Comparison of Crash Models for Ductile Plastics

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1 Abstract

There is interest in quantifying the accuracy of different material models being used in LS-DYNA today for the modeling of plastics. In our study, we characterize two ductile, yet different materials, ABS and polypropylene for rate dependent tensile properties and use the data to develop material parameters for the material models commonly used for plastics: MAT_024 and its variants. We then perform a falling dart impact test which produces a complex multi-axial stress state and simulate this experiment using LS-DYNA. We compare simulation to actual experiment thereby obtaining a measure of fidelity of the simulation to reality. In this way, we can assess the benefits of using a particular material model for plastics simulation.

2 Introduction

Several material models are commonly used within LS-DYNA to simulate rate dependency in plastics. Because some of these models were not originally designed for plastics, there is concern about the ability of the models to accurately capture the complex polymeric behavior. Additionally, the sheer breadth of behavior displayed by polymeric materials makes it difficult to have a single material model capable of accurately capturing all possible effects. It is somewhat challenging to devise a general strategy for the modeling of polymers.

One approach used to attempt to gain some control over this problem is to validate the models with simulations of well-designed experiments that contain some complexity. This carries the assumption that if a simpler experiment correlates well to simulation, more complex simulations would have comparable accuracy. Our work uses the impact of a plastic disc which creates a multi-axial stress state combined with rate dependency as a test bench for a crash model. MAT_024, the piecewise linear plasticity model is a popular elasto-plastic model, where both the stress versus strain curves and rate dependency are defined, combined with a single failure strain for all strain rates. We examine various configurations of the rate dependency formulations, combining LCSS tables, LCSR curves, or Cowper-Symonds (CP) coefficients with the different viscoplastic (vp) formulations.

3 Background

The methodology of testing polymers for rate dependent models such as MAT_024 has been dealt with in previous work [1] and will not be covered in depth for this paper. Briefly, stress-strain measurements are conducted at different strain rates. The measurements cover several decades of strain rate to then permit the establishment of material model parameters for the MAT_024 model. Uncertainties and limitations of the model when applied to plastics have also been covered earlier[1].

More sophisticated material models and related test methodologies have been proposed as described in the literature that offer a possibility to account for more detailed quantification of the actual polymer behaviour [2]. By providing the model with data for shear, compressive and biaxial deformation states, a more accurate rendition of the material characteristic is obtained, including descriptions of post-yield volumetric change and failure. The ability to define a non-Mises yield criterion adds to the versatility of the model. Such models have not been examined in this paper.

Different types of polymers exhibit dramatically different kinds of stress-strain behaviour so there still remains quite a bit of uncertainty when applying these models to simulation. Concerns arise around how the model reproduces behaviours that have not been input into the material model. For example, the MAT_024 material model relies exclusively on uniaxial tension data for elasticity and plasticity, with a von-Mises criterion being used to project the behaviour into shear and biaxial spaces. In plastics, the validity of this assumption can be called into question. In a crash application, deformation is typically multi-axial in nature.

The idea of using a falling dart impact experiment to validate simulation is itself not new. It was proposed by Trantina and Nimmer in their 1993 book [3]. In a 1998 paper, Lorenzo and Lobo [4] showed that it was possible to obtain fairly good correlation starting with a material model obtained from test data and applying it in an LS-DYNA crash simulation.

4 Procedure

A polypropylene and ABS sheet material of thickness 3.17 mm (1/8”) obtained from McMaster Carr were used for this study. Test specimens were cut from the sheet in a single orientation using CNC methods. ASTM D638 Type V tensile bars [5] were used for the development of the MAT_024 material parameters. MAT_024 requires: density, Young’s modulus, Poisson’s ratio, yield stress, uniaxial tensile stress-strain curves [1] over a span of 5 decades of strain rate, decomposed into true stress vs. plastic yield strain. The strain rates used were as recommended in previous work [1] taken up to a maximum of 100/s. All tensile tests were performed on a modified Instron 8872 universal testing machine. The material model parameters, CP coefficients, LCSS curves, or LCSR curves were calculated from the tensile tests at different strain rates using Matereality CAE Modeler for LS-DYNA Software. The resultant material card files were imported into LS-DYNA PrePost for analysis. Figure 1 shows tensile data for the ABS and a corresponding material card.

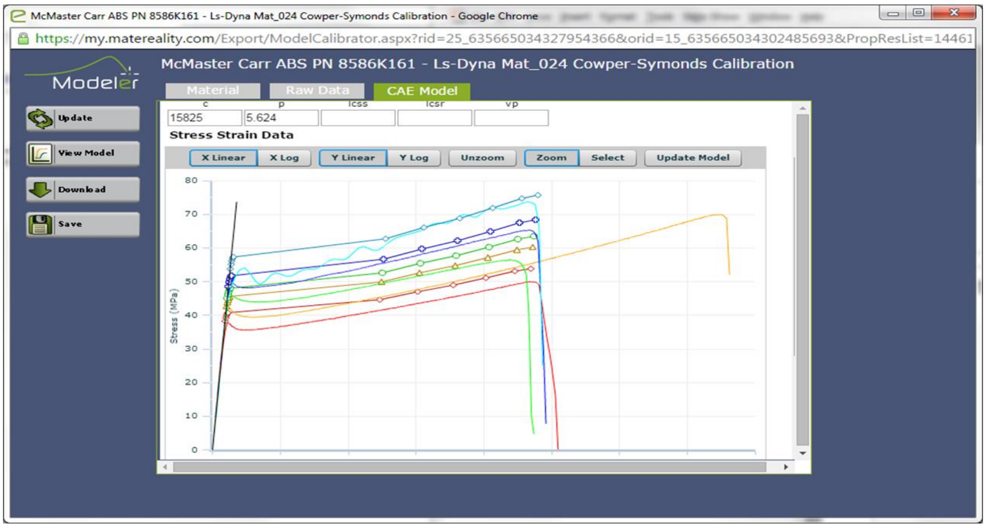

Fig.1: Material model calibration of ABS tensile data to MAT_024 CP using Matereality CAEModeler

Impact tests based on ASTM D3763 [6] were performed using a Dynatup 8250 impact tower to provide a test bench for validating the simulation. A hemispherical tipped dart impactor with a mass of 23kg and radius of 6.35mm was used to impact a circumferentially clamped plate with a radius of 38mm. Specimens for this test were cut from the same ABS and polypropylene plastic used for the tensile experiments. Initial velocity of the dart was 3.35 m/s at the point of impact. From this test force, displacement, velocity, and time were recorded to validate the simulation. It was confirmed that there was no slip in the circumferential clamp during the impact, an important criterion for the setup of the simulation. Additionally, the impactor was not lubricated leading to a no-slip assumption in the simulation as the dart penetrated the plastic plate. The velocity during the impact event was not constant but decreased in proportion to the energy absorbed as the impactor penetrated the sheet.

Two simulations were used to probe the validity of the material models. The type V tensile bar was modeled with Belytschko-Tsay shell elements with the default hourglass setting 1, and thinning enabled. Element size was approximately 0.36mm^2. The tensile test itself was simulated with one end fixed and the other moving at a constant velocity resulting in uniaxial deformation. It was found that using measured failure strains obtained from the uniaxial tensile experiment resulted in premature failure in the falling dart simulations. Accordingly, linear extrapolation was applied to the plasticity curves to extend them to a fail strain of 1.2.

The falling dart simulation was set up using type -1 solid elements (fully integrated for poor aspect ratio) [7], with element sizes around 2mm³. A type 3 hourglass setting (Flanagan-Belytschko viscous form where solid elements have exact volume integration) was used, with and an hourglass coefficient set to 0.1. This setting is equivalent to that used for the tensile bar, because hourglass types 1-3 are equivalent for shell elements. The impactor was modeled as a rigid ball object with the mass of the entire dart in the tip. An eroding surface-to-surface contact setting was used between the impactor and the sheet. The static and dynamic coefficients of friction (FS & FD) were set to 1.

The guidelines from Bala and Day [8] were used for deciding model settings. For each test case, the simulation model was kept unchanged with the exception of the material model parameters. The force vs. time data from the simulation and the experiment was compared.

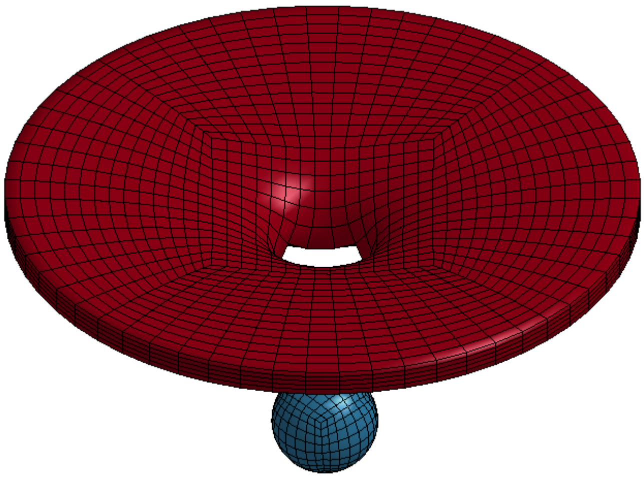

Fig.2: Falling dart impact simulation

5 Results and Discussion

We first performed a "closed-loop validation" to see if we could simulate the original tensile test used to generate the material model parameters. The MAT_024 material models tested covered LCSR. LCSS, and CP rate dependency options along with an evaluation of the three visco-plasticity (vp) settings. The vp formulation relates what type or part of the strain rate tensor is used in the stress calculations, 0 uses the current strain tensors, 1 uses only parts that relate to plastic strain, and -1 uses Cowper-Symonds with deviatoric strain rate rather than total strain rate [9, 10]. To determine which visco-plasticity formulation to use, we ran the MAT_024 model with LCSS setting, for each option and compared it to the 100/s tensile data for the ABS material. For this strain rate vp=1 gave the highest fidelity to experiment, while vp=0 or -1 significantly over-predicted, as seen in Fig. 3.

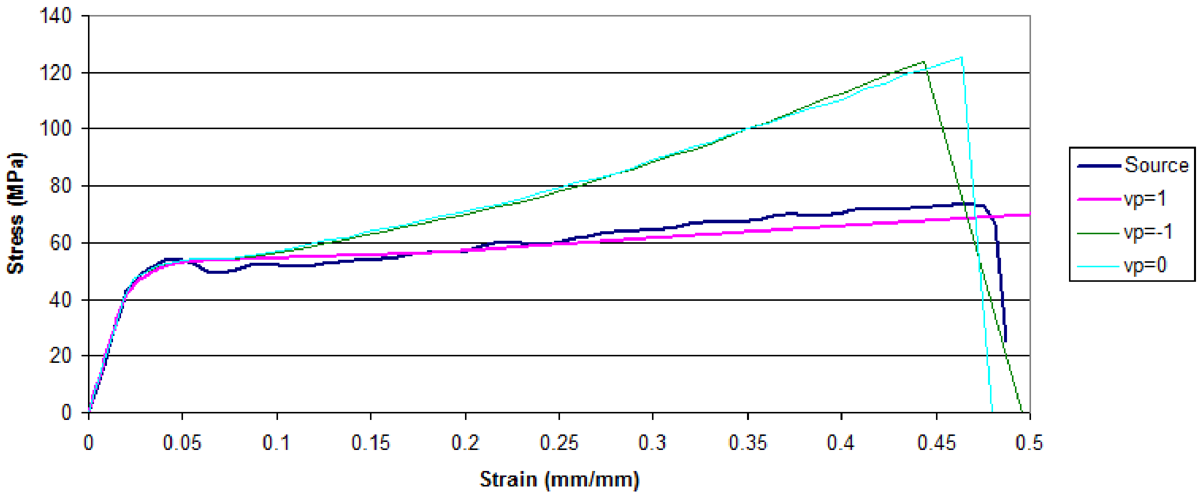

Fig.3: MAT_024 LCSS rate dependency for ABS with varied vp settings

The effect was similar with the LCSR option. In the case of CP option (Fig. 4) the over-prediction was less pronounced but still present. This led us to conclude that a vp setting of 1 was best suited for these materials, which coincides with the recommendations of Bala and Day [8]. Based on this finding, further simulations were conducted with only the vp=1 setting.

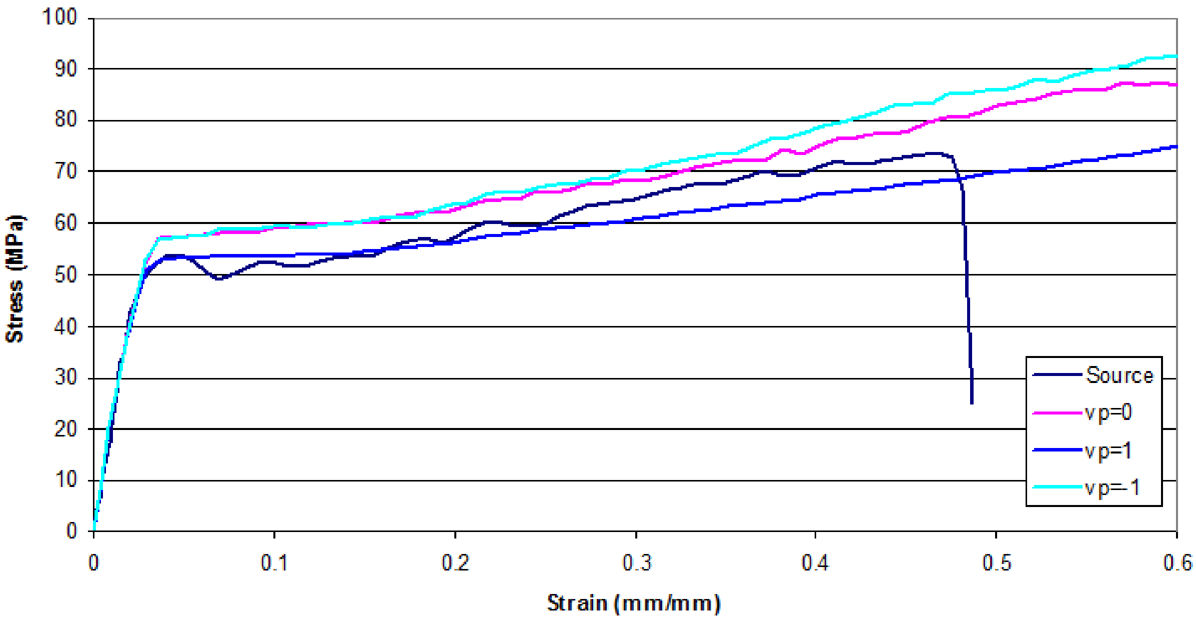

Fig.4: MAT_024 CP rate dependency for ABS with vp settings varied

Fig. 5 shows the validation of the original tensile experiment using a MAT_024 material model with viscoplasticity vp=1 for each rate-dependency option, LCSS, LCSR, and CP. Simulations were all within 6% of the representative curve at the experimental data's failure strain.

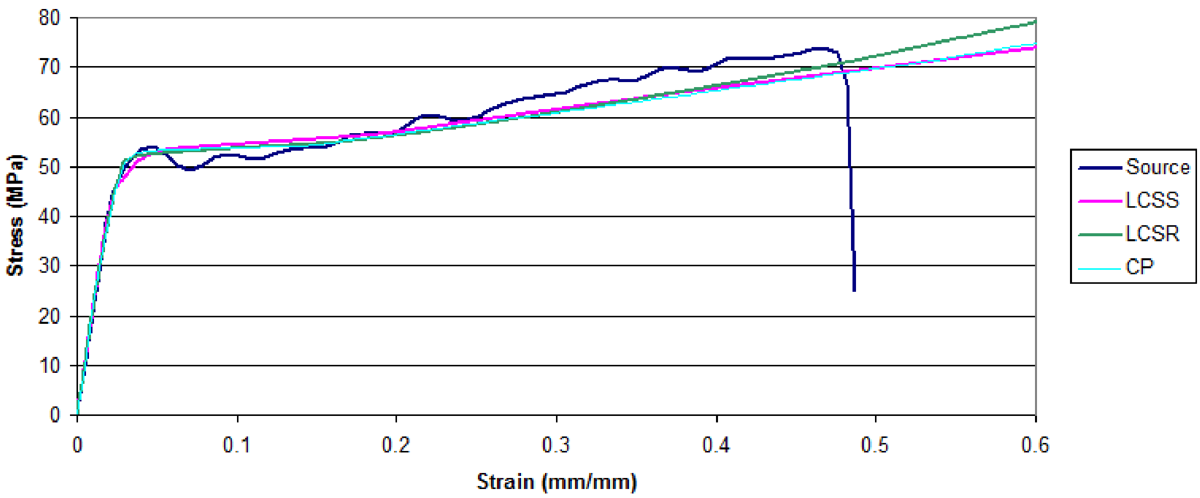

Fig.5: Closed loop validation of tensile test for ABS – MAT_024- LCSS, LCSR, CP with vp=1

Using the same geometric model and simulation settings, validations were performed for the polypropylene material as well. The results are shown in Figure 6.

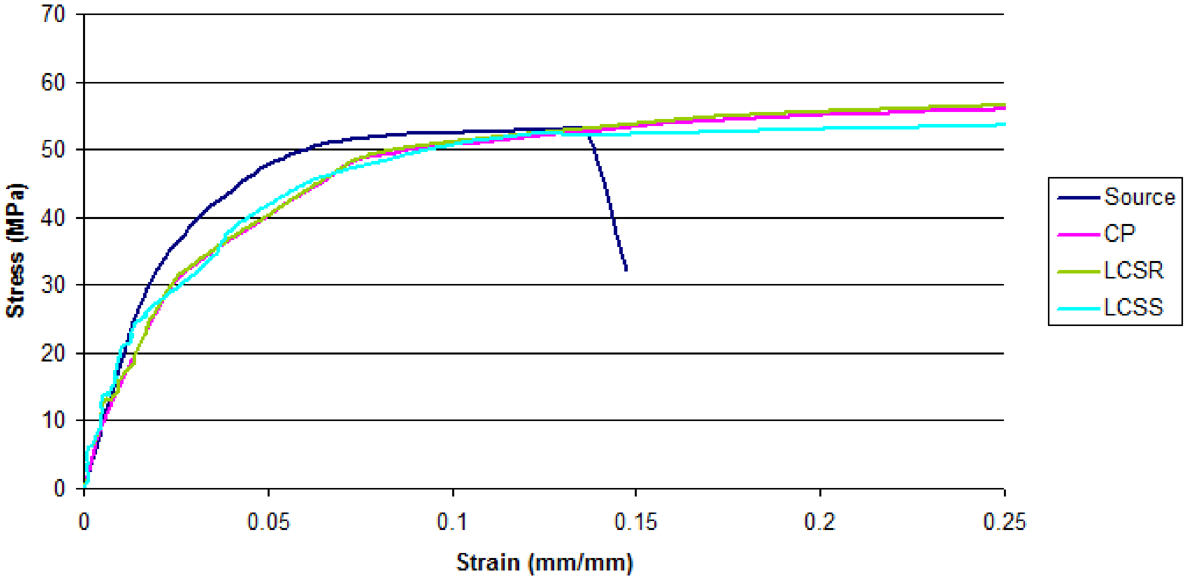

Fig.6: Closed loop validation of tensile test – MAT_024- LCSS, LCSR, CP with vp=1 for PP

We now used the above material models in the falling dart impact simulations to perform what we call an "open-loop validation" where we sought to validate an experiment that was not the source of data used for developing the material model. As with the tensile validation, vp=1 gave the highest fidelity. Validations of MAT_024 with CP, LCSS and LCSR options against the experiment are shown in Figure 7. The option with the highest fidelity was found to be LCSS with vp=1. The variation was quantified by examining the percent error between the peak resultant force and the time where peak force occurs, as well as a visual check for fidelity of the force vs. time curves to the original test data. The percent error of LCSS was 4.1% and -2.6% for force and time respectively. LCSR was the next closest case at an error of 14% force and was almost coincident with CP at 17%. The simulation replicated the experiment up to the point of maximum force, with abrupt failure occurring at that point. It was unable to capture the ductile failure process beyond the peak that is observed in the test data. We believe that the inclusion of a damage model could permit the modeling of this phase.

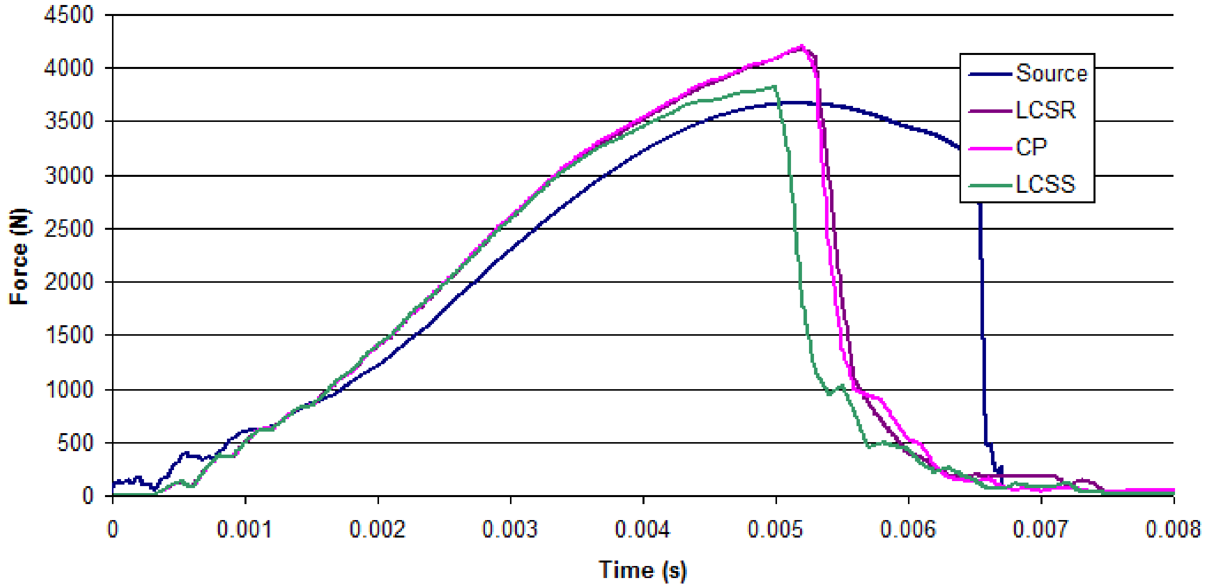

Fig.7: Falling dart (open loop) validation of MAT_024 for ABS with visco-plasticity vp set to 1.

Simulations with polypropylene showed the same trends (Fig. 8) even though the two materials exhibit very different yield and post-yield behavior. The failure of the polypropylene is more abrupt resulting in closer correlation between simulation and test at the point of failure.

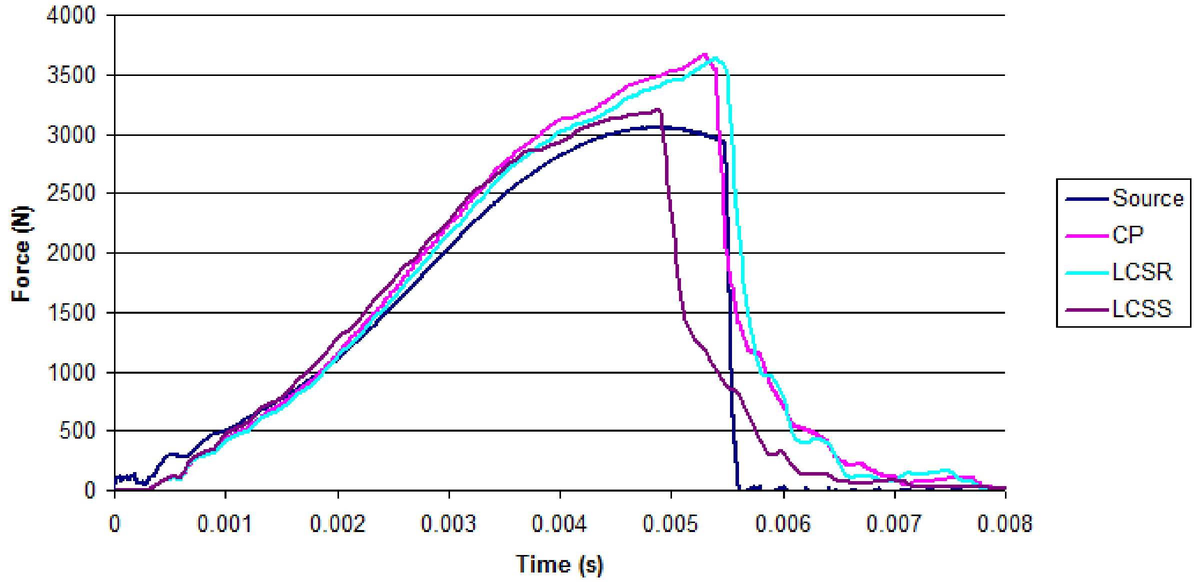

Fig.8: Falling dart (open loop) validation of MAT_024 for PP with visco-plasticity vp set to 1.

CP, LCSS, and LCSR present different schemes for scaling stress to account for strain rate. The observed error with using LCSS and LCSR could relate to how these schemes interpolate and extrapolate the stress-strain curves. In examining the simulation results, we noted that the maximum strain rate during the impact was in the vicinity of 200/s. LCSS uses curves at specific strain rates and with a linear interpolation for stress and strains between those rates. Anything above the maximum 100/s given rate curve defaults to the top curve as there is no means for extrapolation. Similarly, LCSR uses a table of scale factors to apply to the quasi-static curve to account for strain rate effects, but also fails to extrapolate beyond the rates given in the table.

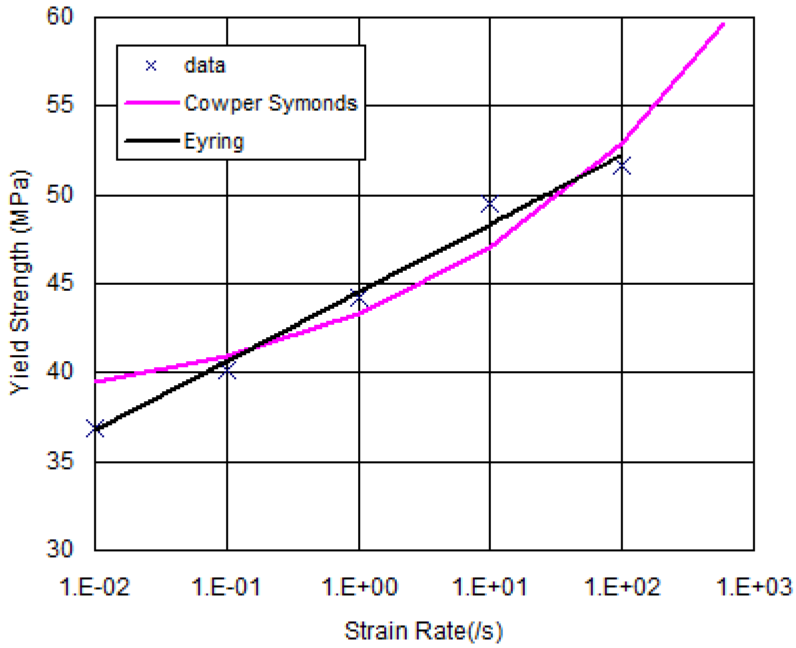

Fig.9: Rate dependency scaling using CP vs. Eyring models

We found that the CP option gave the greatest over-prediction when compared to test data. CP uses the Cowper-Symonds equation [7] for calculating scale factor.

$$\beta = 1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p} \tag{1}$$

This equation gives a continuous function for scale factor that permits extrapolation. However the shape of the curve does not match the rate-dependent behavior of plastics as seen in Figure 9. This results in inaccuracies at the lower strain rates and unknown error beyond the upper boundary of the tested region [1] as the material model shows in Figure 9. In contrast, the Eyring equation seems to give a more realistic representation of polymer rate-dependency.

Some error could be attributed also to how LCSR and CP scale the quasi-static in that the curve shape remains unchanged. Neither of these options can account for cases where the shape of the stress-strain curve is dependent on the strain rate, nor can the MAT_024 model account for the change in failure strain with strain rate, a phenomenon that was observed with the polypropylene.

6 Conclusions and Future Work

The falling dart impact test could serve as a well-structured benchmark experiment for the validation of high strain-rate material models for ductile plastics. The test itself is common and extremely well documented as an international standard for plastics. While containing multi-axial complexity, it possesses boundary conditions that can be well replicated in simulation allowing us to probe the material behaviour without fear of mismatch between simulation and physical experiment. Failure to satisfy this key requirement would seriously mar our ability to make quantitative judgements.

Rate-dependent material models developed using classical high-strain rate tensile test techniques can be used to successfully simulate more complex multi-axial phenomena. The same material model parameters were shown to give good results with shell elements as well as with the solid elements used in the falling dart experiment. There appears to be some need for tuning, such as with the failure strain but this is a known limitation of the MAT_024 material model.

The commonly used MAT_024 material model correlates quite well against the falling dart benchmark. It is possible to quantitatively assess the merits of different rate-dependency options and make sound judgements about the impact of different modelling decisions upon the simulation. While all options perform reasonably well, we observe that the Cowper-Symonds option may tend to overpredict, possibly because the equation does not mimic well the rate-dependency of plastics. We also validate the visco-plasticity 1 option as being best suited to plastics.

Factors unrelated to the material model such as element formulation and hourglass settings were observed to have a large effect on simulation accuracy, almost doubling the error in some cases. The hourglass setting 3 was observed to give good results for this case.

The over-prediction of the MAT_024 material model can be easily overcome by tuning the material card using a scale factor to lower the plasticity curve(s). This can be a suitable next step particularly in cases where the real-life scenarios being simulated are substantially similar to the benchmark. However the validity of such a tuning step for cases where there are other predominant deformation modes is not clear.

It is our intent to use this benchmark to probe other material models commonly used for ductile plastics including MAT_089 and MAT_187. We would also seek to evaluate the benefits of damage models to more accurately predict the degradation in properties following failure.

7 Acknowledgements

We are grateful to Suri Bala of LSTC and Steve Hale from CAE Associates, Inc. for comments and guidance and to Gerald Lindsley, DatapointLabs for performing the experimental work.

8 Literature

[1] Lobo, H., Croop, B., “A ROBUST METHODOLOGY TO CALIBRATE CRASH MATERIAL MODELS FOR POLYMERS“, 2009, http://www.testpaks.com/2009/NAFEMS09.pdf
[2] Du Bois P.A., et al. “A Constitutive Formulation for Polymers Subjected to High Strain Rates” LS-Dyna International Conference Proceedings (2006)
[3] Trantina G., Nimmer R., Structural Analysis of Thermoplastic Components, McGrawHill, Inc., 1993
[4] Lobo H., Lorenzo J., High Speed Stress Strain Material Properties as Inputs for the Simulation of Impact Situations, IBEC, Stuttgart (1997).
[5] ASTM D638-14 Standard Test Method for Tensile Properties of Plastics, ASTM International, (2014)
[6] ASTM D3763-14 Standard Test Method for High Speed Puncture Properties of Plastics Using Load and Displacement Sensors, ASTM International, (2014)
[7] “LS-DYNA Keyword User’s Manual: Volume 2 Material Models“, Revision:5442, 2014, 154-160
[8] Bala, S. Day, J.,"General Guidelines for Crash Analysis in LS-DYNA," 2006 http://blog.d3view.com/wp-content/uploads/2006/11/Crash_Guidelines.pdf
[9] http://www.dynasupport.com/howtos/material/viscoplastic-strain-rate-formulation-vp
[10] “LS-DYNA Theory Manual,“ 2006, 46-47