evaluation. In this paper, C(t), C* and crack opening displacement(COD) are evaluated under elastic-creep condition using finite element analysis (FEA) and considering SFR characteristics.

2. Engineering Equations

*2.1 Engineering Equations for C(t) and C**

For materials which follow power-law secondary creep, $\dot{\varepsilon}_c = A\sigma^n$, amplitude of near-tip stress and strain rate fields can be denoted C(t) for non-steady conditions or C* for steady state.

For elastic-creep condition, Ainsworth and Budden proposed a simple approximation for C(t) as follows [1]:

$$\frac{C(t)}{C^*} = \frac{(1+\tau)^{n+1}}{(1+\tau)^{n+1}-1} \tag{1}$$

where τdenotes the normalized time defined by

$$\tau = \frac{t}{t_{red}}, \quad t_{red} = \frac{K^2}{EC^*} \tag{2}$$

Redistribution time t_{red} is the time taken to redistribute from an initially elastic stress field ahead of a crack to a field described by C*.

Kim et al. found that variations of C(t)/C* with time are relatively insensitive to n, and suggested the equation (3) which gives best fits to numerous finite elements analysis results with 3.5 [2]:

$$\frac{C(t)}{C^*} = \frac{(1+\tau)^{4.5}}{(1+\tau)^{4.5}-1} \tag{3}$$

2.2 Engineering Equation for Creep COD

Creep COD rates can be estimated using reference stress and creep strain rate [3].

$$\frac{\dot{\delta}_c}{\delta_e} = \frac{\dot{\varepsilon}_c}{\varepsilon_e} = \frac{A\sigma_{ref}^n}{\left(\sigma_{ref}/E\right)}\,;\ \sigma_{ref} = \frac{P}{P_L}\sigma_y \tag{4}$$

where $\dot{\delta}_c$ denotes creep COD rates, and δ_e, ε_e denote elastic COD and elastic strain, respectively. P_L means plastic limit load corresponding to applied tension load, P and can be obtained by

$$P_L = 2\sigma_y R_m t\left\{\pi - \theta - 2\sin^{-1}\left(0.5\sin\theta\right)\right\} \tag{5}$$

3. Finite Element Analysis

3.1 Material Properties

Mod. 9Cr-1Mo (ASME Grade 91) steel is a candidate piping material for SFR in Korea and Japan. Table 1 shows material properties of Mod. 9Cr-1Mo used in this paper.

Table I: Material properties of Mod. 9Cr-1Mo steel

Temp(℃)	E(GPa)	σ_y(MPa)	A	n
600	164	247.5	1.28E-27	9.88

3.2 FEA Model

Elastic-creep FEA were performed for pipes with circumferential throughwall crack. A crack half angle(θ) is set to 12.5% of the circumferential length (θ/π=0.125).

Since SFR piping is designed to have thin wall thickness, Rm/t of FEA model is ranged from 5, 10, 30, and 40.

In the elastic-creep FEA, tension was first applied to the FE model and elastic analysis was performed. The load was then held constant and subsequent time-dependent creep analysis was performed. For the analyses, 30% of plastic limit tension was applied.

As C(t) is defined as a line integral close to a crack-tip, it is extracted from the 2nd integral contour of the crack tip. Since C(t) shows path dependence, FE mesh sensitivity was checked by using asymptotic elastic-creep equation. FE COD values were determined from FE displacement results in the mid-thickness at the center of the crack.

3.3 Results

The effects of R_m/t on FE C(t)/C* results are shown in Fig. 1. The C(t) and time t are normalized by the FE C* and redistribution time, respectively. The figure also shows the approximation of Eq. (1)

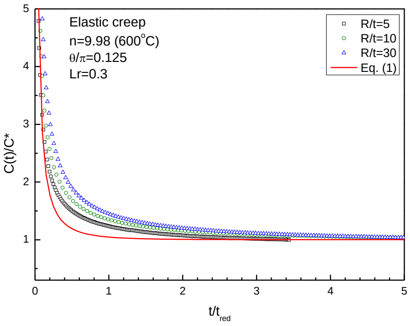

Fig. 1. Elastic creep C(t)/C* results with the estimation result with the equation (1)

Equation (1) estimates C(t)/C* lower than FE results at $t/t_{red} < 2$ while it fits well to the FE results at longer times. In $t/t_{red} < 2$, FE results give more conservative results than the value estimated by the equation (1) as R_m/t becomes larger. Since transient state exists in real plant operating condition and its duration time might be shorter than the redistribution time, C(t) might play more important role than C* on creep fracture mechanics evaluation. To estimate C(t) more exactly in thin piping structure, the effect of R_m/t and other parameters needs to be further studied.

Fig. 2 and 3 show COD rates which were normalized by elastic COD. The normalized COD rate is well fitted to the equation (4) in the case of $R_m/t=5$ while it becomes larger than the equation as a values of R_m/t increases over 5. It is speculated that there is an additional displacement in FE COD due to a bending-like effect that is occurred as crack opens and this effect enlarges as R_m/t increases. For Applying LBB concept, leakage size crack needs to be determined using COD and COA result. To calculate COD more precisely, COD of thin-walled pipe needs to be further studied.

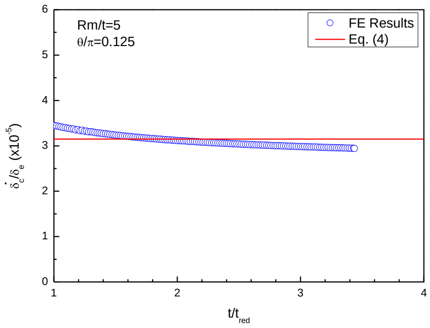

Fig. 2. Elastic creep COD rate results with the estimation result with the equation (4) ($R_m/t=5$)

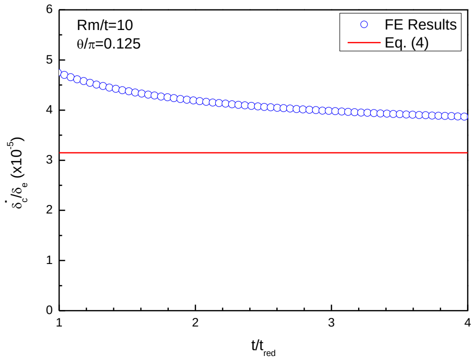

Fig. 3. Elastic creep COD rate results with the estimation result with the equation (4) ($R_m/t=10$)

4. Conclusions

Creep fracture parameters C(t), and C*, and COD are important elements to the assessment of leakage size crack and crack stability for high temperature LBB evaluation. In this study, C*/C(t) and COD rate were evaluated considering SFR thin-walled pipe geometry using FEA. As results of comparing FE results to the existing estimation equations, further study needs to be performed for the thin-walled pipe with R_m/t over 10.

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