Modeling of Plastics for Crash Simulation of Fuel Tanks

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Abstract:

In order to simulate a synthetic fuel tank and the physical response of the fuel during a crash, it is necessary to apply a suitable constitutive law for the tank material. The high impact speeds and heavy local deformations require a sophisticated and reliable material model.
Within LS-DYNA, the Material Law *MAT_OGDEN_RUBBER (#77) allows to capture non-linear elastic behaviour as well as viscous effects. The capability of this material law to adapt to experimental tension tests with different constant strain rates is rather poor. This paper outlines the background of this limitation. In addition, an alternative more complex visco-elastic material model is introduced and the improved adaption to the above mentioned tension tests is demonstrated. The parameter identification is performed by using the optimization software LS-OPT.

Keywords:

Polymers, Crash, Tank, Visco-elasticity, Constitutive Modeling, Optimization, LS-DYNA, LS-OPT, PANDAS

1 Introduction

The material we want to characterize is called LUPOLEN, which is basically HDPE material (High Density Poly-Ethylen). The raw material is manufactured by the company BASELL and it is used among other things for fuel tanks in DaimlerChrysler Commercial Vehicles. In order to simulate crash load cases on such tanks, it is necessary to establish a reliable material model even for high strain rates. LUPOLEN is a strain-rate dependent material and up to a relatively high level of deformation strains are almost full reversible. Therefore, a visco-elastic material model seems to be suitable. Tension tests with different constant strain rates were available (see Figure 1) for the parameter identification. The drawback of these tests is the global measurement of the specimen elongation and the corresponding forces. This means, a homogenous stress-strain field within the specimen is assumed, which is quite improbable due to localization effects for larger elongations.

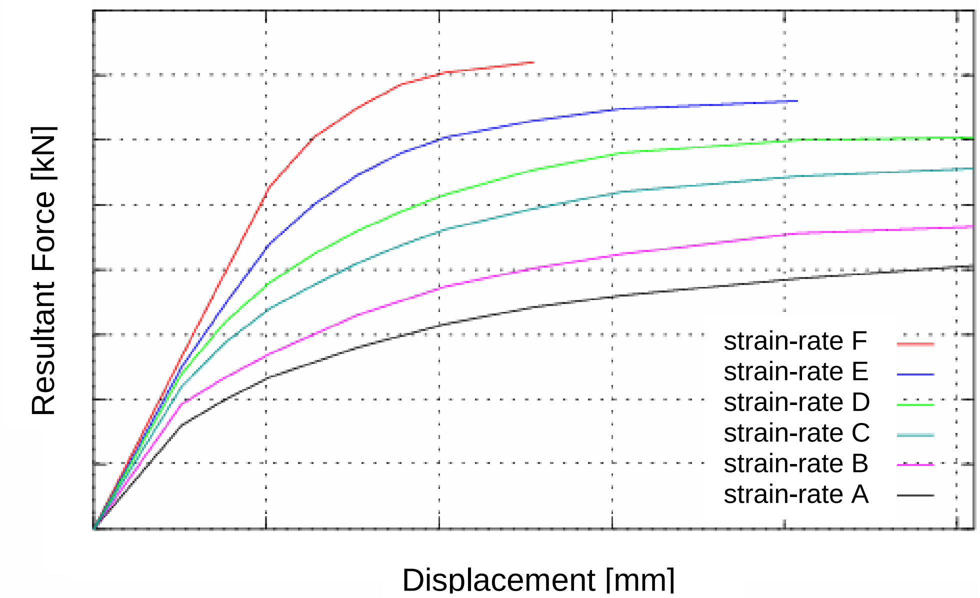


Figure 1: HDPE tension tests [6] with different strain rates; 5mm elongation corresponds to approximately 10% strain; strain rates vary from 2.0e-3 to 1.5e+2 [1/s]

2 Visco-elastic Material Models

In order to model nonlinear elastic behaviour in combination with rate dependant properties a visco-elastic material model is necessary. LS-DYNA provides the material model `*MAT_OGDEN_RUBBER` which is based on a non-linear elasticity law and optional a Prony series of Maxwell elements in parallel [1], as shown in Figure 2.
In addition, a more sophisticated non-linear visco-elastic formulation is considered, which is implemented in the Finite-Element Code PANDAS[1] developed at the Institute of Applied Mechanics (Civil Engineering), University of Stuttgart [2,3].

2.1 LS-DYNA Hyperelastic/Viscoelastic Formulation - *MAT_OGDEN_RUBBER (#77)

LS-DYNA incorporates a finite hyperelastic material law combined with linear visco-elasticity to create a quasi-linear visco-elastic (QLV) expression of sorts. The LS-DYNA law, denoted as Material 77, consists of a non-linear spring in parallel with a Prony series of Maxwell elements, as shown in Figure 2. The hyperelastic part of the material is characterized by the non-linear spring, while visco-elasticity is introduced via the Maxwell elements denoted by linear springs and dashpots in series. This means, only a portion of the elastic response, that associated with the long term residual stress, is non-linear. The stress resulting from the extension of the non-linear spring is added to the stress borne by the extension of the visco-elastic Maxwell elements.

[1] www.get-pandas.com

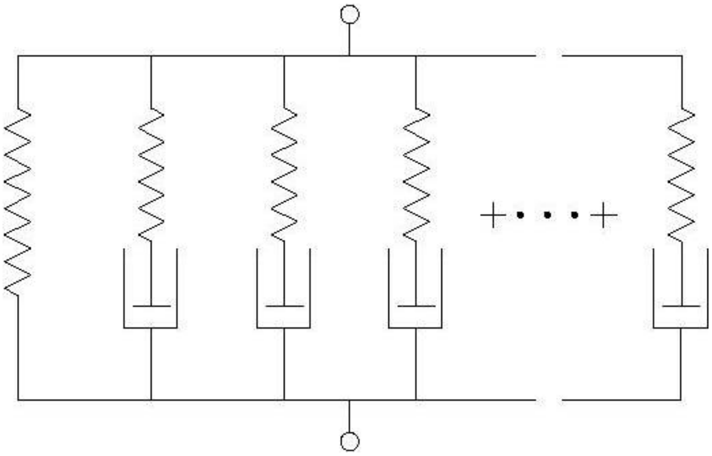


*Figure 2: Generalized Maxwell model used in LS-DYNA (*MAT_OGDEN_RUBBER). A non-linear spring is placed in series with up to six Maxwell elements. For incompressible materials only deviatoric strains are possible so that only the shear moduli, Gi, are considered.*

Hyperelastic Potential Function of the non-linear spring (Ogden Formulation):

$$W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu_j}{\alpha_j}\left(\lambda_i^{\alpha_j} - 1\right) + \frac{1}{2}K\left(J-1\right)^2 \tag{1}$$

Prony series representing the viscos-elastic part (Maxwell elements):

$$g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t} \quad ; \text{ N=1,…,6 } ; \quad \sigma_{ij} = \int_0^t g_{ijkl}(t-\tau)\frac{\partial \varepsilon_{kl}}{\partial \tau} d\tau \tag{2}$$

2.2 Differential Visco-Elastic Formulation in PANDAS

The model corresponds as well as the *MAT_OGDEN_RUBBER in LS-DYNA to the generalized Maxwell model, shown in Figure 2.

However, the main differences of the visco-elastic formulation in PANDAS, compared to *MAT_OGDEN_RUBBER in LS-DYNA, are the non-linear stress contributions of the Maxwell elements and the so called differential formulation using the strain of the dashpot as an internal variable:

$$\begin{aligned}
&\sigma_{long-term} = f_{Ogden}(\varepsilon)\\
&\sigma_{Maxwell} = f_{Ogden}(\varepsilon_{Maxwell-Spring})\\
&\sigma_{Maxwell} = f(\dot{\varepsilon}_{Maxwell-Dashpot})\\
&\sigma = \sigma_{long-term} + \sigma_{Maxwell}\\
&\varepsilon = \varepsilon_{Maxwell-Spring} + \varepsilon_{Maxwell-Dashpot}
\end{aligned} \tag{3}$$

Equation (3) represents a differential equation system. Hereby, the internal variable $\varepsilon_{Maxwell-Dashpot}$ needs to be computed by solving an appropriate evolution equation, using the “Backward Eulerian” time integration scheme. For more information, please refer to [2,3]

3 Adaption to experimental tension tests

The adaption to the experimental tension test with different constant strain rates, as shown in Figure 1, is performed for both material models, in LS-DYNA and PANDAS. In order to get the quasi-static material behaviour of LUPOLEN, tests with extremely slow deformation velocities would be necessary.

For such tests rather low stress values would be expected, due to the creeping properties of the material. Therefore, an artificial long term quasi-static load curve is introduced by scaling the stress values of the lowest strain-rate curve (Curve A) with 1/3. In order to demonstrate the fitting capabilities of the two material models only the strain-rate curves A and B are considered.
The parameter identification of the material models is done by an inverse optimization procedure using LS-OPT. This means, the specimen and the experimental boundary conditions are rebuilt in a finite element model and the material parameters are varied by the optimization software LS-OPT [4], in order to minimize the difference between simulation and experimental results.

The optimization procedure is split in two parts:

1. Simulation and parameter identification of the quasi-static test without considering any viscous effects in the material models.

2. Freezing of the long-term hyperelastic parameters and evaluation of the parameters characterizing the viscous behaviour of the model. The sum of the squares error of two experimental stress-strain curves vs. simulation curves is minimized (Least-Squares Optimization).

In LS-DYNA for the Ogden formulation in equation (1) three terms (n=3) are considered. The Ogden formulation is quasi-incompressible undergoing the assumption LUPOLEN doesn't show significant volume change for large deformations. To capture the viscous behaviour of the LUPOLEN material, represented here only by two curves (A and B), two Prony terms (N=2) are introduced.

In PANDAS for the long-term Ogden function (eq. (3.1)) also three terms are considered. The viscous behaviour is represented by two Maxwell elements each with a two term Ogden function (eq. (3.2)). A two term Ogden function corresponds to a so called Mooney-Rivlin formulation.

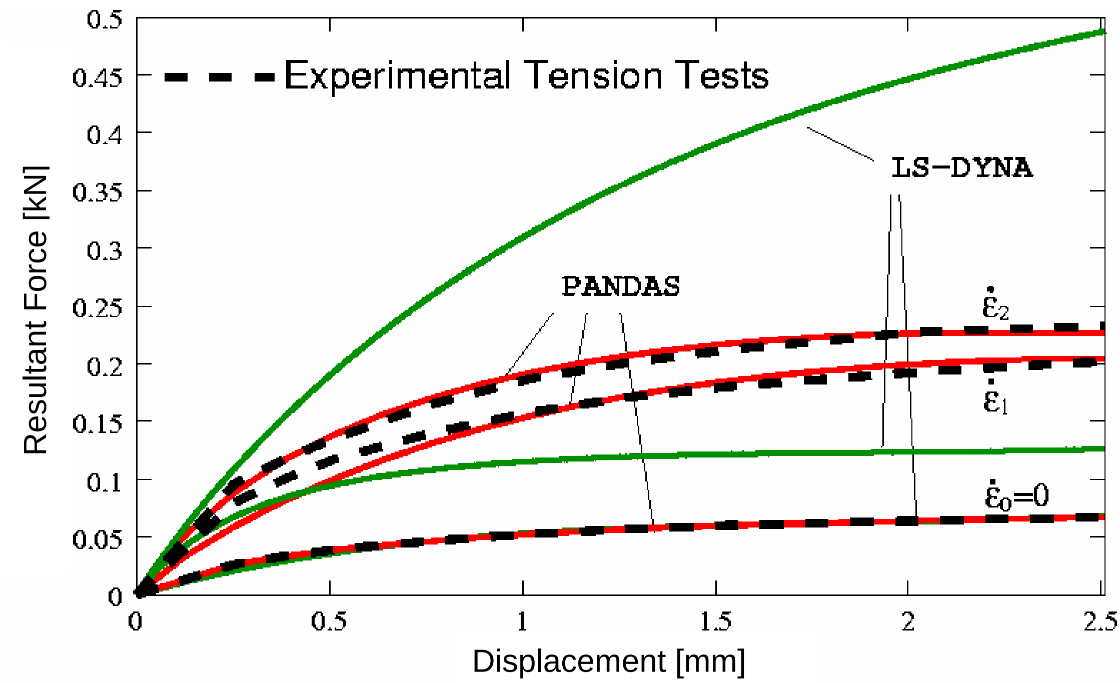
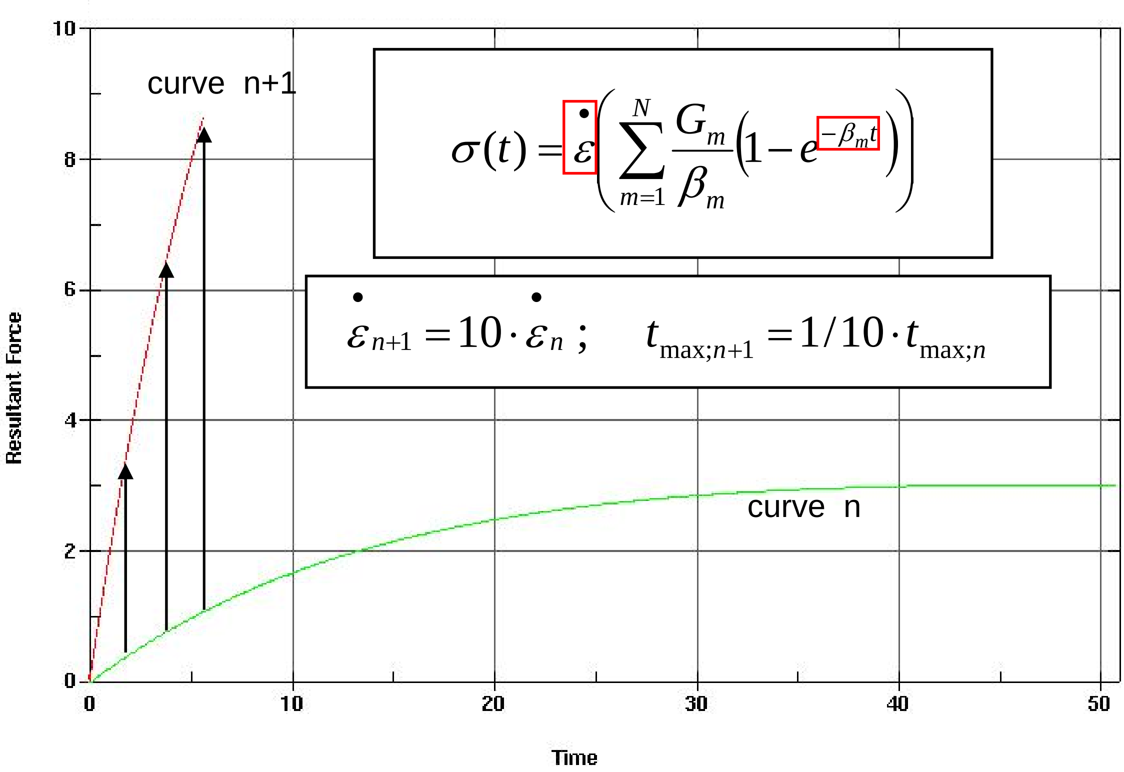


Figure 3: *The capability of the visco-elastic formulations in LS-DYNA and PANDAS to capture tension tests with different constant strain-rates,* $\dot{\varepsilon}_2 = 10 * \dot{\varepsilon}_1$. *2.5mm elongation corresponds to approximately 10% strain (only half of the specimen is considered)*

The curves in Figure 3 demonstrate the rather poor fit of the visco-elastic formulation in LS-DYNA, whereas the fit using the formulation in PANDAS is quite good.
The reason for the bad fit in LS-DYNA is explained in Figure 4. For a constant strain rate $\dot{\varepsilon} = const$ and for a one-dimensional tension test, the integral form in equation (2) can be rewritten in

$\sigma(t,\dot{\varepsilon})$ as it is shown in Figure 4. The strain rate of the upper curve is ten times the strain rate of the lower curve. Due to the linear relationship of σ and $\dot{\varepsilon}$ there is just a scaling with a factor of 10 of the viscous stress values from curve n to curve n+1. This explains the fairly low flexibility for the adaption to the experimental curves in Figure 3.
The maximum strain for both curves is approximately 10%, but curve n+1 reaches the maximum strain in 1/10 the time of curve n. This means, curve n+1 just capture the non-linearity of the first 5ms of curve n. Therefore, with an increasing strain rate the curves tend to become more and more linear.



$$\sigma(t)=\dot{\varepsilon}\left(\sum_{m=1}^{N}\frac{G_m}{\beta_m}\left(1-e^{-\beta_m t}\right)\right)$$

$$\dot{\varepsilon}_{n+1}=10\cdot\dot{\varepsilon}_n\ ;\qquad t_{\max;n+1}=1/10\cdot t_{\max;n}$$

Figure 4: The equation $\sigma(t)$ *represents the viscous stress contribution derived from equation (2) with* $\dot{\varepsilon}=const$ *. The arrows illustrate the linear mapping of viscous stress from curve n to curve n+1. For both curves the maximal strain is approximately 10%.*

4 Conclusions

This paper investigates in the material modelling of High Density Poly-Ethylen, such as LUPOLEN. The material is characterized by strain rate dependent properties and a non-linear material behaviour up to high strain levels. A reversible stress-strain relationship is assumed. This leads to the nessecity of a visco-elastic material model. Therefore, two approaches of the FE-Codes LS-DYNA and PANDAS are compared with regard to the capability of adapting experimental tension tests with different constant strain rates. The identification of the material parameters is performed by using the optimization software LS-OPT.
The implementation in PANDAS come off well with good flexibility and good capability in capturing the experimental tests. The drawback of PANDAS is the complexity of the material model and thus the amount of material parameters, which have to be determined.

The capability of the material model `*MAT_OGDEN_RUBBER` in LS-DYNA to fit experimental curves with different constant strain rates is rather poor. This follows from the quasi linear viscous character of the implementation. Usually for the “Prony series approach” the parameter identification is performed by using relaxation tests.
More details regarding this paper will be found in [5].

5 References

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