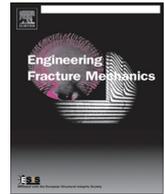




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## Load-independent creep constraint parameter and its application



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### ABSTRACT

A load-independent creep constraint parameter  $R^*$  was proposed, and its load-independence was validated using finite element results in previous studies. A fixed distance  $r = 0.2$  mm from a crack tip is chosen to define the  $R^*$ , and the  $R^*$  at steady-state creep can be used to evaluate constraint level with little conservatism for whole creep time. The  $R^*$  can be used for ranking constraint levels for different specimens or components, and for predicting constraint-dependent creep crack growth rates. The constraint-dependent creep crack growth rate equations of a Cr–Mo–V steel have been obtained, and it may be used in creep life assessments.

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### 1. Introduction

Many experimental and theoretical evidences have shown that crack-tip constraint state has great influence on the fracture behavior of materials, and the loss of constraint causes the increases in fracture toughness [1]. The quantification of constraint has been widely investigated within the elastic–plastic fracture mechanics frame, and led to the development of two parameter fracture mechanics, such as  $J$ - $T$ ,  $J$ - $Q$  and  $J$ - $A_2$  [2–5]. In these approaches, the first parameter  $J$  integral sets the size scale over which high stresses and strains develop, and the secondary parameters  $T$  [2],  $Q$  [3,4] and  $A_2$  [5] were introduced to quantify the crack-tip constraint. The Hutchinson–Rice–Rosengren (HRR) singular stress field or the small scale yielding (SSY) solution with  $T$ -stress = 0 is generally used as the reference field to study the crack-tip constraint [1,3,4,6,7].

Under creep conditions, some experimental and theoretical evidences have shown that constraint can affect creep crack growth (CCG) rate [8–13]. In a recent study, it has been found that there is a significant constraint effect on CCG rate in low  $C^*$  region [14], and the CCG rates increase with increasing out-of-plane constraint (specimen thickness). To achieve accurate structural integrity assessment for high temperature components, it is necessary to find a simple and accurate constraint parameter to quantify the creep crack-tip constraint level in specimens or components, and then the correlation of constraint-dependent CCG rates of specimens or components can be obtained. However, the studies for two-parameter characterization of creep crack-tip fields are very limited. The creep crack-tip stress and strain rate fields are usually described by the  $C^*$ - $Q$  two-parameter and the  $Q$  is used to quantify the constraint [15–17]. The effect of in-plane constraint on CCG using  $Q$  parameter was examined [16]. Combined the  $C^*$ - $Q$  two-parameter concept with the NSW model, Nikbin [13] investigated the effect of constraint on the CCG rate. Based on the  $C^*$ - $Q$  two-parameter concept and finite element (FE) analysis, Bettinson et al. [17] examined the effect of specimen type and load level on the  $Q$  from short to long term creep conditions for elastic-creep materials.

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## Nomenclature

$a$	crack length
$a_0$	initial crack length
$\dot{a}$	creep crack growth rate
$\dot{a}_0$	creep crack growth rate from the standard specimen
$A$	coefficient in the power-law creep stain rate expression
$B$	specimen thickness
$B_n$	net specimen thickness
$C^*$	$C^*$ integral analogous to the $J$ integral
$C(t)$	$C(t)$ integral
$D_0$	material constants of CCG rate
$E$	Young's modulus
$I_n$	dimensionless constant related to $n$
$J$	$J$ -integral
$L$	characteristic length, usually is set as 1 m
$n$	power-law creep stress exponent or power-law stain hardening exponent in Ramberg–Osgood relation
$q$	material constant of CCG rate
$Q$	constraint parameter under elastic–plastic condition
$Q^*$	load-independent constraint parameter under elastic–plastic condition
$R$	creep constraint parameter
$R^*$	load-independent creep constraint parameter
$R_{avg}^*$	average value of $R^*$ along 3D crack front
$R_{z0}^*$	$R^*$ value at specimen center
$r$	distance from a crack tip
$r_c$	creep damage zone
$t$	creep time
$t_{red}$	creep redistribution time
$W$	specimen width
$z$	distance from specimen center along crack front
$\alpha$	strain hardening coefficient in Ramberg–Osgood relation
$\delta_{ij}$	dimensionless function of $n, \theta$
$\varepsilon_0$	yield strain
$\dot{\varepsilon}_0$	creep strain rate at yield stress
$\theta$	polar coordinate at the crack tip
$\sigma_0$	yielding stress
$\sigma_{22}$	opening stress
$\sigma_{ij}$	deviatoric stress
$\bar{\sigma}_{ij}$	dimensionless stress function of $n, \theta$
$\nu$	Poisson's ratio

## Abbreviations

3D	three dimension
CCG	creep crack growth
CT	compact tension
CT2	compact tension specimen with 2 mm thickness
CT5	compact tension specimen with 5 mm thickness
CT10	compact tension specimen with 10 mm thickness
CT10-SG	compact tension specimen with 10 mm thickness and side grooves
CCT	center-cracked tension
FEM	finite element method
LSC	large-scale creep
LSY	large-scale yield
PE	plane strain
PS	plane stress
SENB	single-edge notched bend
SENT	single-edge notched tension
SENT <sub><math>\Delta p</math></sub>	single-edge notched tension with 0.05 W loading point offset
SSC	small-scale creep
SSY	small-scale yield

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