A COMPUTER SIMULATION OF DUCTILE BEHAVIOUR IN A HIGH STRENGTH STEEL

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INTRODUCTION

The ductile fracture of a high strength steel has been simulated by representing the point-wise continuum behaviour of the material in a necking tensile specimen or in notched bars by the macroscopic response of a void model [1]. Geometrically, the model consists of an initially spherical void embedded in a cylinder. A quadrant of this cell is shown in Fig. 1. The displacement of the external boundary of the cell is regulated through the relationship

$$\frac{\dot{R}}{R} = -\alpha \frac{\dot{L}}{L} \quad (\text{i.e. } \dot{\bar{\varepsilon}}_r = -\alpha\, \dot{\bar{\varepsilon}}_z) \qquad (1)$$

where different amounts of radial contraction can be assigned to the cell as it extends through the choice of α. This, in effect, controls the degree of stress triaxiality that the cell experiences. Since the incremental displacement loading is a proportional straining and the model is axisymmetric, the macroscopic stress/strain response of the cell is governed by the following relationships.

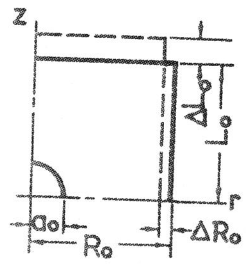

Fig. 1 A quadrant of the axisymmetric cell

$\bar{\varepsilon}_e = \frac{2}{3}(\bar{\varepsilon}_z - \bar{\varepsilon}_r)$ - the equivalent strain

$\bar{\varepsilon}_m = \frac{1}{3}(2\bar{\varepsilon}_r + \bar{\varepsilon}_z)$ - the mean strain

$\bar{\sigma}_e = \bar{\sigma}_z - \bar{\sigma}_r$ - the equivalent stress

$\bar{\sigma}_m = \frac{1}{3}(\bar{\sigma}_z + 2\bar{\sigma}_r)$ - the mean stress

in which $\bar{\sigma}_z$, $\bar{\sigma}_r$ are the average normal stresses along the external boundary of the cell.

The matrix of the cell is assumed to be of an elastic-plastic strain-hardening material which softens irreversibly when one of the following two critical conditions is met locally, the one being that which occurs first as the element of material is loaded.

1. Stress criterion

$$(\sigma_m + \lambda_e \sigma_e)/\sigma_Y = \sigma_{cy} \qquad (2)$$

in which σ_m, σ_e and σ_Y are the local (or microscopic) mean stress, equivalent stress and yield stress in the matrix and λ_e is a parameter which apportions the effect of σ_m and σ_e; σ_{cy} is the normalized critical stress.

2. Strain criterion

$$\varepsilon_e = \varepsilon_c \quad \text{the critical local equivalent strain} \qquad (3)$$

Similar criteria were used by the Beremin group [2] and by Hancock and Cowling [3] to predict the nucleation of the main voids in ductile materials. In our own work [1], we have applied criterion 1 to predict the softening due to the nucleation of second order voids. The need for an alternative criterion of strain control arises when the triaxiality is relatively low, the material is more ductile and its state is more sensitive to strain than it is to stress (c.f. Hancock and Cowling [3]).

RESULTS OF THE COMPUTER SIMULATION

The experimental data of Mackenzie et al. [4] on a high strength steel Q1 were simulated in our work. The tests [4] were done on two orientations of the steel, one in the long transverse direction (ℓ.t.) and the other in the short transverse direction (s.t.).

With a Poisson's ratio $\bar{\nu} = 0.3$, Young's modulus $\bar{E} = 206$ GPa and a yield stress $\bar{\sigma}_Y = 0.27 \times 10^{-2}\ \bar{E}$ the tangent modulus $\bar{E}_t$ of the corresponding continuum material was simulated using a finite-difference program of Li [5]. Table 1 shows the values of $\bar{E}_t$ in its inverse normalized form.

Table 1

$\bar{\varepsilon}_e$ - $(\bar{E}/\bar{E}_t)$

$\bar{\varepsilon}_e$		0.010	0.030	0.040	0.080	0.100	0.120
$\bar{E}/\bar{E}_t$		20	230	270	300	350	470
$\bar{\varepsilon}_e$		0.140	>0.50		>0.60		>0.75
$\bar{E}/\bar{E}_t$	(s.t.)	710	910		-800		
	(ℓ.t.)	510	$740 + (\bar{\varepsilon}_e - 0.50) \times 80/0.10$				-800

A comparison between the computer simulation and the experimental results (reproduced from Fig. 6 of reference [4]) is given in Fig. 2.

The microscopic behaviour of the material was then simulated by using this data in a set of finite element analyses which calibrated the void model shown in Fig. 1. The details of the method have been given by Li and Howard [1]. The elastic constants ν and E, the yield stress σ_Y and tangent modulus E_t of the matrix were taken to be those of the simulated continuum, whilst the geometrical parameters were chosen as

$$r_0 = \frac{a_0}{R_0} = 0.25 \quad , \quad \rho = \frac{L_0}{R_0} = 1 \ ,$$

and the value of λ_e was fixed as 1.7. It now only remains to set suitable values for σ_{cy}, ε_e and e_f (= $-E/E_f$ where E_f is the softening modulus that replaces E_t whenever the appropriate softening criterion is in force).

The response of the cell was computed for a range of values of α, corresponding to different degrees of triaxiality and a comparison between theory and experiment is shown in Fig. 3. A value of α of 0.492 is consistent with the behaviour of material at the centre of a necking bar for which the triaxiality $\bar{\sigma}_m/\bar{\sigma}_e \approx 0.3$ at the strain ($\bar{\varepsilon}_e \approx 0.1$ for many steels) at which necking begins. Values of α smaller than this would be appropriate for material suffering greater degrees of triaxiality in notched bar tests.

In our computations the instability point of the model cell was taken to be the initiation of ductile fracture at a value of the corresponding macroscopic equivalent strain $\bar{\varepsilon}_e$ denoted by $\bar{\varepsilon}_f$. When $\alpha < 0.47$ the point of instability was assumed to have been reached when the overall axial stress $\bar{\sigma}_z$ had attained its maximum with respect to the elongation ΔL_0 of the cell. When $\alpha > 0.47$ the relationship between $\bar{\sigma}_z$ and ΔL_0 involves a long flat plateau and we have taken the instability point to be that where the stress drops off the plateau. Furthermore, the ductility associated with this pattern of deformation means that criterion 2 controlled the softening point of the matrix.

In Fig. 3, which shows the comparison between the simulated data and the experimental results [4], the following values were used

1. (s.t.) case

$\sigma_{cy} = 4.5$ $\quad e_f = -100$ $\quad$ or $\quad \varepsilon_e \geq 0.60$ $\quad e_f = -200$

2. (ℓ.t.) case

$\sigma_{cy} = 6.5$ $\quad e_f = -100$

or $\quad 1.0 \geq \varepsilon_e \geq 0.85$ $\quad e_f = -600 + (\varepsilon_e - 0.85) \times 500/0.15$

$\varepsilon_e \geq 1.00$ $\quad e_f = -100$

With these values the macroscopic response of the void model results in the stress-strain curves of Fig. 4.

CONCLUSIONS

The behaviour of Q1 steel taken from two orientations with respect to the rolling direction has been simulated by choosing appropriate values for the parameters σ_{cy} and ε_e that control the initiation of softening at the second order particles. In those specimens subjected

to high triaxiality at failure ($\bar{\sigma}_m/\bar{\sigma}_e > 1.0$ in Fig. 3) it is the stress criterion 1 that controls the softening of the matrix. However, when there is moderate to low triaxiality ($\bar{\sigma}_m/\bar{\sigma}_e < 1.0$) the response of the cell was insensitive to the value of σ_{cy}, and it is in this regime that the strain criterion 2 takes over.

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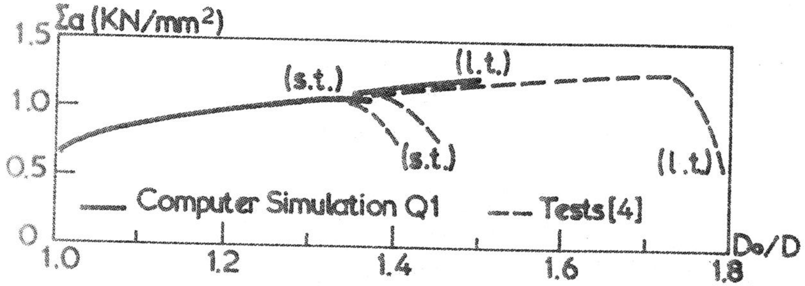


Fig. 2 The average axial stress Σ_a versus the change of diameter D_0/D at the neck

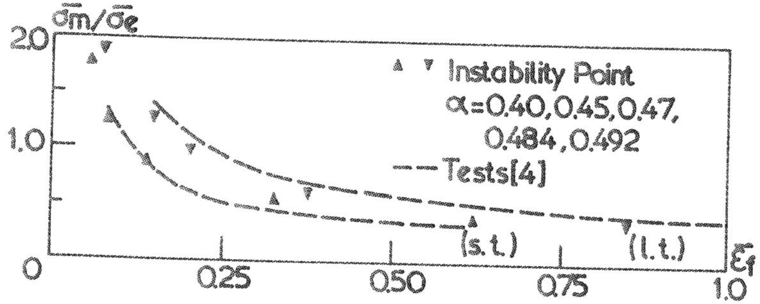
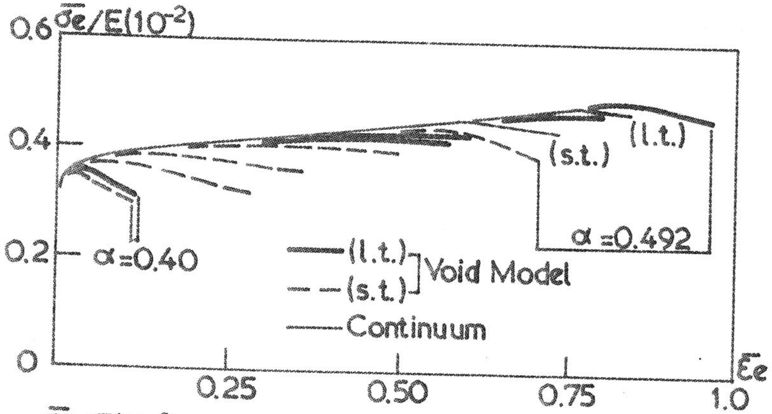
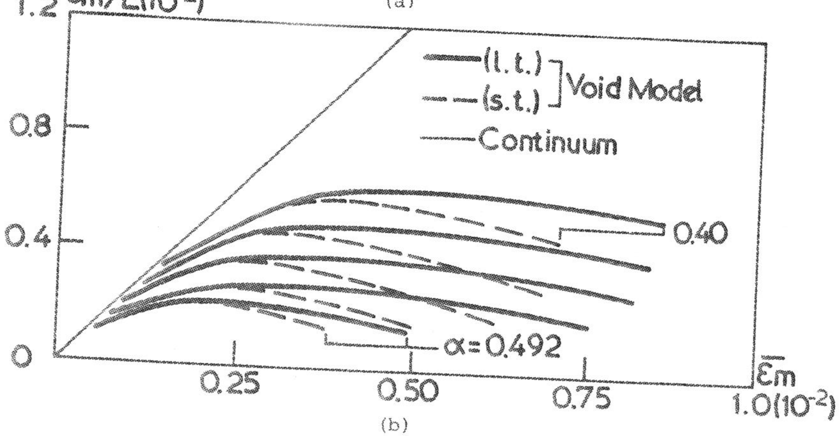


Fig. 3 $\overline{\sigma}_m/\overline{\sigma}_e$ versus $\overline{\varepsilon}_f$ at the instability point
(α = 0.40, 0.45, 0.47, 0.484, 0.492)



(a)



(b)

Fig. 4 The macroscopic stress-strain curves of a void model (α = 0.40, 0.45, 0.47, 0.484, 0.492)