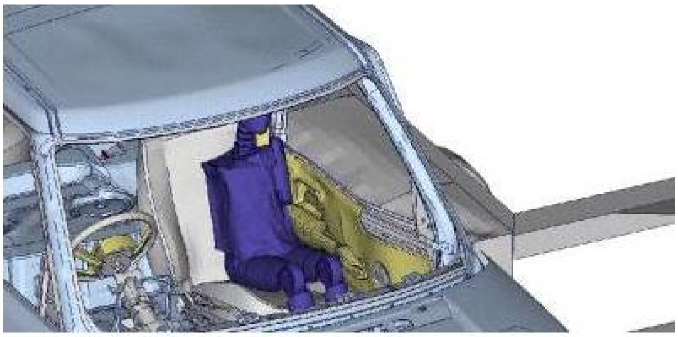
Modelling the Behaviour of Plastics for Design under Impact

Final Project Overview

Introduction



Simulation of a side impact of a motor vehicle

(courtesy of Jaguar Land Rover)

During accidental impact many modern grades of plastics used in commercial and industrial applications are required to sustain large strains before failure occurs. In addition they are expected to limit the forces inflicted upon other objects involved in the impact event. Specifically, for many motor vehicle components it is vitally important that the impact creates as little damage to passengers or pedestrians during a road accident. With the aim of increasing levels of protection, minimum performance levels for motor components are now being specified in US and EC legislation.

Finite element analysis can be used to explore the influence of different materials and component geometries on forces and deformations sustained in an impact event in a virtual environment. This avoids expensive prototyping and thus enables quicker and more accurate materials selection and component design.

Project Aim

The aim of this project was to evaluate the use of computer design methods in predicting performance of plastics during impact. This was achieved by:

- Understanding materials behaviour
- Understanding measurement issues - obtaining high rate data, failure studies
- Further development of cavitation model and coding
- Evaluating models via a case study of real components
- Investigating factors influencing predictions

The main work areas of this project are described below.

Component Part Testing

Two components have been studied within this project. These were obtained by cutting regions from interior door trim panels of a Land Rover vehicle, and were refered to as the armrest (A) and toptrim (B) components. The design of these panels is of importance to Jaguar & Land Rover in order to offer maximum protection to passengers in the event of a side impact. Clamping devices were manufactured to support the components during loading by a hemispherical indenter. Tests were carried out over a range of loading rates (0.01 mm/s - 4 m/s).

The polymer used for the door trim panels is a rubber-toughened, propylene-ethylene copolymer containing talc filler. This type of material shows extensive deformation before failure, and a corresponding decrease in Poisson's ratio with strain. It is part of an important class of plastics that undergo cavitation in microscopic regions of the polymer under stress states where there is a dilatational component of stress that is sufficient to nucleate the cavities. Cavitation also creates additional volumetric strain under tension and it is this that causes the decrease in Poisson's ratio with strain.

Cavitation is usually visible as stress whitening and is responsible for increased toughness by promoting localised shear yielding in the material between cavities. It will therefore lower the yield stress under those stress states for which the hydrostatic stress component is sufficient to cause cavitation. For the material studied here the presence of ethylene groups copolymerised with propylene groups makes the amorphous regions more mobile and therefore more amenable to the nucleation of cavities. The presence of rubber particles provides more sites for cavity formation.

Elastic-Plastic Materials Models

Predictions of impact performance require a materials model that can describe the non-linear and rate-dependent properties observed in tough plastics. For this purpose, modellers use elastic-plastic models that are available within finite element systems. Three elastic-plastic models have been studied within this project. The von Mises model is the simplest, but it is known that this model cannot accurately describe the non-linear deformation behaviour of tough plastics under a wide range of stress-states. The linear Drucker-Prager model is more complex and gives an improvement over the von Mises model by taking account of the influence of the hydrostatic component of stress on yield behaviour, although it still has some limitations for certain types of plastics. The NPL-developed cavitation model is a new elastic-plastic model, which takes account of the influence of cavitation on yielding and plastic flow. This has been coded as a UMAT for use with ABAQUS. A Good Practice Guide (1) and an NPL report (2) and a have been written to provide more information on the use of these models.

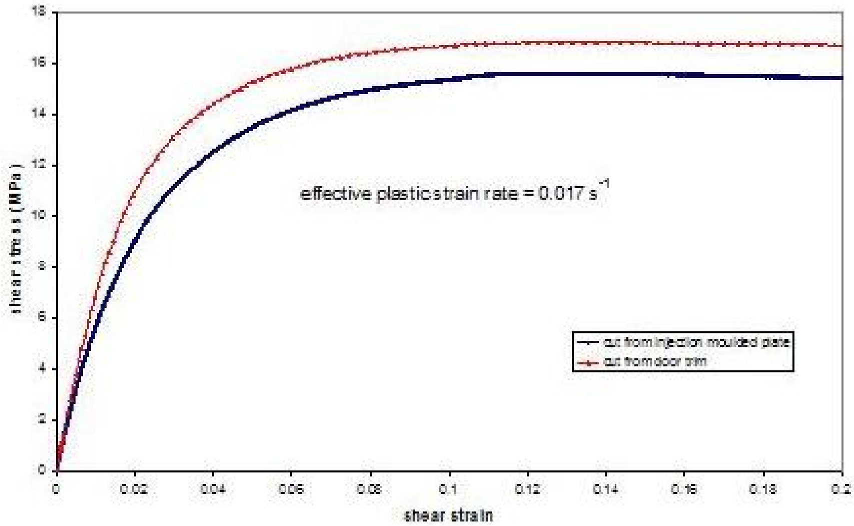
Whichever elastic-plastic model is used for a stress analysis, more accurate predictions will be made if the dependence of properties on strain rate is taken into consideration. In ABAQUS the dependence of yield behaviour on strain rate (rate-dependent plasticity) can be characterised by a series of hardening curves with different strain rates. Rate-dependence must be used to investigate the influence of loading speed. The cavitation model has been extended to include rate dependence in the form of a function.

Materials Characterisation

Characterisation of the plastics material is required to obtain parameters for the elastic-plastic models. The measurement of materials' properties involve tests under tension, compression and shear. Property data were obtained on specimens cut from the door trim panel. Tension tests were carried out over a range of strain rates to obtain rate dependent data. A procedure was developed for deriving properties at typical high speed impact rates by extrapolation from tests at moderately high strain rates, to enable the inclusion of high rate data necessary for impact analyses.

Standard injection moulded specimens were tested in order to investigate the dependence upon the processing conditions. Material properties measured on the injection moulded specimens were different from those obtained from the door trim panels. Investigations showed that the two materials were subtly different, see figure below. Von Mises, linear Drucker-Prager and cavitation model parameters were calculated for both door trim and injection moulded materials. For the main evaluation work, the door trim parameters were used.

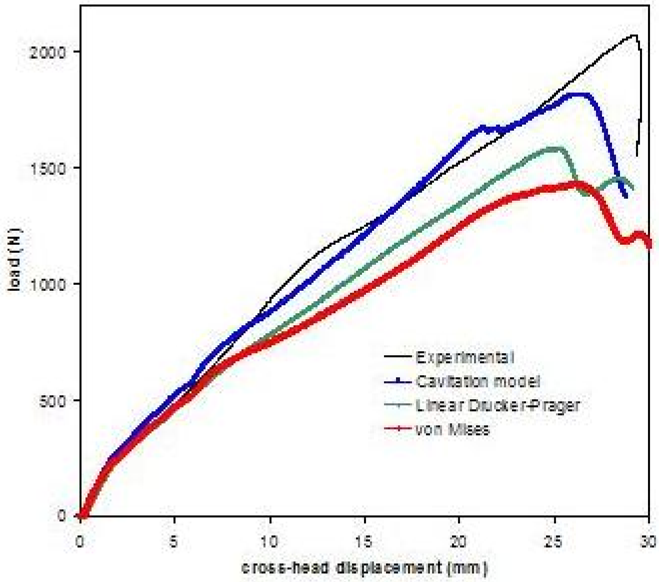
An NPL report (3) was written drawing together the material characterisation of both materials.



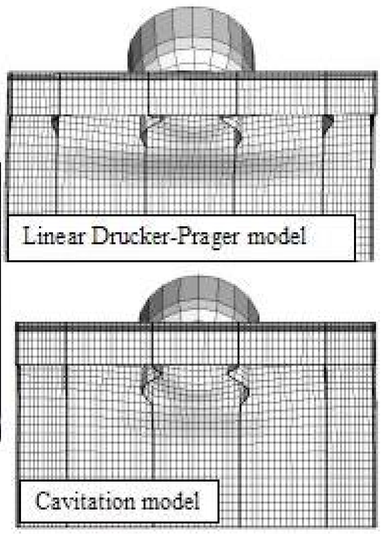
Difference in shear data between door trim and injection moulded specimens

Modelling Performance

Finite element analyses were carried out on the door trim subcomponent parts. The accuracies that can be achieved with the three models studied have been explored through predictions and measurements of the deformation behaviour of the two subcomponents over a range of loading speeds. Force-displacement predictions obtained for both components were compared to the respective experimental data, see figure on right for toptrim predictions. In both cases it was found that the von Mises predictions were furthest from the measured data.



The linear Drucker-Prager model improved upon the von Mises predictions, while the cavitation model produced the closed predictions. This trend was observed at three loading speeds 0.1 mm/s, 10 mm/s and 1 m/s and demonstrates that the more complex models are better at predicting the force-displacement behaviour of the components. Investigation of predicted stresses and strains in one central region showed that the linear Drucker-Prager and cavitation model predicted similar values, although the predicted levels of stress in regions of high strain are different.



The deformed shape of one component was studied in detail. This component had strengthening ribs on the underside. Photographs of components were taken during testing and these were compared to deformed plots predicted by the linear Drucker-Prager and cavitation models. At a displacement of 20 mm, the actual component shows deformation of the inner pair of ribs, with no obvious deformation of the outer ribs. This was consistent in all components photographed. The deformed plot predicted by the cavitation model shows the same level of deformation at 20 mm, while the linear Drucker-Prager predicts that at this displacement the outer ribs would also be deforming, see figure below. This indicates that the cavitation model is more accurately describing the deformation behaviour of the toptrim component.

The experimental set-up of the component tests included carefully marking the central point of the loading face to maximise reproducibility between tests, and also to allow direct comparison with FE analyses. During a vehicle collision, passenger impact may occur anywhere along the component parts. FE can be used to investigate how sensitive the deformation of the component part is to impact location. Both components have been studied using the linear Drucker-Prager analysis, with impact occurring at several different locations to demonstrate the ease with which different loading conditions can be simulated. In both components it was found that impact location could have a significant effect on the component behaviour. For instance, in the case of the toptrim component with the strengthening ribs, impact above a rib resulted in a much stiffer response but a lower maximum load.

FEA was also used to investigate the reproducibilty of experimental tests. The clamping jig for the armrest component needed to be angled prior to testing to ensure the top surface was horizontal. Running analyses with the armrest rotated to simulate misalignment during testing showed only small differences between the predictions indicating that although good alignment is always important for reproducibility in experimental data, exact alignment is not critical in this particular case. The above results are presented in more detail in an NPL report (3) that has been produced as part of this project.

Evaluation of FE model

There are many decisions to be made when setting up an FE model, such as element type, material model selection and analysis type. The FE simulation itself has been analysed by using different element types (solid and shell), different analysis types (rate-dependent, rate-independent; single or double precision calculations) and studying the influence of friction. The effects of element type and friction are described breifly below. For reliable predictions, accurate materials parameters must be used. This has been the focus of sensitivity analyses, summarised below, which have been carried out to indicate how sensitive predictions are to changes in the cavitation model parameters. Further details of the evaluation of the FE model are provided in the Good Practice Guide (1).

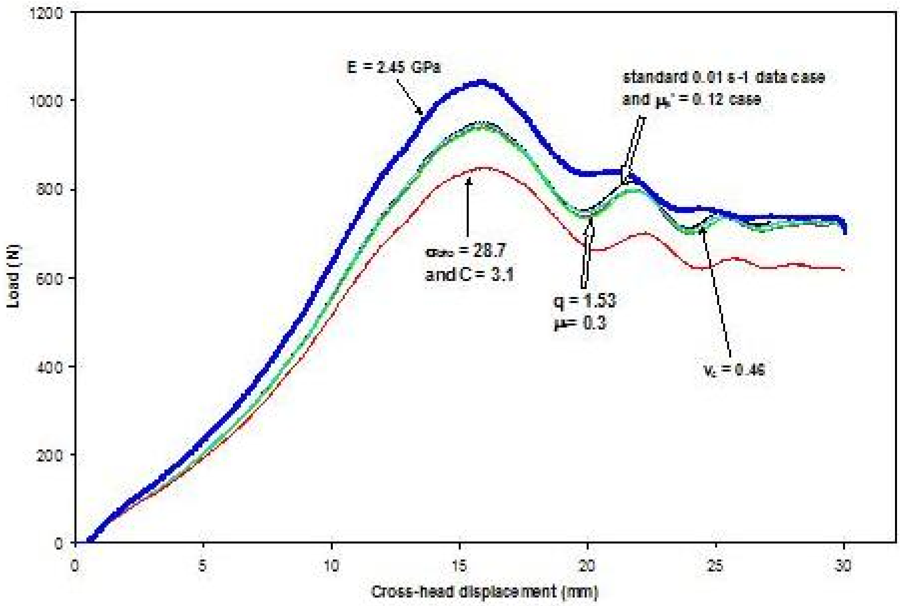
Element Type

The initial modelling of the two component parts used solid, continuum elements to give accurate predictions of stress and strain. This was possible due to the relatively small size of the components. In the automotive industry, shell elements are more commonly used due to the computational savings they deliver. To investigate whether shell elements give similar deformation predictions, the toptrim component was remeshed using shell elements and the analysis rerun with the cavitation model. Both element types produced good predictions of the component behaviour and comparison of the deformed plots at 20 mm show the same level of overall deformation i.e. inner ribs are highly deformed while outer ribs have not started to deform. Analysis of the predicted maximum principal stress and strain values at a central location showed that the stress values are comparable for both element types, but the strains predicted when using shell elements are less than half those predicted from the solid elements.

Friction

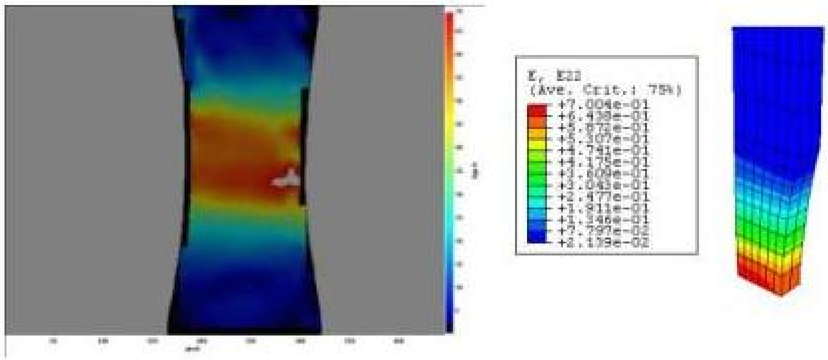
Armrest FE predictions were found to deviate from the experimental data at an extension of 15 mm. This deviation correlated with the predicted partial collapse of the component that was not observed experimentally. One reason for this difference was thought to be due to the lack of friction in the FE models. While friction might keep the indenter central in the laboratory test, the lack of it in the FE model may allow the component surface to slide over the indenter. Therefore friction has been included in an analysis, using a value of 0.2 for the friction coefficient. The inclusion of friction has altered the predicted force-extension plot, as a higher peak load is reached before the load starts dropping off. This leads to an improved correlation with experimental data. The deformed plot obtained from this analysis showed that the armrest component is no longer collapsing to one side, but is staying upright. This matches the experimentally observed deformation.

Parameter sensitivity



A number of parameters are required to use the elastic-plastic materials models. When data are required from tests under two stress states, for example in the calculation of some linear Drucker-Prager and cavitation model parameters, it is likely that the parameter value will depend upon which pair of data points are selected. A small sensitivity study was undertaken to get a feel for the effect of the cavitation parameters on the prediction obtained, to help establish best practice in testing and the analysis of test data for materials characterisation. The parameters have been individually changed to values that roughly correlate to the uncertainty in the measured value. It was found that in most cases, changes in the parameters had no significant effect on the predicted force-displacement curves, see figure left. Lowering the parameters responsible for the rate-dependence calculations within the model was seen to significantly reduce the peak load predicted and demonstrates the importance of including rate-dependent behaviour in impact analyses. Increasing the Young's modulus to a value measured at a higher strain rate had a large effect on the force-displacement plots. This indicates that rate-dependent elasticity could have a place in these analyses. Rate-dependent elasticity has been coded into the cavitation model, but has not been fully verified. This is a subject for further work.

Failure Studies



For most impact simulations, it is necessary to be able to predict under what conditions a component is likely to fail during an impact event. This is of particular concern at high strain rates and low temperatures when the ductility of many plastics is reduced. The measurement of stress and strain levels at failure is not reliable when using test specimens of standard geometry. This is because strain localisation occurs in the specimen during plastic deformation and flow. In previous work at NPL, a new specimen geometry was proposed for the measurement of properties at failure. In this project tests to failure under uniaxial tension have been carried out using this specimen to establish its suitability for a wider range of materials. The method is particularly appropriate for test speeds of 1 m/s or higher and is suitable for tests at different temperatures. High-speed photographs and digital image correlation strain mapping were used to accurately determine strain at failure.

A finite element analysis was carried out to simulate a test at a speed of 1 m/s. The predicted distributions of the axial components of stress and strain show that there is a region of predominantly uniform stress and strain in the specimen centre and that the strain is essentially uniform over a length of around 3 to 5 mm. This gives an indication of the gauge length that should typically be used for strain measurements. These calculations were supported by measurements of the strain distribution under the same conditions by the computer analysis of images of the specimen taken by high-speed photography during a test. The findings of this study have been presented in an NPL Measurement Note (4). This work is the basis of a new ISO Standards work item on Static Properties (5).

Concluding remarks

In finite element systems, elastic-plastic materials models can be used to describe the non-linear, large-strain behaviour of plastics materials. These models can be used to predict forces and deformations associated with a component under impact loading. The accuracy of predictions will depend on the suitability of the model for the polymer being studied and the accuracy achieved in the determination of model parameters.

The aim of this project was to evaluate the use of finite element analysis in predicting performance of plastics during impact. The findings have been presented in a Good Practice Guide, reports, a measurement note and papers. The contents of which include:

- Measurement methods for obtaining necessary experimental data
- Determination of materials models parameters
- Determination of high-rate hardening curves for impact analyses
- Evaluation of three elastic-plastic models
- Evaluation of the finite element model

Outputs

Good Practice Guide

1. NPL Measurement Good Practice Guide No.87, Prediction of the Impact Performance of Plastics using Finite Element Methods, Greg Dean and Louise Crocker

Reports

2. NPL REPORT DEPC-MPR-043 Prediction of the Impact Performance of Plastics Mouldings, G D Dean and L E Crocker

3. NPL REPORT DEPC-MPR-007 Determination of Material Properties and Parameters Required for the Simulation of Impact Performance of Plastics using Finite Element Analysis, G Dean and R Mera

4. NPL Measurement Note DEPC-MN-028 Measurement of Failure in Tough Plastics at High Strain Rates, G D Dean and R D Mera

Standards

ISO/DIS 18872 Plastics – Guide to the determination of tensile properties at high strain rates

- Provisional agreement to progress to an FDIS

Conference and Scientific Papers

- Prediction of the Impact Performance of Plastics Mouldings Part 1: Materials Models and Determination of Properties *G D Dean and L E Crocker* , submitted to Plastics, Rubbers and Composites, March 2006

- Prediction of the Impact Performance of Plastics Mouldings Part 2: Finite Element Simulations *L E Crocker and G D Dean* , submitted to Plastics, Rubbers and Composites, March 2006 Rubbers and Composites, March 2006

ABAQUS Users Conference 2005

- Predicting the Deformation Behaviour of Cavitating Materials, *Louise E Crocker and Greg D Dean*

Polymer Testing, 2004

- Testing requirements for design with plastics under impact loading, *G Dean*

Acknowledgements and support

This work was funded by the UK Department of Trade and Industry as part of the Measurements for Processability and Performance of Materials (MPP) Programme (MPP).

Industrial Advisory Group

- Lucite
- AstraZeneca
- Corus
- Zotefoams
- Avon Rubber
- Brandrex
- Glynwed Pipe Systems
- NGF Europe Ltd
- BP
- RAPRA Technology
- Celsum Technologies Ltd
- Visteon Automotive Systems
- Wallace Instruments
- Polypipe Civils Ltd
- Bespak
- Hydro Polymers Ltd
- Du Pont (UK) Ltd
- Paint Research Association
- Proctor & Gamble
- Automotive Applied Technologies Ltd
- Ross Ceramics Ltd
- RAILKO
- Fleming Polymer Testing & Consultancy
- TA Instruments Ltd
- Amcor Flexibles
- Crown Cork & Seal
- Federal-Mogul
- Linpac Plastics
- Mira
- Innovene
- Arjo Wiggins
- Hi-Technology Group
- Porpoise Viscometers Ltd
- TARRC
- ICO Polymers
- Unilever
- Ford
- Emral Ltd
- Synbra Polymers
- Kistler Instruments
- Peter Cox Associates

- Pilkington PLC
- Polytech Consultants Ltd
- Bohlin Instruments Ltd
- Land Rover
- Perkin-Elmer
- Delcam UK
- Anglian Windows
- Nylacast Ltd
- ThermoHaake

Academic Institutes

- Loughborough University
- Imperial College
- City University
- Southampton Institute
- University of Bradford
- University of Leeds
- University of Sunderland

Contact
Louise Crocker
National Physical Laboratory
Tel: 020 8943 6798 (direct)
E-mail: louise.crocker@npl.co.uk