ELASTOMER RATE-DEPENDENCE:
A TESTING AND MATERIAL MODELING
METHODOLOGY

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Overview

• Motivation and Background
• Testing Comments
• Stress-relaxation Testing
• Prony Series Viscoelasticity
• Family of Constant Strain-Rate Testing
• Summary and Conclusions
Motivation and Background

• Time-dependence of Elastomers
• Stress Relaxation curve fitting exits in Abaqus/CAE for Prony series viscoelastic material definition
• Well defined recipe
• Relatively common for sealing applications (long time)

• New application for time domain dynamic impact events
• Desire to capture rate-dependence of stress-strain curves
• Typical test data is often a family of constant strain-rate stress-strain curves
Motivation and Background

• Typical test data for understanding rate-dependence

Rubber, Constant Strain-Rate Testing

- Strain Rate = 0.01
- Strain Rate = 0.1
- Strain Rate = 1.0
- Strain Rate = 10.0
- Strain Rate = 40.0

Eng. Stress (MPa) vs. Eng. Strain
Motivation and Background

• Another example of typical test data

Vinyl, 35 Durometer, Constant Strain-Rate Testing
Motivation and Background

• No curve fitting in Abaqus for this type of test data
• Testing itself can be more complicated than stress-relaxation testing

• Can we use stress-relaxation testing instead?
• Can we use existing curve fitting to Prony series material model?
• Will we capture the rate-dependence of the loading curves?
• Will we capture the hysteresis loops in the load / unload cycle?

• Focus on stress-relaxation testing at short times (milliseconds)
• All specimens pre-conditioned to remove Mullins effect
• All testing at room temperature
Testing Comments

• All testing performed at Axel Products
• Instron Model 8800 Series servo-hydraulic test instrument
• Crosshead mounted 10 kN low mass high fidelity actuator
Stress Relaxation Testing

- Be consistent about time-frame of interest
- Try to achieve loading of stress-relaxation test at 50 /sec
- Test data taken every 1 millisecond
Stress Relaxation Testing

- Some actual strain-time test data - inertia effects present
Stress Relaxation Testing

• Corresponding Stress-time responses

Stress Relaxation Raw Test Data

Stress (MPa)

0.001 0.01 0.1 1 10 100

Time (secs)

- 10% Strain
- 20% Strain
- 30% Strain
- 40% Strain
- 50% Strain
- 60% Strain
- 70% Strain
- 80% Strain
- 90% Strain
- 100% Strain
Stress Relaxation Testing

- Data processed to align start and remove overshoot
In ABAQUS the time-dependent behavior $G(\tau)$ and $K(\tau)$ can be represented in terms of a Prony series:

$$G(\tau) = G_0 \left( 1 - \sum_{i=1}^{N} \bar{g}_i^p \left( 1 - e^{-\tau/\tau_i^G} \right) \right)$$

material coefficients are up to $N$ pairs of $\bar{g}_i^p$ and $\tau_i^G$

- $G_0$ and $K_0$ are determined from the elasticity definition.
- These are simply a sum of a series of exponential decays.
- For many solid elastomers, the relaxation behavior is dominated by shear relaxation. In these cases it is not necessary to specify $K(\tau)$.
- Rule of thumb is to have as many Prony terms as decades of time data.
Prony Series Viscoelasticity

- It is useful to understand the Prony Series curve shape
- For this we use a Excel-based ”what-if” tool
Prony Series Viscoelasticity

- Shape of the curve is improved with some very early time $\tau$
- Prony series improved with early time test data
Prony Series Viscoelasticity

- Resulting Prony Series curve fit to the stress-relaxation test data
Family of Constant Strain-Rate Data

- Test Result from load / unload cycle
Family of Constant Strain-Rate Data

- Focus on just the load curves

Constant Strain Rate Tests, Loading Only

- 0.01 /sec
- 0.1 /sec (a)
- 0.1 /sec (b)
- 1.0 /sec
- 10 /sec
- 50 /sec

Engineering Stress vs. Engineering Strain
Family of Constant Strain-Rate Data

- Comparison of Prony series material model to test data

![Graph showing constant strain rate tests with model predictions and test data for different strain rates.](Image)
Family of Constant Strain-Rate Data

- How about the load / unload hysteresis loop?

Constant Strain Rate Simulation

<table>
<thead>
<tr>
<th>Engineering Stress</th>
<th>Engineering Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 Model</td>
<td>0.1 Model</td>
</tr>
<tr>
<td>1.0 Model</td>
<td>10 Model</td>
</tr>
<tr>
<td>50 Model</td>
<td></td>
</tr>
</tbody>
</table>
Summary / Conclusions

- Stress-relaxation tests were performed at short times
- Curve fitting in Abaqus/CAE used to calibrate Prony series viscoelasticity
- The material model correlated very well with the test data

- Family of constant strain-rate test data also performed
- Test data not used for calibration
- Prony series material mode represents load curves very well
- Prony series does a poor job representing the hysteresis loop
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