



the department for Enterprise

MTS Adhesives Project 1

Basic Mechanical Properties for Design

Report No 6 June 1996

**TEST METHODS FOR DETERMINING SHEAR PROPERTY DATA FOR
ADHESIVES SUITABLE FOR DESIGN.**

**Part 1: Notched-beam shear (Iosipescu) and notched-plate shear (Arcan)
methods for bulk and joint test specimens.**

PART A: SUMMARY

The Performance of Adhesive Joints

1993-1996

**A research programme
funded by the Department of Trade and Industry**



**THE CENTRE
FOR ADHESIVE
TECHNOLOGY**



NPL
National Physical Laboratory

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1. INTRODUCTION

Stress/strain measurements to failure under shear stress are often required for design with adhesives. In Project 1 of the DTI programme on adhesives, test methods suitable for measuring mechanical properties for design purposes are being evaluated. Shear properties of adhesives in bulk or joint specimen form can be measured by a number of test methods such as torsion, thick adherend shear or notched-shear. The current report describes V-notched specimen shear tests for measuring adhesives in both bulk and joint specimen formats and is a summary of a detailed evaluation of these methods. The full report [1] which describes the test methods and illustrative results in detail is available from the authors. Related reports describe the torsion [2] and thick-adherend shear tests [3] and a final report [4] compares results from each of the techniques in order to provide information that will enable the most appropriate method to be selected for a particular type of adhesive.

A further aim of this work is to provide information on whether the material properties of adhesives are the same in bulk and joint specimens. Bulk specimens will have larger gauge sections which give scope for more accurate measurements of shear strain. Four structural adhesives (1-part epoxy Ciba AV119, 2-part epoxy Evode TE251, 2-part polyurethane 3M 3532 B/A and 2-part acrylic Permabond F241) having a range of mechanical properties typical of engineering adhesives were studied as part of this work. Bulk specimens (up to 4 mm thick) [5] and joint specimens (bondline thickness around 0.5 mm) were prepared for each material.

2. TEST METHODS

Two versions of the test were investigated, referred to here as the notched-beam (Iosipescu) [6] and the notched-plate (Arcan) [7] configurations. These are based on similar versions which have been described in the scientific literature by their originators and others. The test specimens used and methods of load application are shown in Figure 1. The principles of each test are the same. Symmetrical notches are cut in the centre of opposite edges of the test piece. The notch edges meet at an angle of 90° . The central region between the notch roots is the gauge section of the specimen. These tests seem to offer a number of advantages, viz:

- compact, easily manufactured specimens,
- uniform shear stress distribution in the gauge section determined to a good approximation from measurements of applied load and specimen dimensions,
- both modulus and strength measurements can generally be made,
- bulk and joint test specimens can be used,
- tests can be performed in a standard tensile test machine.

Tensile (or compressive) deformations applied to the specimen, parallel to the line joining the notch roots, produce pure shear deformations in the gauge section. Shear strains are measured in the gauge section where finite element analysis has shown that the shear stress is uniform and, to a good approximation, equal to the applied load divided by the product of specimen thickness and notch root separation.

Arcan bulk and Iosipescu bulk specimens were cut from sheets of the adhesives prepared using methods developed earlier in the project [5]. Tensile specimens were cut from the same sheets for comparison. Arcan joint specimens were prepared by bonding two shaped metal adherends to produce a specimen with the same shape as the Arcan bulk specimen. The bondline, running between the two notch roots, forms the gauge section. Excess adhesive fillets were machined off the joint specimens and the bond ends were filed to a concave shape to reduce stress concentrations. Both the bulk and joint specimens were straightforward to prepare.

In the bulk Iosipescu test, loads are applied via the edges of the test specimen and this arrangement is unsuitable for testing thin specimens or relatively soft adhesives. The Arcan test is performed by applying loads via the faces of the specimens and is therefore applicable to thinner bulk specimens and a wider range of adhesives. The report therefore concentrates on the use of the Arcan specimen.

Measuring strain in shear specimens is difficult in comparison with tensile tests due to the relatively small size of the gauge length used for the measurement of strain. Strain gauges can be used but their use is limited by local stiffening of the specimen to which they are bonded and their limited measurement range. To improve shear strain measurement, a prototype shear extensometer was developed for the Arcan test as part of this work. This is illustrated in Figure 2.

Briefly, the extensometer consists of a pair of levers which are needle pointed and contact the test specimen either side of the centre of the specimen. These contacts follow any displacements of the specimen in the direction of the applied load. Since the levers are pivoted, the movement of the specimen generates a deflection at the opposite end of each lever which is measured by a displacement transducer. The lever deflection multiplied by the lever ratio gives the movement of each point. The difference between the movements of the two points is the shear displacement. The horizontal distance

between the contact points is the gauge length. The shear strain is the displacement divided by the gauge length. As the shear strains on the opposite faces of the specimen can show large variations, strains are measured from both faces using a pair of extensometers and averaged to obtain acceptable strain data. Errors in strain measurements from this extensometer arise from uncertainties in the lever ratios and in the gauge length.

Finite element analyses of the bulk and joint Arcan test specimens have shown that the stress distribution in the centre of the gauge section is uniform shear. However, close to the notch roots the shear stress distribution is not uniform and there are tensile stress concentrations which may influence specimen failure. The stress concentrations are dependent on the shape of the notch root.

3. SHEAR MODULUS MEASUREMENT

The shear modulus of adhesives with values in the range 60 MPa to 1200 MPa have been determined by the Arcan test using both bulk and joint specimens. Stress/strain curves, particularly for compliant materials, show discontinuities at very low strains due to slack in the loading assembly. These reduce the reliability of the measurements using this test method. The reproducibility is acceptable. The 95 % confidence level (approximately twice the standard deviation) in modulus measurements on a single specimen (either bulk or joint) is typically less than ± 20 % of the mean value. The shear modulus measurements agree with those expected from tensile tests within these uncertainties. There is scope for increasing the accuracy of the test method through eliminating slack in the load assembly and improvements to the extensometer design shown.

The shear moduli measured for the four adhesives can be used to divide them into two classes. The 1-part epoxy ($G = 1100 \pm 150$ MPa) and 2-part epoxy ($G = 950 \pm 170$ MPa) were classified as 'stiff' adhesives. The 2-part polyurethane ($G = 65 \pm 15$ MPa) and 2-part acrylic ($G = 170 \pm 60$ MPa) were classified as 'compliant' adhesives. The accuracy of the Arcan test was slightly better for the stiff adhesives than for the compliant adhesives. The compliant adhesives showed more sheet to sheet variation in material properties than the stiff adhesives and the moduli data for these are quoted from bulk specimens manufactured at the same time and from the same batch of material as the joint specimens.

Three of the adhesives show good agreement, within the uncertainties, between bulk specimens and joint specimens manufactured from the same batch of adhesive. The fourth, a fast curing acrylic, shows significantly higher moduli in joint specimens (240 ± 80 MPa) than in the bulk specimens prepared at the same time (170 ± 60 MPa). This suggests a difference between the material properties of the acrylic in bulk and joint specimens. However, the modulus values for the joint specimens are within the overall range measured using bulk specimens prepared on different occasions, and the differences observed possibly reflect the difficulties in preparing reproducible bulk specimens of this adhesive. For relatively stiff adhesives, with shear moduli around 1000 MPa, such as epoxies, the values determined by the Iosipescu and Arcan tests agree well with each other and also with values expected from tensile measurements.

4. SHEAR STRESS/STRAIN DATA TO FAILURE

4.1 BULK SPECIMEN TESTS

For all the adhesives studied, strain measurements in bulk specimen tests are fairly reliable up to around 20 % strain. Tests on the stiff adhesives, where the maximum stress occurs before 20 % shear strain, gave reliable stress/strain curves and typical examples are shown in Figure 3. The 2-part epoxy which was the most brittle of the adhesives, tended to fail prematurely at 3-5 % shear strain and 20 to 25 MPa shear stress at stress concentrations near the notch root. No yielding was observed. The 1-part epoxy specimens yielded at around 9 % shear strain, and 46 ± 2 MPa shear stress, and failed between 15 and 30 % shear strain. The stress/strain curves were repeatable and there were no obvious problems with strain measurements.

Strain measurements in bulk specimen tests were less accurate on the compliant adhesives where maximum stresses occurred after 40 % shear strain. There are several problems in measuring large strains in bulk specimens. Due to the limited travel of the extensometer and displacement transducers, the extensometer must be reset (beginning around 20 % strain) in positions away from the centre of the test piece to retain contact with the specimen. The resetting of the extensometers generates uncertainties in the gauge length and the movement of the needle contacts towards the notch root changes the strain measurement from being in a region of uniform shear stress to a non-uniform region.

This latter problem becomes important around 50 % shear strain. At very large deformations there is an apparent rotation of the line joining the notch roots with respect to the axis of loading, clearly observable at strains above 40 %.

Compliant specimens may buckle locally outside of the gauge section in regions where there are compressive stress concentrations. This can occur at strains as low as 20 %, leading to unreliable extensometer contact on the specimen and out of plane movements contribute to the shear displacements measured. Stiff materials and/or thicker test specimens will be more resistant to this buckling and the strain measurements will be reliable at higher deformations. One indication of problems in strain measurement is a divergence between the strains measured by the individual extensometers. When this divergence occurs the measured strains should not be relied on but strain should be estimated from the crosshead movement. The local strain rate within the gauge section is roughly constant at all parts of the stress-strain curve.

A clamping arrangement to restrain the loading frame from lateral movements was used in most of the tests on the compliant adhesives to prevent excessive buckling. These tests show more consistency between different specimens than in the unclamped tests. In the tests using clamps, specimens fail at higher stresses but lower strains than tests without the clamps. Figure 4 shows typical stress-strain curves, measured using clamps, for the polyurethane and the acrylic. In these tests the crosshead movement was used to estimate strain beyond 20 % strain. The acrylic specimens generally failed between 40 and 60 % shear strain, 16 to 18 MPa shear stress and the polyurethane specimens generally failed between 100 and 140 % shear strain, 10 to 13 MPa shear stress. The bulk specimen test can be used to estimate the shear strength of compliant adhesives despite the problems with strain measurement.

In all of the bulk specimen tests (stiff and compliant adhesives), failure was initiated at the edge of the notch, near the notch root, where finite element calculations indicate the presence of tensile stress

concentrations. Although this is outside the gauge section of the specimen, clearly the maximum stress is not a measure of the shear strength of the adhesive unless the adhesive has a definite yield point.

4.2 JOINT SPECIMEN TESTS

Deformations of the metal adherends in the joint tests are small and, as the extensometer gauge length is approximately the bondline thickness, shear displacements are much smaller than those obtained in bulk specimen tests. There is no need to reset the extensometers in any of the tests and buckling is not a problem. High shear strains can be measured more reliably than in the bulk test.

There can be problems with clamping joint specimens as the steel adherends used are harder and the friction between specimen and grip is reduced. In tests on the stiff adhesives, at high loads (800 to 900 N), the steel adherends tended to slip in the grips leading to a rotation of the specimen which introduces an error in the measured strain. This problem can be reduced by lowering the loads through decreasing the bonded area or by improving the grip, eg through using softer adherends. Aluminium strips were bonded to some of the epoxy specimens and the stress/strain curves measured agreed reasonably well with bulk specimen tests, although as Figure 3 shows the maximum stresses achieved are lower than for bulk specimens. Joint specimens manufactured from the 2-part epoxy could be tested to much higher strains than the bulk specimens due to lower stress concentrations in the joint specimen, and in some tests yield stresses can be measured.

Joint specimens of the compliant adhesives do not sustain such high loads as joint specimens made with stiff adhesives and gripping of the specimen does not appear to be a problem. Tests on joint specimens of the compliant adhesives are consistent between specimens. Strain measurements appear reliable with good agreement between the extensometers throughout the stress/strain curve. Typical stress-strain curves are shown in Figure 4.

The stress/strain curves measured on joint specimens of the polyurethane are closer to the stress/strain curves determined for bulk specimens in tests where clamping was used to restrain buckling than those in tests which were unclamped. The failure strains appear slightly lower (80 to 100 %) but the maximum stresses are comparable (10 to 12 MPa).

In the case of the acrylic joint specimens, the modulus is higher than for the corresponding bulk specimens and there is poor agreement between the stress/strain curves for the joint specimen and bulk specimens prepared at the same time. Since bulk specimens of the acrylic showed properties that were highly variable between production batches, it is not clear that the differences between bulk and joint measurements are solely due to differences brought about by the conditions under which the adhesive cures when in a bonded joint. When the joint specimens were compared with bulk specimens of acrylic, prepared at a different time, but which had comparable moduli, the stress/strain curves agreed well. The joint specimens tended to fail at higher strains (60 to 100 %) than the bulk specimens. Failure strengths for the joint acrylic specimens were 20 to 30 MPa.

Failure of the joint specimens is caused by tensile peel stresses at the notch roots and the curve defining performance under a shear stress is truncated. Failure strains are variable and are probably very sensitive to the shape of the notch roots. However, if these can be fabricated to better tolerances then more consistent failure data should be possible. The stress concentrations in the joint tests are lower than in the bulk tests and, consequently, strains to failure are somewhat higher than in a joint test.

5. CONCLUSIONS

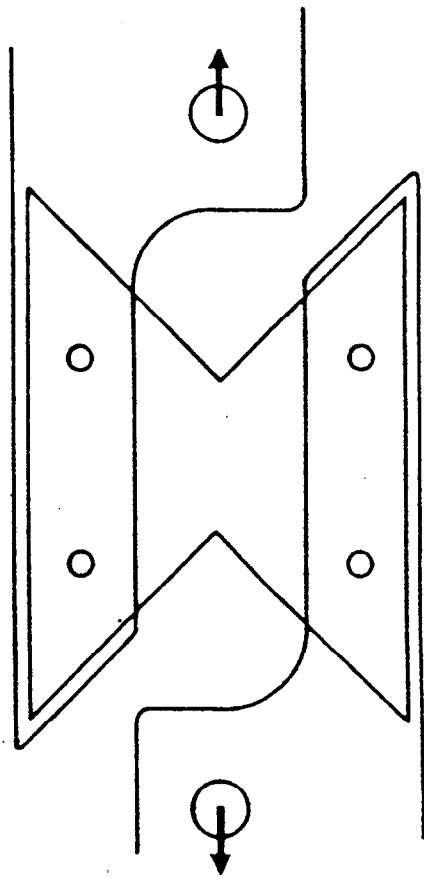
1. The Arcan test method employed in this work can measure shear moduli with an accuracy which is typically better than $\pm 20\%$ at the 95 % confidence level.
 - This accuracy could be increased through specific improvements to the test method and the extensometers.
 - In principle the bulk specimen test should then be significantly more accurate than the joint specimen test for measurements below 10% shear strain.
2. The Arcan test gives reliable stress/strain curves for bulk specimens of adhesives at shear strains below 20 %.
 - Failure at stress concentrations can cause significant truncation of the stress/strain curves for less ductile materials.
 - Where the test extends beyond 20 % strain (usually restricted to compliant adhesives) additional errors can be introduced into the strain measurement arising from limitations in the performance of the extensometer and local buckling deformations in the specimen.
 - The reliability of strain measurement can then be increased through use of the crosshead displacement with a suitable correction.
 - The strains at which measurements become unreliable will be larger for stiff/thick test specimens which are more resistant to local buckling.
3. The joint specimen test appears to be a better test for measuring stress/strain to failure, particularly for compliant adhesives as the above problems are not experienced. Since the specimen deformation is smaller, high strains can be measured more accurately.
 - Strains to failure of brittle adhesives will generally be higher in joint specimens than in bulk specimens. However, the problem of inadequate gripping needs to be eliminated through improvements to the grip assembly to make this test reliable.
4. There is scope for increasing the quality of the data generated through other small improvements to the design of the Arcan test. Final conclusions on the usefulness of the notched-specimen shear tests will be made after comparison with other shear test methods [4].

6. ACKNOWLEDGEMENTS

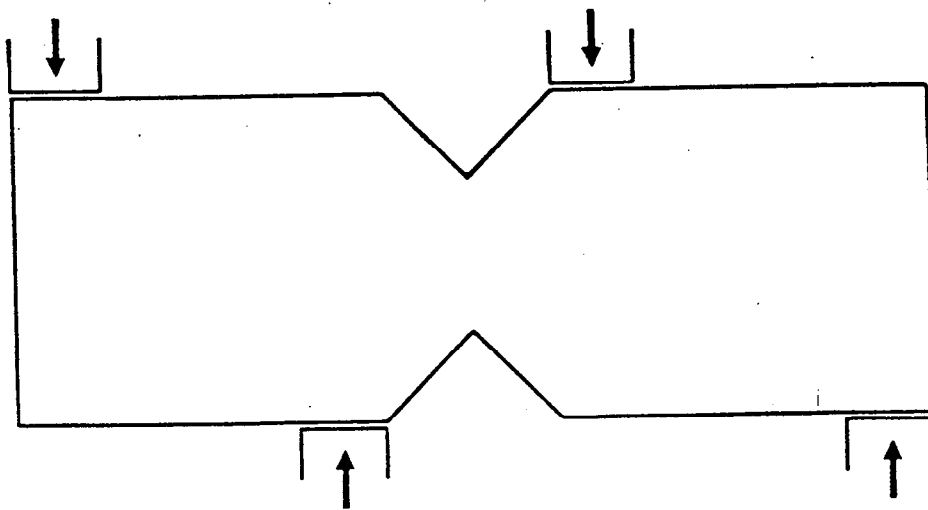
This work forms part of a programme on adhesives measurement technology funded by the DTI as part of its support of the technological competitiveness of UK industry. Other DTI funded programmes are conducted by NPL as prime contractors. For further details please contact Mrs G Tellett, NPL. Copies of the full report (Part B) are available from the authors.

7. REFERENCES

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Arcan



Iosipescu

Figure 1: Notched-beam (Iosipescu) and notched-plate (Arcan) test methods, directions of applied loading are indicated by arrows.

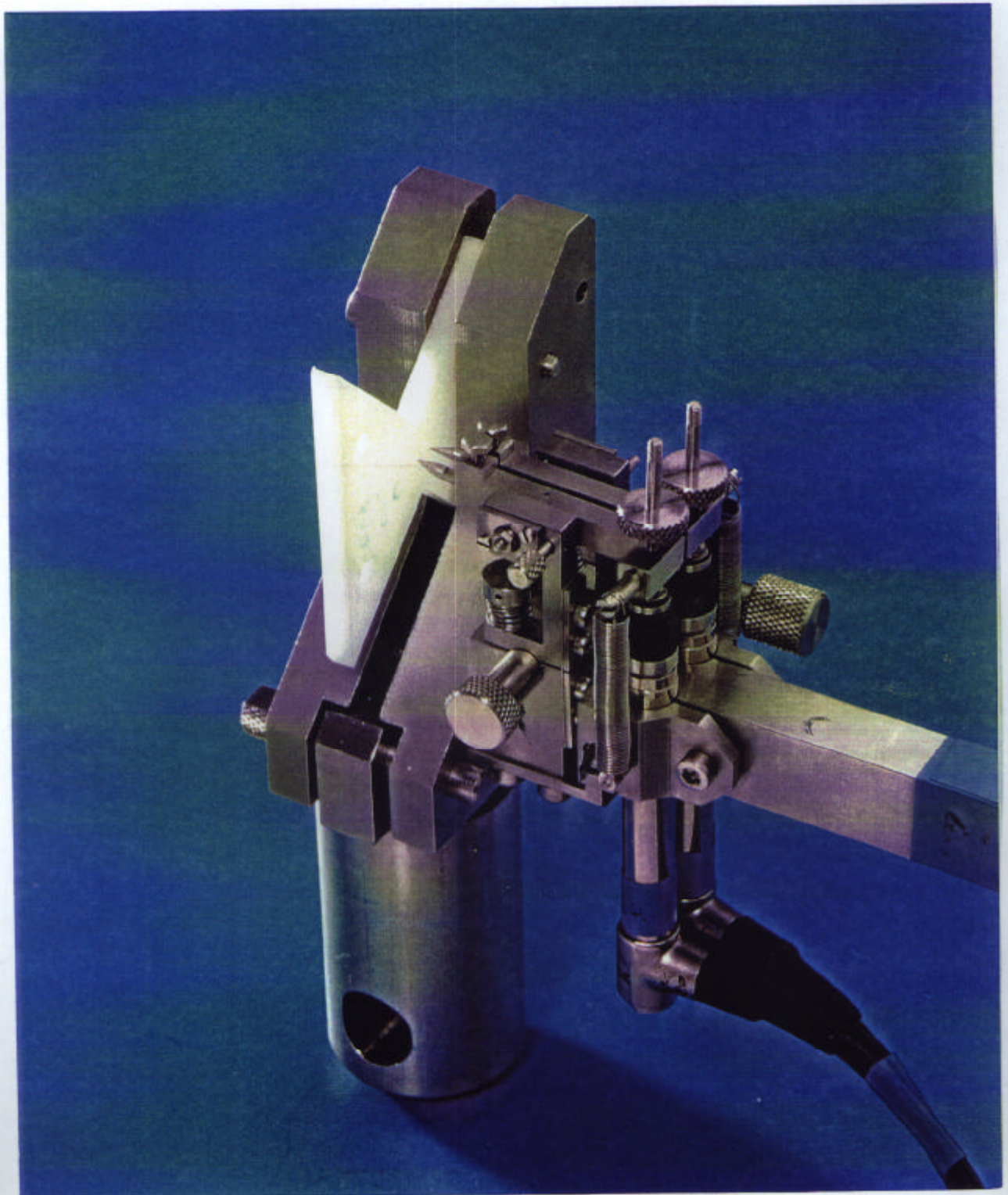


Figure 2: Illustration of the shear extensometer and part of the loading assembly built for the notched-plate test

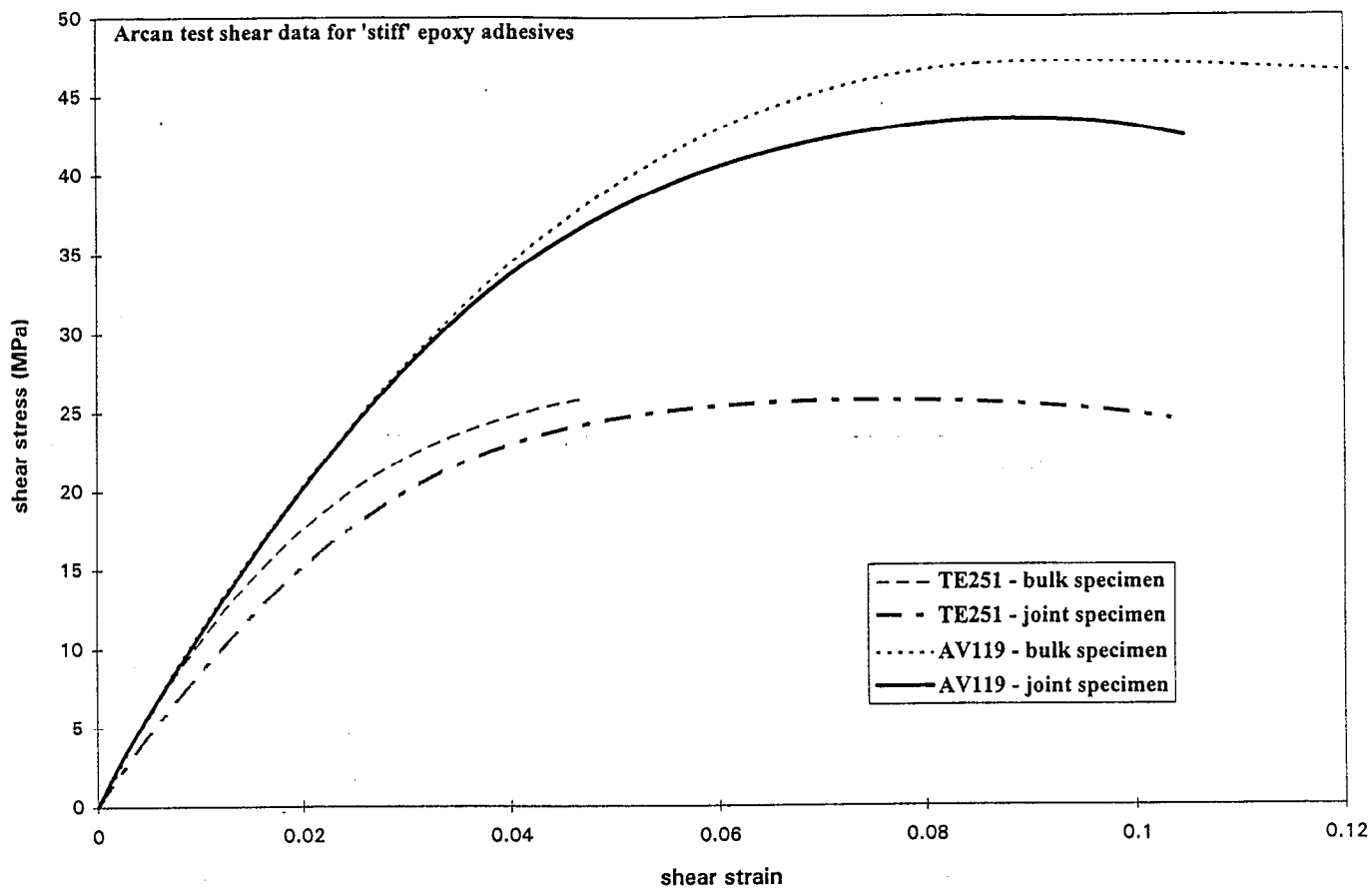


Figure 3: Shear stress-strain curves for 'stiff' epoxy adhesives measured using bulk and joint Arcan test specimens.

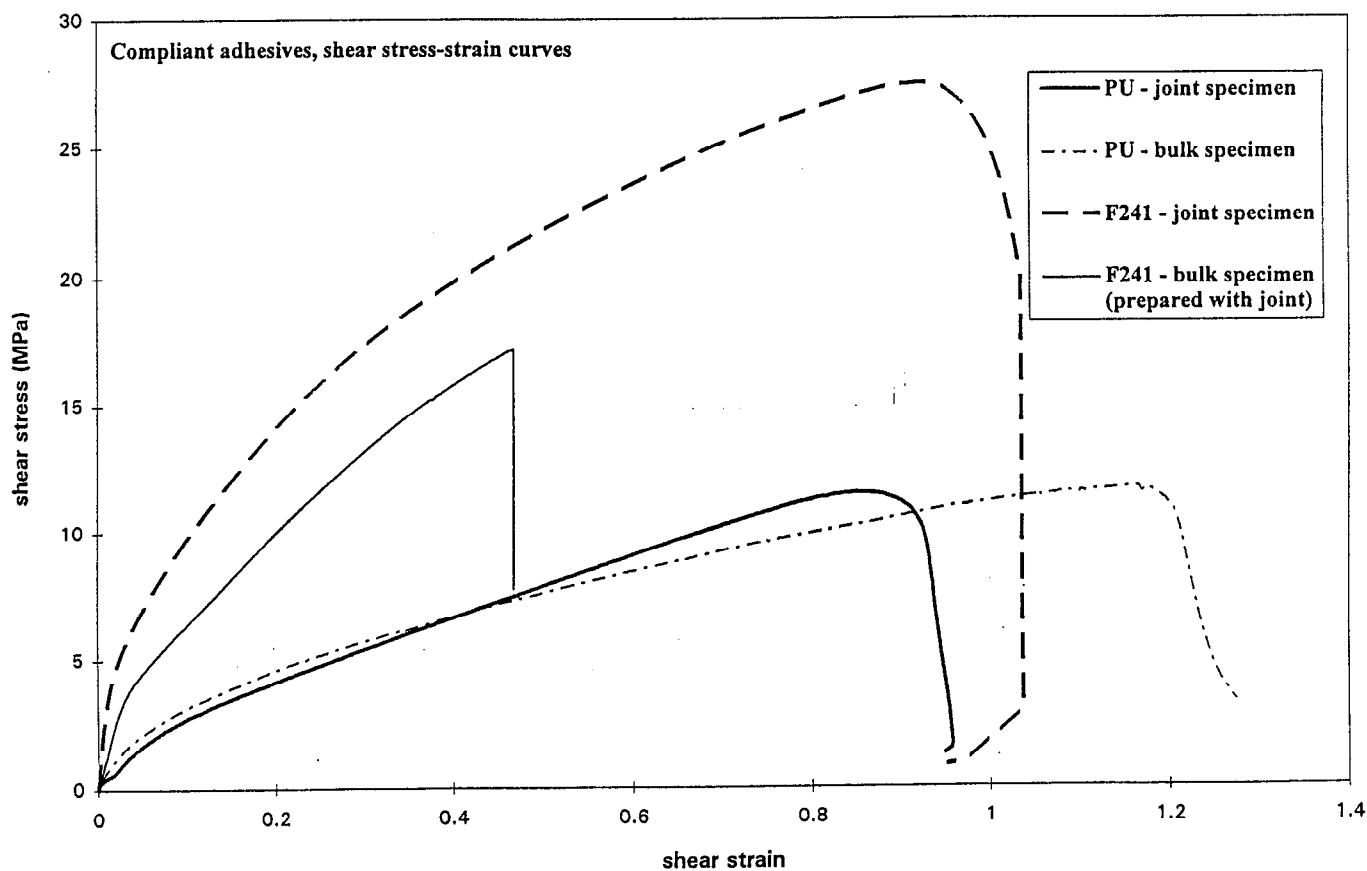


Figure 4: Shear stress-strain curves measured for acrylic F241 and polyurethane 3M 3532 using bulk and joint Arcan specimens.