

Experimental determination of material data for temperature dependent component simulation

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Summary: *Current research is aimed to create functional material models out of test data to use them in numerical simulations. This process contains several material tests such as tensile tests and dynamic mechanical analyses at different temperatures. All determined test results were used as input data to process model parameters. The selected material models are the hyperelastic Odgen- model, the viscoelastic Prony- series and the hyper-viscoelastic Bergström-Boyce model. After the implementation in ABAQUS/CAE, a comparison of real tensile test data and simulated tensile tests under the same circumstances was developed to ensure the correctness of the models. Finally, a Diabolo specimen was modeled and loaded in the same way as in real-life fatigue tests under tensile loading. This simulation provides information about the stress-strain behavior of the specimen and is meant to build calibration curves which are used for strain-based Wöhler curves later on.*

Keywords: *calibration curves, material models, fatigue tests*

1 Introduction

The simulation of the temperature dependent deformation behavior of thermoplastic elastomer components is of prime practical importance for many demanding applications. Temperature and strain dependent material models are needed in these simulations. Four materials are used for this assignment in this study. Two of them are unfilled thermoplastic Polyurethanes (TPu1, TPu2), one filled thermoplastic Polyurethane (TPu+SL) grade and one thermoset cross-linked Hydrogenated Nitrile Butadiene Rubber (HNBR-ED). Thermoplastic elastomer materials offer high degree of elasticity such as rubbers and simultaneously a good processability such as thermoplastics. Furthermore, they are well-known for high elasticity, good abrasion behavior and resistance to petrol based agents. The finite element simulation of thermoplastic elastomers is hard to handle due to the fact that these materials reveal very high ultimate elongations and their stress-strain relationship is highly non-linear [1]. In this assignment all simulations were carried out in ABAQUS/CAE.

2 Material model definition

To describe service relevant material behavior of thermoplastic elastomers, temperature- and rate- dependent material models are required. There are many approaches available to reproduce polymeric material behavior for numerical simulations. This paper covers three well-known approaches named below. All models require material test data to define their parameters and coefficients. However, in addition to the conventional direct implementation of relevant data into the specific models, novel fitting routines have to be applied for deriving relevant model parameters in an indirect approach.

- **Hyperelastic material models:** Hyperelastic material models are popular for isotropic and non- linear materials, which offer elastic behavior even at large strains such as rubber or other elastomeric materials. The fundamentals of hyperelastic material models are the so called strain energy potentials. There

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are a lot of energy potentials available, such as the Arruda-Boyce-, the Marlow-, the Mooney-Rivlin-, the Yeoh- and the Ogden- potential [2]. At this time the Ogden- material model was used for all simulation due to the fact that this model is already pre-defined in ABAQUS/CAE. All model parameters can be defined using tensile test data at different temperatures and strain rates.

- **Viscoelastic material models:** Viscoelastic material models describe rate-dependent material behavior, where dissipative losses caused by internal damping effects and can be used in situations where large strain occurs. This model is designed to describe linear-viscoelastic material behavior [2]. The famous Maxwell element is mostly the first approach when talking about viscoelasticity. In this paper the Prony-series was used, which can be seen as a parallel circuit of Maxwell elements. This is also equivalent to the sum of several exponential-function [3]. The implementation in the finite element software was conducted by generating all Prony-coefficients out of DMA-test data with the help of Viscodata/Viscoshift (Herdy).
- **Rheological network models:** Rheological network structured models are typically used for materials with nonlinear viscous behavior during large deformations [2]. At the moment the Bergström-Boyce material model (B&B model) is used for this assignment, which is a typical material model for elastomers. The model parameters were determined by using the external software PolyUmod (MCalibration), which processes different material test data at the same time.

3 Model parameter determination

As mentioned before proper material tests are needed to create direct input data for the FE tools as well as for the fitting routines to derive model parameters. The first step was to investigate the hyperelastic behavior of these materials under tensile loading as well as dynamic-mechanical-analysis. Type 5A (ISO/DIS 37) specimens were tested under different testing conditions (temperature, strain-rate, frequency). The tests were performed using a BOSE electro-dynamic testing machine equipped with a thermal chamber. All material tests were carried out by using the DIN EN ISO 527 standard, which covers the processes and the required specimens for tests with plastics.

- **Tensile tests:** These tests were realized by using a strain-controlled arrangement to a displacement of 130 mm, which equates to a strain of 520 %. During all tests a load cell ($F_{max} = 3 \text{ kN}$) recorded the present loads and a displacement transducer registered the elongation. As a result, stress-strain curves can be determined. The calculated stresses and strains are all nominal, because the initial area was used all time. Different strain rates from 1 mm/s to 100 mm/s and temperatures from $-40 \text{ }^\circ\text{C}$ to $50 \text{ }^\circ\text{C}$ were performed. Figure 1 depicts schematically the results for thermoplastic elastomers at different temperatures.

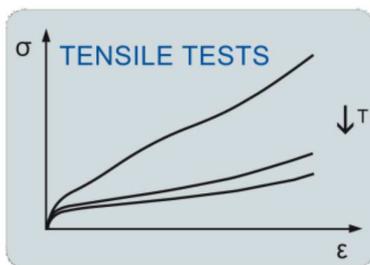


Figure 1: tensile test results

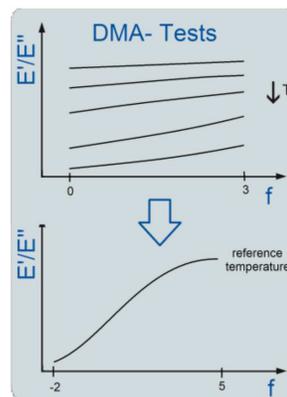


Figure 2: master curve creation

TPu1 shows typical elastic behavior at every strain rate at RT. At -40°C there is a distinctive yield point observed. Within the range of 300% strain and a force of 40 N to 70 N the material breaks at this temperatures. At higher temperatures the typical elastic behavior is noticeable again. Furthermore there is a non-linear temperature dependence of the Young's modulus.

TPu2 shows the typical elastic behavior at RT, no yield point as well as no breaking point. Even at -40°C at strains of more than 500% elastic behavior is observed. Further research shows that there is a linear dependence between the elasticity modulus and the temperature.

The filled thermoplastic polyurethane (TPu+SL) shows a maximum strain within the range of 300% to 400% as well as a distinctive yield point at -40°C . At RT there is typical elastic behavior noticeable. Finally, a considerable dependence of the elastic modulus with respect to the temperature was noted.

For HNBR-ED a failure occurs even at RT within a range of 380% to 500% strain. At -40°C the material breaks between 100% to 150% strain. The elastic behavior can be only determined at 50°C . Turning to the elasticity modulus, a non-linear temperature dependence was detected.

- **Dynamic mechanical analyses:** DMA tests at different testing conditions from -40°C to 40°C and 0.1 Hz to 100 Hz were performed using the same BOSE testing machine. Out of the single curves, one master curve at a larger frequency-range was made. The material behaves of course stiffer at lower temperatures, which means that the curves on the top are tested at lower temperatures than the curves on the bottom. Figure 2 shows the procedure from the single DMA results to a master curve on a log scale. The test results include important data such as the loss- and storage modulus with respect to the frequency. Afterwards these data is processed by using programs such as Viscodata/Viscoshift or PolyUmod's MCalibration.
- **Implementation:** All experimental results are now used to create input data for the numerical simulation software.

The implementation of the hyperelastic Ogden model is quiet easy, because ABAQUS has a pre-defined hyperelasticity model fitting procedure, in which uniaxial test data can be inserted. That means that all tensile test results at different temperatures and strain rates can be implemented at once.

For the Prony-series the software Viscodata/Viscoshift was used. Furthermore, the Prony-series consists of Maxwell elements and with a trial-error procedure, the best order fit was chosen. Based on the minimized error an order of $N = 15$ provided useful results. The implementation in ABAQUS/CAE can be made manually by entering the calculated Prony-series coefficients as well as the dedicated relaxation times.

The B&B material model parameters are generated with the help of PolyUmod's MCalibration. In this program monotonic tensile test results as well as the DMA-test results can be used simultaneously. The software fit reference curves with minimized error to the test data curves in each step. This procedure was carried out using several combinations of test data to get the best-fit model parameters. Finally, a so called Abaqus-Macro can be created which is implemented in ABAQUS/CAE as a user defined model.

4 Simulation

To guarantee the correctness of the created material models, the experimental and the simulation results generated under the same circumstances were compared. This comparison was repeated for all material models, namely for the Ogden model (first, second and third order), a combination of the Prony-series plus the Ogden model and the B&B model. The realization can be seen in figure 3.

Furthermore, displacement-local strain calibration curves, which show the lateral extension in percent with respect to the longitudinal displacement, were calculated. For this purpose a Diabolo specimen, which is used in the displacement controlled fatigue tests, was modeled axis symmetrically and loaded in the same

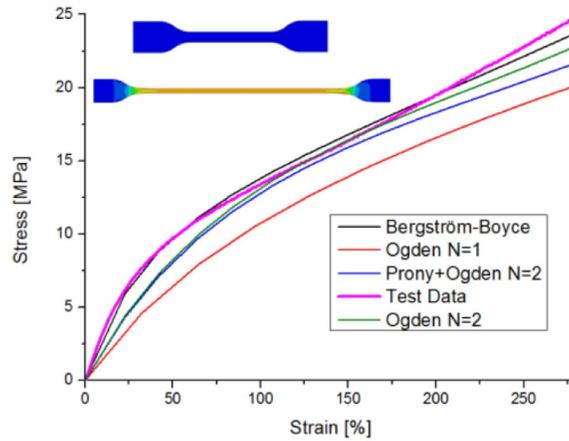


Figure 3: Comparison of tensile test results and the various model predictions

way as during real material tests under tensile loading [4]. Figure 4 shows the procedure for TPU1 and the final calibration curves for all materials investigated.

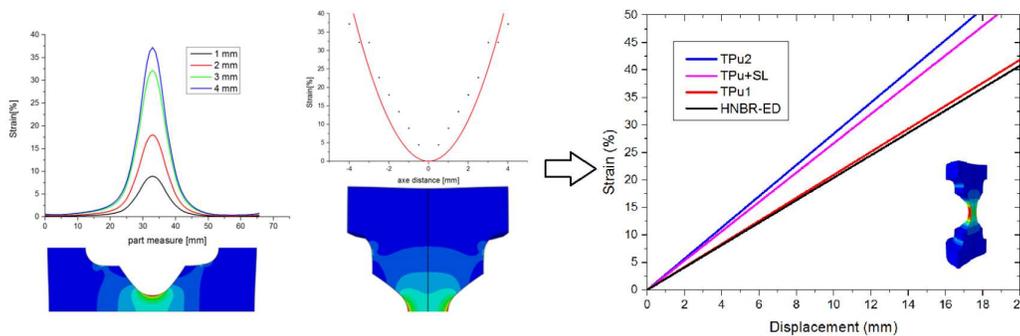


Figure 4: Creating calibration curves

The left side of figure 4 shows the strain in lateral direction with respect to the model measurements in tensile direction. The maximum strain occurs always in the symmetric area in lateral direction and on the outer edge of the part. The middle graph shows the strain in the highest loaded area with respect to the part measurements.. Next step was to generate calibration curves which can be seen on the right side of figure 4. Due to the fact that the single data points appear in a nearly straight line, they are linear fitted. Now the maximum strain which occurs due to a displacement in tensile direction can be estimated. These curves are used for generating local strain based Wöhler curves of fatigue tests. Further research will include the generation of calibration curves for different temperatures.

References

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