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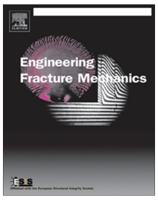

Extended finite element method for power-law creep crack growth

Qinghua Meng *, Zhenqing Wang

College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin 150001, China

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ABSTRACT

The extended finite element method (XFEM) is implemented to model the crack and crack growth behavior in the power-law creep materials. The displacement approximation is enriched near the crack tip by incorporating the asymptotic fields in power-law creep materials. The maximum principle stress criterion is used to specify the direction of crack growth. The maximum principle strain criterion is used to specify the crack initiation. The explicit time integration scheme is employed with an automatic time stepping algorithm. Several crack and crack growth examples are simulated to demonstrate the effectiveness of the proposed method. Numerical results show a reasonably good agreement with the experimental results.

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1. Introduction

Many components are continually exposed to high temperatures in power generation plants, steam turbines, nuclear reactor, aircraft and aerospace power device etc., which are high enough for creep to occur. Such components may contain cracks or must be assumed to contain cracks as part of design life or remaining life analyses. Creep crack growth is often the main cause of failure of these components. The ability to obtain accurate predictions of crack growth under creep conditions is an essential requirement for the lifetime assessment of engineering components operating at high temperature.

A few theoretical and numerical studies have been carried out to predict creep crack growth. The analysis solution of creep crack growth goes back to the work of Hui and Riedel [1], they derived the asymptotic stress and strain fields near the tip of a slowly growing crack for power law creep materials. Further, Riedel [2] employed Kachanov-type damage models to describe creep crack growth under small-scale creep conditions. Murakami et al. [3] analyzed the asymptotic fields of stress and damage of a model I creep crack in steady-state growth on the basis of continuum damage mechanics by employing a semi-inverse method and developed a computational method for creep crack growth using a new creep damage model [4]. The incremental finite element program based upon the implicit time-integration scheme was developed to analyze crack growth in an elastic creeping solid by Hawk and Bassani [5,6]. Finite element creep analyses were used to study crack growth behavior, under constant loading at high temperature, in compact tension specimens by Xia et al. [7] and Zhao et al. [8]. Hyde et al. [9–12] developed a creep damage finite element program to predict creep crack growth in several engineering materials using continuum damage models. Yatomi et al. [13–15] performed an analytical model to predict steady state crack growth based on a modified version of the NSW model [16]. The similar damage model was used to analyze creep crack growth behavior in ASME P92 steel [17,18]. Creep crack growth tests were carried out in compact tension specimens with

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* Corresponding author. Tel.: +86 451 82589364.
E-mail address: mengqinghua@hrbeu.edu.cn (Q. Meng).

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Nomenclature

A	area
$\boldsymbol{a}_j,\boldsymbol{b}_k^l$	nodal enriched degree of freedom vector
$\boldsymbol{b}$	body force
B	creep coefficient
$\boldsymbol{B}$	strain matrix
$C(t)$	contour integral related to the time
$\boldsymbol{D}$	matrix of elastic properties
E	Young's modulus
H	discontinuous jump function
I_n	integration constant
J	path-independent contour integral
K	stress intensity factor
$\boldsymbol{K}$	stiffness matrix
n	creep exponent
$\boldsymbol{n}$	unit normal vector
N	finite element shape function
$\boldsymbol{N}$	shape function matrix
(r, θ)	polar coordinate system
S_{ij}	components of deviatoric stress tensor
t	time
$\bar{\boldsymbol{t}}$	prescribed traction
$\boldsymbol{u}$	displacement tensor
$\bar{\boldsymbol{u}}$	prescribed displacement
v	Poisson's ratio
W	strain energy density
$\boldsymbol{x}$	Gauss point
$\boldsymbol{x}^*$	point closed to $\boldsymbol{x}$
ε	uniaxial strain
ε_{ij}	strain components
ε^c	creep strain
$\boldsymbol{\varepsilon}$	small strain tensor
σ	uniaxial stress
σ_{ij}	stress components
σ_e	equivalent stress
$\boldsymbol{\sigma}$	Cauchy stress tensor
ψ	enrichment function
Γ	closed contour
∇	gradient operator
∇_s	symmetric gradient operator

different crack depths. Finite element analysis of uniaxial and multiaxial state of stress on creep fracture behavior of 2.25Cr–1Mo steel based on continuum damage model was carried out by Goyal et al. [19].

The extended finite element method (XFEM) [20,21] has emerged as a powerful numerical procedure for the analysis of crack problems. The XEFM exploits the partition of unity property of finite elements [22], which allows local enrichment functions to be easily incorporated into classical finite element approximation, to model cracks and crack growth with no remeshing. So far the XFEM has been widely used to model crack and crack growth in fracture mechanic problems. Implementation of the XFEM include three-dimensional crack growth by Sukumar et al. [23] and Areias and Belytschko [24], higher order finite elements by Stazi et al. [25] and Laborde et al. [26], fatigue crack growth by Ferrie et al. [27] and Elguedj et al. [28], cohesive crack growth by Moës and Belytschko [29] and Zi and Belytschko [30], dynamic crack propagation by Belytschko et al. [31] and Réthoré et al. [32] and Song and Belytschko [33], thermoelastic fracture problem by Duflot [34] and Zamani and Eslami [35], fracture in composite materials by Huynh and Belytschko [36] and piezoelectric materials by Béchet et al. [37] and Nguyen-Vinh et al. [38]. In the present paper, the extended finite element method (XFEM) will be extended to model crack and crack growth behavior in materials under creep condition.

The present paper is organized as follows. In Section 2, crack tip fields in creep materials are briefly reviewed. In Section 3, the governing equations and the enrichment functions of the displacement fields are described and the crack growth criterion is also given. In Section 4, the implementation algorithm of XFEM for creep crack growth is presented. Several numerical examples are given in Section 5. Finally, the conclusions are drawn in Section 6.

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