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Prediction of the Performance of Adhesives Under Impact Loading

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INTRODUCTION

Finite Element Analysis (FEA) is used extensively to predict stress and strain distributions in the design of adhesive joints. The analysis of bonded structures under impact loading is becoming increasingly important. Deformation under impact will, in most cases, lead to large strains where relationships between stress and strain are non-linear. Furthermore, the strain rate in the adhesive under impact loading will vary with time and position. Data that demonstrate both the strain and strain rate dependence of properties are therefore needed to predict the performance of the joint under impact.

Fundamental to the analysis of the joint is the choice of model to define the constitutive behaviour of the adhesive. The most commonly used material models, in commercial FEA packages such as ABAQUS, LUSAS, LS-DYNA or ANSYS, for defining non-linear behaviour are elastic-plastic models. These models, which have been developed for metals and soils, assume that non-linear behaviour is due to irrecoverable plastic deformation. They require knowledge of the yield stress-plastic strain behaviour.

Unlike metals, the yield in polymeric adhesives is generally dependent on the hydrostatic component of stress. Data under at least two different states of stress are required to determine the parameters that define the yield behaviour of a material sensitive to pressure. Usually the models are expressed in terms of tensile and compressive yield stresses at equivalent effective strains but this paper will show how yield parameters can be calculated from tensile and shear tests.

DATA AQUISITION

FE models typically require data in the form of elastic constants to describe elastic behaviour and parameters that describe the yield, hardening and flow behaviour to describe plastic (non-linear) behaviour. These parameters are determined using data obtained under two stress states. Stresses above the limit for linear behaviour (i.e. plastic strain $\varepsilon_p > 0$) are defined as yield stresses. Measurements of lateral (ε_l) and longitudinal (ε) strain are needed from tensile tests to generate plots of true stress against true plastic strain that characterise the hardening behaviour. Shear test data have been used here as the second stress-state.

The change in cross-section of the specimen during tensile tests needs to be included to calculate true stress. In tension, the cross-section reduces and true tensile stresses (σ_T) are calculated from measured stresses (σ) and the lateral strain: $\sigma_T = \frac{\sigma}{(1-\varepsilon_l)^2}$. True strains ($\varepsilon_T$) are given by; ε_T =

ln(1+ε). True plastic tensile strains (ε_p) are calculated using the elastic modulus (E): $e_p = e_T - \frac{s_T}{E}$. Plastic shear strains (γ_p) can be calculated from shear strains (γ) shear stresses (τ) and shear modulus (G) using the procedure above. The plastic Poisson's ratio (ν_p) is calculated from the ratio of the lateral and longitudinal plastic strains.

To predict impact performance, materials data are required at varying rates of strain. Tensile test data have been measured using bulk test specimens over a wide range of strain rates using different apparatus. At low strain rates (< 0.05 s^{-1}), modulus, Poisson's ratio and stress-strain (longitudinal and lateral) to failure can be measured accurately on a standard test machine using a combination of clip-on and video extensometers. At intermediate rates (0.05 to 2 s^{-1}, up to ca. 0.1 ms^{-1}), a servo-hydraulic test machine and clip-on extensometers can be used to measure stress-strain data to failure with reasonable accuracy. Relationships can be modelled between strain and crosshead displacement in these tests. At the higher rates (2 s^{-1} to 100 s^{-1}+, 0.1 m s^{-1} to 5 m s^{-1}), stress-displacement data can be measured using either a servo-hydraulic test machine or a falling weight impact machine with a tensile test stage. Strains can be estimated from extrapolation of relationships derived at lower speeds. Figure 1 shows true stress against true strain measured at strain rates between 10^{-4} s^{-1} and 10^{2} s^{-1} for a one-part epoxy adhesive Ciba LMD1142.

Stress-strain data in shear have been measured at low strain rates using a bulk specimen shear test, Dean et al. (1). The test speeds were selected so that the effective strain rates were equivalent to those in tensile tests. For higher rates, stress-displacement data can be measured using either this test or joint specimens. Figure 2 shows true stress-true strain data for tension and shear tests performed at the same effective plastic strain rate. Figure 3 shows yield stress plotted against plastic strain in tension and shear together with plastic Poisson's ratio data.

YIELD PARAMETERS FOR ELASTIC-PLASTIC MODELS

In the low strain, linear region, the theory of linear elasticity using Hook's law is assumed to be valid. The adhesive can be characterised in terms of an elastic modulus (E) and Poisson's ratio (ν). In the non-linear region, plastic deformation is assumed to take place. Rate independent plasticity is based on three fundamental concepts:

1. the yield criterion; determines the stress states necessary for plastic deformation to occur.
2. the hardening rule; describes the changes in the material's resistance to further yield with increasing strain.
3. the flow rule; defines the incremental plastic strains as a function of stress.

A normal assumption is that the same yield criterion can be used for all states of stress, future studies will assess this assumption. Most materials models for polymers in FE codes have been derived from models for metals. For metals, the classical von Mises yield criterion is usually assumed, equation (1). The yield stress in tension (σ_T) is given by the second invariant of the deviatoric stress tensor (J_2), assuming no dependence on the hydrostatic stress components.

$$s_T = \sqrt{3J_2} \quad (1)$$

In general, the tensile yield stress is not constant, i.e. the material will strain harden. Plastic deformation is assumed to take place under constant volume conditions, i.e. ν_p is 0.5. As the data on LMD1142 (Figure 3) show, ν_p can vary and may be less than 0.5 which signifies that the volume increases during yield. The von Mises yield criterion also implies that the yield behaviour in tension is the same as yield behaviour under compression. However, studies on polymers indicate that yield stresses in compression are higher than in tension. Hence, a deviation from the classical von Mises yield criterion is observed. One pressure dependent yield criterion commonly implemented, in different forms, by FE packages is the Drucker-Prager (2) criterion which is given by equation (2).

$$\sigma_{yt} = \frac{\sqrt{3}(\zeta+1)}{2\zeta}\sqrt{J_2} + \frac{(\zeta-1)}{2\zeta} I_1 \qquad (2)$$

where I_1 is the first invariant of the stress tensor and ζ is the ratio of the yield strength in compression to the yield stress in tension at equivalent effective plastic strains. For $\zeta = 1$, this reverts to equation (1).

A further parameter which needs to be defined to implement the Drucker-Prager model is the dilation angle (ψ) which describes the flow behaviour. This is determined from the plastic Poisson's ratio (ν_p):

$$\tan\Psi = \frac{3(1-2\nu_p)}{2(1+\nu_p)} \qquad (3)$$

These parameters can all be determined from measurements made in tension and shear at equivalent strain rates.

CALCULATION OF YIELD AND FLOW PARAMETERS

Using concepts of equivalent stress and equivalent plastic strain derived from the yield criteria in equation (2), equivalent stresses can be located on each of the curves (Figure 3). For shear and tension the following relationship holds:

$$\frac{\sigma_T}{\varepsilon_p} = \frac{\tau_y}{\gamma_p}[2(1+\nu_p)] \qquad (4)$$

In uniaxial tension, σ_T is simply the tensile yield stress and in shear the stress invariants are: $I_1 = 0$ and $J_2 = \tau_y^2$, where τ_y is the shear yield stress. Using these, expression (5) can be derived from equation (2) to relate tensile yield stress to shear yield stress at equivalent points through the yield parameter ζ:

$$\frac{\sigma_T}{\tau_y} = \frac{\sqrt{3}(\zeta+1)}{2\zeta} \qquad (5)$$

For a von Mises material ($\nu_p = 0.5$, $\zeta = 1$), γ_p is $\sqrt{3}\varepsilon_p$. For most materials, γ_p will be approximately twice ε_p which is important when selecting test rates for obtaining yield properties.

Figure 3 illustrates how equivalent yield points are defined through the relationship between secants to the yield stress-plastic strain curves, $E_s = \frac{\sigma_{yt}}{\varepsilon_p}, G_s = \frac{\sigma_s}{\gamma_p} = \frac{E_s}{2(1+\nu_p)}$. The ratio of each yield stress in tension to the equivalent yield stress in shear at each equivalent yield point can be used to calculate ζ in equation (5) as a function of plastic strain.

Figure 4 shows plots of ζ against ε_p for tests at three different strain rates (nominally 1, 10 and 100 $\%min^{-1}$). The values of ζ for the LMD1142 adhesive are nearly independent of strain and there is no significant variation with strain rate. Data acquisition for modelling impact performance could therefore be simplified to measuring only tensile behaviour at high strain rates and assuming that the values for ζ and ν_p obtained at low strain rates are also appropriate for high rates. It was found at other temperatures (0°C and 50°C) that although stress-strain curves were significantly different to the 23°C data that the values for ζ were also close to 1.5. This helps support the assumption that ζ may be independent of strain rate for this material.

In many analyses, only strain independent yield parameters can be used. This assumption appears to be valid for materials such as this epoxy where the yield parameters seem more or less independent of strain. Simplified methods of determining these parameters are needed. For materials which do not strain harden, i.e. where the yield curves in tension and shear plateau, ζ can be estimated simply from the values of these plateau stresses. One method of determining a single value for ζ for strain hardening materials, such as Ciba LMD1142, is to extrapolate the plastic region of the true stress-true strain curves (Figure 2) to the y-axis to define two reference stresses. Values for ζ calculated using this method for the nominal strain rates of 1, 10 and 100 $\%min^{-1}$ were 1.47, 1.62 and 1.55 respectively. These agree reasonably with the values in Figure 4.

CONCLUSIONS

Appropriate yield criteria are required to model adhesives at high strains under multi-axial stress states. Means of obtaining the parameters required for the Drucker-Prager yield criterion from tension and shear measurements have been described. Initial findings for the LMD1142 epoxy adhesive suggest that these parameters are roughly independent of both strain and strain rate.

REFERENCES

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2 Drucker D and Prager W, Quarterly of Applied Mathematics 10 (1952) 157

ACKNOWLEDGEMENTS

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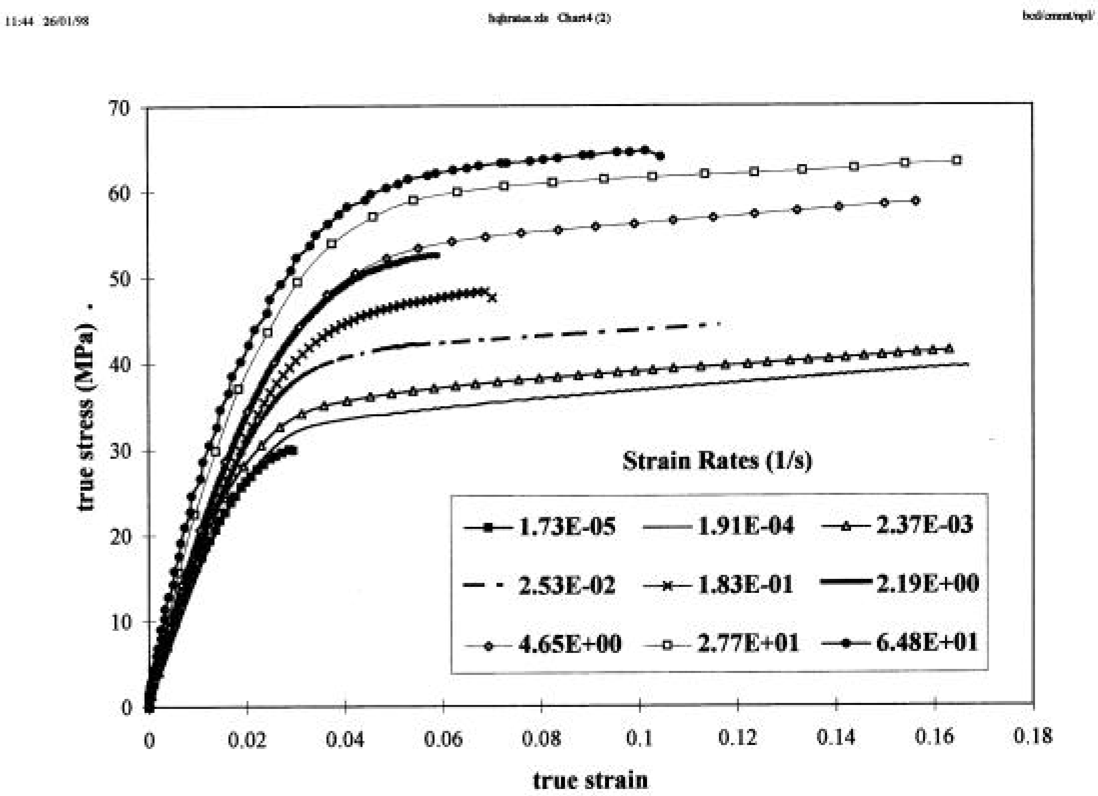

Figure 1: True stress-true strain curves for Ciba LMD1142 epoxy adhesive in tension at 23C

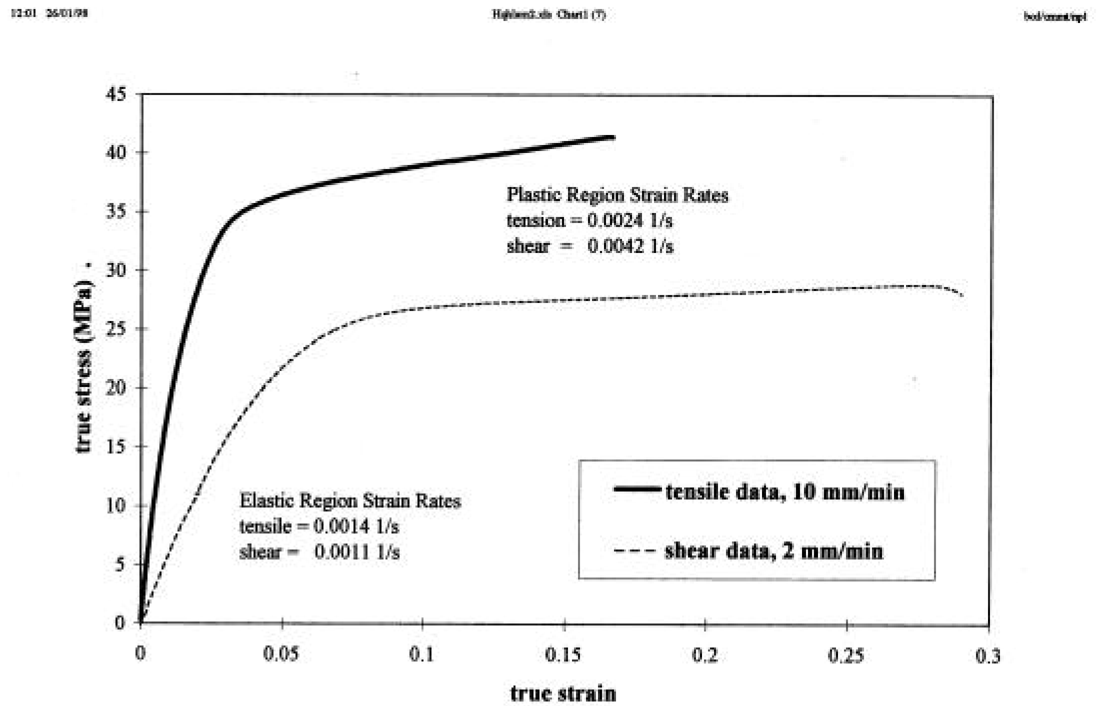

Figure 2: Tensile and shear data for tests carried out at equivalent plastic strain rates at 23C

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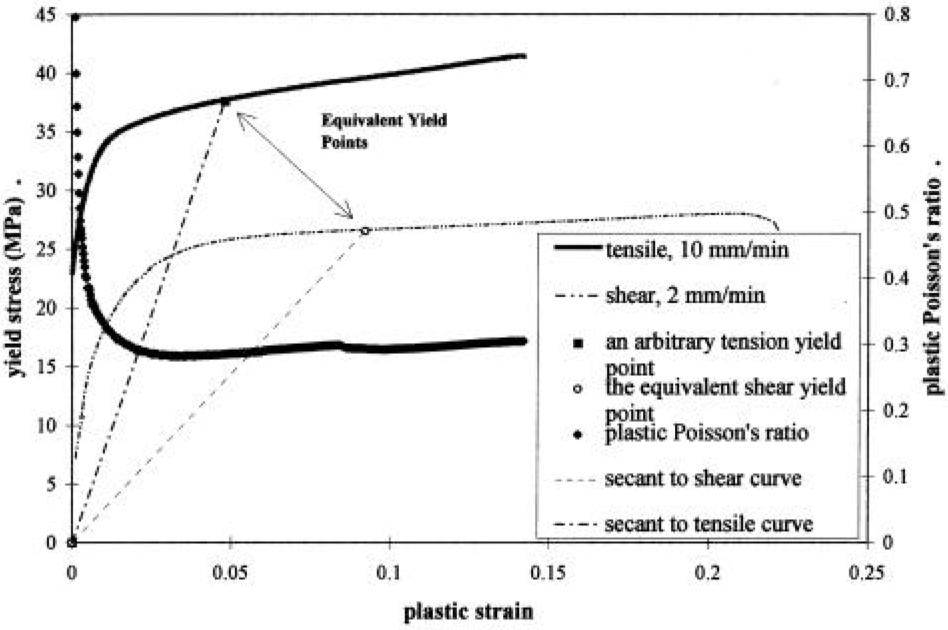

Figure 3: Yield stress-strain curves and Poisson's ratio data used to determine parameters for FE models

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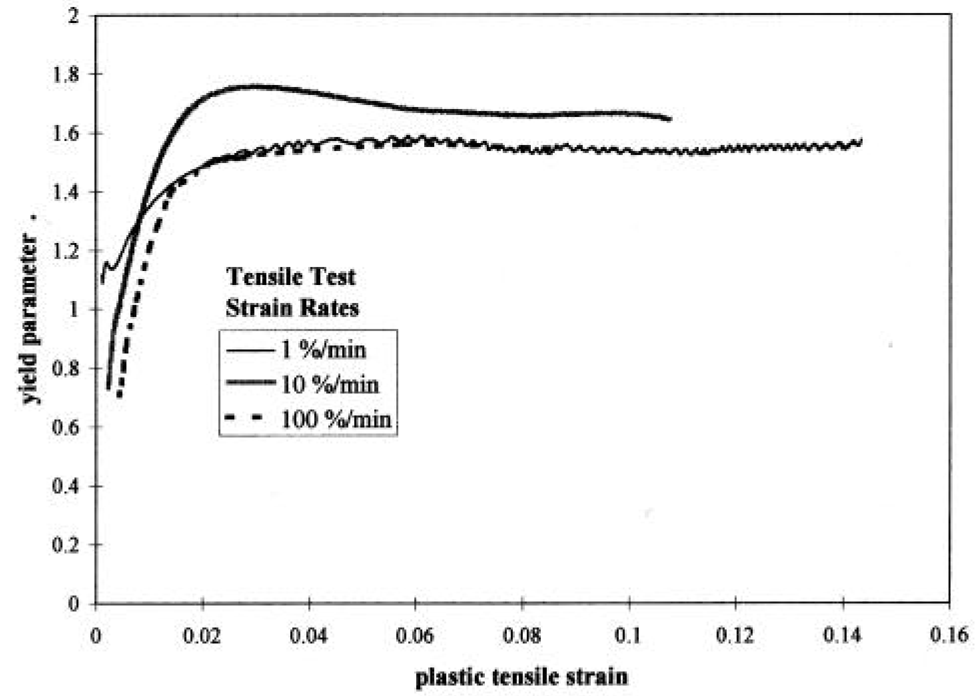

Figure 4: Yield parameters calculated for LMD1142 adhesive at 23C