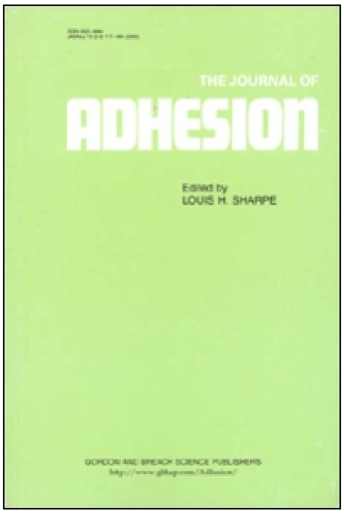

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Investigating the Thin-Film Versus Bulk Material Properties of Structural Adhesives

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Investigating the Thin-Film Versus Bulk Material Properties of Structural Adhesives

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A combined experimental and computational investigation was performed to determine whether the material properties of structural adhesives differ between their thin-film "in-situ" and bulk forms. Shear testing focused on the use of the V-notched Iosipescu shear specimen whereas tensile testing focused on adhesively bonded butt-joint specimens as well as bulk adhesive bar specimens. The apparent shear strength was found to be independent of bondline thickness. Further, shear strengths obtained from bulk adhesive testing were comparable with those from in-situ testing. Results from butt-tensile testing and analysis suggest that the apparent variation in tensile strength as a function of bondline thickness is a result of variations in the adhesive stress state, rather than the actual tensile strength of the adhesive. These results suggest that the adhesive properties obtained from bulk adhesive specimens are valid for use in structural analysis of in-situ thin-film adhesives.

Keywords: Bulk adhesive properties; In-situ properties; Mechanical properties; Shear testing; Structural adhesive; Tensile testing; Test methods; Thin-film properties

INTRODUCTION

Currently, there appears to be considerable confusion and a lack of consensus on whether mechanical properties obtained from the testing of bulk adhesive specimens may be used in the design and analysis

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of thin-film adhesive joints. At the source of this confusion is the question of whether the mechanical properties of an adhesive are different in a relatively thin bondline, or "*in-situ*", versus in bulk form. Certain adhesive test methods, such as the lap joint tests in ASTM D 1002 [1] and ASTM D 3165 [2], utilize the adhesive in its thin-film or *in-situ* form. However, these lap joint tests are known to produce nonuniform states of stress in the adhesive bondline. Thus, these test methods do not provide a simple or straightforward measure of the stiffness or strength properties of the adhesive [3,4]. The thick adherend lap joint test, ASTM D 5656 [5], is believed to produce less variability in the shear stress distribution and lower peel stresses in the adhesive [4]. However, lap joints with "thick" adherends, as in ASTM D 5656, have been reported to produce nonuniform shear stress distributions for some adhesive thicknesses and stiffnesses [6].

Another approach to determine the mechanical properties of an adhesive is through "bulk" adhesive testing, where an entire specimen is cast or machined from the adhesive material. Although currently no ASTM standard tests exist for bulk adhesive testing, many of the standards included in ASTM Volume 8 (Sections 1–4) for plastics or Volume 9 (Sections 1 and 2) for rubbers may be adapted to test the properties of bulk adhesives. Tensile testing of bulk adhesives is relatively straightforward and may be performed using either cast or machined tensile specimens. Shear strength and shear modulus determinations of the bulk adhesive may be accomplished using several test methods, including solid rod torsion testing, the V-notched Iosipescu shear test method, ASTM D 5379 [7], or the recently developed V-notched rail shear test method, ASTM D 7078 [8,9].

Although hundreds if not thousands of adhesives have been characterized in thin-film or *in-situ* form and many test laboratories and researchers have performed bulk adhesive testing, there have been surprisingly few investigations that have addressed the comparison of thin-film versus bulk material properties of structural adhesives. A review of the open literature revealed that among the limited studies that have been published, there is considerable confusion and a lack of consensus on whether mechanical properties obtained from the testing of bulk adhesive specimens may be used in the design and analysis of thin-film adhesive joints. Dolev and Ishai [10] conducted torsion tests on bulk and *in-situ* adhesive specimens to compare mechanical properties under different states of stress. Good correlation between *in-situ* and bulk shear yield strength and elastic modulus was obtained. The authors concluded that elastic and strength properties of an *in-situ* adhesive may be determined by bulk adhesive testing. In contrast, Chai [11] used the "napkin-ring" shear test to show that the ultimate shear strain in a thin bondline was more than 30 times as large as the corresponding bulk material property due to the supposed enhancement of mechanical properties when a material is stressed while under tight spatial constraint. Peretz [12] concluded that the *in-situ* adhesive shear modulus increased with increasing adhesive thickness up to the bulk material's shear modulus. The shear strengths obtained from thin adhesive layers were similar to those obtained from bulk testing. Lilleheden [13] used Moiré interferometry to perform a detailed experimental investigation of modulus variations in adhesives for differing adhesive thicknesses using a modified lap adherend specimen and found no difference in the measured moduli of the adhesive between the thin-film and bulk forms. Tomblin *et al.* [14] investigated the effect of bondline thickness using three test methods: ASTM D 1002, D 3165, and D 5656. Bondline thicknesses ranging from 0.25 to 4.1 mm were investigated using three paste adhesives. Regardless of bondline thickness, the thin-adherend tests (ASTM D 1002 and D 3165) produced lower apparent shear strengths than the thick adherend test (ASTM D 5656). Results from the thick adherend test showed a reduction in the apparent shear strength with increasing bondline thickness for all three adhesives tested. The shear modulus was also reported to change as the bondline thickness increased using the ASTM D 5656 test.

In summary, a review of the open literature reveals that currently there is no clear consensus on the equivalence of thin-film versus bulk adhesive testing. One explanation that has been offered for the existence of differences in mechanical properties of in-situ versus bulk adhesive is the presence of a diffuse region or "interphase" at the boundary between the adhesive and adherend [15,16]. Others, however, have attributed differences in mechanical properties to factors such as variability in adhesive casting and curing conditions, lack of a well-defined state of stress, and inadequate methods of strain measurement [12]. Clearly, a complex state of stress is produced by the geometric discontinuities in many *in-situ* test configurations and by the drastically different material properties of the adhesive and adherends. Thus, it is not clear whether differences in measured properties are due to material-related differences or test/measurement-related differences. The goal of the present investigation was to investigate further whether the mechanical properties of structural adhesives differ when in thin-film (*in-situ*) versus bulk forms. As a result, this investigation addressed whether bulk adhesive properties are suitable for use in the design and analysis of adhesively bonded structures. A combined experimental and computational approach was employed to evaluate the thin-film versus bulk mechanical properties of structural adhesives. Both shear and tensile properties were evaluated, with emphasis on the shear response.

TEST SPECIMEN ANALYSIS

The initial focus of this investigation was the stress distributions produced in the specimen geometries to be used for adhesive testing. Extensive finite element analyses were conducted to determine the effect of specimen geometry and bondline thickness on the stress state in the adhesive bond. All finite element modeling was performed with the ANSYS software package [17].

Shear Specimen Analysis

The V-notched beam "Iosipescu" test, ASTM D 5379 [7], was selected to investigate the shear response of adhesives. For thin-film adhesive testing, the standard Iosipescu specimen was modified by cutting the specimen between the notches and adhesively bonding the two halves back together in a manner that retains the initial geometry as shown in Fig. 1. Previous studies, including those by Wycherley *et al.* [18], Grabovac and Morris [19], and Ding *et al.* [20] have shown that this specimen configuration induces a state of relatively uniform shear stress in the adhesive bondline. For bulk adhesive testing, an Iosipescu shear specimen made entirely from the adhesive was used.

The overall dimensions of the V-notched Iosipescu specimen, 76 × 19 mm, were maintained at their standard values from ASTM D 5379 [7]. Several geometric notch variables were analyzed, including the notch shape (V-notch versus U-notch), notch depth, and notch angle. To investigate the variation in stress state with adhesive bondline thickness, three bondline thicknesses were analyzed: 0.25, 1.3, and 2.5 mm. In addition, a bulk adhesive specimen was analyzed for each notch geometry investigated. Finite element modeling was

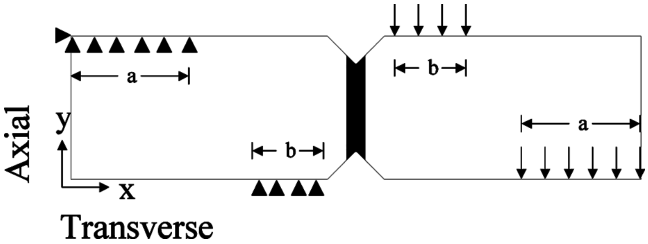


FIGURE 1 Adhesively bonded Iosipescu shear specimen.

performed using a two-dimensional plane stress approximation. Boundary conditions for the finite element model consisted of a vertical displacement applied to one-half of the specimen while the other half was constrained as shown in Fig. 1. The contact areas between the fixture and the specimen (lengths "a" and "b" in Fig. 1) were determined such that both tensile σ_y stresses and penetrations (overlapping y-displacements along the contact surfaces) were prevented. Representative elastic properties were used for both the aluminum (6061-T6) adherends ($E = 70.3$ GPa, $\nu = 0.33$) and the adhesive ($E = 4.2$ GPa, $\nu = 0.37$). Details of the finite element modeling are provided in reference [21].

For the adhesively bonded Iosipescu shear specimen, the most desirable stress state was produced with a V-notch angle of 120° while maintaining the same 3.8-mm notch depth of the original ASTM D 5379 specimen geometry. Figure 2 shows nondimensionalized shear stress contour plots within the adhesive for the three bondline thicknesses investigated using the 120° notch angle. A shear stress contour plot is also shown for the central region of the bulk adhesive specimen with a 90° notch angle, the optimal notch configuration for use with the isotropic adhesive. All stress contours are normalized with respect to the average shear stress between the notches. In addition, Fig. 3 compares the shear stress distributions between the notches for the four adhesive configurations shown in Fig. 2. All four adhesive configurations are shown to produce a relatively uniform distribution of shear stress, within 5% of the average shear stress, in the central adhesive test section. Near the notch tips, stress concentrations are produced in the two adhesively bonded specimens with the greater adhesive thicknesses (1.3 and 2.5 mm). However, the peak shear stress in both cases is less than 7% greater than the average shear stress. Further, these results indicate that the magnitude of the peak shear stress in the bulk adhesive specimen is approximately equal to that of the intermediate bondline thickness specimen.

The presence of in-plane normal stresses within the central adhesive test section was also investigated for all four adhesive configurations. The x-direction, or "transverse" normal stresses, σ_x, were found to be negligible throughout most of the central region for all four adhesive configurations. The y-direction, or "axial" normal stresses, σ_y, were also negligible in the center region for the three bondline thicknesses. However, the axial normal stress, $\sigma_{y,}$ reached values of 25% of the average shear stress for the bulk adhesive specimen, indicating a somewhat significant compressive stress in the axial direction along the specimen centerline. In an effort to assess the significance of the in-plane normal stresses, the von Mises stress, used for predicting

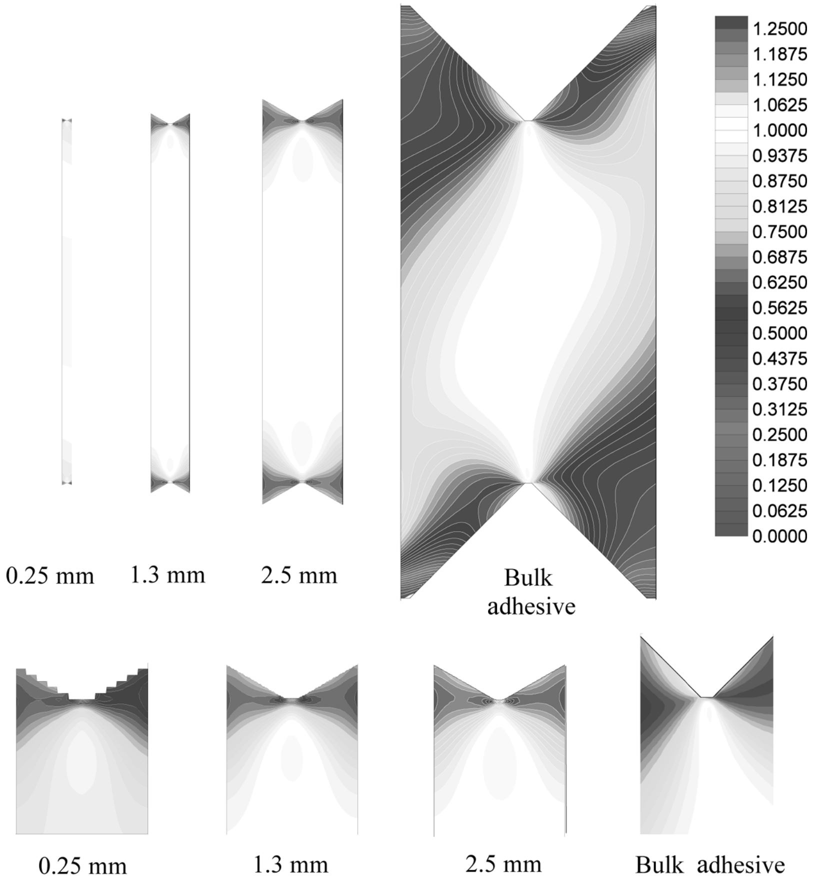


FIGURE 2 Normalized shear stress distributions in full adhesive bond (upper) and in vicinity of notch tip (lower) for three bondline thicknesses and bulk adhesive specimen.

the yielding of ductile materials, was computed in the region of the adhesive. Under conditions of plane stress, the von Mises stress, σ_e, is related to the shear and normal stress components by the relation

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_x - \sigma_y\right)^2 + \sigma_x^2 + \sigma_y^2 + 6\tau_{xy}^2}. \tag{1}$$

For the case of pure shear ($\sigma_x = \sigma_y = 0$), the equation reduces to

$$\sigma_e = \sqrt{3}\tau_{xy}, \tag{2}$$

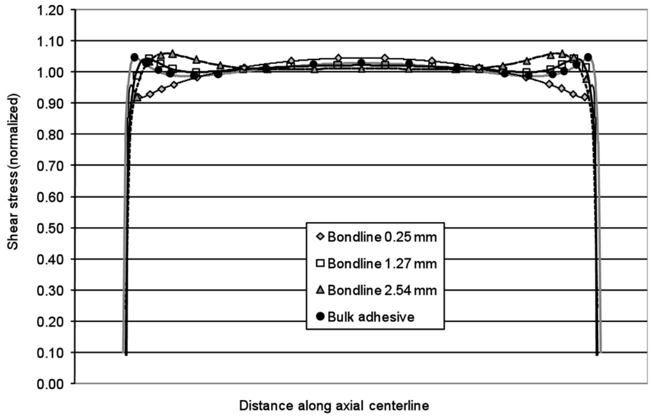


FIGURE 3 Normalized shear stress distribution between specimen notches for bonded Iosipescu specimens with 120° notch angle and bulk adhesive Iosipescu specimens with 90° notch angle.

And, thus, at the optimum stress state of uniform shear stress and zero normal stresses, the von Mises stress will differ from the shear stress by a factor of $\sqrt{3}$. Therefore, the von Mises stresses were normalized by dividing by $\sqrt{3}$ times the average shear stress along the centerline of the adhesive test section. For all four adhesive configurations, maximum value of the normalized von Mises stress within the adhesive was found to be between 1.04 and 1.06. These values were found to be comparable with the normalized shear stress values obtained, which were less than 7% greater than the average shear stress in all four cases.

In summary, a favorable state of stress is produced in the central adhesive test section for all three adhesive bondline thicknesses as well as for the bulk adhesive specimen considered. As a result, the state of stress is not expected to produce any significant differences in the apparent shear strength for the four shear specimen configurations considered. These results suggest that the apparent shear strength obtained from bulk adhesive testing should be comparable with that obtained in the bonded specimens, regardless of adhesive thickness.

Tensile Specimen Analysis

In addition to shear testing, suitable tensile test specimen configurations were desired to investigate whether the material properties of structural adhesives differ between their thin-film and bulk forms under tensile loading. For thin-film adhesive tensile testing, adhesively bonded butt-tensile testing was selected. The butt tensile specimen geometry selected, based on ASTM D 2094 [22], had a square cross-section measuring 12.7 mm on a side (Fig. 4). To investigate the effect of bondline thickness on the stress state in the adhesive, the same three bondline thicknesses were analyzed as for shear testing: 0.25, 1.3, and 2.5 mm. For bulk adhesive testing, a dogbone-shaped tensile specimen was used. Since the geometry of such dogbone-shaped specimens is designed to minimize stress concentrations, no analyses were performed on the bulk adhesive tensile test.

Three-dimensional finite element modeling was performed to investigate the effect of bondline thickness on the stress state in the butt-tensile specimen. Due to symmetry of the rectangular specimen, the required modeled region was only one-eighth of the volume of the full specimen indicated in Fig. 4. The material properties used for both aluminum and adhesive were the same as those used in the analyses of the shear specimens. A uniform pressure was applied to the end of the adherend in the axial direction.

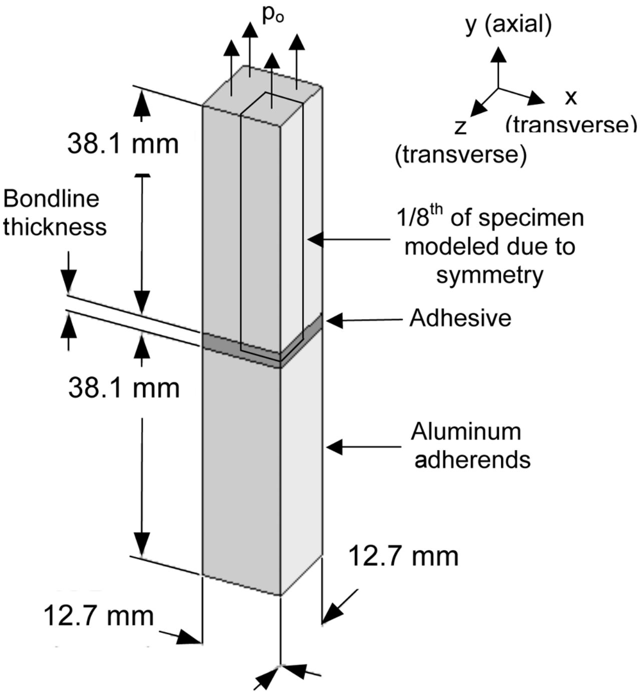
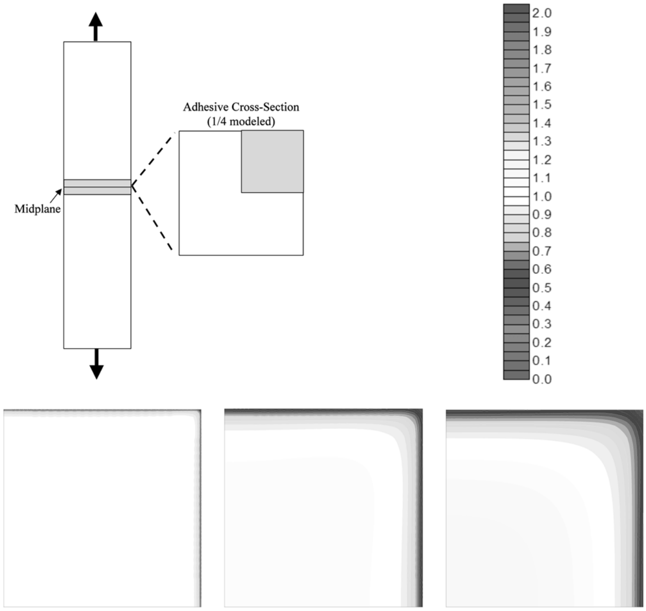


FIGURE 4 Geometry of adhesively bonded butt-tensile specimen.

Figure 5 shows the axial and von Mises stress distributions produced at the central plane in the adhesive bondline for the three bondline thicknesses investigated. The stresses are shown normalized with respect to the average axial tensile stress. The axial normal stress distribution in the thin 0.25-mm bondline is shown to be relatively uniform except around the specimen edges where the stress drops to about 80% of the average value. As the bondline thickness increases, however, the stress state becomes less uniform as the edge nonuniformity (with lower-than-average stress values) extends further into the adhesive. As a result, the axial stresses at the center of the bondline



0.25 mm 1.3 mm 2.5 mm

(a) Axial normal stress

0.25 mm 1.3 mm 2.5 mm

(b) von Mises stress

FIGURE 5 Stress distribution in butt-tensile adhesive bondlines for three bondline thicknesses.

become larger than the average axial stress. These central axial stresses exceed the average axial stress by approximately 10 and 20% for the intermediate (1.3-mm) and thick (2.5-mm) bondlines, respectively. Similarly, the von Mises stress distributions (Fig. 5b) become less uniform as the bondline thickness increases. However, the highest values of von Mises stress occur near the outer perimeter of the adhesive bond. These increased values of von Mises stress are produced by shear stresses in these locations. The magnitude of the edge shear stresses increases as the bondline thickness increases. Significant transverse normal stresses are also produced within the adhesive due to the mismatch in transverse strains of the adhesive and neighboring aluminum adherends. These tensile stresses act to reduce the value of the von Mises stress, resulting in lower values of von Mises stress than the average axial tensile stress.

In summary, finite element results show that the uniformity of the stress state in the adhesive decreases with increasing bondline adhesive thickness. These results suggest that for a thin adhesive bondline, the apparent adhesive tensile strength obtained using the butt tensile test would be expected to be similar to the bulk adhesive tensile strength. However, lower apparent tensile strengths would be expected using increasing bondline thicknesses. It is noted that these same trends are predicted for adhesives with different moduli from those used in these analyses ($E = 4.2\,\text{GPa}$); however, the variability in stresses would differ with changing adhesive modulus.

MECHANICAL TESTING METHODOLOGY

Shear and tensile testing were performed on bulk adhesive, as well as on adhesively bonded specimens with the same three adhesive bondline thicknesses investigated computationally: 0.25, 1.3, and 2.5 mm. The primary focus of these tests was to determine how the apparent shear and tensile strengths of the adhesives varied with bondline thickness and between thin-film and bulk adhesive forms. The primary adhesive used in all testing was Loctite® EA 9394 (Henkel Corp., Bay Point, CA, UAS), selected due to the extensive nature of past material characterization. Two additional adhesives were used for shear testing: Loctite® EA 9360 and Loctite EA 9392 (Henkel Corp.). All three adhesives are two-part epoxy systems consisting of the resin and hardener. The adhesives were cured at room temperature to avoid the formation of thermally induced stresses due to differences in the coefficient of thermal expansion between the adhesive and the aluminum adherends.

Bulk Adhesive Testing

All three adhesives were tested in bulk form for comparison with the *in-situ* properties. To mix the large quantities of adhesive necessary for the bulk adhesive specimens without introducing air bubbles or voids, the two adhesive components were degassed during mixing. Degassing was accomplished by mixing the two components with a motorized stirrer inside a glass bell-jar that was under vacuum. After the adhesive was mixed and degassed, it was transferred into aluminum molds and cast into square adhesive sheets approximately 5-mm thick. The adhesive sheets were cured at room temperature for a minimum of 7 days and subsequently machined into shear and tensile specimens. The bulk adhesive Iosipescu shear specimens were fabricated using a 90° notch angle, determined from finite element analysis to be optimal for isotropic adhesives. For bulk adhesive tensile testing, a tensile "dogbone" specimen was used. Since no standardized test methods exist for the tensile testing of bulk adhesives, the selected specimen geometry shown in Fig. 6 was based on geometric specifications in ASTM D 638 [23] for tensile properties of plastics.

In-Situ Shear Testing

The adhesively bonded Iosipescu shear specimens were comprised of aluminum adherends bonded together between the notches to form a complete Iosipescu specimen as shown in Fig. 7. Based on the results of finite element analysis, a notch angle of 120° was used. The pertinent dimensions that remained constant regardless of bond thickness were the overall specimen height of 19 mm and the notch depth ratio (NDR) of 0.20. The aluminum adherends were computed numerically controlled (CNC) machined from a 94.8-mm thick aluminum plate.

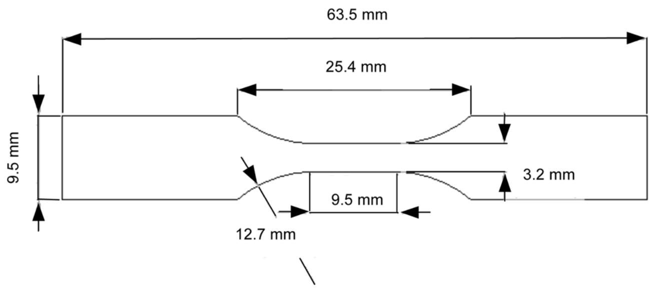


FIGURE 6 Bulk adhesive tensile specimen geometry.

FIGURE 7 Adhesively bonded Iosipescu specimens with three adhesive thicknesses.

Prior to adhesive bonding, all aluminum adherends were anodized with phosphoric acid according to ASTM D 3933 [23]. After the aluminum adherends were anodized, they were adhesively bonded using one of the three adhesives described previously. A bonding fixture was constructed to assist in producing the desired bondline thickness [21]. The adhesive was cured for at least 7 days at room temperature. After cure, the specimens were removed from the fixture and excess adhesive was removed from the specimens by sauding with medium-grit saud paper.

In-Situ Tensile Testing

In-situ butt-tensile specimens were fabricated according to ASTM D 2094 [22]. The adherends were cut from 12.7-mm square aluminum bar stock to a length of 38 mm. A through-hole of 4.76-mm diameter was drilled in each adherend for loading purposes. The aluminum adherends were anodized using the same procedure followed for the bonded Iosipescu specimens. Only the primary adhesive, Loctite EA

FIGURE 8 Butt-tensile specimens with three adhesive bondline thicknesses.

9394, was used for the butt-tensile tests. The final specimens with the three different adhesive bondline thicknesses (0.25, 1.3, and 2.5 mm) are shown in Fig. 8.

Prior to testing the adhesively bonded Iosipescu shear and butt-tensile specimens, the thicknesses of the adhesive bondlines were carefully measured in each specimen using digital calipers. Although the bondline thicknesses of the butt-tensile specimens could be controlled to within a 10–15% coefficient of variation, greater variability was found in the adhesively bonded Iosipescu shear specimens. Thus, apparent strengths from the bonded shear and tensile specimens are presented versus the actual bondline thickness measured in each specimen.

All mechanical testing was performed using a computer-controlled Instron 4303 load-frame (Fugtrou Norwood, MA, USA) equipped with a 25kN load-cell. Testing was performed at room temperature ambient conditions under a constant crosshead displacement rate of 1.3 mm/min.

EXPERIMENTAL RESULTS

Effect of Adhesive Bondline Thickness on Apparent Shear Strength

Both bulk adhesive shear testing and thin bondline shear testing were performed in an attempt to determine the effect of adhesive bondline thickness on shear strength. For the primary adhesive, EA 9394, a total of nine specimens of each bondline thickness were tested. For the other two adhesives, EA 9392 and EA 9360, six specimens with the thin bondline configuration and seven specimens for each of the intermediate and thick bondline configurations were tested. From each test performed, the apparent shear strength was obtained by dividing the maximum applied load by the specimen cross-sectional area in the adhesive between the notches.

The apparent shear strengths obtained from the three adhesives are summarized in Table 1. For each adhesive tested, the average apparent shear strength and coefficient of variation (CoV) are listed for each bondline thickness as well as that obtained from bulk adhesive testing. Note that the actual average bondline thickness is listed for each condition, as well as the CoV of the bondline measurements within the group of specimens. In addition, the apparent shear strengths obtained from each specimen are plotted as a function of bondline thickness in Figs. 9–11 for the EA 9394, EA 9392, and EA 9360 adhesives, respectively. For all three adhesives, the general trend observed was a slight decrease in the apparent shear strength as the bondline thickness increased, although these changes were not statistically significant when examined using the t-test. For comparison, the apparent shear strength data from the bulk adhesive specimens is also included in the plots and gives very similar results within the scatter of the data. Note that these findings are in agreement with results obtained from finite element analysis, which showed that the degree of uniformity in shear stress within the adhesive as well as the peak value of both shear stress and von Mises stress were comparable in all four adhesive configurations.

TABLE 1 Summary of Results from Iosipescu Shear Tests

Loctite EA 9394		Loctite EA 9392		Loctite EA 9360	
Adhesive thickness, mm Ave. (CoV)	Apparent shear strength, MPa Ave. (CoV)	Adhesive thickness, mm Ave. (CoV)	Apparent shear strength, MPa Ave. (CoV)	Adhesive thickness, mm Ave. (CoV)	Apparent shear strength, MPa Ave. (CoV)
0.17 (69.4%)	43.8 (5.6%)	0.23 (24.8%)	34.2 (4.7%)	0.28 (58.0%)	33.2 (8.2%)
1.13 (14.2%)	43.6 (4.6%)	1.26 (8.9%)	33.6 (4.6%)	1.22 (11.0%)	30.5 (2.0%)
2.49 (3.6%)	41.2 (5.9%)	2.50 (3.6%)	32.6 (4.4%)	2.52 (3.4%)	29.3 (3.7%)
Bulk adhesive	41.4 (3.1%)	Bulk adhesive	34.3 (2.0%)	Bulk adhesive	30.4 (7.8%)

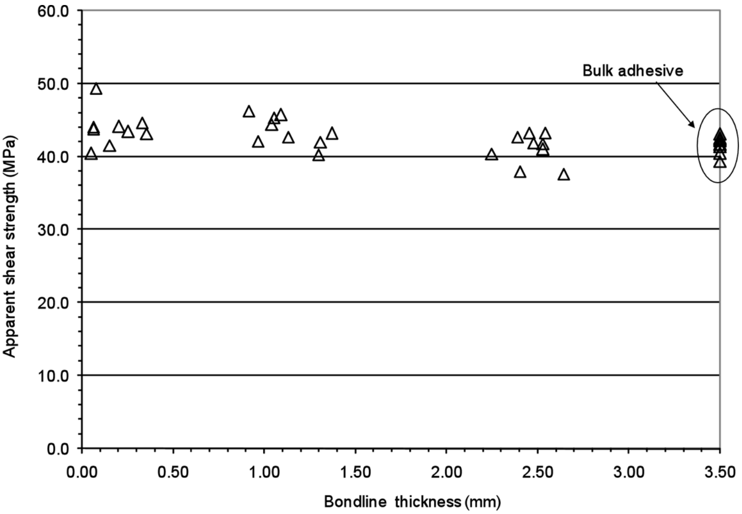


FIGURE 9 Apparent shear strength versus bondline thickness for EA 9394 adhesive.

Crack initiation in the bulk Iosipescu specimens for all three adhesives was very similar. For each adhesive, failure initiated near the notch tip along the notch flank, occurring asymmetrically in both the top and bottom notches. The failure then propagated

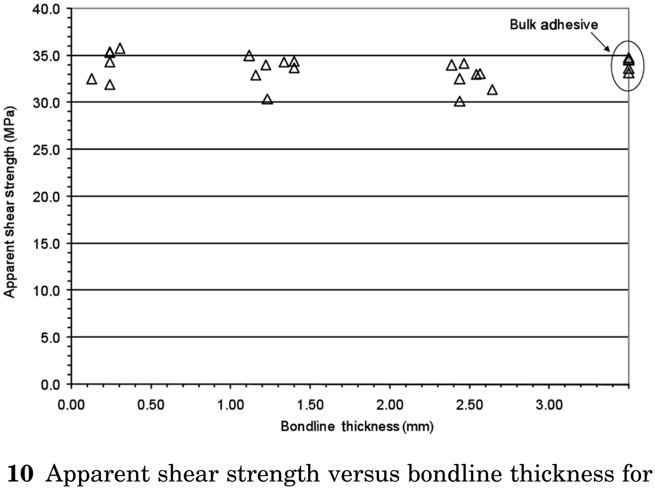


FIGURE 10 Apparent shear strength versus bondline thickness for EA 9392 adhesive.

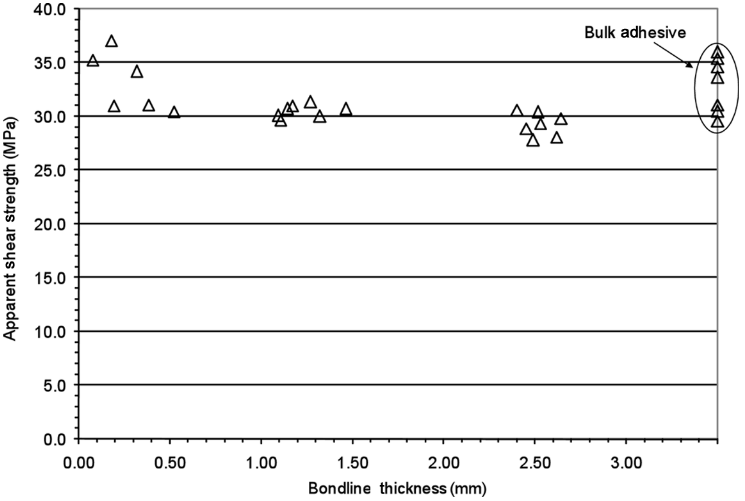


FIGURE 11 Apparent shear strength versus bondline thickness for EA 9360 adhesive.

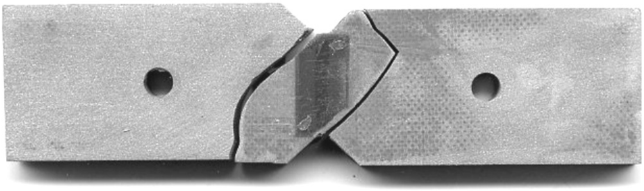
perpendicular to the notch flank. For the EA 9394 and EA 9392 adhesives, failure resulted in specimen fracture into three pieces. For the EA 9360 adhesive, which was much more ductile, cracks initiated in the same locations as the other adhesives but the specimens did not fracture and continued to deform until the fixture bottomed out. Characteristic specimen failures are shown in Fig. 12.

Effect of Adhesive Bondline Thickness on Apparent Tensile Strength

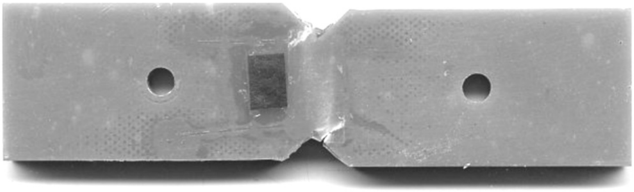
Both bulk adhesive tensile testing and thin bondline tensile testing were performed using the primary adhesive, EA 9394, to determine the effect of adhesive bondline thickness on tensile strength. A total of six tensile specimens were tested for each adhesive thickness and for the bulk adhesive tests. From each test performed, the apparent tensile strength was obtained by dividing the maximum applied load by the specimen's cross-sectional area in the adhesive.

Table 2 summarizes the results for the adhesive tensile tests using the EA 9394 adhesive. For each bondline thickness as well as the bulk adhesive specimens, the average apparent tensile strength and coefficient of variation (CoV) is listed. In addition, the apparent tensile strengths obtained from each specimen are plotted as a function of bondline thickness in Fig. 13. These results show that as the bondline

EA 9394



EA 9392



EA 9360

FIGURE 12 Characteristic failures of bulk Iosipescu specimens for all three adhesives.

thickness increases, the apparent tensile strength decreases. This finding is in agreement with results obtained from the butt-tensile finite element analysis, which showed the tensile stresses across the bondline becoming less uniform with increasing bondline thickness.

TABLE 2 Summary of Results From Tensile Tests

Loctite EA 9394	
Adhesive thickness, mm Ave. (CoV)	Apparent tensile strength, MPa Ave. (CoV)
0.23 (15.2%)	64.8 (7.8%)
1.25 (15.4%)	51.6 (13.3%)
2.50 (10.0%)	44.4 (13.9%)
Bulk adhesive	54.6 (3.7%)

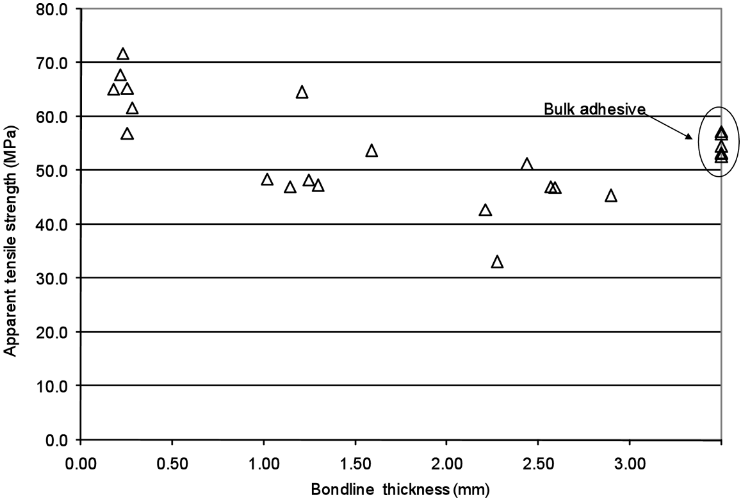


FIGURE 13 Apparent tensile strength versus bondline thickness for EA 9394 adhesive.

Therefore, the experimentally observed change in apparent tensile stress can be explained by the variations in stress distribution throughout the adhesive bondline. Figure 13 also shows that the

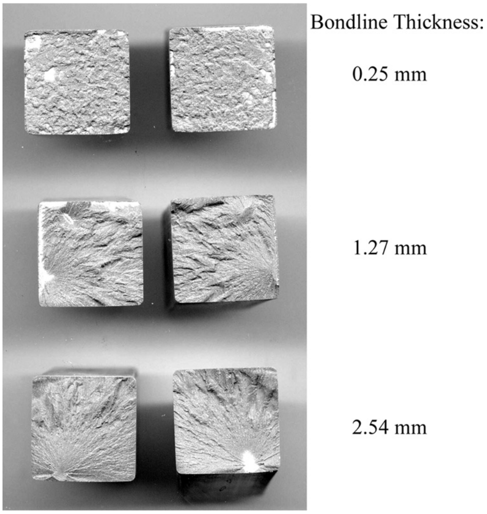


FIGURE 14 Characteristic failures of butt-tensile specimens.

tensile strength values of the bulk adhesive specimens are between that of the thin and intermediate bondline thicknesses.

Failures of the bulk adhesive tensile specimens occurred within the central gage section and on a plane perpendicular to the applied load. Failures of butt-tensile specimens were relatively consistent, and were predominantly cohesive failures as shown by the characteristic failures of each bondline thickness in Fig. 14.

SUMMARY AND CONCLUSIONS

Finite element analysis and mechanical testing were used to investigate whether the mechanical properties of structural adhesives differ between their thin-film *in-situ* and bulk forms. Results from *in-situ* shear testing showed that the apparent shear strength was independent of bondline thickness. Finite element analysis results predict a slight increase in the shear stress concentration as the adhesive bondline thickness increased. These predictions do not conflict with the experimental results, however, since such small differences experimentally would not be statistically meaningful. In addition, shear strengths obtained from bulk adhesive testing were comparable wihth shear strengths obtained from *in-situ* testing. This result was expected, since the shear stress concentrations predicted in the bulk adhesive shear specimens were approximately equal in magnitude to those from the intermediate-thickness bondline specimens. Combined, these results suggest that the shear strength of the adhesives investigated do not differ when tested in their thin-film *in-situ* and bulk forms. In addition, these results show that the Iosipescu shear test configuration is well suited for both *in-situ* and bulk adhesive shear testing.

Results of butt-tensile testing showed that as the bondline thickness increased, the apparent tensile strength decreased. This finding was in agreement with results obtained from finite element analysis, which showed the distribution of tensile stress throughout the bondline becoming less uniform with greater bondline thickness. Therefore, the experimentally obtained decrease in apparent tensile stress appears to be produced by variations in stress distribution throughout the adhesive bondline. These results suggest that the apparent variation in tensile strength as a function of bondline thickness is a result of variations in the adhesive stress state, not variations in the tensile strength of the adhesive.

Overall, the results of this investigation suggest that the observed differences in apparent shear and tensile strengths of structural adhesives between their thin-film *in-situ* and bulk forms are due to differences in the stress state within the specimen configurations and not material related differences. Further, results obtained from this investigation suggest that mechanical properties of adhesives determined from the testing of bulk adhesive specimens are suitable for use in the design and analysis of adhesively bonded structures.

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