

## **HYPERELASTIC MODELLING OF FLEXIBLE ADHESIVES**

**L E Crocker, B C Duncan, R G Hughes and J M Urquhart**

**May 1999**

**Performance of Adhesive Joints Programme  
Project PAJ1 - Failure Criteria and their Application to  
Visco-Elastic/Visco-Plastic Materials**

**PAJ1 Report No 14  
(milestone 17)**

### **ABSTRACT**

Commercial finite element analysis (FEA) software packages are used extensively for the prediction of stress and strain distributions in 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. The aim of this work was to carry out an initial investigation into a variety of material models available in the Finite Element package ABAQUS that may be suitable for predicting the behaviour of flexible adhesives. The material models studied were the simple models; Elastic and Elastic-Plastic, the hyperelastic models; Mooney-Rivlin, Ogden and the Hyperfoam model. Three adhesive systems were studied; 3M DP609, Evode M70 and PPGY5000.

Mechanical testing of bulk adhesive samples was carried out to generate material property data, e.g. Young's modulus, Poisson's ratio. ABAQUS requires test data under uniaxial strain, biaxial strain and planar strain conditions to fully implement the various material models. ABAQUS uses these data to produce the model coefficients required to run the analyses. These Finite Element (FE) predictions have been compared to experimental lap joint test data. The applicability of these models was investigated for each adhesive. Problems with obtaining sufficiently accurate input data and materials with the same states of cure in the joint and bulk specimens led to poor agreement between the FE predictions and the lap joint tests. The Elastic model and the von Mises Elastic-Plastic models appeared inadequate for characterising the flexible adhesives. The hyperelastic models seemed to offer more promise.

A failure criterion based on the energy to failure has been investigated. Elastic strain energies predicted from the FE analyses have been compared to the energy to break obtained from uniaxial testing of bulk samples. However, the problems with the FE predictions prevent a full evaluation from being made. This work will continue in the extension project PAJex2 where the issues arising from this work will be addressed.

© Crown copyright 1999  
Reproduced by permission of the Controller of HMSO

ISSN 1361-4061

National Physical Laboratory  
Teddington, Middlesex, UK, TW11 0LW

Extracts from this report may be reproduced provided that the source is acknowledged  
and the extract is not taken out of context.

Approved on behalf of Managing Director, NPL, by Dr C Lea,  
Head of Centre for Materials Measurement and Technology

## CONTENTS

|                                              |           |
|----------------------------------------------|-----------|
| <b>1. INTRODUCTION</b>                       | <b>1</b>  |
| <b>2. MATERIALS AND SPECIMEN PREPARATION</b> | <b>2</b>  |
| 2.1 BULK ADHESIVES                           | 2         |
| 2.2 LAP JOINTS                               | 2         |
| <b>3. EXPERIMENTAL</b>                       | <b>3</b>  |
| 3.1 UNIAXIAL TENSION                         | 3         |
| 3.2 PLANAR TENSION                           | 5         |
| 3.3 EQUI-BIAXIAL TENSION                     | 6         |
| 3.4 LAP JOINT TESTS                          | 7         |
| 3.4.1 DP609                                  | 7         |
| 3.4.2 PPGY5000                               | 8         |
| 3.4.3 M70                                    | 8         |
| <b>4. FINITE ELEMENT MODELLING</b>           | <b>9</b>  |
| 4.1 ELASTIC MODELS                           | 9         |
| 4.2 HYPERELASTIC MODELS                      | 10        |
| 4.2.1 Description of Hyperelastic Models     | 10        |
| 4.2.2 Derivation of Model Coefficients       | 12        |
| 4.3 MODEL IMPLEMENTATION                     | 13        |
| <b>5. FE PREDICTIONS</b>                     | <b>14</b> |
| 5.1 POLYURETHANE DP609                       | 14        |
| 5.2 ELASTOMER M70                            | 15        |
| 5.3 EPOXY-BUTADIENE PPGY5000                 | 16        |
| <b>6. CONCLUSIONS</b>                        | <b>17</b> |
| <b>7. FUTURE WORK</b>                        | <b>18</b> |
| <b>ACKNOWLEDGEMENTS</b>                      | <b>18</b> |
| <b>REFERENCES</b>                            | <b>18</b> |
| <b>List of Tables and Figures</b>            | <b>18</b> |
| <b>Tables</b>                                | <b>20</b> |
| <b>Figures</b>                               | <b>22</b> |

## 1. INTRODUCTION

Flexible adhesives are characterised by low glass transition temperatures ( $T_g$ ), low moduli and large strains to failure in comparison with structural adhesives such as epoxies. Generally, they are used in non-structural applications such as sealing. However, as design philosophies change, these materials are becoming used in applications where the structural performance is more critical. Methods that predict the behaviour of the flexible adhesives are required for designing these bonded structures. Finite Element analysis (FEA) is widely used to study the deformation behaviour of adhesive joints<sup>(1)</sup>. The ability to predict the deformation and failure of adhesive joints using FEA depends on two main factors; the choice of material model and the reliability of the data input into the model. Flexible adhesives are unlikely to be modelled accurately by the Elastic-Plastic materials models derived for metallic materials, which may be appropriate for structural adhesives. These flexible materials may be closer to rubbers in their properties. Hence, it may be possible to adequately model the response of the adhesive using the hyperelastic material models developed for rubbers.

One aim of Project PAJ1 of the DTI Performance of Adhesive Joints programme was to evaluate the capability of models available in commercial FE packages to characterise flexible adhesive joints. This report describes an initial evaluation performed by comparing the predictions from a number of material models available in commercial FE software packages with experimentally obtained results.

Five material models available in ABAQUS<sup>(2)</sup> were chosen for this investigation. These ranged from the quite simplistic Elastic and Elastic-Plastic models (as may be appropriate for structural adhesives) to the more complex hyperelastic models; Mooney-Rivlin, Ogden and Hyperfoam. The models were selected as representative of different classes of material model and do not encompass the full range of models available.

In addition to predicting the deformation behaviour of the adhesive joint, the FE model should also be capable of predicting when the bond will fail. A valid failure criterion is required to make these predictions. Rubber theory tends to describe failure in terms of strain energies in the material or the strain energy dissipated in the material<sup>(3,4)</sup>. If the flexible adhesives have rubber-like properties then strain energies may give suitable failure criteria. An initial evaluation of a strain energy failure criterion is described in this report.

Accurate modelling requires accurate input data. The data requirements increase as the material models become more complex. For the simplest cases of Elastic and Elastic-Plastic models, data can be obtained from standard uniaxial tensile tests on bulk samples. There is some additional data manipulation required for the Elastic-Plastic models. However, Elastic-Plastic model predictions under multi-axial stress states require a yield criterion. The normal assumption of von Mises yielding, as investigated in this work, is unlikely to hold for visco-elastic, flexible adhesives. Other yield criteria are available but require test data under additional stress states.

For the hyperelastic models, data under more stress states are desirable to obtain the coefficients that are entered into the input files. These data can be obtained from uniaxial, biaxial and plane strain (planar) tension tests on bulk samples. Uniaxial tension tests are well developed, standard methods. However, planar and equi-biaxial tension tests required some apparatus and technique development. Since completing this work a number of improvements have been identified in the test and analysis methods that will be implemented in future work programmes. The quality of results from a simulation using hyperelastic models is strongly dependent on the materials test data provided to ABAQUS.

In this report, the findings of an initial study on methods for modelling the deformation and failure of flexible adhesive joints are described. Predictions obtained from FE analyses are compared with experimental results from lap joint tests. Three different adhesives have been studied in this work. Since adhesive joints may experience service over a wide range of temperatures, the comparisons were performed over a range of temperatures to determine how robust the models were to changes in material properties. This work is to be continued into an extension project that aims to continue the development of methods for designing flexible adhesive bonds.

## **2. MATERIALS AND SPECIMEN PREPARATION**

### **2.1 BULK ADHESIVES**

Three adhesives were studied in this work. These were 3M DP609, Evode M70 and PPGY5000, see Table 1. For the preparation of bulk test samples the adhesives were cast as large plates<sup>(5)</sup>. These were approximately 200 mm x 250 mm x 1 mm. The required test specimens were cut from these sheets. For the uniaxial tests type 1BA ISO 527-2:1993(E) tensile test specimens were pressed from the plates. Planar tests were prepared as rectangles 200 mm by 80 mm. The biaxial test specimens were 45 mm squares. The corners were cut off to reduce stress concentrations.

### **2.2 LAP JOINTS**

Zinc coated steel adherends (50 mm long, 25 mm wide, 3 mm thick) were used for the lap joints. These relatively thick adherends resist out of plane bending. This reduces peel stresses in the adhesive. The stress in the steel remained elastic in all tests. Hence, as there is no permanent deformation of the adherends, they could be re-used. In all cases the surface to be bonded was solvent cleaned prior to bonding. After some initial tests, the surface was also grit blasted to aid adhesion. The grit blasted faces were also solvent cleaned prior to bonding. Re-used adherends were cleaned by grit blasting.

The joints were prepared in a jig to control the bondline thickness to 0.5 mm and the overlap length to 12.5 mm (Figure 1). The joint specimens were cured under the same cure schedules as the bulk specimens. The DP609 joints were cured at ambient temperature for a minimum of 12 hours (and a maximum of 2 weeks). This was a much shorter cure/ageing time than the bulk specimens experienced. Some of the bulk test specimens were several months old when tested. Therefore, some samples were also postcured at 40°C for 2 hours to increase the degree of cure. The M70 lap joints were

cured at 200°C for 45 minutes. Some PPGY5000 samples were cured at 190°C for 20 minutes while others were cured at 190°C for 30 minutes as it was felt that the 20 minutes cure time may have been insufficient to bring the jig to the cure temperature. There is some concern that the thermal history of the heat-cured bulk and the joint test specimens may differ due to the difference in thermal mass of the fixtures used to make bulk and joint test specimens. This could lead to different states of cure and, hence, differences between the material properties of the material in the bulk and joint specimens. This was not investigated in the current work but will definitely need to be addressed in the future. Similarly, there may be differences in the properties of the 2-part polyurethane in the joints that were tested at a much 'younger' age than most of the bulk specimens.

### 3. EXPERIMENTAL

The materials parameters required for the ABAQUS FE analyses were determined from bulk specimen test data. Input data for the Elastic and Elastic-Plastic models could be obtained from uniaxial tension tests. However, data from planar and equibiaxial tension tests are required for accuracy in the hyperelastic models. The latter test methods were developed as part of the project. The bulk specimen tests were carried out over a range of temperatures between -20 °C and 80 °C. All the tests were performed using an Instron 4505 tensile test machine.

#### 3.1 UNIAXIAL TENSION

To model hyperelastic behaviour the concept of material stretches is used. The stretch  $\lambda_i$  along any of the principle axes -  $i = 1, 2, 3$  - is calculated:  $\lambda_i = 1 + \epsilon_i$  where  $\epsilon_i$  is the principle strain. If the material is incompressible then  $\lambda_1\lambda_2\lambda_3 = 1$ . Thus under uniaxial tension the stretches are related:  $\lambda_1 = \lambda_u = 1 + \epsilon_u$  and  $\lambda_2 = \lambda_3 = 1/\sqrt{\lambda_u}$  where  $\lambda_u$  is the stretch along the uniaxial loading direction and  $\epsilon_u$  is the nominal tensile strain.

Uniaxial tensile tests were performed following the standard method ISO 527-2 using a type 1BA specimen and a constant crosshead speed of 4 mm per minute. Strains were measured in the gauge section of the specimen using an Instron video extensometer. This device has a large measurement range which is vital for measurements to failure but is less accurate at low strains. Thus, there may be larger uncertainties in the Young's moduli determined in these tests than would be the case if clip-on extensometry was used. However, the low stiffness of the test specimens precludes the use of clip-on extensometers.

A further series of tests was carried out using a more advanced video extensometer that was capable of simultaneously measuring strains in orthogonal directions. These tests were used to determine Poisson's ratio through the slope of lateral strain ( $\epsilon_2$ ) against tensile strain ( $\epsilon_1$ ) over the whole range of data. Thus, the Poisson's ratio was taken to be independent of strain. This approach had to be used as none of the materials models allow for strain dependent Poisson's ratios. Tensile test data for each of the adhesives at different temperatures are shown in Figures 2(A) to 2(C). The elastic properties are summarised in Tables 2(A) to 2(C).

DP609, Figure 2(A) and Table 2(A), shows the greatest dependence of mechanical properties on temperature. Strains to failure increase from ca. 5 % at -20 °C to over 100 % at 20 °C.  $T_g$  for DP609, around 10 °C to 20 °C, falls within the range of test temperatures used. Thus, at the lowest test temperatures it behaves as a glassy polymer. At the higher test temperatures it is rubber like. The modulus decreases with increasing temperature (the quality of the strain data below 0 °C is poor due to the low strains involved and should probably be omitted from the comparison). However, the strain at failure is at a maximum near  $T_g$ .

M70 was above its  $T_g$  (-35 °C) in all the tests performed. This adhesive has the lowest stiffness of the three adhesives (Table 2(B)). The stress-strain curves have similar shapes (Figure 2(B)). The load bearing capability and modulus of M70 decrease with temperature, whereas the strain at failure does not appear to change much. The data appear to suggest decreasing failure strains at higher temperature. However, the scatter due to the presence of voids in the specimens makes confirmation of this difficult.

PPGY5000 has extremely low tensile strains or stresses at failure for a flexible adhesive (Figure 2(C)). This is despite being tested at temperatures at, or greater than, the  $T_g$  (around -20 °C). There are no dramatic changes in behaviour as the temperature increases. The modulus is the highest of the three adhesives at high temperatures.

Strain energies have been suggested as a criterion for predicting the rupture or failure of flexible adhesive bonds. In this initial study, it was thought that the tensile strain energy would be more appropriate than planar tension or biaxial tension data. This was partly due to an appreciation of the importance of tensile strains in the failure of structural adhesives but also because there should be more confidence in the data derived from tensile tests (due to a better understanding of the local stress distributions). The energy supplied (per unit volume) in stretching the uniaxial tension specimen can be calculated from the area under the stress-strain curve. The strain energy density at rupture may be a possible failure criterion. However, bulk test specimens may fail prematurely if the specimen contains flaws, for example air bubbles or voids included during manufacture, which act as localised stress concentrators. Any premature failure of the bulk specimens will lead to conservative designs through under estimation of the bond strength.

Some theories suggest that rupture of rubbers is due to the energy dissipated in the material through inelastic processes<sup>(3,4)</sup>. Hence, in addition to the stress-strain measurements to failure, hysteresis tests were performed to determine these dissipated strain energies. In hysteresis tests, the direction of the test machine was reversed at approximately 95% of the expected failure stress of the specimen. Stress and strain measurements were made on both the upwards and downwards parts of the test. After a short recovery period the specimen was pulled to failure. It was common for the specimen to fail at lower stress and strain than were reached in the hysteresis test due to damage sustained by the specimen in the hysteresis test. Specimens where the failure stress exceeded the maximum strain in the hysteresis test by 10% or more were omitted from the analysis as the hysteresis test was thought to have been reversed too early. The area under the upwards part of the curve is the failure energy to break ( $U_B$ ).

The hysteresis area enclosed between the upwards and the downwards curves gives the energy dissipated in the material ( $H_B$ ). In rubbers, the failure energy and the hysteresis energy are related through<sup>(3)</sup>:

$$U_B = KH_B^{2/3} \quad (1)$$

Earlier results from the project<sup>(3)</sup> suggested that, above  $T_g$ , the flexible adhesives may follow this relationship.

### 3.2 PLANAR TENSION

Planar tension test specimens are tested in tension with a large aspect ratio (ratio of width to gauge length). If the material is incompressible, then the principle stretches  $\lambda_i$  along the  $i = 1, 2, 3$  axes (corresponding to length, width and thickness respectively) are:  $\lambda_1 = \lambda_s$ ,  $\lambda_2 = 1$  and  $\lambda_3 = 1/\lambda_s$  where  $\lambda_s$  is the stretch in the loading direction (and the nominal strain in the loading direction  $\epsilon_s = \lambda_s - 1$ ).

The ABAQUS manual claims that this test is a ‘pure shear test’ since, in terms of the logarithmic strains:  $\epsilon_1 = \ln \lambda_1 = -\ln \lambda_3 = -\epsilon_3$  and  $\epsilon_2 = -\ln \lambda_2 = 0$ , which corresponds to a state of pure shear at  $45^\circ$  to the loading direction. However, this ‘pure shear state’ may not occur with the flexible adhesives used in this work since most flexible adhesives are slightly compressible.

DP609 specimens were prepared as 60 mm by 100 mm wide rectangles. A grip separation of 15 mm was used. The M70 and PPGY5000 specimens were prepared as 80 mm long by 200 mm wide rectangles. These specimens were clamped with a grip separation of 30 mm. The widened grips clamp the specimen along its wide axis (Figure 3). This constrains the lateral contraction of the specimens provided that the clamping force is maintained. One problem is that, since the specimen will contract in the through-thickness direction, the clamping will not be uniformly maintained at large strains. Some lateral contraction may occur in the width direction and, eventually, the specimen will start to slip from the grips. This may limit the valid ranges of strain for the subsequent analyses. The large size of the test specimen increases the chances of inclusion of a critical flaw within the active area of the specimen leading to premature failure.

Tests were performed at 1.15 mm per minute which was assumed to give the same strain rate as the uniaxial test. Planar test data could show a large degree of scatter. Some typical test data are shown in Figures 4A - 4C. In Figure 4(A) the large difference between the failure strains of the DP609 specimen at 20 °C and the other temperatures is an exaggeration of the uniaxial tension behaviour (in confirmation, large strains to failure in the planar test were also measured at 10 °C and 30 °C). The ranking of the stress-strain curves by temperature for M70 and PPGY5000 in Figures 4(B) and 4(C) is not always consistent with the tensile test data. At most of the test temperatures the repeatability of the limited number of specimens appeared to be good. However, at some test temperatures (20 °C and 60 °C, M70 and 50 °C, PPGY5000) the data were scattered. It was the lower stiffness M70 data that were selected for further analysis. Hence, the anomalous position of the 20 °C and 60 °C curves in Figure 4(B). The higher stiffness PPGY5000 data were selected for further analysis, accounting for the position of the 50 °C curve in Figure 4(C). The reasons for the

scatter seen in some of the temperatures are not obviously apparent. Differences may be due to some specimens slipping from the grips. A further possibility is differences between the state of cure of the specimens. The planar specimens are large and only one can be obtained from each sheet manufactured. Thus, there is no way to carry out repeat measurements on specimens from the same sheet. The large quantity of sheets that have to be manufactured for the planar tests discourages large numbers of repeats. It is possible that data from 'rogue' tests or samples may have been included.

Strains in the planar tests on DP609 were determined from grip movement using the grip separation as the gauge length. Past experience has shown that the nominal gauge length may differ considerably from the grip separation. Strains in the M70 and PPGY5000 specimens were measured using video extensometry. The strains in these tests are likely to be more reliable. However, the 1.15 mm test speed was selected for the 15 mm grip separation used with the DP609 samples. The actual strain rates in the planar tension tests on the M70 and PPGY5000 specimens were discovered on analysis to have been around 25 % of the rates in the tension tests. This difference in strain rates may have an effect on the accuracy of the FE hyperelastic coefficients obtained from the uniaxial, planar and biaxial tension data.

### 3.3 EQUI-BIAXIAL TENSION

Equi-biaxial tension tests require a stress state with equal tensile stresses along two orthogonal directions. Assuming incompressibility, this deformation mode is characterised in terms of the principle stretches:  $\lambda_1 = \lambda_2 = \lambda_b$  and  $\lambda_3 = 1/\lambda_b^2$  where  $\lambda_b$  is the stretch in the perpendicular loading directions. The nominal strain is defined by  $\epsilon_b = \lambda_b - 1$ .

The equi-biaxial stress state is obtainable by stretching a square sheet in a biaxial test machine. A biaxial test fixture for a uniaxial test machine was developed as part of this work since true biaxial test machines are uncommon and expensive. This equi-biaxial test apparatus is shown in Figure 5. The scissor action test frame fits in the tensile test machine. Movement of the crosshead pulls the scissor arms apart. This extends the specimen at  $\pm 45^\circ$  to the axis of the test machine producing an equi-biaxial stress state. At large strains, thinning of the test specimen may lead to slippage in the grips.

Analysis of the geometry of the test frame indicated that the force on the axes of the test specimen is approximately 0.35 times the measured force. This will need to be confirmed by independent measurements. Stress was calculated on the assumption that all stress was uniformly distributed within the section formed by the 28 mm square gripped region. Strains were determined from the vertical movement of 2 gauge marks on the specimen using a video extensometer. These were then resolved into strains at  $\pm 45^\circ$  to the test machine axis. The accuracy and interpretation of the data depend on a number of assumptions that require validation. Tests were carried out at a crosshead speed of 2 mm per minute which gives approximately the same strain rate as the tensile tests. Biaxial test data are shown in Figures 6(A) - 6(C). Except for the low temperature PPGY5000 tests, the data produced by the biaxial tests appear to be reasonably repeatable. DP609 and M70 specimens had reasonably large strains to failure. PPGY5000 specimens, as for the other bulk specimen tests, had low strains to failure.

### 3.4 LAP JOINT TESTS

The lap joint samples were pulled to failure in an Instron 4505 test machine at an extension rate of 0.035 mm per minute. This gave a shear strain rate in the adhesive approximating to the tensile strain rate in the uniaxial tension tests on the bulk specimens. It is important to use consistent strain rates as the mechanical properties of the adhesive are strain rate dependent. The extension of the specimen was measured using a clip-on, knife-edged extensometer with a gauge length of 25 mm. This extensometer straddled the bonded region of the specimen. The location of the extensometer allowed measurement of the local extension of the joint. This removed uncertainties due to extension of the pull rods or slippage at the pin attachments. Despite the use of 3 mm thick, rigid adherends peel failures will still be predominant and therefore accurate predictions of failure were limited.

#### 3.4.1 DP609

The majority of the DP609 lap joint samples were prepared using only solvent cleaning and cured only at ambient temperatures. The force-displacement curves measured at 20 °C indicated a sharp drop in load (Figure 7) even though the joint showed no visible signs of failure. This was also found in some lap joint tests performed at 0 °C and 40 °C. At other temperatures, peeling from the surfaces was readily visible. The force-displacement curves at the lower temperatures (-20 °C, 0 °C and 20 °C) were fairly scattered. The measurements at higher temperatures (40 °C, 60 °C, 80 °C) were more repeatable. Differences in the cure state or physical age of the adhesive will lead to variability in the glass transition temperature ( $T_g$ ). Close to  $T_g$  (ca. 20 °C for DP609) the temperature-dependence of the mechanical properties is greatest. Therefore, measurements made near to  $T_g$  will be most prone to scatter.

Some DP609 joints were post-cured in an attempt to achieve a more uniform cure state closer in structure to the bulk specimens. This tended to increase both the load and extension obtained before failure (Figure 8). However, the mode of failure remained the same. The grit blasted specimens tested showed significantly higher loads to failure. Their force-displacement curves were also more linear. The grit blasting seems to arrest the slow peel failure mode. However, the final failure mode was again adhesive with the adhesive peeling from one of the adherends.

Figure 9 shows a typical force-displacement curve for each temperature. The specimens tested here were prepared using only solvent cleaning and did not undergo a post-cure. It can be seen that the joints are stiff at sub-ambient temperatures (when the adhesive is below its  $T_g$ ) with relatively small extensions to failure. The stiffness decreases considerably at higher temperatures. The lap joints tested at 20 °C have the highest extension to failure. Above 20 °C, the extension to failure decreases as the testing temperature increases. These findings agree qualitatively with the tensile test results. The displacement at failure suggests comparable strains to the uniaxial tension tests at low and high temperatures. However, at the intermediate temperatures (20 °C and 40 °C) the strains to failure are significantly lower than expected. The areas under the force-displacement curves and, therefore, the strain energies are very much higher

at sub ambient temperatures than they are at temperatures at or above  $T_g$ . This contrasts with the uniaxial tension data.

### 3.4.2 PPGY5000

Adhesive failure modes were observed during testing of PPGY5000 lap joints similar to the DP609 joints. In most cases, the adhesive peels away from one adherend. The extensions to failure and maximum loads were small (Figure 10). However, these relatively small extensions to failure correspond with significantly higher strains (20% to 40%) than the strains at failure of the tensile test specimens (up to 8%). The mechanical properties of this adhesive are very sensitive to the state of cure. Samples that had been cured for 30 minutes at 190 °C were found to be significantly stiffer than those cured only for 20 minutes. They sustain much higher loads prior to failure (Figure 11) although the extensions to failure were still small. The samples cured for 20 minutes showed the adhesive peeling cleanly away from one surface. The samples cured for 30 minutes failed with the adhesive peeling from one adherend in some areas and the other adherend in the remaining areas. The force-displacement curves were fairly repeatable at all temperatures. In Figure 10, a typical curve has been selected for each temperature for specimens cured for 30 minutes. Samples tested at 70 °C have the largest extensions to failure. The areas under the force-displacement curves are similar at all the test temperatures. This suggests that the strain energies are approximately the same. The PPGY5000 adhesive is at or above its  $T_g$  (approximately -20 °C) and in a rubbery state at all the test temperatures used.

### 3.4.3 M70

The M70 lap joints all failed cohesively (Figure 12). This was in contrast to DP609 and PPGY5000 lap joints. Also, much larger extensions to failure (>1 mm or 200% shear strain) were observed in these lap joints. These could be due to avoiding the premature failure associated with the adhesive failure mode. For M70 lap joints, the force-displacement curves were fairly repeatable at all temperatures. Figure 13 shows the repeatability in force-displacement curves for lap joints tested at 0 °C and 80 °C. In Figure 14, a typical curve has been selected for each temperature. The extensions to failure are similar for all temperatures. The maximum extensions of the lap joint specimens produce shear strains considerably in excess of 100 %. This is far greater than the strains achieved in bulk specimen tests. The areas under the force-displacement curves and, hence, the strain energies at failure decrease with temperature. The test temperatures used were above  $T_g$  (ca. -35 °C). The M70 adhesive is in a rubbery state even at -20 °C.

## 4. FINITE ELEMENT MODELLING

FEA was carried out to predict the behaviour of the lap joints described in the previous section. The material library in ABAQUS includes several models for time-independent mechanical behaviour. The following five ABAQUS models were selected; Elastic, Elastic-Plastic, Mooney-Rivlin, Ogden and Hyperfoam. These models are described below.

### 4.1 ELASTIC MODELS

Linear elasticity is the simplest form of mechanical property available in ABAQUS. Elastic behaviour means that the deformation is fully recoverable: when the load is removed, the specimen returns to its original shape. The Elastic model can define isotropic, orthotropic or anisotropic material behaviour and is valid for small elastic strains. It is characterised by a linear relationship between stress and strain (Hooke's Law). The simplest form of linear elasticity is the isotropic case where the elastic properties are completely defined by giving the Young's modulus,  $E$ , and Poisson's ratio,  $\nu$ . These are measured using uniaxial tensile tests. For this work, these parameters have been given as functions of temperature. In ABAQUS this model is activated by including the term `*ELASTIC` in the model data section of the input file. The parameters  $E$  and  $\nu$  are given along with the relevant temperature on the line following this command.

The Elastic-Plastic model is a classical metal plasticity model using the Mises yield surface to define isotropic yielding. The material has approximate linear elastic behaviour at low strain. At higher stress (and strain) magnitudes, the material is assumed to exhibit non-linear, inelastic behaviour (known as plasticity). The change from elastic to plastic behaviour occurs at the yield point or elastic limit. To use the Elastic-Plastic model in ABAQUS, the command `*ELASTIC` is used as described above. In addition, the term `*PLASTIC` is added to the model data section. To define the plasticity data required by ABAQUS, true stress and true strain data must be used. The true stress/true strain values can be obtained from the nominal stress/nominal strain data using the equations:

$$\sigma_{\text{true}} = \sigma_{\text{nom}} (1 + \epsilon_{\text{nom}}) \quad (2)$$

$$\epsilon_{\text{true}} = \ln(1 + \epsilon_{\text{nom}}) \quad (3)$$

Equation (2) is an approximation that is only valid if Poisson's ratio is 0.5. The `*PLASTIC` data option defines the true yield stress of the material as a function of true plastic strain. The plastic strain is obtained by subtracting the elastic strain (true stress divided by the Young's modulus) from the total true strain. The first set of data given on the line following the `*PLASTIC` command defines the initial yield stress of the material and, hence, has a zero plastic strain value. The data are given in the format; yield stress, plastic strain, temperature. This data line is repeated as often as necessary to define the dependence of yield stress on plastic strain. ABAQUS assumes that the material is perfectly plastic (i.e. all strain occurs with no further increase in stress) beyond the last yield stress-plastic strain point supplied. Thus, when the largest

effective strain is reached, further displacements of the lap joint are predicted to occur with no further increase in force.

## 4.2 HYPERELASTIC MODELS

### 4.2.1 Description of Hyperelastic Models

The stress-strain behaviour of typical rubber materials is elastic (i.e. recoverable) but highly non-linear. This type of material behaviour is known as hyperelasticity. The Mooney-Rivlin and Ogden models are available in the ABAQUS hyperelastic material model options. These ABAQUS models make the following assumptions; (1) the material behaviour is elastic; (2) the material behaviour is isotropic; (3) the material is incompressible; (4) the simulation will include non-linear geometric effects. In addition, hybrid elements must be used to model the fully incompressible behaviour. ABAQUS uses a strain energy potential (U) rather than Young's modulus and Poisson's ratio, to relate stresses to strains in hyperelastic materials. Two different forms of strain energy potentials are available: a polynomial model (of which the Mooney-Rivlin form is a particular case) and the Ogden model.

The form of the polynomial strain energy potential is

$$U = \sum_{i+j=1}^N C_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i} \quad (4)$$

where U is the strain energy potential per reference volume, N is the polynomial order,  $C_{ij}$  and  $D_i$  are temperature-dependent material parameters,  $\bar{I}_1$  and  $\bar{I}_2$  are the first and second deviatoric strain invariants.  $J^{el}$  is the elastic volume ratio. The  $D_i$  parameters allow for the inclusion of compressibility. However, unless volumetric test data are available  $D_i$  are assumed to be zero. From equation (6) this leads to an infinite bulk modulus, i.e. incompressibility.

The Mooney-Rivlin case is obtained from the polynomial form of the hyperelastic model by setting the parameter N to one, i.e. the first order polynomial. The Mooney-Rivlin model uses only linear functions of the invariants. The initial shear modulus,  $\mu_0$ , and the bulk modulus,  $K_0$ , when  $N=1$  are

$$\mu_0 = 2 (C_{10} + C_{01}) \quad (5)$$

$$K_0 = 2/D_1 \quad (6)$$

To define material properties using the Mooney-Rivlin model, the command \*HYPERELASTIC, POLYNOMIAL, N=1 is added to the material data section of the input file. On the following line, the parameters  $C_{10}$ ,  $C_{01}$ ,  $D_1$ , and temperature are stated. This data line can be repeated to define material constants as a function of temperature.

The Ogden strain energy potential is expressed in terms of the principle stretches. In ABAQUS the form of the Ogden strain energy potential is

$$U = \sum_{i=1}^N \frac{2m_i}{a_i^2} (\bar{l}_1^{a_i} + \bar{l}_2^{a_i} + \bar{l}_3^{a_i} - 3) + \sum_{i=1}^N \frac{1}{D_i} (J^{el} - 1)^{2i} \quad (7)$$

where  $\bar{l}_i$  are the deviatoric principle stretches. N is the order of the polynomial,  $\mu_i$ ,  $\alpha_i$ , and  $D_i$  are temperature-dependent material properties. The initial shear modulus and bulk modulus for the Ogden form are given by

$$m_0 = \sum_{i=1}^N m_i \quad (8)$$

$$K_0 = \frac{2}{D_i} \quad (9)$$

In this work a value of N=3 has been used. This model is selected by including the line \*HYPERELASTIC, OGDEN, N=3 in the material data section of the input file. The first line following this command contains the parameters  $\mu_1$ ,  $\alpha_1$ ,  $\mu_2$ ,  $\alpha_2$ ,  $\mu_3$ ,  $\alpha_3$ ,  $D_1$ , and  $D_2$ , while the second line contains  $D_3$  and temperature. This pair of data lines can be repeated to define the material constants as functions of temperature.

In the absence of volumetric test data, both the Mooney-Rivlin and Ogden models assume that the material is incompressible (i.e.  $\nu=0.5$  and  $D_i = 0$ ). However, for the adhesives studied Poisson's ratio is less than 0.5. The materials are compressible. The ABAQUS model that takes this compressibility into account is the foam hyperelasticity model (known as Hyperfoam). The Hyperfoam model uses the strain energy function

$$U = \sum_{i=1}^N \frac{2m_i}{a_i^2} \left[ \hat{l}_1^{a_i} + \hat{l}_2^{a_i} + \hat{l}_3^{a_i} - 3 + \frac{1}{b_i} \left( (J^{el})^{-a_i b_i} - 1 \right) \right] \quad (10)$$

where N is the order of the polynomial,  $\mu_i$ ,  $\alpha_i$ , and  $\beta_i$  are temperature-dependent material parameters;  $\hat{l}_i = (J^{th})^{-1/3} l_i$ ,  $\hat{l}_1 \hat{l}_2 \hat{l}_3 = J^{el}$  and  $\lambda_i$  are the principle stretches.  $J^{el}$  is the elastic volume ratio and  $J^{th}$  is the thermal volume ratio. The coefficient  $\beta_i$  determines the degree of compressibility and is related to Poisson's ratio,  $\nu_i$ , by the expression

$$n_i = \frac{b_i}{1 + 2b_i} \quad (11)$$

For this work the first order strain energy potential was used, i.e. N=1. This model is used by adding \*HYPERFOAM, N=1 to the material data section of the input file. The parameters  $\mu_1$ ,  $\alpha_1$ ,  $\nu_1$ , and temperature are included on the following line.

#### 4.2.2 Derivation of Model Coefficients

These three hyperelasticity models all rely on fitted material coefficients. It is clear that 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 tests used to obtain the coefficients are uniaxial tension, biaxial tension and planar tension. The data from these three tests must be entered into ABAQUS in the form of nominal stress and nominal strain. The least-squares-fit procedure minimises the relative error in stress. For the Mooney-Rivlin model the polynomial energy potential is linear in terms of the coefficients  $C_{ij}$ ; therefore, a linear least-squares procedure can be used. The Ogden and Hyperfoam energy potentials are non-linear in some of the coefficients necessitating the use of a non-linear least-squares procedure. In both the Mooney-Rivlin and Ogden models the  $D_i$  terms are set to zero signifying that the material is fully incompressible. In the Hyperfoam model the term  $\nu_1$  is set to the experimentally measured value of the Poisson's ratio.

A single continuum, reduced-integration, hybrid C3D8RH element<sup>(2)</sup> with unit dimensions was used to evaluate the hyperelastic model coefficients. This was subjected to uniaxial tension, biaxial tension and planar tension. The predictions were compared with the experimental data. There was good agreement for some data and models, but in other cases the predictions were not so good.

Figure 15(A) shows the input data for M70 at 80 °C. Figures 15(B)-(D) show the single element predictions using the Ogden model for uniaxial, biaxial and planar tension respectively. The quality of the fits is good. However, not all datasets could be adequately modelled as Figures 16 (A)-(D) show for the Mooney-Rivlin model with M70 at 50 °C. The uniaxial data is fitted acceptably but not the planar or biaxial data.

Reasonable fits tended to be achieved with the Mooney-Rivlin and Ogden models rather than with the Hyperfoam model. There were no instances where the Hyperfoam model adequately fitted all three sets of test data. The datasets where there was reasonable agreement between the 1-element model predictions and the test data were those such as Figure 15 where the three tests gave similar stress-strain curves. The biaxial test gave the highest 'stiffness' and the uniaxial test the lowest 'stiffness'. This characteristic is similar to the data reported by Treloar<sup>(6)</sup> that is quoted by ABAQUS in their worked example on hyperelasticity. Datasets with different characteristics (e.g. bigger differences between the curves or changed orders of stiffness) usually gave poor fits to the hyperelastic models.

Poor fits to the hyperelastic models may indicate that the models do not characterise the materials adequately. However, the poor fits may also be indicative of deficiencies in the test data. For example, the strains in the planar test data for DP609 were obtained from crosshead movement rather than direct strain measurement. There may be systematic errors in this strain determination. It is noticeable that, at each temperature, the planar stress-strain curve for DP609 is significantly lower than the

other test data. Although the planar grips have been modified since the DP609 planar tests were carried out, it would be instructive to prepare some specimens to the original dimensions and repeat some of the tests using a video extensometer to measure strain. This may enable determination of a function to calculate strain from grip movement. The data could then be reanalysed using these more reliable strain data.

#### 4.3 MODEL IMPLEMENTATION

The lap joint was modelled using a 2-dimensional model. The 2-D continuum plane strain element CPE8R was used (CPE8RH for the hyperelastic models). The mesh had the following dimensions corresponding to the lap joint specimen; 50 mm adherend length, 25 mm adherend width, 3 mm adherend thickness, 12.5 mm bond length, 0.5 mm bond thickness. It is shown in Figure 17. The lap joint mesh was finest in the adhesive region. The adhesive mesh was divided into three sections, a central section, C1, and two end sections, C2 and C3. The mesh was most refined in these adhesive end regions. The free end of one adherend was fully constrained. The end of the other adherend was constrained only in the y-direction. This end was displaced by a set distance in the x-direction (along the length axis of the specimen) during the analysis.

A number of FE analyses were run for each of the three adhesives studied, using the various material models. For every material model investigated, analyses were run at various temperatures; -20, 0, 20, 40, 60 and 80°C for DP609 and M70 lap joints; 0, 20, 30, 50, and 70°C for PPGY5000 lap joints. Not all the data required for all models were available for all temperatures.

At each temperature, the lap joint model was subjected to a series of different free-end displacements. These displacements ranged from 0.05 mm to 1 mm. A number of outputs was obtained from each analysis. These outputs included the force-displacement curve, tables of energy outputs as well as contour plots of the adhesive region for maximum principle strain, elastic strain energy and Mises equivalent stress.

As mentioned earlier, data for all models were not available at all temperatures, this was especially the case for the Elastic-Plastic model. Plastic strain data could not be calculated for the DP609 and M70 adhesives from the true stress-true strain curves at higher temperatures since the curves were too linear (i.e. elastic only). Coefficients for the hyperelastic models were available for all temperatures although below 20 °C DP609 biaxial data were not available (coefficients were calculated from uniaxial and planar data only). The hyperelastic functions can become unstable at strains that are large relative the strains in the input data. ABAQUS analyses which generate strains in unstable regions of the fits will fail. Occasionally, due to these instabilities, the analysis would fail before the smallest displacement (0.05 mm) had been achieved. Often, particularly for M70 and PPGY5000 where the shear strains in the lap joints were large compared to the failure strains in the bulk specimen tests, the hyperelastic model analyses failed to reach the extensions measured in the tests.

The elastic strain energy was predicted in FE analyses for various element sets defined within the lap joint mesh at each particular displacement. The energy dissipated by

plasticity in the Elastic-Plastic model was also predicted. The lap joint 'failure displacements' are needed to obtain a value for comparison. For each data set the failure displacement was taken as the displacement at maximum load for a typical sample. These samples are those shown in Figures 9, 10 and 14. None of these failure displacements correlated with the displacements used for the FE analyses. The strain energy for the failure displacement was obtained by interpolating between the FE predicted energies at known displacements. The strain energy values were calculated for the element set C2. This is one end section of the adhesive mesh. Each interpolated value was converted into an energy per unit volume. These values were compared to the experimentally measured failure energies. Tables 3, 4 and 5 show the failure energies predicted for DP609, M70 and PPGY5000 adhesives respectively. The results are also shown plotted in Figure 18.

## 5. FE PREDICTIONS

Despite the variable quality of the fits to the hyperelastic models it was decided to attempt to predict the behaviour of the lap joint using all the models. The predicted lap joint force-displacement curves obtained for each adhesive using the five material models were compared with the experimental force-displacement measurements. This produced many plots. Therefore, only the comparisons of the experimental measurements and the FE predictions at certain temperatures are described below. The predicted force-displacement curves are plotted over the extension ranges appropriate to the experimental data.

Many of the analyses failed to reach the extensions measured in the lap joint tests. In some cases analysis failures were due to instabilities in the model fits - extrapolation beyond the range of the input data could produce physically impossible predictions for the material behaviour. However, in other cases the analysis may fail due to elements becoming too distorted or even inverted.

### 5.1 POLYURETHANE DP609

Predictions for the DP609 lap joints show that, over the extension range of typical DP609 lap joints, most of the FE predictions are quite linear. The models do not accurately predict the shape of the experimental lap joint force-displacement curves. At the lowest temperature (-20°C) the experimental curve is very non-linear. All the models substantially underestimate the initial stiffness of the lap joint (Figure 19). Over the extension range of the samples tested all of the predicted force-displacement curves lie below the experimental curve. The initial slope of the stress-strain curve is defined by the elastic modulus of the adhesive. The large differences between the predictions and the experimental data in this region are unexpected. One possible explanation is that the material properties in the joint differ from those in the bulk material used to derive the FE input data.

At 20°C (Figure 20), the Elastic and Elastic-Plastic models overestimate the loads on the lap joint (especially so in the case of the Elastic model). The hyperelastic models (despite the poor fits to the single element simulation) give better predictions at small

extensions. At larger extensions all models overestimate the load. The Mooney-Rivlin model gives the closest approximation for the force-displacement curve.

At 60°C (Figure 21), all the predictions are quite similar. The small extension behaviour is predicted reasonably well by all the models. However, at higher extensions the loads are overestimated. The hyperelastic models give reasonable predictions for most of the experimental force-displacement curve, but overestimate the loads at the highest extensions.

No model has accurately predicted the whole of the DP609 experimental force-displacement curves at any temperature. The three hyperelastic models tend to give the closest predictions but this is generally only at the smallest extensions. All the force-displacement curve predictions are approximately linear over the extension range of interest and do not predict the shape of the lap joint force-displacement curves. However, the DP609 joints fail due to the adhesive peeling from the adherend surfaces. Slow growth of the peeling crack would reduce the load bearing area and introduce curvature into the experimental curves.

The failure energies predicted for the lap joint specimens for each model were calculated for each temperature at the failure extension determined in the lap joint tests. These are summarised in Table 3. For the DP609 adhesive (Figure 18(A)) the failure energies experimentally measured from bulk uniaxial tension samples are higher than those predicted by the FEA. The areas under the lap joint force-displacement curves and, hence, the applied strain energies sustained decrease with temperature. This differs from the bulk specimen data and FE predictions which predict maximum strain energies around 20 °C. All DP609 lap joints failed prematurely at small displacements due to the adhesive peeling away from the adherends. The failure was caused by poor adhesion strength due to inadequate surface preparation. It is thought that suitable surface preparation would have changed the failure mode to cohesive in the adhesive layer. In this case, it is likely that displacements at failure and, hence, failure energies would have been much greater.

## 5.2 ELASTOMER M70

In the case of the M70 lap joints, at -20°C all predicted force-displacement curves lie above the experimental curve (Figure 22). Only analyses using the Mooney-Rivlin and Hyperfoam models ran to the extensions observed experimentally. However, even these models are diverging widely from the large extension behaviour. All other models failed at less than half the experimental extension.

At 20°C the model predictions again lie above the experimental curve (Figure 23). The Mooney-Rivlin and Ogden models give the closest predictions. However, the Ogden model analyses failed at quite a small extension. The Hyperfoam model, although not giving the correct loads, is closest to predicting the approximate shape of the experimental force-displacement curve.

At the highest temperature (80°C) the models all over predicted the force-displacement curves (Figure 24). At this temperature the Elastic and Mooney-Rivlin predictions are approximately linear. The Ogden and Hyperfoam models predict an upward curve. At

80°C the Ogden model gave good fits to the bulk specimen data (Figure 15). However, this does not seem to have led to reasonable predictions of the lap joint performance. However, much of the extension range of the lap joint is likely to be greater than the highest strains measured in the bulk specimen tests.

In summary, for M70 lap joints at all temperatures, the models predicted force-displacement curves that lay above the experimentally obtained curves. The majority of predicted curves did not accurately model the shape of the experimental curves. Most curves were approximately linear or curved upwards. However, it should be noted that the extensions in the lap joint tests produce much larger strains than were obtained in bulk specimen tests. The predictions at larger extensions are produced using extrapolations far beyond the ranges of the input data.

Predicted failure energies from the FE analyses are shown in Table 4. Figure 18(B) shows the failure energies for the M70 adhesive. Here, the failure energies predicted by the models are higher than the experimentally obtained failure energies. This is partly due to the overestimates of forces calculated in the FE analyses. The bulk sample results also failed earlier than expected due to the presence of air bubbles. This reduced the measured failure energy. Energies calculated from the areas under the force displacement curves measured in lap joint tests show similar trends to the uniaxial tension data. However, the magnitudes of the lap joint strain energies are 3-4 times those from uniaxial tests.

### 5.3 EPOXY-BUTADIENE PPGY5000

Many of the FE analyses for PPGY5000 failed before reaching the displacements determined in lap joint tests. This may well have been because these displacements correspond to much larger strains than the input data covered. Predictions for PPGY5000 lap joints at the lowest temperature (0°C) are reasonable for very small extensions (Figure 25). At higher extensions, all models over estimate the loads. At 30°C, the Hyperfoam model predicts a force-displacement curve which lies well below the experimental curve, while predictions for all other models lie above the experimental curve (Figure 26). The Ogden model prediction curves sharply upwards at a displacement of 0.05 mm. The other predictions are approximately linear. At 70°C the predicted Hyperfoam curve still lies below the experimental curve, although now the prediction is much closer to the experimental result (Figure 27). The other models predict much higher stiffness and all curves are roughly linear.

The failure energy predictions (Figure 18(C) and Table 5) tend to be much larger than the energies calculated from the uniaxial data. This is due to the overestimates of force and the greater extension of the lap joint specimens in comparison to the bulk specimens. The uniaxial strain energies decrease with temperature. The FE predicted energies tended to increase with temperature. This does not seem reasonable. Energies calculated from the experimental lap joint data were approximately constant over the range of temperatures.

## 6. CONCLUSIONS

This report has outlined approaches for modelling the behaviour of flexible adhesive joints. Potential material models for characterising the adhesives have been investigated. The Elastic model and standard (von Mises) Elastic Plastic model do not appear to be able to model any of the three adhesives adequately. There are other plastic yield criteria available in ABAQUS and it is recommended that the validity of these is explored in future work.

Hyperelastic models appeared to show more promise. Biaxial and planar test methods have been developed to obtain some of the input data required for these models. The initial data generated from these tests have been used to derive input coefficients for the hyperelastic models in this investigation. The FE study has helped to identify deficiencies in these data. Improvements to the test and analysis methods that will improve the reliability of these methods have been identified. These will be implemented in future work.

None of the material models investigated accurately predicted the whole of the force-displacement curves measured for the lap joint specimens. Most of the analyses produced linear predictions of force-displacement over the extension ranges of interest whereas the test data showed significant curvature. It is possible that other hyperelastic material models, such as higher order polynomial forms of the Mooney-Rivlin model, may predict this curvature more effectively. The Hyperfoam model seems to offer the least promise for modelling the flexible adhesives.

There are some indications, particularly the failure of the Elastic analyses at small displacements, that the mechanical properties of adhesives in the bulk specimens may have differed. Thus, it is difficult to draw conclusions on the applicability of the models. The properties of some of these materials are extremely dependent on curing conditions. More attention should be given to matching the cure states in bulk and joint specimens.

In some cases, the analyses fail at displacements smaller than those measured experimentally. This is due to instabilities in the models outside of the limited range of the bulk specimen data or over-distortion of elements in the adhesive. Many of the hyperelastic analyses extrapolated fitted material properties significantly beyond the strains obtained in bulk specimen tests. This may lead to large uncertainties in the large extension predictions or even cause the analysis to crash.

Given the difficulties in predicting the large extension performance of the joints it is not surprising that the analyses could not accurately predict the failure energies obtained from uniaxial tests on bulk samples. For both the PPGY5000 and M70 adhesives, the predicted failure energies were higher than the uniaxial tension failure energies. For DP609, the predicted failure energies were lower than those measured in uniaxial tests. However in all these tests there was premature failure of bulk specimens through the presence of voids (M70 and PPGY5000) or of joints through inadequate surface preparation (DP609). Hence, it was not possible to make a reliable evaluation of the failure criterion.

## 7. FUTURE WORK

The comparison between the FE model predictions and the lap joint tests indicate there are still problems with the selection of an appropriate FE model and failure criterion for flexible adhesives. Hyperelastic and strain energy failure criteria models may be appropriate but it is clear that better quality input data is needed for confirmation. Following further validation of the equi-biaxial and planar tension tests, more data shall be generated in PAJex2 (the extension project on flexible adhesives). Some of the analyses reported in this work shall be repeated and some additional rubber models available in ABAQUS which may be more suitable will also be investigated. The issues identified in this work will be addressed in the follow-on project PAJex2 (flexible adhesives).

## ACKNOWLEDGEMENTS

This work was funded by the DTI under the Materials Metrology Performance of Adhesive Joints Programme.

## REFERENCES

1. Charalambides M.N. and Olusanya A., The Constitutive Models Suitable for Adhesives in some Finite Element Codes and Suggested Methods of Generating the Appropriate Materials Data. NPL Report CMMT(B)131, April 1997
2. ABAQUS/Standard User's and Theory Manuals, Version 5.8, Hibbit, Karlsson & Sorenson Inc., USA, 1998
3. Olusanya A., A criterion of tensile failure for hyperelastic materials and its application to viscoelastic-viscoplastic materials. NPL Report CMMT(B)130, April 1997
4. Harwood J.A.C. and Payne A.R., J. Applied Pol. Sci. vol 12, pp 889-901, 1968
5. Duncan B.C., Giradi M.A. and Read B.E., The Preparation of Bulk Adhesive Samples for Mechanical Testing. NPL Report DMM(B)339, January 1994
6. Treloar R.G., Transactions Faraday Society vol 40, pp59-70, 1944

## LIST OF TABLES AND FIGURES

### Tables:

1. Details of the three adhesives studied.
2. Elastic properties of the adhesives.
3. Predicted failure energies and experimentally measured failure energies for DP609 samples tested over the temperature range -20°C to 80°C.
4. Predicted failure energies and experimentally measured failure energies for M70 samples tested over the temperature range -20°C to 80°C.
5. Predicted failure energies and experimentally measured failure energies for PPGY5000 samples tested over the temperature range 0°C to 70°C.

**Figures:**

1. Figure showing (A) photograph of lap joint preparation jig and (B) schematic diagram of a typical lap joint.
2. Uniaxial tensile data for (A) DP609; (B) M70 and (C) PPGY5000.
3. Photograph and schematic of the planar test.
4. Planar data for (A) DP609; (B) M70 and (C) PPGY5000
5. Photograph and schematic of equi-biaxial test rig.
6. Biaxial data for (A) DP609; (B) M70 and (C) PPGY5000
7. Force-Displacement curves from DP609 lap joints tested at 20°C showing the loss of load bearing capabilities, although the joints had not appeared to fail. All joints had been prepared using only solvent cleaning as a surface preparation.
8. Force-displacement curves for DP609 lap joints at 20°C showing the difference between post cured samples and samples with grit blasted adherends.
9. Experimental load-displacement curves for DP609 lap joints tested over the temperature range -20°C to 80°C.
10. Experimental load-displacement curves for PPGY5000 lap joints tested over the temperature range 0°C to 70°C.
11. Comparison of force-displacement curves obtained from samples cured at 190°C for 20 minutes and those obtained from samples cured at 190°C for 30 minutes.
12. Photograph of a failed M70 lap joint showing cohesive failure between the adhesive and adherends.
13. Plots of force-displacement curves for M70 lap joints tested (A) at 0°C and (B) at 80°C.
14. Force-displacement curves for M70 lap joints tested over the temperature range from -20°C to 80°C
15. Nominal stress-nominal strain plots for M70 measured at 80°C showing (A) hyperelastic test data and comparisons between these test data and Ogden predictions for (B) uniaxial tests; (C) biaxial tests and (D) planar tests.
16. Nominal stress-nominal strain plots for M70 at 50°C showing (A) hyperelastic test data and comparisons between these test data and Mooney-Rivlin predictions for (B) uniaxial tests; (C) biaxial tests and (D) planar tests.
17. Mesh used in finite element analysis of the lap joint.
18. Plots of Failure energy against temperature comparing predicted results with experimental data for (A) DP609; (B) M70 and (C) PPGY5000.
19. Comparison of DP609 FE predictions with experimental results at -20°C.
20. Comparison of DP609 FE predictions with experimental results at 20°C.
21. Comparison of DP609 FE predictions with experimental results at 60°C.
22. Comparison of M70 FE predictions with experimental results at -20°C.
23. Comparison of M70 FE predictions with experimental results at 20°C.
24. Comparison of M70 FE predictions with experimental results at 80°C.
25. Comparison of PPGY5000 FE predictions with experimental results at 0°C.
26. Comparison of PPGY5000 FE predictions with experimental results at 30°C.
27. Comparison of PPGY5000 lap joint FE predictions with experimental results at 70°C.

## TABLES

Table 1. Details of the three adhesives studied.

| Adhesive | Supplier | Type                                               | Cure                        |
|----------|----------|----------------------------------------------------|-----------------------------|
| DP609    | 3M       | 2-part polyurethane (DP609)                        | room temperature, > 8 hours |
| M70      | Evode    | 1-part polybutadiene (elastomeric) (elastomer M70) | 200°C, 45 minutes           |
| PPGY5000 | PPG      | 1-part epoxy-butadiene (3289Y5000)                 | 190°C, 20 minutes           |

Table 2: Elastic properties of the adhesives.

### (A) DP609

| Temperature (°C) | Modulus (MPa) | Poisson's ratio |
|------------------|---------------|-----------------|
| -20              | 1380.28       | 0.37            |
| 0                | 5779.42       | 0.37            |
| 20               | 230.90        | 0.36            |
| 40               | 30.09         | 0.32            |
| 60               | 18.97         | 0.32            |
| 80               | 24.74         | 0.32            |

### (B) M70

| Temperature (°C) | Modulus (MPa) | Poisson's ratio |
|------------------|---------------|-----------------|
| -20              | 19.43         | 0.35            |
| 0                | 8.45          | 0.35            |
| 20               | 5.11          | 0.35            |
| 40               | 6.08          | 0.35            |
| 60               | 4.09          | 0.35            |
| 80               | 3.89          | 0.35            |

### (C) PPGY5000

| Temperature (°C) | Modulus (MPa) | Poisson's ratio |
|------------------|---------------|-----------------|
| -20              | 350.00        | 0.4             |
| 0                | 181.99        | 0.4             |
| 20               | 184.32        | 0.4             |
| 40               | 105.74        | 0.4             |
| 60               | 82.34         | 0.4             |
| 80               | 57.25         | 0.4             |

Table 3. Predicted failure energies and experimentally measured failure energies for DP609 samples tested over the temperature range -20°C to 80°C.

|            | Energies per unit volume (mJ/mm <sup>3</sup> ) |                     |                   |       |           |              |           |
|------------|------------------------------------------------|---------------------|-------------------|-------|-----------|--------------|-----------|
|            | FE Predictions                                 |                     |                   |       |           | Experimental |           |
| Temp<br>°C | Elastic                                        | Elastic-<br>Plastic | Mooney-<br>Rivlin | Ogden | Hyperfoam | Uniaxial     | Lap Joint |
| -20        | 0.43                                           | 0.44                | 0.45              | xx    | 0.44      | 1.66         | 1.17      |
| 0          | 0.36                                           | 0.99                | xx                | xx    | 0.45      | 0.88         | 0.58      |
| 20         | 4.60                                           | 2.75                | 0.69              | 0.91  | 1.11      | 16.51        | 0.48      |
| 40         | 0.46                                           | x                   | 0.19              | 0.07  | 0.11      | 2.69         | 0.15      |
| 60         | 0.23                                           | x                   | 0.14              | 0.14  | 0.16      | 0.90         | 0.12      |
| 80         | 0.004                                          | x                   | 0.02              | 0.01  | 0.02      | 0.51         | 0.03      |

Table 4. Predicted failure energies and experimentally measured failure energies for M70 samples tested over the temperature range -20°C to 80°C.

|            | Energies per unit volume (mJ/mm <sup>3</sup> ) |                     |                   |       |           |              |           |
|------------|------------------------------------------------|---------------------|-------------------|-------|-----------|--------------|-----------|
|            | FE Predictions                                 |                     |                   |       |           | Experimental |           |
| Temp<br>°C | Elastic                                        | Elastic-<br>Plastic | Mooney-<br>Rivlin | Ogden | Hyperfoam | Uniaxial     | Lap Joint |
| -20        | 3.31                                           | xx                  | 6.92              | xx    | 9.26      | 0.86         | 2.80      |
| 0          | 1.42                                           | xx                  | 2.55              | xx    | 4.11      | 0.68         | 1.87      |
| 20         | xx                                             | x                   | 1.79              | xx    | 2.06      | 0.45         | 1.40      |
| 40         | xx                                             | x                   | 3.43              | xx    | 4.84      | 0.22         | 0.85      |
| 60         | xx                                             | x                   | 1.73              | xx    | 2.18      | 0.23         | 0.83      |
| 80         | xx                                             | x                   | 2.00              | 3.37  | xx        | 0.20         | 0.70      |

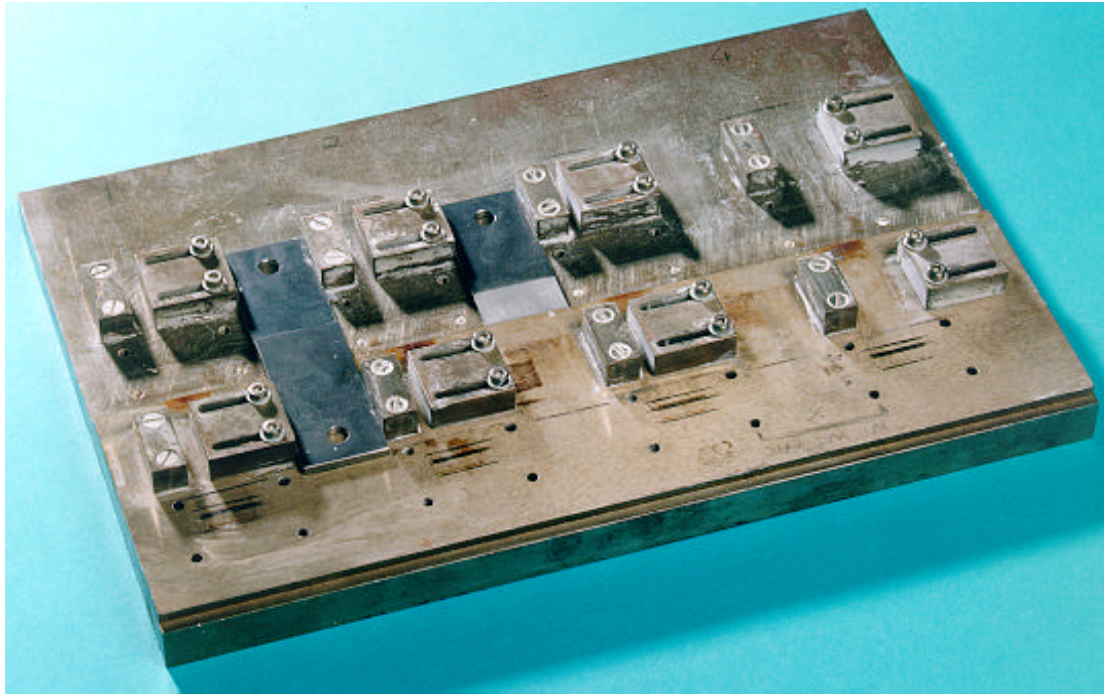
Table 5. Predicted failure energies and experimentally measured failure energies for PPGY5000 samples tested over the temperature range 0°C to 70°C.

|            | Energies per unit volume (mJ/mm <sup>3</sup> ) |                     |                   |       |           |              |           |
|------------|------------------------------------------------|---------------------|-------------------|-------|-----------|--------------|-----------|
|            | FE Predictions                                 |                     |                   |       |           | Experimental |           |
| Temp<br>°C | Elastic                                        | Elastic-<br>Plastic | Mooney-<br>Rivlin | Ogden | Hyperfoam | Uniaxial     | Lap Joint |
| 0          | 1.15                                           | 0.51                | 0.88              | xx    | 0.90      | 0.23         | 0.53      |
| 20         | 1.69                                           | xx                  | 1.16              | 1.19  | 0.53      | 0.17         | 0.54      |
| 30         | 1.86                                           | 0.44                | 1.12              | 1.20  | xx        | 0.17         | 0.47      |
| 50         | 2.91                                           | xx                  | 1.58              | 1.67  | xx        | 0.14         | 0.60      |
| 70         | 3.01                                           | xx                  | 1.74              | xx    | xx        | 0.099        | 0.48      |

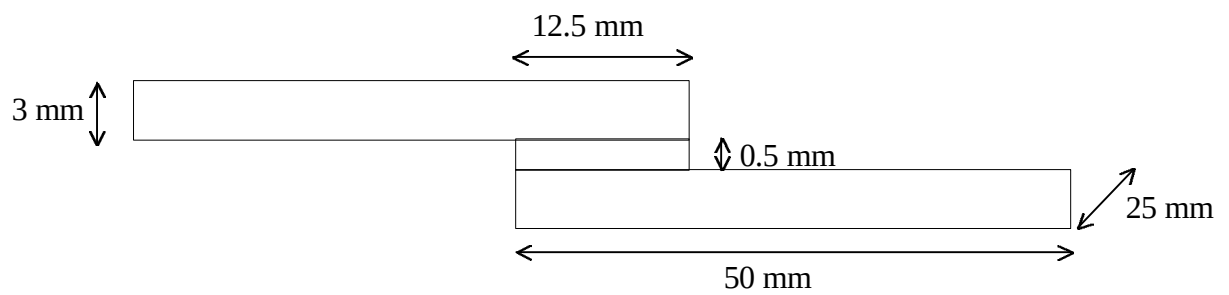
x value not calculated due to lack of test data

xx value not calculated due to analysis failure

## FIGURES



(A)



(B)

Figure 1. Figure showing (A) photograph of lap joint preparation jig and (B) schematic of a typical lap joint.

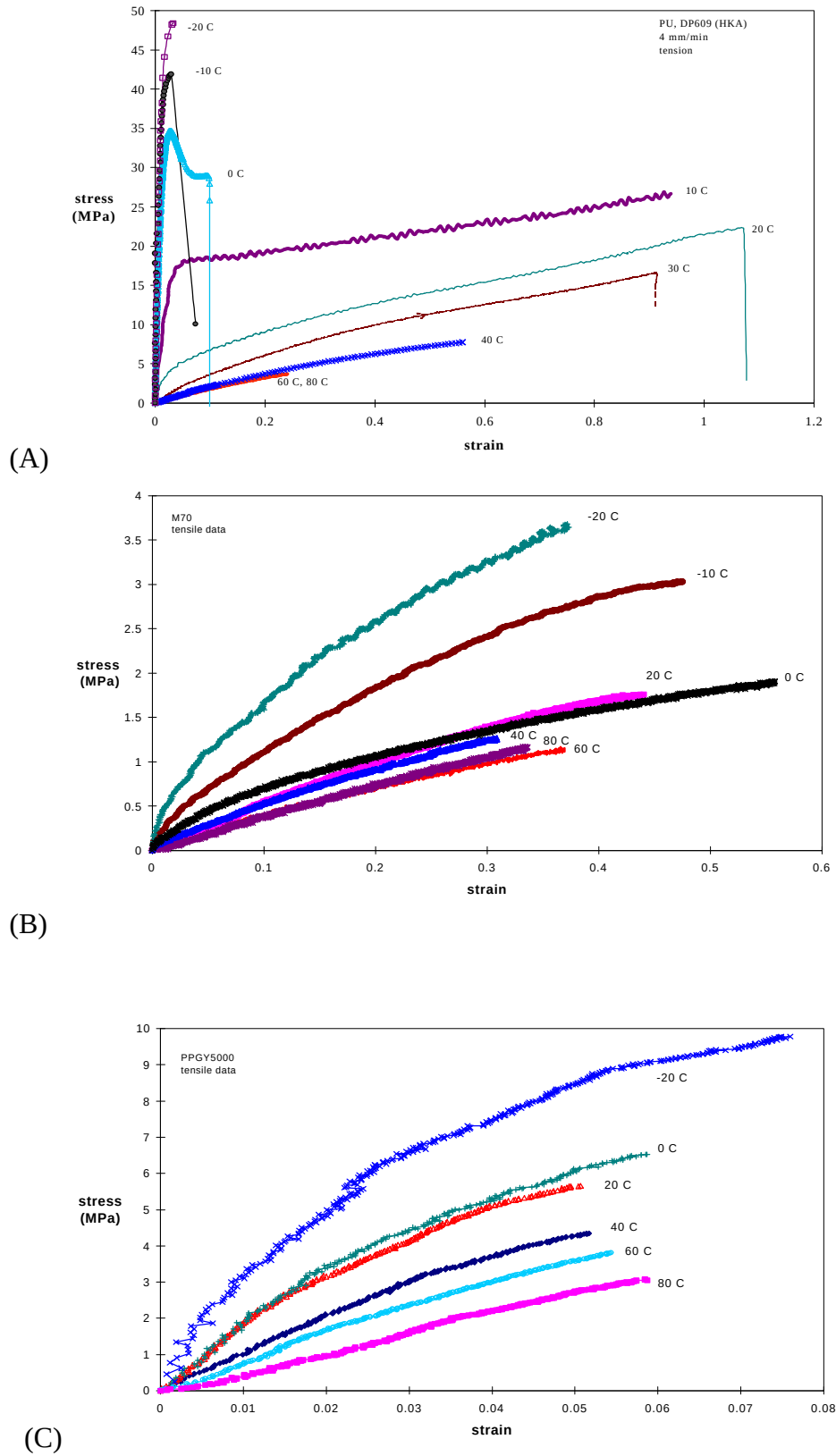


Figure 2. Uniaxial tensile data for (A) DP609; (B) M70 and (C) PPGY5000.

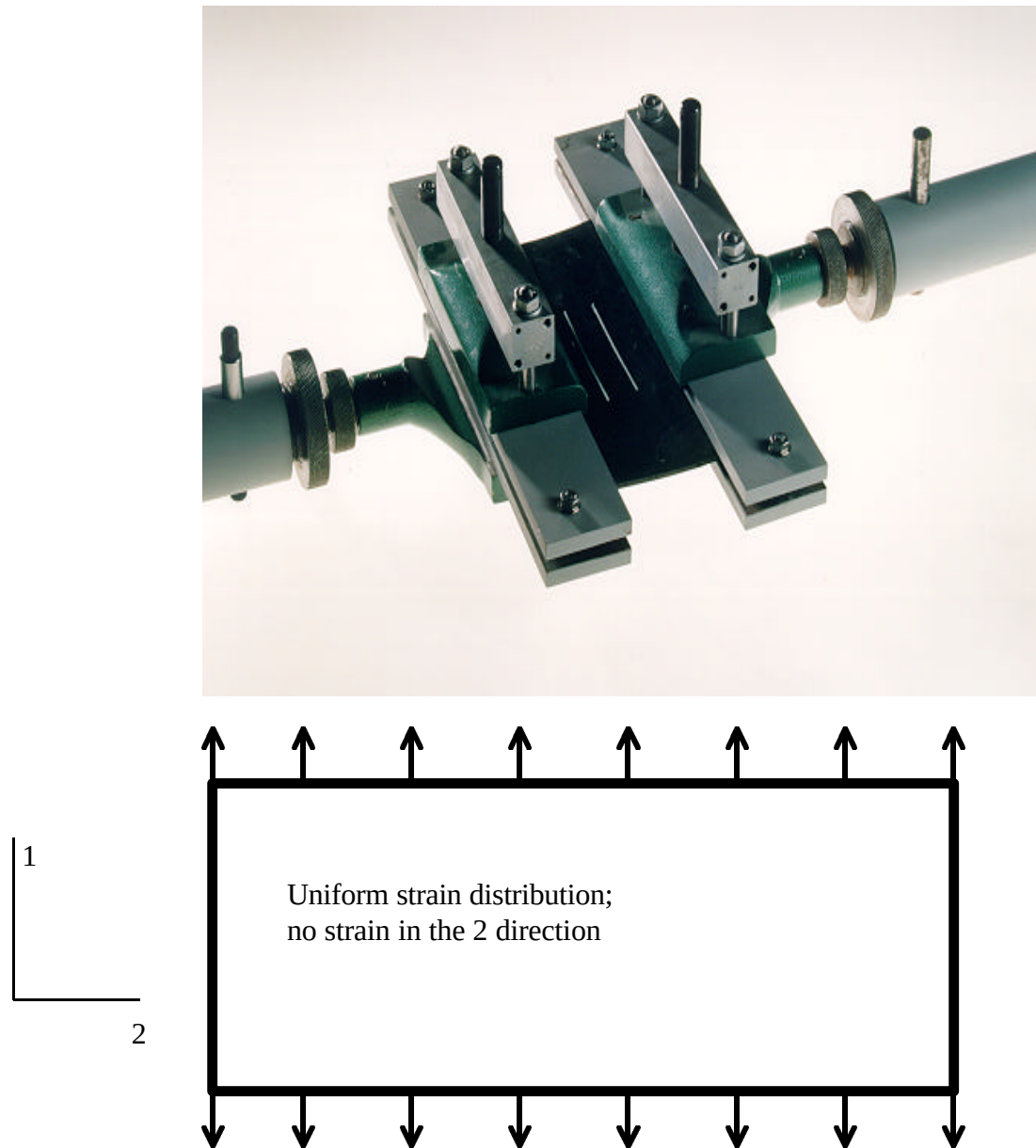


Figure 3. Photograph and schematic of the planar test.

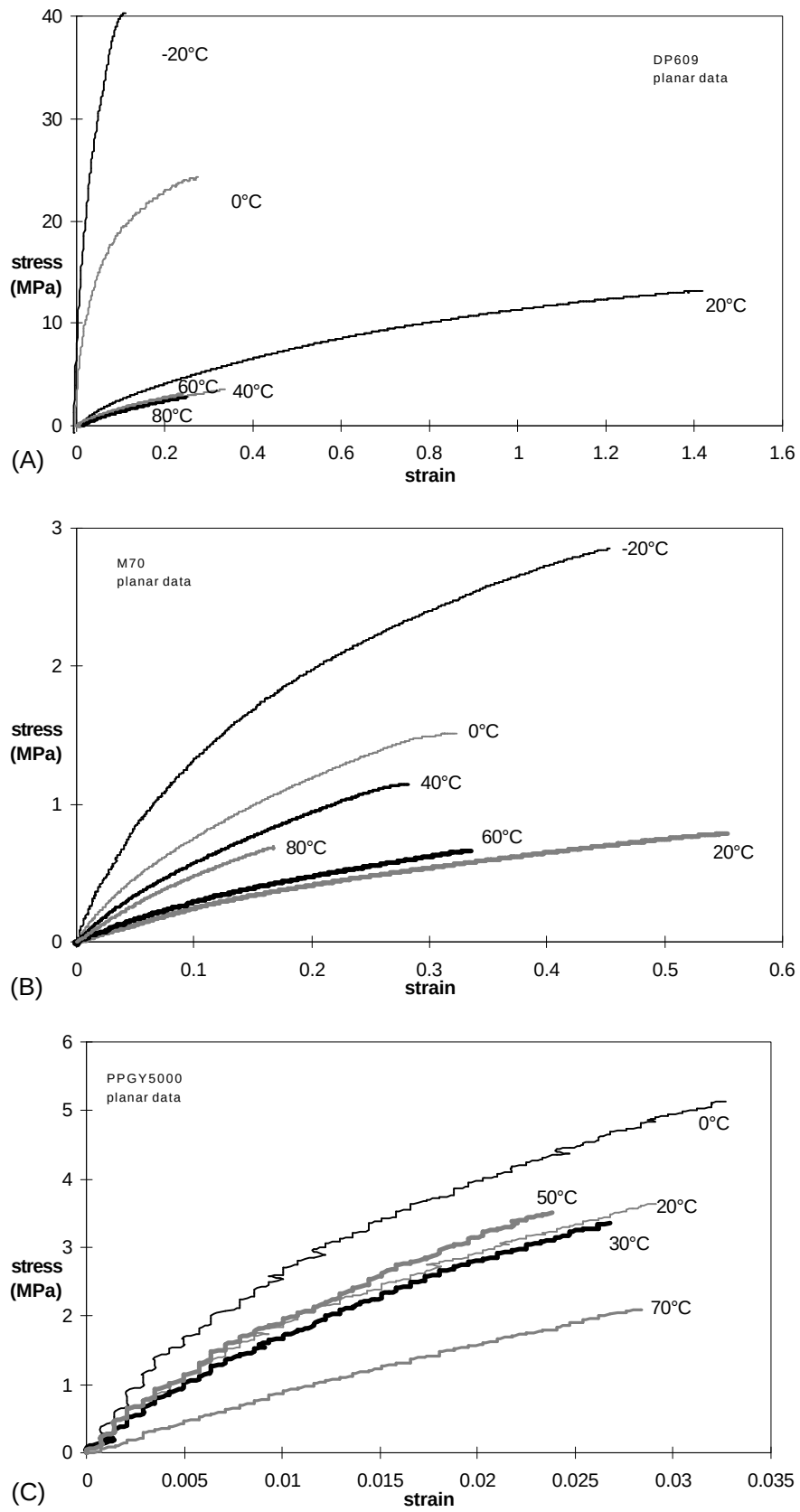


Figure 4. Planar data for (A) DP609; (B) M70 and (C) PPGY5000

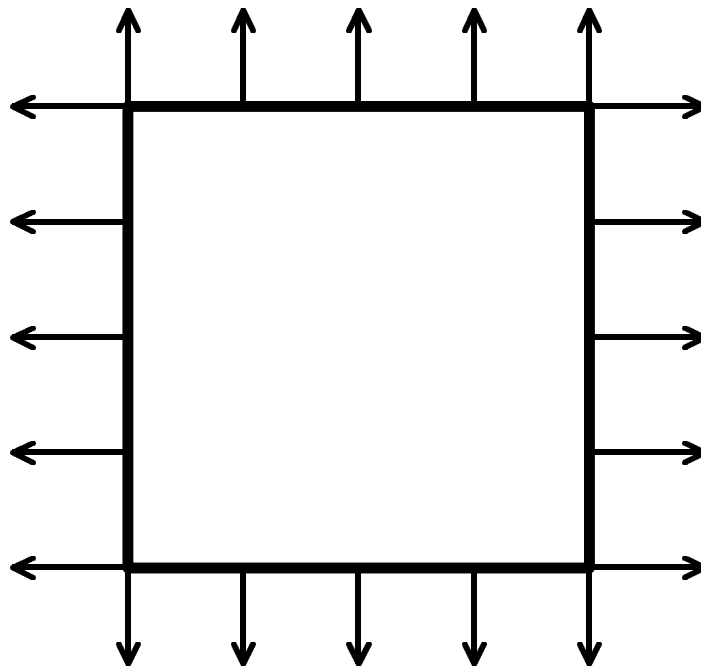
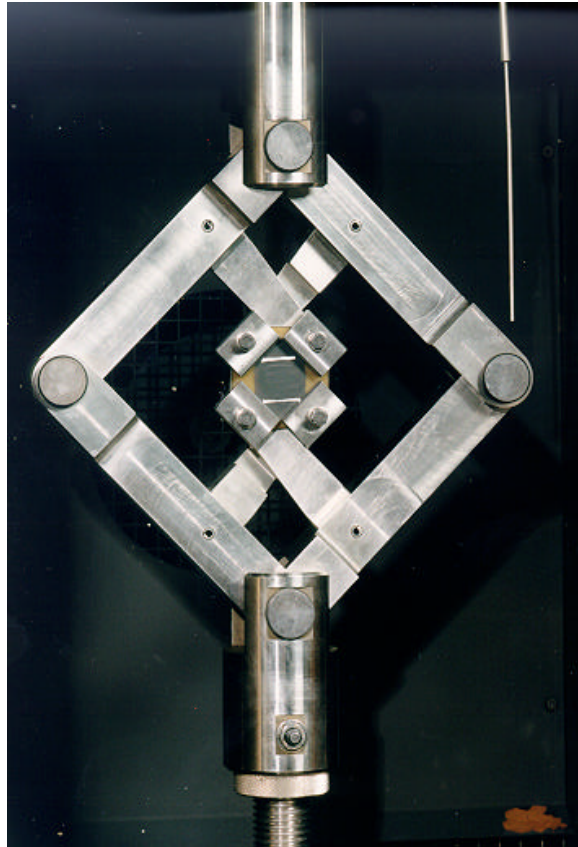


Figure 5. Photograph and schematic of equi-biaxial test rig.

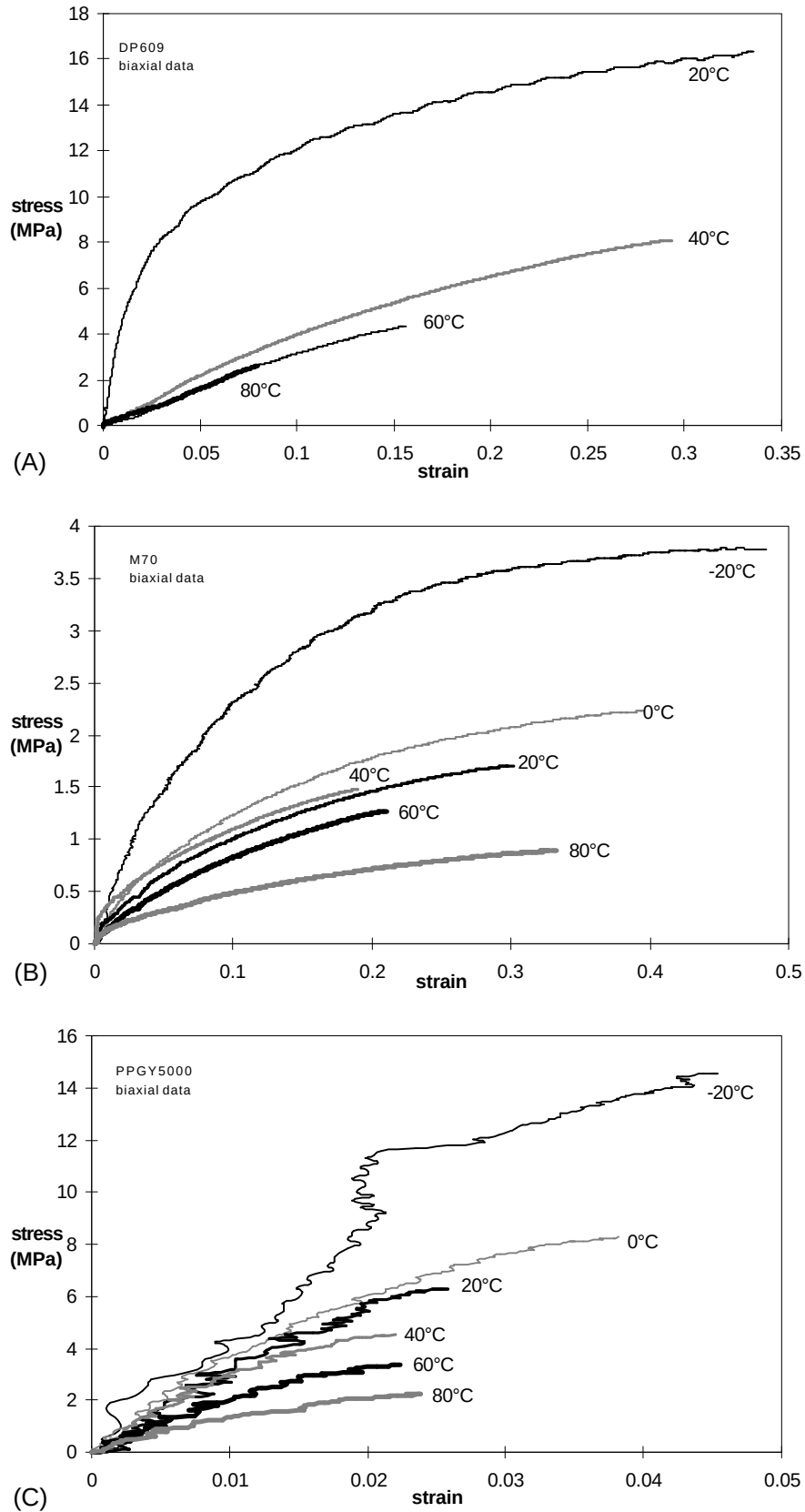


Figure 6. Biaxial data for (A) DP609; (B) M70 and (C) PPGY5000

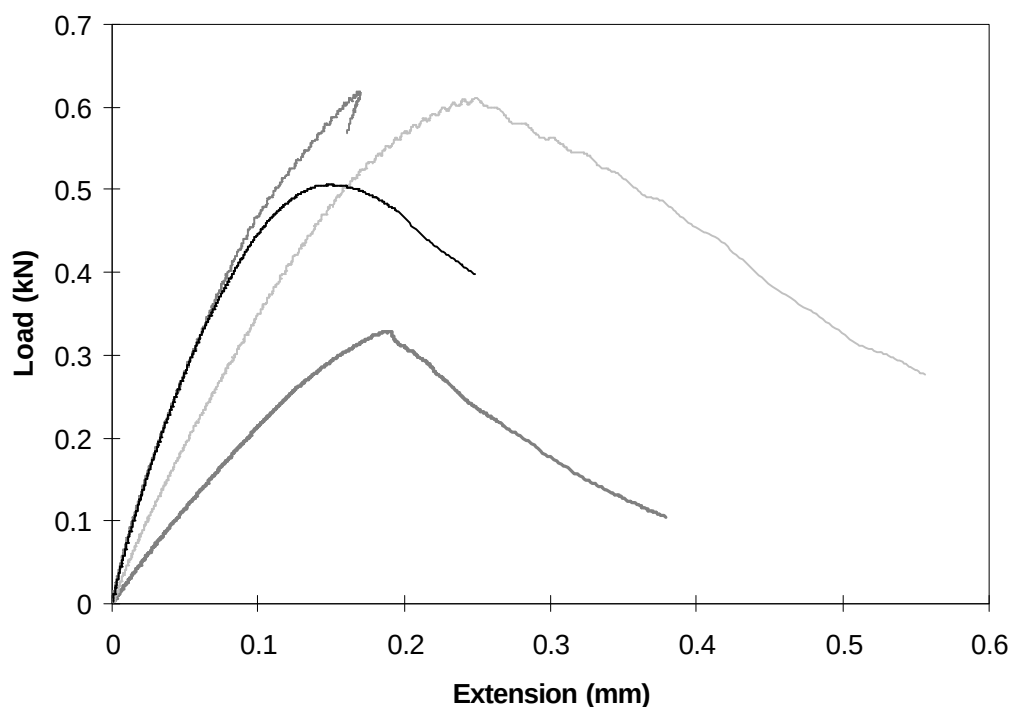


Figure 7. Force-Displacement curves from DP609 lap joints tested at 20°C showing the loss of load bearing capabilities, although the joints had not appeared to fail. All joints had been prepared using only solvent cleaning as a surface preparation.

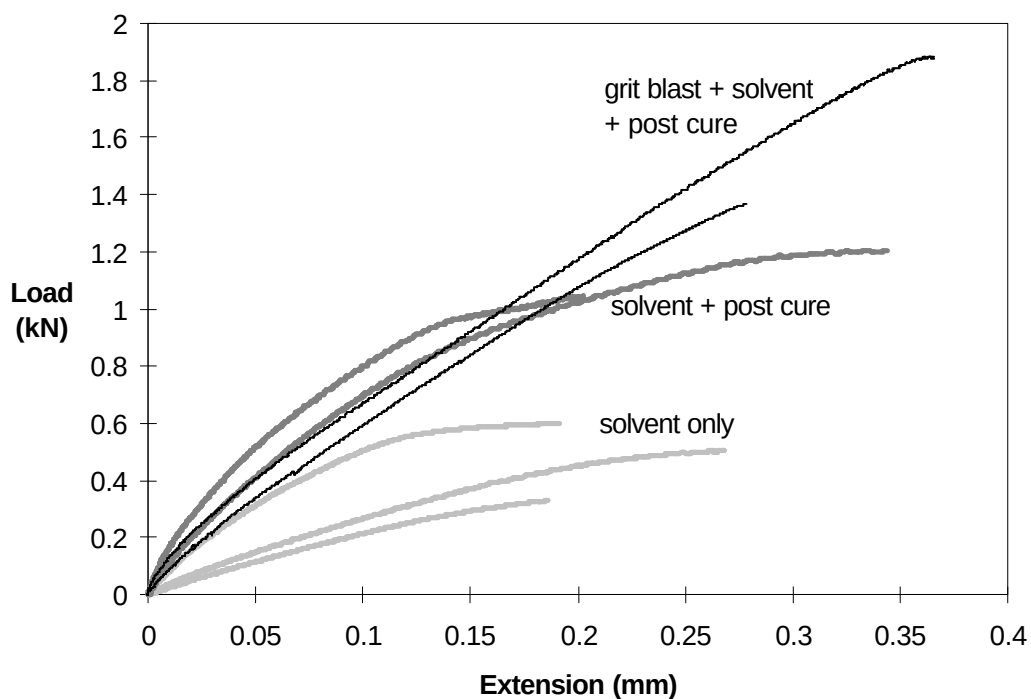


Figure 8. Force-displacement curves for DP609 lap joints at 20°C showing the difference between post cured samples and samples with grit blasted adherends.

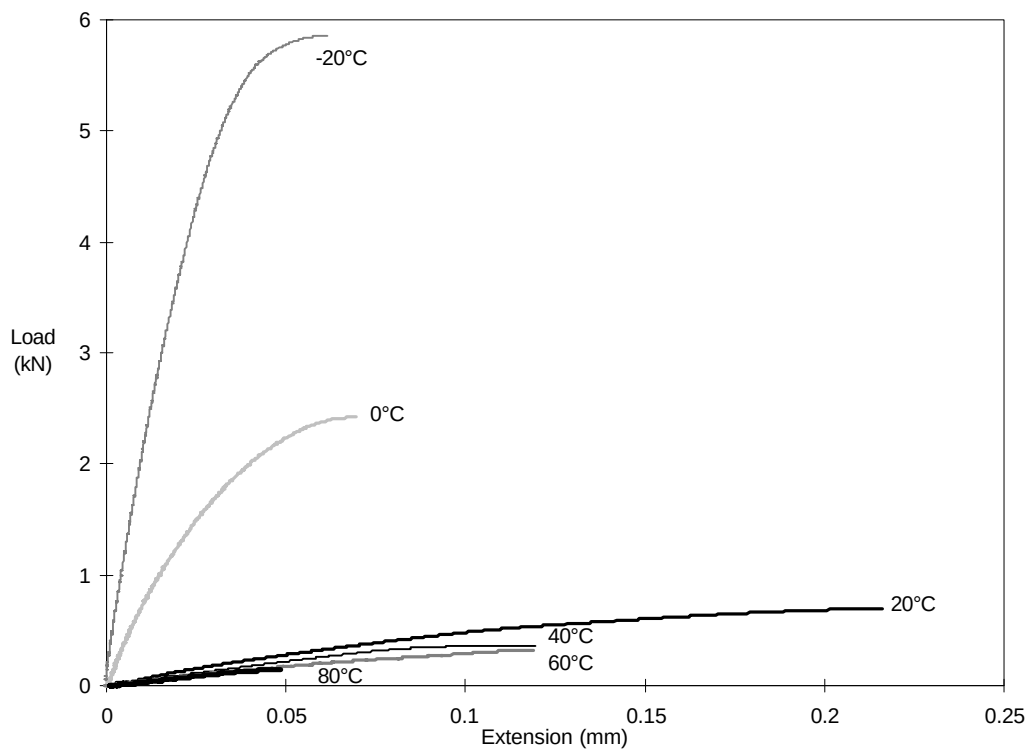


Figure 9. Experimental load-displacement curves for DP609 lap joints tested over the temperature range -20°C to 80°C.

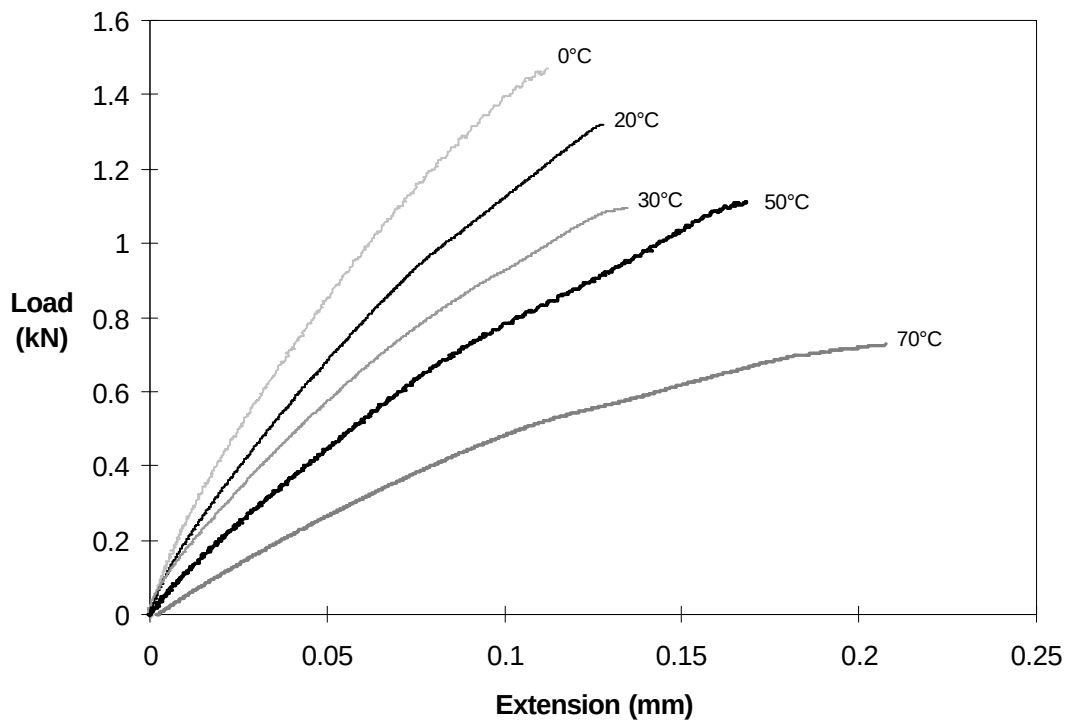


Figure 10. Experimental load-displacement curves for PPGY5000 lap joints tested over the temperature range 0°C to 70°C.

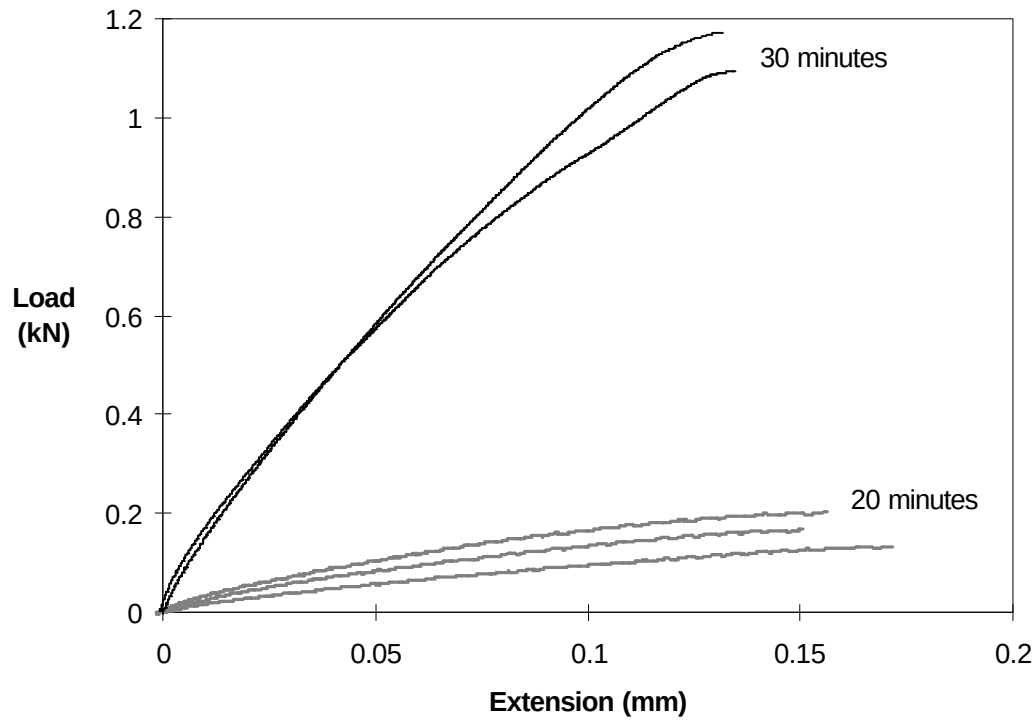


Figure 11. Comparison of force-displacement curves obtained from samples cured at 190°C for 20 minutes and those obtained from samples cured at 190°C for 30 minutes.

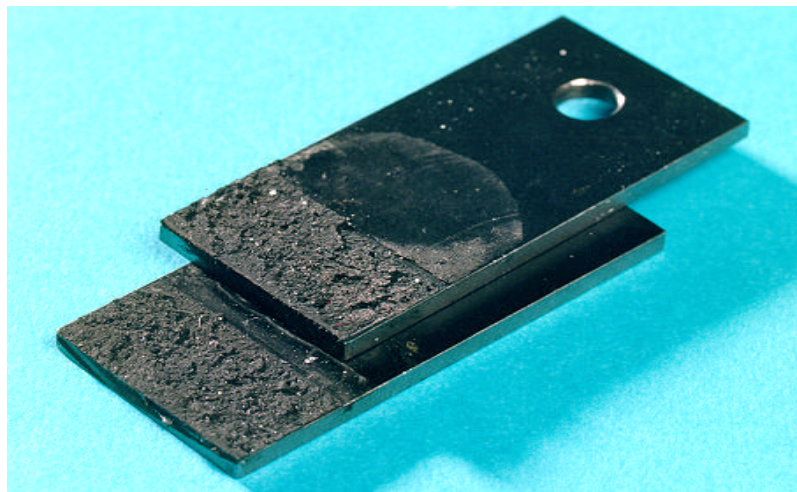


Figure 12. Photograph of a failed M70 lap joint showing cohesive failure between the adhesive and adherends.

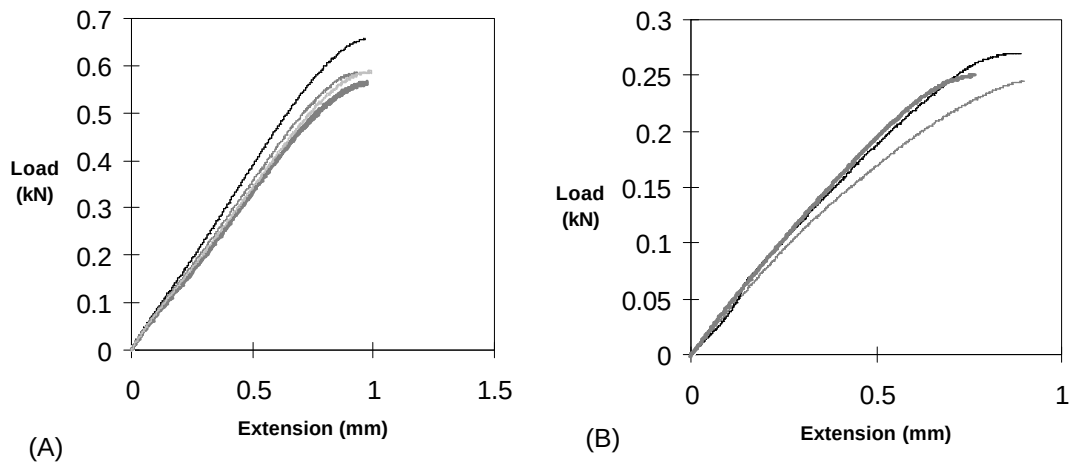


Figure 13. Plots of force-displacement curves for M70 lap joints tested (A) at 0°C and (B) at 80°C.

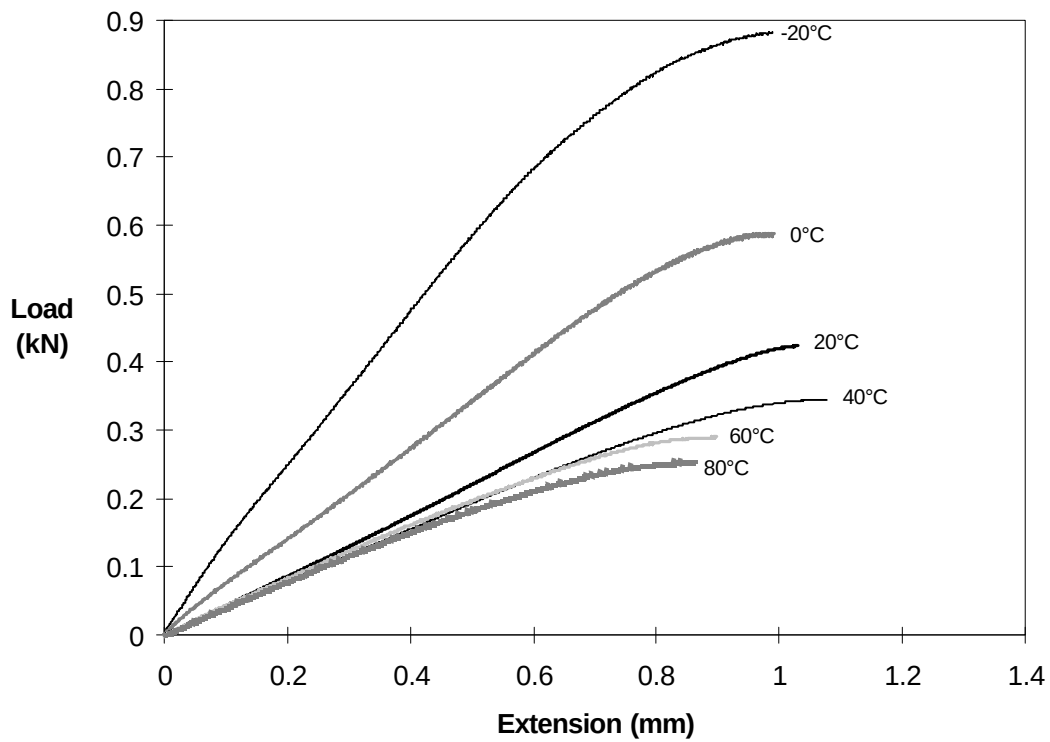


Figure 14. Force-displacement curves for M70 lap joints tested over the temperature range from -20°C to 80°C.

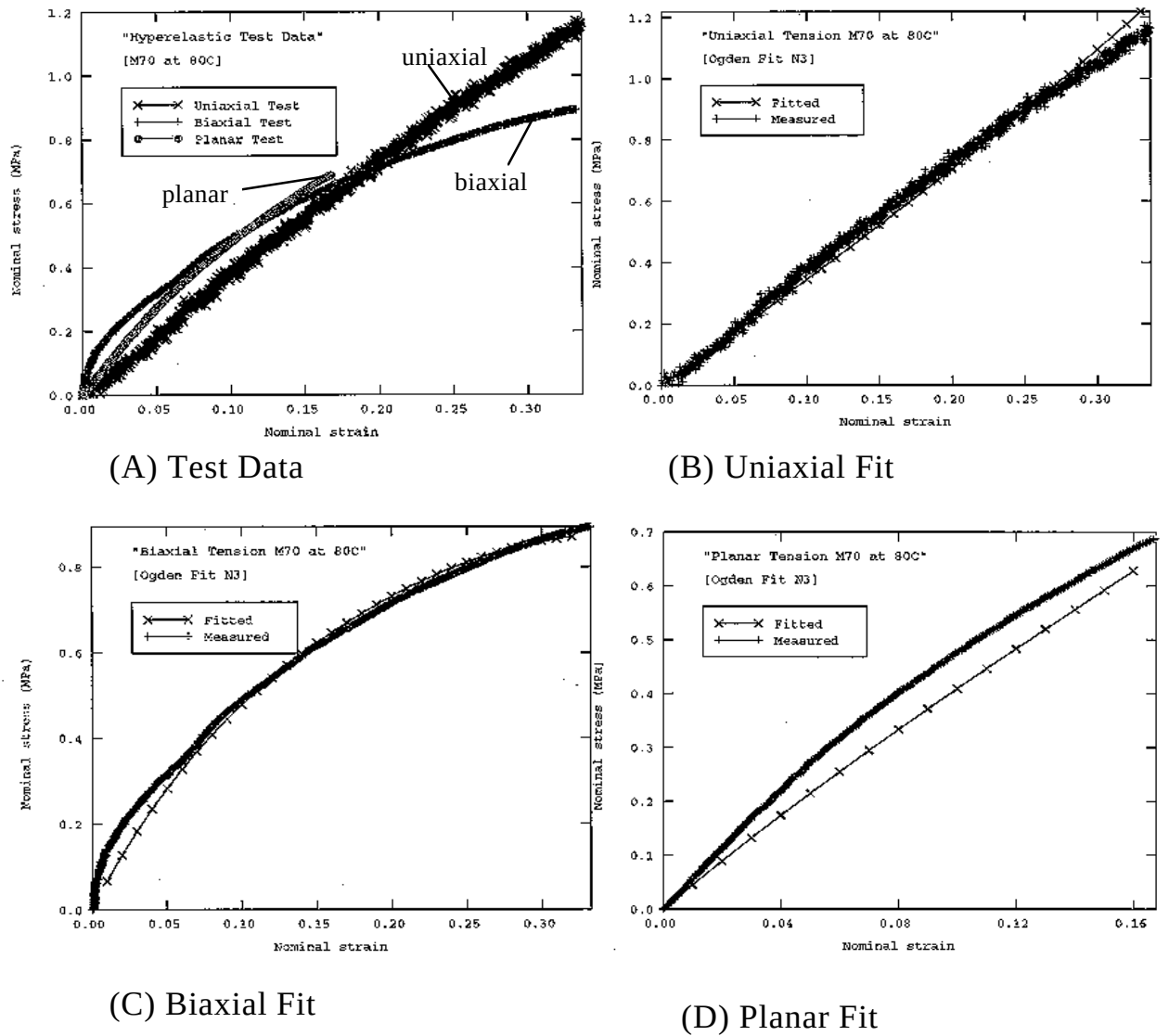


Figure 15. Nominal stress-nominal strain plots for M70 measured at 80°C showing (A) hyperelastic test data and comparisons between these test data and Ogden predictions for (B) uniaxial tests; (C) biaxial tests and (D) planar tests.

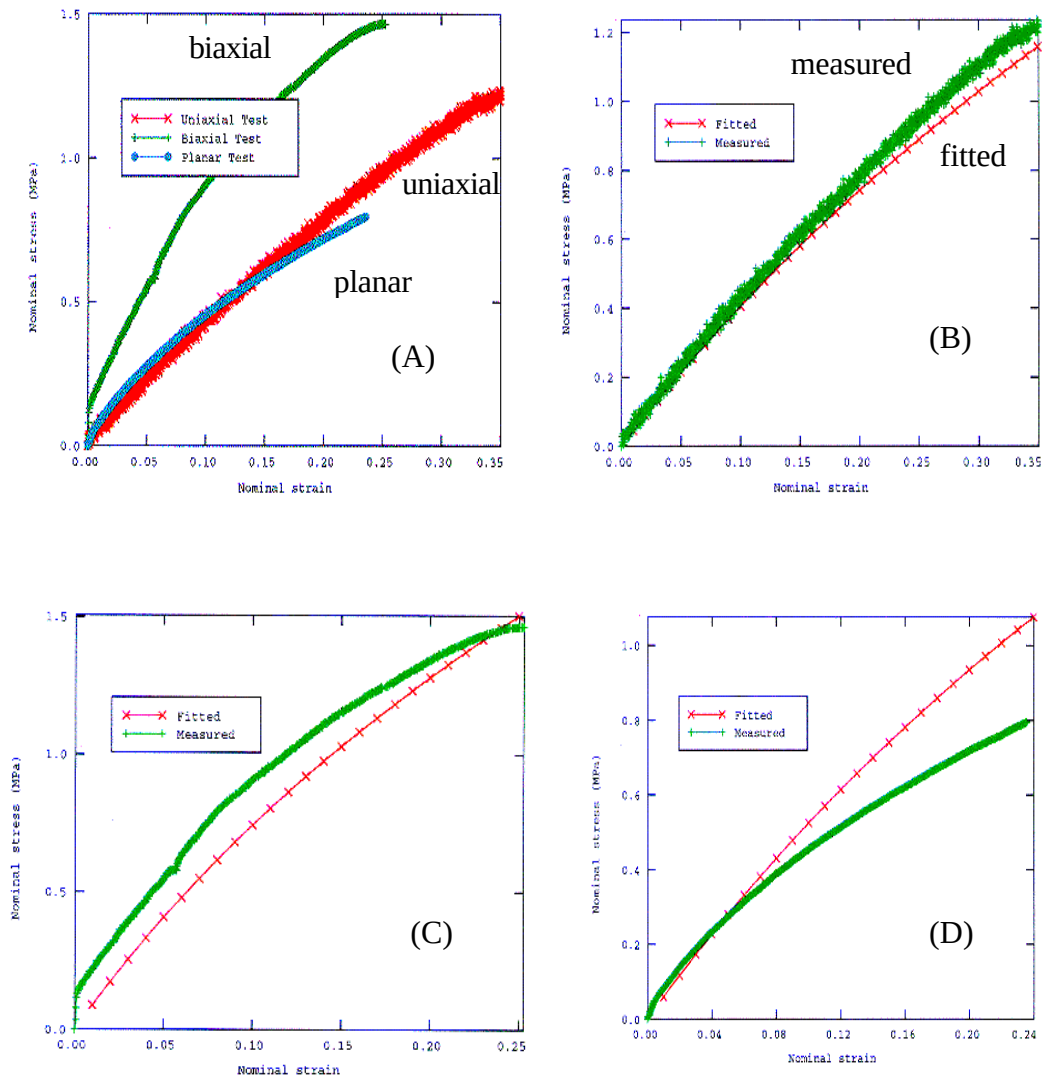


Figure 16. Nominal stress-nominal strain plots showing (A) hyperelastic test data and comparisons between these test data and Mooney-Rivlin predictions for (B) uniaxial tests; (C) biaxial tests and (D) planar tests.

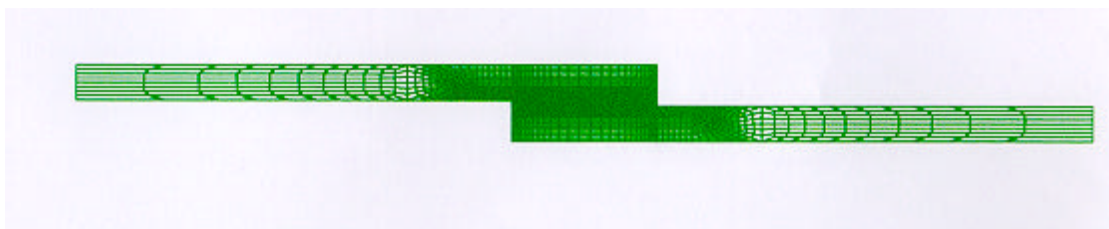


Figure 17. Mesh used in finite element analysis of the lap joint.

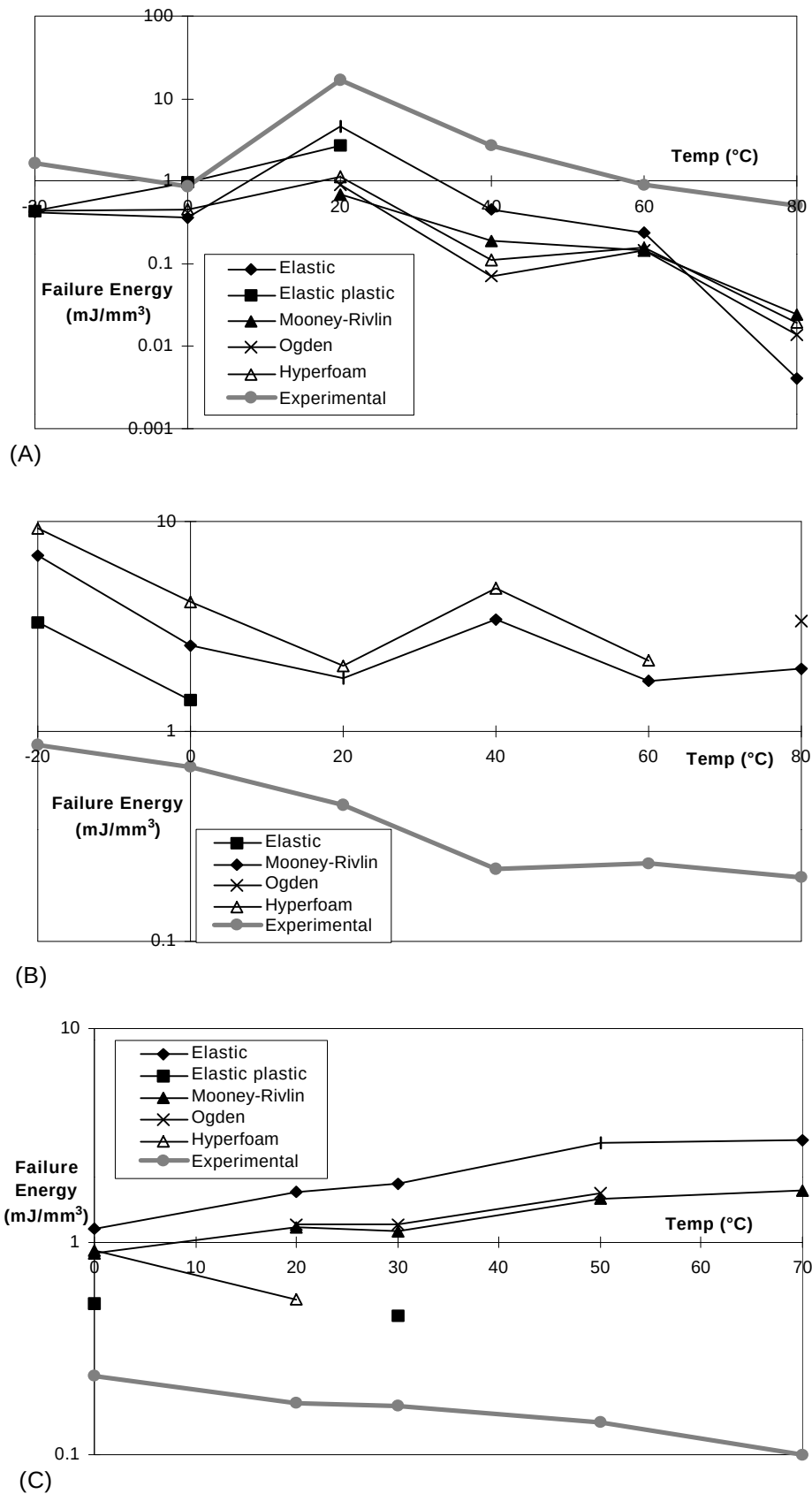


Figure 18. Plots of Failure energy against temperature comparing predicted results with experimental data for (A) DP609; (B) M70 and (C) PPGY5000.

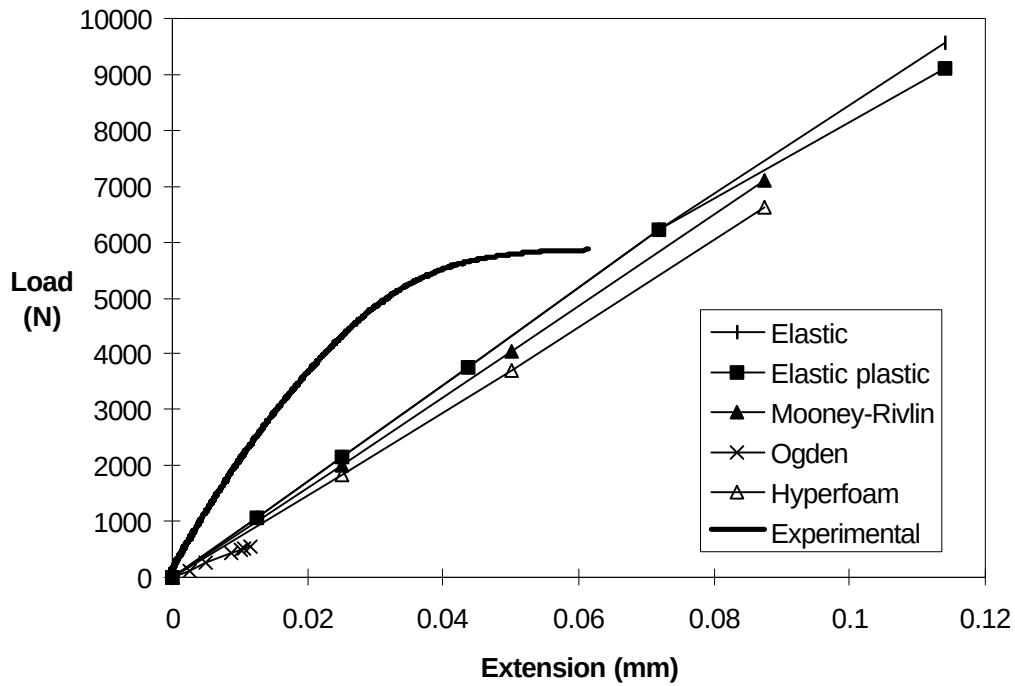


Figure 19. Comparison of DP609 FE predictions with experimental results at -20°C.

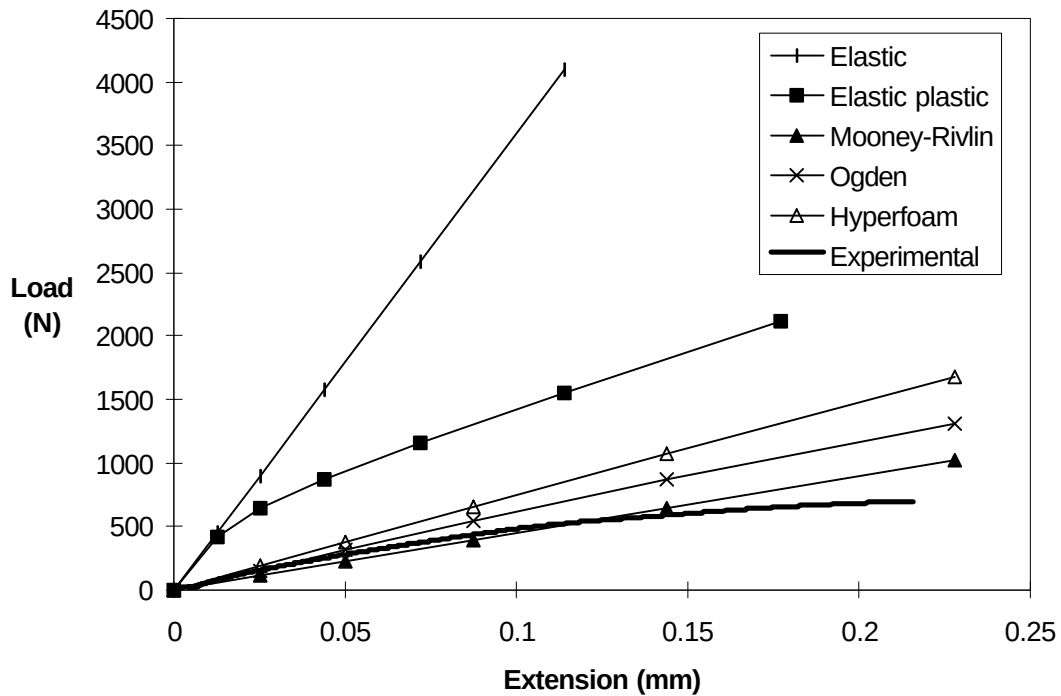


Figure 20. Comparison of DP609 FE predictions with experimental results at 20°C.

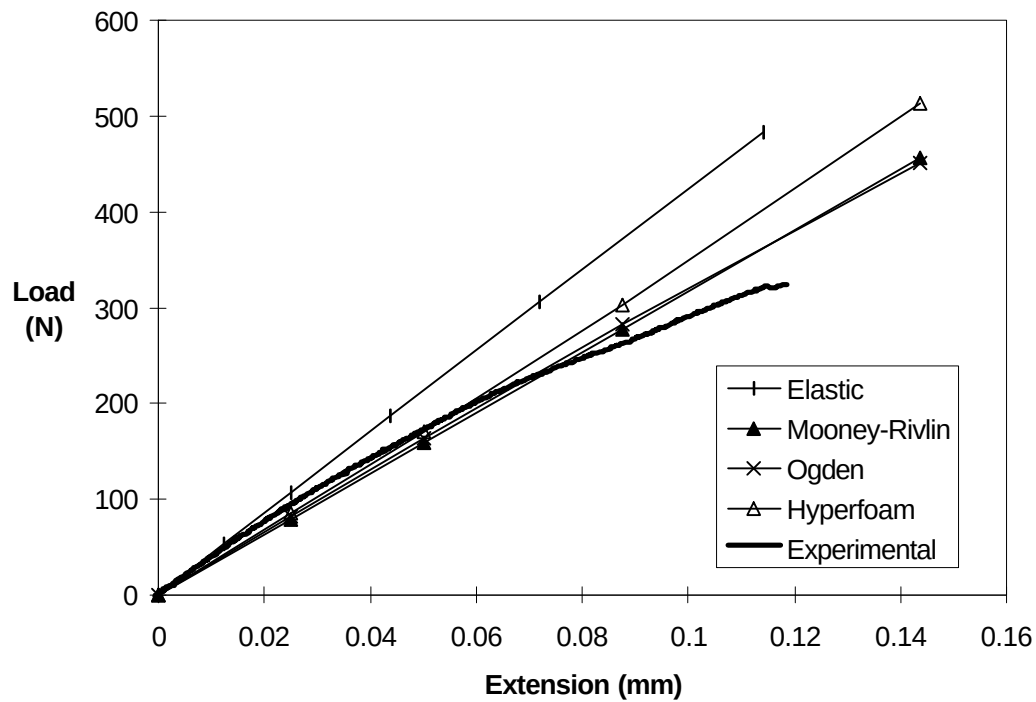


Figure 21. Comparison of DP609 FE predictions with experimental results at 60°C.

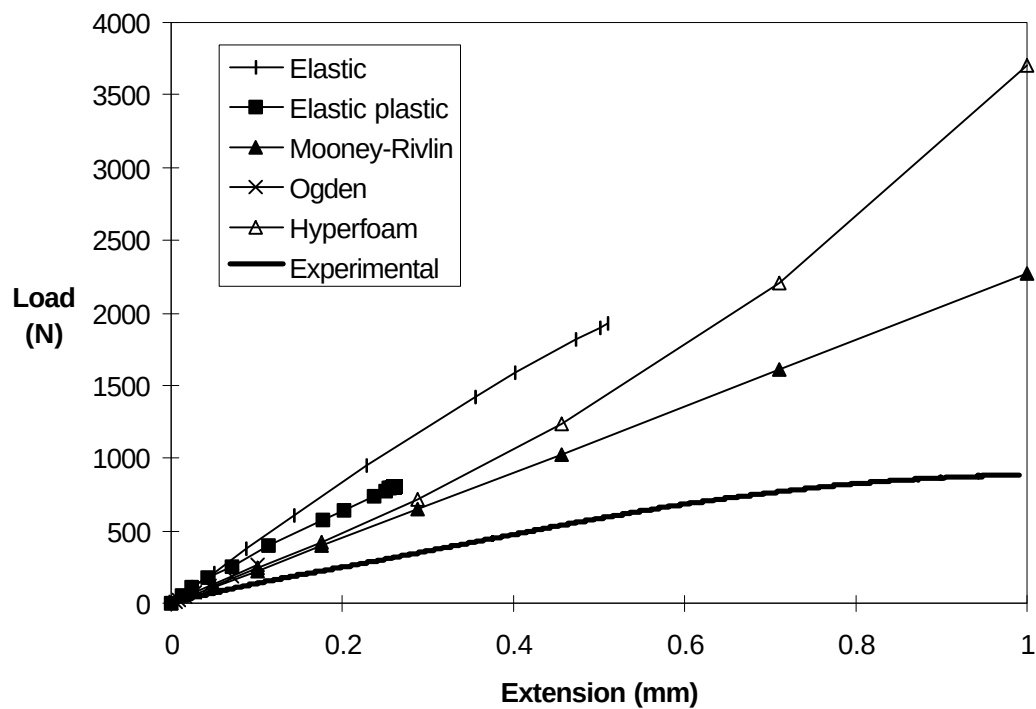


Figure 22. Comparison of M70 FE predictions with experimental results at -20°C.

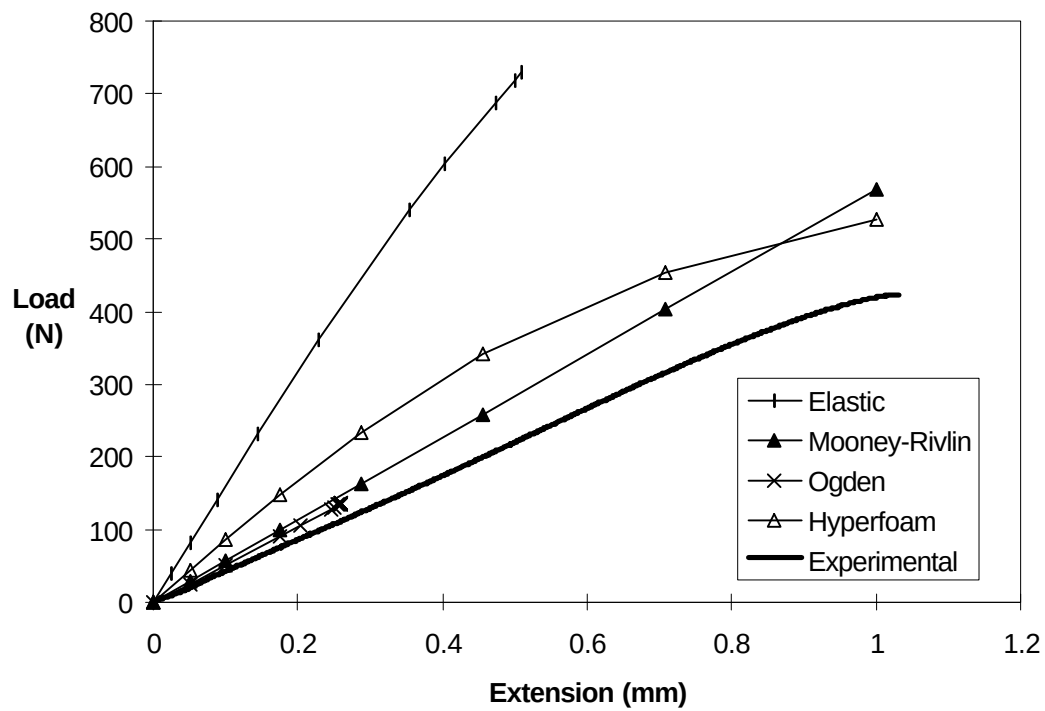


Figure 23. Comparison of M70 FE predictions with experimental results at 20°C.

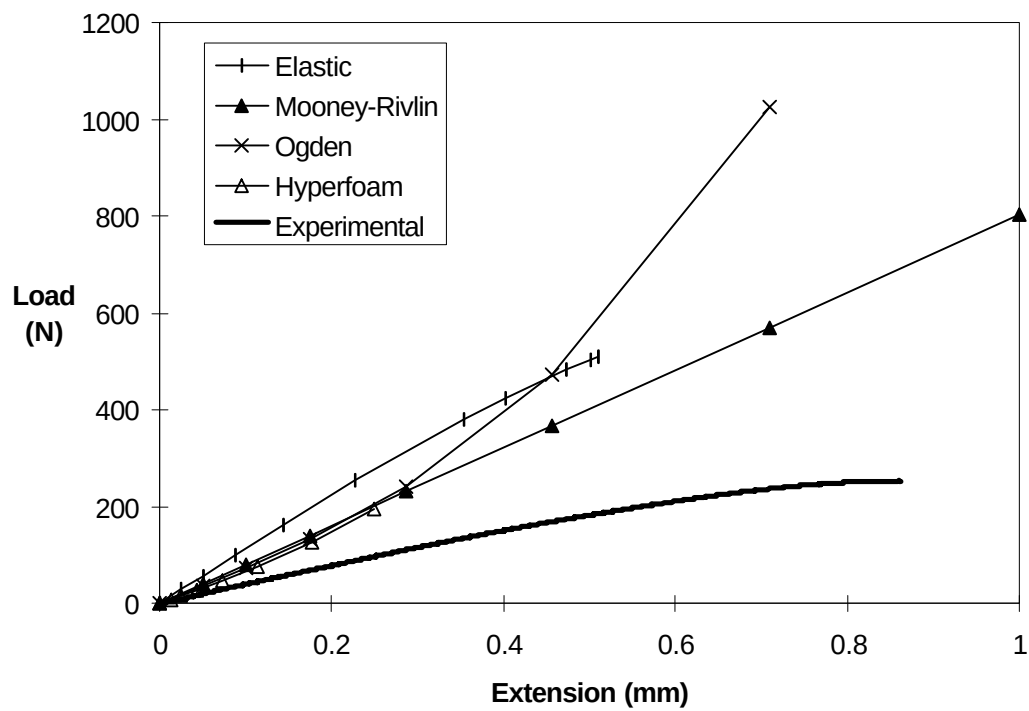


Figure 24. Comparison of M70 FE predictions with experimental results at 80°C.

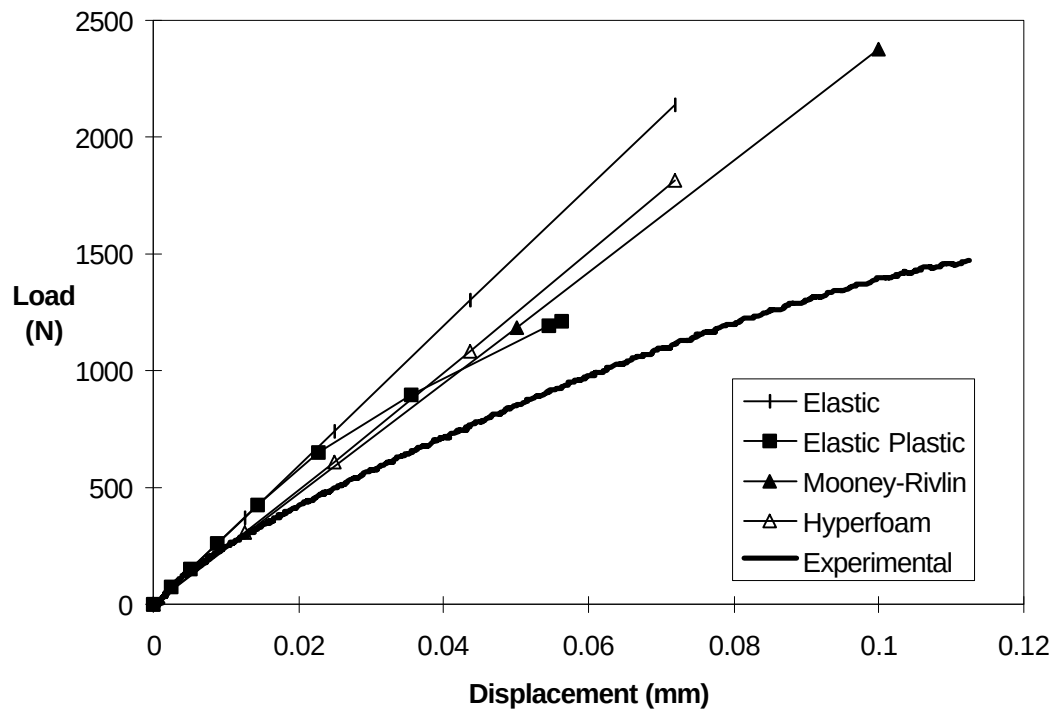


Figure 25. Comparison of PPGY5000 FE predictions with experimental results at 0°C.

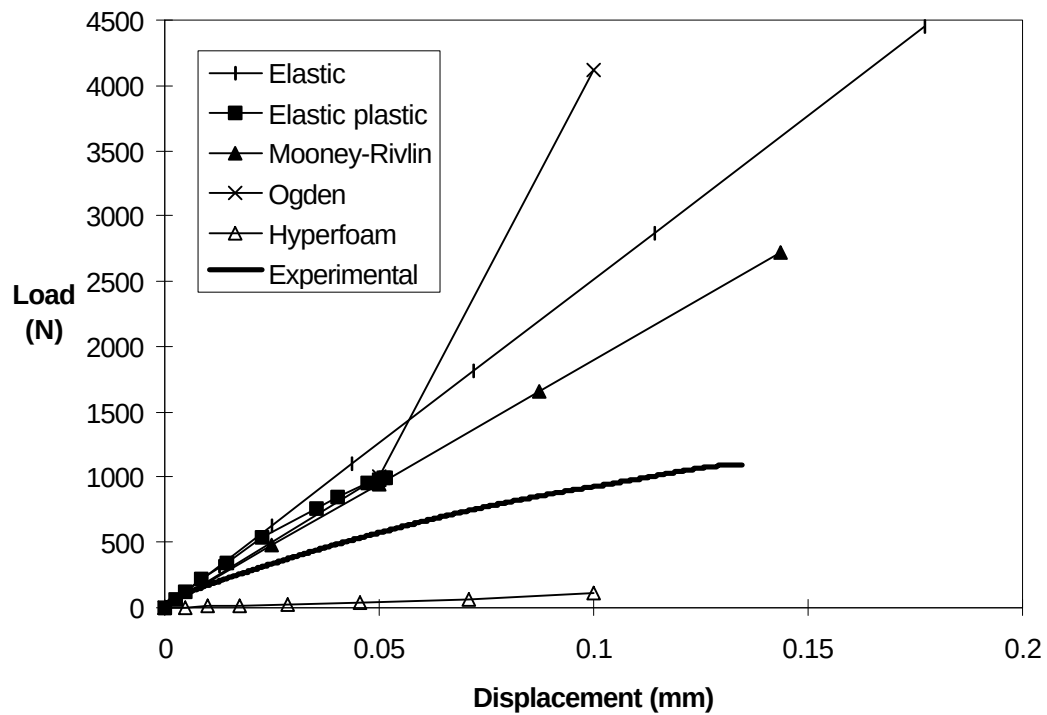


Figure 26. Comparison of PPGY5000 FE predictions with experimental results at 30°C.

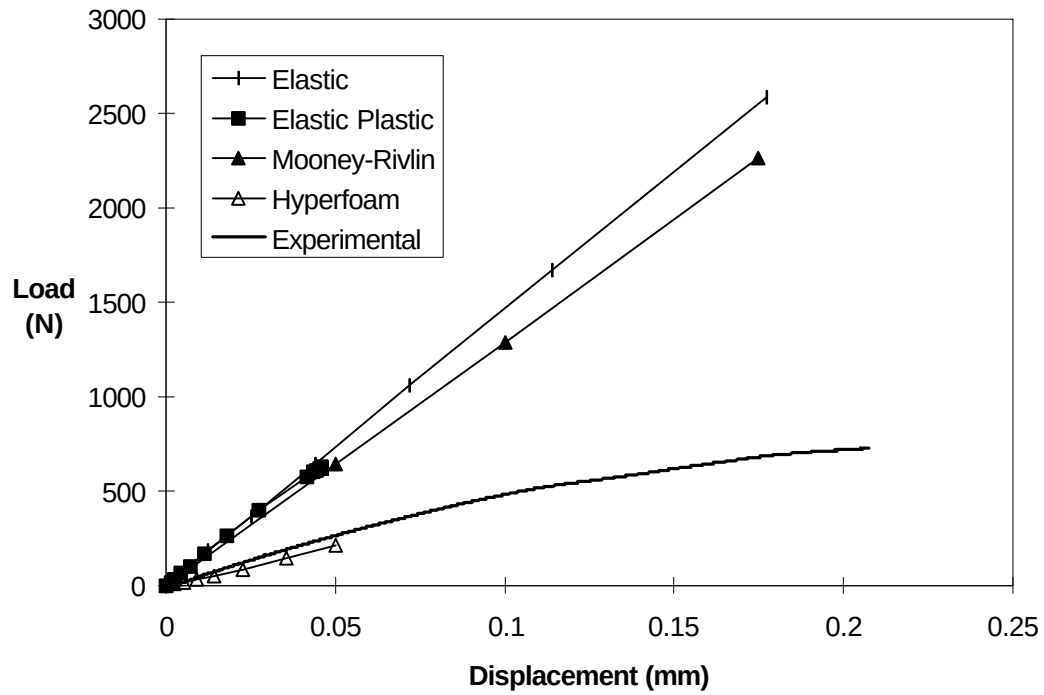


Figure 27. Comparison of PPGY5000 FE predictions with experimental results at 70°C.