Introduction to Modeling Structural Adhesives

3M

1 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.

FEA is a numerical technique that breaks a geometry into simpler parts called elements, and calculates the field properties (stresses, strains, displacements, etc.) of each element. This method enables the modeling of complex geometries and loading conditions, and calculation of stresses and strains anywhere within the bonded structure, including the adhesive layer. The inputs required are the geometry, loads and boundary conditions, and a constitutive model to describe the material behavior under load. The general process of modeling an overlap shear bond is outlined in Figure 1.

Defining the material constitutive model is typically the most challenging part of modeling structural adhesives.[1] Constitutive models range from simple linear elastic models, to sophisticated models that can accurately simulate complex adhesive behavior. Complex models can be more accurate, but are difficult to implement, computationally expensive, and require many more material properties that must be determined experimentally. The ideal material model is the simplest model that generates results with the necessary degree of accuracy.

This paper outlines the process of developing material models for structural adhesives. First, the simplistic tie-break method is briefly described. Then several continuum models are reviewed including linear elastic, hyperelastic, viscoelastic, linear elastic plastic, and viscoplastic models. The capabilities and requirements of each model are outlined, as well as the conditions in which each model should be used. Finally, the cohesive zone damage modeling approach is reviewed.

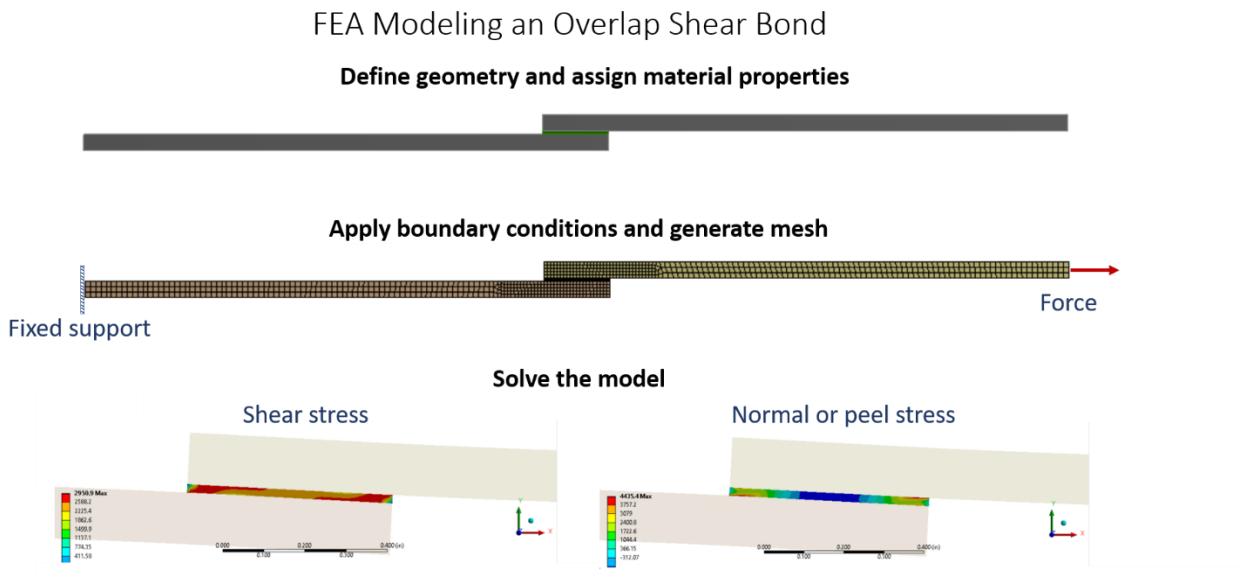


Figure 1: The general process for modeling an overlap shear bond. First the geometry is defined, and material properties are assigned. Then the geometry is broken into elements in a process called meshing. Finally, boundary conditions are applied and the problem is solved.

2 Tie-Breaks

Tie-Breaks is the simplest technique to represent adhesives in a simulation. The method represents the adhesive bond as a tie between two substrates in contact. The contact is most typically described using two parameters: the adhesive tensile strength and shear strength. These serve as failure values to determine when the tie breaks and the substrates lose contact. Although this technique is simple and can be implemented quickly, the representation of the adhesive mechanical response to load is very crude and can result in large errors.[2]

3 Continuum modeling

3.1 Linear elastic models

Other than Tie-Breaks, linear elastic models are the most straightforward method for modeling structural adhesives and are typically used for initial evaluations. These models are computationally efficient and only require two material properties, so they are easy to implement.

Linear elastic models are valid for reversible deformations at small strains[1,3]. In the linear elastic region, the stress is proportional to the strain, and adhesive behavior can be described by Hook's law:

$$\boldsymbol{\sigma} = \boldsymbol{E}\,\boldsymbol{\varepsilon} \qquad \text{Equation 1}$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{\varepsilon}$ is the strain tensor, and $\boldsymbol{E}$ is the elasticity tensor. Strain energy is stored in the material and released upon unloading, so the material returns to its original shape and the unloading path is the same as the loading path.

Modeling linear elastic behavior requires the tensile modulus (Young's modulus E) and Poisson's ratio (υ), which can be measured with a uniaxial tension test.[4] The shear modulus can then be calculated from:

$$G = \frac{E}{2(1+\upsilon)} \qquad \text{Equation 2}$$

The main drawback of linear elastic models is the limitation to small strains and the inability to capture the non-linear deformation of certain adhesives at low strains. Beyond the proportionality limit (Figure 2 and Figure 3) the stress and strain are no longer proportional and linear elastic models result in errors. It is important to know the proportionality limit to ensure that it is not exceeded. In general, the proportionality limit depends on the adhesive, strain rate, and temperature.

3.2 Hyperelastic models

Some flexible structural adhesives (typically polyurethanes) undergo large nonlinear elastic strains that can be described by hyperelastic models (Figure 2).[1,5,6] The stress-strain relationship of hyperelastic materials is described in terms of the strain energy density function $U(\varepsilon)$. Hyperelastic material models can be derived using test data measured in multiple stress states, including uniaxial, biaxial, and planar tension. As an example, some flexible structural adhesives have been successfully modeled with the Mooney-Rivlin model:

$$U = C_{10}(\overline{I_1} - 3) + C_{01}(\overline{I_2} - 3) + \frac{1}{D_1}(J^{el} - 1)^2 \qquad \text{Equation 3}$$

where C_{10}, C_{01}, and D_1 are material properties determined experimentally, $\overline{I_1}$ and $\overline{I_2}$ are the first and second deviatoric strain invariants, and J^{el} is the elastic volume ratio.

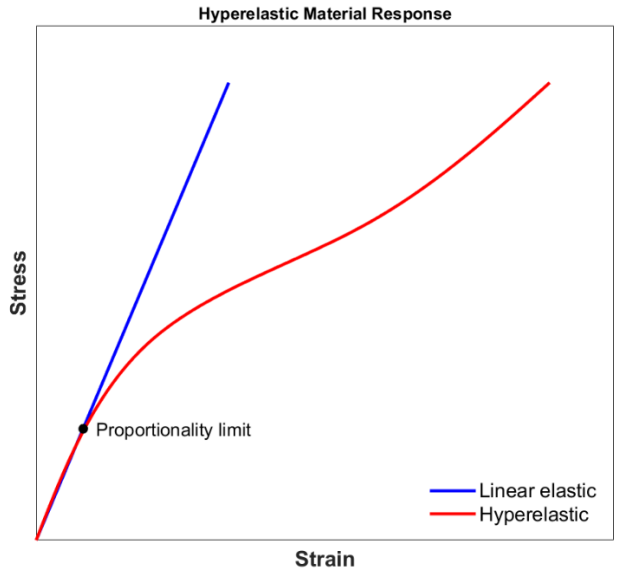


Figure 2: Hyperelastic materials undergo large nonlinear elastic deformations.

3.3 Viscoelastic models

Polymers, including structural adhesives, are viscoelastic materials in nature and exhibit both viscous and elastic behavior. The adhesive material response is temperature and strain rate dependent, with higher stiffnesses at faster strain rates and lower temperatures. Deformation energy is stored as strain energy and dissipated though viscous relaxations in the material. Viscoelastic material models are of interest to simulate creep, stress relaxation, and impact events. However, when dynamic models are used, such as those used in the transportation industry to model crash events and electronics markets to model dropping components, there can be a large simulation time penalty associated with the solution.

At small strains, structural adhesives can be modeled as a linear viscoelastic material. The stress response due to an arbitrary strain history can be evaluated with the hereditary integral:[1,7]

$$\sigma(t) = \int_{-\infty}^{t} E(t-\tau)\dot{\varepsilon}\, d\tau \qquad \text{Equation 4}$$

where $E(t)$ is the relaxation modulus, which can be approximated with a Prony series:

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i e^{-t/\tau_i} = E_0 - \sum_{i=1}^{N} E_i (1 - e^{-t/\tau_i}) \qquad \text{Equation 5}$$

where E_0 and E_∞ are the instantaneous and long term modulus, which define the material response at very high and very low strain rates respectively, N defines the number of terms in the Prony series, and E_i and τ_i are the modulus and relaxation times associated with each Prony series term respectively. The relaxation time is a measure of the time it takes for the stresses in the material to relax, and shorter relaxation times are indicative of more viscous materials. Large strain viscoelasticity requires the generalization of Equation 4 from linear elasticity to hyperelasticity, which needs the definition of a hyperelastic stress function in addition to the Prony series.

The parameters in the Prony series can be determined by fitting data from a dynamic mechanical/thermal analysis (DMTA) test. The DMTA test measures the elastic and viscous response of the adhesive at different frequencies (strain rates) and temperatures. Due to the time-temperature superposition principle, an equivalency can be made between the temperature and strain rate, and a DMTA master curve can be constructed. The master curve can be fit to a Prony series, which can be directly implemented into FEA software. For more information on this process please refer to the related document *Constitutive Models for 3M Pressure Sensitive Adhesives (PSA)*.

The significance of viscoelastic effects over the strain rates and temperatures of interest should be evaluated to determine if a viscoelastic model is required. Structural adhesives are typically used below their glass transition temperature, making viscoelastic effects less significant than PSAs, which are used above their glass transition temperature. If the DMTA master curve indicates that the adhesive properties do not change significantly over the range of interest, errors from ignoring viscoelastic effects can be small. Another approach is to account for viscoelastic effects by measuring the adhesive properties at the strain rates and temperatures of interest. Measurement of adhesive properties at very fast strain rates is required for modeling of crash and impact events.

3.4 Linear elastic plastic models

Structural Adhesives used in high-performance applications are engineered to sustain strains well beyond the yield point, with extensive plastic deformation prior to failure (Figure 3). Plastic strain is initiated at the yield point and involves energy dissipation, resulting in irreversible deformation.[3]

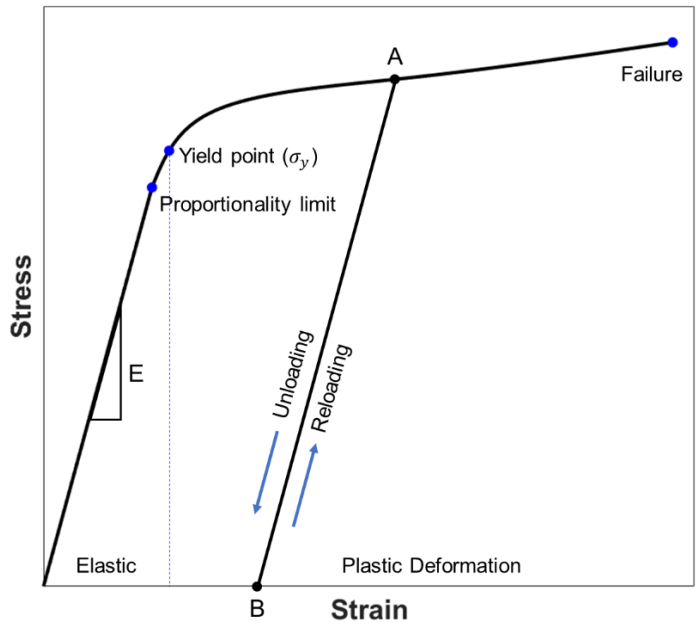


Figure 3: Ductile Structural Adhesives undergo significant plastic deformation prior to failure.

In the plastic region, the strain can be decomposed additively into a recoverable elastic component, and a nonrecoverable plastic component:[2]

$$\varepsilon = \varepsilon^e + \varepsilon^p \qquad \text{Equation 6}$$

Upon unloading, only the elastic deformation is recovered, resulting in permanent deformation (Figure 3). If the material is reloaded, it undergoes elastic deformation following the unloading curve (A-B) until it yields at point A. It then follows the original plastic deformation curve. The yield point can therefore be considered a function of plastic strain $\sigma_y(\varepsilon^p)$ and in the plastic region the stress-stain curve can be regarded as yield stress-strain curve.

Modeling plastic deformation requires a yield criterion, a hardening rule, and a flow law.[8] The yield criterion defines the onset of plastic deformation and can be measured in tension and shear with the uniaxial tension test and thick lap shear test respectively. However, the stress field in a typical adhesive bond is complex, with components of both tension and shear. Mixed-mode yielding can be predicted from the uniaxial results using the Tresca or von Mises criteria. The Tresca yield criterion states that yielding occurs when the maximum shear strength reaches a critical value:

$$Max\{|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_1 - \sigma_3|, \} = \sigma_T \qquad \text{Equation 7}$$

where σ_i are the principal stresses and σ_T is the Tresca stress. The von Mises yield criterion is based on the maximum shear-strain energy:

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \qquad \text{Equation 8}$$

where σ_e is the effective shear stress.

The Tresca and von Mises yield criteria are sufficient for modeling structural adhesives in many applications, but these criteria were developed for metals and do not account for hydrodynamic stress sensitivities observed in polymer systems. For example, the von Mises criterion assumes that the yield stress in tension (σ_T), compression (σ_C), and shear (σ_S) are related by $\sigma_T = \sigma_C = \sqrt{3}\sigma_S$, but structural adhesives can sometimes have significantly higher yield strengths in compression than tension.[9,10]

The Drucker-Prager model incorporates a hydrodynamic stress sensitivity which is suitable to describe pressure-dependent behavior in polymeric materials.[1,8] The exponential form of the Drucker-Prager criteria states that yielding occurs when:

$${\sigma_e}^2 = \lambda {\sigma_T}^2 - 3(\lambda - 1)\sigma_T \sigma_m \qquad \text{Equation 9}$$

Here, σ_m is the hydrodynamic stress and λ is the hydrodynamic stress sensitivity:

$$\lambda = \frac{\sigma_C}{\sigma_T} = \frac{{\sigma_c}^2}{3{\sigma_s}^2} = \frac{{\sigma_s}^2}{3\sigma_T} \qquad \text{Equation 10}$$

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \qquad \text{Equation 11}$$

All required material parameters except for λ can be measured with a uniaxial tension test. Determination of λ requires material properties in an additional stress state, either shear or compression. Typically, the shear properties are measured using the thick lap shear test, because this is the typical loading mode of structural adhesive bonds.

The hardening rule defines how the yield strength increases with plastic deformation. Perfectly plastic materials have no hardening, and the yield stress remains constant with plastic strain. However, real structural adhesives undergo strain hardening, which can be approximated as bilinear or multilinear (Figure 4).[3] Each linear segment is defined by a tangent modulus K. General hardening curves require stress as a function of plastic strain $\sigma_T(\varepsilon_T^p)$. The plastic strain

component can be calculated by subtracting the elastic component from the total strain in Equation 6:

$$\varepsilon_T^p = \varepsilon_T - \varepsilon_T^e = \varepsilon_T - \frac{\sigma_T}{E} \qquad \text{Equation 12}$$

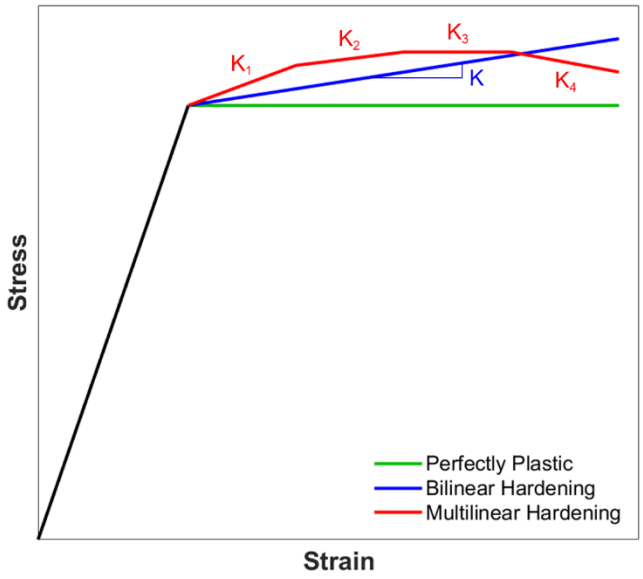


Figure 4: Plastic deformation can be approximated with perfectly plastic, bilinear, and multilinear hardening rules

Hardening rules are characterized as isotropic, kinematic, or mixed.[1] Isotropic hardening rules maintain the same yield stress in compression as in tension. These rules are easier to implement and well suited for modeling large strains, however accurately modeling cyclical loading or load reversal is problematic since they cannot reproduce the Bauschinger effect (softening in compression due to hardening in tension). Kinematic hardening models can accurately model cyclical loading and load reversals but are more challenging to implement and unsuitable for large strains. If both large strains and cyclic loading are required, a mixed hardening rule is required.

The plastic flow rule determines how the plastic strains develop when yielding occurs. The incremental plastic strain is related to the plastic flow potential F by the general flow law:[8,10]

$$d\varepsilon_p = d\lambda \frac{\partial F}{\partial \sigma} \qquad \text{Equation 13}$$

where $d\lambda > 0$ is a hardening parameter. In general, the plastic flow potential is a function of the stresses, hardening parameters, and temperature.

Flow rules are characterized as associated or non-associated. In associated flow, the plastic strain increment is normal to the yield surface and the flow potential is the yield function.[3] In the exponential Drucker-Prager model:

$$F = {\sigma_e}^2 - \lambda {\sigma_T}^2 + 3(\lambda - 1)\sigma_T \sigma_m \qquad \text{Equation 14}$$

Associated flow is a simplification, and structural adhesives typically exhibit non-associated flow. The non-associated flow rule requires a more general expression for F with the parameter λ' substituted for λ in Equation 14:[9]

$$\lambda' = \frac{3(1 - 2\nu^p)}{2(1 + \nu^p)} \qquad \text{Equation 15}$$

$$\lambda' = \tan \Psi$$

were ν^p is the plastic component of Poisson's ratio. The parameter λ' is often expressed as a function of the angle of dilation (Ψ), which characterizes volumetric strain during plastic yielding.[8,9,11] The volumetric strain describes volume increase typically associated with plastic deformation of structural adhesives[10].

Experimental data is typically recorded as engineering or nominal stress vs strain, but material models require values of true stress and true strain. At small strains the error from using engineering stress and strain values is negligible, but larger strains associated with plastic deformation require true stress and strain values. The true stress and strain values can be calculated from the engineering values (σ', ε') from:

$$\sigma = \frac{\sigma'}{(1 + \nu' \varepsilon')} \qquad \text{Equation 16}$$

$$\varepsilon = \ln(1 + \varepsilon') \qquad \text{Equation 17}$$

Equation 16 and Equation 17 are valid until the point of necking, after which direct measurement of the instantaneous cross-section is required.

One approach to account for viscoelastic effects using linear plastic models is by measuring the adhesive properties at the strain rates of interest. The Cowper-Symonds or Johnson-Cook models can be used to describe the strain rate sensitivity in the plastic response.

Actual experimental data and an interpolation scheme to capture the strain rate sensitivity can also be used depending on the FEA code implementation. This approach works well if the modulus of elasticity is not significantly affected by changes in strain rate, and it is amenable to describe adhesive properties when modeling crash and impact events.

3.5 Viscoplastic models

Viscoplastic material models are the most accurate method for simulating structural adhesives, but implementation is extremely complex and time consuming.[1] Rate dependent plasticity enables the accurate simulation of complex material behavior under arbitrary loading conditions, including stress relaxation, creep, and recovery. These models do not have explicit yield surface, and plastic flow occurs at all non-zero stress values, although at low stresses the plastic flow may be negligible. Unified theory models based on overstress are the ultimate method for modeling structural adhesive but can be prohibitively complicated.[10,12] Despite their impressive predictive capabilities, viscoplastic material models are often not practical because they are computationally expensive, require identification of a large set of material properties, and often require user subroutines because they are not available in commercial FEA software. In addition, this level of sophistication is not required for typical engineering decisions.

3.6 Failure criteria

Continuum models assume that the material is continuous and free of cracks or defects, and therefore cannot directly model bond failure. Typically, the stress and strain distributions from the FEA model are compared to a maximum allowable value considered as the failure criterion. For a conservative design, the yield criterion can be used as a failure criterion, but this results in overengineering the adhesive joint. Failure criteria based on the maximum principal stress or maximum shear stress have had some success for brittle adhesives, but this analysis can be challenging due to stress singularities at the joint corners.

Toughened and flexible adhesives are ductile and can withstand significant plastic deformation prior to failure, so stress-based failure criteria are not suitable. The maximum principal strain and maximum shear strain criteria have had more success predicting the failure of ductile adhesives. However, constraints imposed by joint geometry and the nature of the bonded materials can significantly change the hydrostatic stresses (effective pressure) experienced by the adhesive. This in turn affects the actual strain and stress to failure, making

it very challenging, without extensive testing, to determine appropriate maximum values to trigger failure in constitutive models used to describe adhesives. Failure criteria based on the strain energy density are even more accurate because they take all stress and strain components into account.[13] Direct modeling of bond failure is the major limitation of continuum models and requires the cohesive zone modeling approach described in the following section.

4 Cohesive zone modeling

Cohesive zone modeling (CZM) is a damage modeling technique that can simulate adhesive behavior from small elastic deformations to complete failure.[13,14] In this approach, the adhesive layer is replaced with a single row of cohesive elements that are held together by a generalized force called cohesive traction. CZM is computationally efficient and eliminates singularities and mesh dependencies encountered at sharp corners and defects. When a cohesive element fails, the load is redistributed in the remaining elements, resulting in a smooth evolution of the stress field. Unlike fracture mechanics approaches, CZM does not require an initial flaw or knowledge of where a crack initiates, but autonomously initiates damage based on the stress field. The simplicity of CZM results in several drawbacks: stress and strain distributions cannot be predicted in the direction perpendicular to the adhesive thickness, the physical meaning of the fracture process is lost by utilizing an equivalent generalized cohesive force, and the traction-separation relation is dependent on the structure geometry, especially the adhesive thickness and bonding materials.

4.1 The traction separation relation

The traction-separation relation is the constitutive law that defines the response of the adhesive layer. The relation requires an assumed shape, which can be bilinear, trapezoidal, or more general (Figure 5). Structural adhesives can accurately be modeled with simple bilinear traction-separation relations, and several studies have shown that the curve shape has a small effect on model accuracy.[13,15]

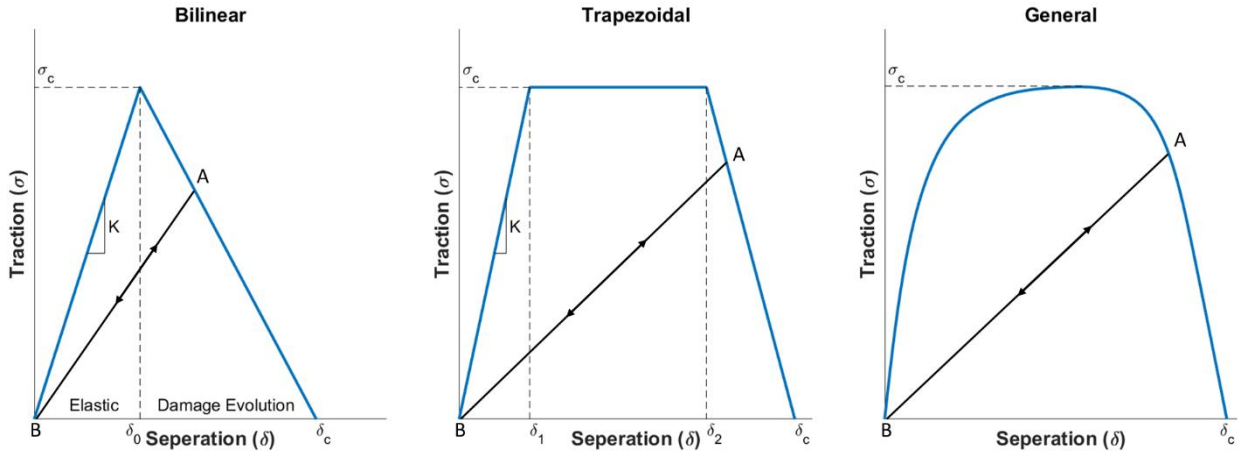


Figure 5: Bilinear, trapezoidal, and general traction-separation relations.

The traction-separation relation can be divided into two parts: the elastic region before damage initiation, and the damage evolution region.[14] Prior to damage initiation, the adhesive is modeled as an elastic material. Damage is initiated at a specified damage initiation criterion (σ_c), and the remainder of the curve describes damage evolution (also called softening). At δ_c the element is completely separated and can no longer bear a load. If the adhesive is unloaded in the damage evolution region, it follows the unloading curve (A-B), resulting in permanent softening. If it is then reloaded, the adhesive follows (B-A) back to the initial curve, and then resume following the traction-separation relation. Other implementations completely forgo damage and implement fully reversible paths for load/unload.

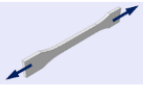
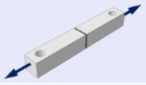
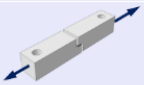
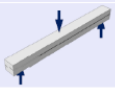
Physical Effect	Test Name	Test Sketch	Material Parameter	Description	Symbol	Unit
Elasticity	Uniaxial Tension Test		Young's Modulus and Poisson's Ratio	Resistance to elastic deformation and transverse contraction in tension	K_I, K_{II}, K_{III}	MPa
Damage Initiation	Thick Adherend Butt Joint Tension Test		Tensile Strength	Maximum stress in laterally constrained tension	σ_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 6: Material properties and tests required to build a cohesive zone material model. The model assumes material properties in the two shear directions (mode II and mode III) are equivalent.

The material properties and tests required to define the traction-separation relation are summarized in **Figure 6**. Prior to damage initiation, the material response is defined by the normalized tensile modulus $K_I = \frac{E}{t_A}$ and Poisson's ratio, both of which can be measured with a uniaxial tension test. The normalized shear modulus $K_{II} = \frac{G}{t_A}$ can be calculated from Equation 2. In general, the adhesive stiffness depends on the bond line thickness due to confinement effects, and thinner bond lines have higher effective stiffnesses. These effects can be measured with the butt tension and thick lap shear test, or the effective modulus can be approximated by assuming complete restriction of lateral expansion as:

$$K_I' = \frac{1-\upsilon}{1+\upsilon-2\upsilon^2} K_I \qquad \text{Equation 18}$$

The damage initiation criterion is typically defined as the ultimate tensile and shear strength in modes I and II, respectively. The ultimate tensile strength is measured with the butt joint test, and the shear strength is measured with a thick lap shear test. Mixed-mode damage initiation can be estimated using a quadratic nominal stress criterion:[15]

$$\left\{\frac{t_1}{\sigma_I}\right\}^2 + \left\{\frac{t_{II}}{\sigma_{II}}\right\}^2 + \left\{\frac{t_{III}}{\sigma_{III}}\right\}^2 = 1 \qquad \text{Equation 19}$$

Here t_I, t_{II}, and t_{III} are the components of the traction vector in the normal, first shear and second shear directions, respectively. For orthotropic materials $t_{II} = t_{III}$.

The damage evolution region is defined by the damage parameter (D), and critical fracture energy (G_c). D has an initial value of 0 at the damage initiation point and increases monotonically to 1 at complete separation.

$$t_i = (1-D)\bar{t}_i \qquad \text{Equation 20}$$

Here $\bar{t}_i$ is the undamaged component of the traction vector. The functional definition of D determines the shape of the damage evolution region of the traction-separation curve. For linear softening D can be defined in terms of the effective displacement as:[15]

$$D = \frac{\delta_m^f(\delta_m^{max} - \delta_m^0)}{\delta_m^{max}(\delta_m^f - \delta_m^0)} \qquad \text{Equation 21}$$

$$\delta_m = \sqrt{{\delta_I}^2 + {\delta_{II}}^2 + {\delta_{III}}^2}$$

$$\delta_m^f = 2(G_c/T_{eff}^0),$$

where δ_m^{max} is the maximum value of effective displacement attained from the loading history and δ_m^0 is the effective displacement at damage initiation. G_c and T_{eff}^0 are the fracture energy and effective traction at damage initiation, respectively.

The critical fracture energy (G_c) is the area under the traction-separation curve. The mode I and mode II critical fracture energies are typically measured using the tapered double cantilever beam (TDCB) test and end notch flex (ENF) tests respectively. The critical energy release rates can be calculated from the tests using the Irwin-Kies equation:

$$G_{ic} = \frac{F}{2w}\frac{dC}{da} \qquad \text{Equation 22}$$

where F denotes the averaged peak force, w the specimen width, and dC/da is derivative of the specimen compliance C with respect to the crack length a. The mixed-mode fracture energy can be measured directly with a mixed-mode bending test, or estimated using the Benzeggagh-Kenane (BK) criterion:[15]

$$G_{C\,mixed} = G_{IC} + (G_{IIC} - G_{IC})\left\{\frac{G_{II} + G_{III}}{G_I + G_{II}}\right\}^{\eta} \qquad \text{Equation 23}$$

where G_I G_{II} and G_{III} are fracture energies in the normal, first shear and second shear directions respectively, G_{Ic} G_{IIc} and G_{IIIc} are the critical fracture energies, and η is a material parameter calculated from a mixed mode test. For orthotropic materials $G_{II} = G_{III}$.

Rate dependencies can be incorporated into the parameters that define the traction-separation relation, but this is a complex process,[16] and it is often easier to measure the material properties at the strain rates of interest and use a tailored model.[17] Rate effects on the damage initiation criteria and fracture energy are more complicated. For example, the damage initiation stress is proportional to the logarithm of the strain rate in many structural adhesive systems.[10] These challenges make the numerical implementation of CZM difficult, and FEA codes show different levels of complexity and capability in their implementations.

5 Model validation

Material models must be validated by experiments to ensure that the model represents the real material behavior with sufficient accuracy.[1] Validation should be done at the coupon level, as well as the subcomponent, component, and completed product level.[17] Coupon level

validation requires tests that were not used in model development. Figure 7 shows a material model validation using the single lap shear and T-peel tests. Figure 8 shows a validation using the 90° double lap shear test, which results in a complex stress distribution with mixed-mode behavior. Subcomponent, component, and completed product level validation are done on customer parts under similar loading conditions as the final application.

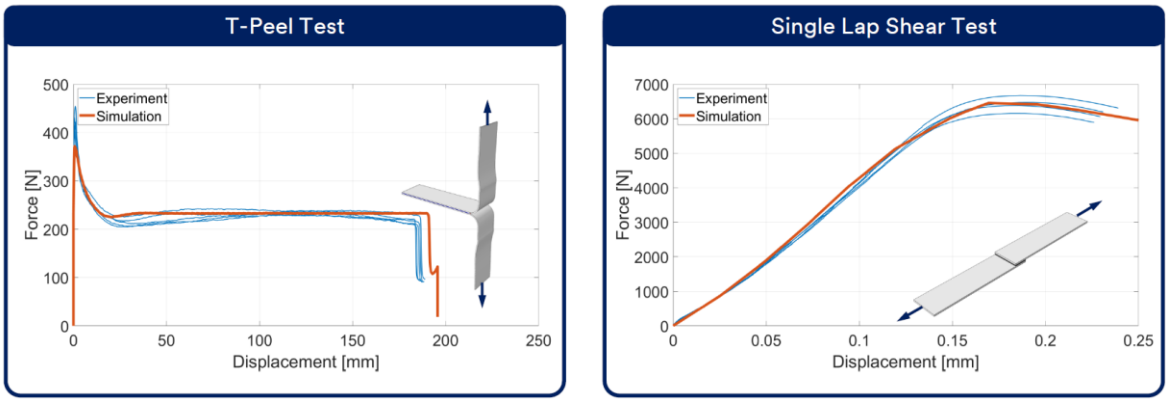


Figure 7: Material model validation using the T-peel and single lap shear tests.

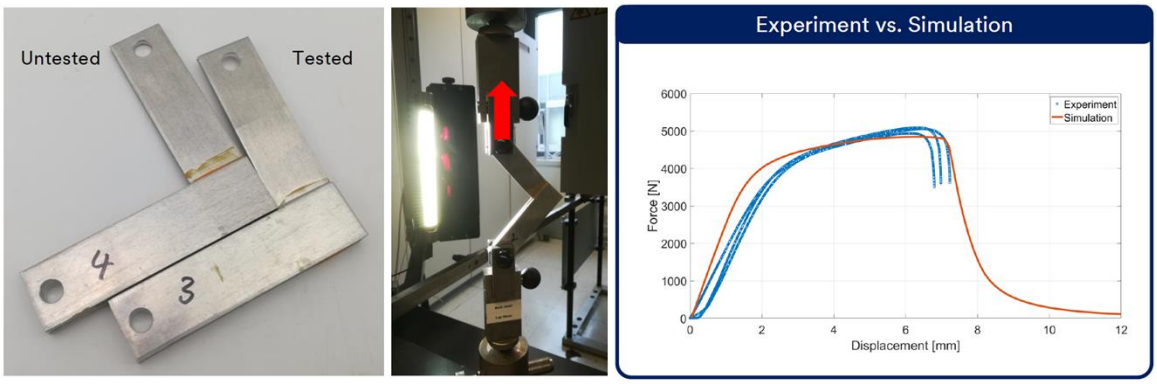


Figure 8: Material model validation using the 90° double lap shear test.

6 Conclusions

Modeling structural adhesive bonds can predict performance and optimize joint design while dramatically reducing the number of experiments required. The material model should reproduce the adhesive behavior of interest with sufficient accuracy to make engineering decisions. In many applications linear elastic material models can be sufficient, and these can be implemented quickly and easily. However, other applications may require simulation of more complex plastic deformations, or temperature and rate dependencies. If direct measurement of bond failure is required, cohesive zone models can be used.

For more information about modeling 3M™ Scotch-Weld™ Structural Adhesives or 3M™ Scotch-Weld™ Structural Adhesive material data cards, please contact 3M at 1-800-362-3550.

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