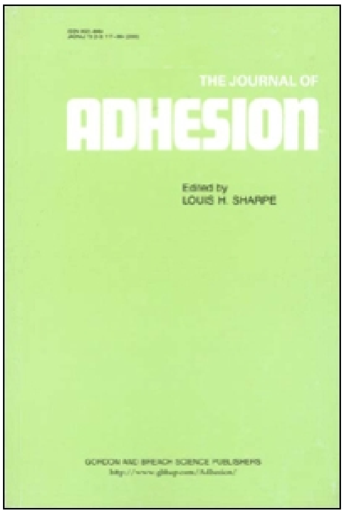

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Cone-and-Plate Shear Stress Adhesive Test

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A test geometry is described which will produce a state of essentially pure constant shear stress in an adhesive bond. The adherends are fabricated from two cylindrical elements, one with a convex conical end section and the other with a flat plate end section. The axes of these two cylinders are aligned and the two end sections are bonded together with the test adhesive. The adhesive test volume is a disk with conical indentation. An analysis of the state of stress in the adhesive, with torsional loading of the adherends, shows that a single component of shear stress is present and this shear stress is essentially constant throughout the adhesive volume for small values of the cone angular opening. The advantages of a constant shear stress adhesive test are many and one of the most significant is the ability to accurately measure in-situ material properties. Preliminary test results are reported.

KEY WORDS Adhesive test method; cone-and-plate shear test; constant shear stress test; in-situ adhesive properties; mechanical properties; torsional test.

INTRODUCTION

Many tests have been devised to evaluate the effectiveness of adhesive structural bonds. These tests have been motivated by the need to measure *in-situ* adhesive material properties, quantify the environmental effects on strength and material properties, and ultimately to be able to predict bond failure. Most of the adhesive tests in use today contain states of stress with multiple stress components, both tensile and shear. In addition, the magnitudes of these stress components vary throughout the adhesive in all the tests currently in use. These compound states of stress within the adhesive layer have made the collection of good engineering design data difficult and have hindered the development of a realistic and reliable failure criterion.

The single-lap joint is used extensively in testing today, due primarily to its simplicity and cost effectiveness. It makes a good, inexpensive quality control test; however, it represents an extremely poor approach to understanding the nature of the adhesive bond and for generating design information. As was pointed out by Hart-Smith,[1] specimens with this test geometry and with practical realistic dimensions, rarely fail in shear, in spite of the basic shear nature of the applied load.

Since most adhesive bonds in practical designs are intended to carry shear loads, new test geometries have been developed to evaluate the shear load nature of the practical joint. This need has led to the development of torsional shear testing of adhesive bonds.[2–6] In these tests two cylindrical adherends are bonded together along their flat end faces with the axes aligned. When these cylindrical adherends are subjected to torsional loading, a state of pure shear stress, which varies directly with the radius of the cylinder, is produced in the adhesive layer. Thus, the adhesive is subjected to a single shear stress component which is free of the multiple stress components present in other tests. However, the major objection to this test geometry is the variation in shear stress magnitude with radius.

In order to achieve a more uniform state of shear stress in this torsion test, the center portion of the cylinder has been removed and the two cylindrical tubes are bonded together at their end faces. This configuration is usually referred to as the "napkin ring test". With this geometry the variations in stress magnitudes are significantly reduced. When practical dimensions are utilized, the differences between maximum and minimum stresses are in the range of approximately 10%. This configuration allows the nature of the adhesive to be studied without contribution from other stress components, even though the magnitude of the shear stress varies throughout the adhesive volume.

An ideal test for an adhesive would be one in which the state of stress in the adhesive consists of a single component of shear stress and the magnitude of this stress would be constant throughout the adhesive. The work reported on here extends the current torsional test techniques, with all of their advantages, to a cone-and-plate geometry which will produce a state of essentially constant shear stress throughout the adhesive. An examination of the equations of equilibrium for this geometry places a limit on the cone angle opening which will assure essentially a state of constant shear stress.

This cone-and-plate geometry is currently utilized to measure fluid viscosity in rheological instruments. Recently, the use of these instruments has been extended to study the mechanical properties of materials which are initially fluid and are undergoing a curing or gelling process converting them to solids.[8] In these tests, the plate element is undergoing an oscillatory displacement of small amplitude and the resulting moment and displacement phase lag of the cone element are used to calculate the shear and loss modulus. These two moduli are recorded as a function of time while these materials are going through their chemical transformation to a solid. The work reported on here extends this effort to evaluate the material properties of solid adhesives including the entire shear stress–shear strain behavior completely to the point of mechanical failure.

TEST GEOMETRY AND SHEAR STRESS

The geometry for the test is shown in Figure 1, and consists of two solid cylindrical adherend elements. In this figure, a section of the cylindrical structure has been removed to show the internal detail. The first of these adherend elements has a conical section on its end and the second has a flat plate section. When the axes of these two adherends are aligned and with the tip of the cone touching the plate, they form a volume which can be described as a thin circular disk with a conical indentation. The test adhesive is placed in this cone-and-plate volume, bonding these two cylindrical elements together, thus forming a continuous cylinder of the two adherends. Note that there is a zero adhesive thickness at the apex of the conical element where it touches the flat plate end of the second element.

The stress produced in the adhesive when a torsional moment M

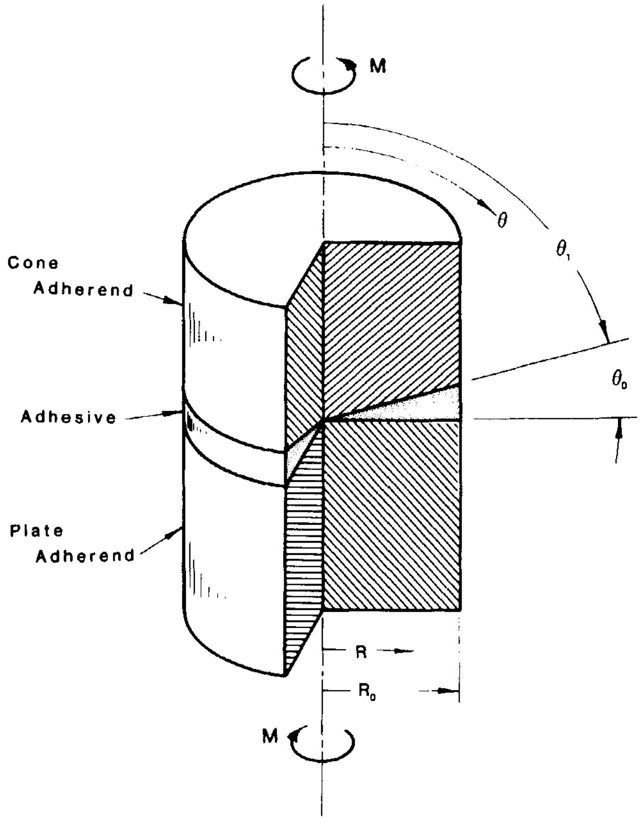

FIGURE 1 Geometry for a cone-and-plate adhesive shear stress test. A section has been cut away showing the internal cone-and-plate structure.

is applied to the two cylindrical elements is best analyzed using spherical coordinates. Even though the loading introduced by moment M is primarily cylindrical, or torsional in nature, the geometry of the deformed adhesive is essentially spherical. The coordinates of this spherical geometry are r, θ, and ϕ, shown in Figure 2, and the origin of the coordinate system is located at the apex of the cone. A shear stress is introduced in the adhesive through the two adherend interfaces by the applied moment M. This shear stress is in the ϕ-direction and is denoted by $\tau_{\theta\phi}$, where

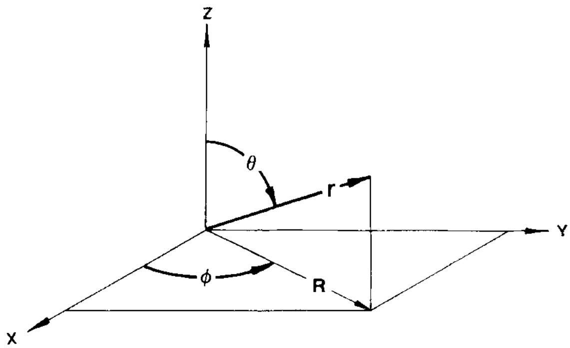

FIGURE 2 Spherical coordinate system for analysis of stress distribution in the cone-and-plate test geometry. The origin of the coordinate system is located at the apex of the cone.

spherical notation has been used. The use of spherical coordinates allows this single shear stress to describe the boundary conditions introduced by the applied moment.

The equations of equilibrium written in terms of stress, for a symmetric stress tensor, will be used to solve for the stress distribution in the adhesive. The equilibrium equations in spherical coordinates are

$$\frac{\partial \tau_{rr}}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial \tau_{r\phi}}{\partial \phi}+\frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta}+\frac{2\tau_{rr}-\tau_{\phi\phi}-\tau_{\theta\theta}+\tau_{r\theta}\cot\theta}{r}+B_r=0 \tag{1-a}$$

$$\frac{\partial \tau_{r\theta}}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial \tau_{\phi\phi}}{\partial \phi}+\frac{1}{r}\frac{\partial \tau_{\theta\phi}}{\partial \theta}+\frac{3\tau_{r\phi}+2\tau_{\theta\phi}\cot\theta}{r}+B_\phi=0 \tag{1-b}$$

$$\frac{\partial \tau_{r\theta}}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial \tau_{\theta\phi}}{\partial \phi}+\frac{1}{r}\frac{\partial \tau_{\theta\theta}}{\partial \theta}+\frac{3\tau_{r\theta}+(\tau_{\theta\theta}-\tau_{\phi\phi})\cot\theta}{r}+B_\theta=0 \tag{1-c}$$

where the body forces are denoted by B.

The remaining five stress components, other than $\tau_{\theta\phi}$, must be evaluated in these equations before we can arrive at a solution. The normal stresses τ_{rr}, $\tau_{\theta\theta}$, and $\tau_{\phi\phi}$ are all zero since there are no normal stresses introduced at the boundaries. In addition, there are no shear stresses introduced at the boundaries in the r- and ϕ-direction and $\tau_{r\theta}=\tau_{r\phi}=0$. Residual stresses, which may be introduced during the adhesive curing process, are assumed to be negligible. A restriction must be placed on the test adhesive material constitutive relationship at this point in order to keep these five stress components at their zero value. This restriction requires that there be no shear stress coupling from $\tau_{\theta\phi}$ to the other normal and shear stresses components. Thus, this single non-zero shear stress component does not include normal or shear stress in any other direction. With this restriction, and lack of other applied stresses, the only non-zero stress is $\tau_{\theta\phi}$, the shear stress introduced by the applied moment.

In addition, the body forces play no important role and are assumed to be negligible. When the body forces and all stress components except $\tau_{\theta\phi}$ are set equal to zero, equations (1) become

$$\frac{\partial \tau_{\theta\phi}}{\partial \theta} + 2(\cot\theta)\tau_{\theta\phi} = 0 \tag{2-b}$$

$$\frac{\partial \tau_{\theta\phi}}{\partial \phi} = 0 \tag{2-c}$$

Equation (2-c) indicates that $\tau_{\theta\phi}$ does not change in the ϕ-direction and reflects the general symmetry of the problem. Separating variables in equation (2-b) and changing from partial to total derivatives, this equation becomes

$$\frac{d\tau_{\theta\phi}}{\tau_{\theta\phi}} = -2(\cot\theta)\,d\theta \tag{3}$$

equation (3) can be integrated directly producing the following result

$$\tau_{\theta\phi} = \frac{C}{\sin^2\theta} \tag{4}$$

where C is a constant of integration which can be evaluated using the boundary conditions.

Equation (4) shows the important result that $\tau_{\theta\phi}$ is only a function of θ. The variation in shear stress for small values of the included cone angle θ_0 are shown in Table I. The cone angle θ_0 is defined in Figure 1. As can be seen in Table I, for any value of θ_0 less than 5°, the shear stress variation is significantly less that 1%. Because of this small variation in stress magnitude, with θ_0 less than 5°, the shear stress can be considered essentially constant throughout the adhesive. This is a significant result since all other adhesive

TABLE I
Comparison of change in shear stress $\tau_{\theta\phi}$ at its maximum value which occurs when $\theta = \theta_1$, and its minimum value which occurs when $\theta = 90°$, for various cone angle openings θ_0

θ_0	θ_1	$\frac{1}{\sin^2 \theta_1}$	Percent change in $\tau_{\theta\phi}$ between $\theta = \theta_1$ and $\theta = 90°$
10°	80°	1.0311	3.11%
5°	85°	1.00765	0.765%
3°	87°	1.00275	0.275%
2°	88°	1.00122	0.122%
1°	89°	1.000305	0.0305%
0.5°	89.5°	1.0000762	0.0076%
0°	90°	1.0	0%

shear stress tests geometries have large variations in shear stress, and most have multiple stress components present.

It should be noted that this is one of those rare problems which can be solved from the stress equilibrium equations. With the simplifications that were utilized, it was not necessary to introduce strain-displacement relations, compatibility conditions or constitutive relationships, except for the shear coupling restriction. The resulting stress solution is very general and has only the restriction previously discussed. The adherends are assumed to have a stiffness several orders of magnitude greater than the adhesive in the present formulation, thus ignoring any deformation of the adherends. The complete elasticity analysis, including deformable adherends, must be completed to confirm the validity of the present solution. This will be completed in future work.

The essentially constant value of shear stress which has been shown to exist in the previous analysis is based on an adhesive with negligible residual stresses and no shear stress coupling to the remaining stress components. Most adhesives are polymers and, as such, do not entirely obey these requirements. But, because this cone-and-plate geometry does produce a state of essentially constant shear stress for a solid with no shear stress coupling, the study of these real materials in a state of potential constant pure shear stress is possible. No other test which is currently being utilized or studied has this potential.

The current ASTM standard test method E229-70 (Reapproved 1981) for Shear Strength and Shear Modulus of Structural Adhesives, referred to as the "napkin ring test", utilizes an outside radius of 2.40 in. (6.10 cm) and an inside radius of 2.20 in. (5.59 cm). This produces a circular ring area for bonding which is 0.20 in. (0.51 cm) wide. For a homogeneous, isotropic adhesive, the variation in shear stress with these dimensions is 9.1%. Note that there is a minimum of an order of magnitude decrease in the shear stress variations between this test and the cone-and-plate geometry. A potential of two orders of magnitude decreases in stress magnitude variation between the two tests is easily possible depending upon the practical limits of the included cone angle θ_0.

The practicalities of alignment and maintaining constant adhesive thickness in the "napkin ring test" introduces other potential sources of error in this test. The cone-and-plate test eliminates these problems. Spacing is automatically controlled by the cone tip touching the plate adherend. Also, axial alignment can be much more easily controlled during the adhesive curing process with a simple split mold.

The constant value of shear stress $\tau_{\theta\phi}$ can be related to the applied moment M by integrating over the area of the plate adherend the product (r) $(\tau_{\theta\phi} dA)$, where dA is the elemental area on the plate surface. Using cylindrical coordinates, with $dA = r d\theta\, dr$, this integral is

$$M = \int_0^{2\pi} \int_0^{R_0} r\tau_{\theta\phi} r dr d\phi \tag{5}$$

where R_0 is the outside cylindrical radius (see Figure 1). With $\tau_{\theta\phi}$ constant, equation (5) becomes after integration

$$M = \tfrac{2}{3}\pi R_0^3 \tau_{\theta\phi} \tag{6}$$

If Φ is defined as the relative angular displacement between the cone and plate elements at the adhesive interfaces, then the relative linear displacement between two elements at any cylindrical radius is given by

$$u_\phi = R\Phi \tag{7}$$

where R is the cylindrical radius (see Figure 1). The shear strain $\gamma_{\theta\phi}$

at any point in the adhesive can be represented as

$$\gamma_{\theta\phi} \simeq \tan \gamma_{\theta\phi} = \frac{u_\phi}{R \tan \theta_0} = \frac{R\Phi}{R \tan \theta_0} = \frac{\Phi}{\tan \theta_0} \tag{8}$$

where the approximation is limited to the shear strain less than 0.1. It has been assumed during this shear strain formulation that the displacement is uniform, which implies that the adhesive is homogeneous. With the shear stress related to the applied moment by equation (6), and the shear strain defined in terms of Φ in equation (8), a shear stress *versus* shear strain diagram can be constructed from the measured variables.

The value of Φ should be measured at the outer periphery of the cylindrical elements and as near to the adhesive as practically possible. Measurement at this position will not entirely eliminate elastic torsional motion of the isotropic cone-and-plate adherends. A correction for the adherend angular twist is easily calculated and can be subtracted from the total measured angular displacement.

It is important that a pure torsional moment be used to load the adherends. Transverse forces can easily be introduced when applying the moment to the adherends. These transverse forces will generate transverse shear stresses parallel to the plate element, as well as normal bending stresses, and result in undesirable stresses in the adhesive. A load frame with torsional capability or a device such as that shown in Figure 3 must be used to load the cylindrical specimen so that only a pure torsional moment is generated.

ADVANTAGES AND USES

The obvious major advantage of this test geometry is its ability to produce a state of essentially constant shear stress throughout the test adhesive. The adhesive thickness varies directly as a function of radius in this geometry; however, the average thickness for practical diameters is near that in actual bonded joints. Accurate shear modulus data and other material properties can be collected since variations in stress magnitude are small enough that they can be considered negligible.

A second major advantage of this test geometry is its ease of fabrication and ability to eliminate misalignment problems. As

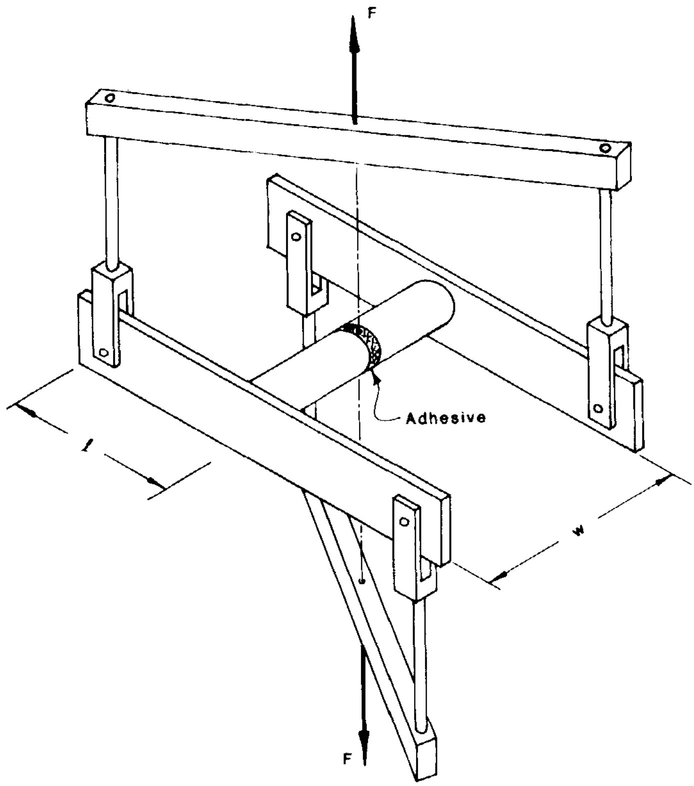

FIGURE 3 Apparatus designed to fit in conventional tensile test machine and produce a state of pure torsion in the cylindrical test specimen.

mentioned earlier, the adherend cone apex touches the plate adherend, maintaining proper spacing throughout the adhesive. Angular alignment of the two cylindrical axes is the only critical adjustment in the specimen bonding process. This angular alignment is easily accomplished by placing the two cylindrical adherend elements in a fixture which maintains alignment during the adhesive curing cycle. With half-inch (12.7 mm) diameter cylindrical adherend elements, each six inches (152 mm) long, placed in a clamping type of holder with a 0.001 inch (0.025 mm) diameter fit, angular misalignment is less than 0.01 degrees.

This is a much simpler procedure than most used in adhesive specimen fabrication techniques. In most of these procedures, glass beads or fibers are included to achieve a constant adhesive thickness. In the current "napkin ring test", obtaining a constant adhesive thickness is critical since large variations in shear stress around the ring are introduced with thickness variations. In addition, alignment of the adherend rings in this test is much more difficult than in the procedure outlined above.

Because of the constant state of shear stress, the viscoelastic effects of relaxation and creep should be equally distributed throughout the adhesive, eliminating stress redistribution effects. This same advantage can be extended to deformation rate information. Again, since stresses are constant, deformation should be constant, and rate dependence of these phenomena are equally distributed throughout the test adhesive. More importantly, the deformation rate is known and well-defined throughout the test.

Many adhesive bond failures are attributed to interfacial failures between the adherend and adhesive. These interfacial failures may occur because of the extremely high local stresses produced in other test geometries. The constant shear stress present in the cone-and-plate test make it an ideal geometry to study interfacial failure. True interfacial failure should produce a complete separation at the surface.

PRELIMINARY TEST RESULTS

Specimens were fabricated using 3M Company's AF 163-2U adhesive. This adhesive is a toughened, unsupported, modified epoxy. Half-inch diameter (12.7 mm) 2024-T4 aluminum adherends were used throughout. The adherends were vapor degreased, deionized, acid etched, and phosphoric acid anodized according to BAC-5555.[7] 3M Company's EC-3960 primer-sealer was applied to the anodized surfaces according to the manufacturer's instructions and cured at 121°C for one hour. Two circular disks of the film adhesive were placed on the adherends, which were then placed in a specimen mold. The mold consisted of two identical plates of aluminum with parallel circular grooves which held the adherends in place during the adhesive curing cycle. Each mold half was coated with mold release and pressure was applied both to the ends of the adherends

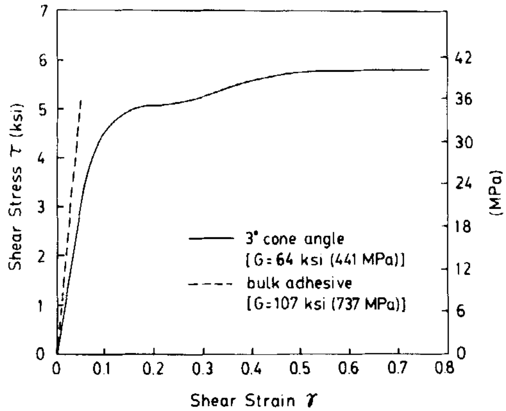

FIGURE 4 Shear stress–shear strain results of AF 163-2U Adhesive (3M Company) in a 3° cone-and-plate geometry with 0.5 inch (1.27 cm) diameter 2024-T4 aluminum adherends.

and to the mold plates with bolts during the one-hour cure at 121°C. The molding procedure resulted in good axial alignment of the adherends and little or no void content in the adhesive.

Torsion tests were conducted on specimens with 3° included cone angles in an Instron load frame with torsional capability. An extensometer was mounted on a special fixture similar to the extensometer fixture used by Dolev.[4] Torque *versus* extensometer output was recorded on an X-Y plotter. The extensometer output was converted into a relative angular displacement using the trigonometry inherent in this device. After correcting for the angular twist of the aluminum adherends, the adhesive shear strain was calculated from equation (8), and the shear stress was calculated from equation (6). Figure 4 represents a typical shear stress-shear strain curve.

Comparisons of the *in-situ* results of this test were made with the bulk adhesive properties. The bulk adhesive shear modulus was calculated from uniaxial tensile test data [$E = 306$ kpsi (2.11 MPa), $\nu = 0.43$] to be $G = 107$ kpsi (0.738 MPa). This uniaxial testing was done on "dog-bone" specimens cut from cast sheets, 0.050 in (1.27 mm) thick. The cast sheets were fabricated from multiple layers of the film adhesive which had been stacked and cured. This bulk adhesive shear modulus value compares with the measured value of $G = 64$ kpsi (0.441 MPa) obtained in the linear region of this test shown in Figure 4. The maximum tensile stress obtained with the uniaxial test of the bulk adhesive averaged 7.5 kpsi (52 KPa) which is equivalent to a maximum shear stress of 3.75 kpsi (2.59 KPa). This value can be compared to a maximum shear stress of 5.6 kpsi (38.6 KPa) obtained with this *in-situ* test. The present cone-and-plate test confirms the variation of *in-situ* adhesive properties with those obtained in bulk testing. The decrease in *in-situ* shear modulus, increased maximum shear stress, and increased strain to failure are in agreement with the results of Dolev.[4]

CONCLUSIONS

The cone-and-plate torsional deformation test produces a state of essentially constant shear stress in an adhesive which has no shear stress coupling material behavior. Most adhesives, as real materials, are close to this idealized behavior. This test has the potential of producing the most accurate engineering and design property data for *in-situ* shear of adhesives of any test currently being utilized.

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