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Possibilities and limitations of linear viscoelastic material models for the numerical evaluation of the long-term behavior of thermoplastics

Characterization and parametrization

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Outline

Motivation and Objectives

Experiments

- **Experimental test setup**
- **Characterization results**

Material model and simulation

- **Linear viscoelastic LS-Dyna material model**
- **Model calibration**
- **Verification simulations**

Conclusions and Outlook

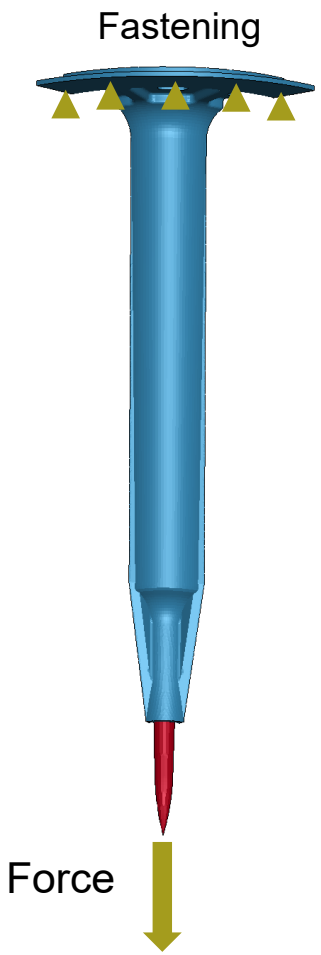
Motivation and Objectives

Viscoelastic material models required for the virtual description of the **long-term behavior** of constantly loaded components

Standard implementation for the representation of viscoelastic material behavior in most software applications only **linear**

Establishing the constraints of linear viscoelastic material models in commercially available FE software solutions

Development of a methodology for an efficient **characterization** of relevant material data and for efficient model **calibration** independent of the particular thermoplastic material

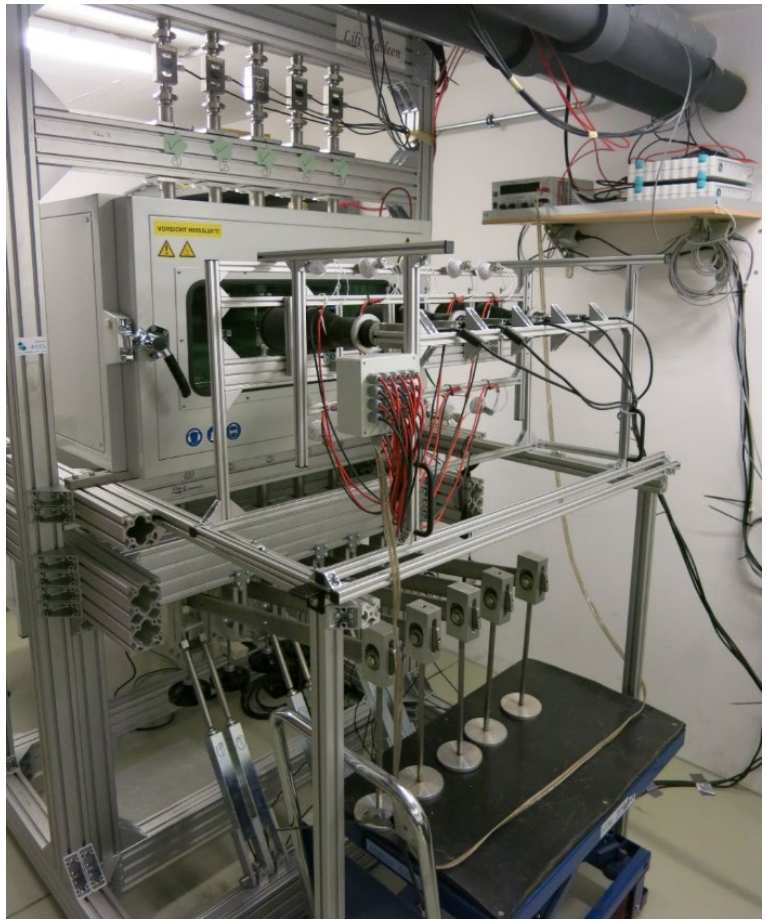


Experimental test setup

Testing equipment

Creep test bench

- **Working range:** 40N up to 10000N
- **Temperature range:** -5°C up to 250°C
- For **static**, respectively, constant **loading** (Creep behavior)
- Load application via **dead weights** and **leverage**
- **Lowest possible leverage:** **1 : 2.5**
- **Maximum laverage:** **1 : 5**
- Designed for **long-term creep tests**
- **Simultaneous** characterization of **up to 5 specimen** at the same temperature and different load levels possible
- **Strain measurement** via **LVDT** or **optically** using telecentric lenses (reliable strain measurement from 0.1% technical strain)



Experimental test setup

Material:

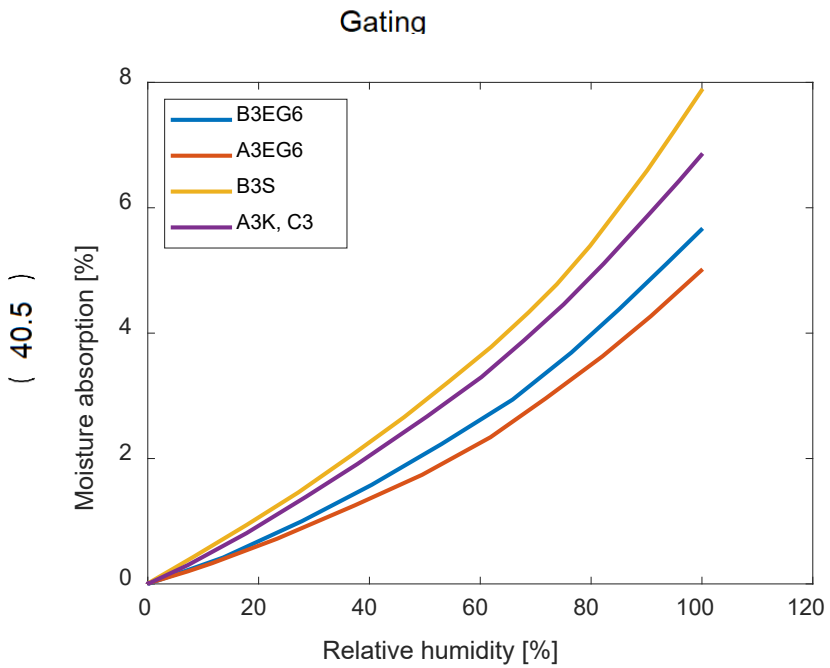
- **PA6GF40**: Impact-modified 40wt% glass fiber reinforced polyamide 6
- **HDPE**: UV stabilized high density polyethylene

Manufacturing:

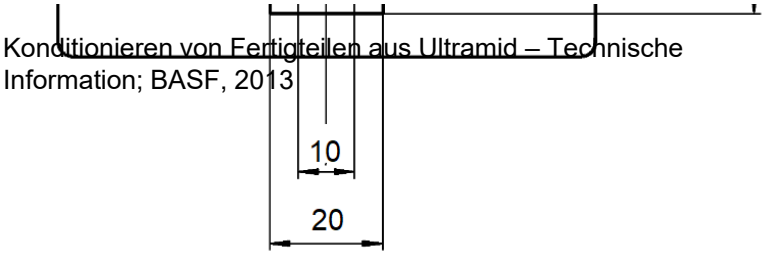
- Injection molded plates
- Specimen extraction via **water jet cutting** in 0°, 45° and 90° regarding to the flow direction

Conditioning of PA6GF40:

- Specimen **dried** at 70°C for 150h
- Subsequent vacuum sealing of the samples in aluminium-coated PE bags



Konditionieren von Fertigteilen aus Ultramid – Technische Information; BASF, 2013



Experimental test setup

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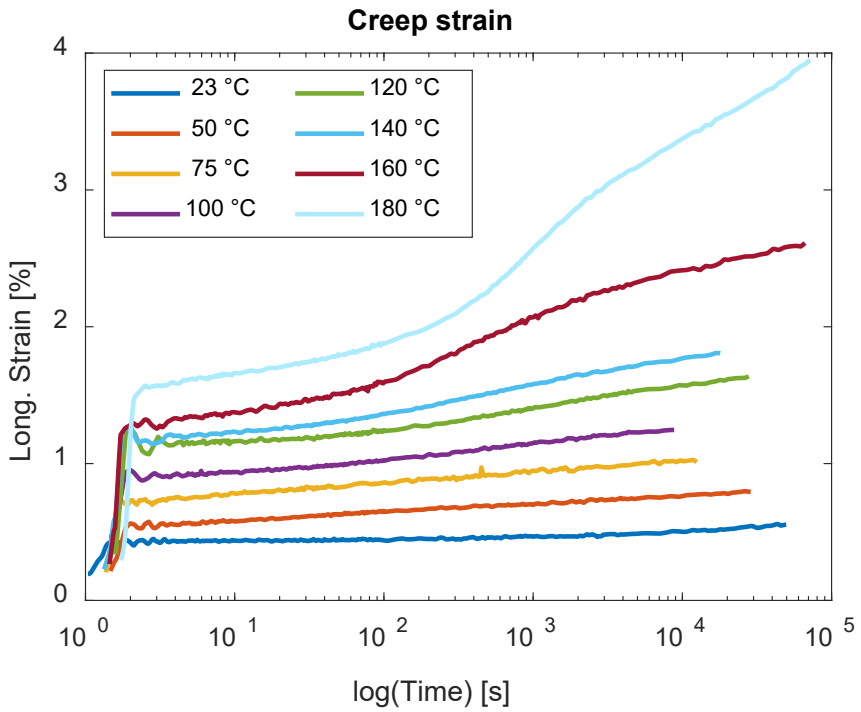
Testing plan

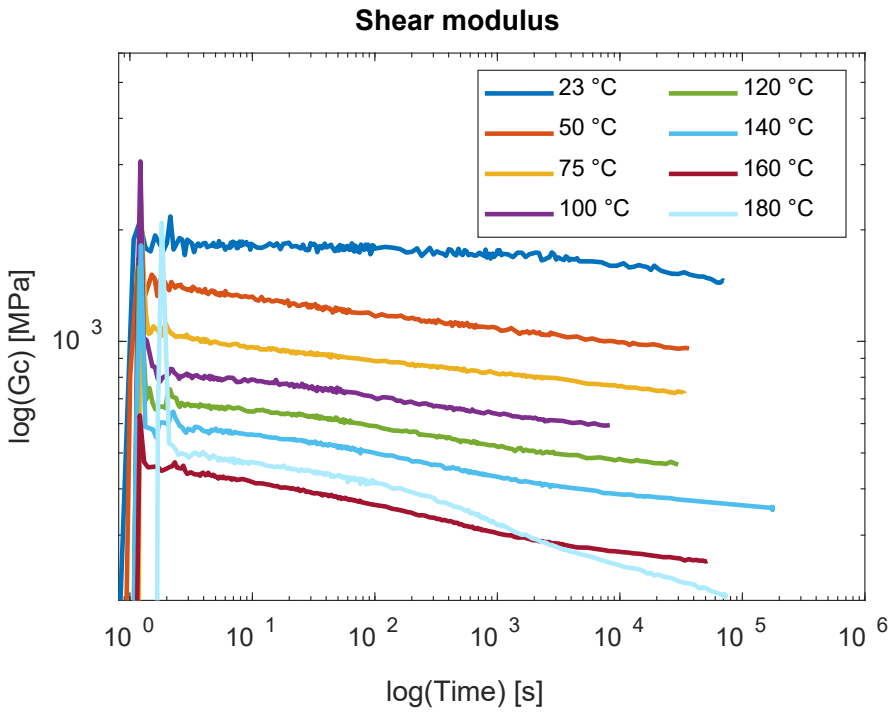
- Creep characterization of the considered materials
- Consideration of three different extraction directions
- Different load levels for a defined temperature range
- Test durations:
  - 8h during the day
  - 15h at night
  - 60h weekends

Material	0°	45°	90°	Temperature range
PA6GF40	20 MPa 30 MPa	17 MPa	14 MPa 21 MPa	23°C, 50°C, 75°C, 100°C, 120°C, 140°C, 160°C, 180°C
PE-HD	2 MPa 4 MPa	3 MPa	2 MPa 4 MPa	20°C, 40°C, 60°C, 80°C

Characterization results

Results for PA6GF40 with 0° extraction direction and 20MPa load level





Creep strain and shear modulus for all investigated temperatures

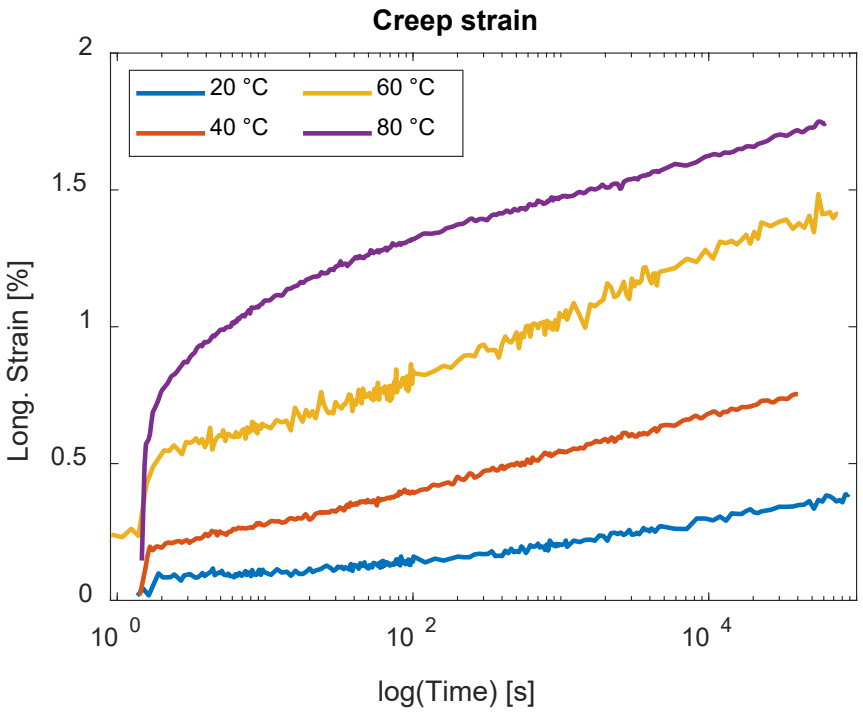
Samples at 160°C and 180°C slipped in the clamping device

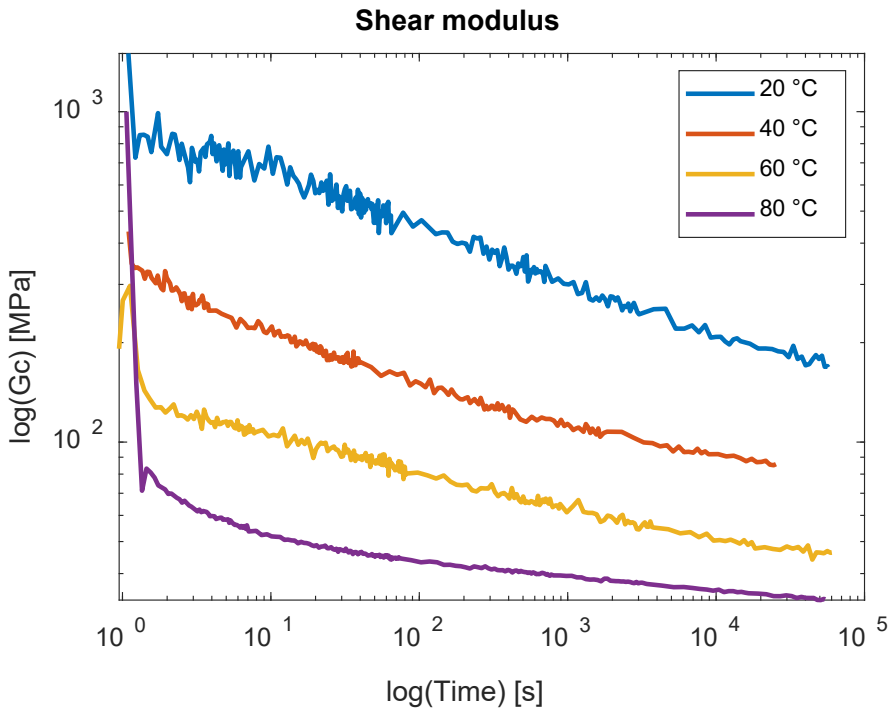
Increasing creep strain with increasing temperature level

Log-Log plot shows an almost linear decrease of the creep modulus as a function of temperature

Characterization results

Results for PE with 0° extraction direction and 2MPa load level





Creep strain and shear modulus for all investigated temperatures

Increasing creep strain with increasing temperature

Log-Log plot shows an almost linear decrease of the creep modulus as a function of temperature

Linear viscoelastic material model

LS-Dyna material model MAT_GENERAL_VISCOELASTIC

- Material model representing a general viscoelastic **Maxwell model** using a **Prony series**
- Definition of up to **18 terms** of Prony series expansion possible

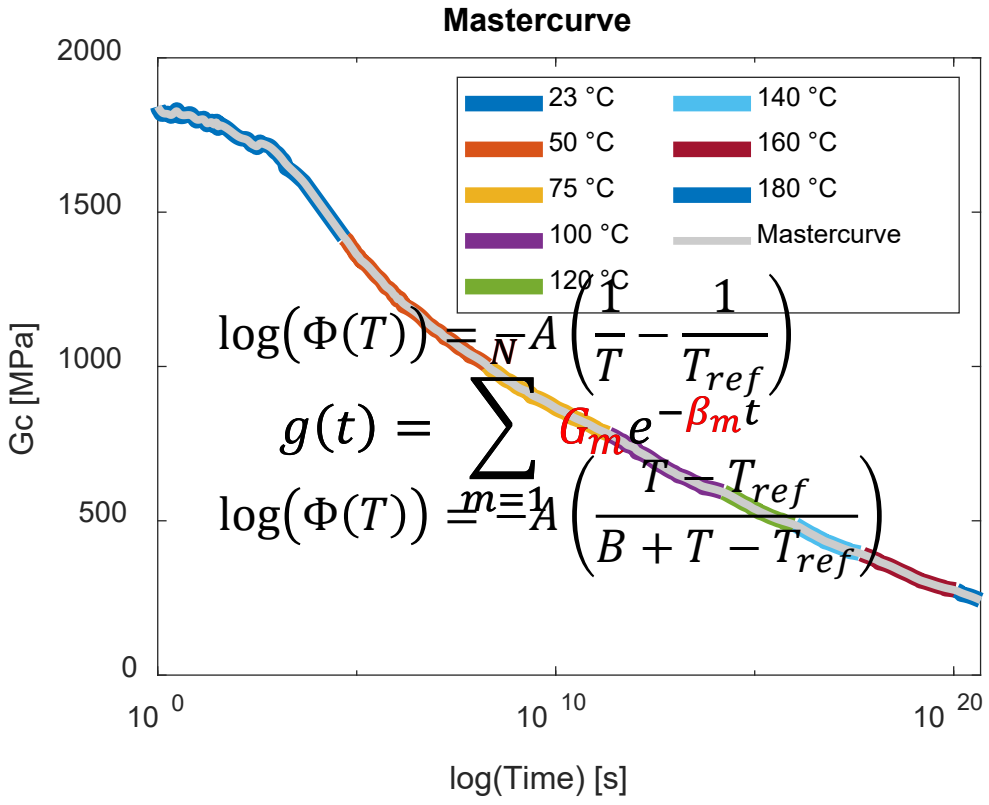
$$g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t}$$

- Provides two possibilities for time-temperature shift:
  - **Arrhenius model:** $\log(\Phi(T)) = -A\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)$
  - **Williams-Landel-Ferry (WLF) model:** $\log(\Phi(T)) = -A\left(\frac{T-T_{ref}}{B+T-T_{ref}}\right)$
- Possibility of considering humidity influences by scaling the material properties depending on the respective moisture content of the material
  - **Not considered so far**

Model calibration

Procedure for the model calibration regarding the measured material data

1. Generation of master curves based on the time-temperature superposition principle
2. Adapting the parameter, respectively, the parameters of the Arrhenius or WLF function according to the generated master curve
3. Definition and optimization of a suitable number of Prony series terms
4. Fitting of the shear moduli, G_m, and the relaxation times, β_m, of the Prony series expansion with respect to the master curve



$$\log(\Phi(T)) = -A\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)$$

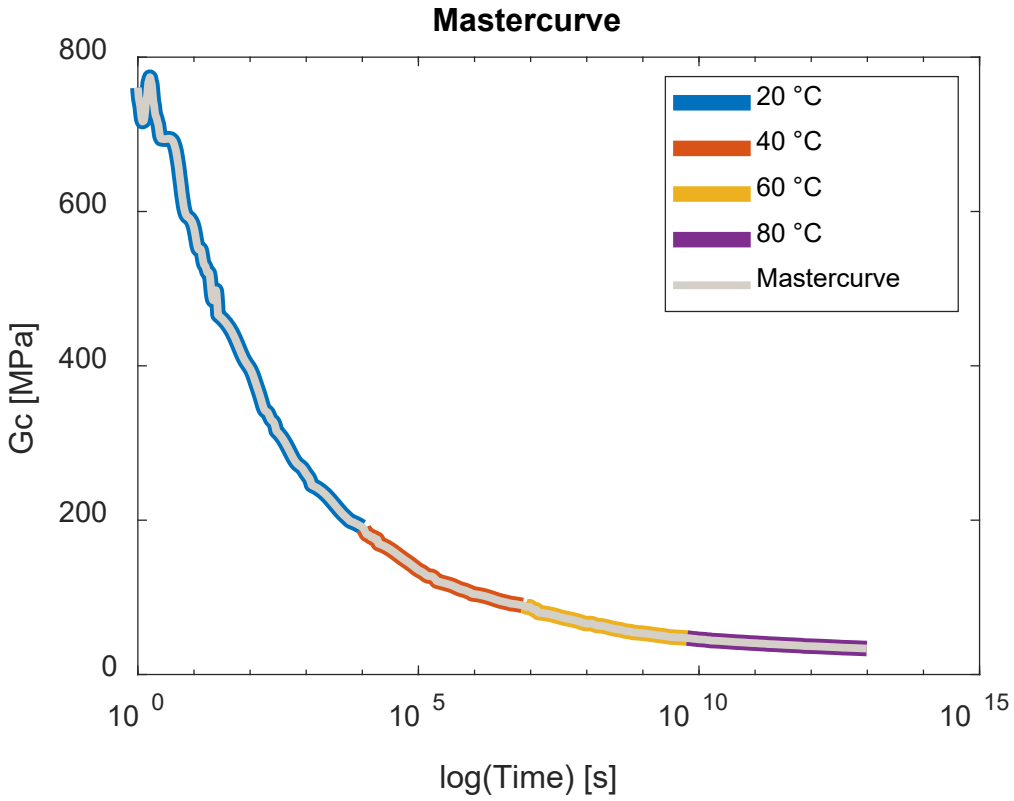
$$g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t}$$

$$\log(\Phi(T)) = -A\left(\frac{T - T_{ref}}{B + T - T_{ref}}\right)$$

Model calibration

Master curve generation

1. Definition of the relevant time interval
2. Seeking tangents of two curves with similar gradient
3. Execution of the time-temperature shift
4. Extraction of the resulting master curve

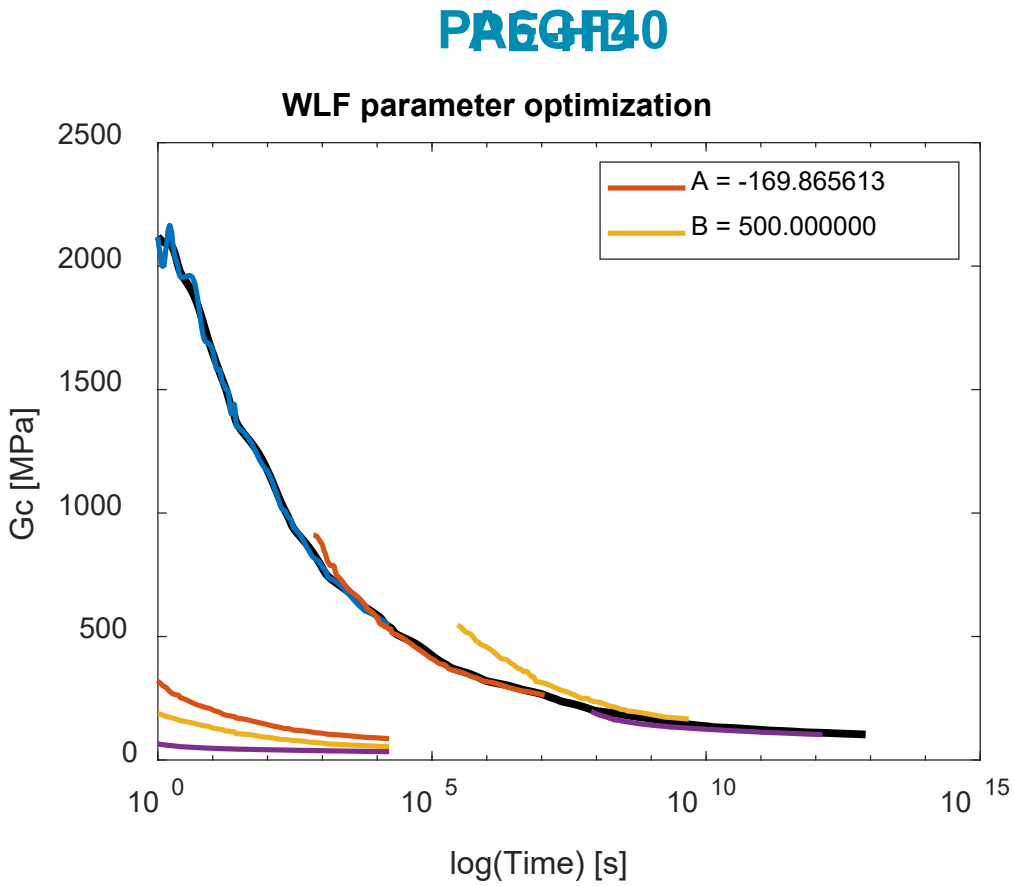


WLF – Parameter optimization

- Williams-Landau-Ferry (WLF):

$$\log\big(\Phi(T)\big) = -A\left(\frac{T - T_{ref}}{B + T - T_{ref}}\right)$$

- Optimization algorithm for adjusting parameters A and B using a nonlinear least square fit based on the minimum distance to the master curve.



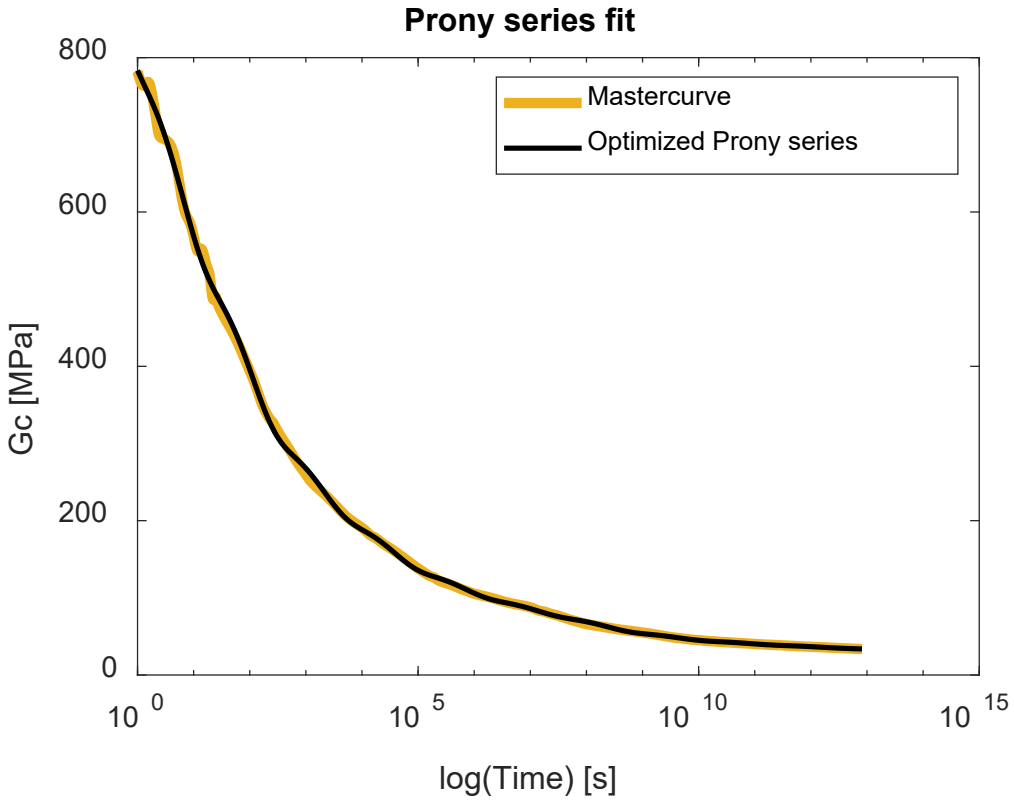
Model calibration

Prony series expansion

- Prony series:

$$g(t) = \sum_{m=1}^{N} G_m e^{-\beta_m t}$$

- Optimization of the number of Prony series terms (N) and the parameters G_m and β_m



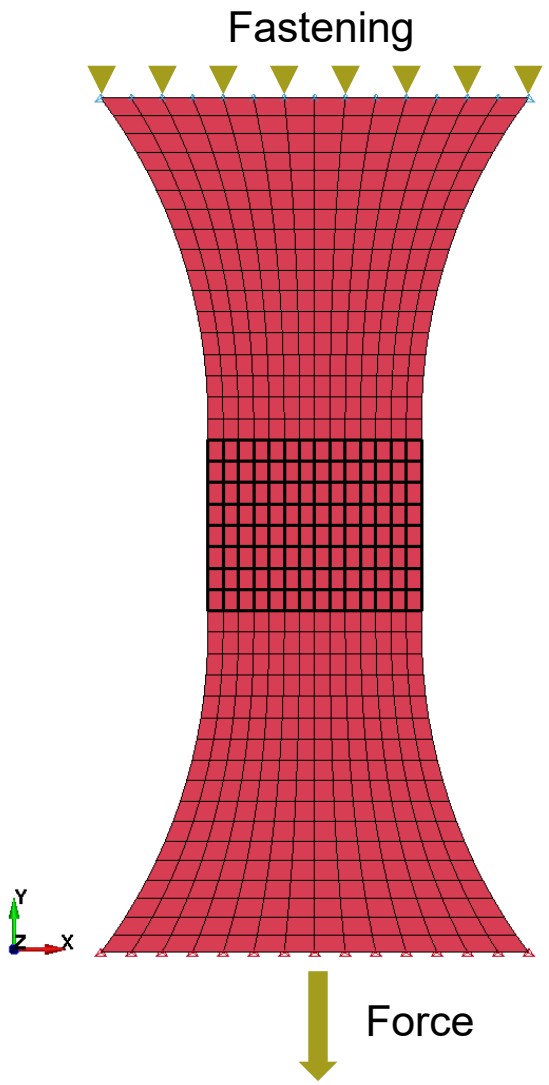
Simulation model

- **Element formulation:**
  Fully integrated S/R solid (Element type 2)

- **Boundary conditions:**
  Fixing the node set on the top side of the specimen
  Applying the load to the node set at the bottom of the specimen

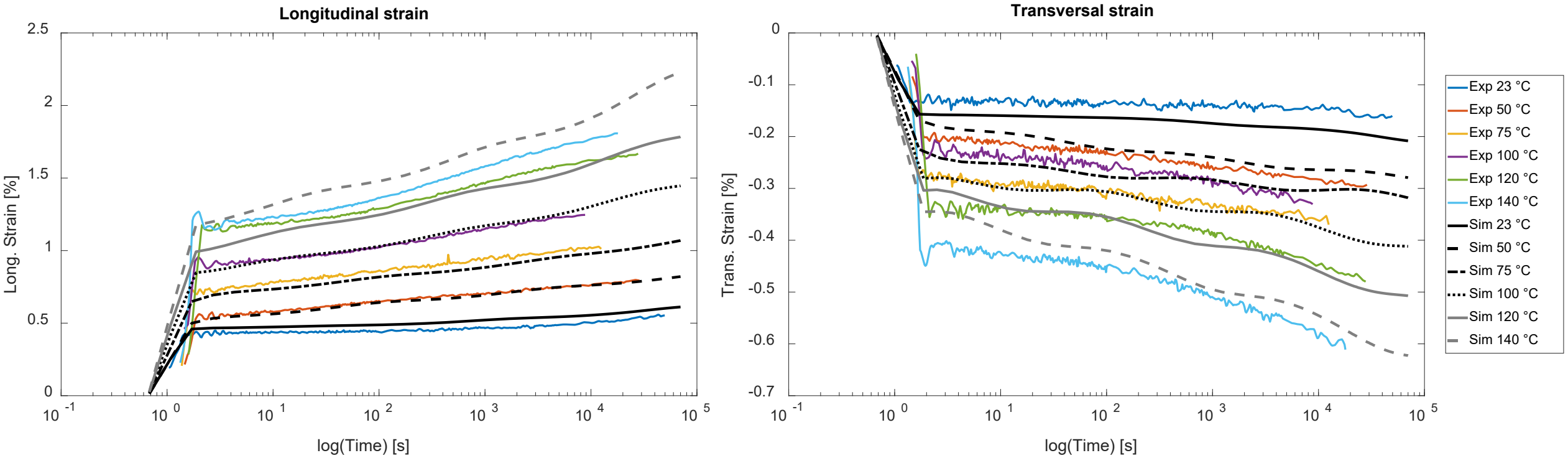
- **Time integration:**
  Implicit analysis

- **Strain evaluation:**
  Averaged over the element quantity in the parallel area of the specimen according to the DIC evaluation



Simulation results

Verification of the model calibration for PA6GF40 at 20MPa for 0° extraction direction



Good agreement of the simulation results with the experimental data in longitudinal direction

Partial deviations of the simulation results in transverse direction

Higher temperatures were not considered since the specimens slipped out of the clamping device

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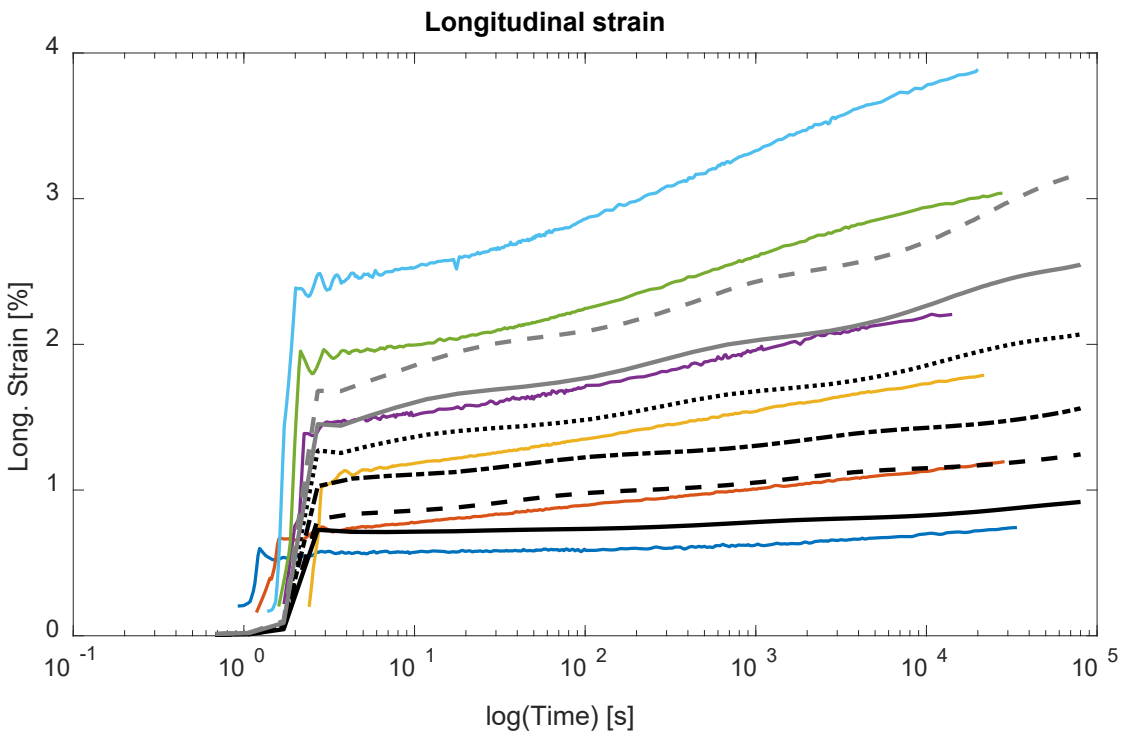
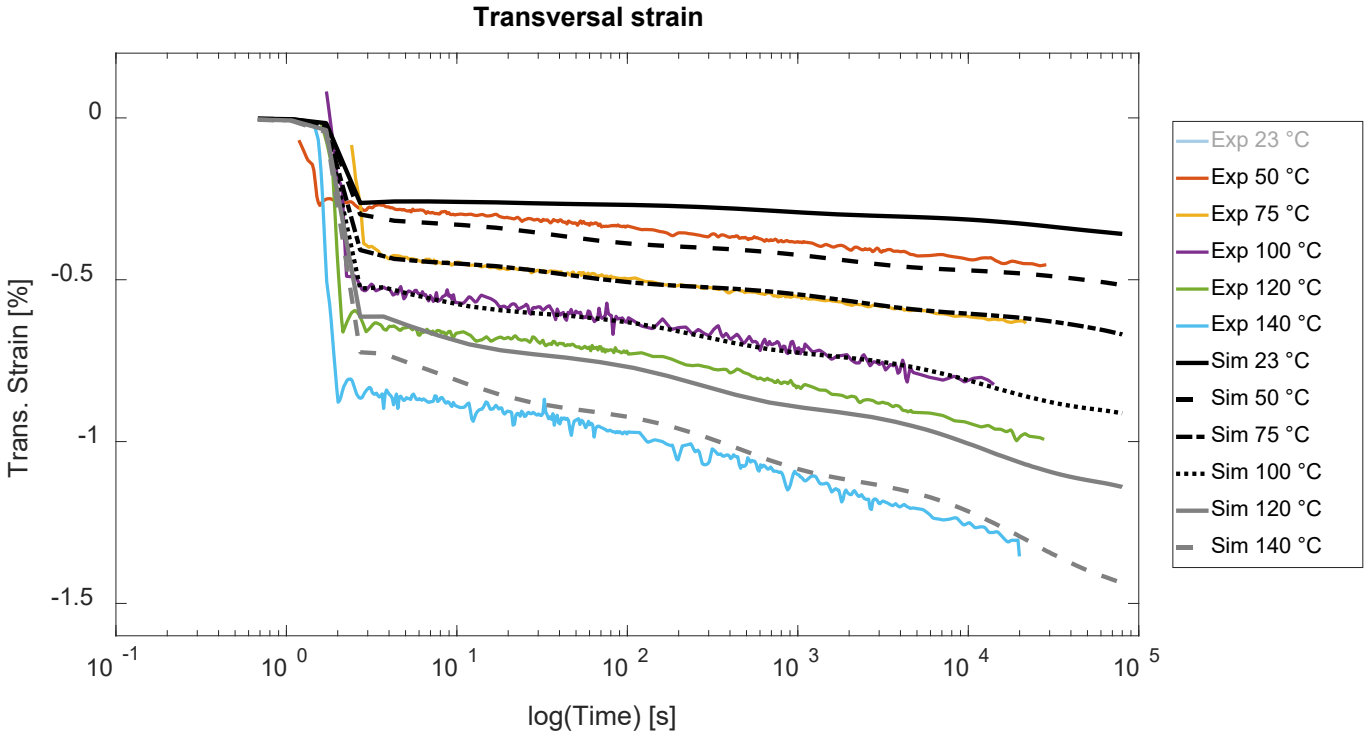
Verification of the model calibration for PA6GF40 at 30MPa for 0° extraction direction





In the longitudinal direction the experimental data can only be roughly reproduced for low temperatures

Good agreement between simulation and experimental data in transvers direction

The linear viscoelastic model cannot reproduce the occurring non-linear effects

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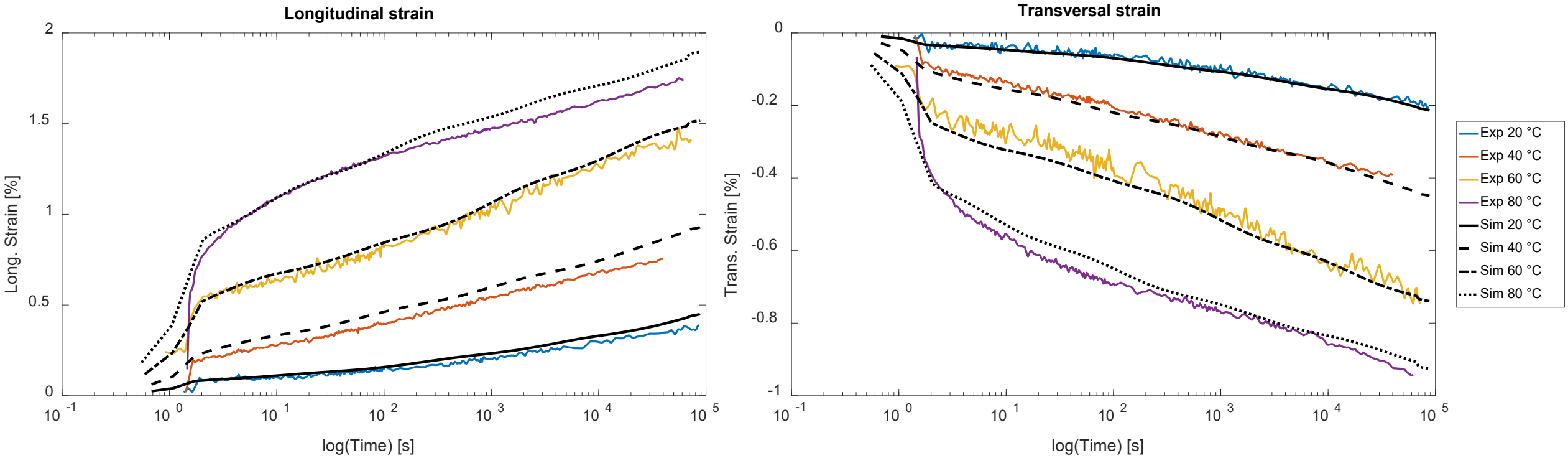
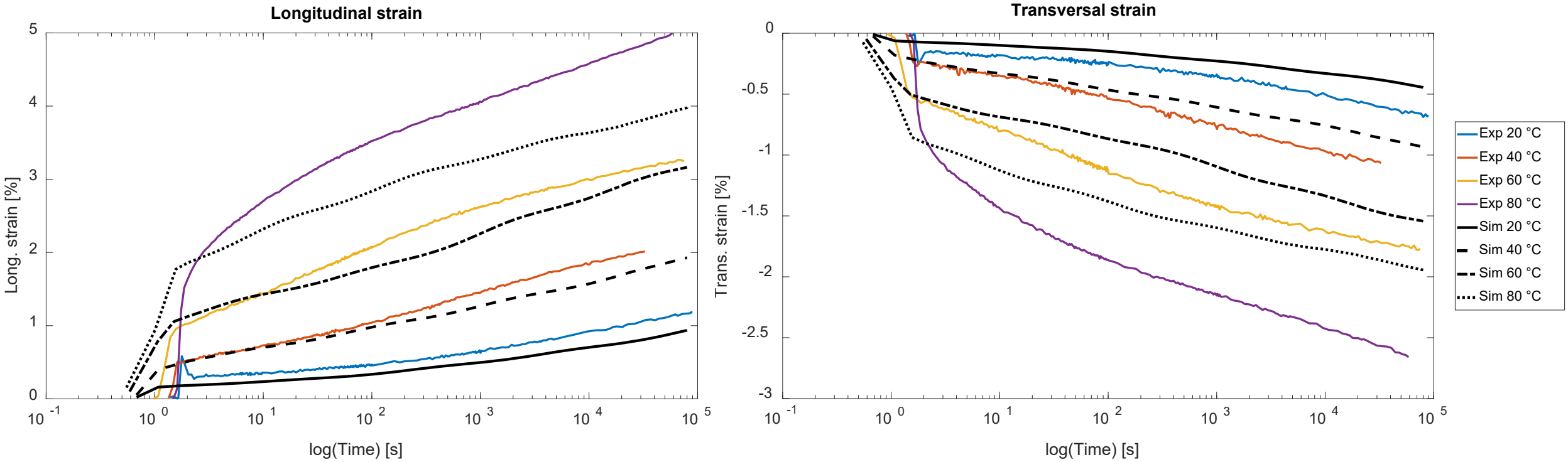
Verification of the model calibration for PE-HD at 2MPa for 0° extraction direction



Very good agreement of the simulation results with the experimental data in both longitudinal and transversal direction

Simulation results

Verification of the model calibration for PE-HD at 4MPa for 0° extraction direction



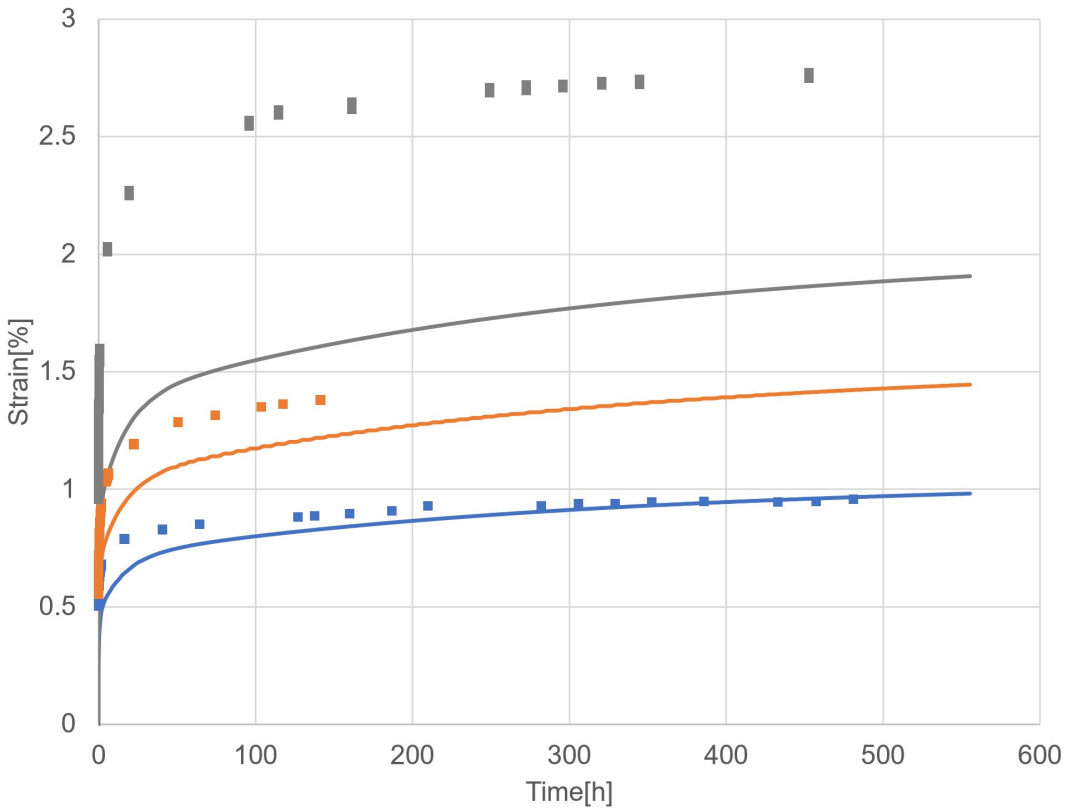
Good agreement of the simulation results with the experimental data for temperatures up to 60 °C

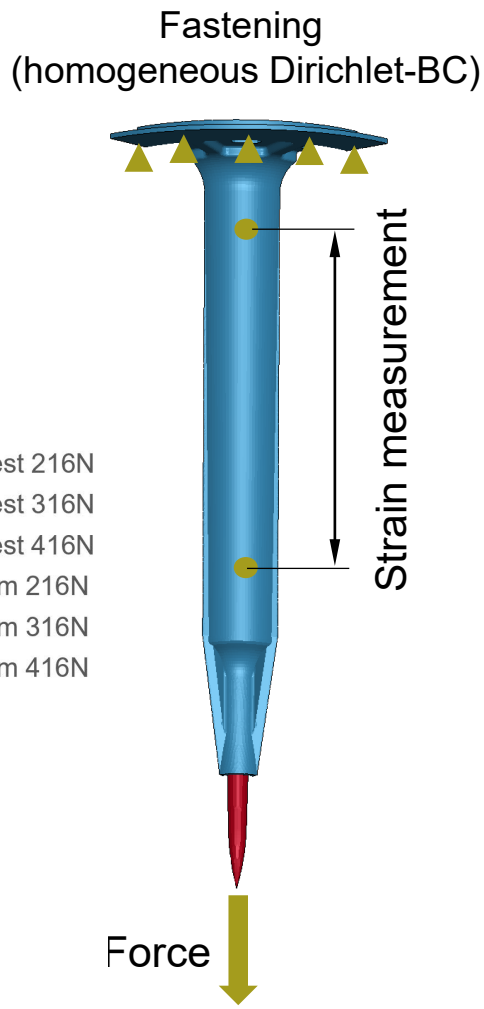
At 80 °C, the linear viscoelastic material model is not capable of adequately reproducing the behavior

Simulation results

Verification on component level

Insulation fastener





Lowest load level can be reproduced reasonably with the calibrated linear viscoelastic material model

Higher load levels show a strongly non-linear behavior and cannot be reproduced with the present model

In this case, material behavior can only be represented by a nonlinear material model

Conclusion and Outlook

Long-term behavior can be characterized with relatively short test times using time-temperature superposition principle

In the temperature chamber of the testing machine there is no constant humidity state over all test temperatures ➔ Critical especially for polyamide

Applied methodology for the semi-automatic creation of master curves and optimization of the relevant model parameters can effectively implemented

Simulations can reproduce the material data adequately within the linear viscoelastic range

Consideration of potential strains due to moisture absorption of the specimens during the test using additional CME measurements

Comparison with non-linear viscoelastic UMAT model based on Gibbs free energy

Additional consideration of creep-recovery and cyclic loading and unloading tests

Acknowledgement

The research work of this paper was performed at the Polymer Competence Center Leoben GmbH (PCCL, Austria) within the framework of the COMET-program of the Federal Ministry for Transport, Innovation and Technology and the Federal Ministry of Digital and Economic Affairs with contributions by the Montanuniversitaet Leoben, 4a engineering GmbH, Hilti AG and Hirtenberger Automotive Safety GmbH. The PCCL is funded by the Austrian Government and the State Governments of Styria, Lower Austria and Upper Austria.