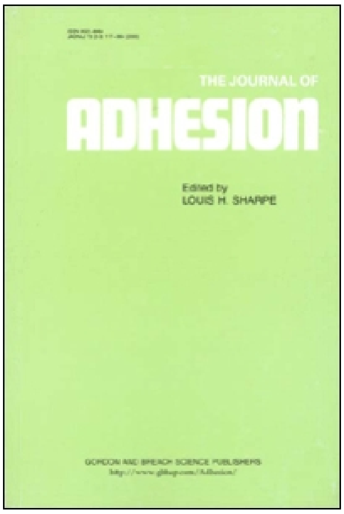

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USE OF THE THICK ADHEREND SHEAR TEST FOR SHEAR STRESS-STRAIN MEASUREMENTS OF STIFF AND FLEXIBLE ADHESIVES

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Five commercial structural adhesives were tested using the thick adherend shear test (TAST). These adhesives have mechanical properties ranging from those of high-strength, heat-cured epoxies to ductile, acrylic-based materials. Consideration was given to the adherend selection and dimensions to approach a uniform shear stress-strain in the bonded area, so that the test could be used with both stiff and flexible adhesives. Comparison of the TAST results was also made with those obtained using the butt torsion test.

The TAST extensometry has been shown to be suitable for measuring the shear strain properties of the adhesives tested without modification. From the shear behavior of the five adhesives measured using the TAST method, and from the results presented in this paper, it can be seen that the TAST method is repeatable and reproducible for a wide range of adhesive types and adhesive properties. From these results, it is possible to generate comprehensive adhesive shear data. Also, the curves from the butt torsion test and the TAST were found to be consistent and give the same behavior of the adhesives tested.

Keywords: Thick adherend shear test; Structural adhesives; Soft adhesives; Shear modulus; Spew fillet

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INTRODUCTION

Accurate stress and strain data for adhesives under well-defined stress-states are needed to calculate stress distribution in a bonded joint using finite element methods. Where bulk specimens of the adhesive are available with properties that are representative of the material in the layer of a bonded joint, then tensile behavior is relatively straightforward to measure using the standard test method and test specimen developed for plastics. However, it is well known that, unlike metals, polymeric materials, and thus adhesives, have different behavior depending on the type of loading they are subjected to. Different critical values should be expected when an adhesive specimen is loaded in tension, compression, or shear. In order to characterize deformation under multiaxial stress-states in the region of strain where behavior is nonlinear, additional stress-strain data are required under a different state of stress. For example, in his recent work, Karachalios [1] has developed a so-called multistage failure criterion for the prediction of strength of adhesively bonded joints, applicable to as many different joint configurations as possible using the basic material properties of the constituent materials, which also requires the stress-strain data of an adhesive in shear. It is claimed that such a criterion is required because different critical variables appear to be necessary when different configurations are analyzed and, since the mechanisms that govern failure in each are different, a variety of steps needs to be taken in order to predict failure in different joint configurations and loading modes; for the Single Lap Joint (SLJ) loaded in bending, the critical value of strain is the tensile strain. On the other hand, when the SLJ is loaded in tension, then the critical value controlling failure is the shear strain. For adhesives, in addition to the tensile test, shear test methods are the most obvious choice for generating these additional data. Among these tests, the torsion test is likely to offer the highest accuracy in shear properties, especially at small strains and thus for the determination of modulus. However, loading *via* a normal tensile tester rather than a specially-built butt torsion test, the thick adherend shear test (TAST) method is an alternative to the butt torsion test since it is much easier to make and test the specimens. The many different types of TAST specimens used have generally been based upon the work of Krieger [2] and Althof [3]. In order to obtain reliable data, particular care must be taken regarding the position of the extensometers and the correction made for the displacement of the adherends. But it should be stressed that the complexity of the stress state is much more dominant in the conventional lap shear specimens—ATSM D 1002-72 [4], BS EN 1465-1995

[5], and ISO 4587-1979 E [6]—since offset loading of the lap joint causes the loaded adherend to bend adjacent to the overlap region.

In order to reduce the nonuniform shear stress distribution in the thick adherend specimen, various methods have been used. Kassapoglou and Adelmann [7] showed by using FE analysis that the adhesive shear distribution along the bond length became significantly nonuniform as the adherend stiffness decreased or the adhesive shear modulus increased. Chiu and Jones [8] tried to improve the shear stress uniformity by increasing the adherend and adhesive thickness. Chalkley and Chiu [9] argued that only tests conducted under strain control could provide a sufficiently accurate characterization of the adhesive shear stress-strain behavior for the design of highly-stressed, adhesively-bonded joints.

Because use of the cross-head displacement to calculate the shear strain is not a reliable method (Lees & Hutchinson [10]), the deformation measuring system needs to be adapted to the test specimen. Most researchers used extensometry to measure the displacements in the adhesive layer, but lasers and Moiré interferometry were also found to be accurate and reproducible (Lilleheden [11]).

As previously mentioned, many different types of TAST specimens have been used, though they have generally been based upon the work of Krieger [2] and Althof [3]. The major differences between the Krieger and Althof approaches are in the positions of the extensometer attached to the specimen and their size. Through consideration of the shear stress profile trough at the center of the adhesive layer, Krieger placed his measuring points at the $\frac{1}{4}$ positions (Figure 1) since the nonuniform distribution of the shear stress meant that there were peel effects at the ends of the overlap. These may affect the strain measurements of the adhesives. This positioning was also designed to prevent false readings due to bending and stretching of the adherends.

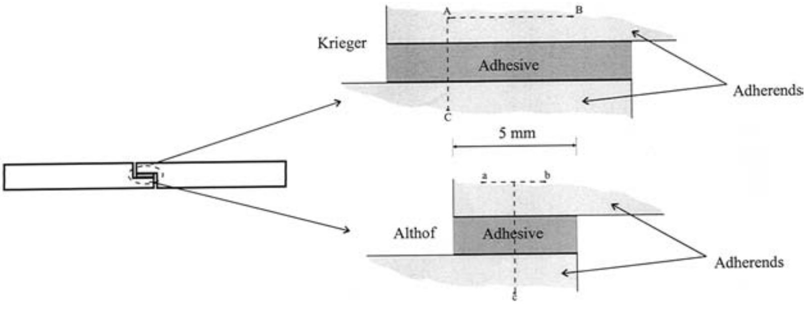

FIGURE 1 Schematic of pin locations for Krieger and Althof extensometry.

Althof, on the other hand, placed his points such that two were at the $\frac{1}{4}$ position and one was in the middle of the overlap, in order to stabilize the device and also to eliminate false readings from rotation of the bondline (Figure 1). This reasoning was backed up by Renton and Vinson [12] who, through the use of an analytical technique with photoelastic verification, determined that the optimum position for a surface contacting extensometer was at the middle of the overlap.

In order to obtain reliable data, many authors have offered various solutions to improve the measurements of the adhesive strains (Lee et al. [13] and Guess et al. [14]). The conclusions reached by them have been broadly similar: measurements should be made as close to the bondline as possible, the adherend material used should be as stiff as possible, thinner bondlines require a more accurate measuring system, and peel stresses at the ends of the overlap are reduced as the adherend thickness is increased.

Above all, Schlimmer and Reiling [15] are still critical of the TAST method, commenting particularly on the uncontrolled strain rate under force or displacement control. They advocate the napkin ring shear test as a more scientific method for determining shear data.

The objective of this paper is to investigate the shear behavior of five different adhesives, two flexible and three stiff, using the thick adherend shear test (TAST). Consideration was given to the adherend selection and dimensions to approach uniform shear stress and strain in the bonded area, the applicability of the test to the stiff and flexible adhesives, reproducibility of the shear stress-strain curve, and comparison of the TAST results with those of the butt torsion test.

PREPARATION OF JOINTS

Adhesive Types

Five commercial structural adhesives were tested. These had mechanical properties ranging from those of high-strength, heat-cured epoxies to those of ductile acrylic-based materials. Details of the adhesives are given in Table 1, and further information can be obtained from the manufacturer's data sheets.

Adherend Material Selection

For the adherends of the test specimens, different researchers have used either aluminum or steel. However, if pure shear in the

TABLE 1 Details of the Adhesives Used for This Work

Name	Manufacturer	Type	Working life	Cure conditions	Postcure procedure
AV119	Ciba Polymers	1-part toughened epoxy	NA	120°C for 1 h	None
ESP110	Permabond	1-part toughened epoxy	NA	150°C for 1/2 h	None
TE251	Evode	2-part toughened epoxy	45 min	Room temp. 7 days	80°C for 1/2 h
F241	Permabond	2-part acrylic	3–5 min	Room temp. 5–15 min	100°C for 1 h
SBT 9245	3M	Epoxy/Acrylic	NA	140°C for 45 min	None

adhesive layer is desired, adherends with highest stiffness are required. Therefore, steel is favored over aluminum as its elastic modulus is three times higher. By employing a higher modulus of elasticity of the adherend, the stress variations in the overlap are reduced. Chiu and Jones [8] showed this by using both aluminum and steel as adherend materials for TAST joints. It was also observed that the aluminum joints consistently failed at a lower shear stress than the steel joints. The mean maximum shear stress for TAST joints with aluminum adherends was 53 MPa but 62 MPa with steel adherends. This was believed to be due to the increase in peel stress in the adhesive layer owing to the larger adherend compliance. In the light of the information given, it was decided to examine the shear properties of the adhesives using steel as the adherend.

Adherend Material Dimensions

As explained above, the geometry of the adherends plays an important part in the behavior of the test system. A short overlap length and high thickness of the adherend reduces undesirable peel effects at the ends of the joint (when compared with a typical lap-shear specimen such as specified in ASTM D1002), and this helps to approach a state of pure shear in the adhesive layer. The dimensions of the test specimens used for this work are those of the ISO 11003-2 [16] standard (Figure 2). The holes in each adherend are necessary if the method of applying load to the joint is through pins, which is recommended for alignment reasons.

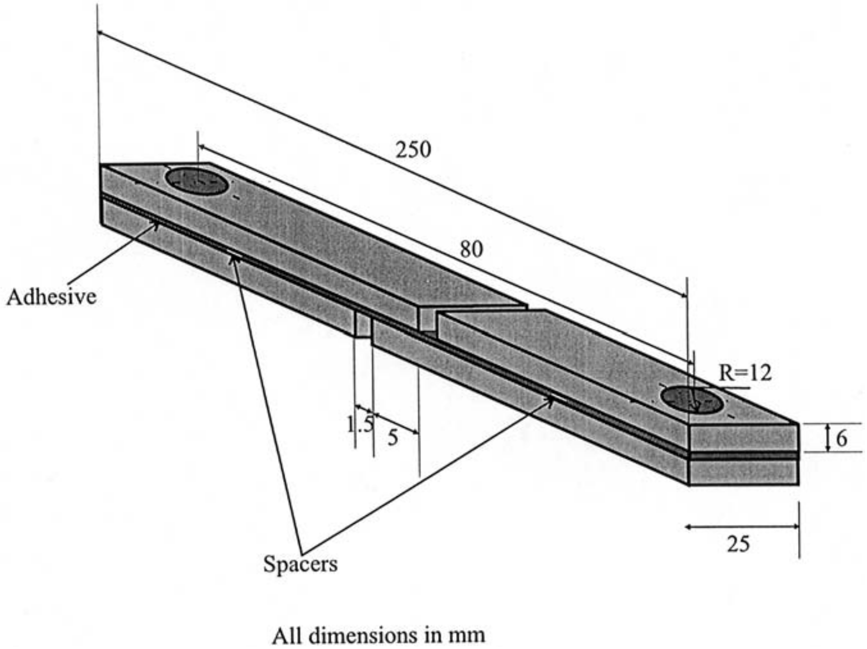

FIGURE 2 ISO specimen dimensions.

Method of Manufacture of TAST Specimens

The ISO standard recommends two methods of manufacture of the TAST specimen:

1. bonding of two sheets together and cutting out bonded bars as shown in Figure 3, or
2. bonding of two preshaped bars together.

In the first method, spacers are left between the two surfaces to be bonded, so that once the faces are brought together the spacers will dictate the bondline thickness of the specimen. When cured, the bonded bars are then machined to the dimensions shown in Figure 2.

This method of manufacture of specimens, while it is a high-volume method and suited to thin film adhesives, introduces a number of uncertainties into the specimen:

1. All the machining work needs to be done without coolant (to avoid any reactions with the adhesive), and the localized increase in

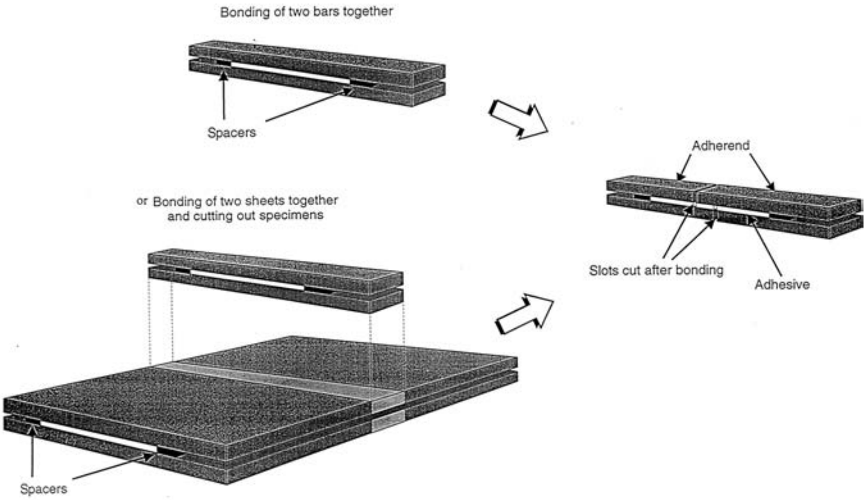

FIGURE 3 Specimen manufacture using bonded sheets.

temperature that machining introduces may affect the adhesive properties.

2. The edge of the bondline is damaged when the slots are cut or when a bar is cut from a sheet.
3. How deep should the slot be cut? Should it be through the bondline or through one adherend only? If the load is not transferred to the adhesive just through the overlap, then the adhesive is under an uncertain combination of shear and tensile loads (Renton [12]).
4. Irregular bar stock surfaces can lead to uncertain bondline thicknesses (Lee et al. [13]). The surface of bar stock is often bowed, such that the thickness of the bar is less at the edges than at the middle. This affects the measurement of the bondline thickness and in turn the calculation of the shear strain in the adhesive, and it may also affect the mode of failure of the specimen.
5. Test specimens cannot be reused (Lee et al. [13] and Chiu & Jones [8]). For testing in an industrial environment, the reuse of adherends plays an important part in the choice of test procedure, especially if their manufacture is labor intensive and costly.

To overcome these obstacles, an alternative method is suggested. First, the adherends should be machined before bonding. Then, they should be bonded while held in an alignment jig and placed in a press to maintain a clamping force during cure. This method of specimen manufacture was chosen in this work, using the dimensions given in Figure 4.

To control the termination of the adhesive layer, to give a suitable shape to the spew fillet, and also to avoid the problem of cleaning out the gaps between adherends, special shims with 45° fillets were made of steel and treated with a release agent. The shims were inserted at the ends of the bond and, after the adhesive was cured, the shims were removed by gently tapping them out of the gap,

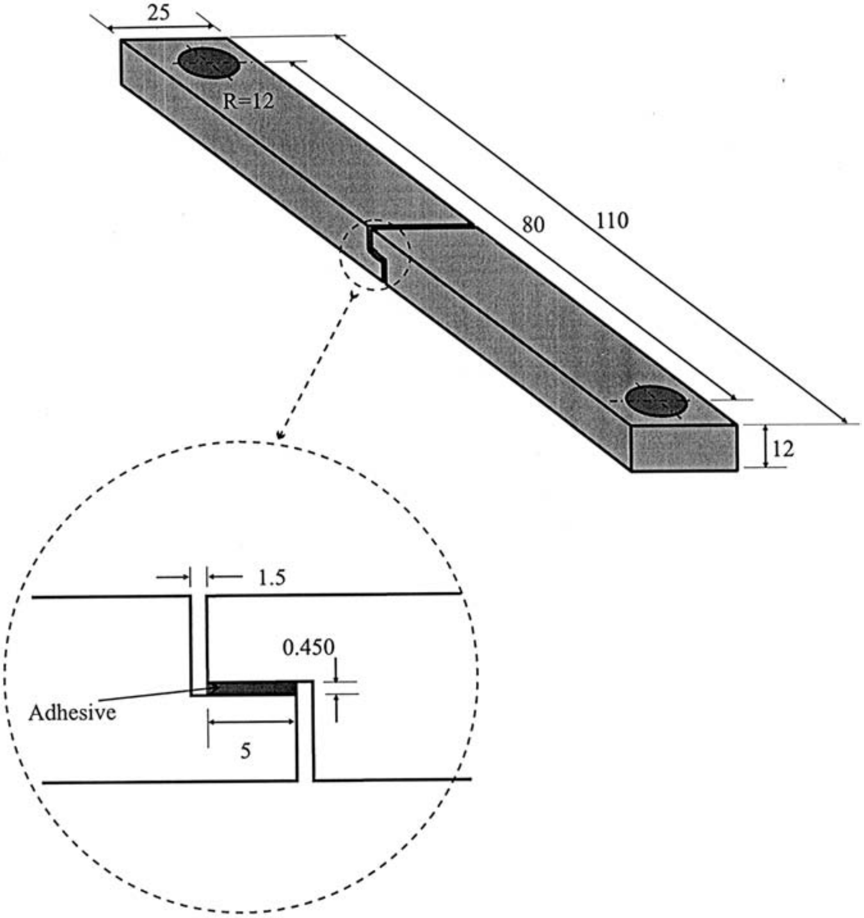

FIGURE 4 Premachined thick adherend specimen.

leaving an accurate and smooth termination of the adhesive in the overlap. The longitudinal gap between the adherends and the overlap length of each specimen was also controlled by means of the use of these shims and the alignment jig.

An accurate measurement of the adhesive thickness can be made by measuring the thickness of each adherend in the overlap region prior to bonding with a digital micrometer, and then subtracting these values from the measured overall bonded thickness of the finished specimen. A uniform adhesive thickness and an accurate knowledge of this adhesive thickness is an important factor in obtaining the true shear properties of the adhesive.

The procedure adopted for the surface preparation of the adherend surfaces to be bonded was as follows: degrease with acetone; wipe; grit blast with alumina; degrease with acetone; wipe.

EXPERIMENTAL SET-UP

Test Rig

The extensometry designed by Althof was used to measure the shear strain in the adhesive layer (Figure 5). The extensometer is based upon an inductive linear variable differential transformer (LVDT). It

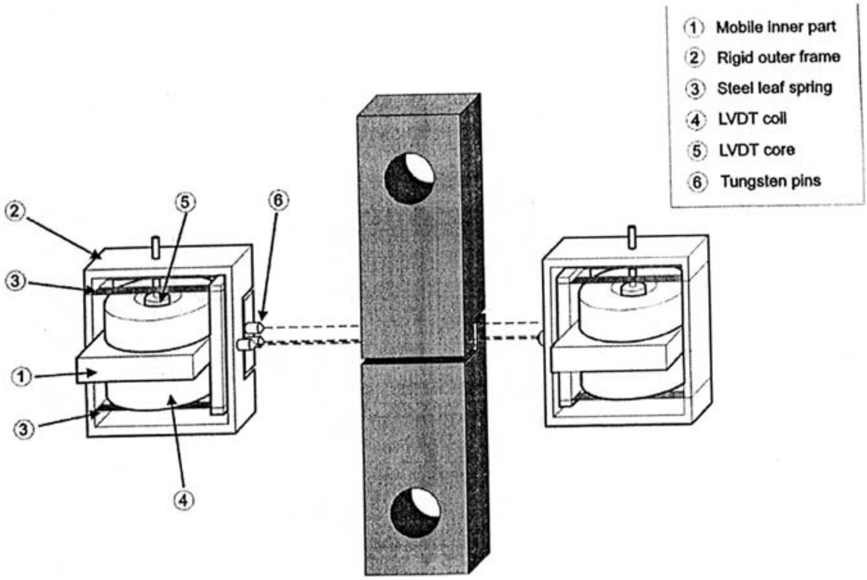

FIGURE 5 Extensometry designed by Althof for TAST.

consists of a mobile inner part surrounded by a rigid outer frame, connected by two steel leaf springs. The springs restrict the motion of the inner part to a perpendicular movement in the direction of their flexure.

The shear displacement of the adhesive layer was measured from the relative movement of the coil of the inductive transducer, held in the inner mobile part, and the core of the inductive transducer, connected to the rigid outer frame. The extensometry is fixed to the specimen by means of an alignment jig which enables the attachment of the extensometer at the same place on each specimen.

The extensometer was fixed to the specimen by three hardened tungsten carbide pins (Figure 6). The pins are arranged such that two pins are fixed to the inner part and the other is fixed to the outer frame.

Two LVDTs were used, one on each side of the TAST specimen, to check for any bending. Movement between the double pins and the single pin was measured by the transducer, as the core and coil move relatively. The transducer output was logged to a computer, as was the load from the testing machine.

FINITE ELEMENT ANALYSIS

The thick adherend shear test has been modelled using the finite element analysis method. The simulations were carried out using ABAQUS, version 5.4, running on a Convex C380 series supercomputer. The results presented here assume linear elastic behavior for both the adherends and the adhesive. These results are important in the elucidation of the measurements of the linear elastic shear modulus using this test method, particularly with respect to the position of the extensometer.

The TAST specimen was modelled in both two and three dimensions by Vaughn et al. [17] and Vaughn [18]. The two-dimensional analyses showed that the adhesive is predominantly in shear over the length of the overlap, with concentrations of peel stresses at the ends. Small direct tensile stresses are present in the adhesive. From the three-dimensional analysis, it was found that the maximum shear stress is at the surface of the joint, and the variation in shear stress across the width is about $\pm 1\%$. Comparing the results of this analysis with those of two-dimensional analyses in plane stress shows good agreement for shear stress, maximum transverse stress, and both x and y displacements. This gives numerical justification to predictions of measured deflections and deductions of shear stress variability carried out using the two-dimensional analyses.

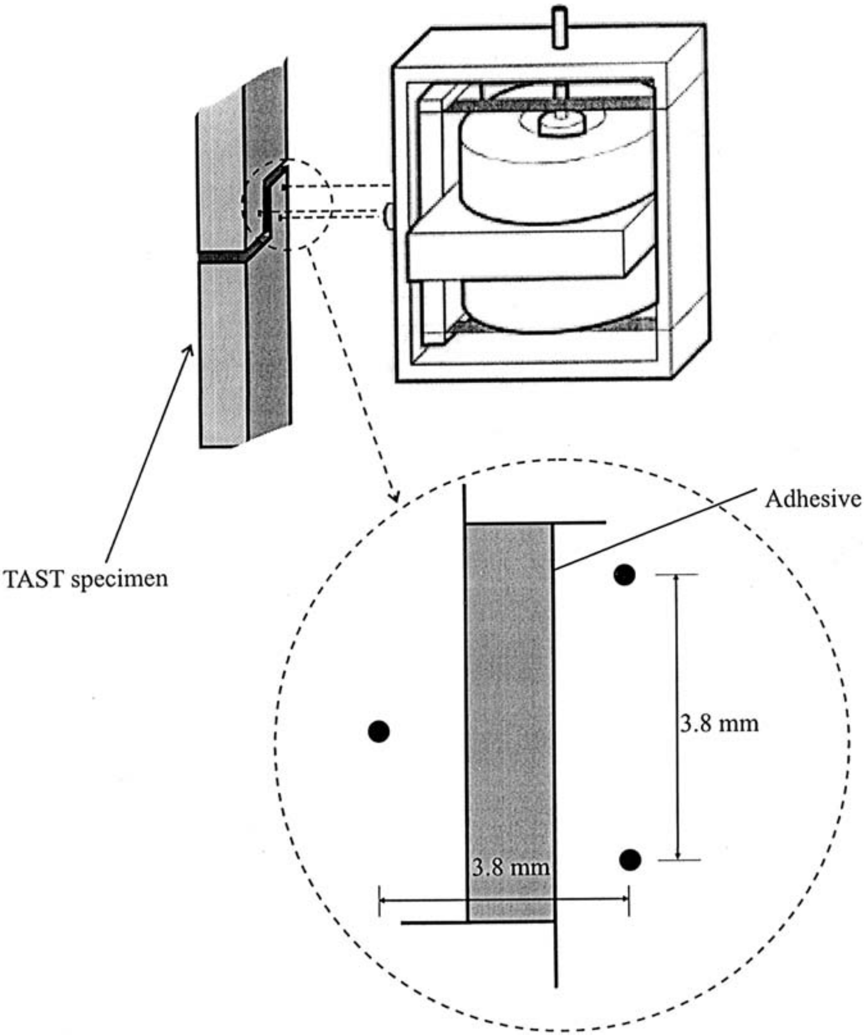

FIGURE 6 Location of pins.

Models were first drawn, including a rounded fillet at the ends of the adhesive. This shape was used to eliminate the singularity which would otherwise arise from the sharp corner at the end of the adhesive. Since a perfectly sharp corner does not exist in practice, this method of modelling the end of the adhesive is likely to be the best simulation of the actual experimental conditions. Using the 2D mesh with 8264 8-noded elements (Figure 7), further analyses were

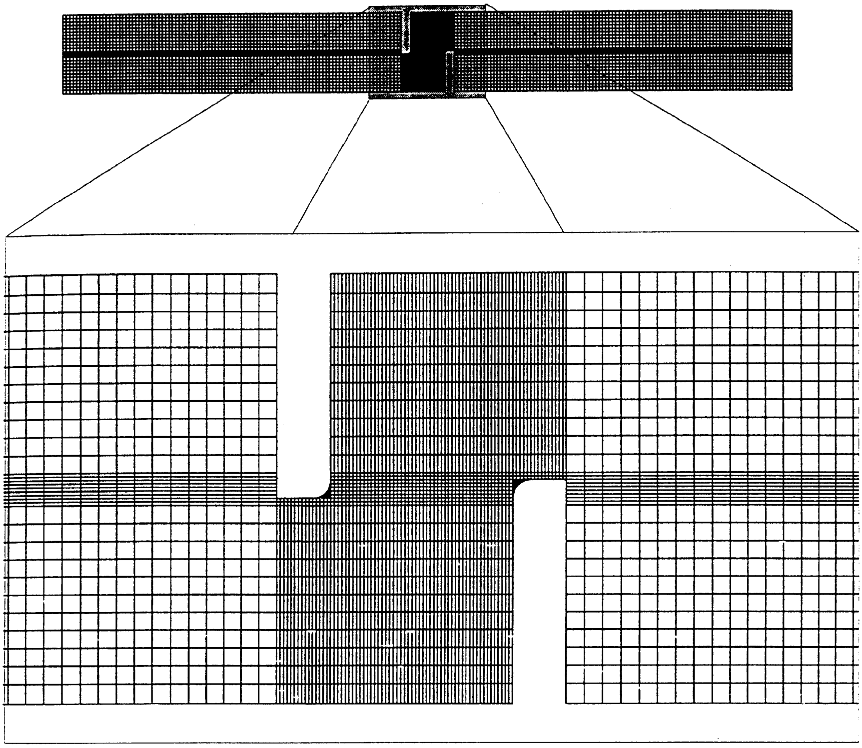

FIGURE 7 2D finite element model of the TAST specimen.

conducted by altering the mesh so that 45° filets were modelled. The change from a meniscus fillet to a 45° fillet does not present such a mathematically pure solution to the singularity at the end of the overlap, but it reproduces the geometry of the experimentally produced fillet joints. The model was then loaded in tension to 2 kN at one end (since the material properties used were linear elastic, the magnitude of the results obtained are proportional to the loads applied) while the other remained fixed.

EXPERIMENTAL DETERMINATION OF THE SHEAR STRESS-STRAIN DATA

Equations

The calculations of shear stress and strain in the adhesive layer assume that the joint is essentially in pure shear and the shear stress along the overlap length is uniform, although some concentrations at the joint ends are inevitable.

It should be kept in mind that the accuracy of the strain measurement depends on the thickness of the adhesive layer and the stiffness of the joint. Thinner adhesive bonds will experience smaller displacements so that relatively higher errors will be associated with measuring the strain.

Since the extensometry not only measures the actual relative displacement of the adhesive layer but also the displacement of the two adherends approximately 1.5 mm to either side of the bondline, a correction for adherend elastic deformation is necessary.

If the deflection of the adhesive layer is known, the shear strain γ can be calculated through the relationship

$$\gamma = \frac{d}{t}, \tag{1}$$

where d is the relative shear displacement across the adhesive layer in mm and t is the thickness of the adhesive layer in mm.

The average shear stress, τ (MPa), is obtained from the equation

$$\tau = \frac{F}{lb}, \tag{2}$$

where F is the applied force in N, l is the overlap length, and b is the overlap width.

Using data from Equations (1) and (2), we can plot the shear stress-strain curve.

Corrections

A number of different procedures for correcting for the compliance of the adherends (see Figure 8) have been evaluated:

1. *Measurement of a "blank."* It is recommend by the ISO standard to correct for the adherend compliance with a "blank" specimen (made out of the adherend material, to the same dimensions as an adhesively bonded joint, and tested in the same manner as a joint). It is claimed that subtracting the deflections of this specimen from those of an actual joint will give the true adhesive strain.

Blank TAST specimens were made by Vaughn [18] with steel and aluminum. In both cases, there was great difficulty in obtaining results which were repeatable and sensible. This was thought to be because the deflections being measured were very small (approximately 0.3 μm per kN load), and that lateral displacement was occurring between the double pins, forcing them to slip.

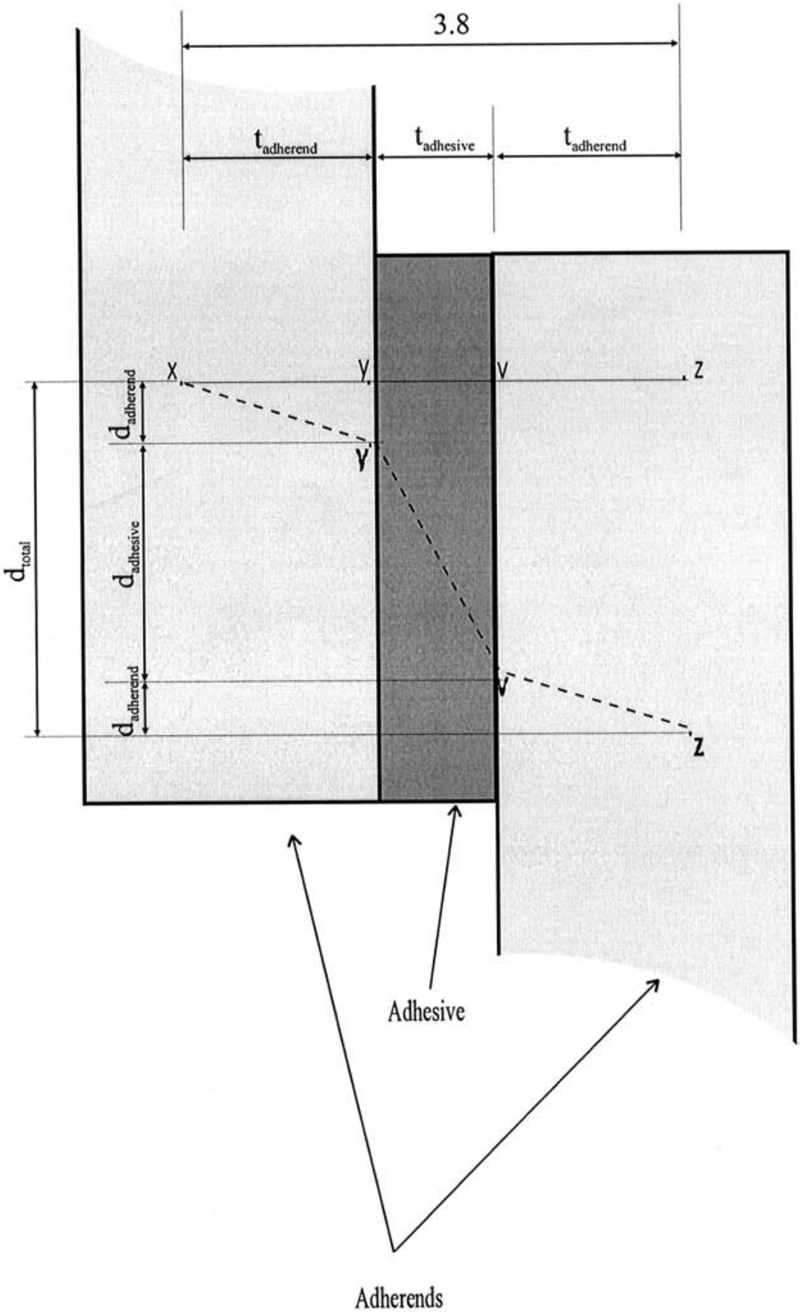

FIGURE 8 An indication of the compliance correction for the adherends.

2. *Finite element predictions*. Further investigation into the "blank" specimen was undertaken using finite element methods. For a 2 kN load applied, assuming the load in the adhesive is carried out entirely in shear, the nominal shear stress in the adhesive is 16 MPa. Figure 9 shows the predicted profile of shear stress along the centre-line of the adhesive (for a bonded specimen) and the adhesive region (for the dummy specimen) in the axial direction. It can be seen that, whereas the shear stress in the adhesive joint is practically uniform along the overlap, the shear stress in the dummy specimen is not and the overall stress state within the dummy specimen is not comparable with that of the adhesive joint. Significant direct stress is also carried in the adhesive region of the steel specimen whereas, in an adhesive joint, it has been shown that an essentially constant shear stress is achieved in the adhesive layer, with a small amount of direct stress.

It was therefore concluded that the "blank" specimen was unsuitable for producing the necessary correction for the adherend compliance.

3. *Through making at least three measurements*. Kassapoglou and Adelmann [7] devised a method whereby performing at least three tests with different pin spacings eliminated the need for any measurement of the adherend deformation. This required modification of the Krieger extensometry and the solving of three simultaneous equations to find the adhesive shear modulus.

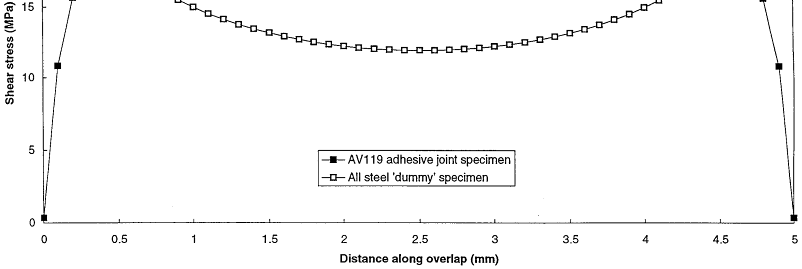

FIGURE 9 Comparison of shear stress along the centre of the adhesive for AV119 TAST joint and a "dummy" TAST joint using a load of 2 kN for the linear elastic case.

4. *Simple elasticity theory.* Since the adherends do not experience plastic deformation, simple elasticity theory should be a good approximation to the deflections (Figure 8).

From Equations (1) and (2) and the relationship

$$G = \frac{\tau}{\gamma} \tag{3}$$

we can estimate the relative displacement of the pins of the extensometer for a certain load applied to a TAST specimen with steel adherends (see Figure 8), where G is the shear modulus, τ is the shear stress, γ is the shear strain. For the steel adherends:

$$G \cong 82.03\,\mathrm{GPa}, F = 2\,\mathrm{kN}, l = 5\,\mathrm{mm}, b = 25\,\mathrm{mm}$$

$$2 \times t_{\mathrm{adherend}} = (3.8\,\mathrm{mm} - \text{bondline thickness } (0.5\,\mathrm{mm})) = 3.3\,\mathrm{mm}$$

$$2 \times d_{\mathrm{adherend}} = ((2 \times t_{\mathrm{adherend}}) \times F)/(G \times l \times b) = 0.6437\,\mu\mathrm{m},$$

where t and d are the thickness and displacement, respectively. And, for the adhesive,

$$G \cong 1.09\,\mathrm{GPa},\ t_{\mathrm{adhesive}} = 0.5\,\mathrm{mm},$$

$$d_{\mathrm{adhesive}} = (t_{\mathrm{adhesive}} \times F)/(G \times l \times b) = 7.339\,\mu\mathrm{m}.$$

This gives an overall displacement of $7.339 + 0.6437 = 7.983$ μm at a load of 2 kN.

The importance of the correction can be realized when a thin adhesive layer, say 0.12 mm, and a stiff adhesive, say 1 GPa shear modulus, are tested using aluminum adherends. In this case, the total displacement of the specimen is shared nearly equally by the adherend and the adhesive, using similar calculations to those made above.

RESULTS

Finite Element Analysis Results

Figure 10 shows the shear stress distribution through the centre of the adhesive layer for both models, with and without fillets. The reduction in shear stress in the interior of the joint can be seen, in addition to a more uniform distribution for the fillet models. Examination of the peel stresses indicates that the fillets also remove the high peel stress concentration from the corner of the adhesives.

Figure 11, Figure 12, and Figure 13 show the distribution of the principal tensile and compressive stresses at the ends of the overlap

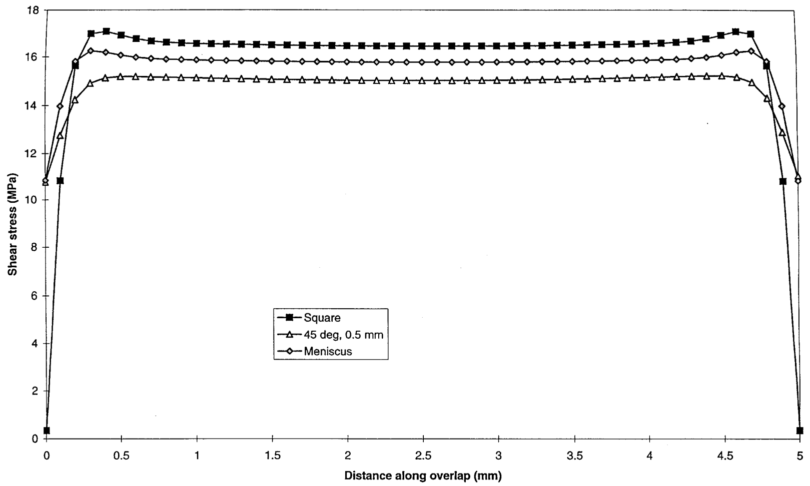

FIGURE 10 Variation of shear stress along the centerline of the adhesive for a TAST joint with different fillets using a load of 2 kN for the linear elastic case.

for the fillet studied. It can be seen that the joint without a fillet (Figure 11) has a maximum tensile principal stress at the lower corner of the overlap (point A), and a maximum compressive principal stress at the upper corner of the overlap (point B), whereas for the joint with

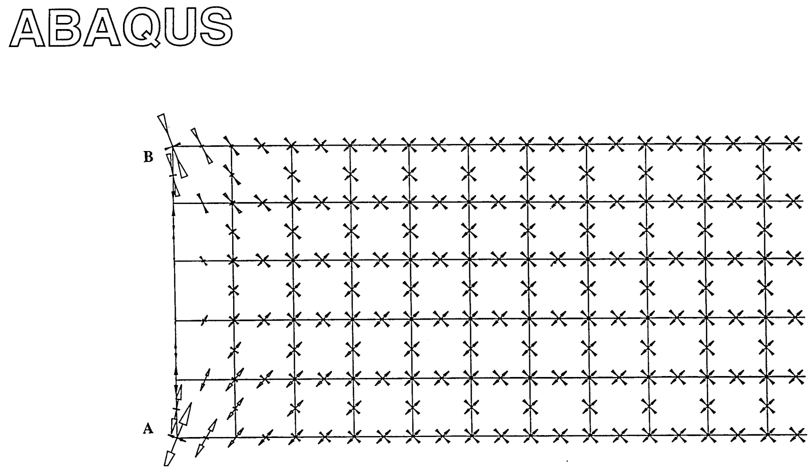

FIGURE 11 Distribution of principal stresses at the end of the overlap for a joint with no fillet using a load of 2 kN for the linear elastic case.

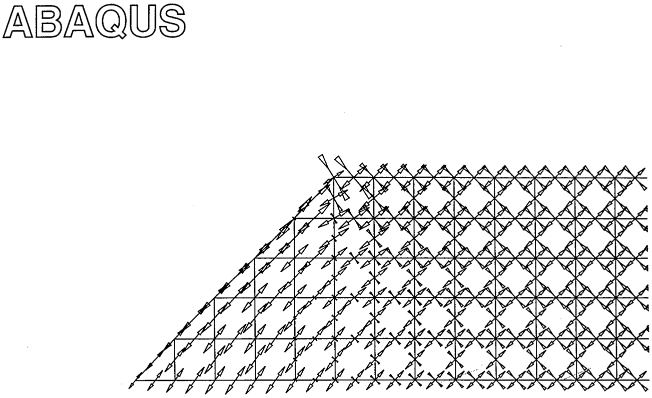

FIGURE 12 Distribution of principal stresses at the end of the overlap for a joint with an 0.5 mm fillet using a load of 2 kN for the linear elastic case.

0.5 mm fillet (Figure 12) the maximum tensile principle stress is close to the upper corner of the overlap (B). The joint with the "meniscus" fillet (Figure 13) has a maximum tensile principal stress at the edge of the fillet, and a maximum compressive principal stress at the upper corner of the overlap.

For all the fillets modelled, it can be seen that the adhesive experiences essentially pure shear up to 0.3 mm from the end of the overlap, as indicated by the equal but opposite principal stresses acting at 90°.

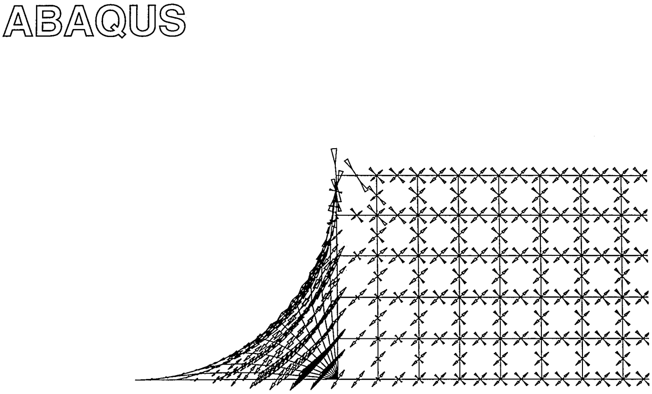

FIGURE 13 Distribution of principal stresses at the end of the overlap for a joint with a meniscus fillet using a load of 2 kN for the linear elastic case.

Experimental Results

All the tests were conducted under the same conditions, namely at constant crosshead speed and at 23°C. For the shear stress-strain behavior, several curves of each adhesive were shown in one figure to see if the TAST method gave repeatable data for different adhesive types. Table 2 shows the data for different adhesives tested with the TAST.

Shear Stress-Strain Data for AV119

The adhesive AV119 is a one-part epoxy, which is stiff and tough when cured. From the shear stress-strain curve to failure (Figure 14), it can be seen that the adhesive remains linear until approximately 20 MPa shear stress and 2% shear strain. Nonlinearity sets in from here and the maximum strength of the adhesive is reached at about 45 MPa shear stress and 6% shear strain. The joints with a 45° fillet exhibited a different shear stress-strain curve near the peak stress from those without fillets. The maximum shear stress was found to be, on average, slightly lower, though the strain to failure was increased considerably, as shown in Figure 14 and Table 2.

Shear Stress-Strain Data for ESP110

The adhesive ESP110 is a one-part toughened epoxy, 30% filled with aluminium powder, which is stiff and tough when cured. From the shear stress-strain curve of failure (Figure 15), it can be seen that the adhesive remains linear until approximately 15 MPa shear stress and 1% shear strain, with the elastic limit of the adhesive reached at about 40 MPa shear stress and 4% shear strain. The stress then levels off until the joint fails. It can be seen that there is a very high degree of correlation between the specimens. Shear modulus measurements of the adhesive were consistent and reproducible (Table 2).

TABLE 2 Shear Data for the Adhesives Tested

Adhesives	Fillet	Max stress (MPa)	Strain to failure	Shear modulus (MPa)	Adhesive thickness (mm)
AV119	No	49.26 ± 1.5	0.132 ± 0.04	1079.2 ± 35	0.520 ± 0.02
	Yes	47.4 ± 0.0	0.420 ± 0.01	1141.6 ± 96	0.537 ± 0.02
ESP110	Yes	49.34 ± 0.4	0.150 ± 0.01	1659.6 ± 76	0.488 ± 0.03
TE251	No	29.9 ± 0.7	0.164 ± 0.03	1065.4 ± 82	0.517 ± 0.05
	Yes	30.3 ± 0.5	0.174 ± 0.01	1058.8 ± 33	0.483 ± 0.03
F241	No	31.42 ± 2.5	0.98 ± 0.04	263.55 ± 9	0.389 ± 0.03
SBT	No	12.62 ± 0.4	1.74 ± 0.1	7.5 ± 0.81	0.430 ± 0.02

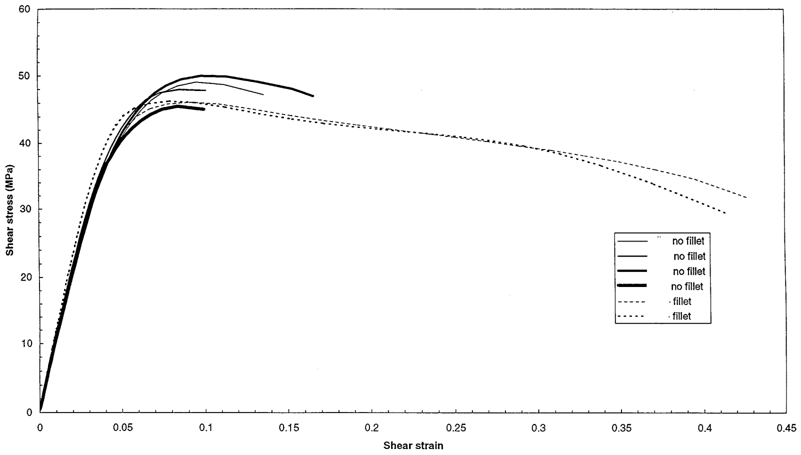

FIGURE 14 Variation of shear stress with shear strain for AV119.

Shear Stress-Strain Data for TE251

TE251 is a two-part, toughened epoxy, which is stiff and tough once postcured. From the shear stress-strain curve to failure (Figure 16), it can be seen that the adhesive remains linear until approximately 12 MPa shear stress and 1% shear strain, with the elastic limit of the adhesive reached at about 22 MPa shear stress and 3% shear strain.

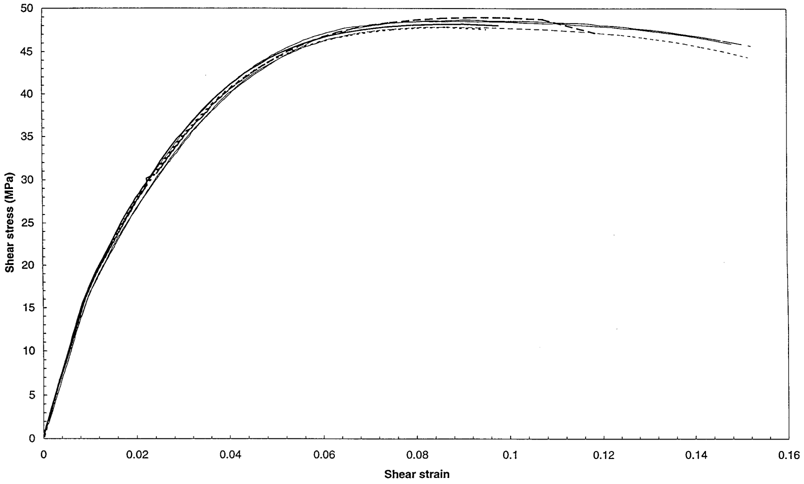

FIGURE 15 Variation of shear stress with shear strain for ESP110.

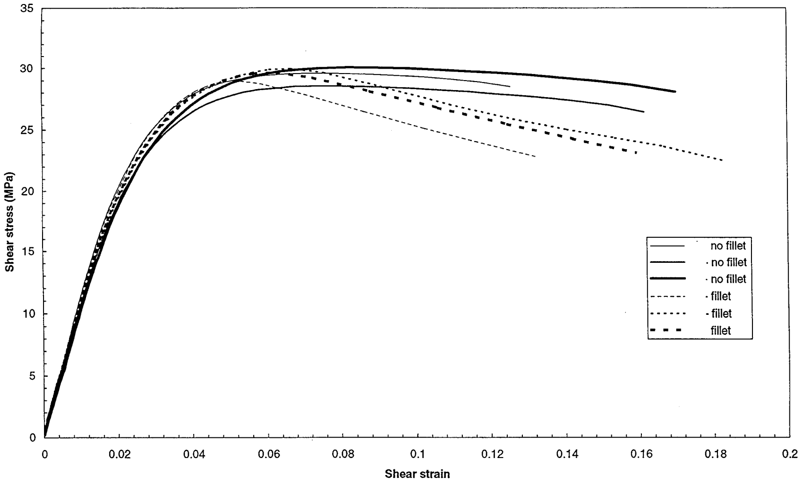

FIGURE 16 Variation of shear stress with shear strain for TE251.

The maximum shear stress of the joints with 45° fillets was found to be similar to those without fillets, though it dropped considerably once yield of the adhesive had occurred, with no obvious increase in strain to failure (Table 2).

Shear Stress-Strain Data for F241

F241 is a two-part acrylic, which is flexible and tough postcure. From the shear stress-strain curve to failure (Figure 17), it can be seen that the adhesive remains linear until approximately 5 MPa shear stress and 1% shear strain. Shear modulus measurements of the adhesive were very different from those of the stiff adhesives, AV119, TE251, and ESP110. The several shear stress-strain curves of F241 in Figure 17 show that the TAST method gives repeatable data for such a ductile adhesive, especially for the shear modulus measurements.

Shear Stress-Strain Data for SBT

SBT is initially a pressure-sensitive adhesive tape which is cured to produce structural performance. From the shear stress-strain curve to failure (Figure 18), it can be seen that it is a flexible adhesive and exhibits a similar behavior to F241, but is very different from the stiff adhesives, AV119, TE251, and ESP110. Above approximately 3 MPa, the shear stress-strain curve is linear almost to failure. For this region, the average shear modulus is about 7.5 MPa. The shear stress-strain curve of the adhesive is not as consistent as for the stiff

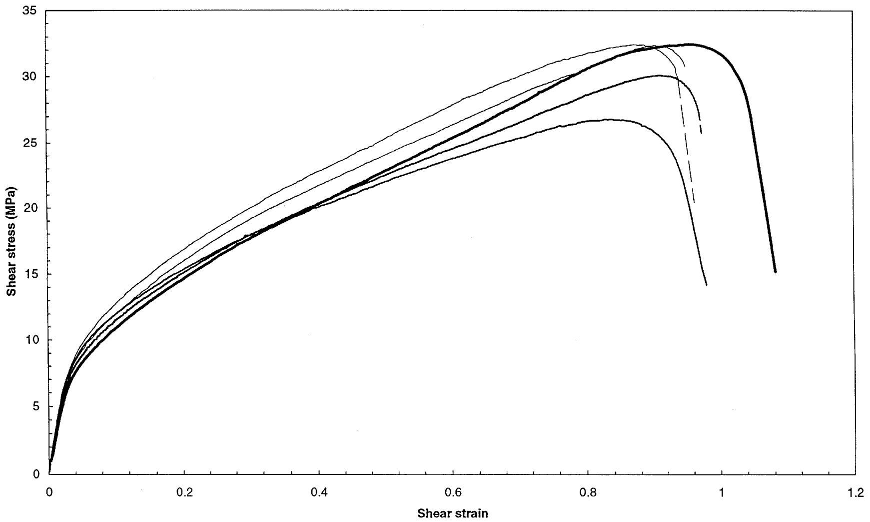

FIGURE 17 Variation of shear stresses with shear strains from the several F241 joints showing the repeatability of the TAST method for such a flexible adhesive.

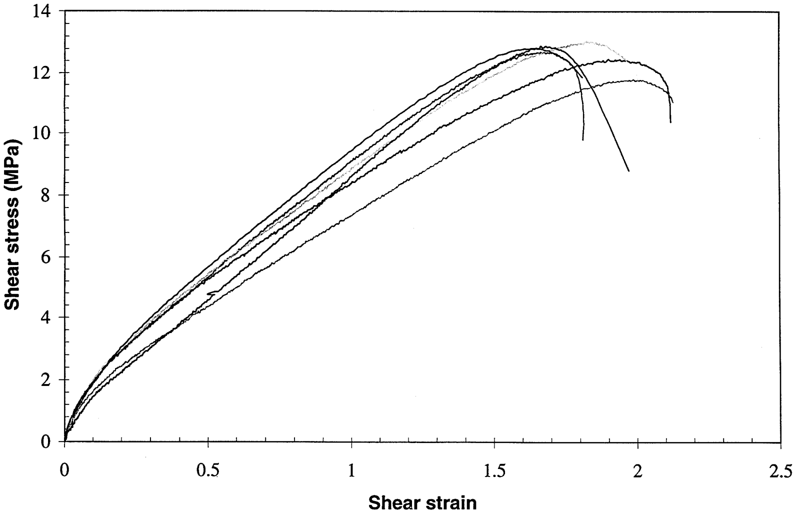

FIGURE 18 Variation of shear stresses with shear strains from the several SBT joints showing the repeatability of the TAST method for such a flexible adhesive.

adhesives. Figure 18 represents the repeatability of the shear stress-strain curves using the SBT joints tested under the same conditions.

Comparison of Shear Stress-Strain Curves of the TAST and the Butt Torsion Test

One flexible adhesive, SBT, and one stiff adhesive, AV119, were chosen for comparison between the shear stress-strain curves from the TAST and the butt torsion test. It is very interesting that the tape (SBT) shear stress-strain curves are very similar from both tests (Figure 19), although a slightly higher maximum shear stress is observed from the butt torsion test. Figure 19 also shows the shear stress-strain behavior of AV119. It is clear that the curves are similar and indicate the same behavior, although the strain to failure from the TAST is slightly lower than that of the butt torsion test.

DISCUSSION AND CONCLUSIONS

Overall, the Althof type of extensometry has good repeatability for the experimentally determined shear stress-strain curves. With

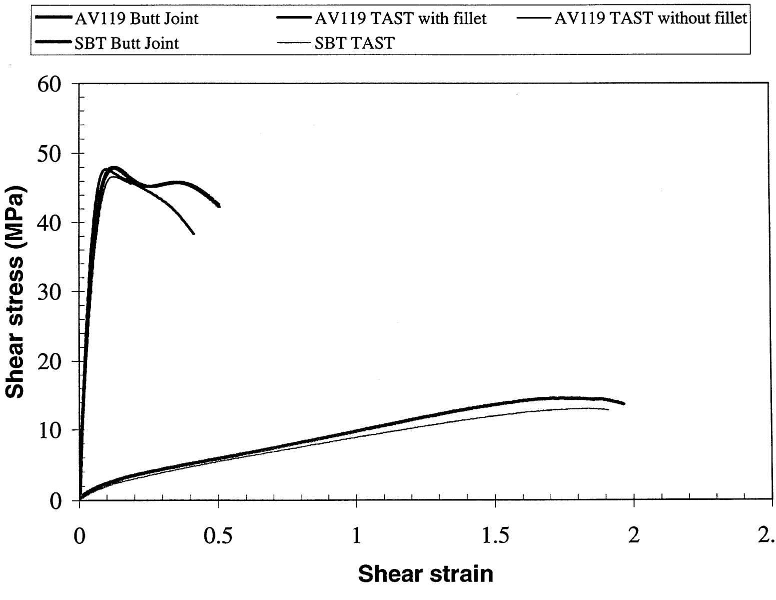

FIGURE 19 A comparison of AV119 and SBT shear stress-strain curves from the TAST and the butt joint specimens.

appropriate amplification, the extensometry is able to record the deformation of the adhesive in the TAST joint, throughout both the elastic and plastic range of the structural adhesives tested here. The importance of amplification of the extensometry becomes paramount as the bondline thickness of the joint decreases, since the displacements associated with the adhesive strain are reduced.

For almost all the adhesive joints produced with a fillet, the measured shear modulus was slightly higher than that for those joints made without a fillet. This is essentially due to the difficulty of defining the true applied shear stress when using a fillet. The maximum shear stress for joints with fillets was slightly lower than for joints without fillets. This is due to 1) the higher degree of constraint imposed upon the adhesive by the presence of the fillet and 2) tensile strains in the fillet allowing yield of the fillet at a lower stress than for the bulk of the adhesive, thus decreasing the maximum shear stress obtained. The introduction of a bondline fillet appears to have a greater effect on some adhesives than others when the specimens are tested to failure. Generally, for the adhesives tested, the strain to failure is increased and the mode of failure is changed, when compared with joints without fillets. Examination of all the failed joints revealed a different mode of cohesive failure for those joints with and without fillets. Joints with fillets are left with adhesive on both adherends with a fracture surface at an angle perpendicular to the maximum principal tensile stress direction (Figure 20), whereas joints without fillets are left with adhesive on one adherend only.

The finite element analyses have shown that the maximum principal tensile stress concentration in a TAST joint without a fillet is at the lower corner of the overlap (position A in Figure 11) and, when a fillet of any dimensions is added, this changes to the point on the fillet closest to the upper corner of the overlap (position B in Figure 11). However, caution must be used in the interpretation of the finite element results since, by virtue of the mesh discontinuity, stress concentrations arise which can obscure or falsify results; to a certain extent, these stress concentrations actually exist in the specimens tested, although, as Peppiatt [19] found, corners as sharp as those modelled do not occur experimentally, and a certain degree of rounding of the adherend corners from a machining process takes place, which will serve to remove the singularity.

Work conducted by Thomas and Adams [20] and Coppendale [21] on the shear testing of bulk adhesives has shown that once the adhesive has yielded, the shear stress attains a constant value. For all the TAST joints, but especially those with fillets, the drop in average shear stress

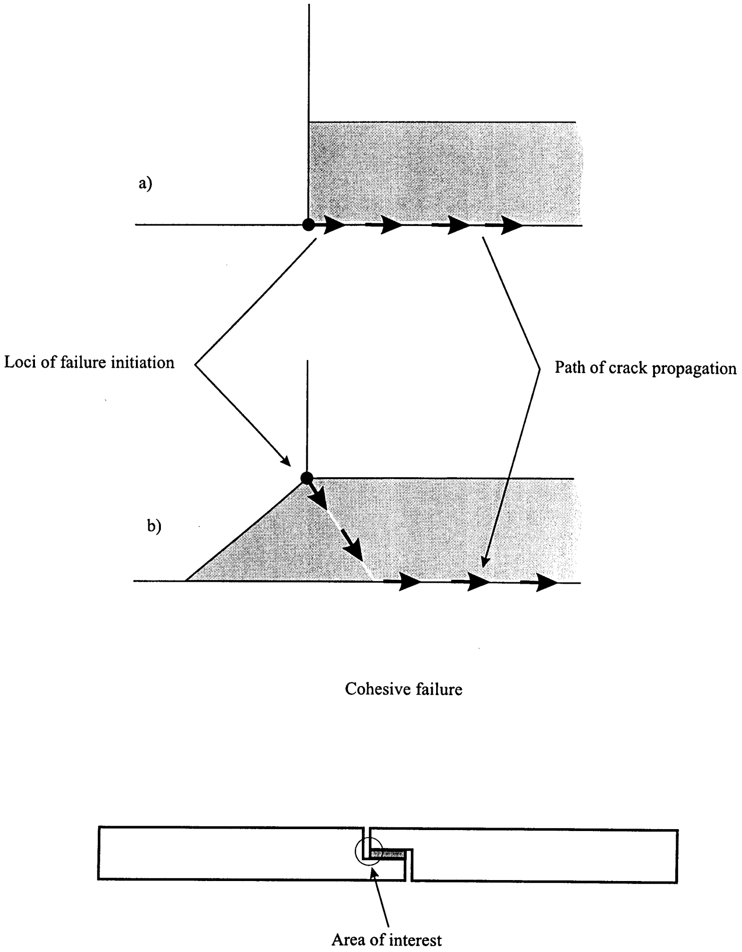

FIGURE 20 Paths of crack propagation for a) joints without fillets and b) joints with 45° fillets.

after yield of the adhesive is thought to be due to crack propagation along the paths identified in Figure 20. The crack initiates at the ends of the overlap and comes together at the center of the joint. This has the effect of reducing the bond area over which the load is acting, and therefore also the load, but would not actually reduce the shear stress experienced by the adhesive. Since the change in area cannot be taken into account when producing the graph, the shear stress appears to drop off.

The finite element analysis showed that, without a fillet, tensile peel stresses are concentrated at the corners of the adhesive layer and the joints fail toward the adhesive corner at the continuous adherend before the shear limit of the bulk of the adhesive has been reached. With a fillet, the tensile peel stresses are reduced to the point where they no longer dominate the mode of failure, and the adhesive reaches its shear limit.

It can be seen from Figure 19 that the curves from the butt torsion test and the TAST are consistent and give the same behavior for the two adhesives tested. The stress-strain concentrations at the ends of the overlap in the TAST do not seem to affect the flexible adhesive (SBT) behavior and it shows its full strain potential, although without a fillet. However, as can be seen for AV119 in Figure 19, the fillet recommended for the stiff adhesives enables the true shear stress-strain behavior to be achieved, and the results agree with those obtained in the butt torsion test in which there is no stress or strain concentration. However, it is clear that AV119 without a fillet fails prematurely; although the full stress is achieved, the full strain is not.

Finally, the TAST extensometry has been shown to be suitable for measuring the shear strain properties of stiff and flexible adhesives. The shear behavior of five adhesives has been measured using the TAST method and, from the results represented in this paper, it can be seen that the TAST method is repeatable and reproducible for a wide range of structural adhesives. It is, however, recommended that high-strength adhesives which have a limited strain to failure, such as AV119, should be tested with a 45° fillet.

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