Characterization and Material Card Generation for Thermoplastics

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Abstract

Modelling polymer materials for crashworthiness applications is still an ongoing and challenging topic. Besides the constitutive model the spatial discretization plays a significant role in setting up predictive models in impact scenarios where damage and fracture are dominating the part deformation. Therefore, the limits of the chosen spatial discretization shall always be kept in mind. However, the present contribution is focused on recent enhancements of constitutive models for polymeric materials. This topic is as well ongoing for many years and has been tackled almost 2 decades ago by the development of MAT_SAMP-1 (#187) in LS-DYNA®. Many years of continuous improvement lead to a versatile and usable as well as predictive model. Unfortunately for the cost of slow execution speed if the parameter set or the various curve definitions were not chosen wisely. Therefore, a simplified model with the aim to have a more competitive model available when it comes to computing speed was developed. The so called SAMP_LIGHT (#187L) model comes with a complete redesign for speed but also with a number of limitations (due to the speed argument) and still seems to be versatile enough for everyday simulations.

The present contribution recalls the features of SAMP-1 and discusses some of the issues that may lead to exaggerated execution time. Then the reduced model is described and a viable approach to convert available SAMP-1 constitutive data towards SAMP_LIGHT is presented. Clearly the limited model may not be as predictive as the fully flavored one – but the drawbacks may not be severe enough to not give it a try.

Introduction

The semi-analytical model for polymers (SAMP-1) was developed to describe the complex deformation and damage behavior of polymers. In its current version, it is able to consider visco-elastic and visco-plastic material properties, can be used to model non-dilatant material deformations (e.g. crazing) with the help of a flexible consideration of plastic Poisson's ratio and furthermore the definition of different yield curves (tension, compression, shear and biaxial) allows the generation of a versatile yield locus. However, this flexibility often requires many iterations on material point level, which have a significant effect on the computational effort.

Practice has shown that often different stress levels in tension and compression, non-dilatant material behavior as well as dependence on the loading velocity (or strain rate) dominate the mechanical material properties of polymers. Therefore, the SAMP_LIGHT constitutive model was developed and implemented in LS-DYNA recently. The model is able to capture the dominant material behavior of polymers and at the same time exhibits higher execution speed compared to the classical SAMP-1 model.

In this contribution the SAMP-1 model with its numerous possibilities is first described briefly, before the SAMP_LIGHT model is introduced. It is assumed that many users of the SAMP-1 model might be interested in the application of the SAMP_LIGHT model as well, hence in the last part of this article straight forward applicable suggestions are made to create a SAMP_LIGHT card from an existing SAMP-1 material card.

An overview to the SAMP-1 model

The initial approach of SAMP-1 (MAT_187 in LS-DYNA, see [4, 5]) was to define a pressure dependent quadratic yield surface (Eq. 1) in the $\sigma_{vm} - p$ space (or sometimes also expressed in $J_2 - I_1$ space), where the parameters A_0, A_1 and A_2 are computed via curve definitions that could be directly converted from experimental data from tension, compression and shear tests (see Figure 1 for a graphical representation of the yield locus).

$$f(p, \sigma_{vm}, \bar{\varepsilon}_p, \dot{\bar{\varepsilon}}_p) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \leq 0 \quad (1)\text{s}$$

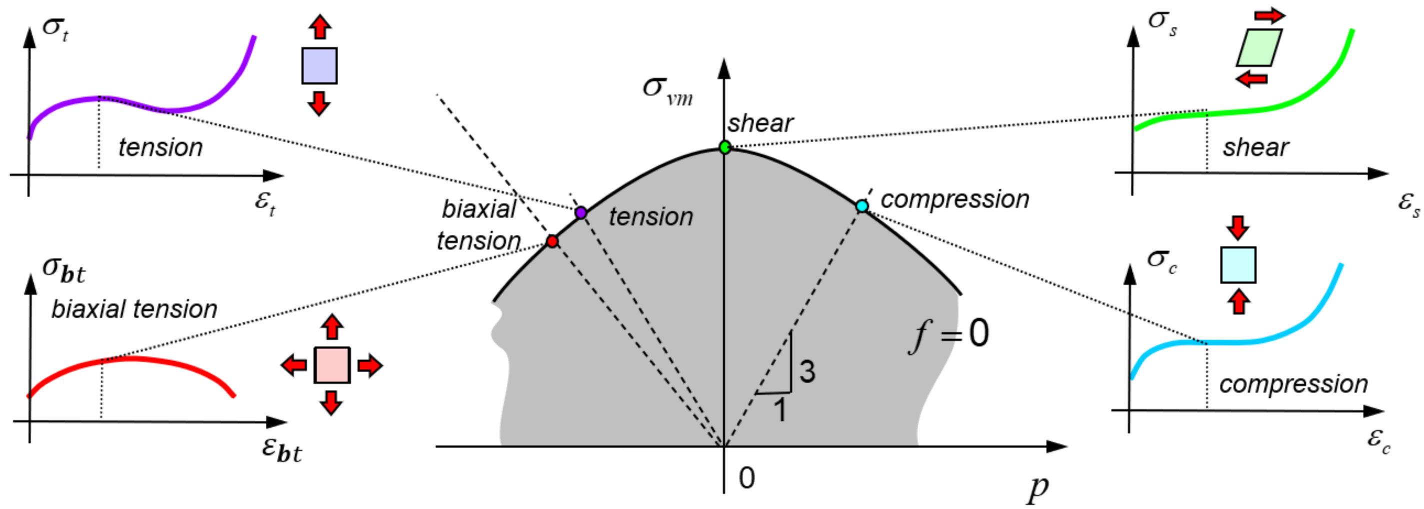

Figure 1: Yield surface in SAMP-1 (Semi-Analytical Model for Polymers)

Since the definition of the parabola only needs three tests, a fourth experiment to define biaxial stress strain relationship was added by a least square fit to the model. Hence if four curves are given this approach is internally used to generate the respective curve defined values for Ai. Furthermore, if for some reasons the user only provides a subset of the curves, the internally computed parameter set for A_i will always ensure a meaningful definition of the yield surface, i.e. the order of the polynomial may be reduced, thus resulting in a less sophisticated yield surface.
The equations to compute the factors A_i from tension, shear and compression tests are:

$$A_0 = 3\sigma_s^2 \qquad A_1 = 9\sigma_s^2 \left(\frac{\sigma_c - \sigma_t}{\sigma_c \sigma_t}\right) \qquad A_2 = 9\left(\frac{\sigma_c \sigma_t - 3\sigma_s^2}{\sigma_c \sigma_t}\right) \quad (2)$$

It is worth noting though, that the equations assume a constant characteristic stress relation during the testing. This means the stress triaxiality η has to be as close as possible to the theoretical value. This is $\eta = 1/3$ for uniaxial tension, $\eta = 0$ for shear and $\eta = -1/3$ for uniaxial compression. Anybody involved in experimental investigations knows, that this is not feasible which resulted in engineering practice eventually in a reverse engineering approach to identify the curve definitions. Furthermore, in a later stage of the development it became clear that using SAMP-1 with arbitrary defined curves may result in sever convergence problems if not in the mathematical impossibility to solve the stress integration algorithm – independent of the chosen plastic potential (also called flow rule, which will be discussed below).

While this freedom was given to the model by the developers intentionally, one needs to stress the point that with unlimited possibilities to define the basic data for the curves that are used to compute A_i, the corresponding evolution of the yield surface w.r.t. equivalent strain space may easily become nonphysical or oscillating. The latter holds particularly if the given curves are not smooth enough. It is therefore strongly recommended to use yield curves with at least a smooth appearance in the first if not also in the second derivative. Since the evolution of the yield surface shows this strong sensitivity, the parameter RBCFAC was added to the formulation, which replaced the parabola with a multi-linear approach (see [6, 7]). The corresponding yield surface is then combined of four linear equations but of course still defined at the same points. In Figure 2 the corresponding graphical representation is given.

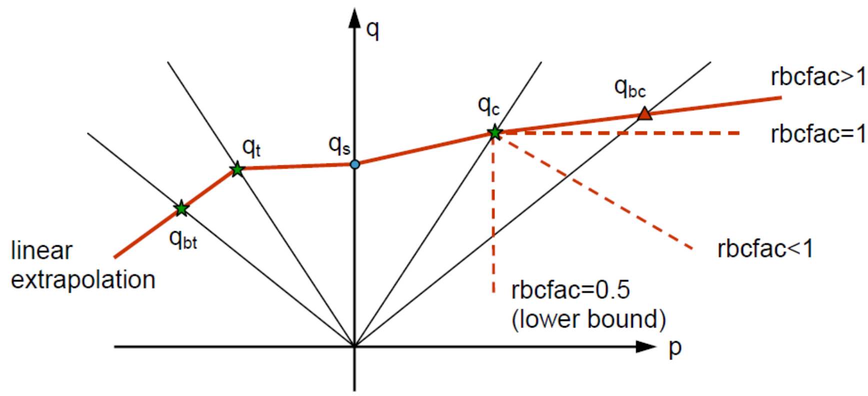

Figure 2: Multilinear yield surface in SAMP-1 when parameter RBCFAC is defined

Strain rate dependency was thought to be easiest measured from tension tests. Hence in SAMP-1 a strain rate dependent table can only be given for the tension test data. The corresponding strain rate amplification factor, computed in a fully visco-plastic sense from the plastic strain rate, is carried over to the shear and compression behaviour. Clearly, from experience in model calibration the strain rate dependence in compression and tension is not identical. And since the parameter identification is done by reverse engineering anyway adding such a feature to a later model seemed reasonable.
When it comes to the yield behaviour, which is often also associated with the term plastic potential, the macroscopic effect of non-isochoric yielding in polymers was also targeted. This is the reason SAMP-1 exhibits a plastic potential that is also dependent on the pressure p (see Figure 3). The corresponding value of α allows to reduce the yield to a pure isochoric (volume preserving) model for $\alpha = 0$:

$$g = \sqrt{\sigma_{vm}^2 + \alpha p^2} \qquad (3)$$

However, this approach also adds the freedom to define α as a function of the equivalent plastic strain, separated in tension and compression, thus allowing the variation of the volumetric behaviour while loading the material point. The value of α can be related to the Poisson's ratio (lateral strain rate over longitudinal strain rate, see [8]) due to plastic deformation ν_{pl} according to:

$$\alpha = \frac{9}{2}\frac{1-2\nu_{pl}}{1+\nu_{pl}} \qquad (4)$$

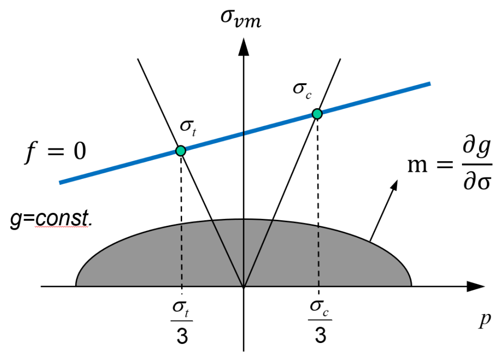

Figure 3: Plastic potential (flow rule) of SAMP-1 and SAMP_LIGHT.

The remaining parameters in SAMP-1 are mainly related to the damage and fracture behaviour of the model. The educated reader will realize that many of the features found in SAMP-1 have in the meantime been carried over to the GISSMO model (MAT_ADD_DAMAGE_GISSMO) and shall therefore not be covered here.

Furthermore, the focus of this contribution is to explain which features were extracted from SAMP-1 and carried over into a new model. Since the stress integration has proven to be very complex in SAMP-1 it was the main goal to simplify the yield surface but to keep the unique features of the model, for instance the flexible definition of the plastic potential or the pressure dependency of the yield surface. Other features, like the complex damage and fracture behaviour were seen redundant with the availability of GISSMO and were abandoned.

Introduction of MAT_SAMP_LIGHT

From the previous paragraph the main development direction of a new and faster model for polymers is already identified: A more simple yield locus was chosen by using a typical Drucker-Prager formulation (see also [9]). Thus from Eq. 1 the quadratic term was removed and hence the corresponding yield surface is defined through uniaxial tension and compression curves collected from and calibrated through experimental data:

$$f(p, \sigma_{vm}, \varepsilon^p, \dot{\varepsilon}) = \sigma_{vm} - A_0 - A_1 p \leq 0 \tag{5}$$

Both can be given strain rate dependent thus allowing a different strain rate sensitivity in both loading directions (compare Figure 4). Furthermore, the applied strain rate is not based on the visco-plastic part of the strain rate but on the total strain rate (Eq. 6) and computed by a running average instead of a fully implicit scheme.

$$\dot{\varepsilon}_n^{avg} = R\dot{\varepsilon}_{n-1}^{avg} + (1 - R)\dot{\varepsilon}_n \qquad \text{(by default R = 0.95)} \tag{6}$$

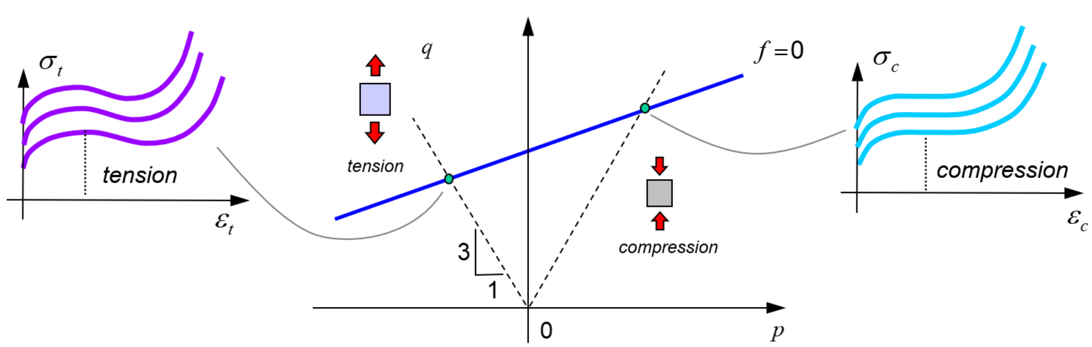

Figure 4: Yield surface of SAMP_LIGHT.

This modification results in a slightly different strain rate within SAMP_LIGHT if compared to SAMP-1 w.r.t. the same loading velocities. Obviously, the is effect is more pronounced at low loading velocities and if the elastic modulus is close to the tangent modulus – which is of course often the case in polymeric materials. Furthermore, the approach to model the volumetric behavior by a curve definition of ν_{pl} has been kept. The graphical representation is given in Figure 3, the corresponding equations are given in (3) and (4). Damage and element erosion have to be realized through MAT_ADD_DAMAGE_GISSMO, since it is not included in SAMP_LIGHT.

Some thoughts when converting data from SAMP-1 to SAMP_LIGHT

Over the past many plastic materials have been tested and calibrated with the SAMP-1 model. However, with sub-optimal definition of yield curves and the complex evaluation of the yield condition and a resulting slow convergence of the stresses integration, the execution speed may often be slow. This is especially pronounced in full car crash models where more and more SAMP-1 constitutive models appeared over time. Furthermore parallelization of the model kept its own challenges: Since the convergence rate of the model strongly depends on the smoothness of the provided curves as well as the many different options the user may choose, it was almost impossible to estimate the extra cost SAMP-1 would cause compared for example to a standard J_2-plasticity model, for instance like MAT_024. Hence it was inevitable to reduce the number of options and simplify the overall approach. Of course, this will eventually lead also to different results if model data from SAMP-1 is simply carried over to SAMP_LIGHT.
While this can be done easily if the source data in SAMP-1 represents a von Mises or Drucker-Prager yield surface which can be represented by SAMP_LIGHT as well, a reverse engineering and/or recalibration is definitely necessary if three or four hardening curve definitions, i.e. representing a parabolic yield surface, are given in the original SAMP-1 data. Hence the adaptation to existing test data may be slightly less accurate. Furthermore, if a strain rate table is used in the source material card one needs to evaluate if the strain rate dependency needs to be recalibrated as well since, as described above, both models use different strain rate measures. Also be advised that in SAMP-1 the strain rate evaluation does not extrapolate above the largest strain rate and below the smallest strain rate. In equivalent strain direction the stress values are extrapolated in both SAMP-1 and in SAMP_LIGHT. Furthermore, SAMP-1 always uses the direct curve discretization (i.e. number of data points) as given by the user, while for SAMP_LIGHT the user may use the CTFLG to choose between a typical LS-DYNA re-discretization or the original curves. For the re-discretization option the parameter LCINT in DEFINE_CURVE of LS-DYNA may be set.

Example

The calibration of a thermoplastic polymer material to the SAMP-1 model has already been discussed in [1]. Here will be demonstrated how an existing SAMP-1 material card can be converted into a SAMP_LIGHT card. It is often sufficient to describe the deformation behavior of thermoplastics by using a Drucker-Prager behavior, see [2] and [3].

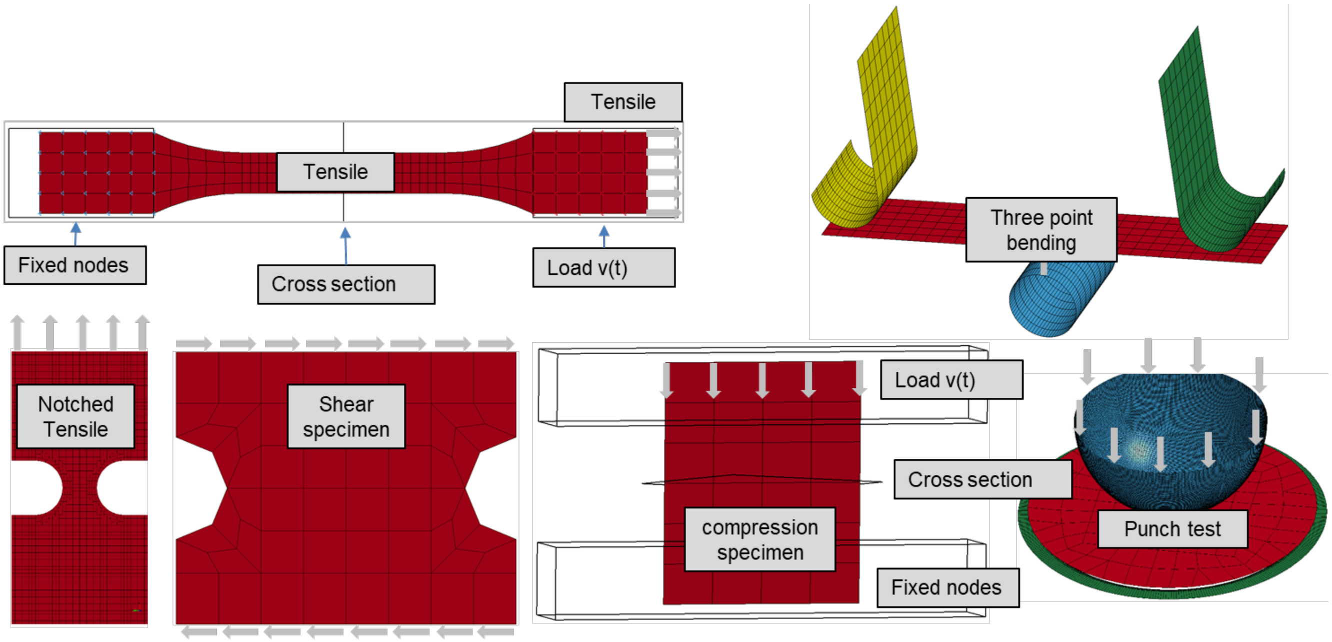

Figure 5: FE-Models to compare both cards

The following calibration is based on the assumption that no experimental data is available, which is typically the case in practice if an existing SAMP-1 card shall be quickly converted to SAMP_LIGHT. Hence a simple FE-model is created to first define base runs with the existing card. For calibration a simple reverse engineering strategy is followed: I.e. the parameters of the SAMP_LIGHT card are defined as optimal if the force vs. displacement curves or engineering stress vs. engineering strain curves of the simulated tests have the smallest possible difference to the curves generated with the SAMP-1 card. In the following the most important parameters of the SAMP_LIGHT card are determined. In contrast to SAMP-1, damage and element deletion in the SAMP_LIGHT model must be realized by an additional card with GISSMO (*MAT_ADD_DAMAGE_GISSMO).

Test		Loading velocity in mm/ms	Strain rate in 1/s
Tension	tenA	5.0 E-4	5.0 E-2
	tenB	5.0 E-1	5.0 E01
	tenC	5.0 E00	5.0 E02
	tenD	5.0 E01	5.0 E03
Bending	benB	1.0 E00	8.4 E00
	benC	2.0 E00	2.6 E01
	benD	2.5 E00	5.8 E-1
	benE	4.0 E00	9.3 E-1
Compression		1.0 E-05	
Punch test		3.0 E-04	
Notched tensile test		3.0 E-04	
Shear test		5.0 E-04	

Table 1: Loading velocities of simulations in finite element models

Figure 5 shows the finite element models applied. The model of the bending sample was taken from within the software *Valimat* (see [10]). For the shear, compression and punch test a mesh of similar element size was chosen in order to keep the computation time low. Apart from the tensile and bending tests, all tests were computed quasi-static. For the tensile and bending tests, dynamic tests were also simulated. In the models a thickness of 3.5 mm is assumed. Table 1 lists all the tests, loading velocities and nominal strain rates.

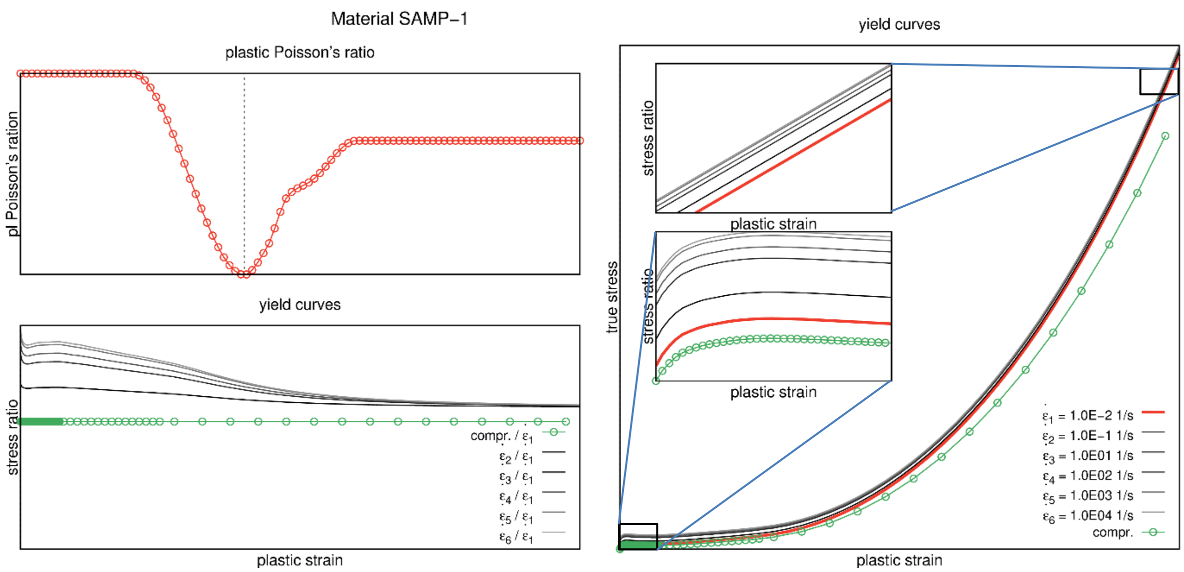

Figure 6: Input curves of an exemplary SAMP-1 card

In Figure 6 the input curve data of the SAMP-1 material card are visualized. On the right side all yield curves are shown. As can be seen clearly, the strain rate dependency is realized by multiplying the quasi-static tensile yield curve with a function. The yield curve for compression was also created by scaling the quasi-static tensile yield curve by a certain factor. The graph in the lower left corner now shows the corresponding scaling factors of the individual curves. The top left graph shows the course of the plastic transverse strain as a function of the volumetric plastic strain, i.e. the curve definition of the plastic Poisson's ratio.
The first step is the identification of the visco-plastic material behavior. This step is necessary, since, as stated earlier, the SAMP_LIGHT model uses a different visco-plastic implementation. The quasi-static yield curve of the SAMP-1 model was selected as base curve for scaling where the number of parameters was minimized by assuming constant values and using logarithmic interpolation in strain-rate direction. An attempt was made to find the best possible agreement between the stress-strain curves of the quasi-static and dynamic tensile tests of the SAMP-1 and SAMP-LIGH simulations using LS-OPT®. Figure 7 shows the result of the calibration. For the variation of four scaling factors at least eight simulations in one iteration are necessary. Since good initial values were chosen, the result could be achieved after 9 iterations already, which means that 4 x 72= 288 calculations were necessary to achieve the result. The dashed red curves show the original stress-strain curve, the thick solid line shows the current result of the fit. A much better agreement of the curves could be found in the low dynamic and medium dynamic calculation (v_1 and v_2).
In the next step the scaling factor for the uniaxial compression yield curve was determined, using a constant factor on the tension curve. Only the compression tests shown above were used for the adjustment. The solid red line in Figure 8 shows the result of the identification, the red dashed curve shows the result without adjustment of the compression properties (i.e. tension and compression curve are identical). Since only one calculation was necessary, only 32 simulations were needed for the identification.

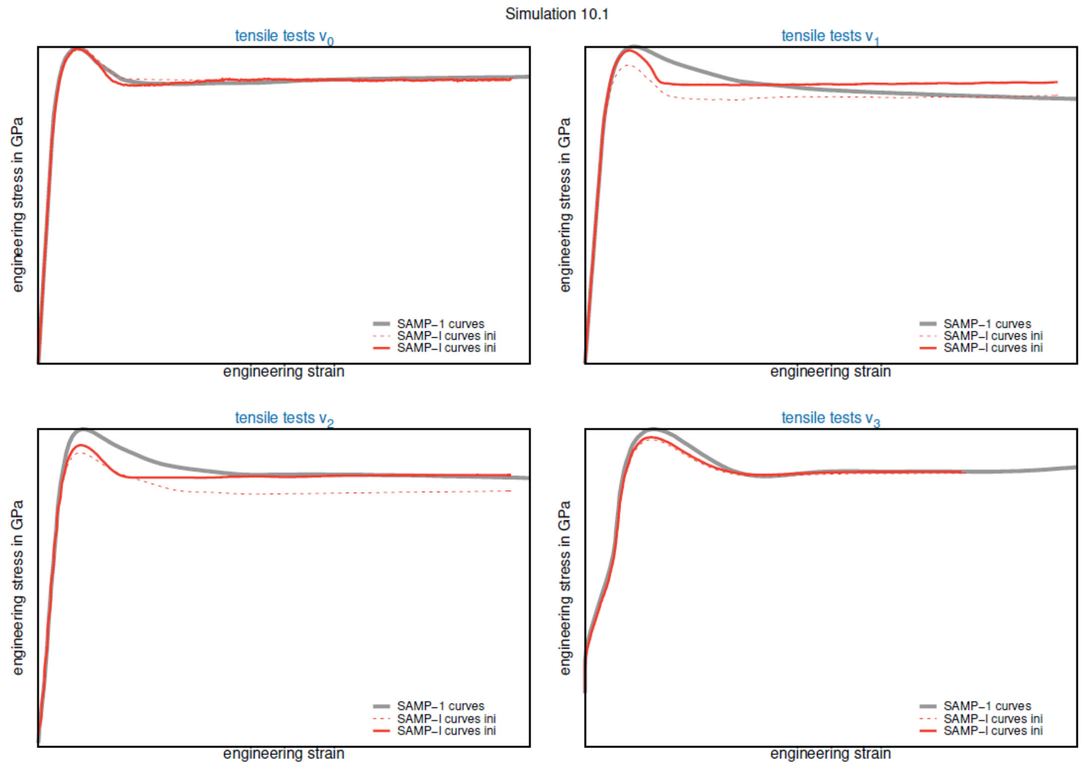

Figure 7: Calibration result of visco-plastic yield curves

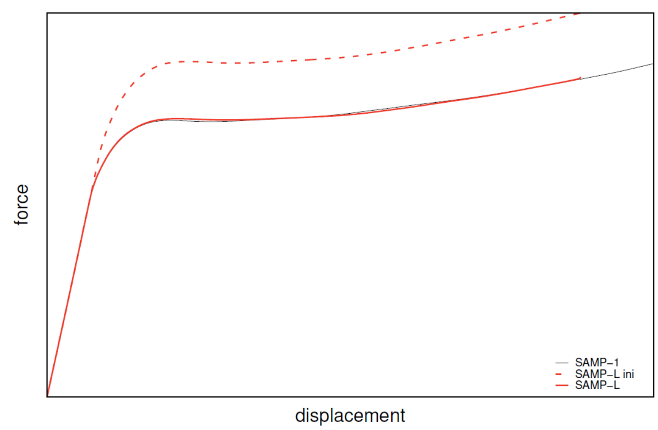

Figure 8: Calibration of compression curve

As the determination of damage parameters goes beyond the scope of this article, the calibration of SAMP_LIGHT is already completed at this point. The curve for the description of the transverse plastic strain was taken over from the SAMP-1 card without any changes. Figure 9 shows the result if the *MAT_SAMP_LIGHT calibration. In the top row of Figure 9, curves of the tensile tests are shown. The second row shows the bending tests and the quasi-static puncture test, shear test, compression test and notched tensile tests are shown below.

At this point it should be noted that the original SAMP-1 card only used tension, compression and plastic transverse strain curves, therefore a good agreement between both cards could be achieved. If shear or biaxial yield curves would have been included in the original SAMP-1 card, a match between the stress-strain curves of both cards could show more differences, especially for load cases in biaxial or shear direction. The differences between the results in the tensile area at higher strains are mainly because constant factors were used for the new calibration.

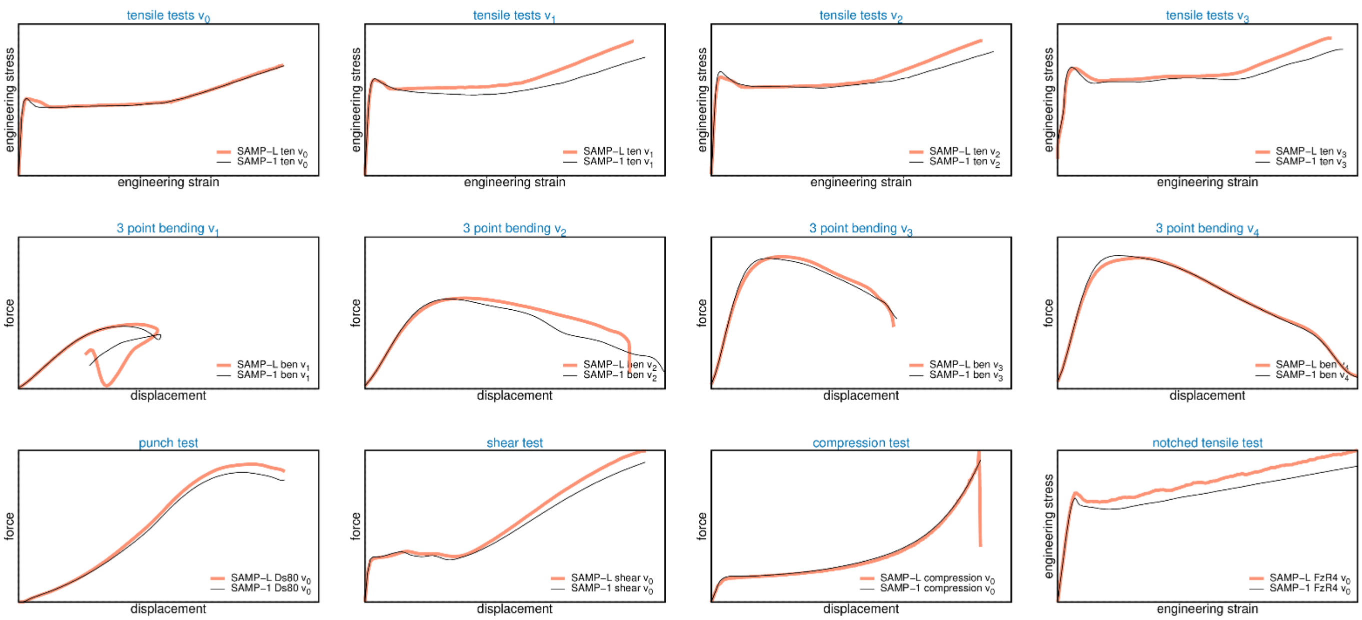

Figure 9: Result of SAMP_LIGHT calibration

Summary

This article describes the new, simplified and therefore efficient semi-analytical material model for polymers, MAT_SAMP_LIGHT. After first describing the classical SAMP-1 model with its possibilities, the new, material model is presented and explained. Finally, an example shows how to create SAMP_LIGHT cards from existing SAMP-1 cards in a simple way. With the help of reverse engineering based on simple finite element models, simulations are created with the SAMP-1 card as the optimization target for a new material card. Subsequently, the most important material parameters are identified.

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