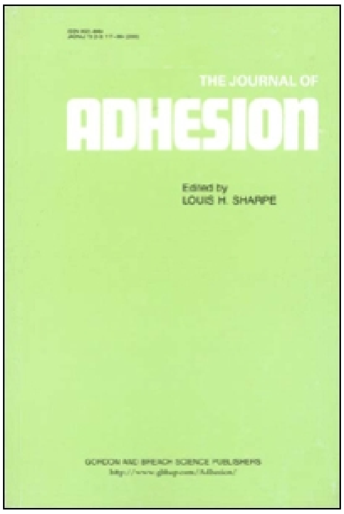


The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

The Shear Stress-Strain Behaviour of Low-modulus Structural Adhesives

F. Kadioglu[a]; R. D. Adams; F. J. Guild[a]
[a] Composites and Adhesives Group, Department of Mechanical Engineering, University of Bristol, Bristol, UK

To cite this Article Kadioglu, F. , Adams, R. D. and Guild, F. J.(2000) 'The Shear Stress-Strain Behaviour of Low-modulus Structural Adhesives', The Journal of Adhesion, 73: 2, 117 — 133
To link to this Article: DOI: 10.1080/00218460008029302
URL: http://dx.doi.org/10.1080/00218460008029302

J. Adhesion, 2000, Vol. 73, pp. 117–133
Reprints available directly from the publisher
Photocopying permitted by license only

The Shear Stress–Strain Behaviour of Low-modulus Structural Adhesives*

F. KADIOGLU, R. D. ADAMS† and F. J. GUILD

Composites and Adhesives Group, Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, UK

(Received 31 December 1999; In final form 29 February 2000)

The shear stress–strain behaviour of two low-modulus structural adhesives has been measured using the butt-torsion test. The Nadai correction for non-linear shear behaviour is explained as it is necessary to understand how this correction can be applied to butt joints. The results for one adhesive were accurately used to predict the strength of a lap joint, and it was shown that the strength of such a joint can approach that of a conventional, modern, structural epoxy. Structural adhesives are usually reckoned to be those with a high strength (50 MPa and upwards) and (these days), a strain to failure of at least 10% in tension, and which usually have a tensile modulus of 2 GPa or so. However, adhesives which are significantly less stiff, less strong, but much more ductile are entering the "structural" arena. In order to evaluate their effectiveness and use in design, it is necessary to be able to measure accurately their stress–strain behaviour. Two such materials are 3M 9245 Structural Bonding Tape (SBT) and 3M 7838 B/A.

Keywords: Butt joint; Shear test; Low-modulus structural adhesives; Structural bonding tape

1. INTRODUCTION

Using a bulk specimen test, it is relatively straightforward to obtain a stress–strain curve to failure under uniaxial tension by employing the standard test specimen ISO 3167 [1] and test method ISO 527-1 [2]

*One of a Collection of papers honoring F. James Boerio, the recipient in February 1999 of *The Adhesion Society Award for Excellence in Adhesion Science, Sponsored by 3M*.

†Corresponding author. Tel.: (0117) 9287743/44, Fax: (0117) 9294423, e-mail: r.d.adams@bristol.ac.uk

developed for plastics. However, it is well known that the stress state in the joint under working conditions is quite complex and tensile stress – strain data alone are not sufficient to analyse it. Therefore, shear tests should be undertaken as well to obtain shear stress – strain values. These two main tests, tension and shear, will help to understand the stress – strain states in the joints when Finite Element Analysis (FEA) is employed.

Some researchers have investigated a number of shear test methods to obtain reliable data; for example, Peretz [3] evaluated the shear behaviour data of adhesives by using a specially-constructed torsion device which enabled the recording of the shear moment-displacement relationship for the adhesive layers. Shear strains and stresses were computed from the recorded torsional moment-displacement curve by assuming a linear shear strain distribution throughout the adhesive thickness and uniform shear strain distribution at the cross-sectional area. The general trend showed an increase of modulus with an increase in thickness up to that of the bulk material modulus, with very little change in shear strength. Adams and Coppendale [4], however, showed no change of modulus with adhesive layer thickness.

Dolev and Ishai [5] conducted an extensive test series on bulk and *in-situ* adhesive specimens with a view to characterising their mechanical properties under different loading modes and states of stress. Although they found that a good correlation existed between the *in-situ* and the bulk properties of shear yield strength and elastic modulus derived from the torsion test, they, too, found that the measured shear modulus of the adhesives in the joint were lower than that of the bulk.

Lilleheden [6] is one of a few researchers who undertook an in-depth experimental investigation of the mechanical properties of an adhesive material in bulk and thin-film forms to explain the reasons for the above discrepancies. In his work, special attention was paid to the following points:

- development of a test specimen that provides a well-defined state of stress in the adhesive layer,
- close resemblance of the curing conditions during manufacturing of the bulk specimen with those pertaining in an actual joint, and
- development of a highly sensitive measurement system.

Lilleheden's system is based on Moiré interferometry which enables continuous analysis of the strain field in the adhesive layer across its thickness at the edge of the bond. Thus, any inhomogeneities in the elastic properties of the adhesive can be detected and quantified.

To determine the mechanical properties of the adhesive material in the thin-film form, a new specimen geometry, based on the thick-adherend specimen in which the adhesive conformed to thin-film conditions, was developed. To achieve this, Lilleheden [6] analysed the stress state in the traditional thick-adherend specimen, followed by a shape optimisation procedure. Finally, it was concluded that from tests on adhesive joints with different bondline thicknesses and on bulk adhesive specimens, that there was no thickness dependency of the elastic properties, which is in agreement with Adams and Coppendale's [4] findings. The main sources of error which led to the incorrect conclusions of the other authors were attributed to:

- variability in curing conditions,
- ill-defined strain field in the test specimen, and
- inadequate measuring system.

Associated with industrial demands, adhesive technology has been introducing new products which exhibit radically different mechanical behaviour. Eventually, different types of shear test methods have been developed for determining the shear properties of these new adhesives. These methods are mainly as follows:

(1) Torsion Method,
(2) Notched Beam Shear (Iosipescu) Method,
(3) Notched Plate Shear (Arcan) Method, and
(4) Thick Adherend Shear Test (TAST) Method.

In order to assess the ease of using and the reliability of these methods, the Department of Trade and Industry (DTI) in the UK through the Measurement Technology and Standards (MTS) budget initiated a series of experimental works with the co-operation of several research centres. For comprehensively understanding adhesive behaviour, three joint specimen tests and three bulk specimen tests were selected, using the methods mentioned above. In making the selection, consideration was made of the accuracy that could be achieved in measured properties and the cost and difficulty of undertaking the test. Bulk specimen tests were included due to the scope for higher precision in the measurement of strain in the adhesive.

Brief descriptions of each methods have been given by Dean *et al.* [7] who conclude that, with certain exceptions, there are no systematic differences between the results from each of the test methods studied. Apparent differences between the shear stress – strain results are attributed to material variability and the precision of the test method.

Also, in the same paper, a general assessment gained from the experimental work was given for selecting the most appropriate test method for determining the shear behaviour of adhesives, regarding the precision in strain measurement. The highest precision in strain measurement is achieved with the bulk torsion test and the precision in the butt joint torsion test is greater than that of the other joints. Where methods for bulk specimen preparation are not available (such as because of exothermic reactions) or there is concern over the quality or structure of thick bulk specimens, which is usually the case for soft materials, the butt joint torsion test is probably the most appropriate alternative method. Vaughn *et al.* [8] have extensively investigated the torsion test method.

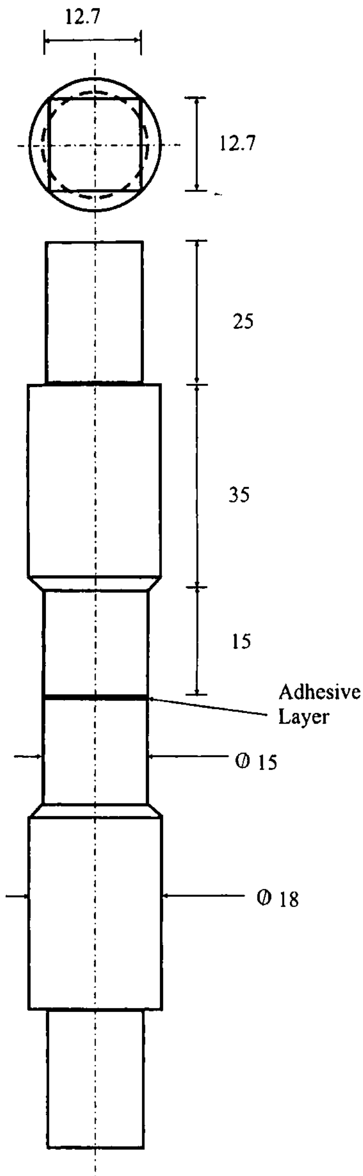
If a torsion test facility is not available, the Arcan *et al.* [9] test method can be suggested for low shear strains, due to the larger gauge length used for the measurement of strain in the specimen.

However, where materials have high shear strains, instead of the Arcan bulk specimen test, the thick-adherend shear test [10] can be used. In the light of these investigations, it was decided that the most appropriate method for determining the shear stress – strain behaviour of an adhesive which was expected to exhibit a high strain to failure, is the butt joint test. With soft (low modulus) adhesives, the bulk torsion test would not be practical as problems would be encountered with the preparation of the bulk specimens and the means of gripping its end. The objective of this study was to investigate the feasibility of using the torsional butt joint test for determining the shear stress – strain behaviour of two flexible adhesives. One of these was 3M 9245 Structural Bonding Tape (SBT), and the other was 3M 7838 B/A, a paste adhesive. To put the results in perspective, the properties of a conventional structural epoxy, AV119 by Ciba, were also measured.

2. PREPARATION OF JOINTS

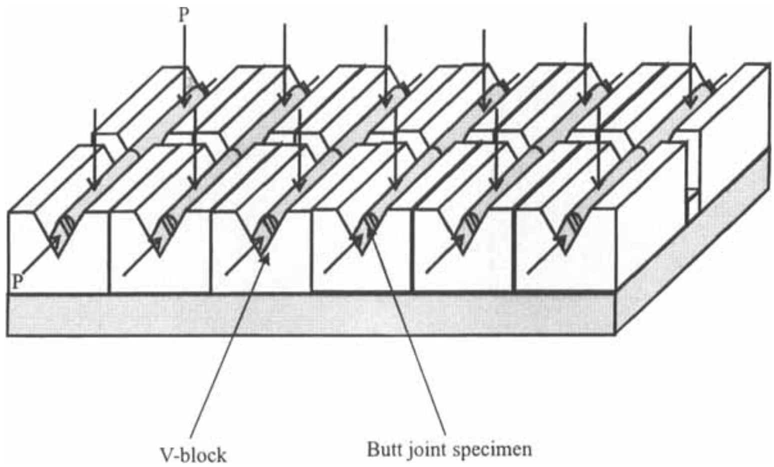
The butt joint is a kind of specimen used for testing the response of an adhesive to shear, tensile and compressive stresses. There are several types of butt joints, usually axisymmetric, but also with square or rectangular shapes. The specimens used here have a round cross-section in the gauge length but have square ends for gripping, as shown in Figure 1.

During the curing process, the joints must be in line and the bond lines be of the required thickness. For that reason, two different types of jigs were used for the epoxy paste and for the tape adhesive joints, as these materials have different states prior to cure (a viscous liquid and solid, respectively). Epoxy butt joints were assembled in an aluminium V-block jig on which six joints could be located at the same time, being positioned horizontally, as shown in Figure 2. The same jig was tried for making joints with the tape. However, some difficulties occurred due to its lack of fillet property and the need to apply pressure to the surfaces to be joined: when the pressure was applied on the joints, it led to misalignment in the V-block jig. Applying pressure to the joints was necessary because the tape was pressure-sensitive during fabrication and the adherend surfaces needed to be in contact with every point for better strength. Finally, another type of jig in which the joints could be assembled vertically was preferred. For that purpose, the authors designed the jig shown in Figure 3, accommodating four joints at the same time. Two steel bars were used to keep the joints in line and, to provide steady pressure on the joints during the cure process, weights were put on the jig. The reason why 9245 Structural Bonding Tape (SBT) should be cured vertically can be explained as follows: since the material softens at higher temperatures, large stresses on the bonded joint need to be accompanied with steady pressure during curing. As it is known that during curing the adhesive shrinks, the contact between the adhesive and adherend surface starts to lose its original interaction. In order to keep permanent contact between them, the vertical jig was preferred. The



All dimensions in mm

FIGURE 1 Butt-torsion specimen.



P: pressure

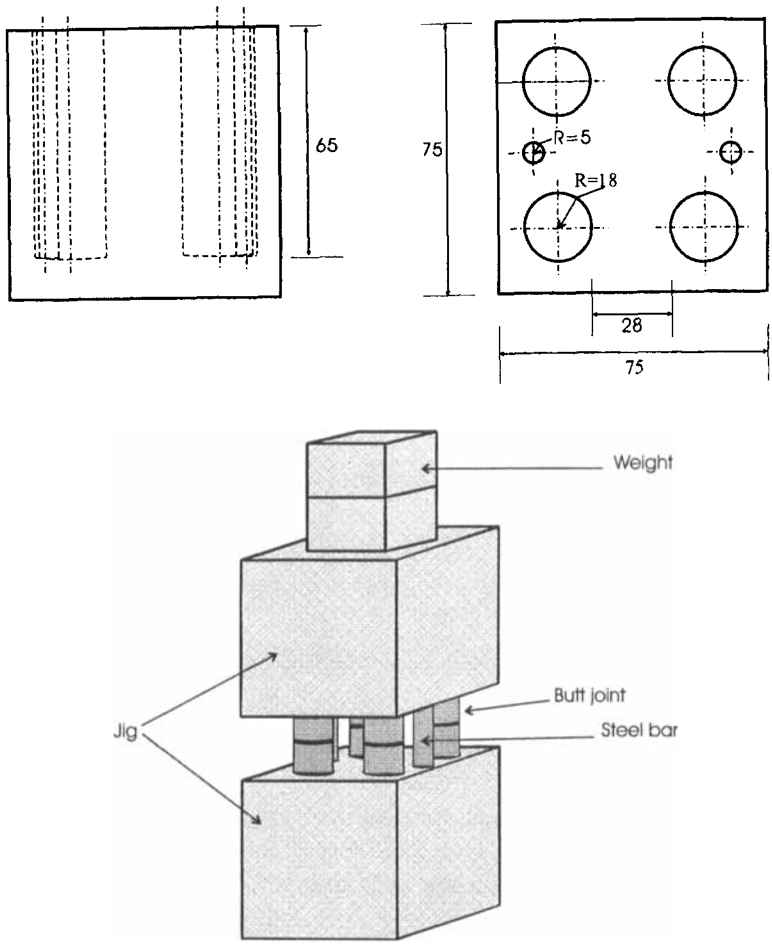
FIGURE 2 V-block jig used for liquid adhesives.

Structural Bonding Tape was cured at 140°C for 45 minutes, according to the manufacturer's instructions.

After curing, the specimens were allowed to cool in the jig and the fillet around the adhesive layer was then machined carefully so that any damage would not affect the joint strength. Following that, each specimen thickness was measured by a projection microscope and the specimens conditioned in a desiccator cabinet for two weeks.

The 3M 7838 B/A adhesive is a two-part adhesive which needs to be mixed in equal parts by weight. The specimens were located horizontally on the V-jig with a 0.5 mm gap. Avoiding any voids in the adhesive layer, the specimens were assembled in line with the required pressure applied at their ends and the adhesive was kept in place in the joint using shaped silicone rubber rings around the joints. The adhesive was cured at room temperature for seven days according to the manufacturer's instructions.

AV119 is a one-part epoxy, manufactured by Ciba Polymers. Like 7838 B/A, it is in its liquid state during fabrication of the joints. A standard cartridge gun was used to apply the adhesive to both



All dimensions in mm

FIGURE 3 Jig used for tape butt joint.

substrate surfaces, which were located horizontally on the V-jig with a 0.5 mm gap. Then, the jig was placed in the previously heated press and a low pressure was applied. The joints were cured at 120°C for an hour according to the manufacturer's instructions.

The fillets formed around the adhesive layer at the outer radius had to be machined away since they produce stress concentration effects on the joint as shown by Adams et al. [11].

3. EXPERIMENTAL SET-UP

3.1. Torsion Device

The principle of the butt torsion test is to apply a torque to a cylindrical rod, loading the material in the butt in pure shear. The applied torque can be measured easily by using a load cell, but the determination of the resulting strain is more complicated. This is because the bondline thickness is very small, which means a very low angular displacement. A nominal thickness of 0.5 mm is usually enough to test butt joints in torsion. The strain in the adherends also has an affect on the total strain, so the strain should be measured as close to the adhesive layer as possible so that the effect of the deformation in the adherends can be kept to a minimum. Any strain in the adherends can be calculated to give the actual displacement due to the torque on the adhesive joint.

All the torsion testing was conducted utilising a variable speed torsional testing machine. This was designed to test specimens under torsional loading, minimising the axial and bending loads on the specimen. The specimens are located in square jaws at either end of the machine. The variable speed motor applies an angular displacement to the specimen under test, driving through reduction gears, and the torque is transmitted to the specimen through hardened steel balls. Specimens with a length between 100 and 200 mm can be accommodated, with a variable speed motor to provide the required surface strain rate for each specific specimen diameter. The direction of the motor is reversible to facilitate unloading a specimen after a test.

The torque applied to the butt joint was measured with a load cell located between the stationary end of the specimen and the frame of the machine. A Sangamo C30 transducer conditioner was used to transfer the output from the load cell to the computer. For greater resolution, if necessary, the gain of the data acquisition processor could be increased. Voltages were recorded at specific time intervals and this was used to determine the strain rate applied to the adhesive.

Linear Variable Differential Transducers (LVDTs) were used to measure the displacement in the butt joints. These transducers were held in place using the specially-designed extensometer arms, shown in Figure 4. The jig was located on the joint specimen using pins

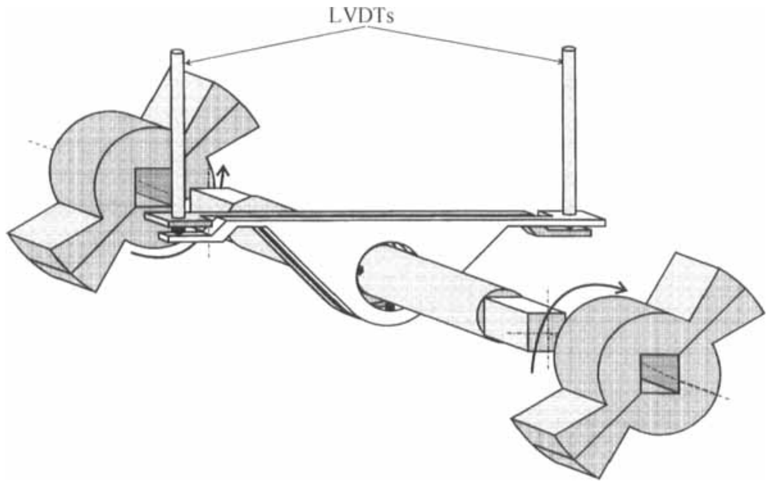


FIGURE 4 Extensometry for butt joint testing.

positioned approximately 4 mm on either side of the adhesive layer. The exact position of these pins was measured accurately following each test. It was important to ensure that the pins were tightened sufficiently to hold the extensometry in place. Two transducers were used, one on each side of the joint, to check that no bending was introduced during the test. The average of the two LVDTs was used to calculate the strain.

4. THEORETICAL DERIVATION OF SHEAR STRESS-STRAIN VALUES FROM THE EXPERIMENTAL DATA

The torque-twist equation for a solid of circular cross-section is:

$$T = GI_p \frac{d\theta}{dx} \tag{1}$$

where

G is the shear modulus of material,
T is the applied torque,
I_p is the polar moment of inertia ($I_p = (\pi R^4/2)$),
R is the outer radius,

and the derivative $(d\theta/dx)$ is the twist per unit length.

Also, for a solid of circular cross-section, the shear stress, τ, at any radius, r, is given by:

$$\tau = \frac{Tr}{I_p} \tag{2}$$

where

τ is the torsional stress, and
r is the radius.

Therefore,

$$\tau = \frac{2Tr}{\pi R^4} \tag{3}$$

The shear strain at any radius, r, for a circular section is given by the equation:

$$\gamma = \frac{r\theta}{l} \tag{4}$$

where

γ is the shear strain,
θ is the angular displacement in radians,
l is the length of the section.

When testing butt joints, the angular displacement is measured using LVDTs located at the distance of a mm from the centre of the joint. The angular displacement (assuming a small angular rotation) is calculated according to the relationship:

$$\theta = \frac{\delta}{a} \tag{5}$$

where δ is the displacement in mm measured by the LVDTs, and a is the length of the extensometer arm.

The angular displacement measured by the LVDTs includes the movement due to the steel adherends as well as the adhesive, since the extensometer is located on the butt joint at approximately 4 mm on both sides of the bondline. The joint is loaded in pure shear and the loads applied to the specimen ensure that the steel adherend is always operating in the linear elastic region. Therefore, a simple strength of materials equation can be used to calculate the strain in the steel. *i.e.*,

$$\gamma = \frac{\tau}{G} \tag{6}$$

The strain can be calculated simply from this relationship, using the measured stress. The shear modulus of the steel adherends was 82 GPa.

In a cylindrical bar of circular cross-section under torsion, the distribution of shear stress given in Eq. (3) is only valid for elastic behaviour of the material. After the yield point has been exceeded, this equation overestimates the actual shear stress. Nadai [12] developed a correction to the measured torque-twist curve that gives the true stress–strain curve.

The shear stress, τ, is a function, $\tau(\gamma)$, of the shear strain. The function:

$$\tau = \tau(\gamma) \tag{7}$$

is the shear stress–strain curve.

If the stress–strain curve of the material in shear is known, it is possible to determine the torque acting on a bar in terms of the unit angular twist. This curve, $T = T(\theta)$, which is called torque-twist curve, may be determined from a torsion test. The torque is given by the integral:

$$T = 2\pi \int_0^R \tau r^2 dr \tag{8}$$

Since $\gamma = (r\theta/l)$ and $dr = (l d\gamma/\theta)$, substituting γ for r, this equation becomes:

$$T = \frac{2\pi l^3}{\theta^3} \int_0^{\gamma_R} \tau(\gamma)\gamma^2 d\gamma \tag{9}$$

where $\gamma_R = (R\theta/l)$.

If the torque-twist curve $T(\theta)$ *vs.* θ is known from a torsion test, it is possible to use Eq. (9) to determine the unknown stress–strain curve of the material for shear. Rewriting Eq. (9) as:

$$T\theta^3 = 2\pi l^3 \int_0^{\gamma_R} \tau(\gamma)\gamma^2 d\gamma \tag{10}$$

it can be seen that the right hand side is a function of the upper limit, γ_R, and, since $\gamma_R = (R\theta/l)$, it is also a function of θ. Differentiating Eq. (10) with respect to θ gives:

$$3\theta^2 T + \theta^3 \frac{dT}{d\theta} = 2\pi l^3 \tau(\gamma_R)\gamma_R^2 \frac{d\gamma}{d\theta} = 2\pi R^3 \theta^2 \tau_R \tag{11}$$

Since $\tau = \tau(\gamma)$, the shear stress, τ_R, at the edge of the circular cross-section can be determined. From Eq. (11), the value of τ_R at the outer radius is given by:

$$\tau_R = \frac{1}{2\pi R^3}\left(3T + \theta \frac{dT}{d\theta}\right) \tag{12}$$

In terms of the torque-twist curve obtained from a torsion test as shown in Figure 5, this equation becomes:

$$\tau_R = \frac{1}{2\pi R^3}(3AC + AB) \tag{13}$$

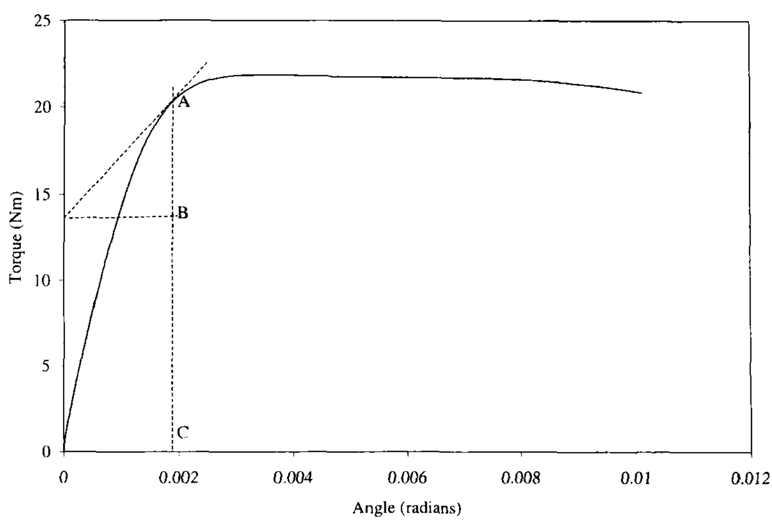


FIGURE 5 Calculation of the true shear stress *vs.* shear strain from the torque-twist data using the Nadai correction.

5. RESULTS

Initial results from the torsion test showed that the tape and two-part epoxy (7838 B/A) were sensitive to the temperature and speed at which the test was carried out. In order to obtain consistent results, each test was conducted at constant speed and temperature. All the tests were conducted at 23°C and 50% relative humidity.

5.1. Shear Stress–Strain Data for AV119

A typical Nadai-corrected AV119 shear stress–strain curve is shown in Figure 6. The behaviour of the adhesive is fairly linear until about 43 MPa and a shear strain of nearly 6%; the specimen eventually failed at a strain of approximately 50%. The shear modulus calculated from the linear part of the curve is 1.08 GPa. The measured maximum shear stress and strain to failure are 50 MPa and 49%, respectively. These results agreed well with other data (Vaughn *et al.* [8]) which gave an average shear modulus of 1.11 GPa, a maximum stress of 48.9 MPa, and a strain to failure of 45%.

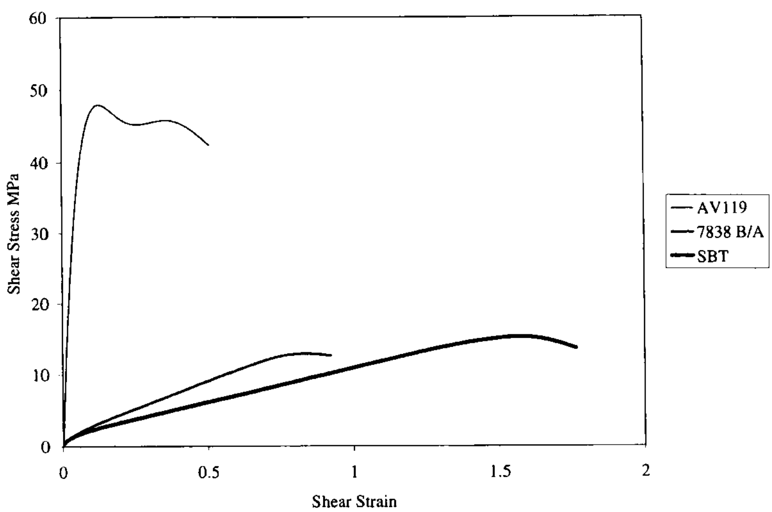


FIGURE 6 Stress–strain curves from butt joint specimens of different adhesives.

TABLE I Shear data for the butt joints

Adhesives	*Max stress MPa*	*Strain to failure*	*Shear modulus MPa*	*Adhesive thickness mm*
AV119	49.05 ± 1.15	0.47 ± 0.01	1.10 ± 0.02	0.550 ± 0.01
7838 B/A	12.86 ± 0.62	0.86 ± 0.04	15.22 ± 0.52	0.485 ± 0.01
SBT	15.26 ± 0.65	1.57 ± 0.08	9.20 ± 0.94	0.435 ± 0.02

5.2. Shear Stress–Strain Data for 7838 B/A

A typical shear stress–strain curve for 7838 B/A is also shown in Figure 6. The behaviour is quite different from AV119. Above approximately 5 MPa, the stress–strain curve is linear almost to failure. For this linear region, the average shear modulus is about 15 MPa. The average maximum shear stress and strain are approximately 13 MPa and 90%, respectively.

5.3. Shear Stress–Strain Data for SBT

A typical stress–strain curve for SBT is given in Figure 6. The curve gives a maximum stress of around 15 MPa at a strain of about 160%. The behaviour of the tape is much more similar to the two-part epoxy (7838 B/A) with its quasi-linear behaviour than to the one-part structural epoxy (AV119). It has fairly high maximum stress when compared with the traditional adhesive tapes, and a high strain to failure. The shear modulus defined by the long linear portion of the stress–strain curve averages at 9.2 MPa, which is less than for 7838 B/A. The major details of all the adhesives tested are summarised in Table I.

6. DISCUSSION AND CONCLUSIONS

The butt joint test has been successfully used for measuring the shear stress–strain behaviour of two flexible structural adhesives, 3M 7838 B/A, and 3M 9245 Structural Bonding Tape.

A conventional structural epoxy such as Ciba's AV119 has a shear stress–strain behaviour which is initially linear, followed by a region in which high strains (up to 50%) are developed with no significant increase in stress (see Fig. 6). Both 7838 B/A and the SBT show quite different behaviour. For most of their shear stress–strain curve, both these materials exhibit an almost linear increase in stress with strain. Whereas with the AV119 any Finite Element Analysis must be non-linear, so as to account for the "yield" region, the two softer adhesives may be considered to be essentially "elastic", thus allowing a simpler analysis run to be followed. Both of the "soft" adhesives showed a useful level of strength (approximately 15 MPa) coupled with 2 to 3 times more strain to failure than the already generous 50% of the AV119.

Because the SBT is soft (the shear modulus 9.2 MPa being about 100 times less than that of the AV119), the distribution of shear stress (and strain) along the length of a lap joint will be almost uniform. It is, therefore, possible to achieve the maximum strength of the adhesive in lap shear. Thus, a 25×25 mm (1 inch square) lap joint should achieve a tensile load of 9.38 kN using an average maximum shear stress of 15 MPa. Much stiffer and stronger adhesives which are usually less ductile will develop stress concentrations at the ends of the joint. Thus, even though the adhesive may be stronger, the joint strength may not be much higher than that using the SBT or 7838 B/A. For example, using mild steel adherends of 25×25 mm, the authors found a fracture load of 9 kN with SBT, which compares well with a value of 11.6 kN with AV119, Karachalios [13]. Thus, an adhesive which is 3.34 times stronger (50 MPa *cf.* 15 MPa) gives steel–steel lap joint strengths about 1.28 times greater. This shows that these soft adhesives, which have a shear modulus of only 10–15 MPa, have a performance which can match that of conventional structural epoxies. The 3M 9245 SBT is truly a structurally-useful adhesive, and the strength of its joints can be accurately predicted from these butt-torsion test results.

Acknowledgement

We would like to thank Mrs. R. Thomas for providing some of the AV119 data.

References

[1] ISO 3167: 1993, *Plastics-Multipurpose test specimens.*
[2] ISO 527-1: 1993, *Plastics-Determination of tensile properties*, Part 1: General principles.

[3] Peretz, D., *J. Adhesion* **9**, 115 (1978).
[4] Adams, R. D. and Coppendale, J., *J. Mech. Eng. Sci.* **18**, 149 (1976).
[5] Dolev, G. and Ishai, O., *J. Adhesion* **12**, 283 (1981).
[6] Lilleheden, L., *Int. J. Adhesion and Adhesives* **14**, 31 (1994).
[7] Dean, G. D., Duncan, B. C., Adams, R. D., Thomas, R. and Vaughn, L. F., *Preprints European Adhesion Conference*, Cambridge, UK, 1996, pp. 113–118.
[8] Vaughn, L. F., Thomas, R., Guild, F. J. and Adams, R. D., *SAEV Fifth International Conference*, Bristol, UK, 1998, pp. 180–185.
[9] Arcan, M., Hashin, Z. and Voloshin, A., *Experimental Mechanics* **18**, 141 (1978).
[10] Vaughn, L. F., Adams, R. D. and Guild, F. J., *Preprints European Adhesion Conference*, Cambridge, UK, 1996, pp. 287–292.
[11] Adams, R. D., Coppendale, J. and Peppiat, N. A., *J. Strain Anal.* **13**, 1 (1978).
[12] Nadai, A., *Plasticity: A Mechanics of the Plastics State of Matters* (McGraw-Hill, New York, 1931).
[13] Karachalios, E. F., Private communication (1999).