

The Application of Finite Element Methods to the Prediction of the Impact Performance of Plastics

G Dean, B Read and B Duncan
Centre for Materials Measurement and Technology
National Physical Laboratory
Teddington, Middlesex TW11 0LW

SUMMARY

This preprint was prepared following an invitation to present a paper on the use of FEA for predicting impact performance at the SPE annual conference ANTEC 98. The length of the paper was restricted by the guidelines from the organisers for preprint preparation.

This paper summarises the current situation in Project CAM6 with the evaluation of the applicability of elastic-plastic models in FE packages for describing the deformation of plastics at large strains. A more full account of the data analysis and the measurement methods used to obtain the data presented will be given in a subsequent report from the Project.

© Crown copyright 1998
Reproduced by permission of the Controller of HMSO

ISSN 1361-4061

National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

Extracts from this report may be reproduced provided
that the source is acknowledged.

Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head of Centre for Materials Measurement & Technology

THE APPLICATION OF FINITE ELEMENT METHODS TO THE PREDICTION OF THE IMPACT PERFORMANCE OF PLASTICS

by

*G Dean, B Read and B Duncan
National Physical Laboratory,
Teddington, Middlesex, UK*

Abstract

The capability to carry out quantitative predictions of impact performance of plastics parts is becoming increasingly available through the use of finite element analysis. The reliability of these calculations depends on the validity of the materials model used by the analysis for describing the deformation behaviour of polymeric materials. In this paper, the availability of potentially suitable models is considered. Emphasis is given to the ability of these models to realistically describe deformation at large strains. Using measurements carried out under tension, shear and compression, it is shown that available models cannot accurately describe stress/strain behaviour over this range of stress states for certain plastics materials. This can be explained by the ability of these materials to deform by a different plastic deformation mechanism in tension from that occurring under shear or compression.

Introduction

A finite element analysis is a powerful method for assessing the performance of a component under impact loading. The analysis will calculate the force deflection curve and stress and strain distributions throughout the component. In conjunction with a failure criterion, the energy absorbed before fracture or up to a deformation limit can also be calculated. The accuracy of the analysis is dependent upon the ability of the materials model used by the FE analysis to describe relationships between stress and strain in the material at the levels of strain and strain rate experienced by the impact.

Deformation under impact will generally take the material to large strains where relationships are non-linear. Many of the models used by FE packages to describe non-linear behaviour are elastic-plastic models. These models have been developed for metallic materials and interpret non-linearity as caused by plastic deformation. The shape of the non-linear part of a stress-strain curve is then determined by the strain hardening behaviour of the material. The inclusion of a dependence of properties on strain rate is relatively straightforward by allowing the materials parameters in the elastic-plastic model to vary with strain rate.

Materials Models

In the absence of non-linear models that have been developed for plastics, it is necessary to select an elastic-plastic model that employs a realistic yield criterion. The most widely used of these models is based on the von Mises yield criterion. This can be expressed in the form

$$\sigma_T = \sqrt{3} J_{2D}^{1/2} \quad (1)$$

The parameter σ_T is a yield stress under uniaxial tension and J_{2D} is a function of the components of applied stress equal to the second invariant of the deviatoric stress tensor. The initial value of σ_T defines the limit of linear behaviour and, in a strain hardening material, σ_T then increases with the plastic strain (ϵ_p). Only a few plastics materials can be accurately modelled by the von Mises criterion. In general, their yield behaviour is sensitive to the hydrostatic component of stress in addition to the shear component. More realistic yield criteria then take the form

$$\sigma_T = \frac{\sqrt{3}(\lambda+1)}{2\lambda} J_{2D} + \frac{(\lambda-1)}{2\lambda} J_1 \quad (2)$$

$$\text{or} \quad \lambda \sigma_T^2 = 3J_{2D} + (\lambda-1) \sigma_T J_1 \quad (3)$$

where λ is a material parameter representing the sensitivity of yield behaviour to the hydrostatic stress J_1 . The parameter λ is the ratio of equivalent yield stresses in uniaxial compression and uniaxial tension. Equivalent yield stresses are stress levels that lie on the same yield surface (ie that have the same effective plastic strain).

In a principal stress coordinate system, the yield surface given by equation (2) for a particular value of σ_T is a cone with an axis that coincides with the hydrostatic stress axis. As σ_T increases with plastic strain, the cone expands uniformly. The yield surface given by equation (3) is a paraboloid. When $\lambda = 1$, equations (2) and (3) are identical to equation (1) for von Mises yielding, and the yield surface is a cylinder.

Equations (2) and (3) are implemented in certain finite element materials models. Equation (2) is used in the linear Drucker-Prager model and equation (3) in the exponent Drucker-Prager model.

The data requirements for the application of any of these models are

- the tensile yield stress as a function of plastic strain $\sigma_T(\epsilon_p)$
- the hydrostatic stress sensitivity parameter λ
- the flow parameter ψ .

The function $\sigma_T(\epsilon_p)$ is derived from measurement of the stress/strain curve in a uniaxial tensile test. The plastic component of strain ϵ_p at each value of σ_T is calculated from the measured tensile strain ϵ at σ_T using

$$\epsilon_p = \epsilon - \frac{\sigma_T}{E} \quad (4)$$

where E is Young's modulus. Since for tough materials strain levels will exceed 0.1, true

values should be used for stress σ_T and strain ϵ and ϵ_p .

Determination of the parameter λ requires additional data from a test under a different stress state. Either shear or uniaxial compression tests can be used for this purpose but there are experimental difficulties in obtaining accurate stress and strain data from these tests, especially at large strains.

The parameter ψ can be determined from the equation

$$\tan \psi = \frac{3(1-2\nu_p)}{2(1+\nu_p)} \quad (5)$$

where ν_p is the plastic component of the lateral contraction ratio and is obtained from a tensile test.

Results and Discussion

Figure 1 shows true stress/true strain curves for a propylene-ethylene copolymer obtained from tests under uniaxial tension, uniaxial compression and shear loading. The data were obtained at the same equivalent plastic strain rate of $4 \times 10^{-3} \text{ s}^{-1}$. The shear data were determined using a version of the Iosipescu test. The compression data were obtained from short specimens whose sides were constrained sufficiently to prevent buckling. The solid curves in the figure show predicted behaviour under compression and shear based on tensile data and the von Mises yield criterion. The errors are apparent and the suitability of the other criteria is now explored.

Using equations for equivalent stress and equivalent plastic strain derived from the yield criteria in equations (2) and (3), equivalent stresses can be located on each of the curves. This means that for any point σ_s on the shear curve, equivalent stress levels σ_T and σ_C can be found on the tension and compression curves respectively.

Considering the conical yield criterion given by equation (2), λ can be calculated from compressive and shear data using

$$\lambda = \frac{2\sigma_c - \sqrt{3}\sigma_s}{\sqrt{3}\sigma_s} \quad (6)$$

or tensile and shear data using

$$\lambda = \frac{\sqrt{3}\sigma_s}{(2\sigma_T - \sqrt{3}\sigma_s)} \quad (7)$$

With the data shown in figure 1, the values obtained for λ over the range of plastic strain are significantly different using compressive and shear data (equation (6)) compared with those obtained using shear and tensile data (equation (7)). This indicates that the yield criterion given by equation (2) is not satisfactory for modelling plastic deformation in propylene copolymer over more than a narrow range of stress states.

Consideration of the paraboloidal criterion given by equation (3) involves replacing equation (6) by

$$\lambda = \frac{\sigma_c^2}{3\sigma_s^2} \quad (8)$$

and equation (7) by

$$\lambda = \frac{3\sigma_s^2}{\sigma_T^2} \quad (9)$$

Although values for λ obtained from shear and tensile data are now slightly closer to those derived using compressive and shear data, differences are still significant.

This inability of the yield criteria represented by equations (1), (2) or (3) to satisfactorily describe the non-linear behaviour of certain plastics materials is even more pronounced for acrylonitrile-butadiene-styrene (ABS) as shown in figure 2. Once again, a consistent value for the parameter λ cannot be derived using these data. Furthermore, the strain hardening behaviour in tension is distinctly different from that in shear and compression. For reference, the solid curves show predicted behaviour under compression and shear based on the tensile data and the von Mises criterion.

These observations on both the propylene copolymer and the ABS are clearly linked with the ability of these materials to deform by two distinct plastic deformation mechanisms. Under shear and compressive stresses, plastic deformation will occur by a mechanism involving predominantly shear yielding and will be accompanied by constant or nearly constant volumetric strain. This mechanism can probably be modelled by the criteria given in equations (1) or (2). Under a tensile stress, a predominantly dilatational yield mechanism is preferred involving the formation of voids by cavitation or crazing. An increase in volumetric strain will be associated with this mechanism which is consistent with a measured decrease in the lateral contraction ratio with tensile strain at strains above the limit of linear deformation.

In order to realistically model these materials in a finite element analysis, a criterion for dilatational yielding is required. The materials model would then have to accommodate both of these criteria. Different hardening functions might also need to be associated with each mechanism. The solver would need to select the appropriate yield criterion for the material in each element of the meshed geometry depending on the stress state within that element.

Conclusions

A finite element analysis of a plastics part loaded to large strains where behaviour is non-linear will generally require the use of an elastic-plastic materials model.

For predictions of impact performance, the dependence of parameters on strain rate would need to be determined at high rates of strain.

The yield criterion in these models is commonly assumed to be von Mises although other criteria are available that include a sensitivity of yield stress to the hydrostatic component of the applied stress.

Whilst these criteria are realistic for certain plastics materials, they appear to be unsatisfactory for materials that can deform in tension by a dilatational yield mechanism. This mechanism is inhibited under

compressive and shear stresses where deformation by shear yielding is dominant.

There are a number of indicators that a particular material can deform by dilatational or shear yielding mechanisms depending on the stress state:

- the material shows stress whitening in tension
- stress/strain curves have different shapes in shear and tension
- values for Poisson's ratio at large strains are significantly less than 0.5 and decrease with increasing strain.

For accurate predictions of stress and strain in these materials, further work is needed to define the form of the criterion for dilatational yielding. Additional test methods may also be needed to determine the materials parameters for this criterion.

The extra cost and effort associated with materials characterisation for this realistic modelling of yield behaviour may not be necessary in many applications. Depending on the loading situation, and hence the stress states generated, it may be possible, with suitable choice of materials data, to employ a more simple materials model without significant loss of accuracy.

Acknowledgements

The work reported here forms part of a research programme on materials measurement and technology funded by the UK Department of Trade and Industry.

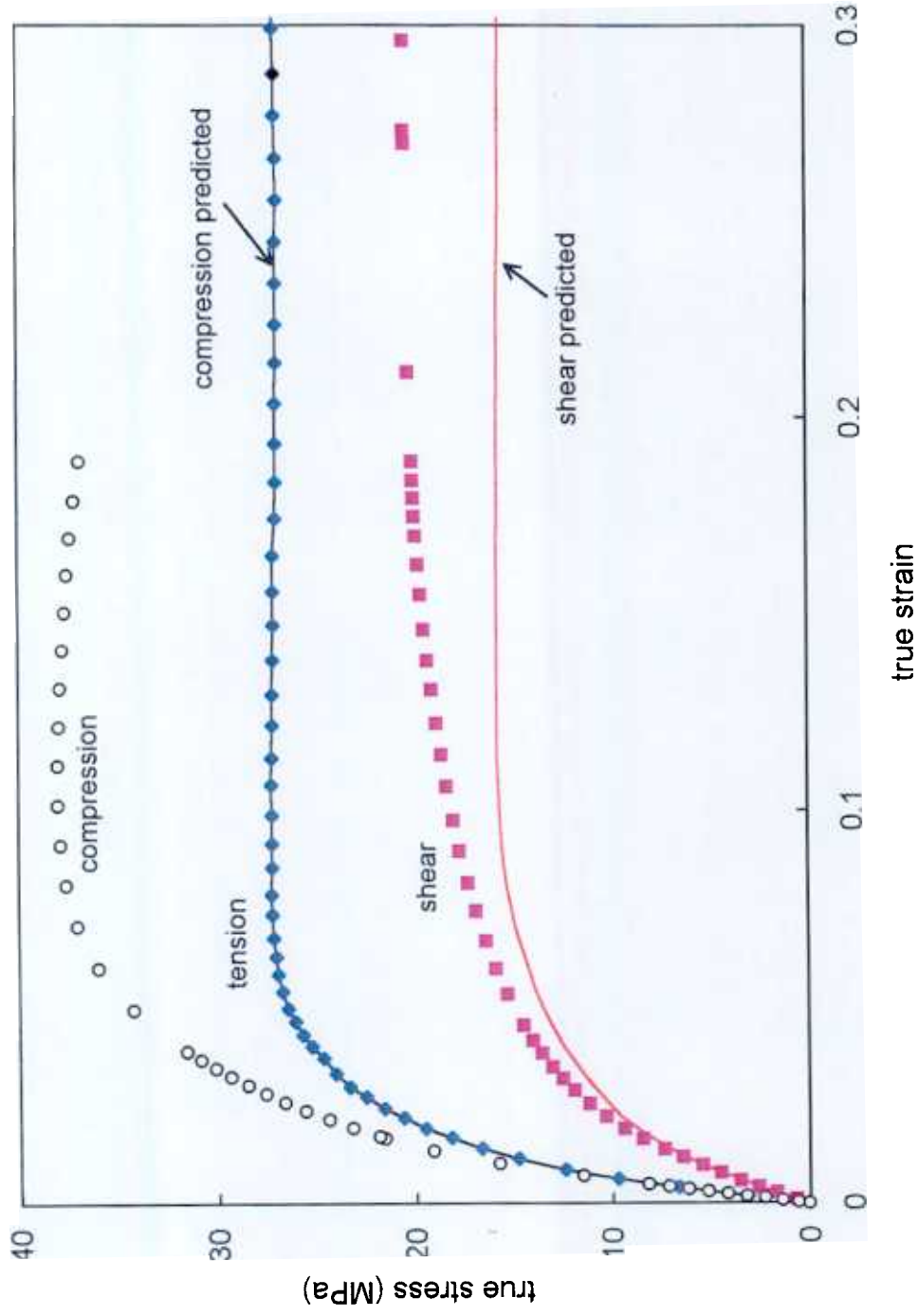


Fig 1 Stress-strain data (point symbols) for a propylene-ethylene copolymer. Continuous lines show behaviour predicted from tensile data using the von Mises model.

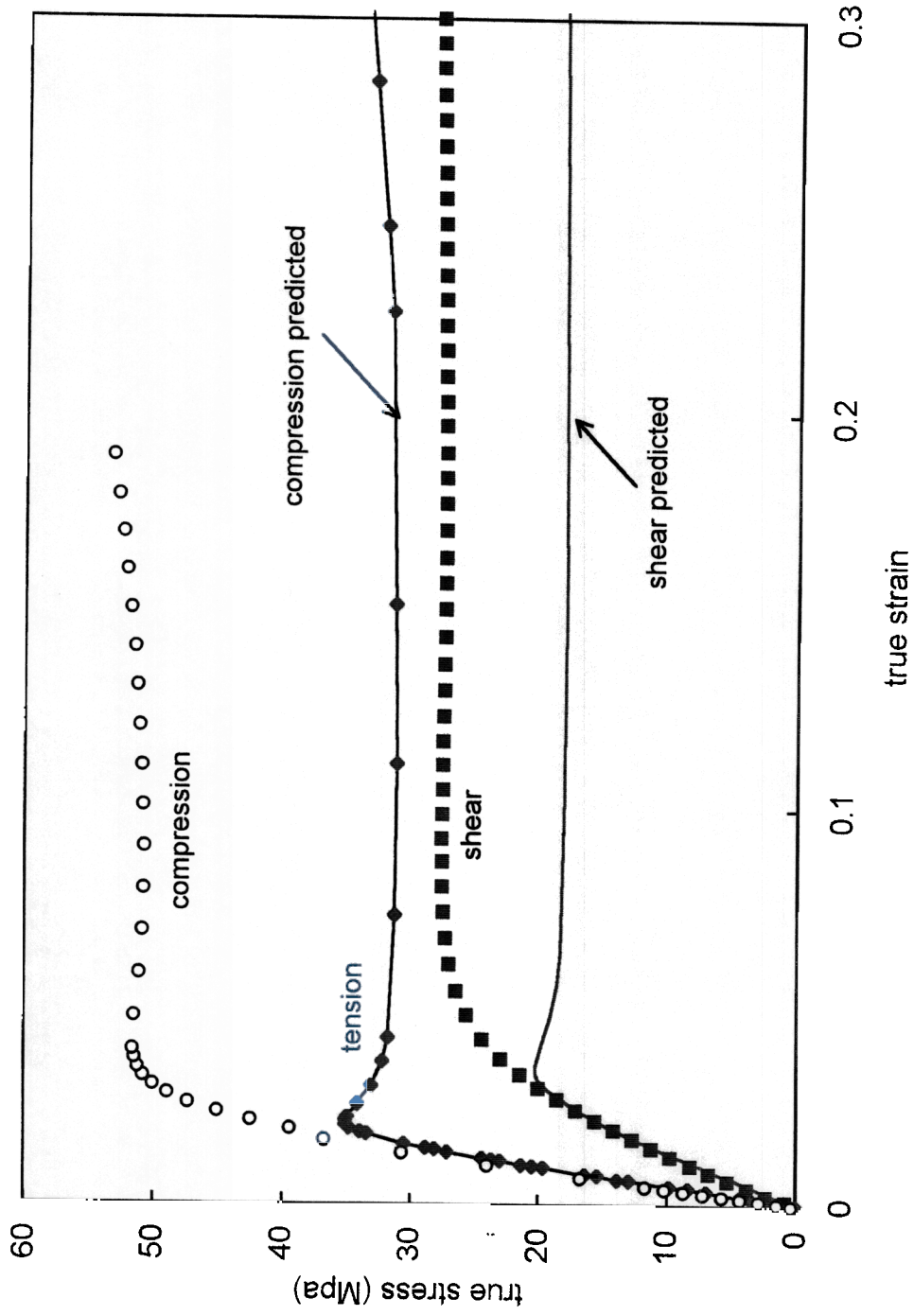


Fig.2 Stress-strain data (point symbols) for ABS. Continuous lines show behaviour predicted from tensile data using the von Mises model.