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Study of creep relaxation under combined mechanical and residual stresses

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ABSTRACT

In this work the elastic and elastic–plastic creep behaviour of cracked structures in the presence of residual stress has been studied numerically. The residual stress is introduced by prior mechanical loading and mechanical stress levels are varied to evaluate the transient crack tip parameter, $C(t)$, in single edge notch bend, SEN (B), and tension, SEN (T), specimens, using the finite-element (FE) method. The near tip stress distributions are examined and the influence of residual stress on the evolution of the stress fields, quantified by $C(t)$, is examined. The values of $C(t)$ obtained from the FE analysis are compared to existing analytical solutions. It has been found that the transient $C(t)$ value provides an accurate characterisation of the crack tip fields under combined primary and secondary stress. It has also been found that the level of conservatism of current $C(t)$ estimation schemes, which account for primary and secondary stress, depends on material properties and the level of primary and secondary stress.

1. Introduction

Loading history is expected to influence the creep response of engineering components and previous work has indicated that a tensile residual stress field can give rise to creep damage in laboratory specimens [1]. Existing structural integrity procedures, e.g. R6 [2] and R5 [3], provide recommendations for the treatment of combined secondary (e.g. residual) and primary (mechanical) stresses. These typically rely on simplified calculations based on stress intensity factor estimations for a range of given residual stress profiles and geometries. Estimation formulae for describing creep relaxation under primary loads have been developed in [4,5] and extended to the case of combined primary and secondary loading in [6]. Creep relaxation of axially loaded cylinders under combined thermal and mechanical stresses was examined in [7], and a modification to existing approaches to account for thermal stress was proposed.

In this work, finite-element studies have been carried out to assess the stress redistribution and associated fracture mechanics parameters during creep, under combined residual and mechanical stresses. Self-equilibrating residual stress distributions are studied, which are inserted by bending of cracked specimens and relax with time under increasing creep deformation. In a previous study [8], the authors have considered relaxation behaviour of bend and tension geometries under combined mechanical and residual stress. This work extends the study to the case of creep under elastic–plastic conditions and also provides comparisons with reference stress solutions for combined primary and secondary stress. Particular attention has been paid to the time for the stress distributions to reach steady state, with crack tip stress and strain fields characterised by the parameter C^*, independent of the initial residual stress distribution. Near crack tip stress fields have also been studied numerically and analytically.

The paper provides the theoretical background of the study in Section 2, the computational approach is summarised in Section 3 and the results are presented in Section 4. Section 4 presents the creep relaxation behaviour under combined secondary and primary stresses for elastic and elastic–plastic creeping materials.

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Nomenclature

a	crack length
A	coefficient in power-law creep definition
B	specimen thickness
$C(t)$	transient creep crack tip characterising parameter
C^*	steady state creep crack tip characterising parameter
C_N	elastic–plastic material coefficient
E	elastic (Young's) modulus
E'	effective elastic (Young's) modulus
J	elastic–plastic fracture mechanics parameter
J_0	initial J
K^p	primary (mechanical) stress intensity factor
K^s	secondary (residual) stress intensity factor
L_r	measure of the proximity to failure of a defected body by plastic collapse
M	bending moment
M_L	limit bending moment
n	power-law creep stress exponent
N	power-law plastic stress exponent
P	load
P_L	limit load
t	time
t_{red}	redistribution time
W	specimen width
$\dot{W}$	strain energy density rate
x	a/W
Z	elastic follow-up factor
β	residual stress quantifying factor
γ	$2/\sqrt{3}$
Γ	crack tip contour
ε	strain
ε_{ref}	total reference strain
ε_y	yield strain
ε^0_{ref}	initial reference strain
$\dot{\varepsilon}$	creep strain rate
$\dot{\varepsilon}_{ref}$	total reference strain rate
$\dot{\varepsilon}^0_{ref}$	initial reference strain rate
σ	stress
$\sigma_{ref}(t)$	total reference stress
σ_y	yield stress
σ^0_{ref}	initial reference stress
σ^p_{ref}	reference stress due to the primary stress
$\dot{\sigma}_{ref}(t)$	total reference stress rate
ϕ	initial plasticity dependent factor
$\Psi(\mathrm{t})$	exponent in definition of creep relaxation based on reference stress method

2. Theoretical background

2.1. Definition of parameters for creep under combined primary and secondary stresses

Due to the time-dependent nature of the singular stress and strain fields, introduced by mechanical loading, around a stationary crack tip during creep, the transient crack tip parameter under creep conditions, $C(t)$, is used to identify the stress and strain distribution (see e.g. [9]) and is defined by

$$C(t) = \int_{\Gamma \to 0} \dot{W}(\dot{\boldsymbol{\varepsilon}}^c)dy - \mathbf{t}\frac{\partial \dot{\mathbf{u}}}{\partial x}ds, \tag{1}$$

where

$$\dot{W}(\dot{\boldsymbol{\epsilon}}^c) = \int \boldsymbol{\sigma} d\dot{\boldsymbol{\varepsilon}}^c. \tag{2}$$