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Characterization of three-dimensional crack border fields in creeping solids

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ABSTRACT

Creep fracture of solids at high temperature is vital to applications of many advanced materials, but most of the previous works are performed within the frame of two-dimensional theory. By using the out-of-plane stress constraint factor T_z, here we derive out three-dimensional asymptotic fields near the border of mode-I through-thickness cracks in power law creeping solids. It is found that the asymptotic fields near the crack border are dominated by both T_z and $C(t)$ integral. Detailed finite element analyses are carefully performed for single-edge cracked specimens and centre-cracked tension specimens to investigate the dominance of the asymptotic solution for the crack border fields. It is shown that the $C(t) - T_z$ description based on the obtained three-dimensional asymptotic solution can provide efficient prediction for the tensile stress ahead of the crack front under small scale creep condition. Under extensive creep conditions, a third parameter Q^* should be introduced to take into account of the loss in the in-plane constraint caused by in-plane geometries and loading configuration at extensive creeping, and a three-parameter $C(t) - T_z - Q^*$ description is proposed and proven to be efficient to predict the tensile stress on the ligament ahead of the crack for both specimens. Therefore, the two-parameter $C(t) - T_z$ and three-parameter $C(t) - T_z - Q^*$ descriptions can provide advanced theoretical basis for small and extensive creeping fracture assessments, respectively.

1. Introduction

According to Riedel (1987), the typical elastic creep-time curve of solids consists of three stages of creeping deformation as shown by Fig. 1. Following an initial elastic strain ε_{el} produced at the instant of loading, the three stages occur progressively over time. In the primary stage, strain ε increases with decreasing strain rate $\dot{\varepsilon}$ as time going. When entering the secondary stage (or steady state regime), strain increases at a constant strain rate obeying the Norton power law. While in the final tertiary stage, strain increases sharply with increasing strain rate and finally leads to fracture when strain reaches the failure value ε_f at time t_r. For most creeping solids, the stationary stage takes most of the creeping life. Therefore, our study in this work will concentrate to the important secondary stage.

With reference to polar coordinates, r and θ, centered at the crack tip, the crack tip fields have been described by Riedel and Rice (1980) using a single parameter $C(t)$ in two-dimensional (2D) ideal plane stress and plane strain states as follows:

$$\sigma_{ij} = \left[\frac{C(t)}{BI_n r}\right]^{\frac{1}{n+1}} \tilde{\sigma}_{ij}(\theta, n), \tag{1.1}$$

$$\dot{\varepsilon}_{ij} = B\left[\frac{C(t)}{BI_n r}\right]^{\frac{n}{n+1}} \tilde{\dot{\varepsilon}}_{ij}(\theta, n), \tag{1.2}$$

$$\dot{u}_{ij} = Br\left[\frac{C(t)}{BI_n r}\right]^{\frac{n}{n+1}} \tilde{\dot{u}}_{ij}(\theta, n), \tag{1.3}$$

where B is the creep parameter and n is the creep exponent of the solids in the Norton power law (or power law creeping),

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + B\sigma^n, \tag{1.4}$$

where E is Young's modulus.

The above solution has been widely recognized as the RR field solution, in which the dimensionless constant I_n and angular functions $\tilde{\sigma}_{ij}$, $\tilde{\dot{\varepsilon}}_{ij}$ and $\tilde{\dot{u}}_{ij}$ depend only on the creep exponent n in plane stress or plane strain state, but quite different in the two limited stress states. These functions can only be solved out through complicated numerical process and the results have been tabulated by Shih (1983). The $C(t)$-integral is path-independent within the creep zone, defined as the region where the equivalent creep strain $\bar{\varepsilon}^c = \left(\frac{2}{3}\varepsilon^c_{ij}\varepsilon^c_{ij}\right)^{1/2}$ exceeds the equivalent elastic strain $\bar{\varepsilon}^e = \left(\frac{2}{3}\varepsilon^e_{ij}\varepsilon^e_{ij}\right)^{1/2}$ (Riedel and Rice, 1980).

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