ON THE EFFECT OF QUASI-STATIC LOADING RATES UPON THE FRACTURE TOUGHNESS OF ORDINARY STRUCTURAL STEEL

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For a cracked structural component the crack tip loading rate very often exceeds the maximum rate prescribed in current fracture toughness standards, e.g. ASTM E813. In a previous work, Lorentzon and Eriksson(1), it was found that loading rates at and just above the ASTM limit significantly affect the fracture toughness of ordinary structural steels. The effect of the loading rate upon the stress and strain distribution around a Modus I plane strain crack tip has been calculated with the finite element method. A boundary layer formulation based upon Westergaard's exact analytical solution for an infinite plate and a Perzyna visco-plastic material model has been used. The results show that viscous effects are significant only very close to the crack tip.

INTRODUCTION

It is generally accepted that in ferritic steels there is a competition between stress controlled brittle fracture and strain controlled ductile fracture. It is also experimentally verified that the brittle to ductile transition temperature is affected by quasi-static loading rates and that most metals and alloys exhibit some increase in flow strength with loading rate, e.g. Blazynski (2). The greatest strain rate sensitivity is usually found in body-centred cubic (BCC) materials. It can therefore be expected that rate dependent constitutive laws must be used to explain the effect of quasi-static loading rates on the fracture toughness of structural steels.

The main objective of this paper is to investigate if quasi-static loading rates at and just above the ASTM E813 limit have a significant influence on the stress and strain distribution at the tip of a stationary crack. A circular region around the crack tip was modelled with finite element method (FEM). A closed form solution boundary displacements corresponding to an infinite plate were imposed on the outer boundary of the modelled region. The material was assumed perfectly visco-plastic and modelled according to Perzyna (3).

METHOD

FEM-model

A disk-shaped FEM-model was used to study the influence of quasi- static loading rates on the the stress and strain fields around a stationary crack under plane strain conditions and Mode I loading.The elements of the model were eight-nodes

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isoparametric and arrayed in 31 circumferential layers of eight elements centred around the crack tip. The element size increased with the distance from the crack tip. The size of the smallest element length is of the order 0.5 mm and the radius of the model was set to 100 mm.

In the crack tip elements 1/r-strain singularities were obtained by collapsing the crack side nodes on to one point in the unloaded state. During loading such nodes were allowed to displace independently. The total number of degrees of freedom was 1584. The J-integral, which is path independent for a linear or non-linear elastic material, was calculated for nine paths through the Gauss integration points of the elements surrounding and at different distances from the crack tip.

The calculations were made with the commercial code ADINA 6.1.4 on a 266 MHz Alpha DEC workstation.

Loading

The model was loaded by imposing prescribed displacements at the nodal points on the outer boundary of the model. The displacements were calculated from Westergaard's analytical solution for an infinite wide plate with a through crack by using an identity pointed out by Unger et al (4), which yields exact analytical solutions of the stress strain and displacements fields.

The boundary displacements were imposed at constant dK/dt-rates and the maximum load corresponded to K=100 MN/m $^{3/2}$. The loading rates used in this investigation are shown in table 1

Table 1

Time to max load [s]	Loading rate dK/dt [MPa √m/s]	Markers used in the Graphs
100	1	*
1	100	**

Material model

A perfectly visco plastic material model (3) was selected for a preliminary study. As in small strain theory of plasticity the total strain is the sum of an elastic and an inelastic strain.

$$\varepsilon = \varepsilon^{e} + \varepsilon^{vp} \qquad (1)$$

The plastic strain rate is described by

$$\dot{\varepsilon}_{ij}^{vp} = \frac{3}{2}\gamma\left(\frac{\sigma_e}{\sigma_y} - 1\right)^{n} \frac{S_{ij}}{\sigma_e} \qquad (2),$$

where σ_e is the von Mises effective stress, σ_y the static yield stress, S_{ij} the stress deviator, γ a fluidity parameter and n an exponent.

In order to choose appropriate material constants, the material model was plotted for a uniaxial stress state, Fig 1. The material constants, table 2, were chosen in order to obtain both a significant strain rate dependence at low strain rates and a behaviour in uniaxial tension which is characteristic for ordinary structural steels.

Table 2

Material	σ_y [MPa]	E [GPa]	ν	γ [s^{-1}]	n
Mat1	300	210	0.3	0.01	1
Mat2	300	210	0.3	0.1	2
Mat3	500	210	0.3	40	2

Two materials with rate independent properties and different yield stress were chosen as static reference materials, table 3. The results are compared in Fig 2-5.

Table 3

Material	σ_y [MPa]	E [GPa]	E_t [GPa]	ν
Refm1	300	210	2.1	0.3
Refm2	500	210	2.1	0.3

The material description was implemented as a user-defined subroutine in the Adina code.

Solution method

A full Newton-Raphson iteration method was used to obtain equilibrium. The total solution process for a time step involves updating the stresses and other history dependent quantities from time *t* to *t+dt*. The updating was performed by subdividing the total strain increment from time *t to t+dt* into subincrements. For each subincrement the implemented user subroutine was called. The stress integration was performed by employing backward integration. Equilibrium iterations and stiffness reformations were thus performed at every solution step.

RESULTS

Crack opening stress

The influence of loading rate on the crack opening stress σ_{yy}, ahead of and normal to the plane of the crack is shown in Fig 2-4. The opening stress is shown at the end of the loading ramps.

The crack opening stress is affected only within a very narrow region ahead of the crack tip . At distances greater than the reference materials plane strain plastic zone size $r_p=(1/6\pi)(K_I/\sigma_y)$^2 from the crack tip the loading rate influence is negligible. The maximum extent of the plastic zone in the symmetry plane was about 5.9 10^{-3} m in Mat1 and Mat2 or six elements of the finite element model and 2.1 10^{-3} m in Mat3.

As expected the loading rate influence is greater in Mat1 than in Mat3 but almost altogether negligible in the latter.

J-Integral

In the plane strain small scale yielding regime the J-integral is related to the applied stress intensity K by the equation

$$J=(1-\nu^2)\frac{K^2}{E} \qquad (3),$$

where E is the young's modulus and ν Poisson's ratio. Outside the plastic zone of the reference materials the calculated J-contour integrals were found to deviate from the J-value obtained with eqn (3) by typically less than 3.5 percent at the end of the loading ramps. In all cases path independence was observed as exemplified by Mat2, Fig 6. J_{max} in this graph is calculated according to eqn (3). However, with increasing loading rate path independence is lost close to the crack tip.

Deformation

At the low loading rate the differences between the crack tip opening displacements (CTOD) corresponding to the visco-plastic and the static elastic-plastic solutions were negligible for all five materials.

At the high loading rate crack opening was delayed for Mat1 and Mat2 but no significant effect was observed for Mat3. The effect of the loading rate on the crack tip opening displacements for Mat2 is shown in Fig 5.

DISCUSSION

The most significant effect of the loading rate on the crack tip stress fields is that the crack tip opening stress σ_{yy} is increased drastically immediately ahead of the crack tip. This effect increases with the loading rate and decreasing distance from the crack tip. As the stress field around the crack tip affects the process region. The loading rate in this region will be considerable. Because the effect upon the stress field is strong but localised it is sufficient that the fracture process itself is only weakly stress rate dependent.

Quasi-static loading rate seems to delay crack tip deformation. Similar observations were made by Little et al (5) for a rate dependent elastic-plastic materials.

These two observations taken together means that a lower fracture toughness will be obtained for stress induced fracture with increased loading rate and a higher fracture toughness for strain induced fracture if a critical stress or strain over a critical distance ahead of the crack tip must be obtained for fracture.

The strong effect of quasi-static loading rate upon the stress and strain fields around the crack tip and the observed behaviour of structural steels means that fracture toughness testing of such materials must be performed at an appropriate loading rate.

The Perzyna visco plastic model gives significant effects of the loading rate only very close to the crack tip. As a compromise between the material model parameters and the behaviour of structural steel, one material, Mat2, has been chosen for future studies. The deformation hardening of the Perzyna model tends to zero with increasing strain in uniaxial loading. The characteristic strain for this behaviour increases with loading rate. This behaviour means however that the flow of energy towards the crack tip is gradually reduced. A modified model with a non-zero hardening should give a better description of the behaviour of structural steels. This can be done by increasing the static yield stress of the Perzyna model with increasing effective strain.

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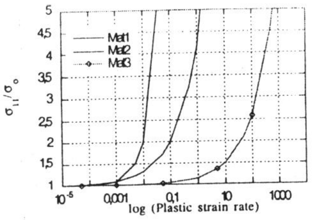

Figure 1. Uniaxial Stress/rate behaviour, equation (1).

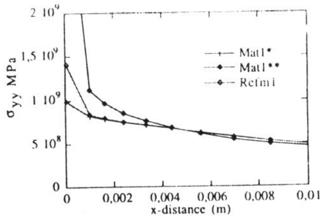

Figure 2 . Influence of loading rate on crack opening stress.

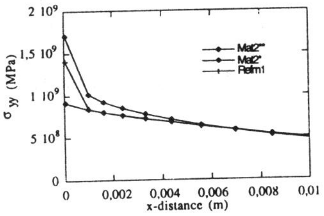

Figure 3 . Influnce of loading rate on crack tip opening stress(Mat2, Refm1)

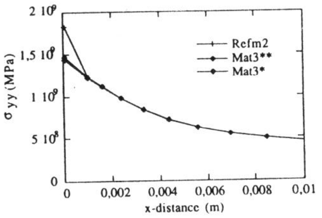

Figure 4. Influence of loading rate on crack tip opening stress.(Mat3, Ref

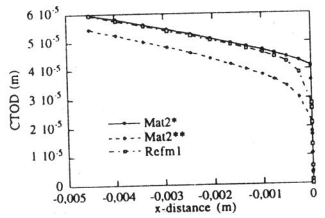

Figure 5. Influence of loading rate on crack tip opening displacement.

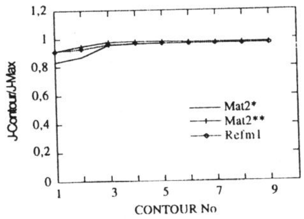

Figure 6. Path independence of the J-contour Integral.