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# Development of Cohesive Zone Models for 3M™ Structural Adhesives

## Introduction

As structural adhesives are used in more critical applications, the need for predictive techniques to evaluate adhesive performance has become essential. Finite element analysis (FEA) has emerged as a powerful tool for modeling adhesive behavior under a wide range of conditions. FEA can dramatically reduce design cycle time by decreasing the number of experiments and optimizing joint design. [1,2]

Modeling structural adhesives requires a constitutive material model and a corresponding set of material properties. Continuum models can accurately predict stress distributions in the adhesive, but are numerically expensive and cannot effectively predict bond failure. Cohesive zone models (CZM) are a damage modeling technique that can simulate adhesive behavior fromsmall elastic deformations to complete failure.[3] CZMsare computationally efficient and eliminate singularitiesand mesh dependencies encountered at sharp cornersand defects. This white paper outlines the developmentand test-coupon validation of cohesive zone models for 3M™ Structural Adhesives.

## The Cohesive zone Model

Cohesive zone models simulate the adhesive bond with a generalized cohesive traction force holding the adherends together. The response of the adhesive layer to loads is described by a traction-separation curve[3]. An example of a bilinear traction-separation relationship is shown in **Figure 1**. The curve is split into two parts: an elastic region and a damage evolution region. Each of these regions is described by a set of adhesive material properties[3], which are summarized in **Figure 2**.

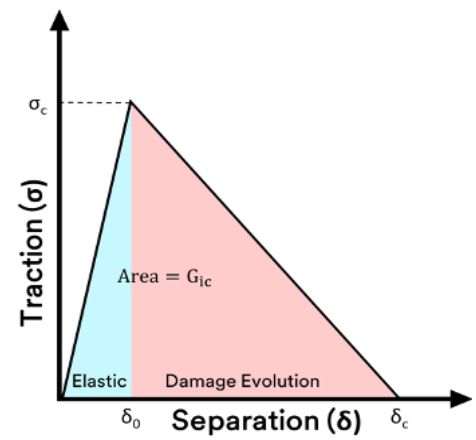


**Figure 1:** Bilinear traction-separation curve with linear elastic behavior and a linear decrease in traction after damage initiation.

| Physical Effect | Test Name | Test Sketch | Material Parameter | Description | Symbol | Unit |
|---|---|---|---|---|---|---|
| Elasticity | Uniaxial Tension Test | | Young's Modulus and Poisson's Ratio | Resistance to elastic deformation and transverse contraction in tension | $K_I, K_{II}, K_{III}$ | MPa |
| Damage Initiation | Thick Adherend Butt Joint Tension Test | | Tensile Strength | Maximum stress in laterally constrained tension | $\sigma_I$ | MPa |
| | Thick Adherend Shear Test | | Shear Strength | Maximum stress in shear | $\sigma_{II} = \sigma_{III}$ | MPa |
| Damage Evolution | Tapered Double Cantilever Beam (TDCB) Test | | Mode I Fracture Energy (Critical Energy Release Rate) | Resistance to crack propagation in Mode I (opening mode) | $G_{IC}$ | $\frac{N}{mm} = \frac{kJ}{m^2}$ |
| | End-Notched Flexure (ENF) Test | | Mode II Fracture Energy (Critical Energy Release Rate) | Resistance to crack propagation in Mode II (shear mode) | $G_{IIC} = G_{IIIC}$ | $\frac{N}{mm} = \frac{kJ}{m^2}$ |

**Figure 2:** Material properties and tests required to build a cohesive zone material data card (MDC). The model assumes the adhesiveis isotropic, and the material properties in the two shear directions (mode II and mode III) are equivalent.

# Adhesive Material Properties

In the elastic region, the material response is defined by the normalized tensile modulus $K_I = \frac{E}{t_A}$ and Poisson's ratio (υ). Here is the adhesive layer thickness. These properties are then used to calculate the normalized shear modulus $K_{II} = \frac{G}{t_A}$.

$$K_{II} = \frac{K_I}{2(1+\upsilon)} \qquad \text{Equation 1}$$

The damage initiation criterion is the peak of the traction separation relation and marks the onset of material response degradation. The damage initiation criterion is typically defined as the ultimate tensile and shear strength in modes I and II respectively. The ultimate tensile strength $(\sigma_I)$ is measured with the butt joint test, and the shear strength $(\sigma_{II} = \sigma_{III})$, is measured with a thick lap shear test. Mixed mode damage initiation can be estimated using a quadratic nominal stress criterion[5]:

$$\left\{\frac{\sigma_I(\delta)}{\sigma_I}\right\}^2 + \left\{\frac{\sigma_{II}(\delta)}{\sigma_{II}}\right\}^2 + \left\{\frac{\sigma_{III}(\delta)}{\sigma_{III}}\right\}^2 = 1 \qquad \text{Equation 2}$$

Damage evolution describes how the material stiffness is degraded after damage initiation. The damage evolution region is defined by the damage parameter $(D)$, and critical fracture energy $(G_{ic})$. $D$ has an initial value of 0 at the damage initiation point, and increases monotonically to 1 at complete failure:

$$\sigma_i = (1-D)\bar{\sigma}_i \qquad \text{Equation 3}$$

Here $\bar{\sigma}_i$ is the undamaged traction vector component.

The critical fracture energy is the area under the traction-separation curve (**Figure 1**). The mode I and mode II critical fracture energies are typically measured using the tapered double cantilever beam (TDCB) test and end-notched flexure (ENF) tests respectively (**Figure 3**). The critical fracture energy can be calculated using the Irwin-Kies equation:[1]

$$G_{ic} = \frac{F}{2w}\frac{dC}{da} \qquad \text{Equation 4}$$

Here, $F$ denotes the average peak force, $w$ the specimen width, and $dC/da$ the derivative of the specimen compliance $C$ with respect to the crack length $a$. The mixed mode fracture behavior can be estimated using the Benzeggagh-Kenane (B-K) law:[5]

$$G_{C\,mixed} = G_{IC} + (G_{IIC} - G_{IC})\left\{\frac{G_{II}+G_{III}}{G_I+G_{II}}\right\}^2 \qquad \text{Equation 5}$$

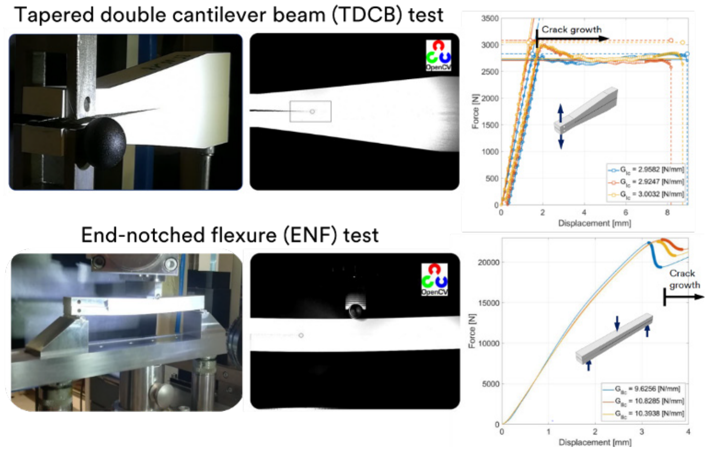


**Figure 3:** TDCB and ENF testing setup and results. The location of the crack tip is measured with 3M proprietary crack tip location tracking algorithm.

# Material Data Card Assembly

The adhesive material properties can be implemented into a material data card (MDC), which can be imported directly into FEA software. An example of a cohesive zone MDC for Abaqus is shown in **Figure 4**.

In general the material properties depend on the strain rate and joint geometry, especially the bond line thickness. Material properties should therefore be measured under conditions similar to those expected in the end use.

| Physical Effect | Test Name | Test Sketch | Symbol | Value | Unit |
|---|---|---|---|---|---|
| Elasticity | Uniaxial Tension Test | | $K_I$ | 2530.0 | MPa |
| | | | $K_{II} = K_{III}$ | 900.0 | |
| Damage Initiation | Thick Adherend Butt Tension Test | | $\sigma_I$ | 45.0 | MPa |
| | Thick Adherend Shear Test | | $\sigma_{II} = \sigma_{III}$ | 28.0 | MPa |
| Damage Evolution | Tapered Double Cantilever Beam Test | | $G_{IC}$ | 3.0 | $\frac{N}{mm}$ |
| | End-Notched Flexure Test | | $G_{IIC} = G_{IIIC}$ | 10.5 | $\frac{N}{mm}$ |

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** --------------------------------------------------------------------
** 3M Structural Adhesive - Material Model for ABAQUS
** --------------------------------------------------------------------
** IMPORTANT: The material model must not be applied for physical
**            conditions other than those specified below!
** --------------------------------------------------------------------
** Loading: (Quasi-)Static
** Temperature: RT
** Adhesive Thickness: 0.3 mm
** Units:  [Length] - Millimeter, [Force] - Newton,
**         [Time] - Seconds, [Temperature] - Kelvin
** --------------------------------------------------------------------
*Material, name=Adhesive
*Elastic, type=TRACTION
 2530.0, 900.0, 900.0
*Damage Initiation
 45.0, 28.0, 28.0
*Damage Evolution
 3.0, 10.5, 10.5
** --------------------------------------------------------------------
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**Figure 4:** Adhesive material data card for Abaqus.

# Test Coupon-Validation

Material models must be validated by experiments to ensure that the model represents the real material behavior with sufficient accuracy. Validation should be done at the coupon level, as well as the subcomponent, component, and completed product level. **Figure 5** shows coupon level validation using the T-peel and single lap shear tests. **Figure 6** shows a validation using the 90° double lap shear test, which results in a complex stress distribution with mixed mode behavior. 3M customers can validate 3M™ Structural Adhesives in their own designs using these 3M-provided test coupon-validations.

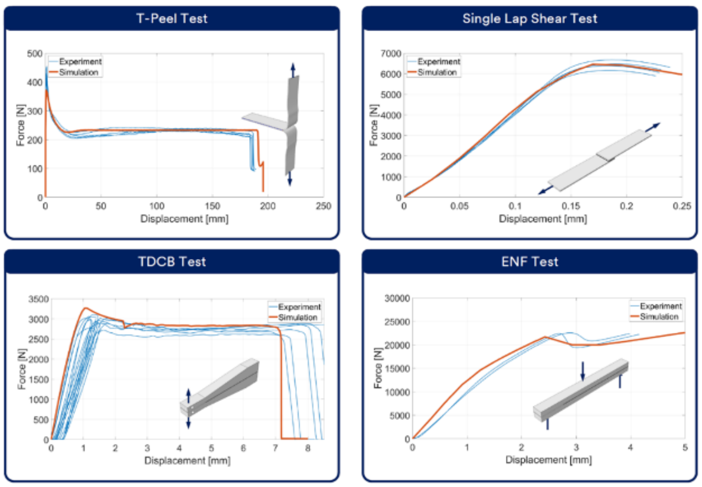


**Figure 5:** Coupon level validation of the cohesive zone material model using the T-peel and single lap shear tests.

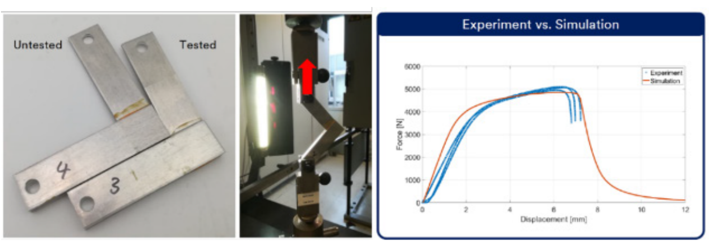


**Figure 6:** Coupon validation of the adhesive model with mixed mode behavior by the 90° double lap shear test.

# Conclusions

Providing customers with validated MDCs enables accurate and rapid assessment of adhesive performance and joint design. For guidance implementing structural adhesives in your application, reach out to the experts at 3M.

# Resources

[1] Da Silva, L. F. & Campilho, R. D. Advances in numerical modelling of adhesive joints. (Springer, 2012).

[2] Shimamiya, T., Chiaki, S., Yokoi, E., Furusawa, T. & Sato, K. Simulation of Adhesively Bonded Parts for Multi-Material Bonding Structure. (2015).

[3] Sun, C.-T. & Jin, Z.-H. Fracture mechanics. (Academic Press, 2012).

[4] Gustafson, P. A. & Waas, A. M. The influence of adhesive constitutive parameters in cohesive zone finite element models of adhesively bonded joints. Int. J. Solids Struct. 46, 2201–2215 (2009).

[5] Trimiño, L. F. & Cronin, D. S. Evaluation of Numerical Methods to Model Structural Adhesive Response and Failure in Tension and Shear Loading. J. Dyn. Behav. Mater. 2, 122–137 (2016).

[6] ABAQUS. Defining the constitutive response of cohesive elements using a traction-separation description. https://abaqus-docs.mit.edu/2017/English/SIMACAEELMRefMap/simaelm-c-cohesivebehavior.htm. (accessed on 4/2/2020)

[7] Greve, L. & Andrieux, F. Deformation and failure modelling of high strength adhesives for crash simulation. Int. J. Fract. 143, 143–160 (2007).

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