

**Project PAJ2
Report No 10**

**A Proposed Failure
Criterion for Tough
Adhesives**

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SUMMARY

Tensile tests on bulk specimens and butt-joint specimens of adhesives have been used to develop a criterion for ductile failure based on a critical level of strain. Earlier work on butt-joint specimens loaded in torsion has indicated that adhesives can tolerate large shear strains without failure. It was concluded that a significant level of volumetric (dilatational) strain is therefore needed to cause failure, but the results of the tests reported here show that the critical level is dependent upon the magnitude of the associated shear component.

A criterion is proposed that is consistent with the failure strains obtained from the above tests on an epoxy and an acrylic adhesive. Further work is now needed to investigate whether the criterion can be used to predict when failure will occur in joint test specimens of different geometry. To achieve this, it is necessary to use finite element methods to accurately predict the strain level and strain state in the region of the adhesive layer where failure initiates. Experience with the application of these methods to the stress analysis of the butt-joint specimen loaded in tension and other joint test specimen geometries has revealed that strains cannot be confidently predicted with adequate accuracy. It is concluded that a new materials model needs to be developed for adhesives.

1 INTRODUCTION

Toughened adhesives are ductile materials that can deform to large strains before failure. This ductility allows bonded structures to sustain loads and deformations that are significantly above those required under normal service conditions. However, under severe conditions, such as impact for example, failure of a bond will be induced by the initiation and propagation of a crack, and the load-bearing capability of the structure will be lost or reduced. In order to predict when the onset of failure will arise, a failure criterion is needed. A criterion may take different forms for different loading histories but, for a given type of loading, should be applicable to a wide range of joint geometries.

In the work reported here, a criterion is proposed which implies that failure will initiate when a critical level of strain is reached at some location in the adhesive. The criterion is based on results that have been obtained on specimens that have been loaded monotonically to failure in a timescale of several minutes. It is expected that the criterion will be applicable to failure under impact loading although some of the parameters in the criterion will depend upon strain rate. Results have been obtained on specimens that have been loaded to failure under three different states of stress. These are

- tensile tests on bulk specimens where the stress state is uniaxial tension
- torsion tests on butt-joint specimens where the stress state is pure shear
- tensile tests on butt-joint specimens where a high degree of triaxial tension is generated.

The selection of these tests has been guided by a requirement that the strain state and magnitude at the probable site of failure in each specimen can be determined experimentally with high accuracy.

2 PREVIOUS WORK

A review (1) of the scientific literature on the subject of failure of toughened plastics and adhesives was prepared for a research project on Failure Modes and Criteria (2) that formed part of an earlier programme on adhesives funded by the DTI. An Industry Briefing Document (3) has also been prepared summarising the conclusions drawn from the project.

It is apparent from this earlier work that the failure of adhesive joints is a complicated subject. As part of the work, data were obtained from tests to failure on a variety of types of adhesive using a range of specimen geometries, but no criterion was able to unambiguously correlate the results. Of the criteria considered, those based on some critical level of strain seem to be physically the most reasonable. Work carried out at the same time in a related project (4) indicated that the failure of adhesives is not very sensitive to the magnitude of the shear component of the strain field. This is discussed further in section 4.3 and has guided the investigation reported here into consideration of a criterion based on a critical level of the volumetric (dilatational) component of the strain. This is consistent with a deformation process which involves cavitation of rubber particles followed by distortion of the adhesive around these particles. When this distortion reaches a critical level, failure is initiated. The strain criterion proposed here assumes that the critical distortion is characterised by some measure of the state and magnitude of the average strain in the surrounding adhesive. It is considered here that this measure is governed predominantly by the magnitude of the volumetric component of strain although some contribution from the shear component is also included.

3 MATERIALS

Two toughened adhesives were studied in this work. Details of these are listed in table 1.

Table 1. The adhesives studied

Adhesive type	Supplier/code
1-part, toughened epoxy	Ciba / LMD 1142
2-part, ambient-temperature curing acrylic	ITW Plexus / MA310

Sheets of the bulk adhesives of thickness between 2 and 3 mm were prepared following procedures that are now standardised (5). Sheets of the epoxy adhesive were cured at 150 °C for 2 hours. The acrylic adhesive has an ambient temperature cure but to minimise any changes in properties with time after moulding, sheets were postcured at 40 °C for 2 hours.

4 EXPERIMENTAL

4.1 TENSILE MEASUREMENTS ON BULK SPECIMENS

Tensile tests were carried out using an Instron universal testing machine type 4505. Test specimens were standard dumbbell-shaped bars (ISO 3167) of length 150 mm and width 10 mm in the gauge section and were machined from cast sheets of the bulk adhesive. The machined edges were polished.

The strain at failure was measured using a Messphysik ME64 video extensometer. Since this device is non-contacting, it avoids any risk of premature initiation of failure that could arise with extensometers that contact the specimen. A video camera (with zoom lens) is employed to generate an image of the specimen on a computer screen, and the distance

between gauge marks on the specimen surface is determined from the number of pixels between the marks. Strains are then calculated from the changes in this distance during a test.

4.2 TENSILE MEASUREMENTS ON BUTT-JOINT SPECIMENS

The loading assembly for tensile tests on butt-joint specimens is shown in figure 1. The specimen consists of two 25 mm diameter hardened steel rods that are bonded together at end faces. An alignment jig was used during the bonding to ensure that the adherends were accurately coaxial. A v-shaped groove was machined in the surface of each adherend at a distance of 2.75 mm from the face to be bonded. The depth was 1.0 mm. These served to locate an extensometer consisting of an assembly of displacement transducers that were used to determine the axial deformation around the adhesive bond in response to an applied load. The extensometer is shown in figure 2. It consists of two rings with knife edges on their inner surfaces. Each ring locates in one of the grooves in a bonded specimen. One of the rings supports three precision inductive displacement transducers that are equally spaced around the ring. The core of each transducer is supported by an elastic suspension that permits friction-free movement of the core and supplies a restoring force to any displacement. The core of each transducer contacts the surface of the second ring. The transducers record the combined axial deformation of the adhesive and the distortion of the region of the adherend between each bond face and the corresponding v-groove.

The specimen is loaded through universal joints linked to each adherend. These are intended to minimise any bending forces applied to the specimen arising from misalignment of the test assembly. Any non-uniform loading is recognised by differences in the transducer outputs. Differences were generally small under the application of force levels where behaviour was linear. However, as the adhesive starts to soften at higher strains, the strain would increase substantially in one region of the adhesive and rise more slowly or even decrease in other regions. This is an unstable situation and gives rise to an increasing bending moment in the specimen with further loading. In order to maintain a

uniform axial strain in the adhesive it was necessary to manually apply a counteracting moment throughout a test that was sufficient to ensure that the output from each transducer increased at the same rate.

In the design stage of the butt-joint specimen, finite element analyses were carried out to explore the location of stress and strain concentrations in the adhesive layer. An elastic-plastic model was used with the assumption of von Mises yielding. Regions of high strain, are localised at the top and bottom circumferences of the adhesive layer at the interface with the corner of each adherend. The strains in these regions are singular if the corners of the adherends are sharp. The singularities could be removed by adding a radius to the corners but this only moved the regions of strain concentration closer to the specimen axis and had the disadvantage that the strain distribution in the plane of the adhesive layer became less uniform. Plane adherend faces have therefore been used so far, although further studies have since been made to determine the strain distribution in the adhesive at failure. These are discussed in section 5.3.1.

4.3 SHEAR MEASUREMENTS ON BUTT-JOINT SPECIMENS

Shear stress/strain curves have been measured on a variety of adhesives as part of an earlier project (4). In torsion tests on bulk specimens and on butt-joint specimens (6), it was observed that large shear strains were reached before failure in all the adhesives studied. This was particularly evident in tests on butt joints in torsion where strains exceeding 30% were achieved on materials with breaking strains of less than 3% in tension. It was concluded that, in the absence of a dilatational component of stress, the failure of adhesives is insensitive to the magnitude of a shear stress or strain. The failure of other shear test specimens at relatively small strains, for example in thick adherend shear tests, is then ascribed to the presence of dilatational strains associated with peel forces at bond ends. These are absent in butt-joint specimens loaded in torsion.

No butt-joint torsion tests have been carried out on the adhesives studied in this report, but, based on the earlier work, it will be assumed that failure strains under pure shear will be very large.

5 DETERMINATION OF STRAINS AT FAILURE

5.1 NOMENCLATURE

ϵ_{u1}^f	engineering strain at failure in the direction of the specimen axis of bulk specimens loaded in tension.
$\epsilon_{u2}^f, \epsilon_{u3}^f$	engineering strains at failure transverse to the specimen axis of bulk specimens loaded in tension.
ϵ_{b1}^f	engineering strain at failure in the adhesive along the direction of applied force in butt-joint specimens loaded in tension.
$\epsilon_{b2}^f, \epsilon_{b3}^f$	engineering strains at failure along orthogonal axes in the plane of the adhesive in butt-joint specimens.
ν^f	the lateral contraction ratio (Poisson's ratio) at failure.
I_1^f	the first invariant of the strain tensor at failure, considered here to comprise true strain components, and equal to the volumetric strain (see equation 3).
I_{2D}^f	the second invariant of the deviatoric strain tensor at failure and a measure of the square of the effective shear strain (see equation 4).

5.2 TENSILE TESTS ON BULK SPECIMENS

Stress/strain curves obtained from tensile tests on bulk specimens of both adhesives are shown in figure 3. Tests were carried out on about 10 specimens of each adhesive and the results presented in figure 3 are typical of specimens that showed no visible sign of an air bubble in the failure surface. The strain components ϵ_{u1}^f and ϵ_{u2}^f at failure were determined from the video extensometer records of these tests. The Poisson's ratio at failure was calculated from the equation

$$\nu^f = -\frac{\epsilon_{u2}^f}{\epsilon_{u1}^f} \quad (1)$$

Mean values for ϵ_{u1}^f and ν^f for each adhesive are given in table 2.

Table 2 - Values obtained for stress and strain components at failure of tensile tests on bulk and butt-joint specimens

Adhesive	ϵ_{u1}^f	ϵ_{b1}^f	ν^f	I_{u1}^f	I_{u2D}^f	I_{b1}^f	I_{b2D}^f
LMD 1142 epoxy	0.20	0.135	0.34	0.041	0.145	0.127	0.073
MA 310 acrylic	0.09	0.055	0.20	0.050	0.060	0.055	0.031

In these tests the strain state at failure is given by the components ϵ_{u1}^f , ϵ_{u2}^f and ϵ_{u3}^f where

$$\epsilon_{u2}^f = \epsilon_{u3}^f = -\nu^f \epsilon_{u1}^f \quad (2)$$

The volumetric strain is equal to the first strain invariant which at failure is

$$\begin{aligned} I_{u1}^f &= \ln(1 + \epsilon_{u1}^f) + \ln(1 + \epsilon_{u2}^f) + \ln(1 + \epsilon_{u3}^f) \\ &= \ln(1 + \epsilon_{u1}^f) + 2\ln(1 - \nu^f \epsilon_{u1}^f) \end{aligned} \quad (3)$$

Here, true strains have been used since ϵ_{u1}^f is large.

The shear component of the strain is given by the root of the 2nd invariant of the deviatoric strain tensor I_{2D} which at failure is

$$\begin{aligned}
 I_{u2D}^f &= \left\{ \frac{1}{6} \left[(\ln(1 + \epsilon_{u1}^f) - \ln(1 + \epsilon_{u2}^f))^2 + (\ln(1 + \epsilon_{u2}^f) - \ln(1 + \epsilon_{u3}^f))^2 \right. \right. \\
 &\quad \left. \left. + (\ln(1 + \epsilon_{u3}^f) - \ln(1 + \epsilon_{u1}^f))^2 \right] \right\}^{1/2} \\
 &= \frac{1}{\sqrt{3}} \left[\ln(1 + \epsilon_{u1}^f) - \ln(1 - \nu^f \epsilon_{u1}^f) \right]
 \end{aligned} \tag{4}$$

5.3 TENSILE TESTS ON BUTT-JOINT SPECIMENS

Figure 4 shows measured force / extension curves for both adhesives obtained from tests on butt-joint specimens. At least three specimens of each adhesive were tested, and the curves shown are typical. In all cases, failure was cohesive with no sign of any loss of adhesion with the adherends.

5.3.1 Finite element analyses of the butt-joint specimen

Finite element analyses were used to determine strain components at failure of the adhesive from the measured values for the extension of the specimen at failure. Analysis of the results of tensile and shear tests on bulk specimens of each adhesive and tensile tests on butt-joint specimens has indicated that the deformation behaviour of the epoxy material is best described by the exponent Drucker-Prager model whilst the linear Drucker-Prager model appears better for the acrylic. This work has been discussed in a separate report (7). Using these models in the Abaqus finite element package, it was possible to quite accurately predict the force/extension curves derived from the butt-tension tests shown in figure 4. However, using the standard solver code, it was not

found possible to obtain solutions all the way to failure of the adhesive. The analysis would not converge at large extensions. This problem was overcome using the explicit solver code, although predictions were only possible for the acrylic material because the exponent Drucker-Prager model cannot be used with the explicit solver in Abaqus.

The values used for the parameters in the linear Drucker-Prager model for the acrylic adhesive are shown in table 3. Their determination is described in reference (7).

**Table 3 - Values for the parameters used in the FE analysis
of butt-joint specimens of the acrylic adhesive**

Youngs modulus (GPa)	2.36
Poissons ratio (elastic)	0.37
Strain hardening function	Derived from fig 3
Angle of friction β	62°
Flow parameter ψ	40°

Force/extension curves predicted using FE analysis are compared with the experimental curve for the acrylic adhesive in figure 5. Figure 5a shows comparisons using a strain hardening function in the analysis based on tensile data (see figure 3). It is observed that the predicted curve shows a drop in the force caused by the softening evident in the hardening function. This behaviour is not observed in the experimental data so predictions were also made using the hardening function based on shear stress/strain data (see reference (7)). Comparison with experimental results is then satisfactory as shown in figure 5b.

Using the hardening function based on shear data, calculations were made of strain distributions in the adhesive. Figure 6 shows the variation of strain components with radial position in the central plane of the adhesive at the extension at failure (~30 μ). It is apparent that the axial component is uniform except for an apparent increase in a narrow

annular region a few mm in from the circumference of the adhesive layer. It is unclear whether this increase in strain is real and, if so, whether it is linked to the reduction in strain at the free surface of the adhesive or the singularity in the strain distribution (see figure 7) arising from the assumed sharp corner at the circumference of the bonded face of each adherend. This region of elevated strain was observed in analyses using the standard solver code but, as mentioned earlier, solutions could not be obtained at strains near to failure. Using both the explicit and standard solver codes, the level of the strain in this region was observed to decrease when a finer mesh was used.

The singularity caused by the sharp corner of the adherend influences the strain distribution in the adhesive in that region as shown by the strain map in figure 7. As expected, the size of the zone of strain concentration depends on the size of the mesh in the FE analysis.

It is unclear whether either of these regions of local strain concentration will be responsible for the initiation of failure in butt-joint specimens. In the analysis of results reported here, it will be assumed that the size of these regions is sufficiently small as to have a negligible effect on the failure of the specimen. It is assumed, therefore, that the onset of failure is determined by the strain level and strain state in the remainder of the adhesive where these are predominantly uniform.

5.3.2 Determination of failure strains

As expected, figure 6 confirms that strain components ϵ_{b2}^f and ϵ_{b3}^f in a plane transverse to the applied load are zero. An approximate value for the axial strain component at failure ϵ_{b1}^f is given by the ratio of the extension at failure to the adhesive thickness. This calculation does not however take account of the small contribution to the measured extension from the deformation of the parts of the adherends within the extensometer gauge length and the non-uniform strain distribution near the circumference of the

adhesive. For the acrylic adhesive, a better estimate of ϵ_{b1}^f can be obtained from figure 6. A mean value of 0.055 has been chosen as recorded in table 2.

With the epoxy adhesive, the analysis using the exponent Drucker-Prager model and the standard solver code would not proceed beyond an extension of 45 microns. At this extension, the analysis gave the axial strain in the adhesive as 0.085. At this strain, the deformation in the adhesive was totally plastic so it can be assumed that all further extension is confined to the adhesive layer. Assuming an extension at failure of 70 microns from figure 4, the axial strain at failure is estimated to be 0.135 as recorded in table 2.

For the strain state in the butt-joint specimen, the strain invariants at failure I_{b1}^f and I_{b2D}^f are given by

$$I_{b1}^f = \ln(1 + \epsilon_{b1}^f) \quad (5)$$

and

$$I_{b2D}^{f/2} = \frac{1}{\sqrt{3}} \ln(1 + \epsilon_{b1}^f) \quad (6)$$

Values for these strain components are also given in table 2.

6 A PROPOSED FAILURE CRITERION

It is apparent from table 2 that a failure criterion invoking a critical volumetric strain (I_1) at failure is inadequate for explaining the results obtained from tensile tests on bulk and butt-joint specimens. An alternative criterion is therefore explored involving contributions from both volumetric and deviatoric ($I_{2D}^{1/2}$) strain components. For this purpose, the data

in table 2 are plotted in figure 8 on axes of I_1 against $I_{2D}^{1/2}$. A suitable function that defines the criterion should approach the $I_{2D}^{1/2}$ axis asymptotically to be consistent with the observation made in section 4.3 that tough adhesives can sustain a high pure shear strain without failure. In addition, the function should be symmetrical about the I_1 axis so that the criterion is independent of the sign of the shear strain. The following function fits the available results and meets these criteria

$$I_1 = A \exp - B I_{2D} \quad (7)$$

Values for the parameters A and B for each adhesive are given in figure 8. According to this failure criterion, ductile failure will occur when the strain state and magnitude defined by the quantities I_1 and I_{2D} are such that

$$\ln \frac{I_1}{A} + B I_{2D} \geq 0 \quad (8)$$

7 FURTHER WORK

The validity of this criterion should be assessed by an evaluation of its ability to predict the failure of adhesive joints. Finite element analyses should be carried out on selected joint test specimen geometries to determine strain levels in critical regions of the adhesive layer. When the deformation applied to the specimen reaches a level whereby the equality in equation (8) is satisfied, then the criterion predicts that failure of the joint will occur. Predictions should then be compared with experimental values for deformation at failure.

The success of such an evaluation is critically dependent on the accuracy with which strain levels in the adhesive can be calculated using finite element analysis. This will be dependent on the validity of the materials model used in the analysis and the accuracy with which the materials parameters in the model have been measured for the adhesive of interest. The data reported here and in reference (7) from bulk and butt-joint specimens

reveal that in general, there are limitations in the use of available materials models with adhesives. This means that the accuracy of strain predictions is uncertain. The confidence in predictive accuracy is also reduced by the influence of factors such as singularities in the joint and the dependence of results on the mesh size and configuration. The importance of these factors seems particularly relevant in analyses where relatively large extensions of the joint are involved.

Studies in these areas are being carried out as part of project PAJ2 and will be described in a final report. The subjects will be investigated in greater depth in the extension project which will also explore the possibility of improving predictive accuracy by developing a new materials model for adhesives and implementing this in an FE system.

8 CONCLUSIONS

Tough adhesives can sustain deformation well beyond the strain level at which the maximum stress is reached.

This suggests that an investigation to define a suitable failure criterion for these materials should explore functions based on a critical level of a state of strain.

Tests on butt-joint specimens in torsion indicate that the onset of failure is not very sensitive to the magnitude of the shear component of strain.

Furthermore, tests on bulk specimens and butt-joint specimens in tension reveal that failure does not occur at a critical level of the volumetric (dilatational) strain. This implies that, whilst a significant volumetric strain component must be present to initiate failure, the critical level is dependent upon the magnitude of the associated shear component.

The criterion

$$\ln \frac{I_1}{A} + B I_{2D} \geq 0$$

where A and B are material parameters that depend on temperature and strain rate, is satisfied by the strains at which failure occurred in the bulk and butt-joint tensile tests of the epoxy and acrylic adhesives studied here.

The use of this criterion for predicting the onset of failure in adhesive joints of arbitrary geometry relies on the ability to accurately calculate strain levels in the region where failure initiates. This requires a realistic materials model for the adhesive that can describe its deformation behaviour at large strains.

Further work is needed to evaluate whether the failure criterion can be used to predict the onset of failure in other joint geometries.

9 ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

- Figure 1 Test assembly for butt-joint tensile tests.
- Figure 2 Section detail of the extensometer for the butt-joint tensile test showing location grooves on the specimen.
- Figure 3 Typical curves for true stress and Poisson's ratio against true strain obtained from tensile tests on bulk specimens of the epoxy and the acrylic adhesives.
- Figure 4 Typical curves for the force against extension obtained from tensile tests on butt-joint specimens of the epoxy and the acrylic adhesives.
- Figure 5 Comparisons of measured and predicted force vs extension curves for tensile tests on butt-joint specimens of the acrylic adhesive. Predictions are based on the linear Drucker-Prager model using hardening functions derived from (a) tensile data and (b) shear data.
- Figure 6 Calculated distribution of strain components at failure with radial position in the centre of the adhesive in a butt-joint under a tensile stress. The linear Drucker-Prager model was used with an explicit solver code.
- Figure 7 Map of the axial strain component in the adhesive in the region of the singularity caused by the corner of the adherend in a butt-joint specimen.
- Figure 8 Plots of strain components I_1 vs $I_{2D}^{1/2}$ (see equations 3 and 4) at failure from tensile tests on bulk and butt-joint specimens of the epoxy and acrylic adhesives. Data are taken from table 2.

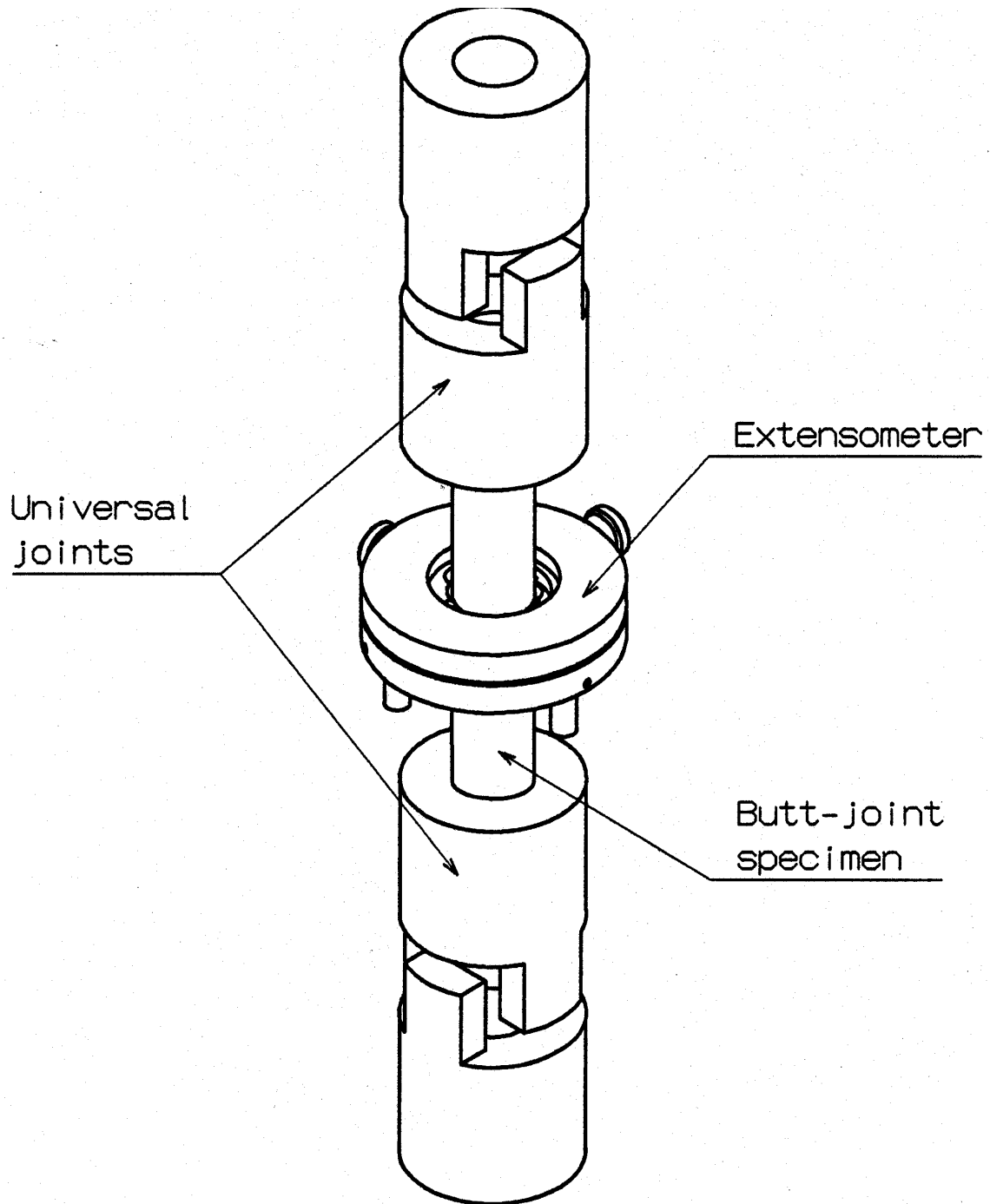


Figure 1 Test assembly for butt-joint tensile tests.

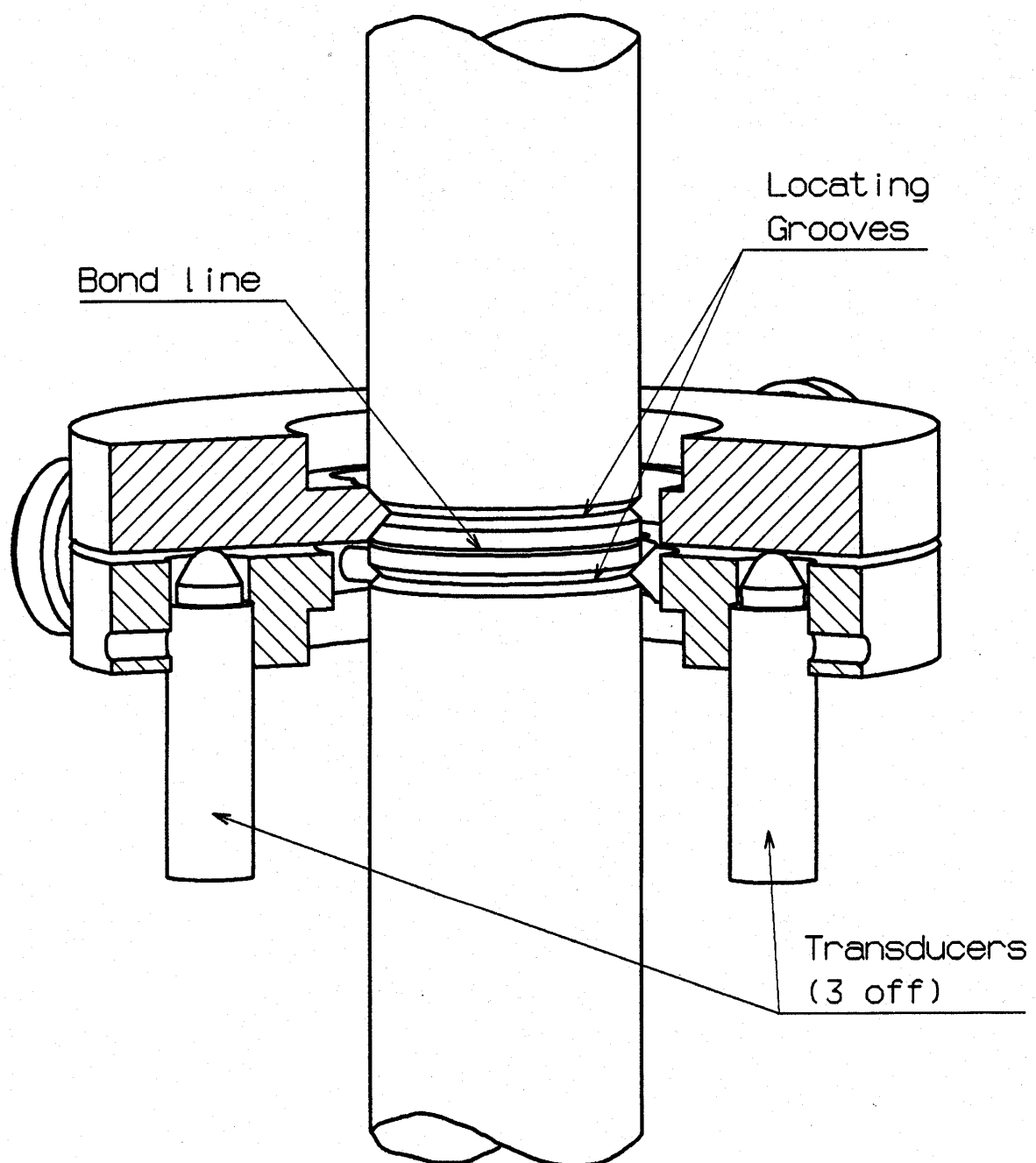


Figure 2 Section detail of the extensometer for the butt-joint tensile test showing location grooves on the specimen.

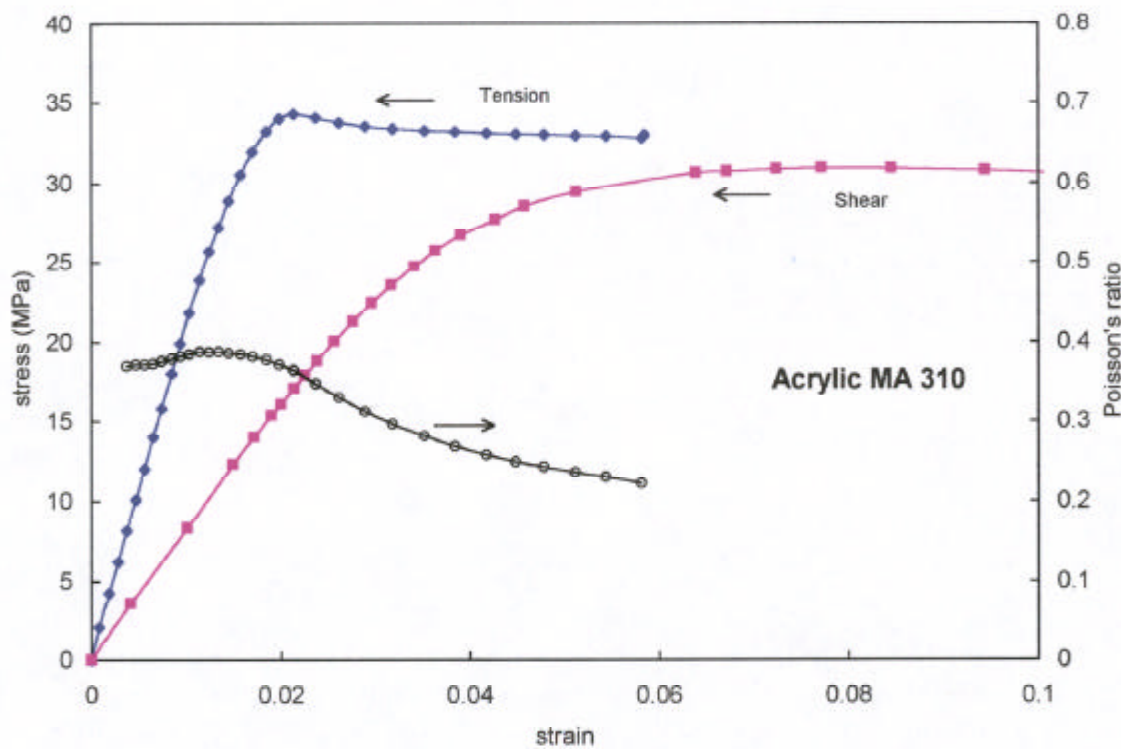
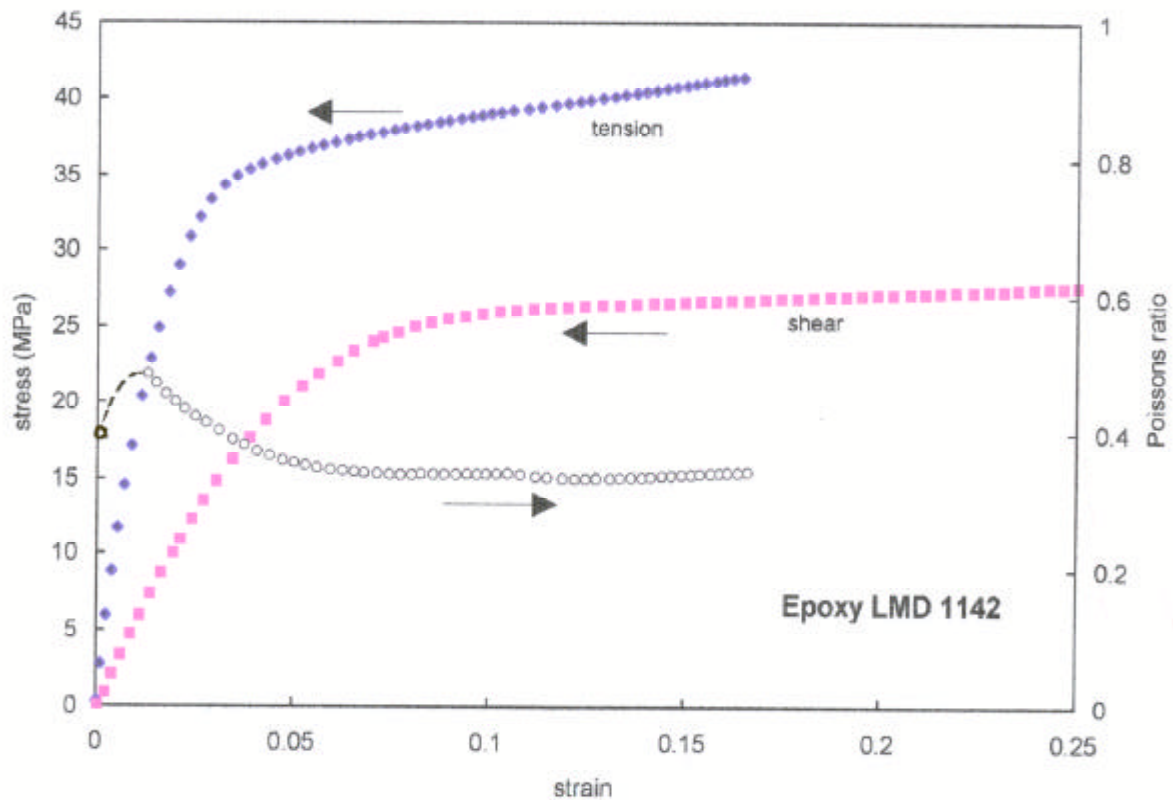


Figure 3 Typical curves for true stress and Poisson's ratio against true strain obtained from tensile tests on bulk specimens of the epoxy and the acrylic adhesives.

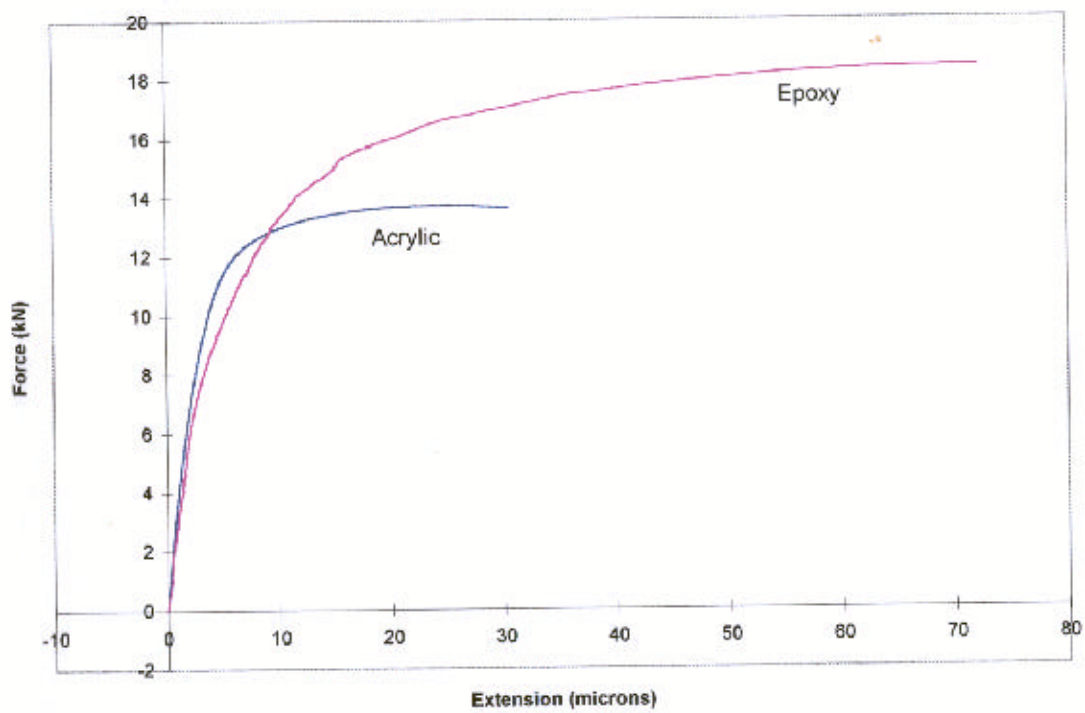


Figure 4 Typical curves for the force against extension obtained from tensile tests on butt-joint specimens of the epoxy and the acrylic adhesives.

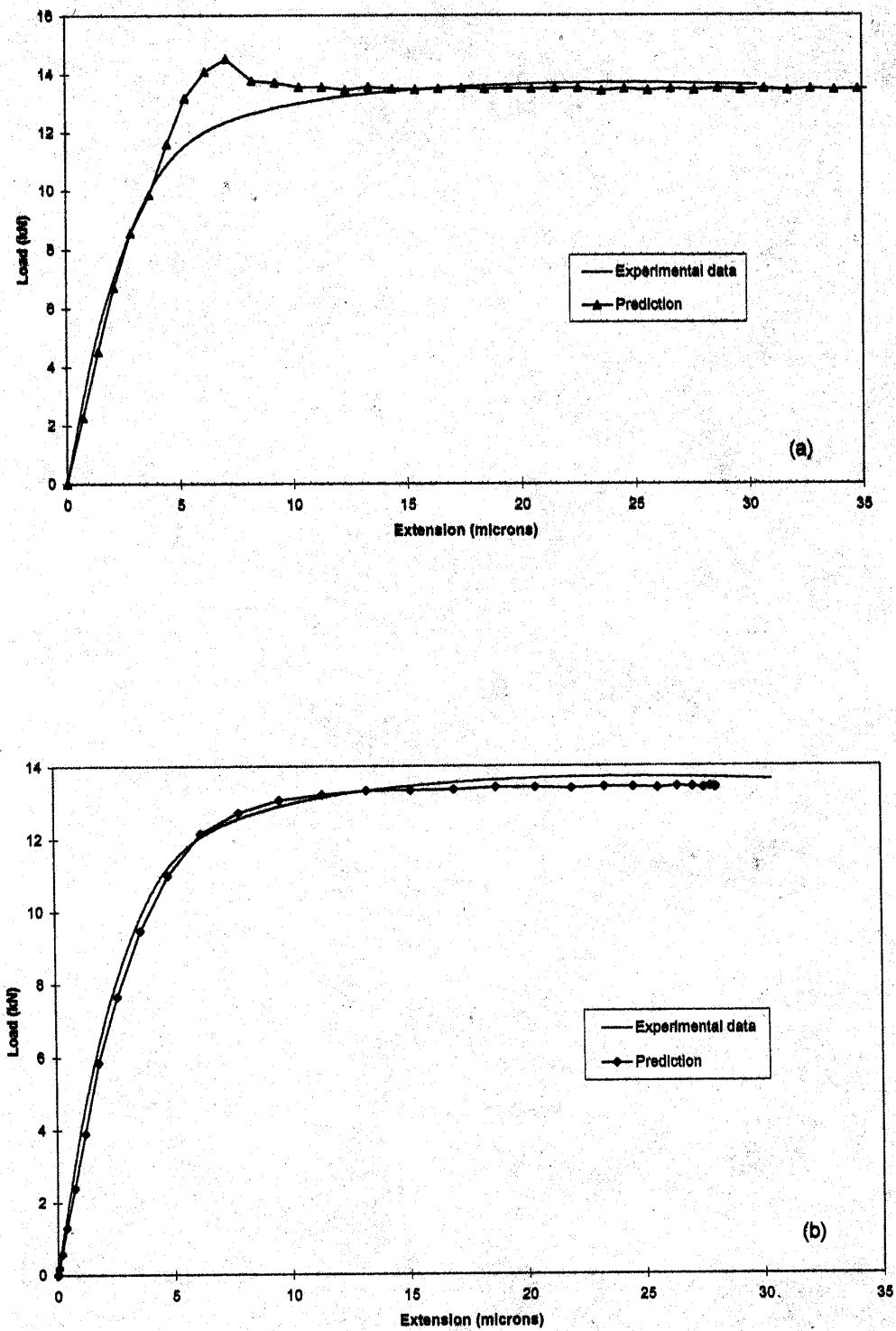


Figure 5 Comparisons of measured and predicted force vs extension curves for tensile tests on butt-joint specimens of the acrylic adhesive. Predictions are based on the linear Drucker-Prager model using hardening functions derived from (a) tensile data and (b) shear data.

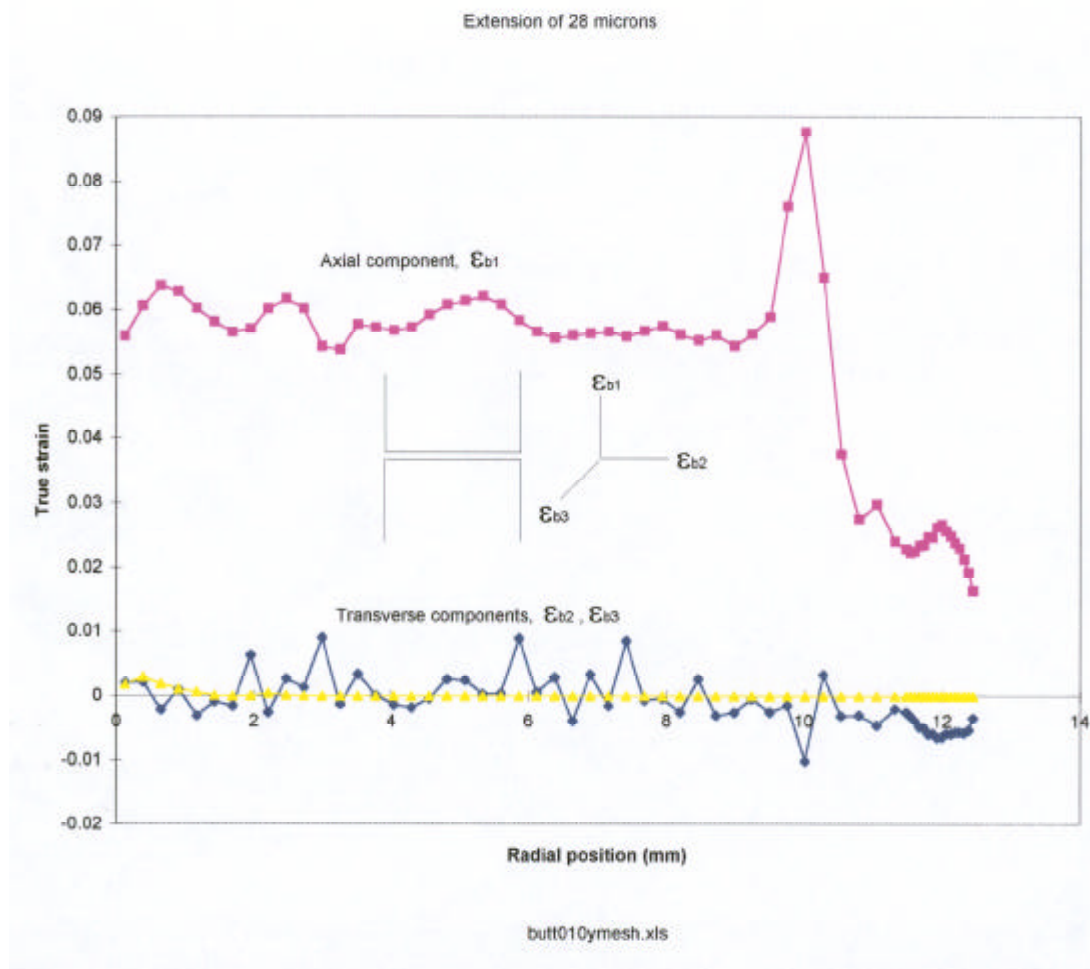


Figure 6 Calculated distribution of strain components at failure with radial position in the centre of the adhesive in a butt-joint under a tensile stress. The linear Drucker-Prager model was used with an explicit solver code.

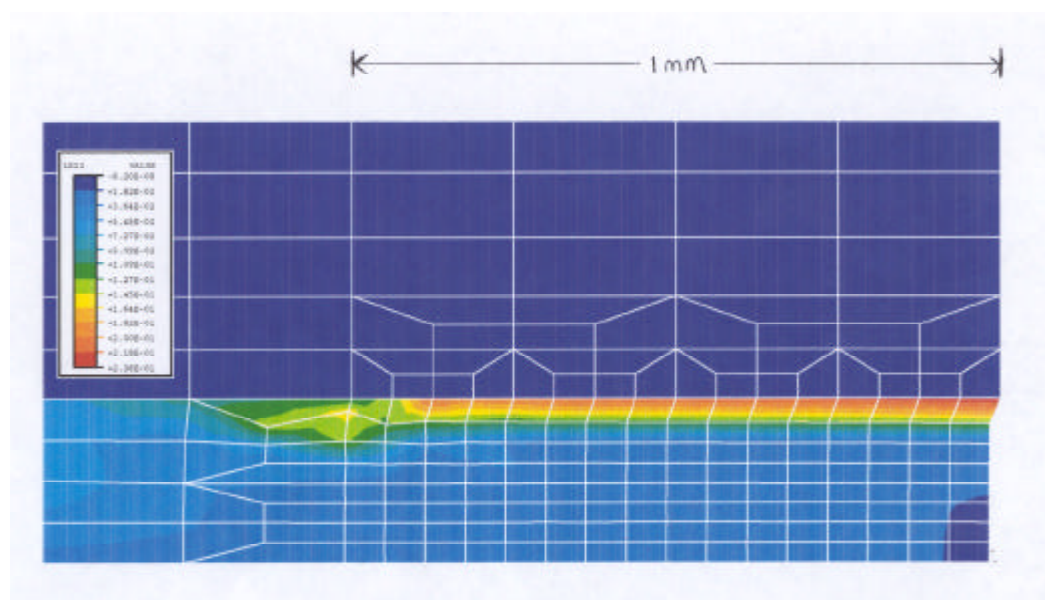


Figure 7 Map of the axial strain component in the adhesive in the region of the singularity caused by the corner of the adherend in a butt-joint specimen.

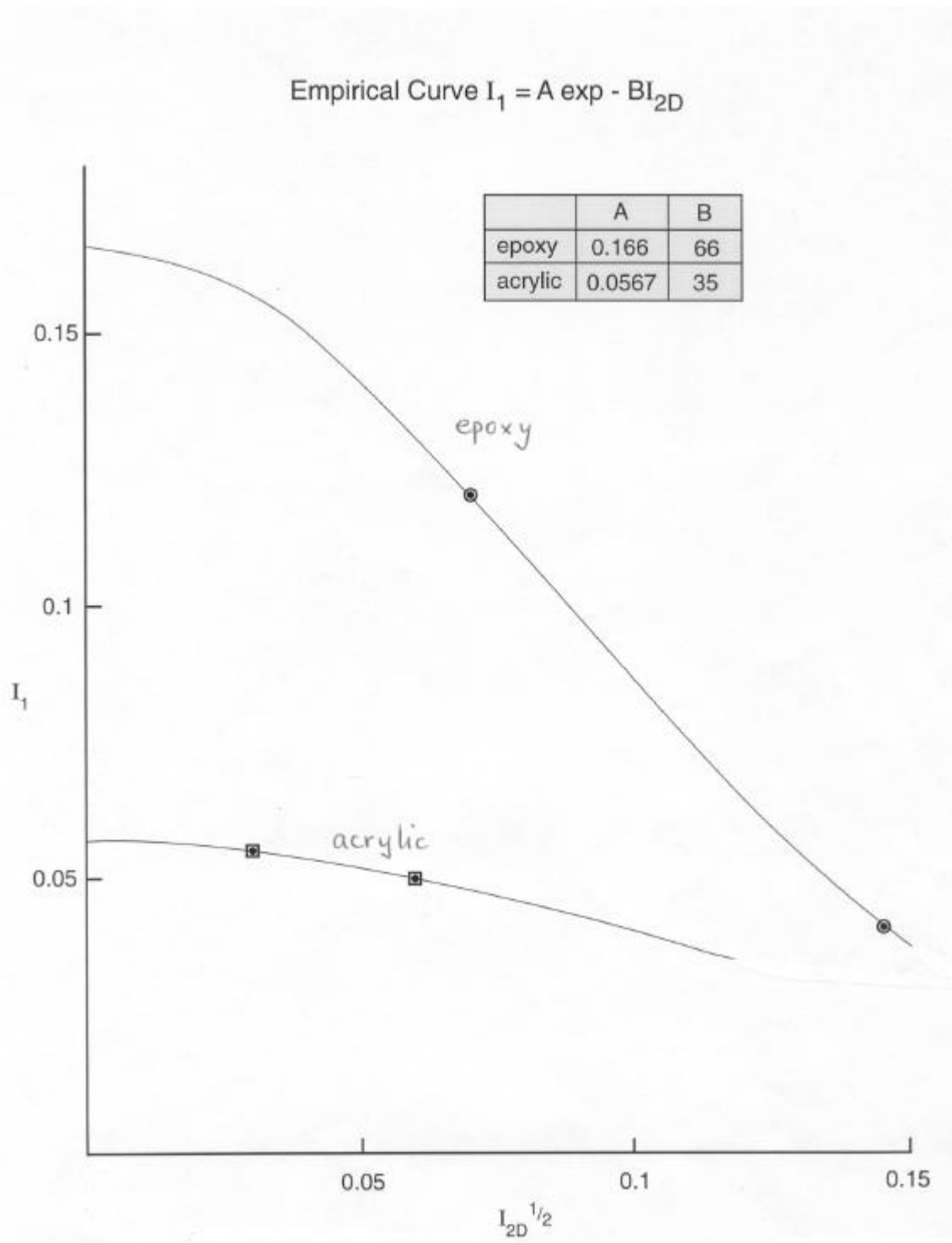


Figure 8 Plots of strain components I_1 vs $I_{2D}^{1/2}$ (see equations 3 and 4) at failure from tensile tests on bulk and butt-joint specimens of the epoxy and acrylic adhesives. Data are taken from table 2.