Experimentally Calibrating Cohesive Zone Models for Structural Automotive Adhesives

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Outline

- Cohesive Zone Modeling (CZM) Introduction
- Experimental Measurement of Cohesive Laws
- Measuring Adhesive Joint Toughness at High Rates
  - Rate dependent CZM
- Inverse Calibration Approach
Cohesive Zone Modeling (CZM)
Predicting Failure of Adhesive Joints

• Stresses in adhesive joints can be highly complex

• Behavior of bonded joints during crash events is a significant concern
Cohesive Zone Modeling

Cohesive zone modeling is an approach for modeling failure of adhesive joints in finite element analyses.

The adhesive deformation/failure is defined by relating the applied stress on the adhesive, $\sigma$, to the separation of the adhesive, $\delta$:

$$\sigma(\delta)$$
Cohesive Zone Models captures several commonly measured mechanical properties:

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Related CZM Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus, $E$</td>
<td>Stiffness, $k$</td>
</tr>
<tr>
<td>Strength, $\sigma$</td>
<td>Max Stress, $\sigma_{\text{max}}$</td>
</tr>
<tr>
<td>Toughness, $G_C / J_C$</td>
<td>$J$</td>
</tr>
<tr>
<td>Strain to Failure</td>
<td>$\delta_c$</td>
</tr>
</tbody>
</table>

Due to differences in the stress state between a tensile specimen and an adhesive joint, the properties do not match exactly.
Measurement of Cohesive Zone Laws
CZM Calibration

• Cohesive Zone Models must be experimentally calibrated for every adhesive

• Calibration can be done using standard test specimens widely used in the adhesives industry

• For joint designers using finite element analysis, having the cohesive zone model parameters allows them to predict performance of joints made with different/new adhesives
The traction separation law is defined as the derivative of the $J$-integral ($J$) with respect to the adhesive separation ($\delta_o$).

$J$ and $\delta_o$ are both measureable using standard adhesive test specimens.

$$J = \int_0^{\delta_c} \sigma(\delta) \, d\delta$$

$$\sigma(\delta) = \frac{dJ}{d\delta}$$
The J-integral is a measure of crack driving force and can be applied to adhesive joints.

J has units of joules/meter$^2$.

\[ J = \int_{\Gamma} W \, dy - T_i \frac{\partial u_i}{\partial x} \, ds \]

\[ W = \text{strain energy density} \]
\[ T_i = \text{normal traction vector} \]
Measuring J-Integral for Adhesive Joints

- The DCB specimen has a very simple J-Integral solution, depending only upon the applied load, $P$, and the beam opening angles, $\theta$.

- The beam angles can be measured with digital image correlation.

\[ J = \frac{2P \sin(\theta/2)}{b} \]
Measuring Crack Separation, $\delta$

- The crack separation, $\delta$, can be measured using digital image correlation.
Once we have measured $J$ as a function of $\delta$, we have to differentiate:

$$\sigma(\delta) = \frac{dJ_I}{d\delta}$$

This is best done by first fitting the data with a smooth function.
Final Cohesive Zone Model

Fit Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>1.5 GPa</td>
</tr>
<tr>
<td>$\sigma_{\text{max}}$</td>
<td>28.4 MPa</td>
</tr>
<tr>
<td>$J_{\text{IC}}$</td>
<td>2508 J/m$^2$</td>
</tr>
<tr>
<td>$\delta_{\text{fail}}$</td>
<td>0.12mm (48%)</td>
</tr>
</tbody>
</table>

- The CZM for this adhesive is shown in red
Check – Simulated DCB Specimen

We can check the cohesive zone model accuracy by simulating different tests to compare the measured and predicted load/displacement profiles.
High Rate Measurement of Toughness
Rate-Dependent Cohesive Zone Models

- Adhesives can exhibit highly rate-dependent properties.
- Rate-dependent Cohesive Zone Models are required.
- MAT-240 in LS-DYNA is one such model that is used in the automotive industry.
- To calibrate these models, we need to measure toughness as a function of loading rate.

Increasing Rate
- $J$ increases
- $\sigma_{\text{max}}$ increases
Impact-Rate Mode I Toughness

- A dowel pin is driven into the sample at 2-7 m/s. The crack tip strain rate is in the 100s per second.

\[ J = \frac{E' b^3 (\theta_1 - \theta_2) \sin(\theta_1)}{3L^2} \]

- The J-Integral is calculated using the beam rotations measured by DIC.

\[ E' = \frac{E}{(1 - v^2)} \]
Impact-Rate Mode I Toughness

\[ J = \frac{E' b^3 (\theta_1 - \theta_2) \sin(\theta_1)}{3L^2} \]

- No measurement of load
- No measurement of crack length

Video duration = 14 ms
Rate-Dependent Toughness

Impact DCB method

J curves for an automotive adhesive measured at three loading rates

\[ J_1 (J/m^2) \]

Normalized Test Time
Rate Dependent Fracture Toughness

For finite element models, the properties must be provided as a function of crack tip strain rate, which can be experimentally measured or simulated.
Mode II Toughness: Elastic-Plastic ENF

- Mode II ENF specimens for tough adhesives can be very large (~1 m in length) if linear elasticity is to be guaranteed in the beams.

- Using the J-integral solution for the ENF specimen allows for some plasticity in the beams during the experiment.

\[
J = \frac{P}{b} \left[ 0.5\theta_A - \theta_B + 0.5\theta_C \right]
\]

- No measurement of crack length

- The beam rotations, \(\theta\), at point A, B, C are measured with DIC.
High Rate Mode II Toughness Measurement

- This method can be done at high rates using high speed videography to capture the specimen deformation.

\[
J_{II} = \frac{P}{b} [0.5\theta_A - \theta_B + 0.5\theta_C]
\]
Elastic-Plastic ENF J-Solution Validation

Using FEA, we can check that the test specimen dimensions are such that the plastic deformation in the beams does influence the results.

Assumed Cohesive Law

- $S = 45\, \text{MPa}$
- $\Gamma = 20\, \text{kJ/m}^2$

“Measured” J value

- $J_{IC} = 20.3\, \text{kJ/m}^2$
- $\Gamma = 20.0\, \text{kJ/m}^2$

\[ J = \frac{P}{b} [0.5\theta_A - \theta_B + 0.5\theta_C] \]
Inverse Calibration Approach
Material Model Parameters

- LS-DYNA MAT_240 has 16 parameters
- Measuring all of these accurately can be difficult
- One option is to measure a few parameters and use inverse calibration methods to optimize the rest of the parameters

<table>
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<tr>
<th>Parameter</th>
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<th>Mode II Value</th>
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<tbody>
<tr>
<td>Modulus (MPa)</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$J_o$ (J/m$^2$)</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$J_{inf}$ (J/m$^2$)</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$\dot{\epsilon}_G$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$T_o/S_o$ (MPa)</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$T_1/S_1$ (MPa)</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$\dot{\epsilon}_T/\dot{\epsilon}_S$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$F_G$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
</tbody>
</table>
Inverse Calibration Methodology

Model Parameters to Be Solved For

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<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$J_{0}$ (J/m$^2$)</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$J_{111}$ (J/m$^2$)</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td>$\epsilon_0$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$T_0/S_0$ (MPa)</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$T_1/S_1$ (MPa)</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$\tilde{\epsilon}_T/\tilde{\epsilon}_f$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
<tr>
<td>$F_0$</td>
<td>Inverse calibration</td>
<td>Inverse calibration</td>
</tr>
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</table>

Fracture Experiment

Finite Element Model of Experiment

Predicted Load-Displacement to Experiment

Experiment

Model
Model Parameter Optimization

- Can optimize CZM to different experiment types and loading rates
- The inverse calibration is done using optimization software
Summary
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• Cohesive zone modeling is an powerful method for predicting adhesive joint failure that is becoming more widely used

• These models can be experimentally calibrated using industry-standard test specimens

• High-rate toughness is particularly of interest for automotive adhesives

• For joint designers using finite element analysis, having the cohesive zone model parameters allows them to predict performance of joints made with different/new adhesives