Creep constitutive equations for predicting creep response of a P91 steel

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Abstract

Creep modelling has assumed considerable importance in recent years in view of the growing needs to develop high temperature materials for modern super critical and ultra super critical power plants. In this study three sets of creep/damage coupled models, namely Kachanov-Rabotnov, Liu and Murakami and Dyson and Mclee, are coded in MATLAB to predict the creep behavior of the ferritic steel. Uniaxial simulations result indicate that the Kachanov-Rabotnov is its limited use over a wide stress range and is not able to capture physical nature of damage mechanisms with single damage variable .Moreover as a result of small punch test simulations it is concluded that the damage parameters are obtained from small punch test are more reliable than those ones obtained from the uniaxial test data since the material under small punch test includes multiple deformation mechanisms such as compression, tension, is most likely prone various damage mechanisms**.**

Keywords: creep modelling, p91 steels, small punch testing, power plant

1. Introduction

The life time creep assessment of P91 steel, commonly used material in high temperature application, is still an important problem.Therefore, creep modelling has gained considerable importance in recent years in view of the growing needs to develop materials to be used in modern super critical and ultra super critical power plants. Recent studies on such models are given through [1]**.**

These models generally attempt to characterize the full creep curve, including the primary, secondary and tertiary creep stages. Nonlinear nature of the strain time plot requires a large number of stress and temperature dependent parameters to describe its shape. In this study three sets of creep/damage coupled models were used , namely, Kachanov-Rabatnov-Hayhurst (KRH), Liu and Murakami [3] and Dyson and McLean [2] to predict the creep behaviour of the ferritic steel. These three sets of creep/damage models are compared in their capability of predicating uniaxial creep behaviour of the P91 steel under various constant stresses at 625 ^{o}C . Dyson and Mclee creep model is then used to implement into the commercial code ABAQUS via CREEP and USDFLD subroutines in order to predict the creep failure and rapture time of the P91 steel under various constant loads at 625 ^{o}C.

2. Constitutive equations of the creep models

In this formulation internal state variables characterizing the states of hardening/recovery and damage are introduced into the creep potential and the flow rule that are usually used to establish constitutive equations of multiaxial creep.
creep models.

2.1. Kachonov-Robatnov Constitutive Equations

The classical Kachonov-Robatnov Constitutive Equations consists of a pair of coupled creep/damage equations. The uniaxial form of the constitutive equations for as given below.

$$\frac{d\varepsilon_{cr}}{dt} = A\left(\frac{\sigma}{1-\omega}\right)^{n} t^{m} \tag{1}$$

and the damage evolution equation is expressed

$$\frac{d\omega}{dt} = B\frac{(\sigma\ \ )^{x}}{(1-\omega)^{q}}\, t^{m} \tag{2}$$

Where ε_{cr} is the creep strain, σ is the applied constant stress and ω is the scalar damage variable that represents cavitation damage varying from, 0 to a critical damage value, The model includes a set of parameters, A, B, q, x, m and n that need to be identified.

Table 1: Material constants of Kachonov-Robatnov Model [4])

Material	A	N	M	B	$\emptyset$	χ
Bar 257	$1.092\cdot10^{-20}$	8.462	$4.754\cdot10^{-4}$	$3.537\cdot10^{-17}$	7.346	6.789

2.2. Dyson and Mclee Constitutive Equations

In this particular constitutive equations multi variable variables constitutive equations are proposed to include following mechanisms: cavitation damage from cavity nucleation and growth precipitate coursing, dislocation accumulation and strain hardening during primary creep. The form of the constitutive equations proposed for uniaxial conditions is given by the following set of equations

$$\dot{\varepsilon} = A\sinh\left\{\frac{B\,\sigma(1-H)}{(1-\emptyset)(1-w)}\right\}$$
$$\dot{H} = \frac{h\,\dot{\varepsilon}}{\sigma}\left\{1-\frac{H}{H^{*}}\right\} \tag{3}$$

$$\dot{\emptyset} = \frac{K_C}{3}(1-\emptyset)^4$$
$$\dot{w} = DA\sinh\left\{\frac{B\,\sigma(1-H)}{(1-\emptyset)(1-w)}\right\} \quad \text{cont. (3)}$$

In the given set of equations above, the second one describes the primary creep due to initial strain hardening and the formation of dislocation microstructure. In the third one, the damage variable, $\emptyset$ reflects the effects of precipitate coarsening that may restrict the deformation within grain interior. The fourth relation in Eq. (3) .describes the effect of cavitations damage that reduces the load bearing section and accelerate the creep damage.

Table 2: Material constants of Dyson and Maclee [4]

Material	A	B	H	H^*	K_c	D
Bar 257	$6.216\cdot10^{-8}$	0.15	$1.0\cdot10^{4}$	0.35	$4.998\cdot10^{-4}$	2.0

2.3. Liu-Murakami Constitutive Equations

Liu and Murakami[3] was proposed the creep damage model extending the micromechanics based constitutive equation of Hutchinson and Riedel. The form of the constitutive equations proposed for uniaxial conditions is given by the following set of equations.

$$\frac{d\varepsilon}{dt} = A\sigma^n \exp\left[\frac{2(n+1)}{\pi\sqrt{1+3/n}}\omega^{3/2}\right]$$
$$\frac{d\omega}{dt} = \frac{B[1-\exp(-q_2)]}{q_2}(\sigma)^{\chi}\exp(q_2\omega) \quad (4)$$

where A, n, M, q_2 and χ are the material constants. The term, $\frac{2(n+1)}{\pi\sqrt{1+3/n}}\omega^{3/2}$ in Eq. 16 describes the microcrack parameter, ρ and ω is a function of damage microstructure(micro crack length and density).

3. Predicating the creep behaviour

All three creep models mentioned above are used to predict the creep response of the of P91 steel under constant stresses of 70,83,97,93 and 100MPa at 625°C. The results obtained from three models are presented in Figure1.

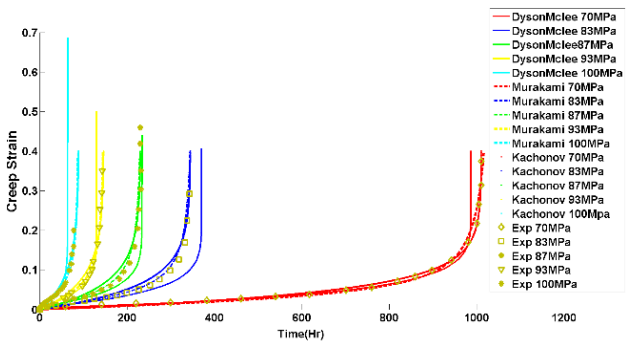

Figure 1: Uniaxial creep test simulation of three creep models

These result clearly indicates that the Kachanov-Rabotnov is its limited use over a wide stress range and is not able to capture physical nature of damage mechanisms with single damage variable. Small punch test is a promising tool to characterize elastic, plastic and creep properties of materials. It is relatively new method that uses miniaturised samples having dimensions of 0.25-0.5 mm thickness and 8-10 mm diameter. The small punch tests are simulated under different loads from 270 to 314 at 600˚C and the result obtained as displacement versus creep time is ploted in Figure 2

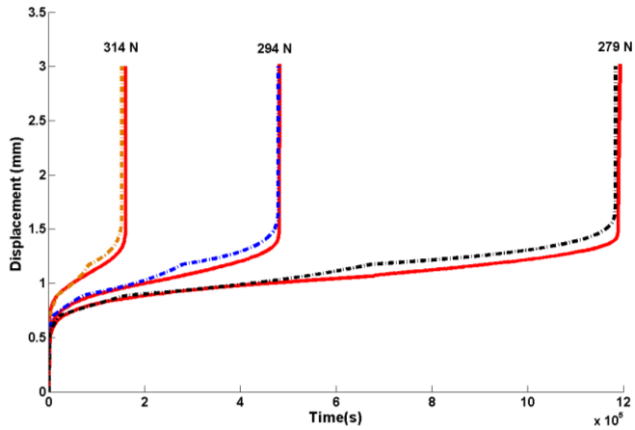

Figure 2: Small Punch creep test simulation of the creep models

As one can see from Figure-7 that the calibrated constitutive constants fit closely with the calculated curves to the experimentally observed displacement time curves under constant loads of 276N, 294N, and 314N, respectively..

4. Conclusions

The creep properties and the behavior of the P91 steel that are widely used for welded steam pipes in the construction of power plant components are determined by means of uniaxial and small punch experiments in conjunction with finite element analyses. As a result of these finite element analyses it is founded that the material parameter set determined only from the conventional uniaxial set may not be used directly in simulation of any structural components that operate under high temperature and stress conditions. Therefore one may conclude that the damage parameters are obtained from small punch test are more reliable than those determined from the uniaxial test data

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