

Analysis of Failure Tests on Uniaxial Tensile and Plate Specimens of ABS

G Dean* and L Wright[†]

*NPL Materials Centre
and

[†]Centre for Mathematics and Scientific Computing
National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

SUMMARY

The centre-loaded plate test, described in earlier reports, has been used to obtain measurements on ABS specimens at failure. Failure occurs in this test under a stress state that is equibiaxial tension. Results are compared with measurements of failure under a uniaxial tensile stress. In both of these tests, failure follows extensive plastic deformation which is promoted by the nucleation of cavities in the rubber particles.

Criteria for failure are considered which propose that a component of strain in the matrix material between cavities reaches a critical value at failure which is independent of the applied stress state. Expressions are given for the plastic volumetric strain and the effective plastic strain in the material between cavities. The results of experiments and associated data analysis are described that enable calculation of these strain components at failure in the uniaxial tension and plate tests. For this purpose, the evaluation of a new specimen geometry is described for determining properties at failure under uniaxial tension.

The results of these experiments are not sufficiently accurate to verify the use of a failure criterion based on a critical component of strain at failure. However, within the bounds of the uncertainties in experimental data, the results are consistent with a criterion based on a critical value for the plastic volumetric strain in the matrix polymer between cavities.

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National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

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1 INTRODUCTION

A major part of Project CPM1.1 has been concerned with an evaluation of the accuracies of different materials models for predicting the deformation of tough plastics. For this purpose, predictions of the deformation of a centrally loaded circular plate that is supported near its circumference (see figure 1) have been compared with experimental measurements. Measurements were made of force against central deflection and surface strain in the centre of the plate in specimens of an ABS and a propylene copolymer. ABS specimens failed at ambient temperature (23 °C) by rapid crack propagation. At this temperature, the propylene copolymer deformed without cracking up to the maximum central deflection which was determined by the promotion of buckling at the outer circumference of the specimen. In order to promote failure by crack initiation, specimens were cooled to temperatures below ambient. Tests to failure have also been carried out on these materials under uniaxial tension. This report is concerned with the analysis of the results from these tests to evaluate potential criteria, proposed here, for ductile failure in polymers.

In these tests, both materials were observed to undergo extensive plastic deformation involving the nucleation of cavities. Under uniaxial tension, cavity nucleation starts above a few percent strain and is complete at most temperatures and strain rates before a tensile strain of 0.05. At higher strains, plastic flow occurs in the regions of polymer between cavities which involves orientation of the polymer molecules in these regions and some cavity growth⁽¹⁾. The structure of the molecular network must undergo significant changes under these circumstances. Molecular orientation gives rise to an increase in stiffness (orientation hardening), but at sufficiently high strains, the network will become weaker through the disentangling of molecules at temporary cross-links or the rupture of tie molecules in these regions. Ductile fracture then follows.

In this report, criteria for failure are explored based on the presumption that failure occurs when some measure of the deformation of the polymer material between cavities reaches a critical value. Since the stress changes very little during the stages of plastic deformation prior to failure, criteria based on critical components of strain are considered. Expressions are derived in section 2 for components of strain in the material between cavities. These are

likely to be a more relevant measure of the state of plastic deformation than components derived from the total strain tensor at failure. The magnitudes of these strain components at failure calculated in plate tests and uniaxial tension tests are compared in section 5 to explore their validity as a criterion for failure. Emphasis has been given to the analysis of results on the ABS polymer.

The magnitude and state of strain in the region of failure in plate specimens has been determined by a combination of experimental measurements and finite element analyses. These results are discussed in section 3.

Tests under uniaxial tension were carried out initially using ISO standard tensile specimens. These are waisted specimens in which the central region has parallel sides of length greater than 60 mm. Measurements of strain at different locations in this region revealed that, during plastic flow, the strain is not uniform along the gauge length of the specimen. The extent of the variation with position depends on the polymer type and the temperature and strain rate of the tests. Consequently, the determination of strain at failure is unreliable using the ISO specimen and an alternative specimen geometry has been selected and used for the tensile tests reported here. The selection of a suitable specimen geometry has been supported by finite element calculations which are discussed with the results of tensile tests in section 4.

2 DERIVATION OF PLASTIC STRAINS BETWEEN CAVITIES

In earlier reports^(2,3), expressions were derived that enabled calculation of two components of the plastic strain between cavities. These give a measure of the shear component ϵ_o^p , and the volumetric component ϵ_{VM}^p of the plastic strain in the material between cavities. In this section, expressions relating these quantities to components of strain in uniaxial tension and plate tests are derived. Values for ϵ_o^p and ϵ_{VM}^p can then be calculated at the point of failure in these tests to explore their use as a criterion for ductile failure in plastics.

The effective plastic strain ϵ_o^p is used to characterise plastic strain hardening under shear in the cavitation model through the hardening function $\sigma_o(\epsilon_o^p)$ Here $\epsilon_o^p = \gamma_s^p / \sqrt{3}$ and

$\sigma_o = \sqrt{3} \sigma_s$ where γ_s^p and σ_s are the plastic shear strain and the shear yield stress determined for uncavitated material. Components of the macroscopic plastic strain increments $d\epsilon_{ij}^p$ are related to increments in ϵ_o^p by equating the plastic work done in the voided material under a given stress state σ_{ij} to the equivalent plastic work for the matrix material (repeated subscripts indicating summation)

$$\sigma_{ij} d\epsilon_{ij}^p = (1-f) \sigma_M d\epsilon_o^p \quad (1)$$

Here f is the volume fraction of cavities and σ_M is the effective yield stress ($\sqrt{3} \sigma_s$) of the matrix polymer between cavities. For the ABS material, which is rubber-toughened, σ_M will increase as rubber particles cavitate and are thus replaced by cavities. For a fully cavitating, rubber-toughened polymer, σ_M is the yield stress for the polymer without rubber at the effective plastic strain ϵ_o^p . It follows by integrating equation (1), that the effective plastic strain under a uniaxial tensile stress σ_T is related to the plastic tensile strain ϵ_T^p by

$$\epsilon_o^p = \frac{\sigma_T \epsilon_T^p}{(1-f) \sigma_M} \quad (2)$$

Failure initiation in the plate tests occurs in a region of equibiaxial tensile stress σ_{bT} (see section 3.3). The strain at the plate centre is also equibiaxial and, from equation (1), the plastic component ϵ_{bT}^p is related to ϵ_o^p by

$$\epsilon_o^p = \frac{2 \sigma_{bT} \epsilon_{bT}^p}{(1-f) \sigma_M} \quad (3)$$

An expression for the plastic component of the volumetric strain between cavities was derived in an earlier report⁽³⁾ and is

$$d\epsilon_{VM}^p = \frac{d\lambda}{(1-f)} \frac{2\mu'}{\sigma_M} \left(1 - \frac{\mu' \sigma_k}{\sigma_M} \right) \quad (4)$$

where μ' is the flow parameter defined by the flow potential F (see equation (7)) and σ_k is the hydrostatic component of stress. The quantity $d\lambda$ is determined from expressions for the flow law

$$d\epsilon_{ij}^p = d\lambda \frac{\partial F}{\partial \sigma_{ij}} \quad (5)$$

and the equivalence of plastic work, equation (1). Thus

$$d\lambda = \frac{(1-f) \sigma_M d\epsilon_o^p}{\sigma_{ij} \partial F / \partial \sigma_{ij}}$$

Assuming the flow potential F takes the form for non-associated flow⁽³⁾

$$F = \frac{\sigma_e^2}{\sigma_M^2} - (q_1 f)^2 + 2q_1 f \cosh \frac{3\sigma_k}{2\sigma_M} \left(1 - \frac{\mu' \sigma_k}{\sigma_M} \right)^2 \quad (7)$$

then under a uniaxial stress σ_T

$$d\lambda = \frac{(1-f) \sigma_M d\epsilon_o^p}{\frac{\sigma_T}{\sigma_M} \left\{ \frac{2\sigma_T}{\sigma_M} + q_1 f \sinh \left(\frac{\sigma_T}{2\sigma_M} \right) + \frac{2\mu'}{3} \left(1 - \frac{\mu' \sigma_T}{3\sigma_M} \right) \right\}} \quad (8)$$

Substituting equations (2) and (8) into equation (4) and integrating gives the following expression for the plastic volumetric strain in the matrix under uniaxial tension

$$\epsilon_{VM}^p = \frac{2\mu' \left(1 - \frac{\mu' \sigma_T}{3\sigma_M} \right)}{(1-f) \left\{ \frac{2\sigma_T}{\sigma_M} + q_1 f \sinh \left(\frac{\sigma_T}{2\sigma_M} \right) + \frac{2\mu'}{3} \left(1 - \frac{\mu' \sigma_T}{3\sigma_M} \right) \right\}}$$

Under an equibiaxial stress σ_{bT} , the expression for $d\lambda$ is

$$\frac{(1-f) \sigma_M d\epsilon_o^p}{2 \frac{\sigma_{bT}}{\sigma_M} \left\{ \frac{\sigma_{bT}}{\sigma_M} + q_1 f \sinh \left(\frac{\sigma_{bT}}{\sigma_M} \right) + \frac{2\mu'}{3} \left(1 - \frac{2\mu'}{3} \frac{\sigma_{bT}}{\sigma_M} \right) \right\}} \quad (10)$$

Substituting equations (3) and (10) into equation (4) and integrating gives the plastic volumetric strain between cavities under biaxial tension as

$$\frac{2\mu' \left(1 - \frac{2\mu'}{3} \frac{\sigma_{bT}}{\sigma_M} \right) \epsilon_{bT}^p}{(1-f) \left\{ \frac{\sigma_{bT}}{\sigma_M} + q_1 f \sinh \left(\frac{\sigma_{bT}}{\sigma_M} \right) + \frac{2\mu'}{3} \left(1 - \frac{2\mu'}{3} \frac{\sigma_{bT}}{\sigma_M} \right) \right\}} \quad (11)$$

Equations (2), (3), (9) and (11) enable the effective shear and volumetric components of the plastic strain between cavities to be calculated at failure under uniaxial and biaxial tensile stress states from a knowledge of parameters in the cavitation model and stress and strain levels at failure under these stress states. The parameters in the model have been determined in earlier work and are listed in table 2 in section 5. Stresses and strains at failure have been measured using tests on tensile and plate specimens that are described next.

3 FAILURE MEASUREMENTS IN TESTS ON CIRCULAR PLATE SPECIMENS

3.1 APPARATUS

The apparatus developed for loading the plate specimens is shown in figure 1. The specimen has a diameter of 120 mm and rests on a circular support of diameter 100 mm which is the upper edge of a cylindrical tube. The edge has a radius of 5 mm. For tests at low speed, the cylinder is fixed to the moving cross-head of a universal testing machine. The specimen is loaded through a hemispherical steel surface that is bolted to the upper part of the loading assembly. Clamped to this part is a bracket which passes through a slot in the wall of the cylinder and supports a mirror at an angle of 45° to the vertical. This allows the lower surface

of the plate to be viewed by a camera positioned remote from the test assembly. The specimen is loaded by raising the supporting cylinder. In this way, the centre of the specimen remains fixed with respect to the photographic plane of the camera. The central deflection of the plate is determined from measurement of the cross-head movement.

Measurements of surface displacement were made at a single speed of 0.1 mm/s. Load against central deflection measurements were made over a range of loading speeds. For speeds up to 1 mm/s, the apparatus was mounted in a screw driven tensile testing machine. For higher speeds up to 1 m/s, a servohydraulic machine was used and the support cylinder was fixed whilst the hemispherical surface was attached to the actuator.

3.2 MEASUREMENT OF STRAIN IN THE PLATE SURFACE

The strain distribution in the lower surface of the specimen has been estimated by a photographic method which involves measuring the movement of reference marks on this surface with increasing deflection of the plate. Reference marks were positioned along 2 perpendicular lines through the centre of the face of the specimen. These lines were drawn with a black felt-tip pen. A very fine line was scribed through the centre of these lines using a sharp stylus. The stylus was also used to define a cross at radial distances of 5, 10, 15, 20, 25 and 30 mm from the centre of the plate. The specimen surface was photographed using a Nikon D1 digital camera with a Sigma 180 mm macro lens and a dedicated flash. The light sensing element in this camera consists of an array of 1320 x 2010 pixels. The camera was positioned at a distance of 930 mm from the plate surface at which point the reference marks on the specimen filled the field of view. Simple image processing software was used to display a photographic image on a screen. Each fine cross appeared lighter than the surrounding area of black ink, and its centre could be located by eye to a single pixel enabling the coordinates to be identified. The photographic system was calibrated to enable horizontal displacements of the reference points during plate deformation to be determined from the changes in pixel coordinates.

RESULTS OF FAILURE TESTS ON PLATE SPECIMENS OF THE ABS

Figure 2 shows force vs central deflection plots measured on plate specimens of the ABS polymer at 23 °C. Tests have been carried out at test speeds of 0.1 mm/s, 10 mm/s and 1 m/s with repeat tests at each speed as shown in the figure. All the specimens failed by rapid crack propagation. Values for the central deflection at failure range from 16 to 26 mm with the majority of values lying in the range 21 to 25 mm. The deflection at failure appears to be insensitive to the test speed.

A fairly typical crack pattern in a failed specimen is shown in figure 3. The distance between the path of the crack and the plate centre ranged from 0 to 15 mm although for most of the specimens tested, this distance was between 5 and 10 mm. In order to assist the determination of stress and strain levels at failure in plate specimens, finite element calculations have been carried out to predict stress and strain distributions in the lower surface of the specimen. The linear Drucker-Prager materials model with rate-dependent plasticity was used for the analyses with Abaqus. The experimental hardening curves for ABS at different strain rates are shown in figure 4a. Values for the other properties required by the model are listed in table 1. These have been obtained from the results of tests reported earlier⁽²⁾.

Table 1 Values for the properties required for finite element analyses using the linear Drucker-Prager model in Abaqus

Property	ABS	Propylene copolymer
Young's modulus (GPa)	2.3	1.6
Poisson's ratio	0.38	0.39
$\tan \beta$	1.55	0.88
$\tan \psi$	0.9	0.75
Hardening functions	Fig 4a	Fig 4b

Calculated distributions of principal stress and principal strain components with radial position in the lower surface of a specimen are shown in figure 5 at a central deflection of

23 mm which is the mean value at which failure occurs. The loading speed was 0.1 mm/s and a value for the coefficient of friction between the plate surface and the loading and support surfaces of 0.25 was used.

These calculations show that the maximum stress and strain occurs at the plate centre and that there is a region of predominantly uniform, equibiaxial stress within a radius of 15 mm of the centre. This is presumably therefore the region of crack initiation. The presence of a small stress and strain bias away from the centre may predispose crack initiation to locations away from the centre as observed in the failed specimens.

The predicted stress values in figure 5a are considered to be fairly accurate. Although the yield criterion in the linear Drucker-Prager model has been shown to have limited validity for rubber-toughened plastics, yield stresses under equibiaxial tension lie close to the yield surface for this model. Stress predictions using the new cavitation model confirm the accuracy of these calculations near the plate centre. There is evidence from earlier work⁽⁴⁾ however that the strain predictions in figure 5b are higher than actual values. Horizontal components of the displacement of marks on the plate surface have been measured with increasing central deflection using the method described here in section 3.2. Measured displacements of points located 5 mm and 10 mm from the plate centre are compared in figure 6 with predicted values derived from the above strain calculations. Predictions compare well with experiment when the central deflection is small and deformation is predominantly elastic, but calculated displacements lie progressively above measured values at larger deflections. These results indicate that actual displacements are around 70% to 80% of predicted values at a centre deflection around 23 mm. Accordingly, for the purpose of estimating the strain at failure in plate specimens, the values of the principal strains at the centre of the plate in figure 5b have been reduced by a factor of 0.75 when comparisons are made with the results of failure tests under uniaxial tension in section 5 (see table 2).

4 MEASUREMENT OF FAILURE UNDER UNIAXIAL TENSION

4 SPECIMEN GEOMETRY

Figure 7 shows results of tensile stress against tensile strain measurements on a single specimen of a rubber-toughened polypropylene. The specimen geometry and dimensions were the same as the ISO tensile specimen⁽⁵⁾. Simultaneous strain measurements were made using a video extensometer in 3 separate regions of length 10 mm near the centre of the specimen. The results illustrate the distribution of strain that can occur in specimens of this geometry at strains above that corresponding to the peak in stress. The extent of the strain localisation depends on the flow behaviour of the polymer and hence the test temperature and speed. In extreme situations, the localisation is clearly visible through necking but for many materials the extent of the non-uniformity in strain is less extreme and less apparent.

In order to obtain more meaningful measurements of strain, and, in particular, of strain at failure, an alternative specimen geometry has been chosen that is illustrated in figure 8. The waisted region is defined by a constant radius that locates the maximum stress, and hence onset of flow, at the centre of the specimen. There may be scope for optimising the values chosen for the radius and depth of the waist. Larger values for the radius and a smaller reduction in the specimen width may produce a more uniform stress state in the centre of the specimen but could lead to the localisation of strain outside the region of strain measurement. An optimum specimen geometry may be dependent on polymer properties as indicated by stress analyses of the geometry described next.

4.2 FINITE ELEMENT ANALYSES OF THE NEW SPECIMEN GEOMETRY

Finite element analyses of stress and strain distributions in specimens of the geometry depicted in figure 8 have been carried out using property values derived for the ABS and propylene copolymer materials. The linear Drucker-Prager materials model was used with rate-dependent plasticity. The hardening curves at different strain rates are shown in figure 4a

for ABS and in figure 4b for the propylene copolymer. Figure 4c shows how the data for ABS in figure 4a have been sampled and extrapolated to high strains for use in the FE analysis. Values for the other parameters required by the linear Drucker-Prager model are listed in table

Figure 9 shows distributions of the components of stress acting along the 3 symmetry axes of the specimen. The calculations were made using a 3-D analysis and the explicit solver in Abaqus at an extension of 4 mm and an extension rate of 0.2 mm/s. These results show that there is a region of essentially uniform, uniaxial stress in the specimen centre of length about 7 mm. The stress state is not pure uniaxial since the analysis indicates a small, transverse, in-plane stress rising to 1 MPa at the specimen centre. The stress in the through-thickness direction is zero. The small transverse stress is attributable to the profile of the specimen and the associated high strain gradient during flow. Distributions of the components of strain along the specimen axes are shown in figure 10. These show strain localisation which is only partly caused by the specimen geometry. The flow behaviour of the polymer is responsible for most of the strain localisation. The results in figure 10 indicate that the strain is essentially uniform over a length of between 3 and 5 mm in the specimen centre. This gives an indicator of the gauge length that should ideally be used for strain measurements in the flow region. There are some further general observations

- the transverse strain in the plane of the specimen decreases through the width and is on average less than the strain in the through-thickness direction. This is presumably a result of the non-zero, transverse in-plane stress discussed above.
- the extent of strain localisation is strongly influenced by the hardening behaviour of the polymer. Predicted strain localisation is therefore greater if rate-dependent hardening is neglected and a single curve is used in the analysis.

The extent of strain localisation is also dependent on the shape of the hardening curve, and this has given rise to a dependence of the calculated strain distribution on test speed for the ABS polymer. The dependence of hardening behaviour on strain rate for this material is shown in figures 4a and 4c. This shows that the extent of strain softening is greater at the lower strain rates than at higher rates. This leads to a higher predicted strain localisation at a

low test speed (0.2 mm/s) compared with that obtained at a higher speed (20 mm/s) as shown in the strain maps in figure 1

The sensitivity of strain distributions to the representation of hardening behaviour, added to the fact that the stress analysis is trying to predict an unstable situation, imply that the strain levels shown in figures 10 and 11 are probably not quantitatively accurate. They do however support the use of this specimen geometry for strain measurements in the flow region if extensometers can be employed with a gauge length in the range of 3 to 5 mm. With such a small gauge length, adequate accuracy in strain measurement is only possible for strains above around 0.05. The standard tensile specimen should therefore be used for tensile measurements up to the maximum in stress. At higher strains where the material undergoes plastic flow and particularly for the determination of the strain at failure, the specimen described here should give more meaningful strain measurements.

4.3 RESULTS OF FAILURE TESTS UNDER UNIAXIAL TENSION

The results of tensile tests on ABS using specimens with the geometry described in section 4.1 are shown in figure 12. Values for true stress are plotted against true strain. The gauge length of the specimen over which the strain was measured was 5 mm and the end point of each curve corresponds to a tensile failure within the gauge length. The tests were carried out at speeds of 1 mm/min, 10 mm/min and 100 mm/min giving plastic strain rates in the centre of the specimens shown with the results.

Strain values at failure are observed to lie in the range 18% to 42%. Contrary to the results on plate specimens shown in figure 2, there appears to be a dependence of failure strain on test speed. There is also a greater variability in the failure strain between specimens than observed with plate specimens.

5 DISCUSSION OF RESULTS

The objective at this stage of the study is to use the results of the failure tests in figures 2 and 12 to explore the validity of possible failure criteria based on the strain components introduced in section 2. Any interpretation of results is however made difficult by the large uncertainty in the strain at failure under a uniaxial tensile stress. The reason for the wide variability in failure strain between specimens is not known. When such a phenomenon is observed in materials testing, it is often attributed to a distribution of flaws or weak regions that induce premature failure. Whilst the area in the tensile specimens in which failure can initiate is relatively small (5 mm x 10 mm) compared with the plate specimens (30 mm diameter), it is not apparent what might be the origin of these weak regions.

An alternative explanation may lie with the strain localisation that occurs in tensile specimens that has been described in section 4. Although a small gauge length was used (5 mm), it is possible that the strain is not uniform even over this short length, as indicated by some of the finite element analyses in section 4.2. If this were true, then strain localisation might be more severe at the lower speeds because of the different hardening behaviour at low strain rates (see figures 4a and 11). The implication of this is that the strain at the point of failure in the lower speed tests may be larger than the values recorded which are simply average values over a region of non-uniform strain. The variability between specimens at any speed may be due to irreproducibility in other factors that determine the extent of strain localisation. Strain localisation is caused by instability in deformation by plastic flow and is readily induced in the uniaxial tensile test because of the uniform stress across the specimen cross section. Strain localisation is less relevant in the plate tests because of the stress distribution in the specimen, and this is consistent with the narrower range of failure strains observed in these tests.

If this is a valid interpretation of the tensile data in figure 12, then the tests with the higher strains at failure are expected to have a more uniform strain in the gauge length of the specimen, and these strain values are therefore more indicative of the strain at failure under uniaxial tension. Best estimates of values for the strains at failure under uniaxial and biaxial stress have been taken from the results in figures 12, 2, 5 and 6 and are given in table 2. Also shown in table 2 are experimental values for the other quantities in equations (2), (3), (9) and (11) required for the calculation of strain components ϵ_0^p and ϵ_{VM}^p at failure. Values for the

yield stresses σ_T , σ_{bT} and σ_M also need to refer to conditions at failure. These stresses vary with plastic strain and strain rate through the processes of molecular orientation hardening and cavity growth⁽¹⁾. The influences of these processes on the variation of yield stresses with plastic strain and strain rate have not been fully included in the model. However, we note that the influence of cavity growth in decreasing the yield stress tends to cancel the influence of orientation hardening which increases yield stresses. Furthermore, these stresses appear in the expressions for ϵ_o^p and ϵ_{VM}^p as ratios σ_T/σ_M and σ_{bT}/σ_M and the ratios will vary less with strain and strain rate than the individual stresses. The ratios shown in table 2 have been derived from stress data at an effective plastic strain of 0.03 and a plastic strain rate of 0.003 s⁻¹.

Table 2 Values of the quantities in equations (2), (3), (9) and (11) at failure under uniaxial and biaxial stress

ϵ_T^p	0.42
ϵ_{bT}^p	0.19
σ_T/σ_M	0.32
σ_{bT}/σ_M	0.24
f_{uniaxial}	0.40
f_{biaxial}	0.43
μ'	0.16
q_1	1.5

The values for the volume fraction f of cavities at failure in table 2 have been calculated using the cavitation model and contain a small contribution from cavity growth which is different for each stress state.

Table 3 gives values for ϵ_o^p and ϵ_{VM}^p at failure under uniaxial and biaxial tension calculated using equations (2), (3), (9) and (11) and the parameters in table 2. It should be noted that there is a significant uncertainty in the accuracy of the values recorded in table 3. This stems

mainly from uncertainties in the determination of the strains at failure given in table 2. The value for failure in plate tests was based on a mean value for the central deflection at failure. Under uniaxial tension, the strain recorded was the largest value measured, and it has not been possible to obtain some mean value based on a larger number of valid results. More accurate measurements of strain at failure are needed before any conclusion can be drawn on whether ϵ_o^p or ϵ_{VM}^p reach a critical value at failure. However, the results in table 3 suggest that if such a criterion is valid, then it is more likely to be based on a critical value for the volumetric component ϵ_{VM}^p than the shear component ϵ_o^p .

Table 3 Calculated values for the plastic components of shear and volumetric strain between cavities at failure in uniaxial tension and plate tests

	ϵ_o^p	ϵ_{VM}^p
Uniaxial tension	0.22	0.26
Biaxial tension	0.16	0.21

6 CONCLUSIONS

In the centre-loaded plate test described here, specimens of ABS fail by rapid crack propagation at a deflection of the plate centre that lies in a narrow range around 23 mm. The deflection at failure does not vary significantly with test speed in the range 0.1 mm/s to 1000 mm/s. At this deflection, according to finite element analyses, the maxima in stress and strain lie at the centre of the lower surface of the plate where the stress state is predominantly uniform and equibiaxial over a region of approximately 20 mm diameter.

Determination of the magnitude of the strain at failure in plate specimens has not been achieved with confident accuracy. Comparisons of predicted surface displacements with experiment at central deflections below failure indicated that strain values calculated using finite element analysis with the linear Drucker-Prager materials model are inaccurate. A correction to predicted strain at failure values has been possible through these comparisons.

A new test specimen geometry has been evaluated for determining the strain at failure under uniaxial tension. This is considered to give more accurate measurements than use of the ISO standard specimen.

Measurements of the strain at failure in ABS under uniaxial tension vary widely between test specimens and indicate an increase with strain rate in the range 0.004 s^{-1} to 0.4 s^{-1} . This may be real and caused by a failure process involving the disentangling of temporary cross-links during plastic deformation of the polymer material between cavities. For a given molecular mobility and hence disentanglement time, the strain for disentanglement will increase with strain rate. Alternatively, despite use of the new specimen geometry and a small gauge length, the strain distribution in this length may not be uniform with the consequence that the strain at the location of failure in the low speed tests may be higher than the average value measured for the gauge length. Finite element analyses of strain distributions in the new specimen under uniaxial tension show higher strain localisation at the lower test speeds.

Based upon a theory for the micromechanics of rubber-toughening of plastics, expressions have been presented for the effective plastic strain and the plastic volumetric strain in the polymer material between cavities. Values for these strain components at failure under uniaxial and biaxial tension are similar, although values for the volumetric strain are closer than for the effective shear strain. Allowing for some experimental uncertainty in the determination of the quantities required by the calculations, the results are consistent with the plastic volumetric strain reaching a critical value at failure under different applied stress states.

This latter conclusion should be confirmed through more accurate measurements of strain at failure in uniaxial tension and plate tests.

7 ACKNOWLEDGEMENTS

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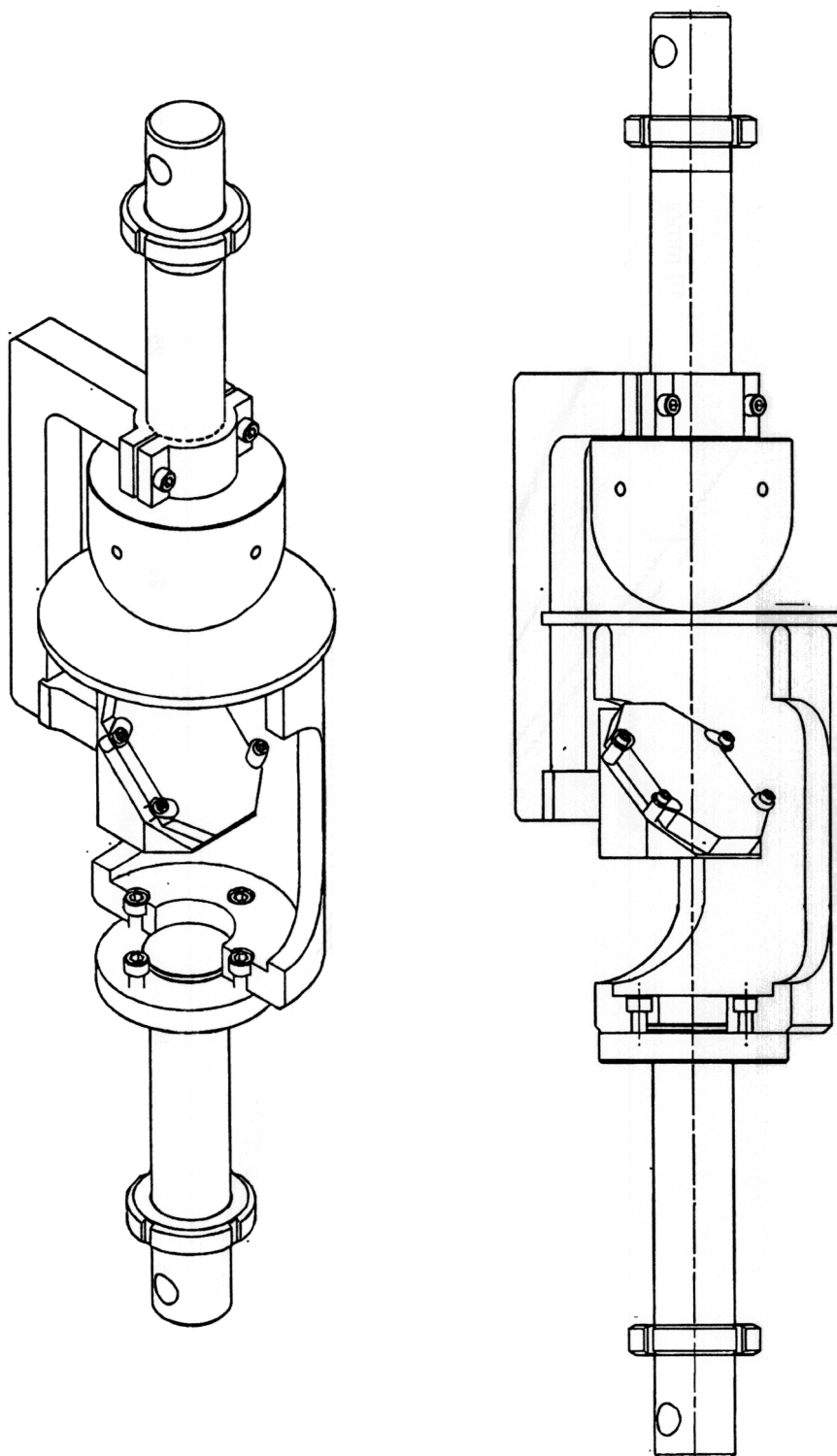


Figure 1 Apparatus for testing plate specimens. The mirror beneath the specimen enables measurements to be made of surface displacements in the deformed specimen.

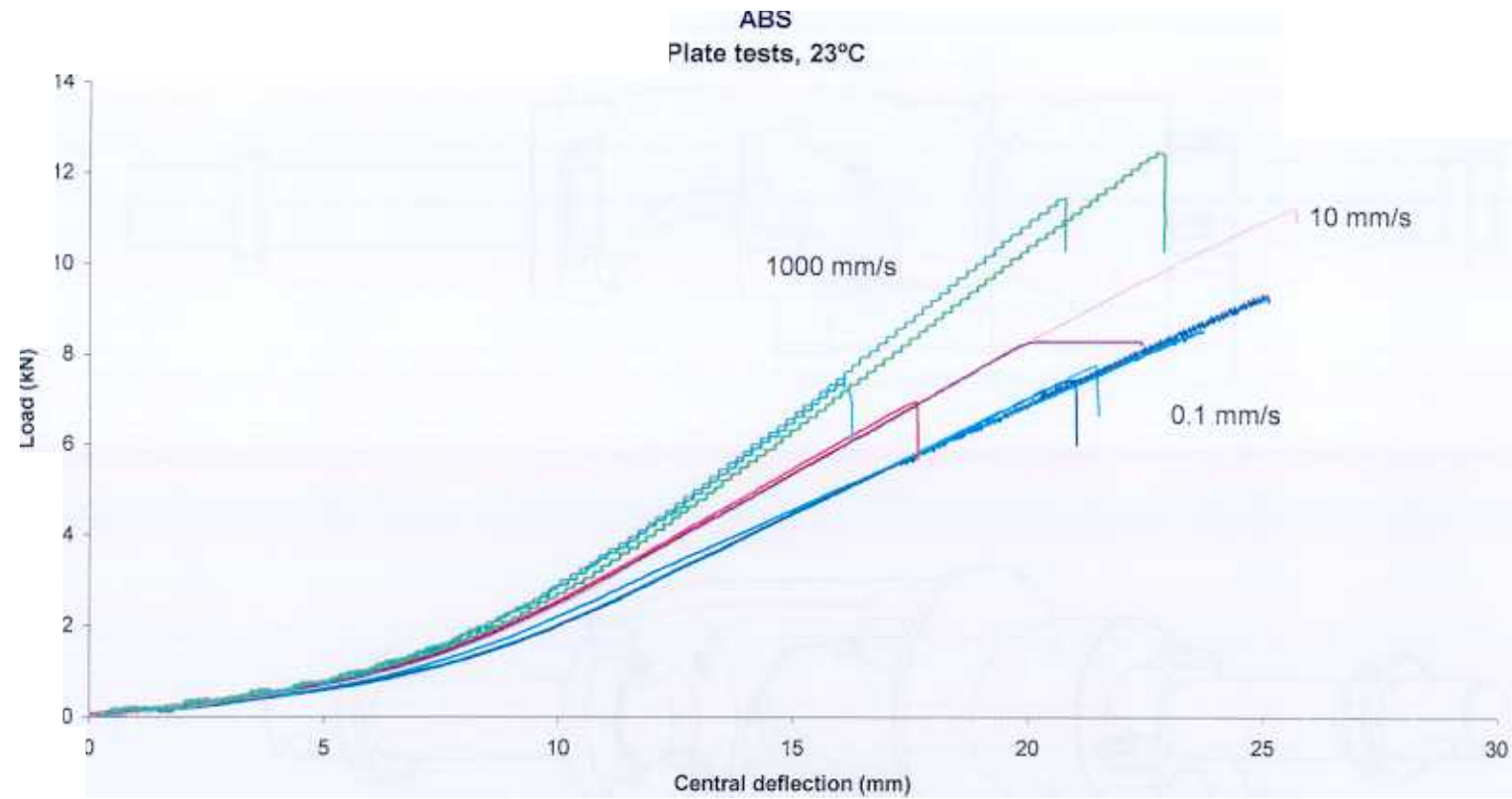


Figure 2 Measured force against central deflection of plate specimens of ABS at different test speeds



Figure 3 Illustration of a failed plate specimen of the ABS polymer. The lighter region around the plate centre is evidence of cavitation produced by the spherical loading surface.

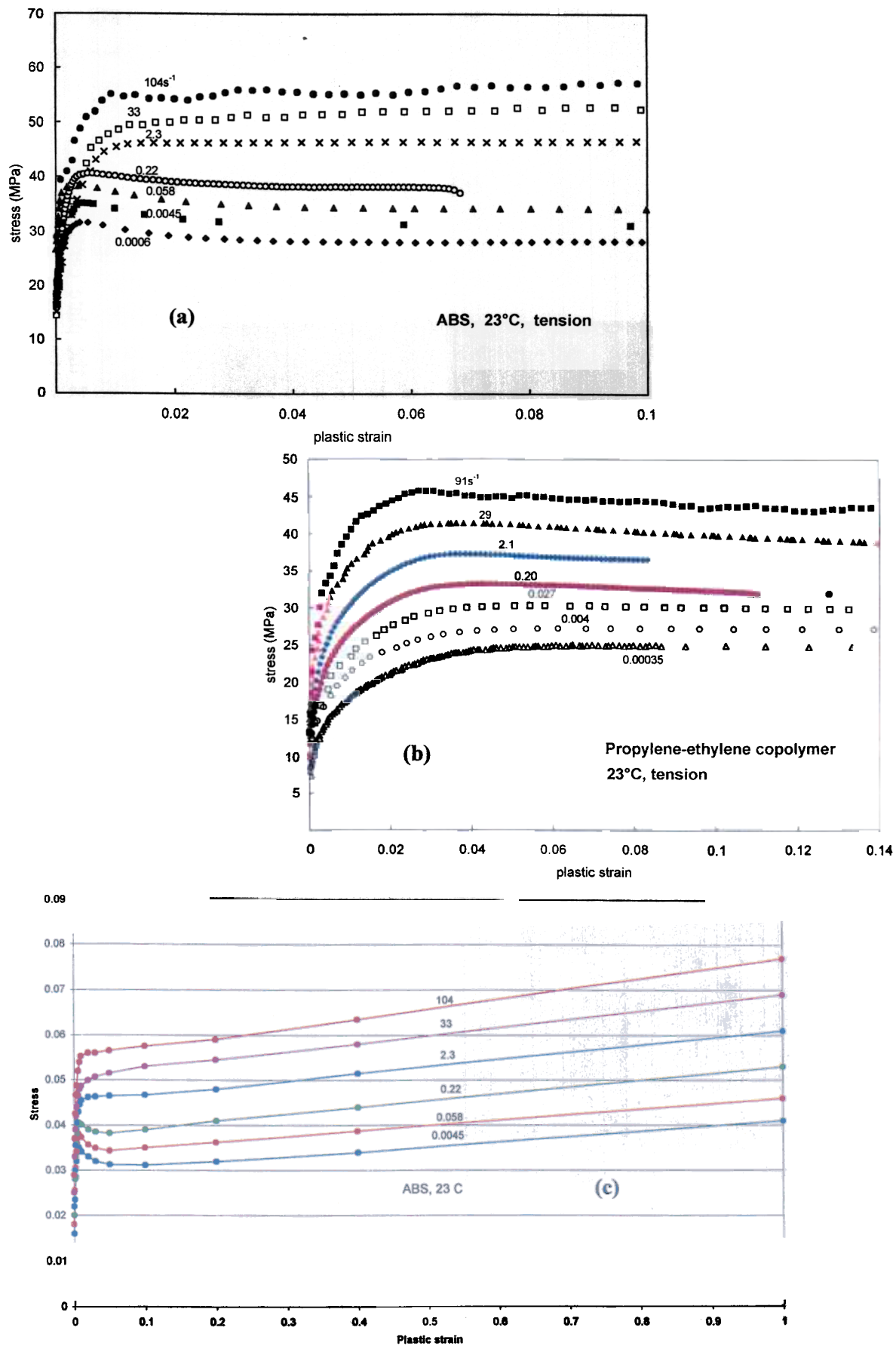


Figure 4: Tensile hardening curves for (a) the ABS and (b) the propylene copolymer at the strain rates shown with each curve. (c) shows the experimental data used for ABS in the models of the new specimen.

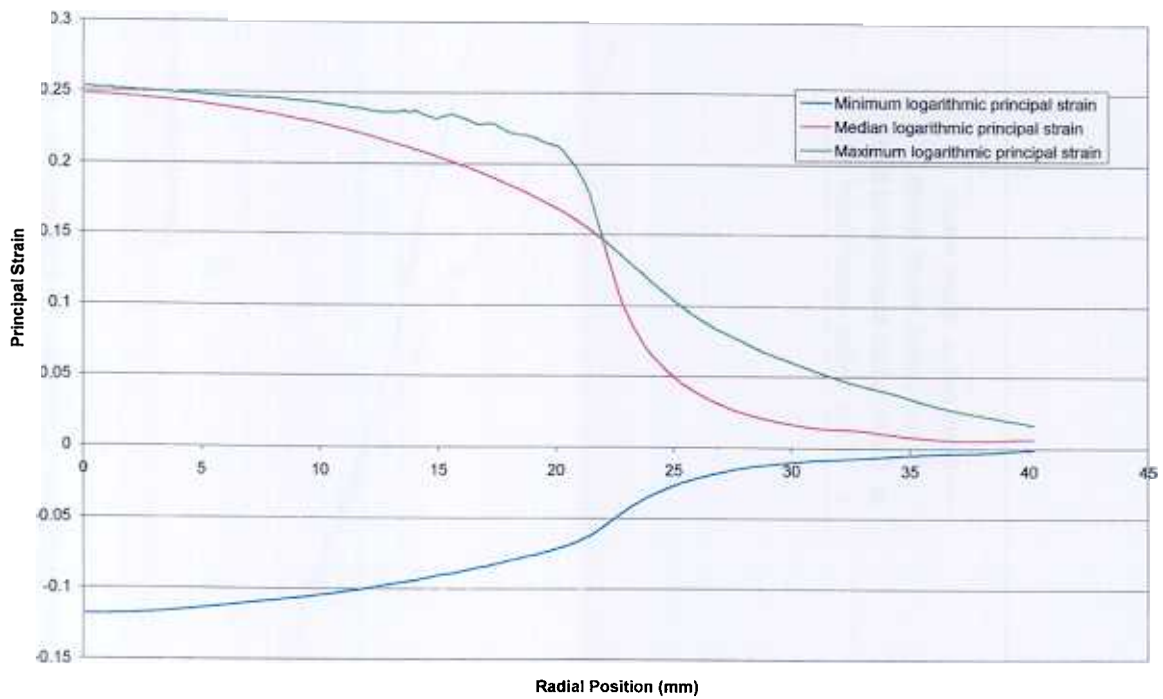
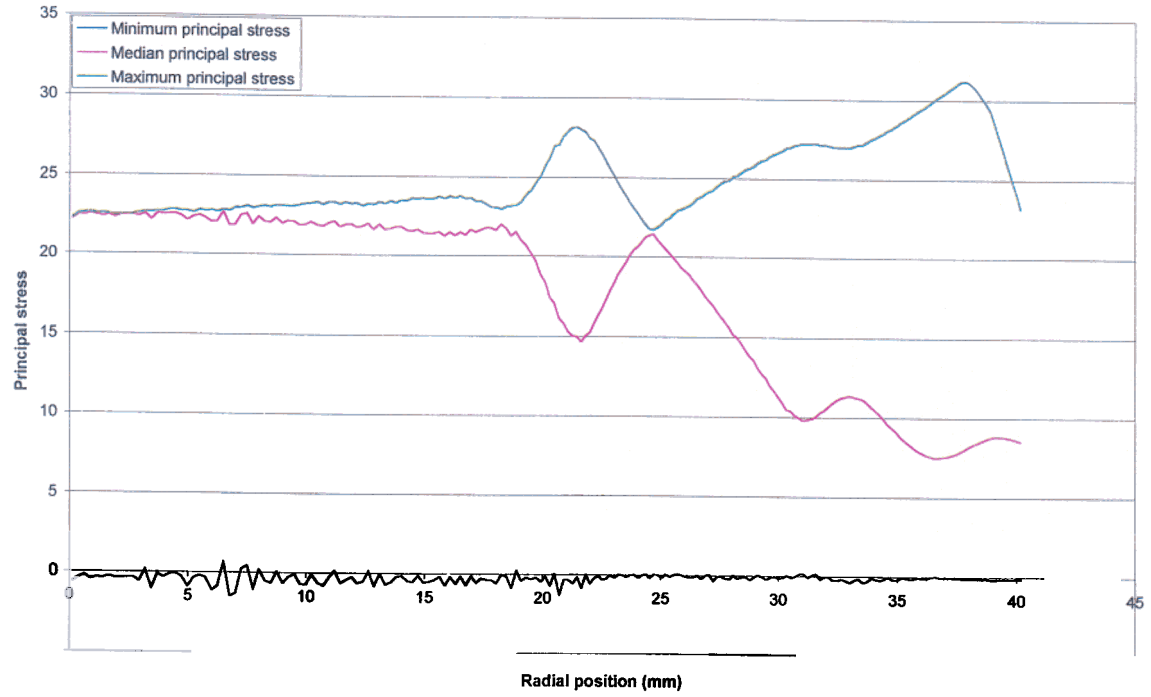


Figure 5: Distributions of components of (a) principal stress and (b) principal logarithmic strain with radial position in the lower surface of a plate specimen of ABS at a central deflection of 23 mm. The model used was the linear Drucker-Prager model with rate-dependent plasticity and a loading speed of 0.1 mm/s.

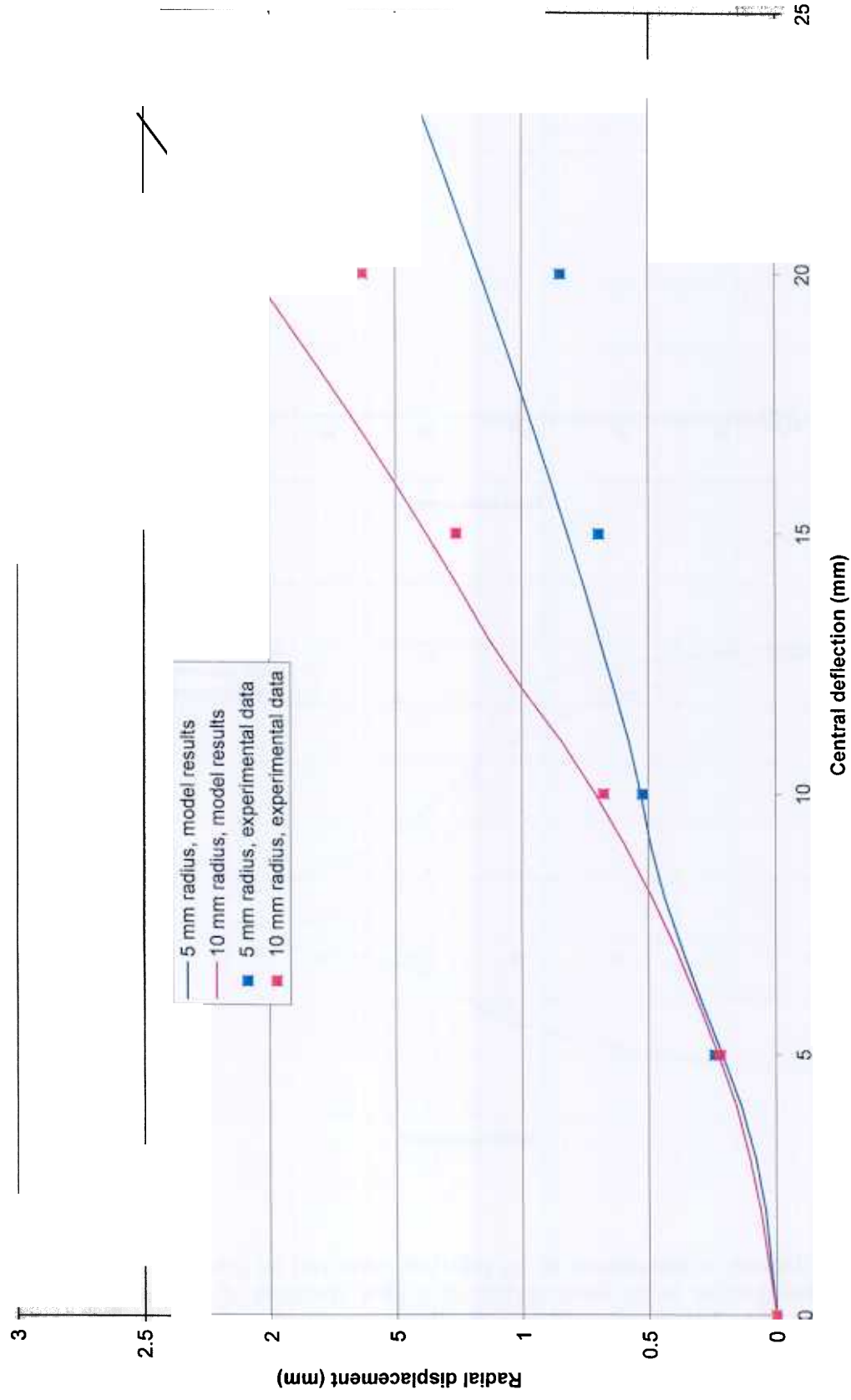


Figure 6: Comparison of model predictions and measured displacements on the lower surface of a centrally loaded ABS plate

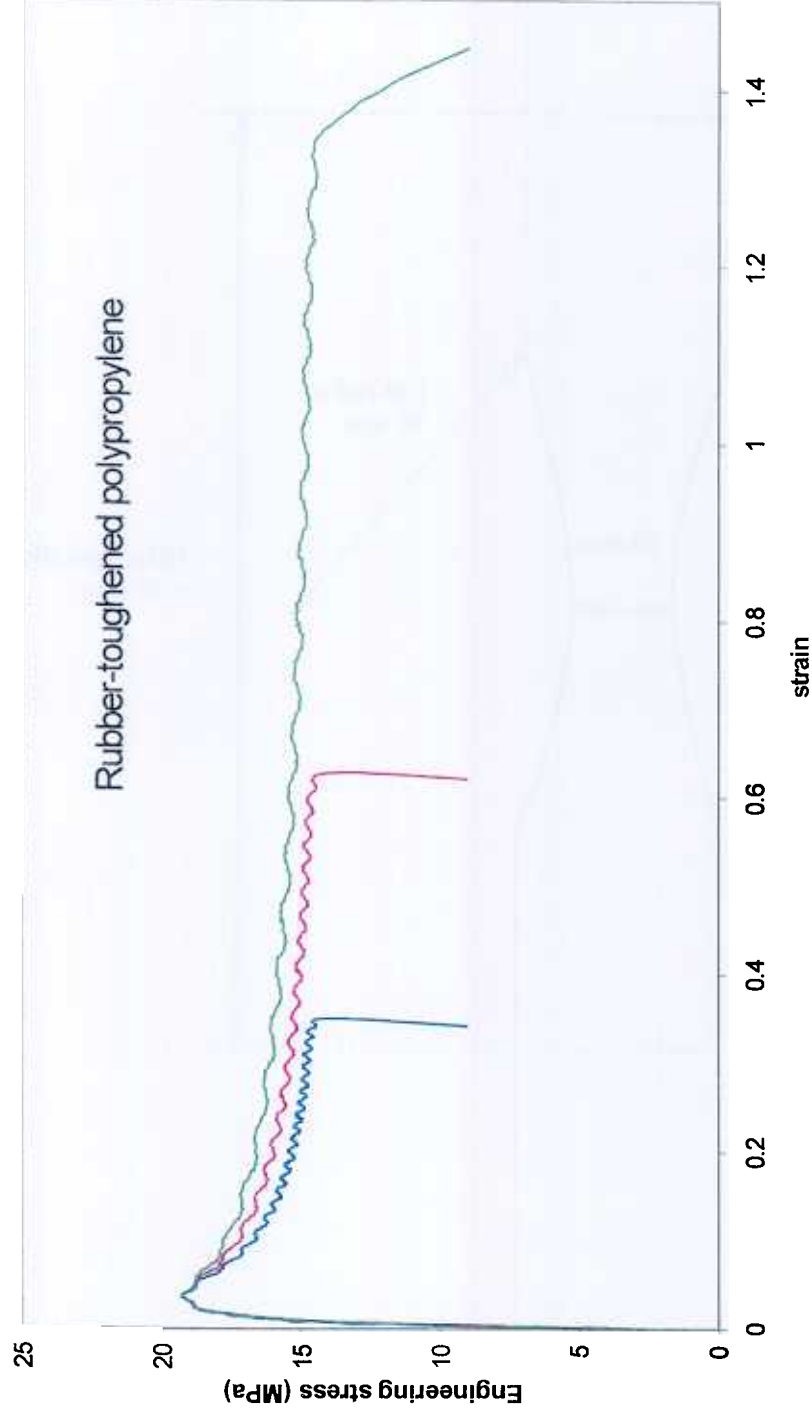


Figure 7

Stress/strain curves for a rubber-toughened polypropylene measured in a tensile test on a specimen having the geometry specified in the ISO Standard ISO 527-2 (4). A gauge length of 10 mm was used at 3 separate locations along the length of the specimen.

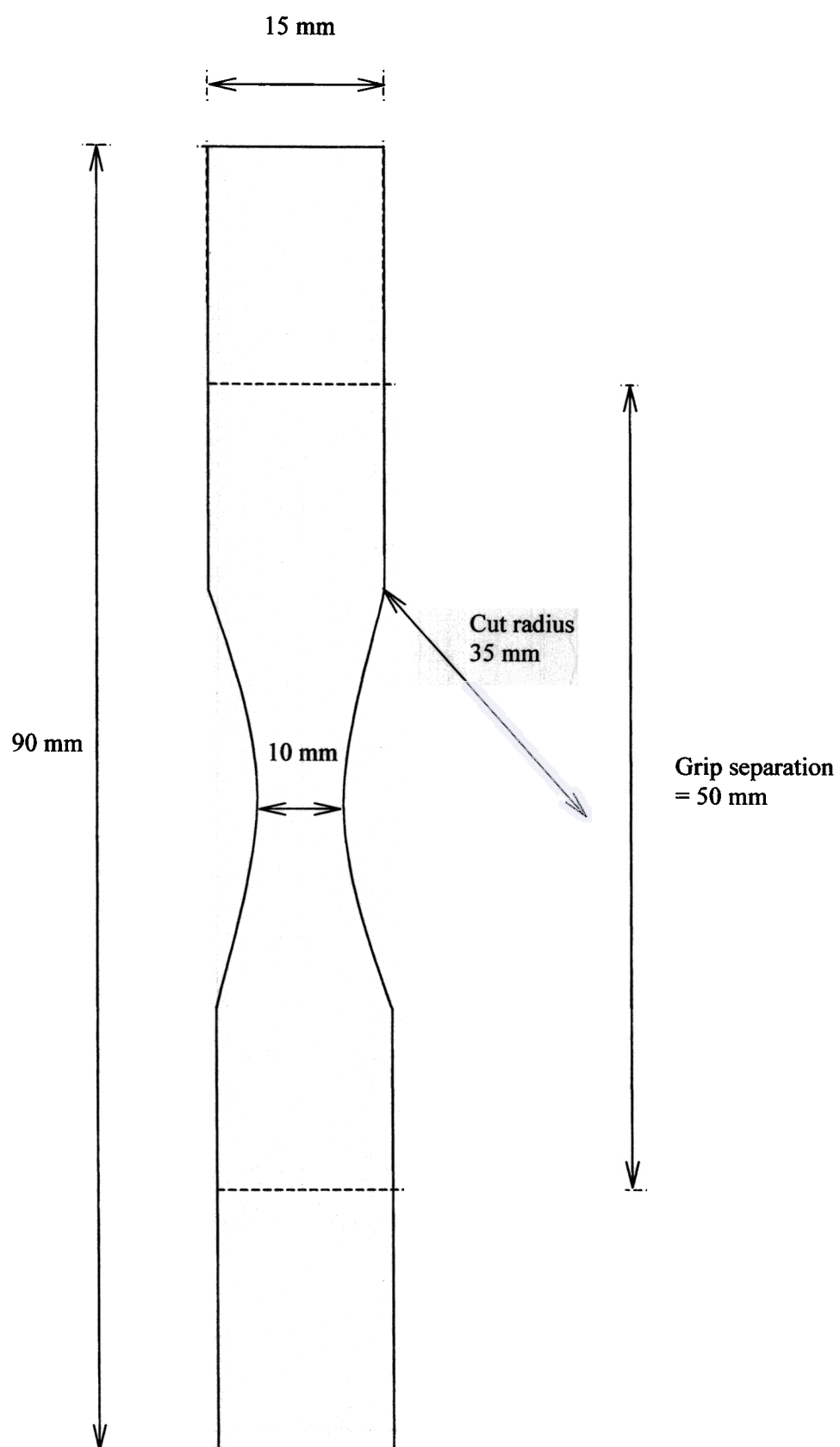
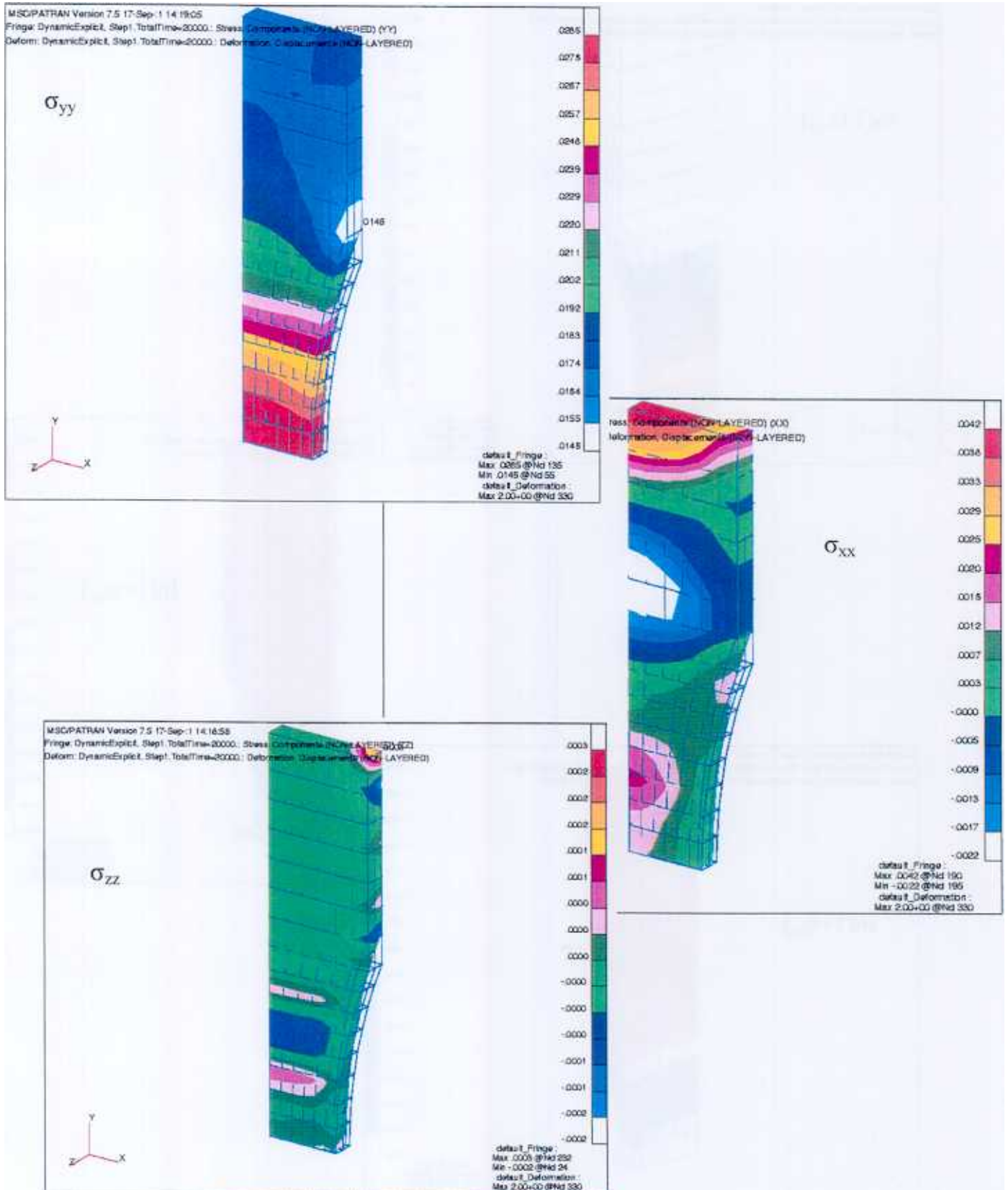


Figure 8: Diagram of the waisted specimen geometry



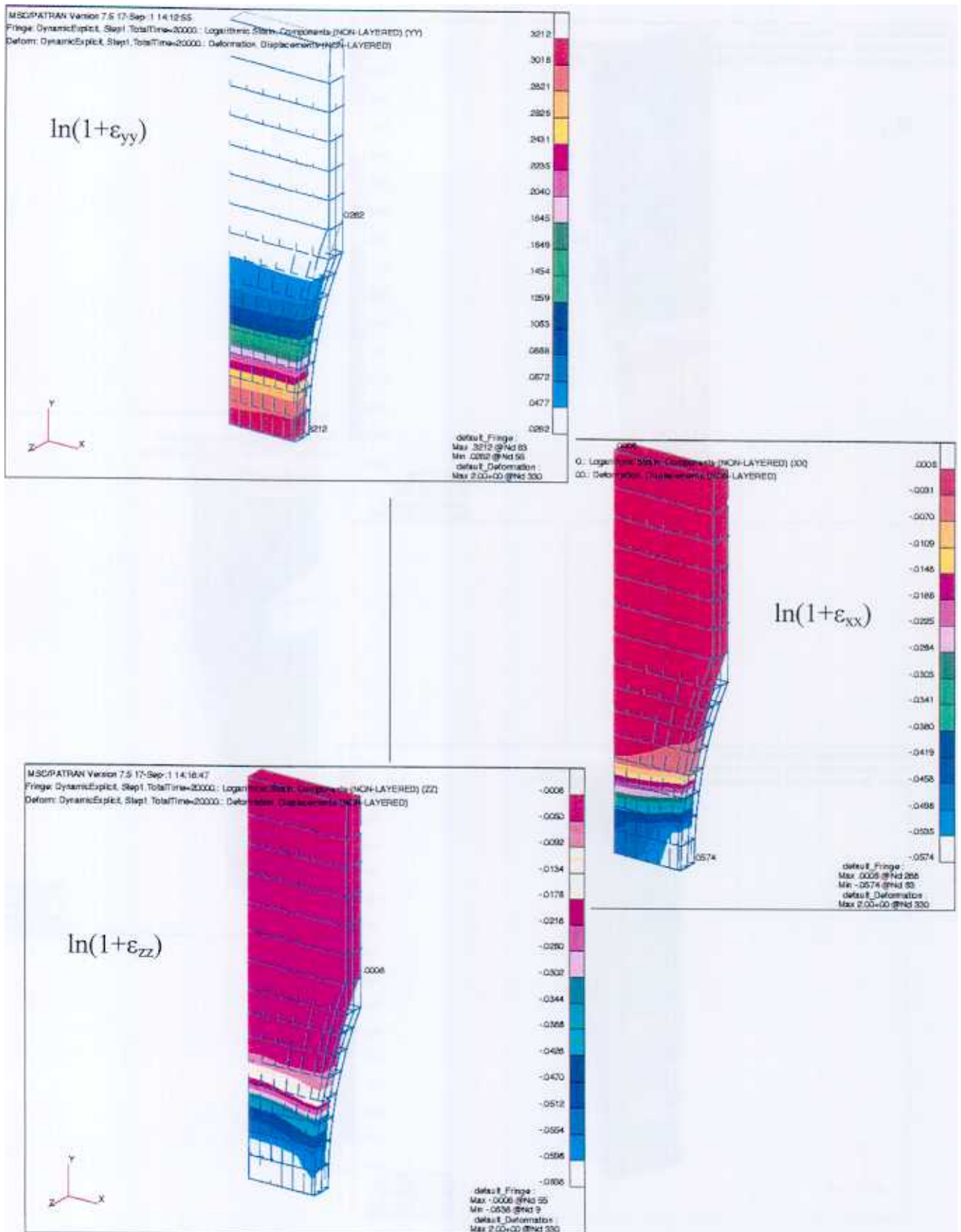


Figure 10: Distributions of strain components in the new specimen geometry at a length extension of 4 mm.

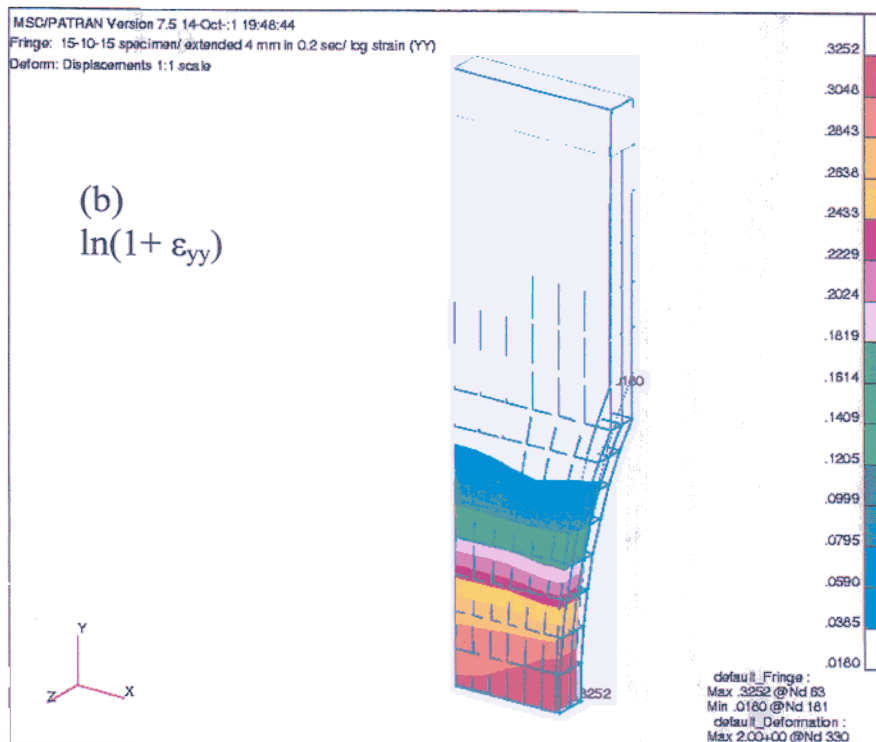
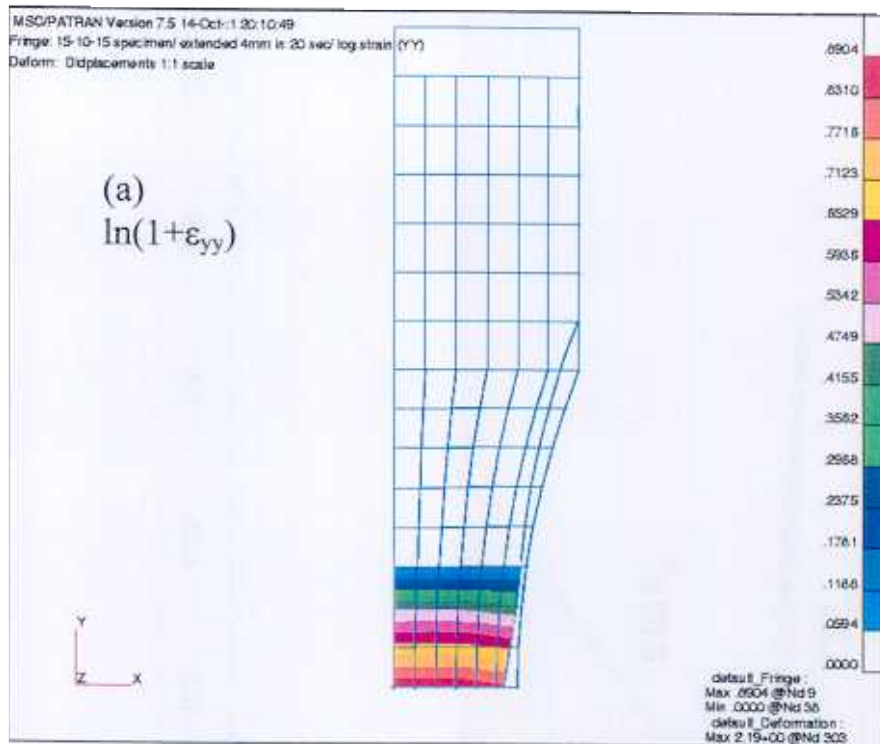


Figure 11: Distributions of the logarithmic axial strain in ABS specimens with the new geometry at loading speeds of (a) 0.2 mm/s and (b) 20 mm/s, predicted using rate-dependent plasticity and the hardening curves as shown in figure 4(c).

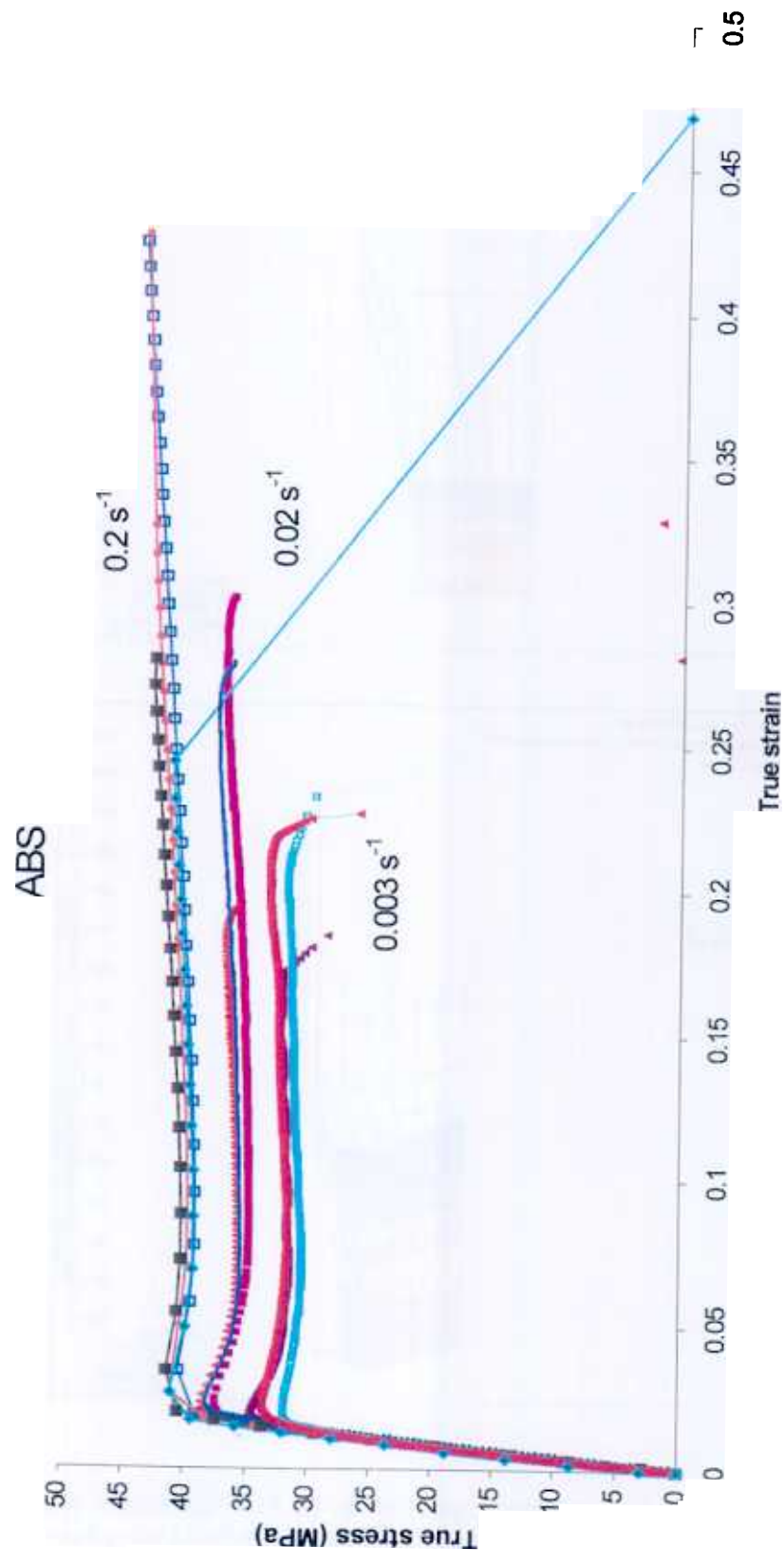


Figure 12 Tensile stress/strain curves to failure for ABS at the strain rates shown measured using test specimens with the new geometry