Adhesive Simulation and Measurements

- The Coupled Simulation Process
- The UMAT Subroutine in ABAQUS
- From Measurements to Simulation Model
- Automotive Simulations and Validations

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The Coupled Simulation Process

**Input:** Temperature Measurement (during the paint drying oven)

**Output:** Temperatures: $T(t)$

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**Input:** Crash FE Model (containing connections e.g. adhesives)

**Output:**
- Deformations: $u(t)$
- Stresses: $\sigma(t)$

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**THESEUS-FE Oven**

Thermal Simulation

Body in White Model/Mesh

Calibration of THESEUS-FE Oven Model

**Output:** Temperatures: $T(t)$

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**ABAQUS/UMAT**

Mechanical Simulation

Body in White Model/Mesh

UMAT for Adhesives:

Adhesives
The UMAT Subroutine in ABAQUS

Deformations \( \varepsilon = \varepsilon^{\text{visco elast.}} + \varepsilon^{\text{plast.}} + \varepsilon^{\text{therm.exp.}} - \varepsilon^{\text{curing shrink}} \)

Input:
- Strains \( \varepsilon = [\varepsilon_{11}, \varepsilon_{22}, \ldots, \varepsilon_{23}] \)
- Temperatures
- State variables

Output:
- Adhesive curing level: \( p[0..1] \)
- Stresses \( \sigma = [\sigma_{11}, \sigma_{22}, \ldots, \sigma_{23}] \)

https://www.3ds.com/products-services/simulia/products/abaqus/

* UMAT = User defined subroutine for special materials in ABAQUS
From Measurements to Simulation Model

(for Adhesive: Betamate 1480)
From DMA Measurements to Simulation Model (for BM 1480)

**Diagram:**
- **Complex Modulus ($E^*$):**
  
  \[ E^* = \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma_0 e^{i\omega t}}{\varepsilon_0 e^{i(\omega t - \delta)}} = \frac{\sigma_0}{\varepsilon_0} e^{i\delta} = \frac{\sigma_0}{\varepsilon_0} \cos \delta + i \frac{\sigma_0}{\varepsilon_0} \sin \delta \]

- **Storage Modulus ($E'$):**
  
  \[ E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \]

- **Loss Modulus ($E''$):**
  
  \[ E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta \]

- **Loss Factor (tan $\delta$):**
  
  \[ \tan \delta = \frac{E''}{E'} \]

- **Frequency Range:** 0.5-33 Hz

**Equation:**

\[ \omega = 2\pi f \]

**Notes:**
- Fully cured adhesive
- 4x10x80 mm
- Temperature chamber
- Oscillation

**Maxwell Model:**

\[ E(t) = E_0 e^{i(\omega t - \delta)} \]

\[ E^* = \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma_0}{\varepsilon_0} e^{i(\omega t - \delta)} \]

\[ E' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \]

\[ E'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta \]

\[ \tan \delta = \frac{E''}{E'} \]

**Graphs:**
- Storage modulus and Loss modulus
- Frequency range: 0.5-33 Hz

**Equipment:**
- DMA = Dynamic Mechanical Analysis
- Betamate 1480 (fully cured)

**Additional Information:**
- Temperature chamber
- Oscillation
- Fully cured adhesive 4x10x80 mm

**Mathematical Equations:**

\[ Tension \ stress \ \sigma(t) \]

\[ Strain \ \varepsilon(t) \]

\[ \omega t \]

\[ \tau_i = \tau_{i0} a_T \]

\[ Maxwell \ Model \]
From DMA Measurements to Simulation Model (for BM 1480)

Measured Storage Modulus: E’ in the frequency domain (0.5-33Hz)
(every curve a different temperature)

Temperature shift $\omega \rightarrow \omega a_T$

Ref. temp.: $T_0 = T_g = 115^\circ C$
from DSC (see next slide)

Shifting master curve at ref. temp. $T_0$

Maxwell Model

$E(t) = E_\infty + \sum_{i=1}^{N} E_i \exp(-t/\tau_i)$

$E_\infty = E_\infty(\omega)$

$\tau_i = \tau_i(\omega)$

$\omega = \omega(\tau)$

$T_g = T_0$

Measurement range

$E(\omega) = E_\infty + \sum_{i=1}^{N} E_i \left(\frac{\omega \tau_i}{1+(\omega \tau_i)^2}\right)$

E’ in the time domain

Relaxation function at ref temp. $T_0$

$\tan \delta = \frac{E’}{E’}$

Frequency range: 0.5-33Hz

E’ in the frequency domain (10^{-7}-10^{20}Hz)

Shifted master curve at ref. temp. $T_0$
DSC = Differential Scanning Calorimetry
- Used to derive a simulation model for the curing ratio
- Used to measure the glass transition temperature $T_g$

Curing ratio:

$$p = F_1(1 - c_1) + F_2(1 - c_1 - c_2) + F_3(1 - c_1 - c_2 - c_3) + (1 - F_1 - F_2 - F_3)(1 - c_1 - c_2 - c_3 - c_4)$$
From Rheometer Measurements to Simulation Model (for BM 1480)

Temperature chamber
Heating rate: 3K/min

\[ \omega = 2\pi f, f = 1 \text{Hz} \]
\[ R = 25\text{mm} \]
\[ d = 1\text{mm} \]

Adhesive

BM 1480 (uncured)

BM 1480 (fully cured)

Temperature chamber
Heating rate: 3K/min

\[ \omega = 2\pi f, f = 1 \text{Hz} \]
\[ R = 25\text{mm} \]
\[ d = 1\text{mm} \]

Adhesive

Temperature chamber
Heating rate: 3K/min

\[ \omega = 2\pi f, f = 1 \text{Hz} \]
\[ R = 25\text{mm} \]
\[ d = 1\text{mm} \]

Adhesive

BM 1480 gel point at:
- Temperature 162°C
- Time 47.3 min
- Curing ratio \( p_{gel} = 0.425 \) (model)
Automotive Simulations and Validations
Automotive Sunroof Submodel

Pre-calculated temperatures:
Radiation heating from bottom side

Transparent shell mesh: inner and outer metal sheets of sunroof

Betamate 1480

Measured [Jendrny 2004]
Simulated (ABAQUS/UMAT)
Pre-calculated temperatures:
Paint drying oven

**BMW 5 Series Touring (2006)**

*Full animation video available...*
Automotive Body in White

Finite Element Model (BMW E61, symmetric half model)

Adhesive: Totalseal 1198

roof bow

roof liner

[Eis/Paulke 2006]
Measurements

Validation: Temperatures and Relative Displacements

- rel. displ (meas.)
- rel. displ (sim.)
- curing level
- dT (outer - inner)
- inner temp. (meas.)
- outer temp. (sim.)
- inner temp. (sim.)

[Validation: Temperatures and Relative Displacements diagram]

Relative displacement [mm] vs. Time [s] plot with various curves indicating different measurements and simulations.

Validation: Temperatures and Relative Displacements

- rel. displ (meas.)
- rel. displ (sim.)
- curing level
- dT (outer - inner)
- inner temp. (meas.)
- outer temp. (sim.)
- inner temp. (sim.)

[Eis/Paulke 2006]