Finite Element Modeling of Thermoplastics at Different Temperatures

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Outline of Presentation

- Experimental Data for Polycarbonate (Lexan)
- Calibration of Plasticity and Creep Models
- Parallel Network Model:
  - Theory
  - Calibration
  - FE Simulation
Problem Statement

- Limited experimental data available from the raw material manufacturer (non-linear viscoplastic material)
- What material model to select?

Goals:
- Demonstrate how to effectively use both creep and uniaxial tension data
- Demonstrate the material model calibration procedure
- Demonstrate the use of an advanced user-material model in Abaqus
Experimental Data

- Uniaxial tension at different temperatures
Experimental Data

Young's modulus as a function of temperature

\[ f(x) = -3.39x + 2439.93 \]

\[ R^2 = 0.97 \]
Experimental Data

Uniaxial creep experiments were performed at stresses between 15 MPa and 40 MPa.
Experimental Data

- Creep strain as a function of time for different stress values

![Graph showing creep strain as a function of time for different stress values](image)

- Experimental data: $T=23$ deg C, 15 MPa
- Experimental data: $T=23$ deg C, 20 MPa
- Experimental data: $T=23$ deg C, 25 MPa
- Experimental data: $T=23$ deg C, 30 MPa
- Experimental data: $T=23$ deg C, 35 MPa
- Experimental data: $T=23$ deg C, 40 MPa

27 days
Experimental Data

- Creep compliance as a function of time and stress
- The material is NOT linear viscoelastic
Experimental Data

- Uniaxial fatigue data
Material Model Selection

- Linear viscoelasticity
  - not-sufficient since the material is non-linear viscoelastic
- Elastic-Plastic with rate-dependence
- Elastic-Plastic with creep
- Viscoplastic user-material model
  - Parallel Network Model from the Veryst Engineering PolyUMod library

What material model works best?
Metal Plasticity Model – Calibration

*Elastic
*Plastic
*Rate Dependent, type=power law
Metal Plasticity Model

The rate-dependent plasticity model does not capture the non-linear creep response very well.
The material model calibration was performed using the MCalibration software from Veryst Engineering. This software can calibrate any material model in Abaqus.

*Elastic
*Plastic
*Creep, law=strain
Metal Creep Model

The plasticity-based creep model does not capture the non-linear creep response at high stresses.
Parallel Network Model (PNM)*

*The PNM is commercially available for Abaqus/Standard and Abaqus/Explicit from Veryst Engineering
Viscoplastic Flow Behavior

Power-law flow rate:

$$\dot{\gamma}^p = \left( \frac{\tau}{f_p f_{\varepsilon p} \hat{\tau}} \right)^m f_{\theta}$$

Exponential yield evolution:

$$f_{\varepsilon p} = f_f + (1 - f_f) \exp \left[ -\varepsilon_p^{max} \frac{\varepsilon_{\hat{\varepsilon}}}{\hat{\varepsilon}} \right]$$

Symbols:
- $\dot{\gamma}^p$: viscoplastic flow rate
- $\tau$: driving shear stress
- $\tau^{\text{hat}}$: flow resistance
- $m$: flow activation exponential
- $f_p = 1$
- $f_{\varepsilon}$: yield evolution factor
- $f_{\theta}$: piecewise linear temp factor
- $\varepsilon_p^{max}$: max plastic strain
- $\varepsilon^{\text{hat}}$: characteristic transition strain
- $f_f$: final yield evolution factor
Damage Model

Rate of damage accumulation:

\[ \frac{dD}{dt} = \frac{1}{t_0} \exp \left[ \left( \frac{\sigma_e}{\sigma_{ref}} \right)^m \right] \]

No damage \((D=0)\) at time \(t=0\)

Element failure when \(D > 1\)

\(\sigma_e\) = Mises stress
\([t_0, \sigma_{ref}, m] = \) material parameters

This damage model enables fatigue predictions
Material Model Calibration

Loadcase

name = V01 creep 35 MPa
fileName = creep_23degC_35MPa.txt
loadingMode = uniaxial
strainType = engineering
stressType = engineering
control = stressControl

Loadcase

name = V01 creep 40 MPa
fileName = creep_23degC_40MP.txt
loadingMode = uniaxial
strainType = engineering
stressType = engineering
control = stressControl

Material Model = Parallel-Network-Model
## Network 1

| EType | a | b | c | d | e | f | g | h | i | j | k | l | m | n | o | p | q | r | s | t | u | v | w | x | y | z |
| 1     | 2 | 0 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
| 0     | 0 | 0 |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |

EI_type

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<tr>
<th>N</th>
<th>T1</th>
<th>f1</th>
<th>T2</th>
<th>f2</th>
<th>T3</th>
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<tr>
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<td>0</td>
<td>273</td>
<td>0</td>
<td>296</td>
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</tr>
<tr>
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<td>0</td>
<td>0.527498</td>
<td>0</td>
<td>0.7578</td>
<td>0</td>
</tr>
</tbody>
</table>

Output Comments

R2 value for load case 1: 0.968756
R2 value for load case 6: 0.979933
R2 value for load case 7: 0.961049
Average R2 (without fitnessWeight): 0.972056
Fitness value (R2) of the simulation results: 2.7944

Simulation done

Run Time: 00:00:00
Function Evaluations: 7
# Material Model Parameters

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Neoprene Hyperelastic: $[\mu, \kappa]$</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network A</td>
<td>[174 MPa, 2000 MPa]</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameters</th>
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</thead>
<tbody>
<tr>
<td>Network A temperature dependence: 5 pairs of $[T, f]$ values</td>
<td>$[(243 \text{ K}, 0.64), (273 \text{ K}, 0.53), (296 \text{ K}, 0.76), (333 \text{ K}, 0.67), (363 \text{ K}, 0.60)]$</td>
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<thead>
<tr>
<th>Model Type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Network B: Neoprene hyperelastic: $[\mu, \kappa]$</td>
<td>[601 MPa, 2000 MPa]</td>
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<thead>
<tr>
<th>Type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Network B hyperelastic temperature dependence: 5 pairs of $[T, f]$ values</td>
<td>$[(243 \text{ K}, 1.11), (273 \text{ K}, 1.24), (296 \text{ K}, 1.28), (333 \text{ K}, 1.12), (363 \text{ K}, 1.30)]$</td>
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<thead>
<tr>
<th>Model Type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Network B flow: $[\tauHat, m]$</td>
<td>[14.2 MPa, 33]</td>
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<th>Type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Network B flow evolution: $[f_f, \epsilonHat]$</td>
<td>[3.2, 0.0037]</td>
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<tr>
<th>Type</th>
<th>Parameters</th>
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<tbody>
<tr>
<td>Network B flow temperature dependence: 5 pairs of $[T,f]$ values</td>
<td>$[(243 \text{ K}, 0.006), (273 \text{ K}, 0.023), (296 \text{ K}, 18.1), (333 \text{ K}, 4243), (363 \text{ K}, 12784)]$</td>
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<tr>
<th>Model Type</th>
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</thead>
<tbody>
<tr>
<td>Damage accumulation model: $[t_0, \sigma_{ref}, m]$</td>
<td>[5e-6 s, 50 MPa, 1]</td>
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</table>
Model Predictions

The PNM captures the strain-strain response in monotonic loading at different temperatures.
Creep Predictions

The PNM captures the non-linear creep response.
Creep Predictions

Comparison between experimental and predicted creep behavior
Damage Model Predictions

Predicted damage accumulation during a monotonic uniaxial tension simulation
Damage Model Predictions

Predicted fatigue behavior from the damage model.
Exemplar FE Study

- PC hook loaded with an increasing force
- The top of the hook was fixed
- Abaqus/Explicit with 27k C3D8R elements
- Failure at a critical damage level
- Room temperature
Exemplar FE Study

Large pre-existing notch
Damage Model Predictions

Configuration just before final failure
Summary

- Thermoplastic materials are non-linear materials: viscoplasticity, creep, failure
- Abaqus built-in plasticity models with strain rate dependence and creep can capture some of the experimental data
- Advanced user-material models (UMAT/VUMAT) can be used to accurately predict almost any aspect of isotropic and anisotropic polymers