

The Hyperelastic Properties of a Polyurethane Adhesive

by

Bruce Duncan

Project PAJex2 - Flexible Adhesives

PAJex2 Report No 4

May 2001

THE HYPERELASTIC PROPERTIES OF A POLYURETHANE ADHESIVE

Bruce Duncan

May 2001

**Performance of Adhesive Joints Programme
Project PAJex2 - Flexible Adhesives**

PAJex2 Report No 4

Summary

In the Performance of Adhesive Joints extension project 'Flexible Adhesives' (PAJex2) a selection of hyperelastic material models are under investigation to determine the suitability of these models for predicting the behaviour of a flexible adhesive in bonded structures. The initial adhesive selected for study appeared to be poorly characterised by the hyperelastic material models studied. It was agreed with the Industrial Advisory Group that an alternative adhesive should be studied in order to determine if this finding was applicable to other classes of flexible adhesives. Experimental and FE modelling results presented in this report indicate an improved agreement between the model predictions and test results for the polyurethane adhesive selected.

© Crown copyright 2001
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 NPL Materials Centre

CONTENTS

1.	INTRODUCTION	1
2.	EXPERIMENTAL METHODS AND RESULTS	1
2.1	UNIAXIAL TENSION TESTS	1
	2.1.1 Test Specimen	1
	2.1.2 Tensile Tests	1
2.2	ARCAN SHEAR TESTS	4
2.3	LAP JOINT TESTS	4
	2.3.1 Specimen Preparation	4
	2.3.2 Lap Joint Test Method	5
3.	FINITE ELEMENT ANALYSES	7
4.	COMPARISON OF FEA AND EXPERIMENTAL MEASUREMENTS	8
4.1	LAP JOINTS	8
4.2	ARCAN TESTS	8
5.	CONCLUDING REMARKS	9
6.	ACKNOWLEDGEMENTS	9
7.	REFERENCES	9
APPENDIX A Uniaxial Tension Data		11
APPENDIX B Lap Joint; Test and FEA Data		15

1. INTRODUCTION

In the Performance of Adhesive Joints extension project 'Flexible Adhesives' (PAJex2) hyperelastic material models are being investigated to determine whether they are suitable for predicting e.g. the behaviour of a flexible adhesive in bonded structures. The original flexible adhesive studied in the programme, an elastomeric adhesive, M70 supplied by Evode Ltd, could not be modelled accurately using either hyperelastic or elastic plastic models⁽¹⁾ probably due to the presence of fillers and additives. It was agreed with the Industrial Advisory Group that an alternative adhesive should be studied to ascertain the suitability of the models for other types of flexible adhesive. A 2-part polyurethane adhesive, DP609 supplied by 3M Ltd, was selected for study. This report describes the bulk and lap joint properties of this adhesive.

Earlier work in the project⁽¹⁾ suggested that the full suite of test data from uniaxial tension, planar tension, biaxial tension and volumetric compression specified for characterising hyperelastic behaviour in the ABAQUS manual⁽²⁾ did not necessarily give superior FEA predictions compared with test data obtained from uniaxial tension data only. Methods have been developed for obtaining volumetric properties from uniaxial tension tests⁽³⁾. Therefore, the decision was made to characterise the material properties of the adhesive using only data from uniaxial tension tests.

2. EXPERIMENTAL METHODS AND RESULTS

Test specimens were prepared using DP609 adhesive, which was supplied by 3M Ltd in 400 ml twin pack cartridges. Adhesive was dispensed through static mixing nozzles. The adhesive has a working life of ca. 8 minutes at room temperature and develops handling strength within a few hours although cure continues over longer periods of time and maximum strength is not achieved until days later.

2.1 UNIAXIAL TENSION TESTS

2.1.1 Test Specimen

The tensile test specimen used was the half-size dumb-bell shaped specimen specified in ISO 527-2⁽⁴⁾. The parallel gauge length of the specimen is 30 mm long by 5 mm wide. Shaped specimens were punched from bulk sheets. These were cast, between 0.5 mm and 1.5 mm thick, using specimen preparation techniques developed previously^(5, 6). The sheets were left to cure for 7 days after manufacture and then post-cured at 50 °C for 90 minutes. This was done to minimise any further curing during the period until the specimens were tested to ensure that cure states were similar.

In order to check the state of cure, glass transition temperatures (T_g) were measured using dynamic mechanical thermal analysis (DMTA). Values determined 1 day and 3 months after post-cure were consistent with peaks in the loss modulus (E'') around 17 ± 1 °C. Specimen width (w_0) and thickness (t_0) were measured prior to testing.

2.1.2 Tensile Tests

Tensile tests were performed using an Instron 4505 universal test machine fitted with a 5 kN load cell to measure force (F). All tests were performed with an initial grip separation of $65 \pm$

2 mm in order to minimise variations in strain rate. Testing was carried out at three displacement rates (1, 10 and 100 mm min⁻¹) at 20 ± 0.2 °C. Further tests at 10 and 100 mm min⁻¹ were performed at 0 ± 0.2 °C and 40 ± 0.2 °C.

Strains were determined using a Messphysik video extensometer capable of simultaneous measurement of axial extension (δ) and specimen width (t) to determine axial strain (ϵ_a) and lateral ($\epsilon_l = [t_0 - t]/t_0$) strain. To improve measurement accuracy the specimen gauge regions were painted white, using a thin layer of flexible correction fluid, to give better contrast and to minimise problems in the measurements caused by specimen whitening at large strains.

The measurement of axial and lateral strain enables calculation of true stress-true strain curves and volumetric strain-true stress curves. Assuming that lateral strains in the width and thickness directions are the same then these properties are defined:

$$\text{true stress } s_T = \frac{F}{wt} = \frac{F}{w_0(1-e_l)t_0(1-e_l)} = \frac{F}{w_0t_0(1-e_l)^2} = \frac{s}{(1-e_l)^2}$$

$$\text{true strain } e_T = \ln(1+e_a)$$

$$\text{volumetric strain} = \text{Current Volume/Original volume; } = V/V_0 = (1+\epsilon_a)(1-\epsilon_l)^2$$

where $V_0 = l_1 l_2 l_3$ and $V = l_1(1+\epsilon_a)l_2(1-\epsilon_l)l_3(1-\epsilon_l)$

Tensile test results are summarised in Figure 1 with the data measured shown in Figures A1-A7, Appendix A. Curves were averaged in order to determine input data sets for FEA. Failure properties are summarised in Table 1. The tensile properties were reasonably repeatable.

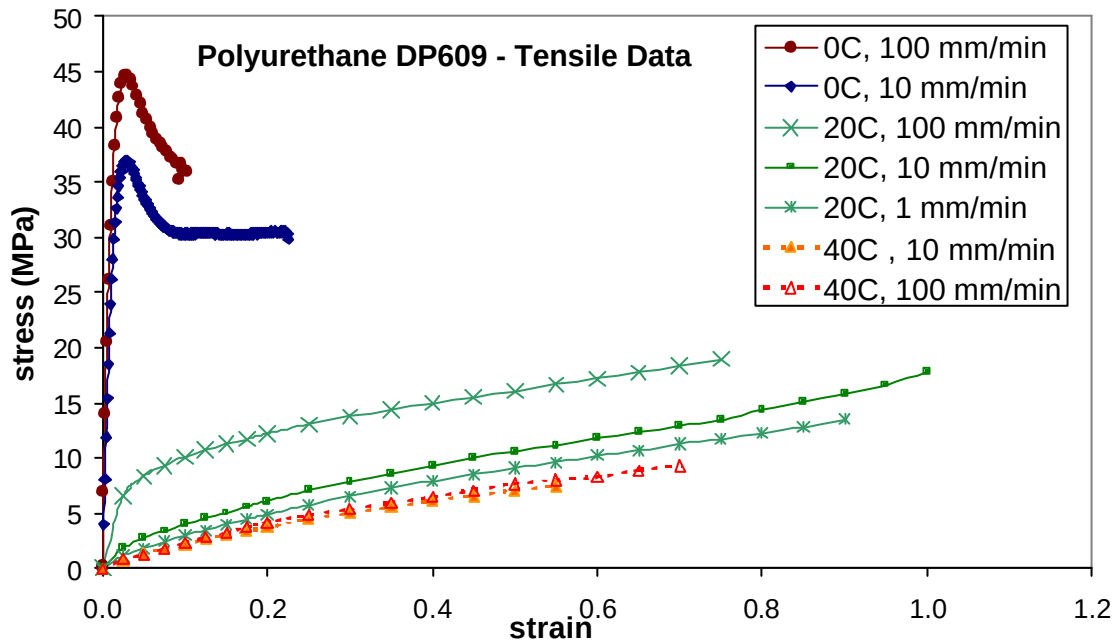


Figure 1: Tensile test data for polyurethane DP609 adhesive

The tensile data reflect the measured T_g value of 17 °C. At the higher temperatures, the adhesive is flexible and has a large strain to failure. At the lowest temperature 0 °C the adhesive is approaching a glassy state. The modulus has increased significantly whilst the

strain to failure has decreased. The peaks seen in the stress strain curves suggest plastic yield followed by softening. Near to the T_g , the properties of the adhesive are very sensitive to strain rate and, as shown in Figure 2, can exhibit glassy behaviour at very high strain rates. Therefore, at some combinations of lower temperatures and high strain rates, it is very unlikely that hyperelastic models will apply. In these situations, elastic-plastic models are probably more suitable. The plots of true stress-against true strain shown in Figure 2 are linear at quasi-static strain rates. This is also the case at higher temperatures.

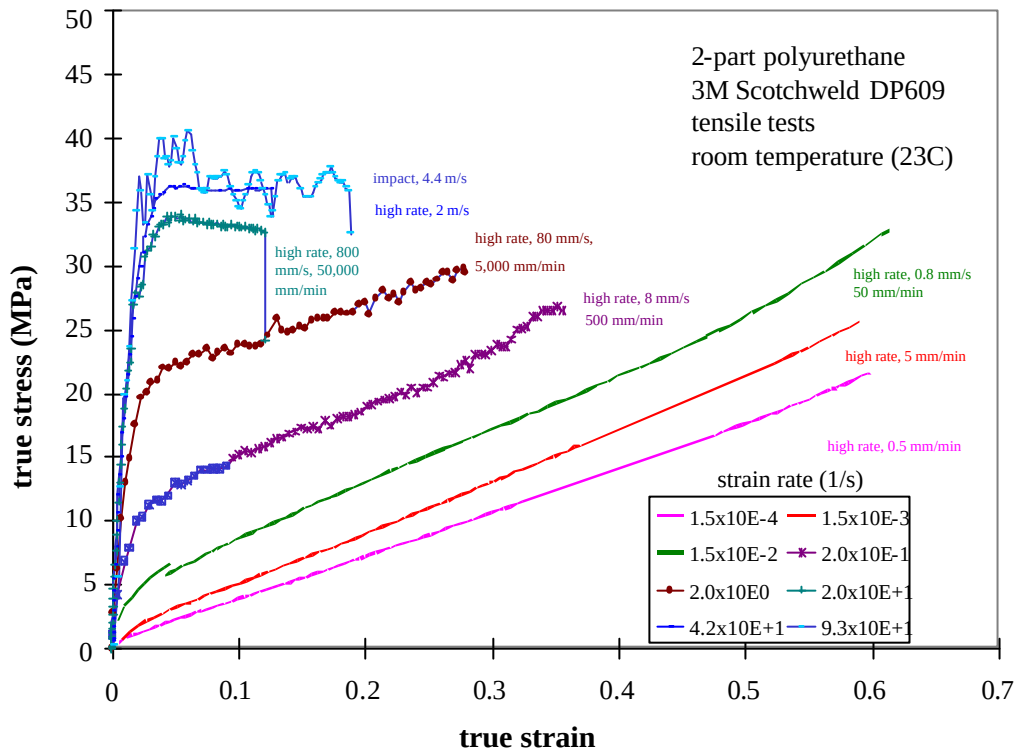


Figure 2: True stress-true strain curves for DP609 adhesive at different strain rates at room temperature

Temp °C	Speed mm min ⁻¹	Rate s ⁻¹	max stress (MPa)	max strain	lat strain	true stress (MPa)	true strain	volume ratio	E (MPa)	Poisson's Ratio
40	100	0.030	8.8	0.625	0.154	12.3	0.484	1.161	24.7	0.242
40	10	0.003	7.1	0.563	0.140	9.6	0.446	1.154	19.4	0.273
0	100	0.043	44.8	0.029	0.009	45.6	0.029	1.010	3107	0.288
0	10	0.003	38.2	0.027	0.009	38.8	0.026	1.009	2200	0.332
20	100	0.030	21.6	0.901	0.201	33.8	0.640	1.213	52	0.233
20	10	0.003	15.8	0.864	0.183	23.8	0.619	1.240	30	0.231
20	1	0.0003	13.7	0.904	0.190	21.0	0.644	1.248	30.6	0.239

Table 1: Summary of averaged uniaxial tension properties for polyurethane adhesive DP609. Values given for stress, strain and volume ratio are averaged at failure except for those at 0 °C which are averaged at the point of maximum load.

2.2 ARCAN SHEAR TESTS

One of the questions raised in the earlier investigation of the elastomeric adhesive was whether the hyperelastic adhesives give an accurate representation of the shear behaviour of materials. Different adhesive joint configurations were investigated with the predicted performances being markedly different to those measured. However, owing to the low stiffness of the elastomeric adhesive it was not possible to prepare testable bulk shear specimens with a thickness comparable to the tensile specimens. Therefore, there is also doubt as to whether bulk and joint materials have the same properties.

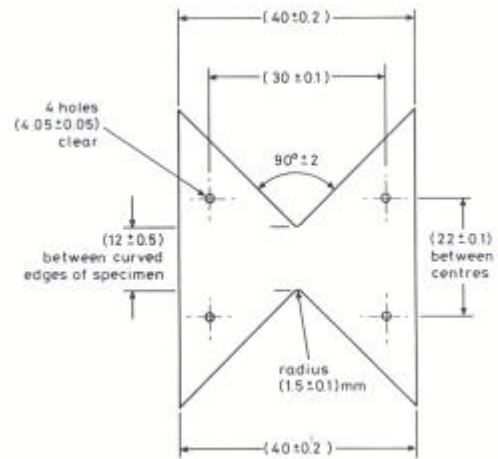


Figure 3: Arcan shear test specimen

The polyurethane adhesive has a higher elastic modulus than the elastomeric adhesive and, as the test specimens have sufficient rigidity, it is possible to measure the shear properties of the bulk adhesive using the Arcan shear test⁽⁷⁾. Arcan specimens were cut from the cast adhesive sheets. These were tested at the same temperatures and strain rates as some of the tensile specimens.

The large extensions achieved in the specimen before failure in tests at 20 °C or above meant that strain determinations made using shear extensometers developed for this test were unreliable at the latter parts of the test. A method was developed for determining strains in the specimen using video extensometry. The Messphysik video extensometer was run in dot matrix mode to determine the positions of contrasting dots placed on the surface of the specimen near the contact points of the shear extensometer. From the measured locations of these dots, it was possible to determine shear strains in the gauge region of the test specimen.

2.3 LAP JOINT TESTS

2.3.1 Specimen Preparation

Single lap joints were manufactured using 1.5 mm thick mild steel sheet that had been guillotined to make adherends 100 mm long by 25 mm wide. 25 mm square end tabs were also formed. (See Figures B6 and B7 in Appendix B).

The adherends were degreased using acetone then grit blasted using an aluminium oxide abrasive. They were then degreased again prior to being coated with a 2-part epoxy primer 3M 1945 B/A. This was mixed in equal volumes according to manufacturer's instructions and applied to the steel using a paintbrush to fully coat the areas being bonded. The coating was allowed to cure for a minimum of 16 hours before bonding. The primed surface was degreased prior to bonding.

Samples were bonded, in sets of 6 using a jig to control both alignment and overlap length, nominally 12.5 mm. End tabs were bonded to improve specimen alignment during testing. Attempts were made to set bondline thickness at either 0.25 mm using ballottini (glass beads) or 1 mm using copper wire. Most of the specimens were manufactured to a 0.25 mm bondline thickness, but those tested at 0 °C had 1 mm thick bondlines. A reasonable quantity of

adhesive was dispensed onto a non-stick surface and applied to adherends using a spatula. The viscosity of the mixed adhesive increased noticeably during the several minutes that it took to manufacture the specimens.

Overlap length was determined from the difference between the sum of the adherend lengths and the length of the bonded test piece. Bondline thickness was determined from the difference between the thickness of the bonded test piece and the sum of the adherend thickness. The measured thickness could differ significantly from the nominal thickness particularly for the specimens with a nominal 0.25 mm thick bondline. Excess adhesive fillets were cut from the ends and sides of the bondline using a sharp scalpel. This was done carefully as damage, e.g. nicks, at the end of the glue line could promote premature failure.

The lap joint specimens were allowed to cure overnight before they were released from the jig. Cure was allowed to continue for 7 days and then the specimens were post cured at 50 °C for 90 minutes.

2.3.2 Lap Joint Test Method

Lap joint specimens were tested using an Instron 4505 test machine fitted with a 5 kN load cell. Test temperatures were controlled to the same levels as the uniaxial tensile tests. The test speeds were set to give similar nominal strain rates to the tension tests. The test machine speed was set to give rates of extension across the bondline divided by the bondline thickness similar to the three nominal strain rates achieved in the uniaxial tension tests (1, 10 and 100 mm min⁻¹ are equivalent to 3×10^{-4} , 3×10^{-3} and 3×10^{-2} s⁻¹ respectively). Extensions were measured using knife-edged extensometers that straddled the bondline. The results are shown in Figures B1-B5 and summarised in Table B1, Appendix B.

There is a large degree of scatter between the specimens tested. The specific reasons for the scatter are not known but factors affecting the measured results could include:

- Uncertainties in the determined strain value due mostly it is believed to inaccuracies in the determined bond line thickness as:
 - The thickness of the primer layer is difficult to determine and the assumption that it is negligible may not be correct for thin bonds.
 - The practice of subtracting the adherend thickness from the total bond thickness in order to determine a small bond thickness will lead to large uncertainties in this value once the limiting accuracies of the measurements and devices are taken into consideration.
 - The initial slopes of the tests performed at 0 °C, where the bond thickness was larger, were much more reproducible. The uncertainties in the thickness determination at the larger bond thickness will be less significant.
- Variations between the tests occurred in actual strain rate in the adhesive layer. This happens as strain rate can only be determined after the specimen has failed. Initial, low extension tests to set the machine speed do not always seem to correlate well with the strain rates observed at higher strains. Additionally, the uncertainties in the bondline thickness discussed above will also impact on the accuracy of the strain rates.

- The mode of failure in the specimens seemed to vary.
 - Some specimens were characterised by adhesive failure with the adhesive layer coming cleanly from the adherend, this was generally associated with low extensions to failure;
 - Some specimens showed evidence of detachment of the primer from the metal adherends. There seemed to be two failure modes; one associated with high failure loads and extensions where primer detachment was patchy and the second at lower loads where primer seemed to peel off the adherends at the end of the bondline. This second type of primer failure was thought to be due to damage to the primer layer occurring when the fillets were removed.
 - Some specimens showed cohesive failure in the adhesive layer mixed with either adhesive or primer failure. This was linked to higher failure extensions.
 - Some specimens appeared to be deficient in adhesive in the centre of the bondline. These specimens exhibited low stiffness.
- The adhesive cures on mixing and, hence, the cure state and ‘spreading’ properties of the adhesive would be changing as a series of joints were made. This could affect the adhesive’s ability to fully wet the adherends. Statistical analysis of the effect of order in the batch might reveal if this was significant although the limited data may not give conclusive answers.
- Stress concentrations at the end of the bondline promote failure. These will be sensitive to the exact shape of the adhesive layer at the ends. The excess fillets were removed to leave a ‘square end’ but this could not be done precisely. Further to the likelihood of different shaped bond ends in the specimens is a possibility that the adhesive and/or primer layers could have been damaged in the fillet removal process, promoting premature failure.

The above discussion suggests that there may be methods for improving the consistency of these lap joint tests. Areas to be explored further include:

- Increasing bondline thickness to reduce uncertainties in thickness.
- Producing specimens with shaped fillets during manufacture to reduce sensitivity to the shape of the bondline end and remove the potential for damaging the end of the glue layer.

The failure of flexible adhesives will be reported in more detail in a further report planned for the Flexible Adhesives project⁽⁹⁾. This will cover the single lap joint and alternative adhesive joint geometries.

3. FINITE ELEMENT ANALYSES

FE analyses were run using the ABAQUS/STANDARD solver. Specimens were meshed using FEMGV. Previous work had suggested that higher order hyperelastic models were less suited to flexible adhesives. From a practical point, avoiding the more complex higher order models is preferred as the FE solutions converge more easily with lower order models. The first order polynomial or Mooney-Rivlin model was used for the initial analyses. The results of these are shown in Figures B1-B5, Appendix B. The deviatoric (C_{01} and C_{10}) and volumetric (D_1) coefficients were obtained (at each strain rate and temperature) by fitting to the measured tensile stress-strain and true stress-volumetric strain curves respectively.

Finite element meshes were created of the lap joint specimen using the geometry of the test specimen and adherends. The overlap length was 12.5 mm and meshes with bondline thickness values of 0.25 mm and 1 mm were created. The model was meshed with first-order plane strain (CPE4) elements. The element density was increased at the ends of the bondline where stress concentrations were expected. The influence of the primer layer on the joint extension was assumed to be negligible and, since no properties were available, the primer layer was not incorporated in the model results reported in this report. The models were created with no adhesive fillet or rounding of the adherend corners. Both these parameters affect the stress distribution at the end of the overlap. An investigation of the influence of these will be described in a further report. The mesh for the glue line is shown in Figure B6, Appendix B.

Two nodes, 25 mm apart on either side of the overlap at approximately the position where the extensometers contact the test specimen, were designated gauge nodes and used to determine the shear extension of the adhesive layer. Nodes opposite to these could be used to simulate a second extensometer. However, as predicted bending in the model is minimal, the differences in extensions determined from the two sides are insignificant. Nodes on the outside edges of the surfaces at the tabbed ends were constrained in order to simulate the effects of the test machine grips. One end was held stationary in both the 1- and 2-directions whilst the other end was constrained in the 2-direction and pulled in the 1-direction. The force was calculated at this end of the specimen. The FE model and constraints are shown in Figure B7, Appendix B.

An FE model was also created of the Arcan shear specimen (Figure 4). Gauge nodes were defined in the specimen on either side of the centre line in order to predict the movement of the gauge points on the test specimen.

4. COMPARISON OF FEA AND EXPERIMENTAL MEASUREMENTS

4.1 LAP JOINTS

Appendix B shows comparisons between the experimental force-extension curves measured at 5 different combinations of strain rate/temperature and FEA predictions. Uniaxial tension data measured at corresponding strain rates and temperatures were used as the input materials properties.

The 0 °C case was modelled using an elastic-plastic model to represent the adhesive layer. The results show some sensitivity in the predictions to the thickness of the adhesive layer. When the mesh for the 0.25 mm specimen was used the modelling significantly underpredicted the stiffness of the joint. However, when the specimen was meshed with a bond thickness of 1 mm (comparable with the specimen) the agreement is much better. The specimen behaviour at large strains is not predicted accurately. This is most likely due the initiation of failure in the corner stress concentration regions before the bulk of the adhesive layer yields.

At 20 °C and 40 °C, the adhesive was modelled using the Mooney-Rivlin hyperelastic model. The predicted curves, although more linear than the measurements, fall roughly in the average of the measured curves. One possible reason for the scatter in the slopes of the measured stress-strain plots at low strains is uncertainties in the determination of bond thickness when the thin (0.25 mm) bondlines were used. In contrast, the 1 mm thick specimens, where bond thickness could be determined more accurately, tested at 0 °C gave much more reproducible low strain curves.

The linearity of the predicted curves is probably related to the linear nature of the true stress-true strain curves determined in the tensile tests. The reasons why there is more curvature at higher strains in the experimental lap joint results are not definitely known. However, speculatively, the curvature may be due to the formation and slow growth of cracks before peak load is reached. Cracks have been observed to grow slowly in bulk specimen tests, such as the Arcan test, and similarly in T-peel tests on this material. This supports the theory that the curvature is caused by slow rupture of the adhesive. Additional tests to detect and photograph the formation and growth of cracks in DP609 joint specimens are planned in order to establish whether the adhesive begins to rupture before the maximum joint strength is reached.

4.2 ARCAN TESTS

Figure 4 shows the comparison between the FEA model of the Arcan shear tests and the experimental measurements. The agreement between the two is very good and suggests that it is possible to model the shear behaviour of the material from tensile data using hyperelastic models. Failure in the Arcan specimen is due to tensile stress concentrations near the notch roots. These stress concentrations are predicted in the FE model.

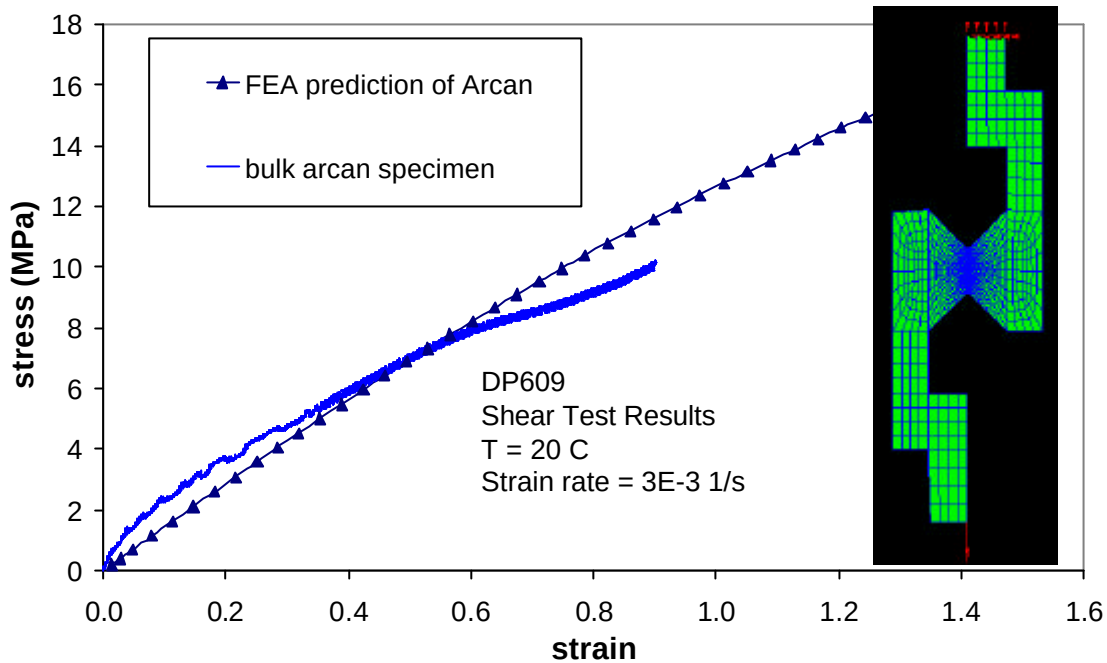


Figure 4: Comparison between measured and predicted behaviour in the Arcan shear test.

5. CONCLUDING REMARKS

The material properties of polyurethane adhesive, determined using uniaxial tension tests, have been used to obtain deviatoric and volumetric coefficients for hyperelastic material models. The resulting predictions of lap joint and Arcan shear behaviour show reasonably good agreement with experimental measurements. The agreement between predicted and measured joint performance appears to be superior to the corresponding findings for the elastomeric adhesive. FE predictions are still more linear than the measurements but this may be due to the onset of crack growth in the joint specimens before the maximum load is achieved in the tests. The scatter in the lap joint measurements prevents definitive conclusions from being drawn regarding the accuracy of the FE models. However, a number of possible causes of the scatter in the data have been identified and some changes to specimen geometries and preparation methods could improve the quality of the data. A further report is planned that will investigate, in more detail, the failure of joint specimens bonded using flexible adhesives.

6. ACKNOWLEDGEMENTS

This work was funded by the Department of Trade and Industry as part of the Performance of Adhesive Joints programme. Elena Arranz (NPL) is thanked for her assistance in carrying out the experimental work. The author is grateful to Greg Dean, Louise Crocker and Bill Broughton (NPL) for their advice. 3M (UK) Ltd are thanked for supplying materials.

7. REFERENCES

1. Duncan, B.C., Crocker, L.E. and Urquhart, J.M., 'Evaluation of Hyperelastic Finite Element Models for Flexible Adhesive Joints', NPL Report. CMMT(A)285, September 2000.

2. ABAQUS/Standard User and Theory Manuals, version 5.8, HKS Inc, USA, 1998.
3. Crocker, L.E. and Duncan, B.C., 'Measurement Methods for Obtaining Volumetric Coefficients for Hyperelastic Modelling of Flexible Adhesives', NPL Report. CMMT(A)286, January 2001.
4. ISO 527-2: 1993, Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics.
5. Dean G. D. and Duncan B.C., 'Preparation and Testing of Bulk Specimens of Adhesives', NPL Measurement Good Practice Guide No 17, July 1998.
6. Duncan, B.C., 'Test Methods for Determining Hyperelastic Properties of Flexible Adhesives', NPL Measurement Note No. CMMT(MN)054, October 1999.
7. Dean G. D. and Duncan B.C., 'Test Methods for Determining Shear Property Data for Adhesives Suitable for Design. Part 1: Notched-beam (Iosipescu) and notched-plate (Arcan) methods for bulk and joint test specimens', NPL Report CMMT(B)56, April 1996.
8. ISO 3167:1993, Plastics – Multi-purpose Test Specimens.
9. Duncan, B.C., Crocker, L.E., Mera, R. Urquhart, J.M and Broughton, W.R., 'Investigation of Failure Criteria for Flexible Adhesives', NPL Report in preparation, 2001.

APPENDIX A – Uniaxial Tension Data

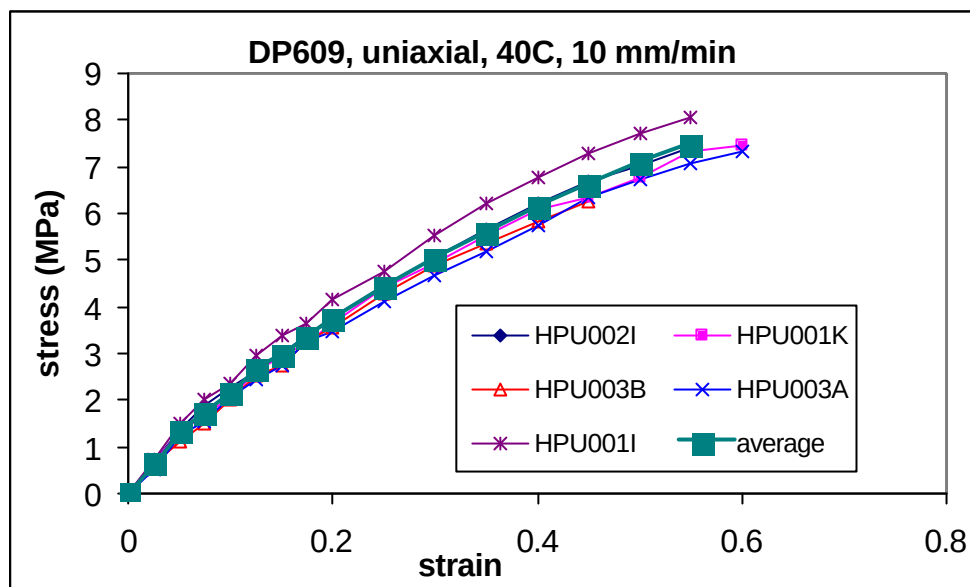


Figure A1: Uniaxial tension data at 40 °C and 10 mm min⁻¹ (rate = 3×10^{-3} s⁻¹)

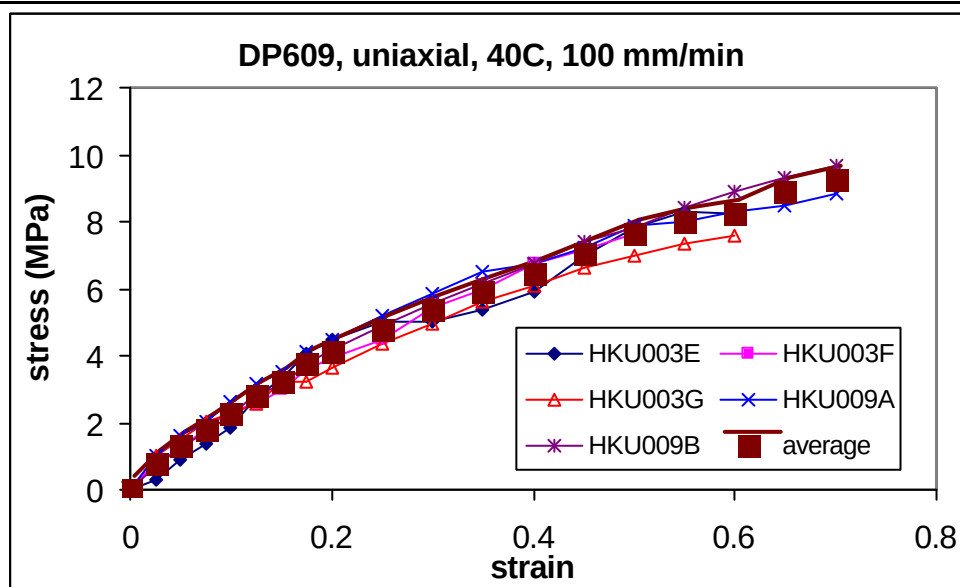


Figure A2: Uniaxial tension data at 40 °C and 100 mm min⁻¹ (rate = 3×10^{-2} s⁻¹)

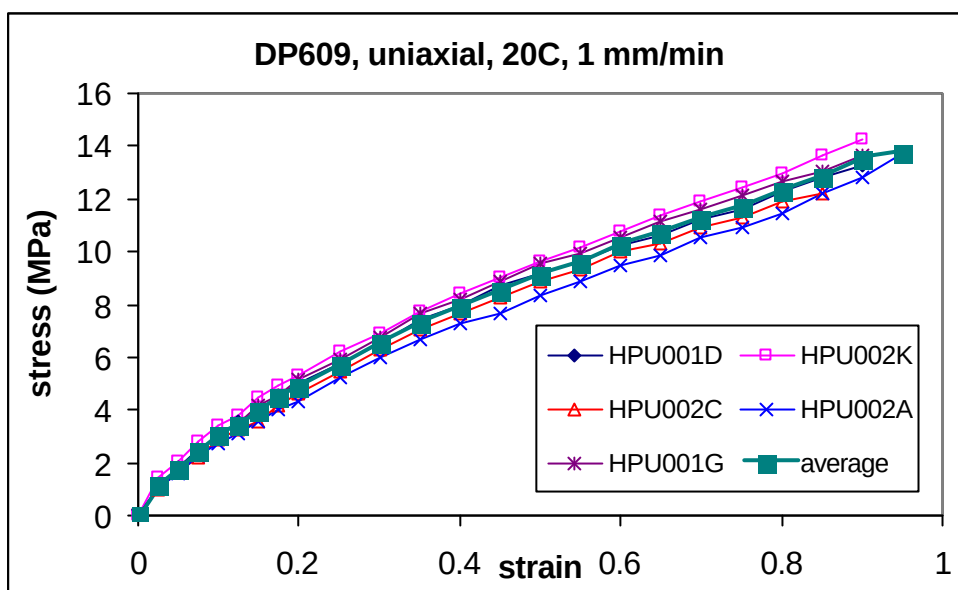


Figure A3: Uniaxial tension data at 20 °C and 1 mm min⁻¹ (rate = 3×10^{-4} s⁻¹)

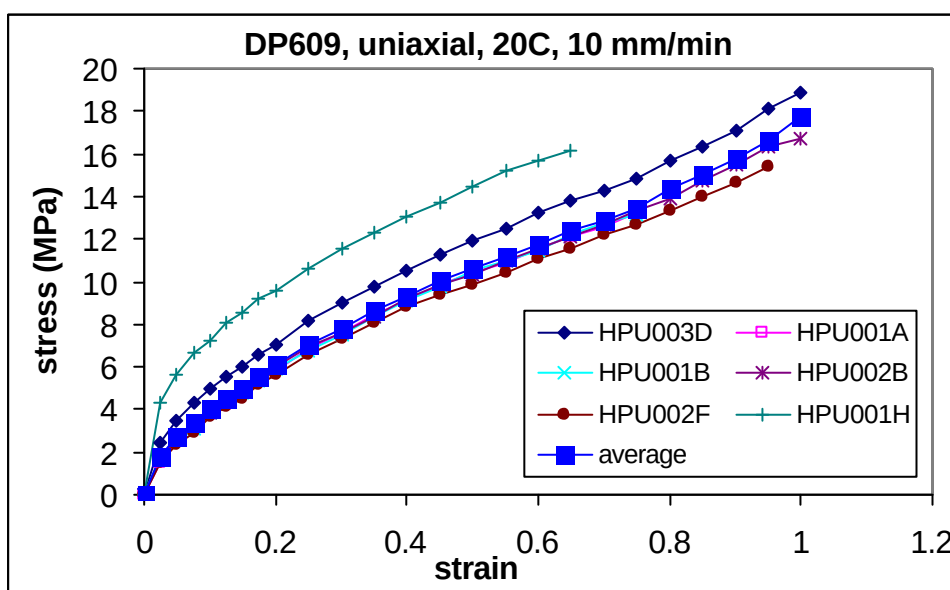


Figure A4: Uniaxial tension data at 20 °C and 10 mm min⁻¹ (rate = 3×10^{-3} s⁻¹)

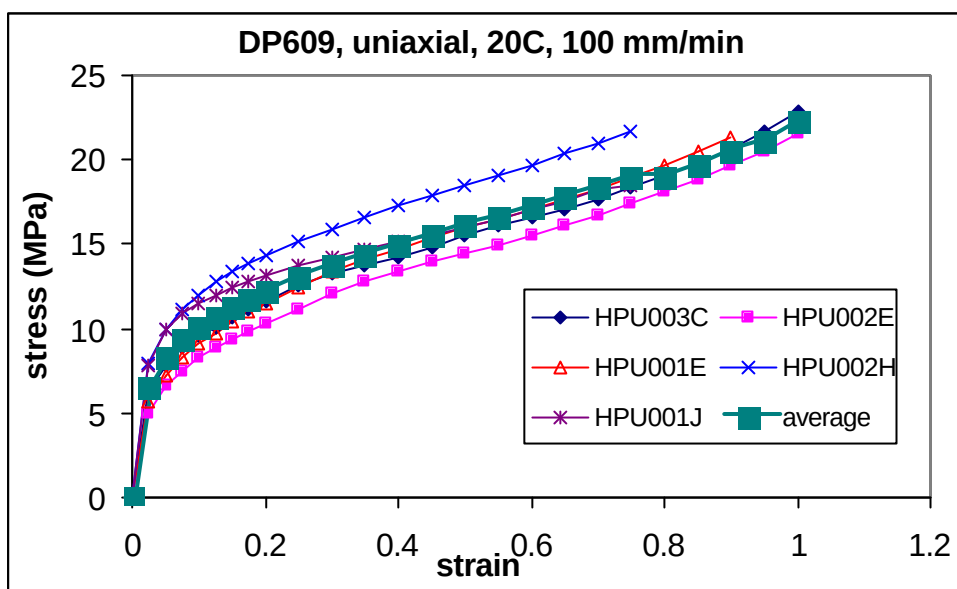


Figure A5: Uniaxial tension data at 20 °C and 100 mm min⁻¹ (rate = 3×10^{-2} s⁻¹)

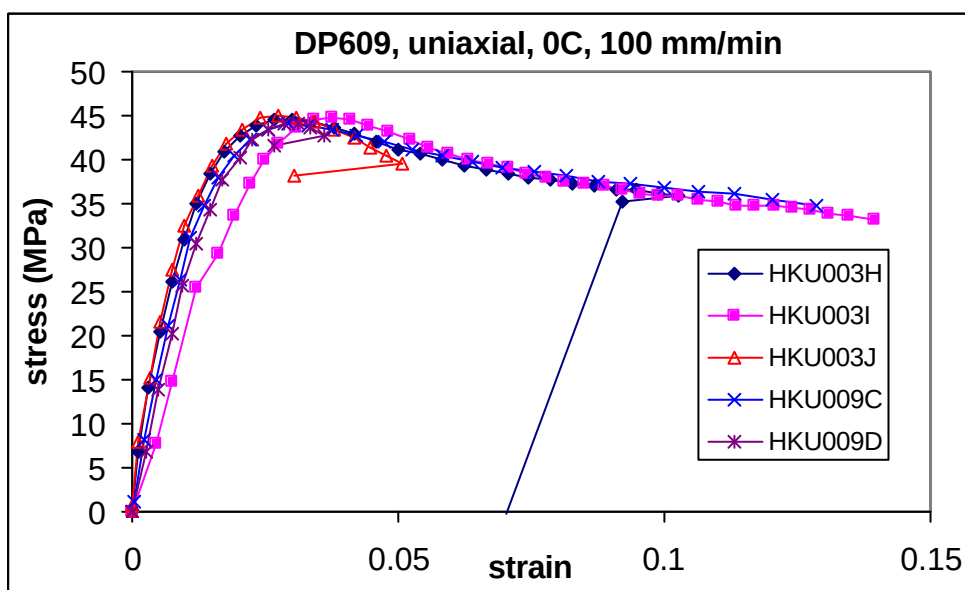
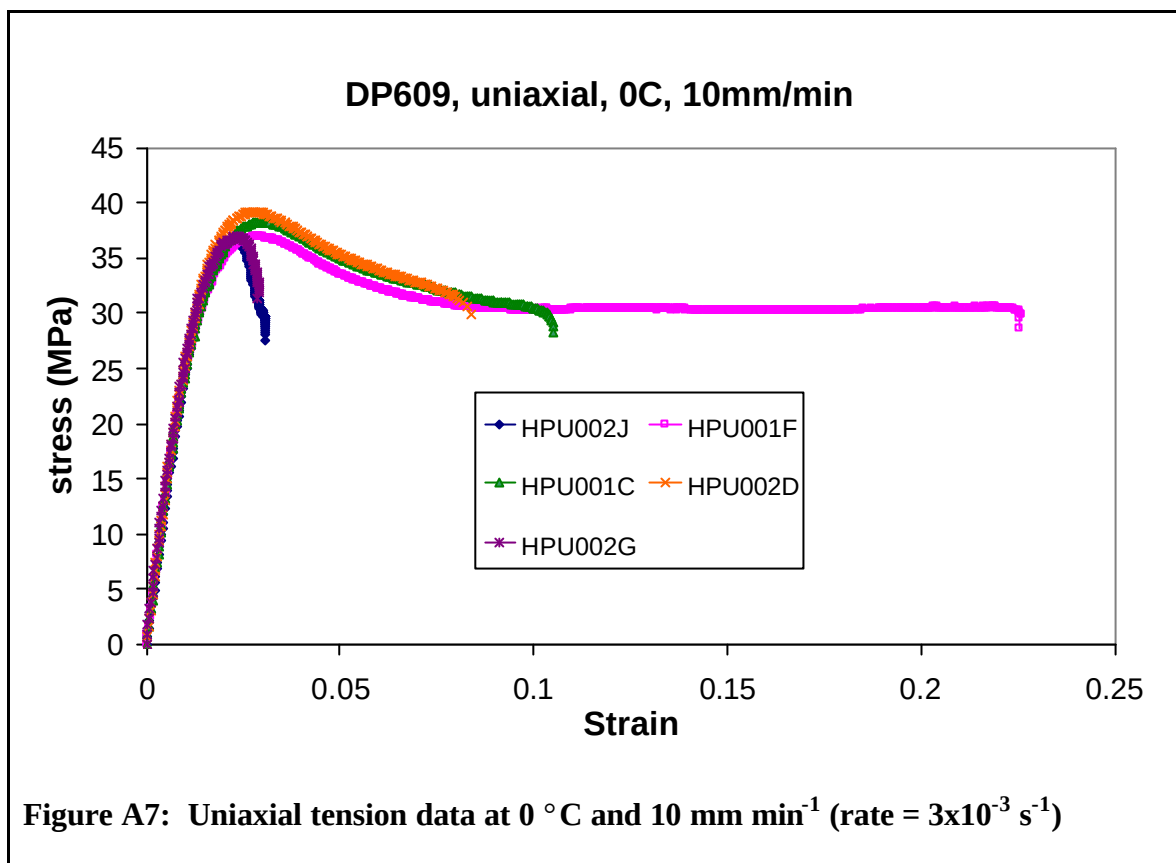


Figure A6: Uniaxial tension data at 0 °C and 100 mm min⁻¹ (rate = 3×10^{-2} s⁻¹)



APPENDIX B – Lap Joint; Test and FEA Data

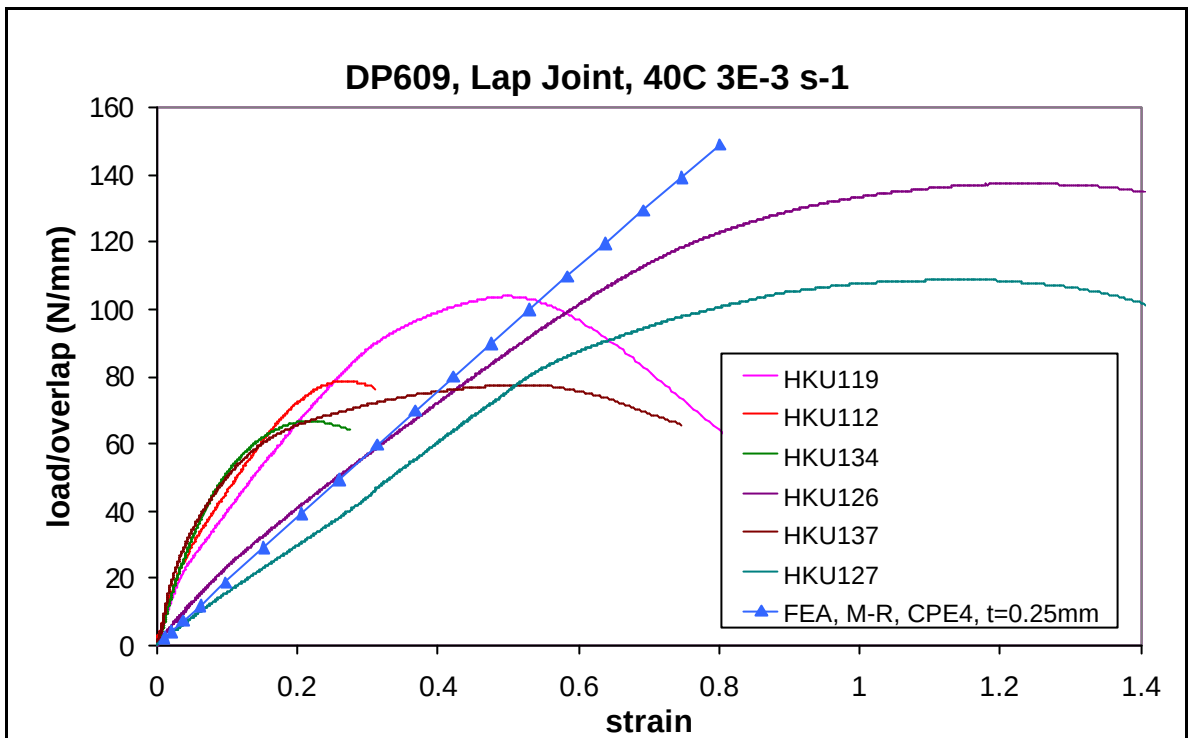


Figure B1: Comparison of Lap Joint test and FEA prediction curves at 40 °C and strain rate = $3 \times 10^{-3} \text{ s}^{-1}$

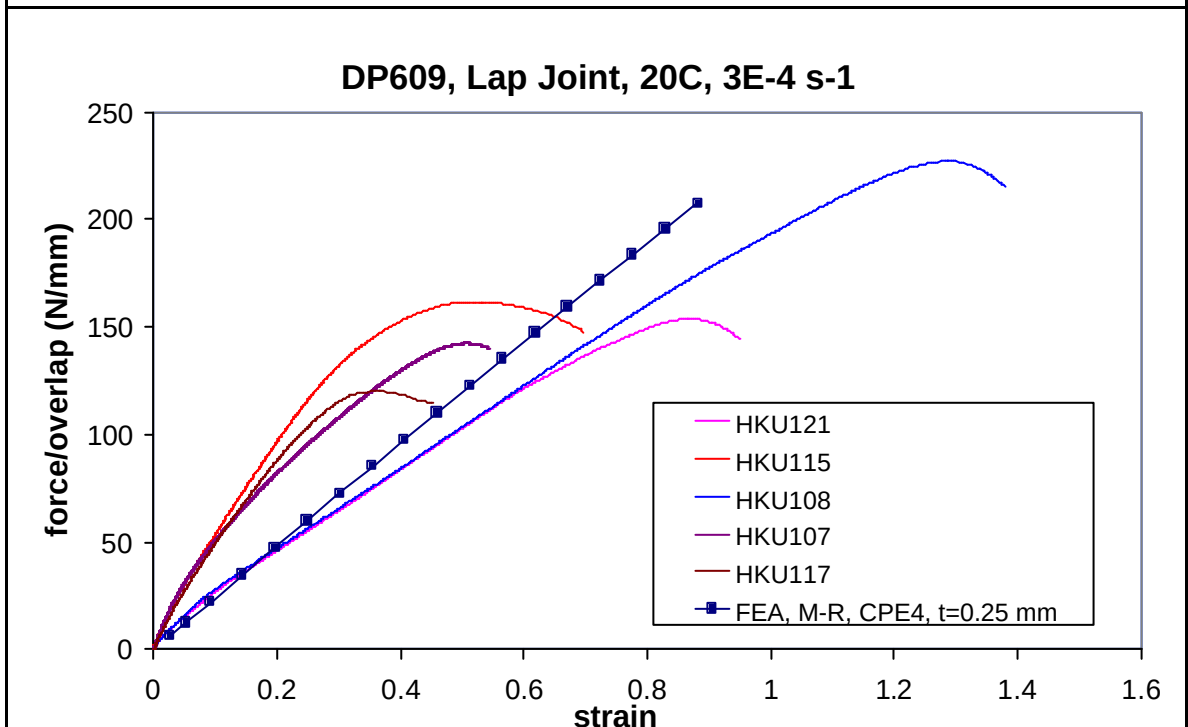


Figure B2: Comparison of Lap Joint test and FEA prediction curves at 20 °C and strain rate = $3 \times 10^{-4} \text{ s}^{-1}$

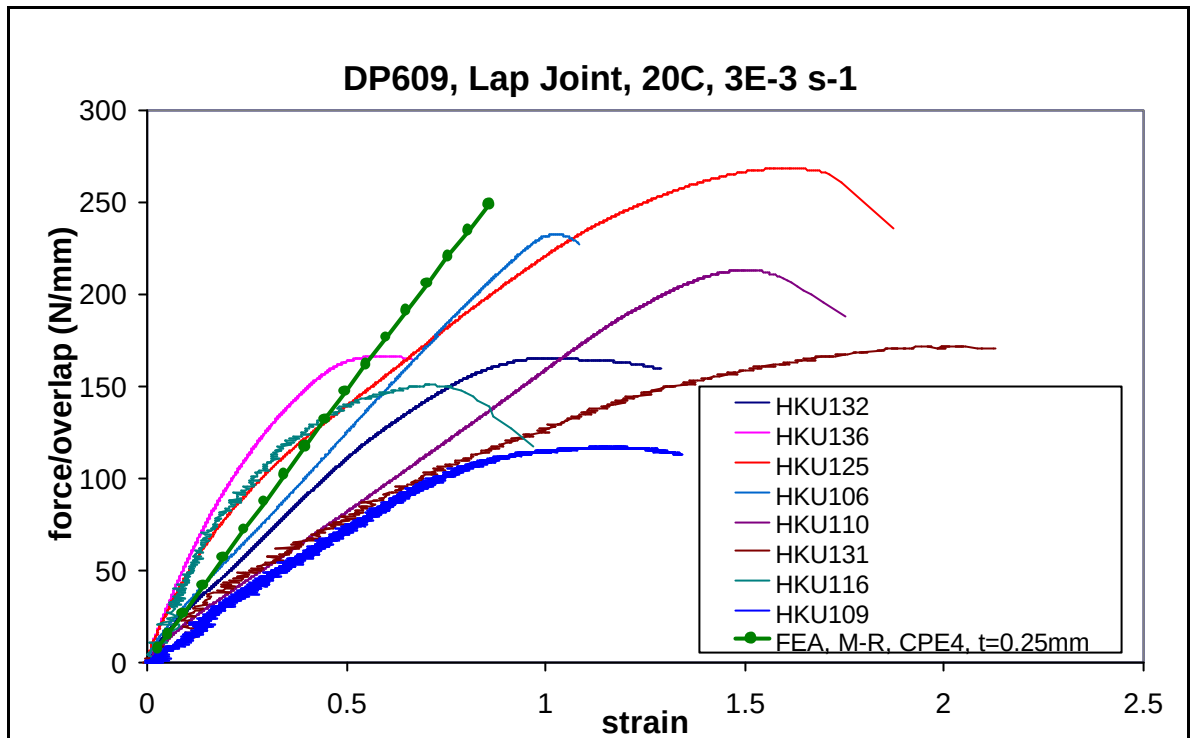


Figure B3: Comparison of Lap Joint test and FEA prediction curves at 20 °C and strain rate = $3 \times 10^{-3} \text{ s}^{-1}$

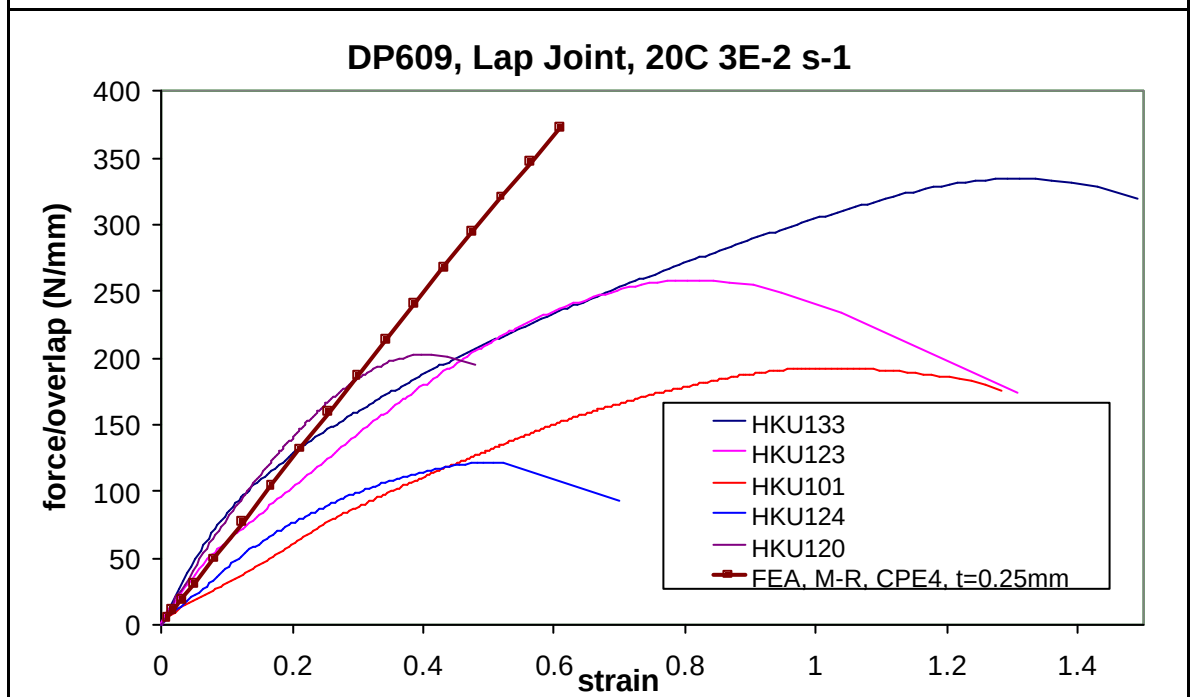


Figure B4: Comparison of Lap Joint test and FEA prediction curves at 20 °C and strain rate = $3 \times 10^{-2} \text{ s}^{-1}$

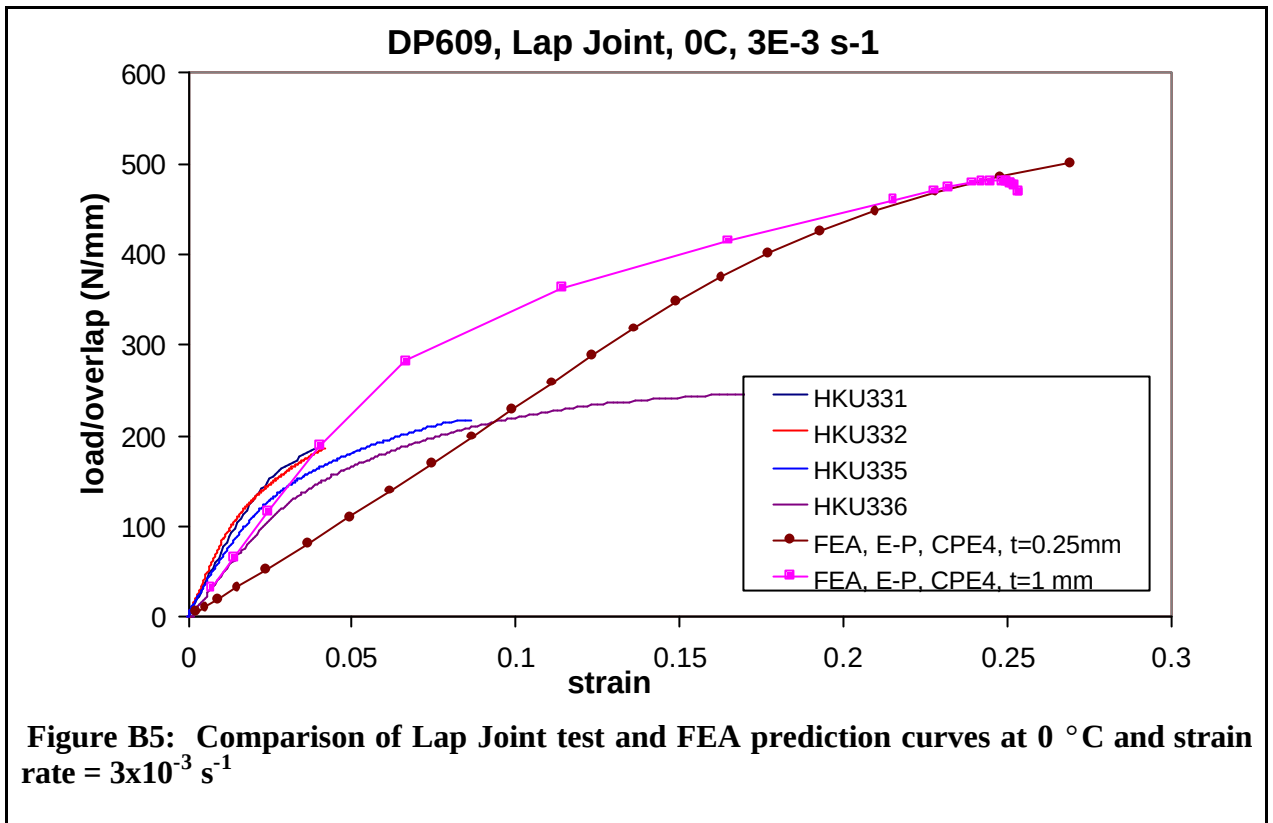


Figure B6: Detail of mesh representing the adhesive glue line



Figure B7: Detail of FE model and boundary conditions

Temp °C	Rate s^{-1}	Force Max (N)	Ext (mm)	Bond thickness (mm)	Overlap (mm)	strain	Force/overlap (N/mm)
40	4.2E-03	1227	0.118	0.21	12.9	0.649	95.5
20	3.2E-04	2051	0.157	0.22	12.8	0.708	160.9
20	3.3E-03	2430	0.240	0.22	13.1	1.180	185.9
20	2.4E-02	2867	0.175	0.21	12.8	0.806	222.0
0	3.0E-03	2962	0.089	1.04	14.3	0.085	209.1

Table B1: Summary of lap joint test results