

VERIFICATION OF HYPERELASTIC TEST METHODS

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Summary

Commercial finite element analysis (FEA) software packages are used extensively for the prediction of the performance of adhesive joints. The accuracy of any prediction will depend on the validity of the material model employed and the reliability of the test data input into the chosen model. Methods for obtaining design data for flexible adhesives are being investigated in Project PAJ1.

The hyperelastic material models being investigated for characterising flexible adhesives require input data measured under conditions of plane strain and equi-biaxial tension. Studies verifying the test methods, developed in PAJ1, for generating these data are described in this report.

The lap joint specimen used in PAJ1 has been further investigated. 3-D FEA has been used to explore the effects of misalignment of the test specimen. The force-extension response will be little affected. However, peel stresses will be greatly increased. This may lead to premature failure of the specimen.

The studies described in this report have cleared up some of the uncertainties identified in earlier studies. The measurement methods employed have now been validated and better measurement practices identified. Therefore, future studies can be carried out with more confidence in the reliability of the test data.

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1. INTRODUCTION

Finite element analysis (FEA) software packages are frequently used for predicting the performance of adhesive joints through analysis of stress and strain distributions in materials. The accuracy of FE predictions depends on the validity of the material model employed and the reliability of the test data input into the chosen model. Project PAJ1 of the DTI Materials Metrology programme Performance of Adhesive Joints aims to provide improved tools for designing with flexible adhesives. A previous report [1] introduced the concept of modelling flexible adhesive joints through considering the adhesive as a rubber-like material whose behaviour could be described by Hyperelastic models [2].

This initial investigation [1] highlighted a number of issues that may have contributed to relatively poor FE predictions of the behaviour of lap joint specimens that were tested to study the suitability of the Hyperelastic models. This area will be investigated more comprehensively in the follow-on project PAJex2. The current report addresses some of the specific areas of concern highlighted in the initial study.

One of the main areas of concern was that the planar and equi-biaxial test methods were not sufficiently developed to produce the reliable data required for modelling. Sections 2 and 3 describe a validation exercise for these tests incorporating experimental and FE investigations. A further area of concern was the lap joint tests used to evaluate the models. It was suspected that the material in the joints may have experienced different cure conditions to the bulk adhesive material used to obtain the FE model input data. A brief investigation of this is described in Section 4. The FEA in the initial study used an idealised 2-D lap joint. Section 5 outlines a comparison with a 3-D model of the joint. The model did not allow for potential problems such as misalignment of the adherends of test machine. FE studies to predict the likely effects of minor misalignments of the test machine have been undertaken.

2. PLANAR AND BIAXIAL TEST METHODS FOR HYPERELASTIC MODELS

The Hyperelastic material models rely on data from a number of different states of stress in order to predict behaviour under multi-axial stresses. The normal procedure is to supply the analysis with test data supplied under uniaxial, planar and equi-biaxial tension. The FE software uses least squares fitting sub-routines to find the constants for the hyperelastic models. The uniaxial tension test is straightforward and well understood. However, development of the planar and equi-biaxial methods is more recent.

This Section describes validation of these methods through experimental studies. FEA studies of the equi-biaxial test are described in Section 3. The objective was to (1) demonstrate the validity of the methods, (2) identify problem areas and (3) verify the calculations for determining stress and strain from force-extension measurements.

2.1 EXPERIMENTAL

The test machine used consisted of a 4505 Instron fitted with a 10 kN load cell.. The Instron was controlled using Instron's Series IX software which records the load cell and the crosshead displacement outputs. Stress was calculated from the load values obtained from the load cell using the following equation:

$$s = \frac{F}{b \times c} \quad (1)$$

where, s is the stress, F is the load; b and c are the width and thickness of the specimen. For uniaxial and planar test specimens the load used is that directly measured. However, in the equi-biaxial test the extension of the specimen is at $\pm 45^\circ$ to the axis of the test machine. Geometrical corrections are applied to resolve the angular components and account for the leverage in the biaxial test frame

Strain was determined from specimen displacement measurements using a non-contacting Messphysik ME64 video-extensometer. Images in the field of view of the camera are analysed to locate the positions of contrasting gauge marks on the specimen surface. The changes of gauge mark positions relative to their starting positions are used to determine strains. This device has the capability of measuring extensions simultaneously in two orthogonal directions. For example, the axial extension and transverse contraction of a uniaxial test specimen may be measured to determine Poisson's ratio. A further advantage of this device is that measurements may be made over several gauge sections. A more specialised module of the extensometer software allows measurement of the location (in 2-dimensions) of contrasting dots on the specimen. This can allow a limited degree of strain mapping. Both techniques were used in this validation exercise.

In normal operation, the video-extensometer measures displacement between the two sets of axial and transverse gauge-lines. The strains in each direction are calculated using the following expression:

$$e_t = \frac{d_t - d_i}{d_i} \quad (2)$$

where, e_t is the strain at time t , d_i is the initial distance between the gauge-lines ($t=0$) and d_t is the distance between the gauge lines at time t .

The objective of this work was to investigate the accuracy of the planar and equi-biaxial tensile test methods. Thus, specimens with repeatable material properties were required. Adhesive specimens were unlikely fulfil this criterion and, therefore, the specimens were all cut from a 1.6 mm thick sheet of rubber (designated HKL).

Material properties are strain rate sensitive. One problem of the initial study may have been that insufficient attention was paid to this. As a result, strain rates in the planar tests were significantly different from the equi-biaxial and uniaxial tension tests. The strain rate dependence of the material properties of flexible adhesives will be studied in PAJex2. In the current work all of the tests were conducted at extension speeds that gave a constant strain rate of approximately 7.9% strain/min. This was the strain rate obtained from a 90mm long ISO tensile specimen uniaxially drawn at a displacement rate of 4mm/min. Strain rates were checked from the experimental measurements. The

strain-time plots obtained from each of the test methods are shown in Figure 1. As can be seen from this graph the strain rates are approximately the same in each of the tests $7.92 \pm 0.97\%$ strain/minute. The two exceptions to this are the planar tests that have been conducted with grip separations of 40 and 50mm. In these two tests it can be seen that the strain suddenly stops increasing after approximately 90 seconds. This is due to the specimens slipping in the grips. Changing the specimen geometry will alter the extension speed required to achieve the same strain rate. It is recommended as good practice that the strain rates should be determined as a preliminary testing stage. These should be used to guide adjustments to the extension speeds to obtain the necessary strain rate.

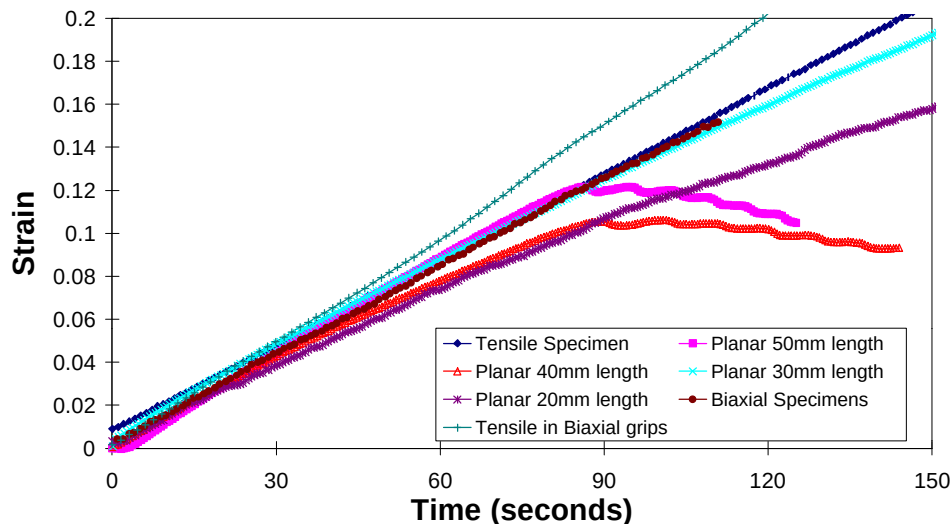


Figure 1: Strain rate behaviour obtained from the different test specimens

2.2 PLANAR TEST

The key feature of the planar test is that, unlike conventional uniaxial tensile tests, there are no lateral strains. Experimentally this is achieved by using specimens with an extremely high aspect ratio (Figure 2). The specimen's width is considerably larger than the grip separation. 200mm wide specimens are tested with grip separations no larger than 50mm. The grips prevent contraction in the width direction. Thus, the specimen is tested in a condition of plane strain rather than the plane stress condition that characterises the uniaxial tension test. An area of concern was that the planar test specimen may not necessarily experience pure plane strain in the test. A series of experimental measurements was made to confirm plane strain conditions.

The influence that the aspect ratio of the specimens has on the stress-strain behaviour of the specimens was assessed by measuring stress-strain curves with four different grip separations (50, 40, 30 and 20 mm). To verify that the strains are planar the axial and lateral strain distributions were also examined in these specimens.

Planar tests were conducted using a set of 300mm wide grips. To ensure the specimens were securely held in the grips four additional clamping bolts (to the apparatus shown in Figure 2) were added along the length of the grips to improve the uniformity of clamping. The specimens used in the planar tests were 200mm wide and 1.6mm thick. These had two sets of perpendicular gauge-lines marked, using a white marker pen,

along the two principal axes (Figure 3). This was to allow measurement of the axial extension and any transverse contraction. Axial extension was determined simultaneously at several locations along the width of the specimen to confirm the uniformity of the strain distribution.

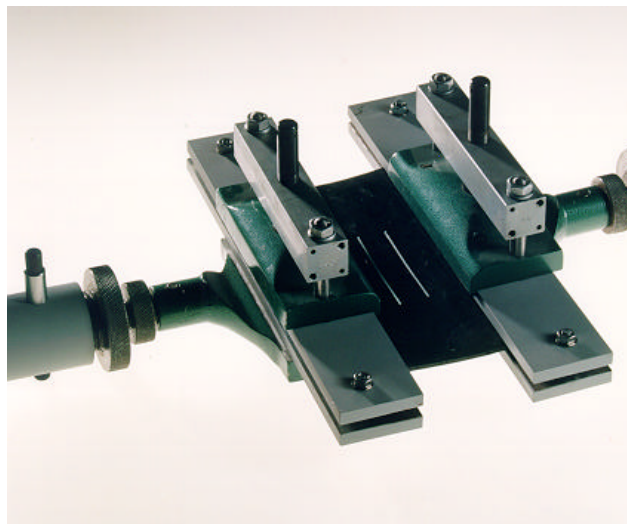


Figure 2: Planar specimen and grips

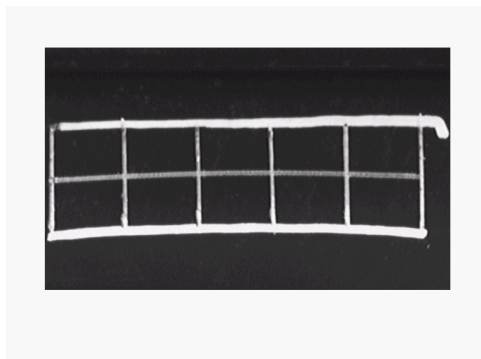


Figure 3: Gauge marks for assessment of strain distribution in the planar test

The discontinuities shown in the stress-strain curves in Figure 4 (at approximately 0.8MPa) for the specimens with grip separations of 40 and 50mm are due to the specimens slipping in the grips. The contraction in the thickness direction is not constrained and the grip pressure diminishes as the specimen extends. This problem may be overcome by bonding tabs along the edges of the specimen. In addition to improving the grip on the specimen these tabs will also constrain lateral contractions. Measurements of axial extensions at different locations along the width of the specimen indicate that the axial strains are uniform (unless the specimen slips).

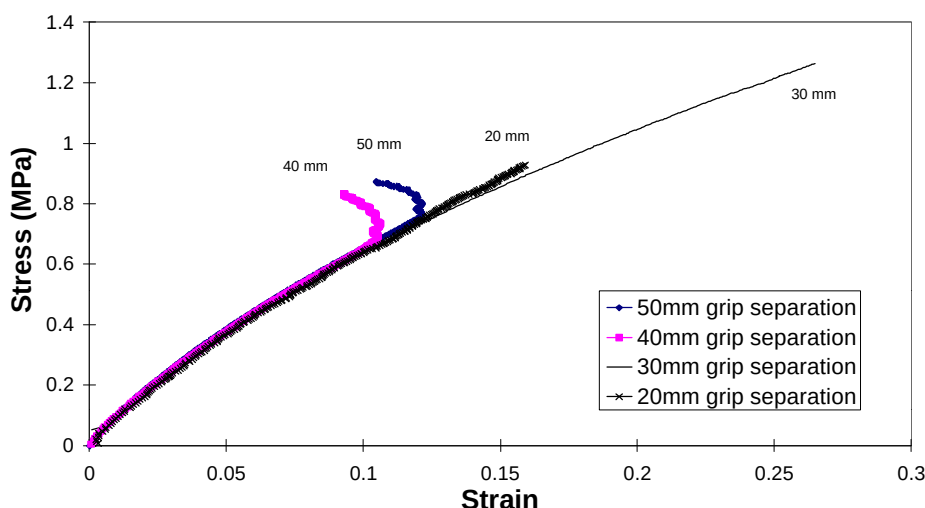


Figure 4: Planar stress-strain curves at different aspect ratios

Figure 4 shows that the stress-strain curves are not influenced by the grip separation and that the same stress-strain curves are obtained at aspect ratio values ranging from 4 to 10. Figure 5 shows that the lateral strains are negligible compared to the axial

strains, unless the specimen slips in the grips. Consequently, the strains produced using this test procedure can be assumed to be planar.

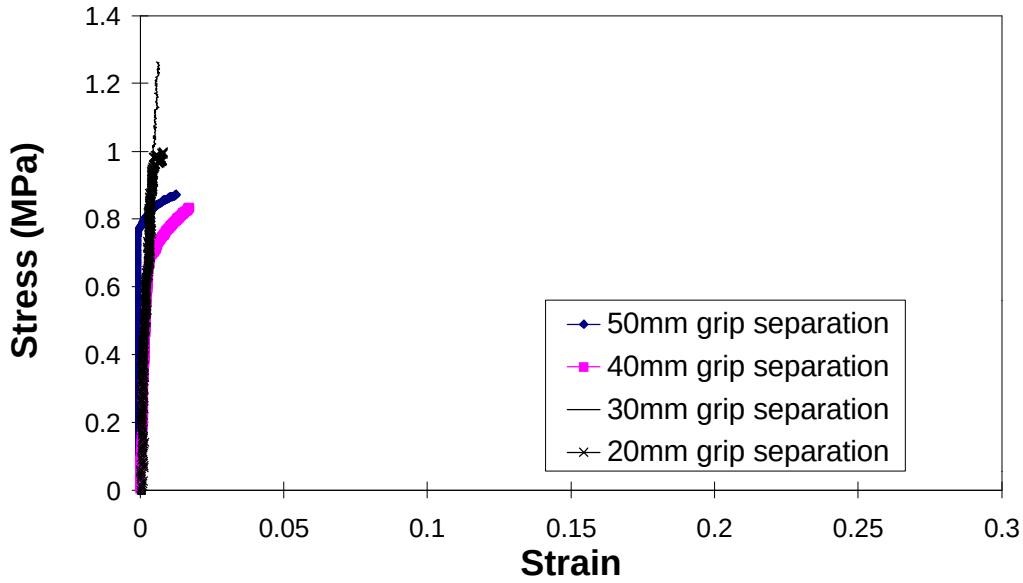


Figure 5: Lateral strains produced in the planar test specimens at different aspect ratios

2.3 BIAXIAL TEST

The biaxial grips used in this work are shown in Figure 6 and a detailed description of their design is given in a previous report [1]. The specimens used in the biaxial tests were prepared from 45mm squares of HKL rubber whose corners were removed off to reduce stress concentrations. Load was measured using the load cell and the biaxial stresses in the specimen were determined as follows:

$$P = 0.354760057 \times F$$

$$\text{Biaxial Stress} = \frac{P}{a \times c} \quad (3)$$

where, F is the force measured in the load cell, P is the force in the specimen, a is the grip separation (28mm) and c is specimen thickness. The value of a increases as the specimen is stretched. Therefore, the true stress will be less than the measured stress. However, ABAQUS uses the measured stress data as input.

The stresses produced in an equi-biaxial test are the same along both of the principal axes. One purpose of this current work was to experimentally confirm that the strains are in fact the same throughout the specimen. To confirm the equi-biaxial nature of the strains a grid of 16 dots was marked onto the specimen, Figure 7. The dots were printed onto adhesive-backed labels for easy application onto the specimen. The x-y positions of the dots were recorded during the experiment using the dot measurement function on the video extensometer. The distance between each set of dots in the grid was then determined using the Pythagoras' theorem and the strain determined using the same expression as used in the planar test. The strains in the specimen were then calculated at different positions on the grid (Figure 8). The stress-strain behaviour of the material at different positions within the specimen is shown in Figure 8.

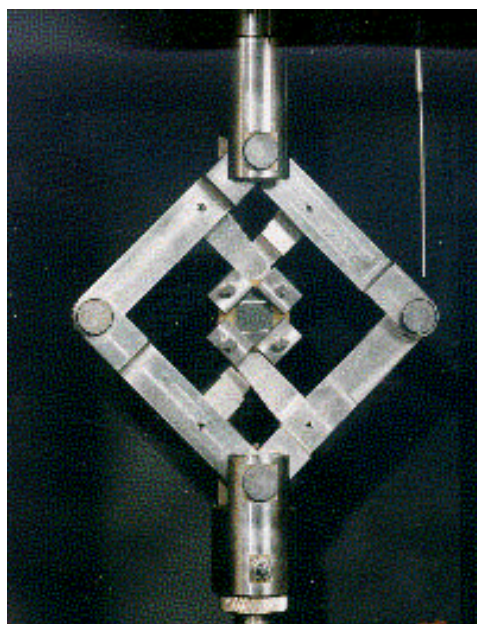


Figure 6: Biaxial grips used to produce equi-biaxial stresses in the specimens



Figure 7: Grid of dots used to measure the strain in a biaxial specimen

To assess whether biaxial grips produce equi-biaxial strains the stress-strain behaviour along the two principal axes (6-11 and 7-10) in the centre of the specimen has been determined. As can be seen from Figure 9, the stress-strain curves obtained along these two main axes are virtually identical up to a strain of approximately 0.1. At no point do they deviate by more than 0.015 strain. It would therefore appear reasonable to conclude that the strains at the centre of the specimen are equi-biaxial. It can, however, be seen that towards the edge of the specimen the strains may not be completely equi-biaxial (figure 8). This may result either from variations in the specimen or due to the edge of the specimens slipping in the grips.

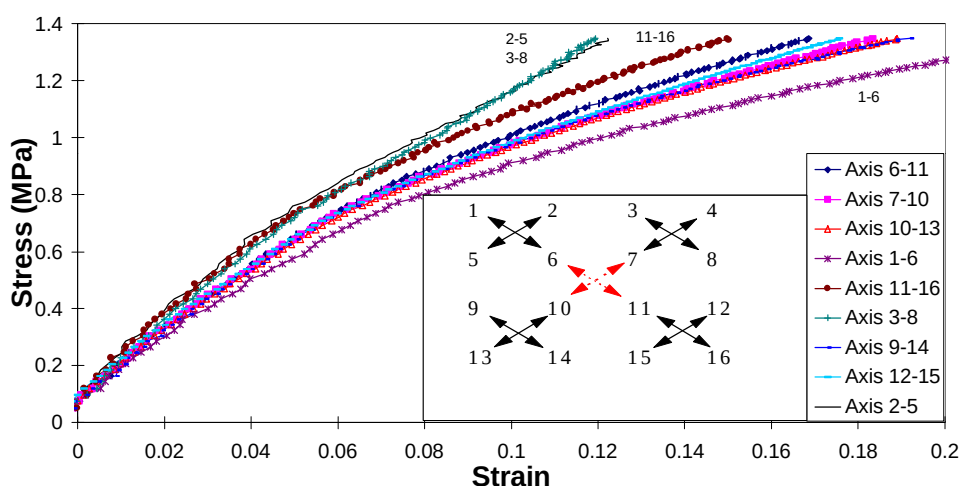


Figure 8: Stress-strain curves along the principal axes of a biaxial specimen

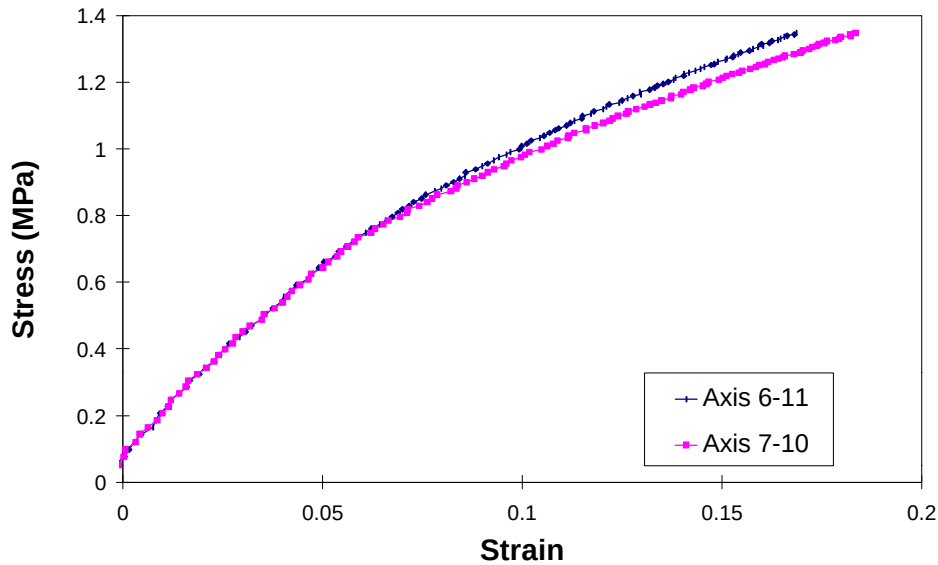


Figure 9: Stress-strain curves at the centre along of a biaxial specimen

Tests were conducted to confirm that the correction (Equation 3) that was derived to resolve the biaxial forces is correct. A pair of identical tensile specimens was tested, gripped at right angles, in the biaxial frame. The stress-strain curves that have been obtained from this test are shown in (Figure 10). To verify the biaxial stress equations the results obtained were compared to those obtained from a conventional uniaxial tensile test. In, Figure 11, it can be seen that the tensile results obtained using the biaxial grips are the same as those obtained from the uniaxial tensile test. This clearly demonstrates the validity of the corrections used to determine the biaxial forces.

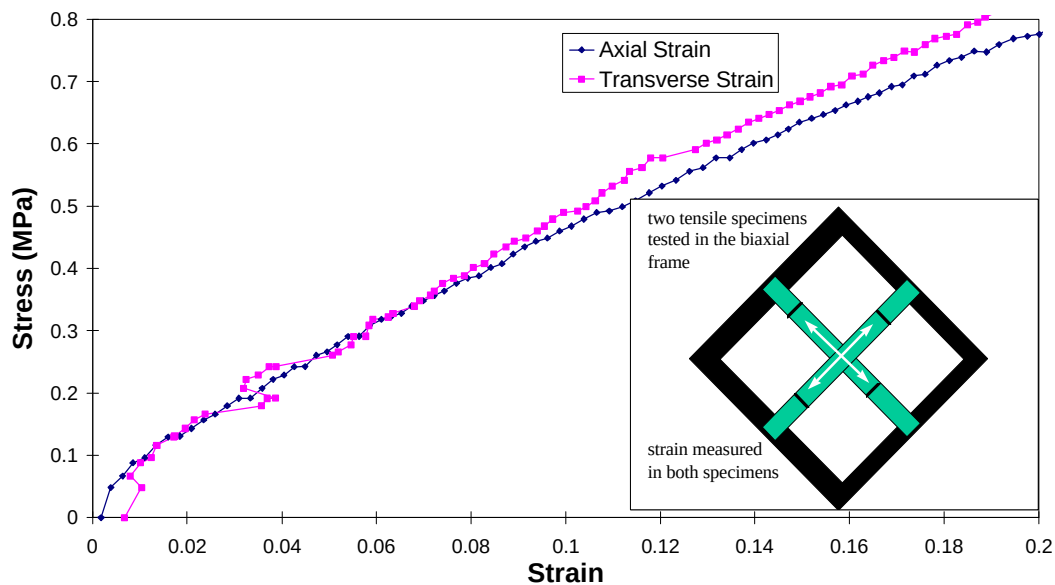


Figure 10: Stress-strain curves obtained from two tensile test specimens held along the two main axes in the biaxial grips

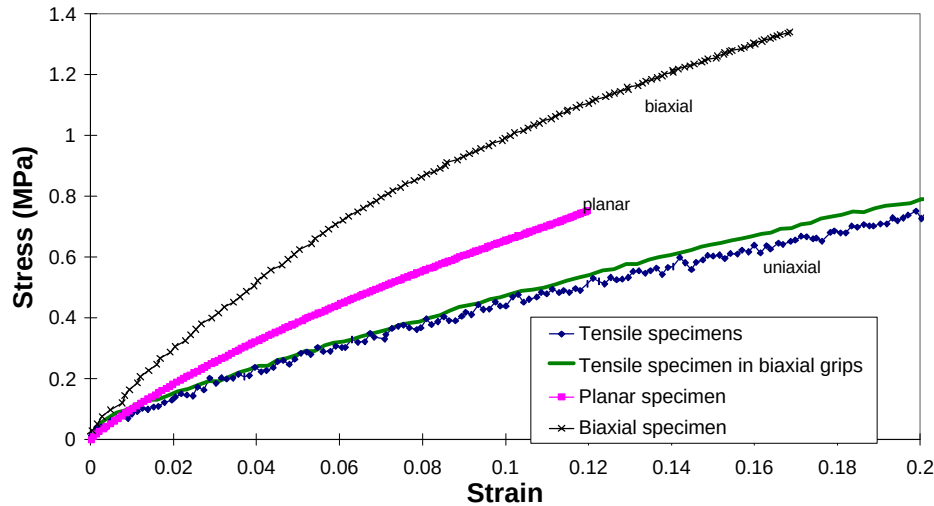


Figure 11: Stress-strain curves for uniaxial, planar and biaxial tests

Finally it can also be seen from Figure 11 that there are significant differences in the stress-strain curves obtained from uniaxial, planar and biaxial tests. The differences in the stress-strain behaviour are due to the different lateral stresses that are present in the specimens. In the uniaxial tensile test the edges of the specimen are unconfined and contract laterally when an axial stress is applied to the specimen. This allows high axial strains to be produced in the specimen at relatively low stresses. By contrast in the planar tests the specimens are sufficiently wide that the material at the centre of the specimen is unable to contract laterally. As a consequence, the axial stress required to produce a particular strain in these tests is considerably larger than that needed in a tensile test. The largest lateral stresses are, however, found in the biaxial test in which the specimen is drawn simultaneously in both directions. As a result, the stress required to draw the material to a particular strain in a biaxial test is considerably larger than that required in either the tensile and planar tests. The relative positions of the stress-strain curves agree with those measured by Treloar [3] that are quoted in the ABAQUS example on hyperelastic properties.

3. FE STUDY OF EQUIBIAXIAL TENSION TEST

3.1 MATERIAL MODELS

The material library in ABAQUS [2] includes several models of elastic behaviour. Linear elasticity is the simplest form of elasticity. Elastic behaviour means that the deformation is fully recoverable; when the load is removed, the specimen returns to its original shape. The stress-strain behaviour of typical rubbers is elastic (i.e. recoverable) but highly non-linear. This type of behaviour is known as hyperelasticity. The following four models have been used to analyse the biaxial specimen; the simple Elastic model, and the hyperelastic models; Mooney-Rivlin, Ogden and foam hyperelasticity (known as Hyperfoam). These models were described in detail in a previous report [1].

The Elastic model, the simplest of the material models employed, uses the linear relationship between stress and strain. For an isotropic material the elastic properties

are completely defined by the Young's modulus, E , and Poisson's ratio, ν . These are obtained from uniaxial tension tests on bulk specimens.

ABAQUS uses strain energy potentials to relate stresses to strains in hyperelastic materials. The three hyperelasticity models all rely on fitted material coefficients. Clearly the ability of a model to predict material behaviour will be strongly dependent on the choice of these coefficients. A convenient way of defining a hyperelastic material is to supply ABAQUS with experimental test data. ABAQUS then calculates the constants using a least-squares method. In this work the experimental methods used to obtain the coefficients are uniaxial tension, biaxial tension and planar tension. In the Hyperfoam model, the experimentally measured Poisson's ratio is used to allow for material compressibility. Both the Mooney-Rivlin and Ogden models assume that the material is incompressible (i.e. $\nu=0.5$) unless volumetric data is also provided. However, in the case of a first order Mooney-Rivlin analysis, as used in this work, the model can be set up to allow for compressibility. The Mooney-Rivlin coefficients calculated from the experimental data are C_{10} and C_{01} (temperature dependent material parameters). A further term D_1 allows for compressibility. If $D_1 = 0$, the material is incompressible. A value for D_1 can be calculated as described below.

The initial Young's modulus, E_0 , and the bulk modulus, K_0 , when $N=1$ (i.e. first order polynomial) are:

$$E_0 = 6(C_{10} + C_{01}) \quad (4)$$

$$K_0 = 2/D_1 \quad (5)$$

also
$$K_0 = \frac{E_0}{3(1 - 2\nu_0)} \quad (6)$$

therefore
$$K_0 = \frac{6(C_{10} + C_{01})}{3(1 - 2\nu_0)} \quad (7)$$

and
$$D_1 = \frac{(1 - 2\nu_0)}{C_{10} + C_{01}} \quad (8)$$

Hence a value for D_1 can be calculated from the Mooney-Rivlin coefficients and the experimentally measured Poisson's ratio.

A single continuum, 8-noded, reduced-integration, hybrid C3D8RH element with unit dimensions was used to evaluate the hyperelastic model coefficients. The results ABAQUS calculated using the hyperelastic coefficients were compared to same the experimental data used to obtain the coefficients. This gives a measure of the reliability of the coefficients. The predictions fitted the experimental data reasonably well for all three test types (although the fit of the planar data was usually the poorest) for each of the three models. Examples of these plots are shown in Figure 12 where the

experimental data are compared to the Mooney-Rivlin predictions. The fitted data appear more linear than the measured data.

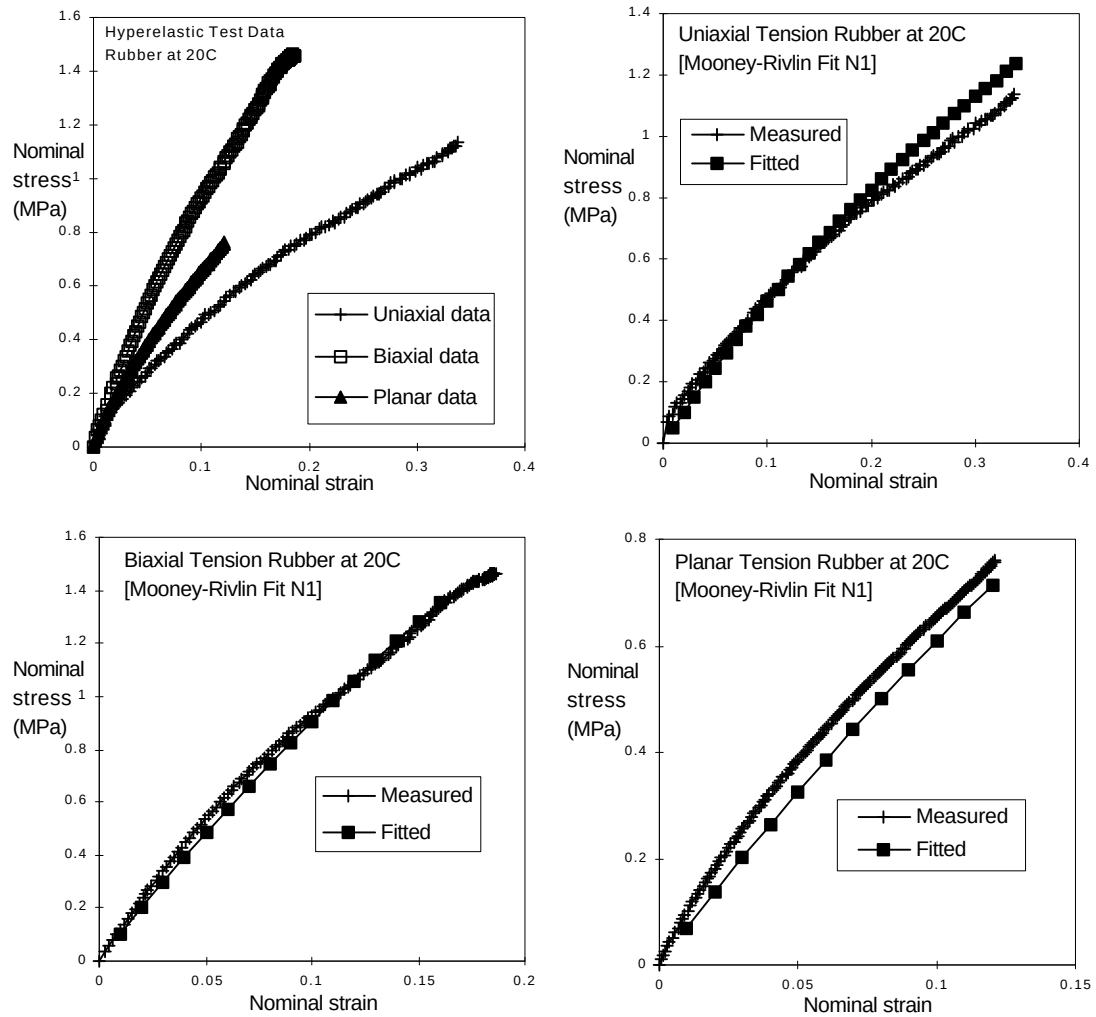


Figure 12: Input test data and single element predictions for fitted Mooney-Rivlin constants

3.2 MODELLING THE BIAXIAL SPECIMEN

The biaxial test specimen is nominally 45 mm square and 1.6 mm thick. When mounted in the biaxial test grips, the measurement region is a 28 mm square section in the centre of the specimen as shown in Figure 2. The specimen was modelled using the 2-dimensional continuum plane stress element CPS8RH. The mesh of the specimen was generated both as a square, and as a square with the corners removed (shown with dotted lines in Figure 13). This was done to investigate whether removing the corners alleviated any stress concentrations.

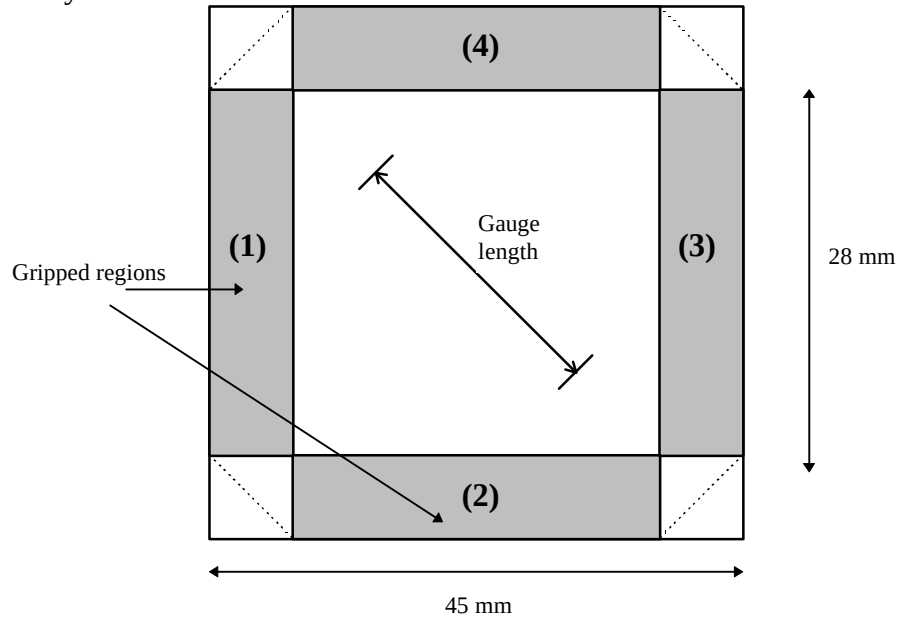


Figure 13: Schematic diagram of biaxial test specimen. The hashed regions show the position of the grips, while the dotted lines show how the corners were removed for some analyses. The gauge line is parallel with the loading direction.

ABAQUS/standard was used for the analysis. To represent the gauge length region, two nodes were located within the mesh that were 20 mm apart along the diagonal. These nodes were given a local co-ordinate system in addition to the global co-ordinate system of the model. This local co-ordinate system had a y direction parallel with the gauge line (and the loading axis of the biaxial grips). The displacements of these nodes in both the local and global co-ordinate systems were used to confirm the method of calculating the biaxial extension and hence biaxial strain. Nodes within the gripped regions labelled (1) to (4) in Figure 13 were constrained from moving in the horizontal and vertical directions. During the analysis the node set representing the gripped regions labelled (1) and (3) were displaced in the horizontal direction. Gripped regions (2) and (4) were displaced in the vertical direction. Displacements giving similar gauge length extensions to those measured experimentally were applied.

3.3 FE PREDICTIONS

One of the aims of this piece of work was to confirm the calculation of biaxial extension and hence biaxial strain, from the experimentally measured gauge extension. Experimentally, the gauge extends in the loading direction that is at 45° to the biaxial co-ordinate system (i.e. the global co-ordinate system in this model). The biaxial extension had been calculated using the following relationship;

$$\begin{aligned} \text{biaxial extension} &= \text{gauge extension}/\sqrt{2} \\ \text{biaxial gauge length} &= \text{gauge length}/\sqrt{2} \end{aligned} \quad (9)$$

Therefore the strains determined from the extension of the gauge marks will equal to the strains in biaxial directions. This is shown schematically in Figure 14. The correlation between strains determined using this gauge and biaxial strain in the centre of the specimen has been confirmed by FEA.

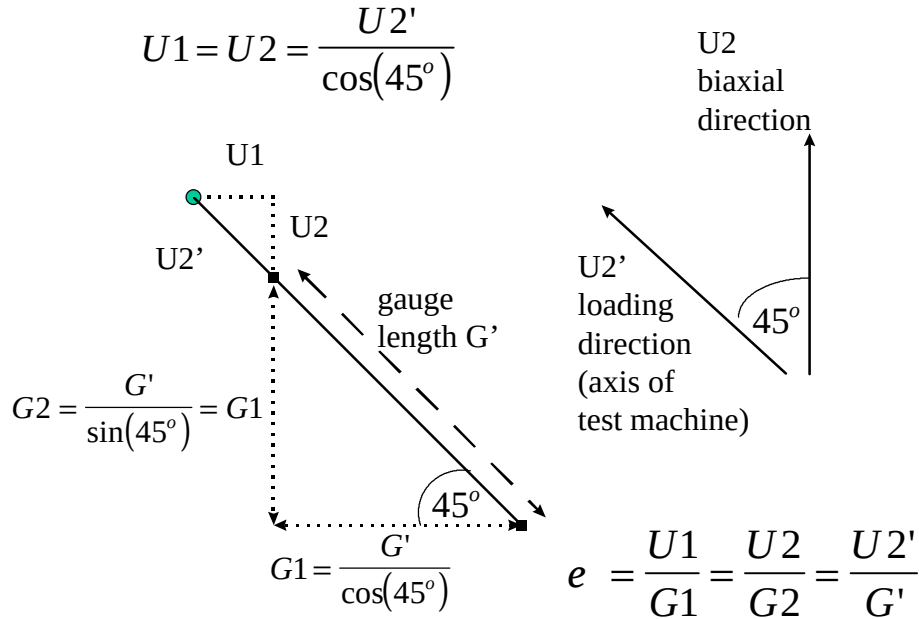


Figure 14: Schematic diagram showing the relative displacements of a node using the global co-ordinate system (U1 and U2), and a local co-ordinate system (U1' and U2')

The FE analyses were used to predict the biaxial force and biaxial extension of the square biaxial test specimen. These data were used to calculate the biaxial strain and biaxial stress. For each of the four material models investigated, the predicted stress-strain curves were compared to those obtained from the experimentally measured biaxial force and biaxial extension. Unfortunately, the relationship between reaction forces predicted in the FEA and stress values predicted in the central elements appeared to depend on the material model and corner element configuration. It is thought that the force required to deform the specimen in the corners between the grips may be significant and contribute to the total force. This will be investigated in future work.

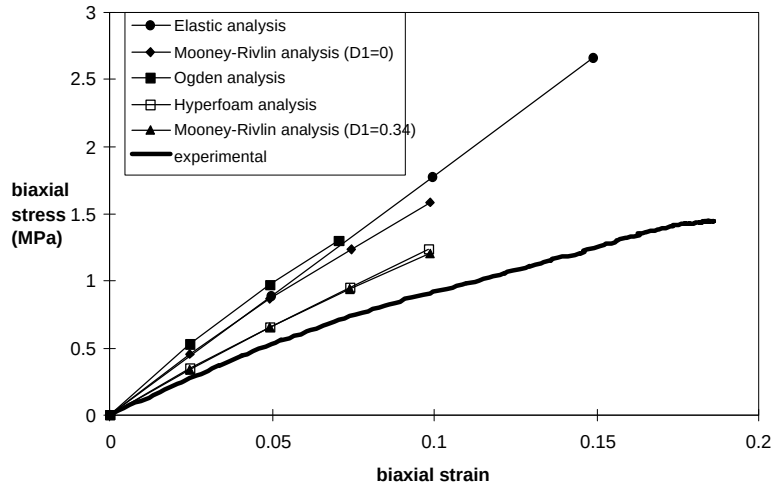


Figure 15: Biaxial stress-strain predictions

Stress values were calculated from the predicted reaction force divided by specimen cross-section. Strains were calculated from the predicted gauge length extensions. The resulting stress-strain curves were used for the comparison with the experimentally determined biaxial stress-strain. The Mooney-Rivlin model was run twice, firstly with $D_1=0$ (i.e. material incompressibility) and then incorporating compressibility through setting $D_1 = 0.34$ (calculated from equation (8)). The resulting predictions for all models are compared with the experimental data in Figure 15.

All predictions overestimate the biaxial stress at a given biaxial strain. The Elastic, Ogden and Mooney-Rivlin ($D_1=0$) model predictions produce the largest overestimates. The Hyperfoam and Mooney-Rivlin ($D_1=0.34$) analyses give the closest predictions. Both these analyses have taken material compressibility into account, and both give very similar predictions. For the investigation into the stress/strain distributions in the measurement region, the Mooney-Rivlin ($D_1=0.34$) material model was chosen.

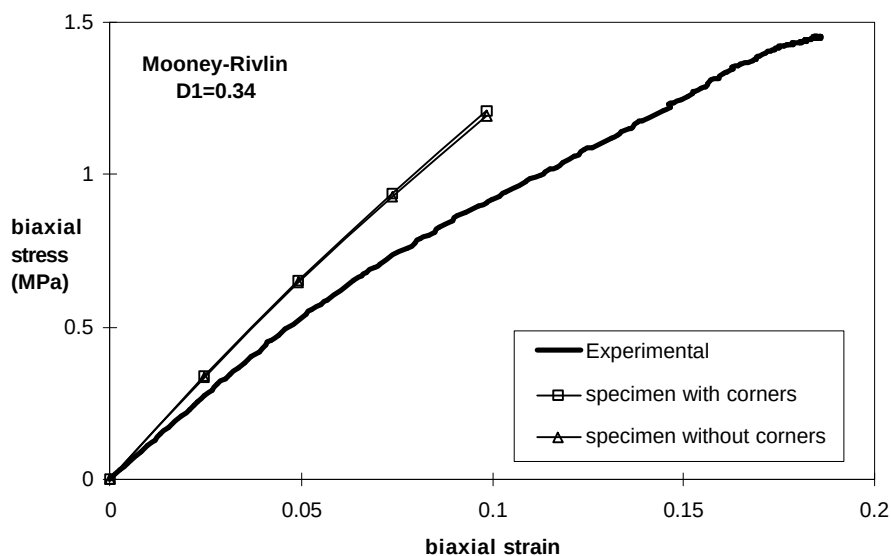


Figure 16: Biaxial stress-strain with and without corners

Analysis of the biaxial specimen with corners removed showed that the biaxial stress-strain curves obtained were very similar to those predicted for the specimen with corners. An example of this is given in Figure 16 which shows the prediction obtained using the compressible Mooney-Rivlin material model. The same degree of correlation was seen in predictions from analyses using the other material models studied.

To investigate the uniformity of stress and strain in the measurement region of the biaxial specimen, contour plots were obtained for the stresses S_{11} , S_{22} and for the strains E_{11} , E_{22} . The stress and strain contours are plotted on the undeformed mesh. All plots show the final stress/strain distribution after a 5.5 mm displacement.

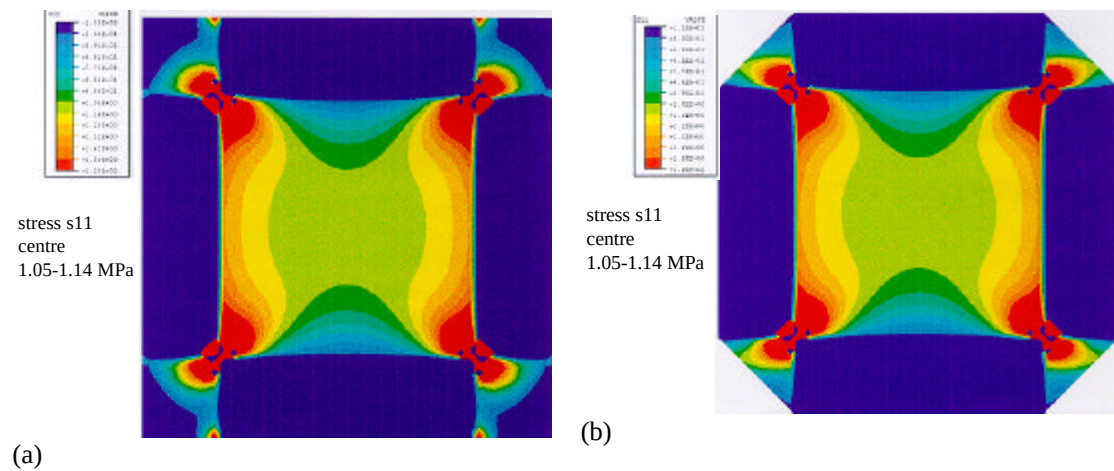


Figure 17: Contour plot of stress (S_{11}) distribution in biaxial specimens

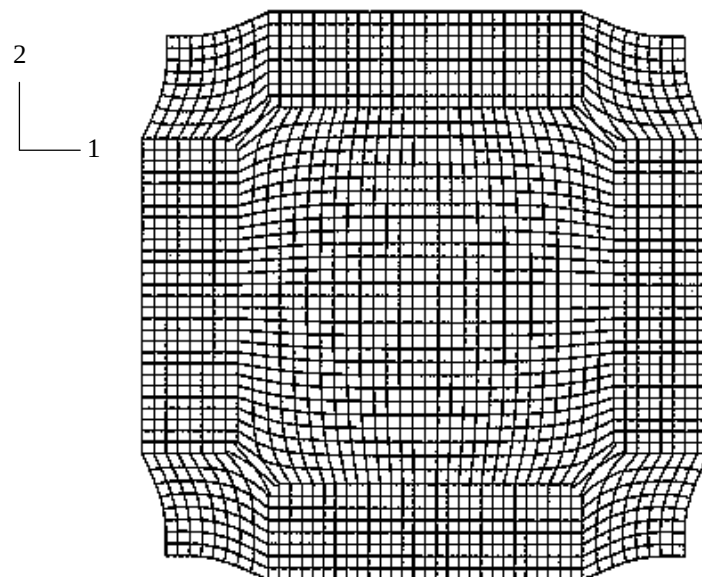


Figure 18: Deformed mesh for the specimen with corners

Figure 17 shows the contour plots of stress S11 for (a) the biaxial specimen with corners and (b) for the specimen without corners. There is no obvious difference between the stress distributions in the two plots. Therefore it appears that removing the corners of biaxial specimens has little effect on the uniformity of the stress or strain distributions in the measurement region. Removing the corners does reduce the predicted reaction forces at the grips. Therefore, the corners must bear some of the load. The contour plot of stress S22 is, as expected, identical to that of S11 but rotated through 90°. This also proved to be the case for the biaxial strains. The FEA shows peaks in the stress and strain near the corners of the grips. The plot of the deformed mesh (Figure 18) shows significant element distortion near these corners. This was common for both specimen types.

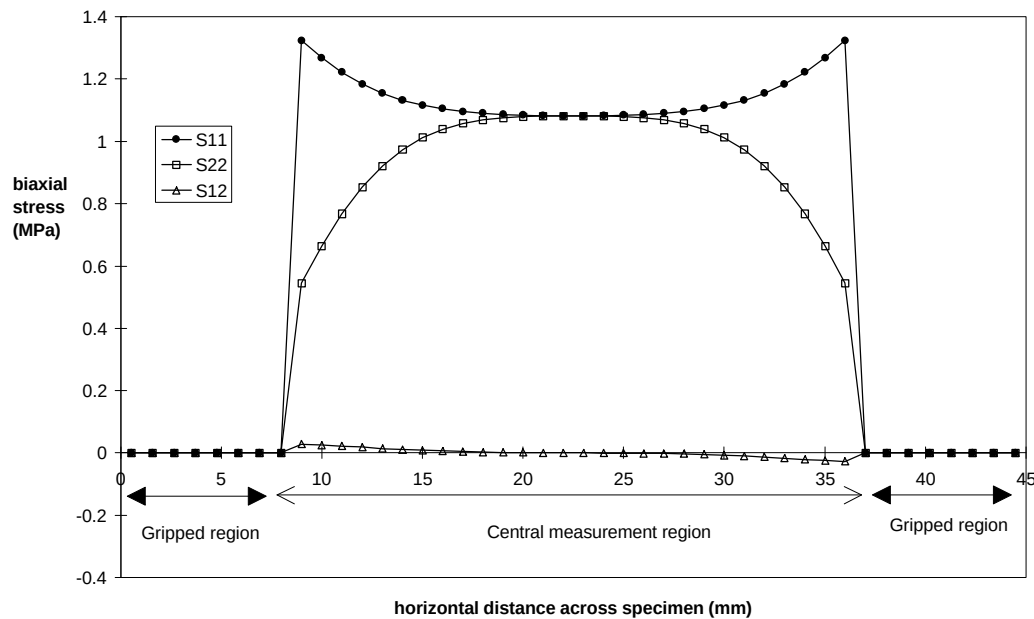


Figure 19: Stress distribution in centre of biaxial specimen

Figure 17 shows that the biaxial stress is uniform in the central region of the measurement area. The magnitude of the stress rises towards the edges and corners of the measurement area. The uniformity of stress in the central area can also be seen by studying the stress in elements along the horizontal mid-line of the biaxial specimen. In Figure 19, the biaxial stresses are plotted against distance across the specimen. The stresses S11 and S22 are low in the grip regions and then rise to a uniform level in the central region. The stress S11 rises rapidly to a peak close to the edge whilst S22 rises more slowly to the same level in the centre. As expected for the biaxial stress state, the calculated shear stress values are negligible.

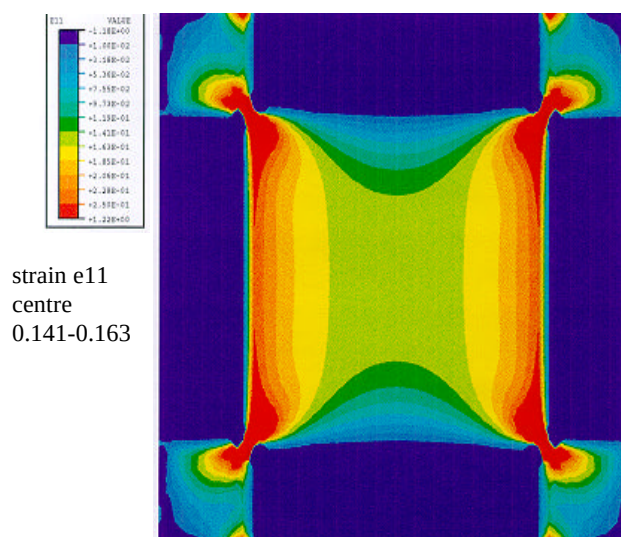


Figure 20: Strain (E11) distribution in biaxial specimen

Figure 20 shows a contour plot of the strain E11 in the biaxial specimen. Again, the strain is uniform in the centre of the specimen. As before, the contour plot of strain E22 is identical, but rotated 90°. The strain distribution can be seen more clearly in Figure 21 where the strains E11 and E22 in elements along the horizontal midplane are plotted against the distance across the sample. It can be seen clearly that the strains E11 and E22 are uniform in the centre of the biaxial specimen. The strain distribution is qualitatively similar to the stress distribution. Shear strains are negligible in the centre. The plot of the deformed mesh suggests that significant shear strains and stresses may occur in the corners.

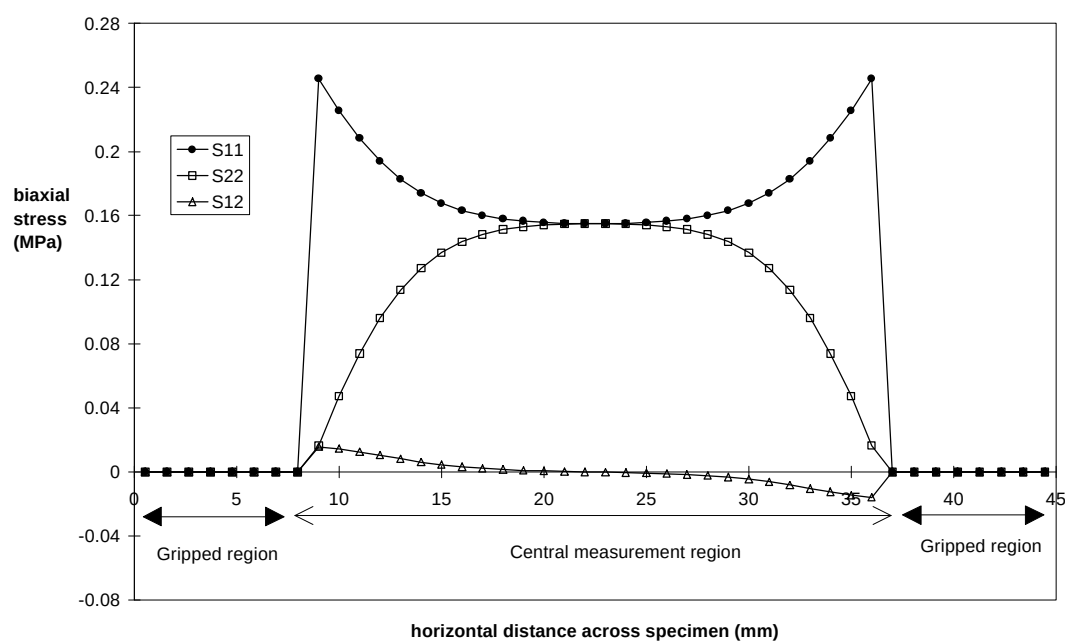


Figure 21: Strain distribution in the centre of the biaxial specimen

3.4 FE CONCLUSIONS

FE analysis of the biaxial specimen has confirmed that the biaxial strain in the centre of the specimen is equal to the measured gauge strain. Investigations into potential material models have found that the models that take material compressibility into account are more suitable for predicting the behaviour of the rubber specimens under equi-biaxial strain. These are the Mooney-Rivlin (with $D_1 = 0.34$) and Hyperfoam models.

The contour plots of biaxial stress and biaxial strain indicate that there is uniformity of stress and strain in the central area of the measurement region. This uniformity was seen more clearly in plots of stress/strain for a horizontal line of elements across the centre of the biaxial specimen. There are stress concentrations in the corners of the biaxial specimens. Alternative specimen geometries to reduce these stress concentrations may need to be considered.

4. COMPARISON OF BULK AND JOINT MATERIALS

One of the concerns raised in the previous work [1] was that the material in joint specimens may have different properties to the material in the bulk specimens used to determine the material properties for FE analyses. If this is the case then FE has little chance of accurately predicting the joint performance. For two-part, room temperature curing adhesives it should be possible to match the adhesive properties by ensuring that the bulk and joint test specimens are kept under similar environmental conditions and tested at similar ages. However, for one-part, high temperature curing adhesives the solution may not be as straight forward. The samples may experience different thermal histories during the curing processes owing to the different thermal capacities and heat transfer properties of the fixtures in which they are cured. This could lead to different thermal properties.

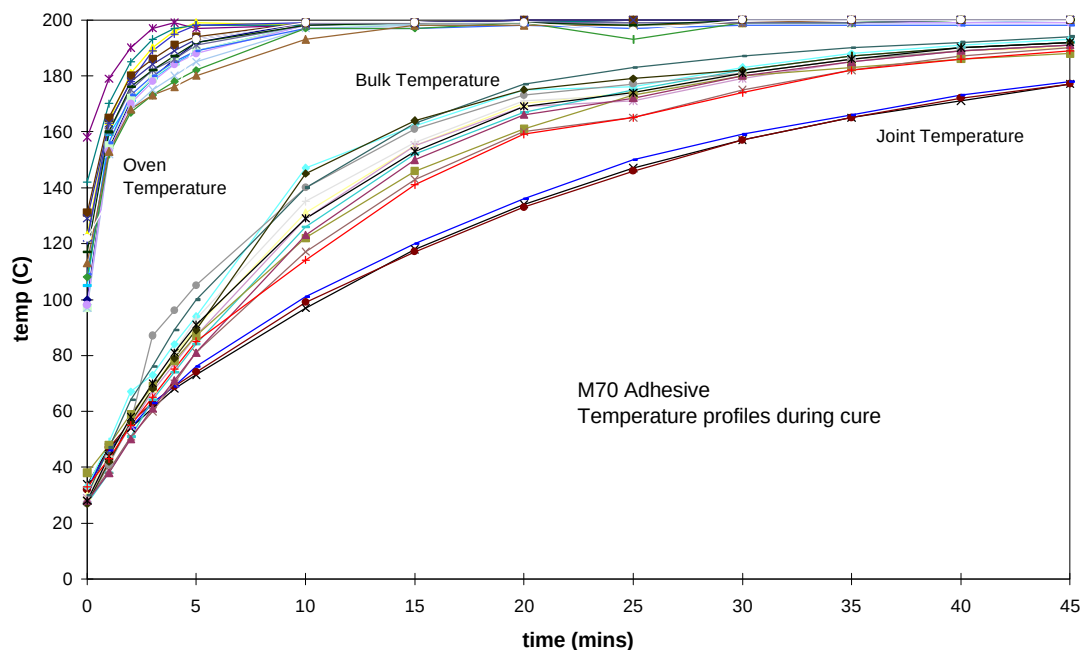


Figure 22: Temperature profiles whilst curing M70 specimens

Some tests were determined to check the thermal history of joint and bulk Evode M70 specimens during cure. Temperatures of the fixtures were determined during the curing process using thermocouples either in or close to the adhesive. The nominal curing conditions were 200 °C for 45 minutes. The oven takes 5-10 of these 45 minutes to stabilise at the 200 °C cure temperature. The results of these measurements (Figure 22) clearly indicate that the bulk specimens heat up faster than the joint specimens. However, even the bulk material does not reach 200 °C in the 45 minutes. The joints do not even reach 180 °C in the cure period. One consequence of this is that the adhesive in the joint is likely to be under-cured in comparison to the bulk material.

DMTA measurements were performed to investigate the significance of these temperature differences during cure. DMTA samples were prepared in the joint preparation fixture using PTFE release film to separate the adhesive from the lap joint adherend. In this way, it was thought that miniature 'bulk' specimens (25 mm by 12.5 mm by 0.5 mm thick) for DMTA measurements could be made with properties corresponding to the material in the bondline of joints. Figure 23 shows DMTA measurements on M70 specimens cured in the bulk and joint specimen preparation fixtures.

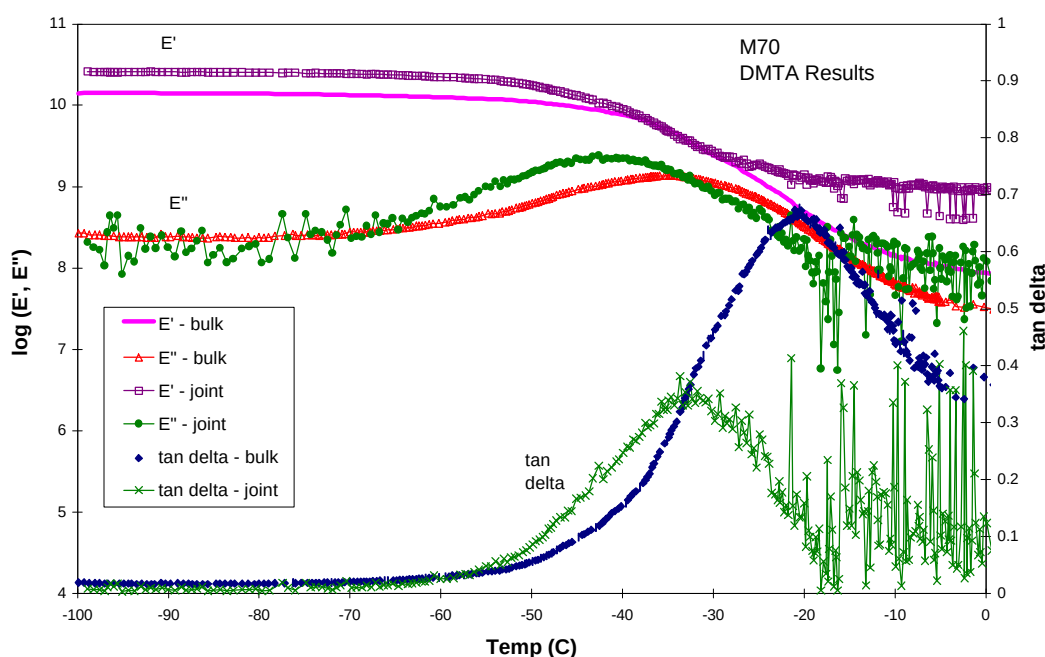


Figure 23: DMTA measurements of T_g

Figure 23 indicates that T_g , the glass transition temperature (measured by both the $\tan \delta$ and E'' peaks), of the material cured in the joint configuration is approximately 8 °C lower than the bulk material. This difference is significant in comparison to the sample to sample variability of approximately ± 1 °C in the measured T_g values of either bulk or joint materials.

The different cure states of the material prepared in the bulk and joint fixtures may be a cause of some of the errors in the prediction of the force-extension curves by FEA. The curing process for these fixtures should be modified to improve the similarity in the thermal history of the adhesives in the different fixtures during cure. One logical

step would be to increase the oven temperatures when curing joint specimens since the they do not reach the same temperature as the bulk specimens at the end of the cure process.

5. FE MODEL OF LAP JOINT

The lap joint used in the experimental and modelling work in the project was modelled in 3-D. This was done to investigate whether the approximating the joint as a 2-D model introduced any uncertainties into the results of the hyperelastic analyses. The 3-D model also allows some exploration of the potential influence that misalignment of the test machine could have on experimental results.

5.1 3-D MODEL

The 3-D model constructed from 'brick' elements is shown in Figure 24. The element types used were C3D8H (3-D continuum, 8-noded hybrid) for the adhesive layer and C3D8 (3-D continuum, 8-noded) for the steel adherends. Due to the high computing costs of 3-D models the mesh is much coarser than that used with 2-D models. All FE analyses were performed modelling the adhesive layer using the Mooney-Rivlin model and the material constants obtained in earlier work for DP609 (60 °C). The steel adherends were modelled as elastic-plastic materials. Constraints were applied to the nodes at the ends of one of the adherends to create an end that was fixed in 3-dimensions. Figure 25 shows a comparison of the force-extension curves predicted from FE analyses run using the 2-D and 3-D models.

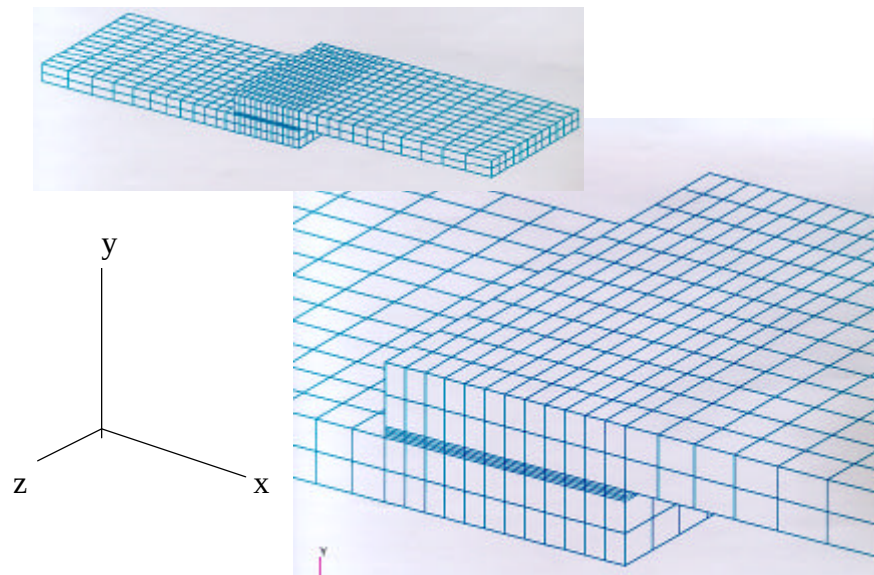


Figure 24: 3-D lap joint mesh

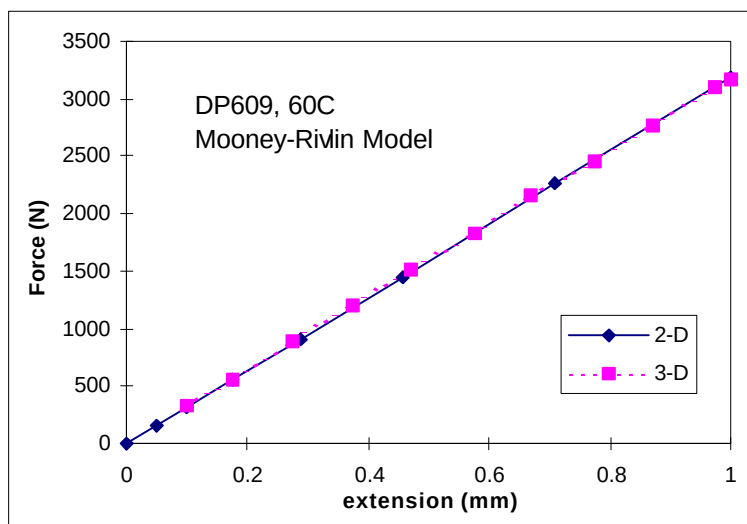


Figure 25: Comparison of 2-D and 3-D models

The 3-D results almost exactly overlap the 2-D results. Therefore, the 2-D model is a valid approximation for predicting the force-extension performance of the joint.

5.2 SIGNIFICANCE OF MISALIGNMENT

Misalignment of the test machine acting in the x-axis may take place in either the y- or z-axes. In the analyses the y-axis coincides with the thickness of the bondline and the z-axis with the width of the adherend. Therefore, misalignments will be symmetrical in the z-direction but not in the y-direction. Each analysis was performed in two steps. The first step applied a 1 mm deflection in either the y- or z-direction to the end of the adherend that was then deflected in the second step by 1 mm in the x-direction. The 1 mm deflection perpendicular to the direction of testing was thought to represent a fairly severe misalignment of the test machine.

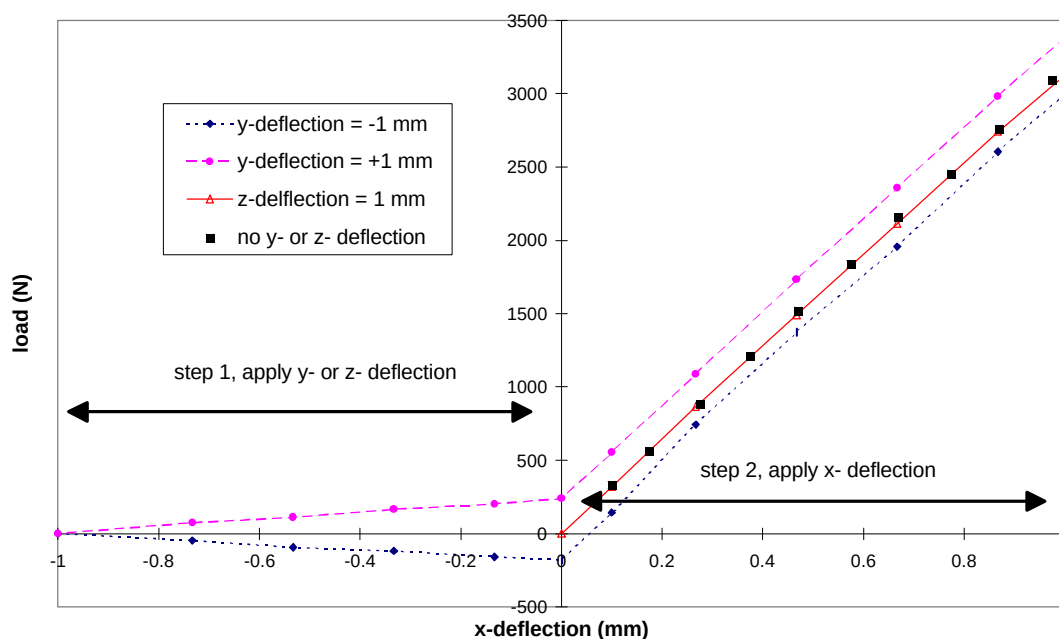


Figure 26: FE predicted force-deflection curves on applying different offsets.

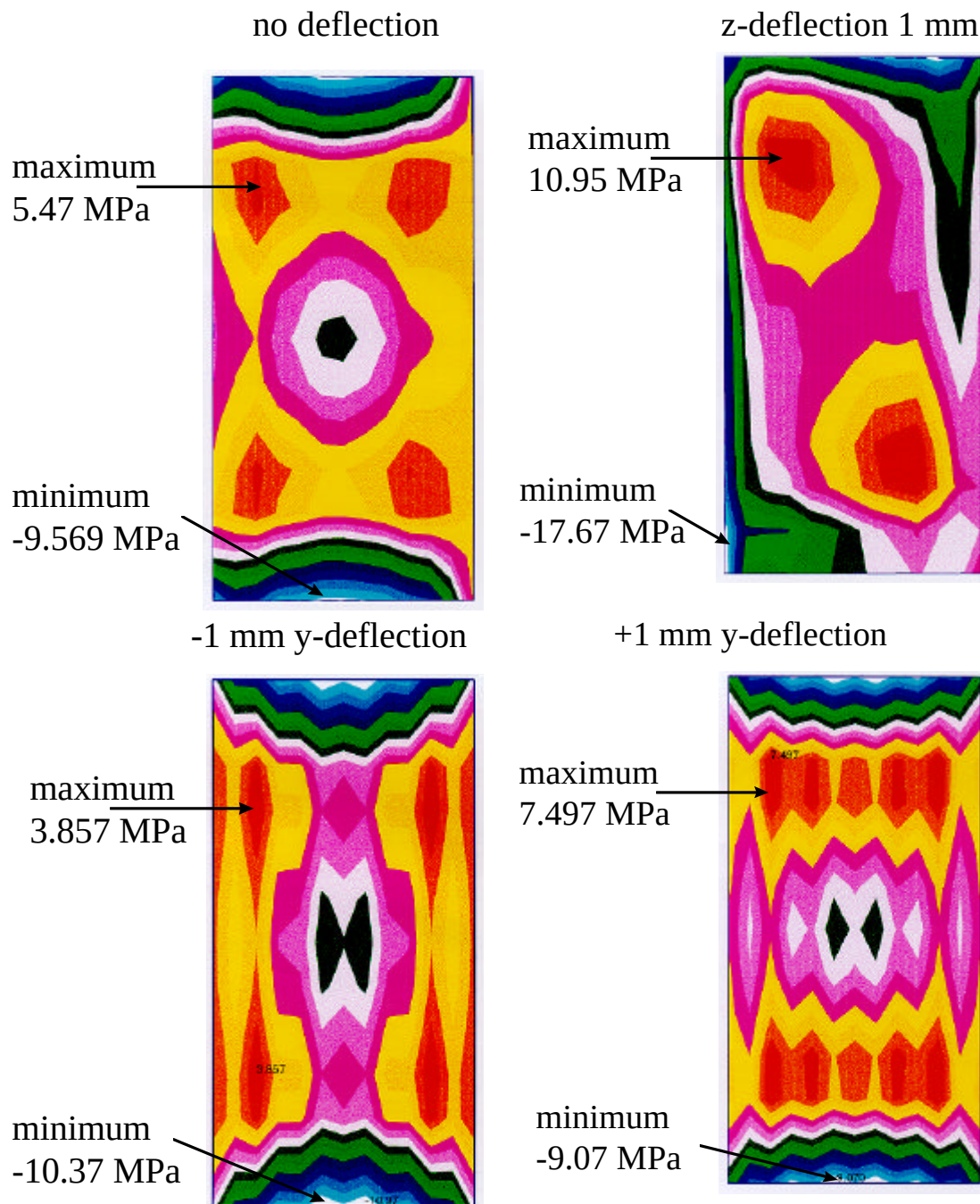


Figure 27: Peel (S_{yy}) stress predictions for the four loading cases in Figure 26 (extension 1 mm)

As Figure 26 shows, the initial out-of-plane deflections have little influence on the shape of the subsequent force-deflection curve when pulled in the x-direction. Applying deflections in the y direction produces ‘initial’ offset forces before the start of the second (x-deflection) step. However, in an actual test any offset forces would be removed through the adjustment of the crosshead position before the test was run. Thus, in practice, few effects are predicted in the force-extensions measured with slight misalignment errors.

Whilst the force-deflection results may not be strongly influenced by the misalignment the stress and strain distributions will be affected. The coarse FE mesh used to model

the 3-D joint prevents accurate determination of the magnitude and location of the maximum stress regions. However, it is clear from Figure 27 that the stress distribution within the adhesive layer will be significantly influenced by misalignments. In two of the cases illustrated in Figure 27 - the z-deflection and +1 mm y-deflection - the peak values of the peel stress (S_{yy}) predicted by the FEA are significantly greater than those predicted in the undeflected case. Thus, specimens tested with these types of misalignments are likely to experience premature failure with respect to the perfectly aligned case.

6. CONCLUDING REMARKS

The results presented in this report demonstrate that the planar and equi-biaxial tension test techniques give the plane-strain and equi-biaxial stress states required to generate input data for the hyperelastic modelling of flexible adhesives. This work has also demonstrated the capability of the 2-directional video extensometer for validating such experimental techniques.

Experimental measurements have shown that the planar test is insensitive to the exact specimen aspect ratio. These tests have also shown that the contraction of the test specimen is minimal.

FEA and experimental measurements have shown that the stress and strain distributions in the centre of the biaxial specimen are indeed equi-biaxial. The exercise also verified the geometrical corrections required to resolve the force and extension components measured along the axis of the test machine into stress and strain within the specimen. Thus, confidence in the reliability of the test data obtained has been increased.

The brief FEA study of the 3-D lap joint has shown that the predictions agree with the 2-D models. This confirms that, for the hyperelastic models, a 2-D model is a reasonable approximation. The likely influence of minor misalignments of the test machine was also studied by FEA. Whilst small misalignments will have little effect on the force extension measurement they can significantly increase peel stress. This could lead to premature failure of the joint specimen. These effects may be responsible for the premature peel failures of the DP609 (polyurethane) adhesive joints tested in earlier work [1]. More attention shall be paid to the alignment of the test machine in future work.

Differences have been found between the properties of heat-curing adhesive specimens prepared in the bulk specimen and joint specimen fixtures. The temperature profiles during cure of material in these fixtures are not the same. Different cure schedules should be employed to ensure that the temperature profiles A method has been demonstrated for preparing small adhesive specimens to provide material for comparison with the bulk specimens. These can be used for developing cure schedules for preparing representative test samples.

In summary, many of the uncertainties in the measurement methods identified in earlier work have been resolved. The planar and equi-biaxial tension test methods have been verified. There is now more confidence in the reliability of the data produced. Better

test practices have been identified for bulk specimen and joint specimen tests. These should lead to more accurate and reliable techniques for obtaining data for designing with flexible adhesives.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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