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Potting Adhesion Investigation Using Double Cantilever Beam Tests

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ABSTRACT

The adhesive properties of an elastomeric potting material were investigated experimentally using double cantilever beam (DCB) specimens. In these tests, the applied load and opening displacement were measured, with the goal of quantitatively characterizing the adhesive strength of the thin layer of potting material. The DCB tests were also simulated using a finite element model that incorporated an adhesive traction-separation model to represent the compliance of the potting layer and evolving (weakening) strength of the potting-to-metal adhesive interfaces. The test and simulation results were used to determine a range of traction-separation model parameters, expressed in the form of correlated probability distributions, that constitute a good calibration of the model over the range of variability exhibited in the test series.

1 INTRODUCTION

Sylgard 184¹ is a silicone elastomeric potting / encapsulation material. Throughout this report, this material is referred to as an adhesive, even though it possesses relatively little adhesive strength (which is desirable in many applications).²

¹Sylgard 184 is the brand name of a product manufactured by DowDuPont (formerly Dow Corning), a chemical product company in Michigan, USA.

²A high adhesive strength can be an undesirable property for potting materials in many applications, for example when a relatively fragile component is potted into a stiffer component, the two components have significantly different thermal expansion properties, and the assembly is subjected to large temperature changes.

A series of Sylgard debonding experiments were conducted at the University of South Carolina in August 2018 [2]. The adhesive strength of a thin layer of Sylgard material was investigated, using double cantilever beam (DCB) specimens. In these tests, the applied load and beam displacements were measured. Different tests were conducted which loaded the adhesive layer in mode-I (opening mode), mode-II (shear mode), and in a mixed mode.

This report reviews these tests and test results, and describes a mechanical model capable of simulating the debonding process. Simulations of the tests are described, and distributions are given for the model's parameters that result in simulation results that span the range of the observed test results.

2 SPECIMENS AND TESTS

Eight DCB specimens were tested in this initial test series. All DCB specimens were tested using an Instron 5568 load frame and using stereo DIC to measure displacement. Three different displacement modes were tested (pure opening mode, pure shear mode, and a 45-degree mixed mode), varying the angle in which load was applied for each mode. The tests were run at quasi-static rates (0.03mm/min and 0.003 mm/min). Two mixtures of Sylgard were used. Full details on the specimen preparation and test procedures are provided in Appendix 1.

3 ANALYSIS OF TEST RESULTS

The test results are interpreted here with the aid of the finite element simulation results. The finite element model and an analytical solution for DCB load vs. opening displacement response are described in Appendix 2.

3.1 Opening Mode Response

Using the analytical solution, values were determined for the traction-separation model parameters (peak traction, separation at peak traction, and separation at complete failure) that resulted in a good match to each DCB test. Then, these parameters were utilized in a simulation of each test, using the the finite element model of the specimen. A typical DCB response is shown in Figure 1. The displacements in this figure are exaggerated to illustrate the bending deformation. The figure shows the transverse component of stress in the beams and adhesive layer. The region in front of (to the right of) the peak stress is responding elastically. The region behind

Figure 1: The DCB specimen under a mode-I load, with displacement exaggerated by 400X to illustrate the bending of the arms and varying separation along the adhesive layer. Color in this figure represents the Y (transverse) component of stress in the beams and in the adhesive layer.

(to the left of) the peak stress is the fracture process zone, in which the adhesive is responding in its damaged state.

The measured and predicted applied force and opening displacement at the free edge of the adhesive layer are shown in Figure 2 for two of the mode-I tests. The calibrated traction-separation model is also shown, with its critical energy release rate (G_c) indicated in the plot legend.

The applied force initially increases proportionally to the opening displacement, indicating a linear elastic initial behavior. As the peak force is reached, further opening displacement is associated with an ever-decreasing applied force in a quasi-static equilibrium process, as expected from analytical solutions and the finite element model. There is considerable variability exhibited between these tests. The agreement between the measured and predicted results is good, but it is important to note that each simulation was calibrated to each test. Typically, the differences between nominally identical tests is greater than the discrepancy between the predictions and the measurements.

Two Sylgard 184 formulations, referred to by the ratio of base resin to the curing agent (90:10 and 95:5) were tested. The 90:10 formulations were not analyzed in this report because the associated test data was not available, however, Sutton [2] reported a significant difference in strength between the two formulations: the 90:10 (“group C”) tests showed a higher energy release rate, higher peak stress, and lower

Figure 2: Test and simulation results for DCB Test #1 (top) and Test #8 (bottom). The measured and simulated applied force vs. opening displacement at the free edge of the adhesive layer are shown in the bottom plot. The traction-separation model used to simulate this test is shown in the top plot, using the same abscissa as the load vs. displacement plot. The initial behavior of Test #1 is due to a “sticky” shim, as explained in [2].

separation at failure than the 95:5 tests. Other researchers [5] have reported that the ratio of the Sylgard components has a strong effect on elastic modulus. The elastic modulus is likely to correlate with adhesive strength.

The rate of separation appears to have a small influence on the measured adhesive strength. Two “Group F” tests were conducted at a separation rate 1/10 of the other tests (0.003 mm/min vs. 0.03 mm/min), and they exhibited a critical energy release rate that was slightly lower than the values determined for the corresponding higher-rate tests. One test (identified as “Group A, trial”) used a much faster separation rate (0.5 mm/s), yet it exhibited adhesive strength similar to the tests that used the 0.03 mm/min separation rate.

3.2 Shear Mode Response

The shear (mode-II) load case exhibited a linear load-displacement relationship all the way to the point of maximum load. At the moment of peak applied load, the shear displacements were much larger ($\sim 10X$) than the opening displacements in the mode-I tests. The peak applied loads were somewhat larger than the peak loads in the opening-mode tests.

The shear-mode traction-separation parameters were determined by a similar process to that described above for determining the opening-mode parameters. The traction-separation model had a significantly larger ($\sim 5X$) energy release rate than the opening-mode models because the Sylgard layer is very compliant in shear. The predicted applied force and opening displacement at the free edge of the adhesive layer is plotted in Figure 3.

It was observed in simulations of the shear-loaded DCB specimen that the shear stress and shear displacement along the length of the beam were nearly uniform. For this reason, the entire bond reached its peak shear stress at almost the same moment. At this point, the fracture process zone rapidly developed and traveled across the entire specimen, resulting in a sudden drop in load. This behavior is consistent with a traction-separation curve with a steep back-slope.

Because the shear stress and shear deflection were nearly uniform over the length of the beams, the average shear stress (computed as the applied force divided by the entire area of the adhesive layer) and average shear strain (computed as shear deflection divided by adhesive layer thickness) were used to compare to previous shear-mode tests [3]. These values, as well as their ratio (which is an estimate of the front-slope stiffness) and the general characteristics of the response, are in good agreement with the previous shear tests. For example, a similar linear response in shear stress vs. shear displacement was observed in Iosepescu shear specimens, up to the moment of peak stress.

Figure 3: Test and simulation results for DCB Test #6, showing the measured and simulated applied shear force vs. shearing displacement at the free edge of the adhesive layer.

It is noted that, due to Sylgard’s very low shear modulus, the DCB specimens are very compliant in shear, and do not behave like “normal” DCB specimens in which the shear displacement at the unloaded end can be treated as negligible. This is described in more detail in Appendix 3.

3.3 Mixed-Mode Response

Two DCB tests were conducted in a mixed mode (opening and shear), in which the load-line was inclined at an angle of 45-deg with respect to the axis of the specimen. The simulation for this load case uses a combination of the independent opening-mode and shear-mode traction-separation models. The mode mix (a term used by the analysis code to define how the opening and shear mode models are combined) was defined by normal and shear energy contributions rather than by traction components. The critical energy release rate was defined by the Benzeggagh-Kenane (BK) fracture criterion for a general mixed-mode deformation process:

$$G^c = G_n^c + (G_s^c - G_n^c) \left(\frac{G_s}{G_n + G_s} \right)^\eta \quad (1)$$

Figure 4: Test and simulation results for two DCB tests. In these tests the load line was inclined at an angle of 45 degrees with respect to the axis of the beams.

where G_n and G_s are the work done by the normal and shear tractions and their conjugate displacements, G_n^c and G_s^c are values of G_n and G_s at failure in pure mode-I and mode-II deformation, and η is treated as a parameter. The value of η was determined by comparing the load-displacement³ prediction from a family of simulations to the results of tests 4 and 5. A value of $\eta = 1.0$ provided a reasonable agreement with the measured results. The measured and simulated responses are shown in Figure 4.

4 CALIBRATION OF ADHESIVE MODEL PARAMETERS

As described previously, traction-separation model parameters were initially determined that represented the best fit to the measured force vs. displacement results of each test independently. Note that the parameters for the opening mode and shear mode traction-separation models are independent of each other. The mixed-mode response is determined by a combination of these two pure modes, as described in the previous section. Because the number of DCB tests in this test series was small, with only one or two tests conducted at each load rate and deformation mode, it was

³The displacement used for this comparison was the total separation displacement across the two beams at the free edge of the adhesive layer: $d = \sqrt{d_n^2 + d_s^2}$.

desired to seek a family of traction-separation models in the form of a multivariate distribution of model parameters that represented the range of variability exhibited by the set of tests as a whole. This was done using the following scheme:

1. A large set of candidate traction-separation model parameters (K_{nn} , σ^p , G_c) were created by drawing random samples from independent uniform distributions. The range of these distributions was chosen to significantly exceed the range that resulted in good agreement between prediction and test results - in other words, to produce a broad range of load-displacement predictions. Because the parameters were chosen in this way, it was expected that many of the parameter sets would result in poor agreement with the measured results.
2. The DCB response was computed for each candidate parameter set, using the analytical solution (because it is convenient and fast to do so). Then, a per-test error metric $e_{i,j}$ and all-test error norm were calculated for each parameter set i and test j :

$$e_{i,j} = \int_0^{x^*} (F^j(x) - F^{j,i}(x))^2 dx / x^* \quad (2)$$

$$norm_i = \sum_j e_{i,j} / N \quad (3)$$

where F^j is the force measured in test j , $F^{j,i}$ is the force predicted in the simulation of test j using parameter set i , x is the opening or shear displacement at the free edge of the potting, and x^* defines the range over which the error measure is defined. This is an integrated mean-squared error. The error norm for parameter set i is simply the sum of the per-test error metrics averaged over the N nominally-identical tests.

3. The set of all candidate traction-separation parameter sets was then culled: all parameter sets that resulted in an error metric greater than some threshold were removed from consideration.
4. The culled set of input parameter sets were then treated as a vector of samples of “good” parameter sets, from which a mean vector and covariance matrix were computed.

The culling process systematically removed parameter sets that contained combinations of the three parameters that, taken together, produced outlier load-displacement results; this results in a correlation between the remaining parameter sets. It is found that, for example, there is a negative correlation between peak traction and energy release rate: parameter sets that have a relatively large peak traction also have a relatively small energy release rate. This is expected, because a parameter set that had

Table 1: Traction-Separation Model Parameters (Mean Values)

Mode-I (opening)		
Peak normal traction	σ^p	0.45 MPa
Elastic stiffness	K_{nn}	53.8 MPa/mm
Critical energy release rate	G_c	7.9 mJ/mm ²
Mode-II (shear)		
Peak shear traction	τ^p	0.17 MPa
Elastic stiffness	K_{ss}	0.66 MPa/mm
Critical energy release rate	G_c	40.1 mJ/mm ²

high values for both of these parameters would have produced a load-displacement curve that greatly exceeded the measured behavior and would therefore have been culled.

The result of this process is a multivariate distribution of the three traction-separation model parameters. The mean values for these parameters are given in Table 1. The linear correlation between the parameters is expressed by the covariance matrix. A representative set of load-displacement curves generated from the multivariate distribution is shown in Figure 5. The parameters for simulations of other Sylgard potting applications and load cases can be treated as random samples drawn from this multivariate distribution, and can be expected to represent a range of adhesive strength that includes the range observed in the DCB test series.

5 CONCLUSION

Dual-cantilever beam tests are well suited for measuring the adhesive debonding properties of a Sylgard layer. The set of test results indicated a well-controlled manufacturing and loading processes, and gave a good indication of the range of behavior that is reasonable to expect in Sylgard potting applications. The adhesive strength observed in mode-I and mode-II loading of the double cantilever beam (DCB) specimens was in good agreement with previous LANL testing results [3, 4]. The test results have been used to estimate probabilistic model parameters for a traction-separation adhesion model, with uncertainty representing both the variability exhibited in the test series and the approximate fit of the model.

Figure 5: A family of opening-mode load-displacement curves calculated using the analytic DCB solution, with traction-separation model parameters treated as correlated random variables drawn from a multivariate distribution. Three test results (tests 1,2, and 8) are shown by black dashed lines.

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Appendix 1: DCB Specimen Preparation and Testing Details

Test Summary

Eight DCB specimens were tested at University South Carolina August 8th and 9th, 2018 by two Los Alamos engineers and two graduate students of USC. All DCB specimens were tested in tension with an Instron 5568 load frame and using stereo DIC to measure displacement. Three different modes were tested, varying the angle in which load was applied for each mode. The tests were run at quasi-static rates (0.03mm/min and 0.003 mm/min). Two mixtures of Sylgard, 90:10 and 95:5, were used.

Materials and Sylgard Preparation

Aluminum specimens were sanded with polishing paper with 600 grit, cleaned with water then acetone. An air knife was used to blow off any residue. It was not investigated on whether or not the air knife was attached to a filter of any kind.

Shims with a thickness of 0.002 inches and an estimated 0.75 inch length were placed between aluminum beams. Clear scotch tape was used to hold the beams and shims together. The Sylgard mixture was then inserted between the beams, filling from the taped underside until it overflowed on the top as Figure 6. Great care was taken in this process to prevent any bubbles from forming in the Sylgard. No bubbles were observed in any of the samples.

The samples were left to cure overnight for a minimum cure time of 20 hours. Table 2 lists the two Sylgard mixtures, degassing time and cure time. For further validation of cure time, the leftover Sylgard was left out by the samples with a stir stick in the cup. After the 20 hours of cure time the Sylgard in this cup was hard which validated that the samples were completely cured.

Table 2: Sylgard Preparation Details

Mixture	Degassing Time	Cure Time	Batch Mixed
95 : 5	26 min 5 s	20 hours	LJM2018208-7
90 : 10	21 min 9 s	20 hours	LJM2018208-8

After all samples were cured and dry, the tape was removed and the samples prepped for DIC paint. All samples were spray painted white as a base. Some samples were

speckled using the air brush and some were speckled using spray paint, as shown in Figure 7. The results of this variance in speckle method were not thoroughly investigated and both methods yielded quality DIC data with acceptable uncertainty values in the Vic-Snap program.

Specimen / Load Frame Interface

Three modes with different load paths were tested. These modes varied the angle in which load was applied to the sample and are illustrated in Figure 8.

Four pins connected the DCB to the fixture which connected to the load frame. This fixture was also aluminum and had pin holes for the various modes desired for this test. This fixture was then loaded onto the Instron 5566 load frame. These stages of the test assembly are shown in Figure 9.

The DIC setup included two USB 3.0 Pointe Grey cameras at a 22.29 stereo angle. The calibration was done with a 9x9 3 mm calibration card. The cameras were powered on for several hours prior to the test, but not capturing images. Historically this is bad practice as the camera internal components will shift giving false strain readings as they capture images for the first hour or so. However strain was not calculated for these tests therefore not having “pre-test images” captured is not a concern.

Figure 6: Specimen beams prior to (left) and after (right) Sylgard application.

Figure 7: Example of airbrushed speckle (left) and spray paint speckle (right).

Figure 8: Various modes tested.

Figure 9: DCB specimen loaded into fixture (left) and under test in the load frame (right).

Table 3: Test Conditions

Test No	Mode	Sylgard Mixture	Rate (mm/min)	Peak Load (N)
1	1	95:5	0.03	52.93
2	10	95:5	0.003	45.38
3	1	95:5	0.003	35.67
4	1/2	95:5	0.03	71.70

Test Measurements

The testing conditions are summarized in Table 3.

All failures were the debonding of the aluminum and Sylgard, seemingly at random failing on the upper or lower beam. Shims on the leading edge were removed so that the test was not impacted by any sylgard adhering to the plastic. This also introduced a crack tip starting at the center of the camera's field of view. Unfortunately the load line, where the pin holes were located, was not always in view of the camera therefore the measurement of the initial crack is difficult to determine for those specific test runs. A photograph of the specimen after failure is shown in Figure 10.

Figure 10: Two examples of the fully-debonded specimen.

Digital Image Correlation Analysis

The initial post processing of the images was done at USC and again at LANL as the original post processing information was not delivered to LANL. The post processing done by LANL was done by extracting data in three main areas: the top specimen, the lower specimen and a small box over the Sylgard itself. Six points of interest were extracted from the DIC analysis. For modes 1 and 2 no coordinate transformations were done, however for the mixed-mode loading configuration a transformation was applied. The points of interest and coordinate transformation are illustrated in Figure 11. The calculation of displacement at each of the six points was used to calculate relative displacements and used in further analysis.

Table 4 gives the subset size, step size and initial crack length for the DIC data. The first two variables are used in the post processing of the DIC. Subset size controls the area of the image that is used to track the displacement between images. This size must be large enough that there is a distinctive pattern contained in the area used for correlation. The step size controls the spacing of the points that are analyzed. For example, a step size of 2 means that a correlation will be done at every other pixel in horizontal and vertical directions. Therefore a smaller number requires a longer time for the correlation than a higher step size. The crack length is simply the difference between points A and C or B and D and is calculated after the correlation processing.

Table 5 is the initial position data collected by the DIC. Because the Vic-3D software generates an arbitrary origin in the Cartesian coordinate system, having the X,Y values of each points of interest is valuable. This data can then be used to calculate

Figure 11: Points of interest for DIC analysis (left) and coordinate transformation for the mixed-mode loading condition (right).

Table 4: DIC Image Analysis

Test No.	Subset Size	Step Size	Initial Crack Length (mm)
1	27	7	24.2856
2	27	7	20.0229
3	27	7	21.8949
4	27	7	Not enough data
5	27	7	Not enough data
6	27	7	Not enough data
7	27	7	21.2385
8	27	7	20.4384

Table 5: DIC Initial Point Locations

		A	B	C	D	E	F
1	X	31.8371	n/a	7.5514	7.5530	6.9309	7.7425
	Y	0.8546	no data	-0.0432	-3.3551	15.3879	-15.4630
2	X	33.9346	33.5075	13.9117	16.9355	13.7265	12.5564
	Y	-0.9861	-3.9531	-0.3741	-4.0005	15.4195	-16.6894
3	X	33.3235	33.4921	11.4286	11.4993	10.9989	10.7795
	Y	0.4236	-2.4749	-0.2824	-3.3345	16.2326	-15.8322
4	X	no data	no data	4.0871	3.99118	5.77468	4.3980
	Y	no data	no data	-3.7807	-0.5227	-19.2638	12.4536
5	X	no data	no data	-0.0283	0.0537	-0.5877	1.0931
	Y	no data	no data	-5.7785	-1.2086	-20.8749	8.8454
6	X	no data	no data	2.1560	5.8273	-13.9575	14.8008
	Y	no data	no data	12.5638	12.6275	12.2010	12.5027
7	X	29.7211	no data	8.4826	8.3996	8.0297	8.7651
	Y	1.12668	no data	0.7297	-2.7330	15.5898	-15.9078
8	X	29.5116	29.6860	9.0732	9.0439	8.8924	8.7972
	Y	0.8296	-2.0298	0.4906	-3.0807	15.7747	-16.1255

the absolute distance between points A and C for instance giving the initial crack length. This data long with the displacement over time data is given in the DIC Summary spreadsheet.

Appendix 2: Modeling of the Adhesive Layer

The dual cantilever beam tests were conducted with the purpose of quantitatively characterizing the adhesive strength of Sylgard potting. The adhesive debonding behavior is described by a traction-separation model, which in turn is a component of a model of the DCB specimen. The goals for the modeling effort were:

1. Identify a debonding model and modeling techniques capable of efficiently simulating the DCB tests, specifically by reproducing the measured load and opening displacements.
2. Determine a range of debonding model parameters that result in simulation predictions that span the range of DCB test results measured in the USC test series.
3. Incorporate the model identified here into other models of LANL applications of interest. This goal puts constraints on the debonding model that are not exercised in the DCB tests: a specific structural analysis code must be used, the modeling approach must permit thermal and mechanical effects to be modeled, and a broad range of load cases (such as partial debonding, followed by unloading and reloading) must be treated.

Analytic Solutions

A good approximation of the mechanical behavior of the double cantilever beam specimen is an elastic beam resting on a spatially-distributed foundation. In the adhesively-bonded DCB specimen the foundation's load-deflection response (where load is either the normal- or shear-direction force per unit area of the beam's surface) is the traction-separation behavior of the adhesive layer.

Analytic solutions have been developed that relate the applied force to the opening or shear displacement between the beams. In the case of DCB tests, in which the applied force and opening displacements are both measured, and it is desired to determine the load-deflection properties of the foundation - that is, the traction-separation behavior of the adhesive layer. A J-integral approach can be used to directly infer the form of the traction-separation relationship of the adhesive layer, with certain assumptions about the evolution of the deformations. An alternate approach is to assume, a priori, a parameterized traction-separation relationship, and to determine the values of those parameters that best reproduce the measured load-deflection.

An analytical solution to the DCB problem has been published by Skec [6], using an assumed model of the foundation behavior that consists of a bilinear load-deflection

relation. Skec's solution is based on Timoshenko beam theory, and therefore accounts for both bending and shear deformation.

Determination of Traction-Separation Model

Assuming, a priori, a particular form for the traction-separation model may appear to be a disadvantage: we would prefer that an analysis of the experimental results reveals the form of the traction-separation behavior. However, when the goal is to determine a parameter set that provides a good approximation over a range of conditions and material variability, rather than uniquely characterizing each individual test, it is advantageous to define a single, parameterized traction-separation model. In addition, using this approach is compatible with the use of a general finite element structural analysis, which permits the DCB experiment to be simulated with few restrictions.⁴

A bilinear traction-separation model has some properties that make it a reasonable approximation in many situations. It is defined by a minimal number of parameters (3): the peak traction, the separation at peak traction, and the separation at fully-damaged state.⁵ A linear front slope is consistent with a linear elastic (constant stiffness) undamaged response which is a good approximation, at least initially, for many materials. The linear front-slope also permits an evolving elastic damage behavior to simulate elastic unloading and reloading at a degraded (reduced) modulus, associated with response beyond the peak stress (elastic limit). The linear back-slope is somewhat arbitrary, but experience from previous Sylgard testing has indicated that the shape of the back slope is weakly related to the load-deflection behavior of the joint.⁶

Finite Element Model of the DCB Specimen

A simple model of the DCB specimen used in the USC testing was developed for the mode-I (opening mode), mode-II (shear mode), and mixed loading configurations. It is a plane stress model which assumes loading and response only in the plane of the beam's length and height (zero stress or deformation in the out-of-plane width

⁴For example, no restrictions are placed on the beam response, such as an assumption of linear elastic behavior or a requirement that plane sections remain plane; the specimen's boundary conditions can be modeled with fidelity; large deformation may be analyzed; etc.

⁵Equivalently, the traction-separation model can be parameterized by its front slope stiffness, peak traction, and energy release rate.

⁶The peak stress and area under the traction-separation function (which is the critical energy release rate, G_c) strongly influence the load-deflection behavior of the joint, and hence are good parameters to characterize the traction-separation model; the shape of the back-slope, for a given G_c , has been found to have a weak influence.

direction). The Sylgard layer is modeled with a single element through the thickness; this element (referred to as a “cohesive element”) must represent the behavior of the adhesive layer itself and of the two interfaces between the layer and the beams. The behavior of the cohesive elements is governed by a traction-separation model.

The simulations were conducted in displacement control: the loaded end of the beams were guided at a constant velocity, either in the opening-mode direction, the shear-mode direction, or at a 45-degree angle to the beam axis. The resulting net force (at the point of application), and total opening or shearing displacement between the two beams (at the free edge of the Sylgard adhesive layer) are the computed responses of the simulation.

The simulated response of the DCB specimen was stable during the development and initial traveling of the fracture process zone. No artificial damping was required to obtain converged static solutions. As the fracture process zone reaches the right end of the specimen, the applied load gradually falls to zero. It is noted that other modeling approaches (namely, using cohesive elements to represent the interfaces only, and using continuum (“normal”) finite elements to represent the bulk behavior of the adhesive layer) resulted in unstable behavior, especially in shear, and required artificial damping to obtain a converged solution.

Verification of Finite Element Model

The load-deflection behavior predicted by the finite element model of the DCB specimens was verified by comparing to the analytical solution mentioned previously. The agreement was excellent for the initial response (up to the peak force), but began to be influenced by the finite length of the specimen after the peak force was reached.⁷ Figure 12 illustrates the load-displacement response calculated using the analytical solution and the finite element model with three specimen lengths (1.0, 1.2, and 1.5 times the specimen length of the DCB test series). The results are nearly identical until the debonding process approaches the free (unloaded) end of the specimen.

⁷The analytical solution assumed an “infinitely long” specimen length, meaning sufficiently long that the opening displacement at the unloaded end could be assumed to be zero.

Figure 12: The load vs. opening displacement solutions, as predicted by an analytical solution (which assumes a “long” beam) and three finite element simulations, using three specimen lengths. The assumed traction-separation curve is shown in the top plot.

Appendix 3: Shear Response of DCB Specimen

Sylgard has a very low elastic shear stiffness: its initial shear modulus (G_0) has been measured in various tests at between 0.1 and 1.1 MPa, with a strong dependence on the cure characteristics and on the particular Sylgard formulation under test. These values are less than one thousandth of Sylgard’s bulk modulus (K), indicating that this material deforms nearly incompressibly. The DCB specimen had a bond-layer thickness of 0.5 mm (20 mil), which is large compared to the thickness of adhesive layers in typical bonded joints. These factors contribute to a very compliant shear response.

A consequence of the adhesive layer’s low shear stiffness is that the DCB specimens used in the shear-mode tests were not sufficiently long to behave as a “normal” DCB specimen loaded in shear: specifically, the shear deflection at the unloaded end of the specimen was not zero (as expected for a “long” specimen with a thin, stiff adhesive layer). In fact, simulations indicate that the shear stress and shear deflection were approximately uniform from over the length of the specimen. J-integral approaches (not used here) that depend on the assumption of zero relative displacement at the unloaded end of the DCB specimen would not be accurate in these tests, because the specimen is not long enough to permit neglecting the contribution to the J-integral from the unloaded-end of the specimen.⁸

To confirm and illustrate the DCB specimen length issue described above, a simulation was conducted using a much longer DCB specimen (1270 mm, 10 times longer than the DCB specimen used in the USC tests). This length is sufficient to make the shear displacement and shear stress at the unloaded end of the beam small (0.008 mm and 0.01 MPa, respectively). The length of the fracture process zone is the same as for the actual specimen, but with this long specimen the simulation predicts a stable, progressive travel of the FPZ from left to right, with a sustained, nearly constant force of approximately 400 N. Figure 13 illustrates the deformed shape of this long DCB specimen loaded in shear, and illustrates that the DCB response is primarily a bending response at the loaded end, with relatively small bending or shear at the unloaded end.

⁸An estimate of the shear-loaded DCB specimen length required to satisfy the assumption of a zero-displacement boundary condition on the unloaded end of the specimen is given in reference [1]; for the dimensions of the DCB specimen and elastic properties of Sylgard, the minimum length required for the usual J-integral evaluation is greater than a meter.

Figure 13: The deformed shape (greatly exaggerated) of a very long DCB specimen, under a pure shear load. The deformation of the beam arms is primarily bending because the applied loads and adhesive shear tractions create a bending moments about each beam's neutral axis. The shear displacement at the right (unloaded) end of the beam is close to zero. (Note: the apparent penetration at the left end of the beam is due to the exaggerated deformation.)

Appendix 4: Modeling Approach for Thermomechanical Problems

The cohesive element approach described throughout this report has proven to be accurate and efficient for modeling debonding in a constant-temperature environment. However, in applications of interest, the environment is not constant temperature, and the potting layer model is required to simulate heat transfer and thermal expansion as well as the mechanical behaviors of mixed-mode debonding and post-debonding compression and shear, with the possibility of sliding with friction. An alternate modeling treatment for the Sylgard adhesive layer has therefore been developed, in which the adhesive debonding is treated as a property of the potting-to-substrate interfaces rather than as a property of the potting layer itself. In this “cohesive contact” approach, the Sylgard potting layer itself is modeled using continuum elements and a constitutive material model that is elastic (no damage or failure is modeled). One or both of the interfaces on each side of the Sylgard layer are modeled using a contact interaction that obeys a traction-separation rule. The cohesive contact approach has some key advantages, but suffers from stability issues leading to convergence difficulties. A comparison of these two modeling approaches is given here, then a method of improving the stability is described.

Comparison of Cohesive Elements and Cohesive Contact Modeling Approaches

The cohesive element modeling approach treats the behavior of the adhesive as a property of the cohesive elements only, whereas the cohesive contact approach uses separate modeling methods to simulate the behavior of the bulk layer and the behavior of the interfaces. This difference in modeling idealization leads to differences in capabilities and performance, such as:

- Accuracy: both modeling approaches are capable of reproducing the analytical solution for the purely mechanical mixed-mode debonding of the double cantilever beam specimen.
- Stability: The cohesive element modeling approach permits a stable solution with relatively large time steps and no artificial damping required. The cohesive contact approach requires small time steps and the use of artificial damping to permit a stable response. The difference in total solution time may be significant, depending on other details of the model. The artificial damping also has the potential to give inaccurate results if the level is set too high. The stability of the two treatments is described in more detail below.
- Post-failure mechanical behavior: After the debonded (fully-damaged) state has been reached, the cohesive contact treatment permits the potting layer

to continue to carry compressive stress and shear stress, via friction at the potting-to-adherend interfaces. The cohesive element treatment permits the layer to carry compression, but no shear, because in the fully-damaged state the elements have zero cohesive strength. Thus, no frictional shear strength is possible with cohesive elements.

- **Thermal expansion:** the continuum elements used in the cohesive contact treatment use a general-purpose material model capable of simulating thermal expansion. The cohesive elements do not simulate thermal expansion (this is a limitation of the analysis code). In thin-layer applications, this is a minor effect (even taking into account the unusually high coefficient of thermal expansion of Sylgard).
- **Heat Conduction:** The cohesive contact approach allows heat conduction through the continuum elements of the adhesive layer, and heat conduction across the layer’s interfaces via a standard “gap conduction” contact model. The cohesive elements do not support heat conduction. However, workable solutions have been developed to model the heat conduction via “parallel” continuum finite elements that have zero stiffness but physically-realistic heat transfer properties. Alternately, heat conduction can be simulated directly between the adherend surfaces (“jumping over” the Sylgard layer) with a gap conductance model.

The underlying reason for the difficult solution convergence with the cohesive contact modeling approach is related to the localized softening of the bond’s stiffness during the evolution of damage. In the cohesive contact approach, it is the interface that softens during debonding, while the layer stiffness remains constant. This situation can be simplified as two springs in series, with the stiffer spring undergoing degradation of its stiffness, as illustrated in Figure 14. If the non-damaging spring is sufficiently compliant, the system does not possess a continuous path of equilibrium states as its total extension is increased (as in a displacement controlled test). In modeling the potting joint using cohesive contact, the interface is stiffer than the continuum layer, especially in shear, as Sylgard has a very low shear modulus and the thickness of the layer is significant. An analysis code cannot solve for the displacements in this mechanical system without introducing damping or treating the problem dynamically. In the cohesive element approach, the layer softens during debonding, and the interfaces remain unchanged. This is analogous to a single softening spring, for which there is a continuous path of equilibrium states as this spring is extended.

Potting Layer “Shim” Modeling Approach

A candidate modeling approach that avoids the stability issues described above has been termed the potting layer “shim” treatment. It is a variant of the cohesive

Figure 14: Two springs in series: a linear, non-failing spring k_1 and a nonlinear spring k_2 . The load-deflection behavior of each spring is shown in the upper-right plot. The load-deflection behavior of the system is shown in the lower-right plot, for two values of k_1 . When k_1 is sufficiently compliant (relative to k_2), there is no continuous path of equilibrium states, assuming a monotonically-increasing x_2 .

contact approach: the potting layer is modeled using continuum elements and the adhesive debonding is treated as a property of the interfaces. However, the mechanical behavior of the layer is artificially modified: its shear stiffness (defined by its initial shear modulus, G_0), is increased by a large factor (100X), while its through-thickness stiffness (defined by G_0 and its bulk modulus, K) is held constant. This permits the actual shear compliance to be modeled as a property of the interface, rather than of the layer.

This modeling approach is stable because the progressive elastic damage reduces the stiffness of the interface, which is the weaker (less-stiff) element of series-combination of the interface and layer. This results in a locally-stable softening evolution. The fact that all elastic compliance and strain energy is modeled in the interface (rather than split between the interface and the layer) permits an energy-based mixed-mode damage evolution criterion, which was found to model the DCB experiments well. Finally, the artificially-augmented shear stiffness of the layer prevents a type of non-physical deformation that arises when the layer is modeled with a single continuum element through the thickness. A mesh using a single element through the thickness is far too coarse to accurately represent the deformation of the layer in the debonding region, but because the elastic compliance is treated as a property of the interface rather than as a product of the layer's mesh and material model, the desired behavior of the system is achieved despite the coarse mesh used for the layer.

This modeling approach has been carefully evaluated by comparing it to the cohesive element modeling approach, using the double cantilever beam tests and also an example problem consisting of potted double hemispherical shells [4]. Both temperature-

driven thermomechanical load cases and purely mechanical load cases were considered. The shim modeling approach gives simulation results that are essentially identical to the cohesive element approach, and also gives nearly identical solution efficiency (as judged by the number of time steps required to solve each load case).