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A unified multiscale ductility exhaustion based approach to predict uniaxial, multiaxial creep rupture and crack growth

K. Nikbin

Department of Mechanical Engineering, Exhibition Road, London SW7 2AZ, United Kingdom

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ABSTRACT

Numerical and analytical methods for predicting uniaxial damage have largely depended on the constituent components of the stress/strain measured data which have inherent scatter. Models developed for this purpose have also attempted, with some degree of success, to address the fundamental issues of failure mechanisms within a multiaxial stress state context. This paper presents a new analytical/empirical/a postpriori unifying approach to predict creep damage and rupture under uniaxial/multiaxial and crack growth conditions by deriving a multiscale based constraint criterion. Essentially, the model links the global constraint due to geometry in a globally isotropic material with a microstructural constraint arising from creep diffusional processes occurring in a sub-grain locally anisotropic microstructure. Furthermore, it is shown that the model is consistent with the established NSW crack growth model (Nikbin et al., 1984, 1986; Tan et al., 2001) which is routinely used to determine the plane stress/strain bounds for cracking rates in fracture mechanics geometries and cracked components. The concept assumes that at very short times an initial upper shelf material tensile strength and global plasticity and power law creep control creep damage failure and sub grain multiaxial axial stress state dependent failure strain dominates the long term diffusion/dislocation controlled creep response. It is established that the material yield strength in the short term and a measure of creep failure strain at the creep secondary/tertiary transition region described at the limits by the Monkman-Grant failure strain (Monkman and Grant, 1963), are the important variables in both the uniaxial and multiaxial failure processes. For verification creep constitutive properties from long term data from uniaxial and multiaxial and crack growth tests on Grade P91/92 martensitic steels from various databases (EPRI, private communications; NIMS data base), are used to establish the procedure.

1. Background to creep damage modelling

Life cycle for validated material characterisation used in high temperature plant could take up to 10–15 years. Understanding damage and quantifying it to predict creep rupture and crack initiation and growth from mainly accelerated tests has been the subject of many years of research [9–15]. This has been with the chief aim of reducing the production and verification time cycle of new alloys. There are numerous creep rupture ductility models which suggest mechanism change and base their assessment on parametric power law, multi-parameter methods, exponential fits and theta projection [16–18]. They are all used to some degree of success in uniaxial rupture predictions but they are not appropriate for use under

E-mail address: k.nikbin@imperial.ac.uk

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Nomenclature

MG	Monkman-Grant strain
MSF	Multiaxial Strain Factor
NSW	Nikbin, Smith, Webster Model
σ_1, σ_m	principal, mean stresses
$\sigma_e \equiv \bar{\sigma}$	von Mises stress (MPa)
σ_{eff}	effective stress (MPa)
t, t_r, t_i	time, time to rupture (hours), time to crack initiation
σ_t	failure stress at time t
$h = (\sigma_m/\sigma_e)$	constraint parameter
$h_o = 0.33$	value of h at plane stress
$h_o^* = h_o/h$	normalised h from plane stress h_o
α	multiaxial stress state parameter
A, n	The Norton's creep constant and creep index
$e^{-Q/RT}$	the temperature activation terms
β, B', b', A', A''	Material constants in the relevant equations
ε_{MG}	MG failure strain, (/1)
ε_f, ε_{RA}	Elongation (EL) failure strain and reduction in area. (RA), (/1)
ε_f^*, ε_f	multiaxial failure strain and the uniaxial failure strain
ε_{fMG}^* and ε_{fMG}	MG multiaxial failure strain and the MG uniaxial failure strain
ε_o^* (MSF)	Multiaxial Strain Factor, $\varepsilon_o^* = (\varepsilon_{fMG}^*/\varepsilon_{fMG})$
a, Δa, da	crack length (mm), crack initiation length, crack length increment
$\dot{a} = da/dt$	crack growth rate (mm/h)
$\dot{a}_I$, $\dot{a}_s$	initial and steady state crack growth rate (mm/h)
B	sample thickness
U^*	the potential energy rate
C^*	creep crack growth rate parameter integral (MJ/m^2 h)
I_n, r_c, A_{rc}	stress exponent, creep process zone, Creep
$\emptyset = n/(n+1)$	creep crack growth rate constant as a function of creep index
D	creep crack growth rate constant
dr	element ahead of the crack tip
$MN/UB/LB$	Mean/Upper/Lower Bounds

multiaxial conditions. The effects of multiaxiality testing and modelling using notched bars have also been developed in various ways to some degree of success [19–29]. For example, one approach to assess constraint [21–24] is the use of a multiaxial stress state parameter, α, deriving an effective rupture stress, σ_{eff}, from the bounds derived from principal and von-Mises stresses, σ_1 and σ_e, giving

$$\sigma_{eff} = \alpha\sigma_1 + 1 - \alpha\sigma_e \tag{1}$$

In a simple form when $\alpha = 0$ the failure is σ_e controlled and when $\alpha = 1$ the failure is σ_1 controlled. These models have been used to predict multiaxial failures in notched bars and cracked components. This approach highlights the importance of deriving a constraint term where creep cracking is concerned.

There are also available two categories of models that deal with multiaxial creep damage which are in turn analytical and numerical. In practice computationally intensive elastic/plastic/creep analysis methods are needed to derive useful results. One approach is the remaining multiaxial ductility based models which relate stress state described by a constraint parameter $h = (\sigma_m/\sigma_e)$ to multiaxial ductility [30,31] and the second approach is the continuum damage modelling (CDM) [32–39]. The latter uses different types of constraint based arguments including Eq. (1) to determine the effects of multiaxiality under creep conditions.

Reviews of creep CDM models [14,15] highlights in depth the various isotropic damage models and their corresponding microstructure damage mechanisms. In most cases they need to establish complex constitutive relationships and define a larger number of variables to perform the predictions. Furthermore, using the CDM based models that need to derive α and h from notch bar tests to predict multiaxial rupture over long term, use numerically derived skeletal stresses in their analysis [23]. These skeletal stresses are at best numerical approximations of the notch region stress state, normalised against the creep index n. Therefore, they are only an approximate representation of the controlling stresses at the notch throat. Thus the CDM predictions from such approximations, plus the fact that upto seven materials variables may need to be determine in the analysis [15] from experimental data make their use limited to a qualitative understanding of the problem. The assessment using CDM are likely to be further diluted and unrealistic for very long test times assessment