

**Project PAJ3 - Combined Cyclic Loading
and Hostile Environments 1996-1999**

Report No 6

**Environmental Degradation of Adhesive Joints
Single-Lap Joint Geometry**

W R Broughton, R D Mera and G Hinopoulos

August 1999

Environmental Degradation of Adhesive Joints Single-Lap Joint Geometry

**W R Broughton, R D Mera and G Hinopoulos
Centre for Materials Measurement & Technology
National Physical Laboratory
Teddington
Middlesex TW11 0LW, UK**

ABSTRACT

The single-lap shear test is the most widely used method for producing in-situ shear strength data on adhesively bonded joints. The simplicity and low costs associated with specimen manufacture, testing and data analysis has contributed to the widespread use of this method for assessing environmental and fatigue resistance. This report evaluates this method in terms of fitness for purpose in assessing environmental performance and provides a guide to specimen geometry, manufacture and testing. The report also includes an evaluation of the perforated single-lap joint, which is assumed to promote accelerated ageing by shortening the diffusion path of moisture. The results of a comprehensive study will show that for a moisture sensitive adhesive system, the introduction of holes has no major effect and that temperature and exposure time have a far greater influence on strength retention. A number of tools have been employed in data interpretation. These include finite element analysis, statistical techniques, analytical modelling, fractographic analysis, dynamic mechanical thermal analysis and mechanical testing.

© 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 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

1	INTRODUCTION.....	1
2	SINGLE-LAP TEST	2
2.1	SPECIMEN GEOMETRY, PREPARATION AND TESTING.....	2
2.2	DATA ANALYSIS.....	3
2.3	EVALUATION OF SINGLE-LAP TEST GEOMETRY	4
3	ACCELERATED TESTING.....	8
3.1	EXPERIMENTAL PROGRAMME	8
3.2	TEST RESULTS.....	9
3.3	DYNAMIC MECHANICAL THERMAL ANALYSIS (DMTA).....	13
3.4	DISCUSSION.....	13
4	ELEVATED TEMPERATURE TESTS.....	15
5	CONCLUDING REMARKS	16
	ACKNOWLEDGEMENTS.....	16
	REFERENCES	17
	APPENDIX 1 - BONDING FIXTURE.....	18
	APPENDIX 2 - FEA OF SINGLE-LAP JOINT - INFLUENCE OF ADHERENDS.....	20
	APPENDIX 3 FEA OF SINGLE-LAP JOINT _ INFLUENCE OF MOISTURE.....	24

1. INTRODUCTION

Adhesive joints are expected to retain a significant proportion of their load bearing capacity for the entire duration of the service life of the bonded structure. Service conditions can often involve exposure to combinations of static or fatigue load and hostile environments (i.e. marine, hot/wet, weathering or chemical). It is therefore essential that the end user and adhesive manufacturer possess the necessary tools for selecting and characterising an adhesive system, to ensure reliable bond performance under hostile operating conditions which can often be experienced for periods of 25 to 50 years. Optimising joint performance requires an understanding of the failure mechanisms involved in environmental degradation, and validated test methods and design methodologies suitable for predicting material degradation and life expectancy.

Despite all the obvious weaknesses, the single-lap shear test is the most widely used method for producing in-situ shear strength data on adhesively bonded joints. The simplicity and low costs associated with specimen manufacture, testing and data analysis has contributed to the widespread use of this method for assessing environmental and fatigue resistance. This report evaluates the single-lap shear test in terms of fitness for purpose in assessing environmental performance and provides guidance on specimen geometry, manufacture, testing and finite element analysis. **Throughout this report, statements of particular importance or relevance are highlighted in bold type.**

The report also includes an evaluation of the perforated single-lap joint, which is assumed to promote accelerated ageing by shortening the diffusion path of moisture. The results of a comprehensive study will show that for a moisture sensitive adhesive system, the introduction of holes has no major effect and that temperature and exposure time have a far greater influence on strength retention. An integrated approach was used to assess joint performance, combining finite element analysis (FEA), statistical methods, thermal analysis (i.e. differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA)) and fractographic analysis. Mechanical tests were carried out on unconditioned (i.e. dry) and moisture conditioned adhesive joints and bulk resin specimens.

The research discussed in this report forms part of the Engineering Industries Directorate of the United Kingdom Department of Trade and Industry project on “Performance of Adhesive Joints - Combined Cyclic Loading and Hostile Environments”, which aims to develop and validate test methods and environmental conditioning procedures that can be used to measure parameters required for long-term performance predictions. This project is one of three technical projects forming the programme on “Performance of Adhesive Joints - A Programme in Support of Test Methods”.

2 SINGLE-LAP TEST

This section discusses the basic test geometry used for generating tensile shear data and provides a number of recommendations based on experimental results and numerical analysis.

2.1 SPECIMEN GEOMETRY, PREPARATION AND TESTING

The single-lap test (Figure 1) essentially consists of two rectangular sections, typically 25 mm wide, 100 mm long and 1.5 to 2.0 mm thick, bonded together, with an overlap length ranging from 12.5 to 25 mm [1]. Variations of this test method are included in both national and international standards [2-4]. **End tabs, cut from the same material as the adherend sections, are adhesively bonded to the specimen.** The end tabs are typically 37.5 mm in length. The end tabs have been introduced to reduce (not eliminate) the eccentricity of the load path that causes out-of-plane bending moments, resulting in high peel stresses and non-uniform shear stresses in the adhesive layer. BS EN 1465 [2] does not specify the use of end tabs, but specifies that the long axis of the specimen coincides with the direction of the applied force through the **centre line** of the grip assembly.

The single-lap specimen is easy to prepare and test. **A bonding fixture is recommended to ensure correct overlap and accurate alignment of the adherend. Special care is needed to ensure that bond line thickness is uniform.** Appendix 1 shows technical drawings of the fixture used at NPL to produce single-lap joints from 1.5 to 2 mm thick adherends with an overlap length of 12.5 mm. The fixture, which allows for up to six individual specimens to be bonded at a time, has no facility to control the adhesive fillet. Alternatively, large test panels (typically 180 mm wide) capable of providing 6 specimens can be made and then cut into specimens. Adherend surfaces should be prepared according to ISO 4588 [5] for metals and ISO 2818 [6] for polymer matrix composites (PMCs). Checks should always be made to ensure that there is no mechanical damage due to machining or handling (i.e. adherend bending). Testing is conducted using standard tension/compression mechanical test equipment with a suitable pair of self-aligning (either manually operated or servo-hydraulic wedge-action) to hold the specimen.

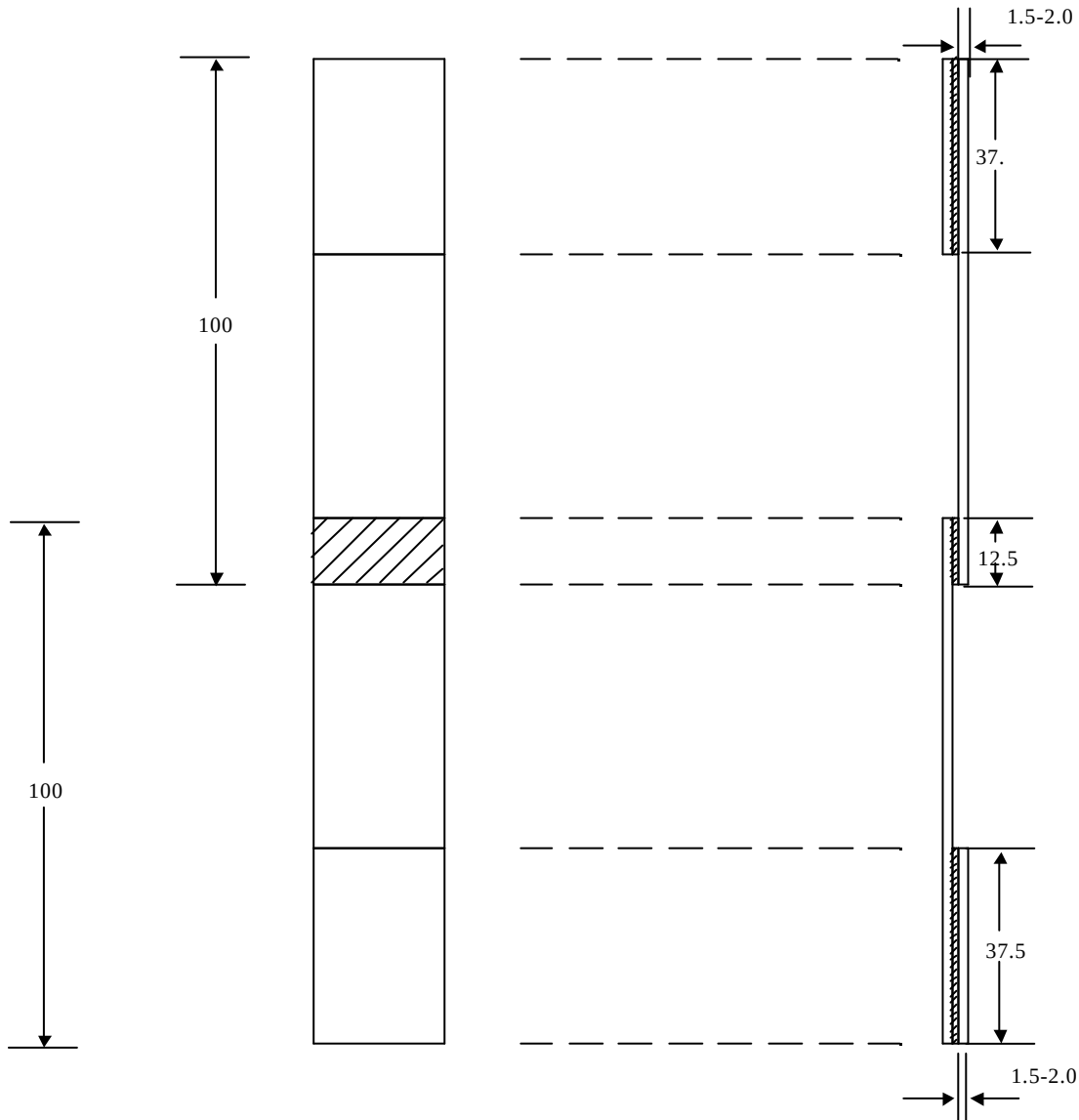


Figure 1 Schematic of single-lap joint (dimensions in mm).

2.2 DATA ANALYSIS

The lap-shear strength t is given by:

$$\tau = \frac{P}{bL} \quad (1)$$

where $\mathbf{P}$ is the maximum load, $\mathbf{b}$ is the joint width and $\mathbf{L}$ is the joint overlap length. The analysis assumes the adherends are rigid, and that the adhesive only deforms in shear. In fact, the resultant stress distribution, across and along the bond length is very complex (see Appendix 2) and is dependent on adhesive and adherend properties, and joint geometry.

Efforts to reduce stress concentrations formed at the bondline ends may include the use of tapered or bevelled external scarf and radius fillets at the bondline ends (**NB. The use of absolutely rigid adherends will not prevent the formation of stress concentrations at the bondline** (see Appendix 2)). Significant increases in the “apparent” shear strength of single-lap joint, compared with square-ended bondlines, can be achieved through the

formation of a fillet or spew at the overlap ends. Further increases in strength may be achieved by rounding the ends of the adherends. The spew also acts as a barrier to water and chemical ingress from the surrounding environment. A number of points are worth noting:

- Controlling fillet or spew geometry is not always possible; as a number of adhesives undergo minimal flow during cure.
- The use of tapered or bevelled external scarf and radius fillets at the bondline ends will reduce the effects of peel stresses induced by eccentricity in the loading path.. These additions will add to the costs of specimen manufacture.
- **The average shear strength does not correspond to a unique material property of the adhesive, and therefore cannot be used as a design parameter.**

It is recommended that “apparent” shear strength is given in terms of load per unit width (N/mm) rather than by load per unit area (see Equation 1).

The experimental results presented in Table 1 (see Section 2.3) show that the load per unit width does not double by increasing the overlap length by a factor of 2. In fact, the results show that a law of diminishing returns applies (i.e. load bearing efficiency of the joint decreases with increasing overlap).

2.3 EVALUATION OF SINGLE-LAP TEST GEOMETRY

A series of tensile test were conducted on a range of metallic and PMC materials bonded with Araldite® 2007 (also known as AV119), a single-part epoxy paste supplied by Ciba Speciality Chemicals. The tests were carried out on both standard and non-standard geometries (see Table 1) under standard laboratory conditions (23°C/50% relative humidity) to BS EN 1465 [2] specifications.

Standard specimens consisted of two rectangular sections, 25 mm wide, 100 mm long and 1.4 mm thick, bonded together, with an overlap length of 12.5 mm. Prior to bonding, the adherends were degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina. The surfaces to be bonded were then degreased again with 1,1,1-trichloroethane. The bondline thickness (0.25 mm) was controlled using 250 µm ballontini glass spheres. A small quantity of the glass spheres, 1% by weight, was mixed into the adhesive. Specimens were clamped in a special bonding jig (see Appendix 1) and then heated to 140°C for 75 minutes to cure the adhesive.

Table 1 Failure Load Per Unit Width for AV119 Epoxy Adhesive Joints

Adherend Thickness/Overlap Length	Load/Width (N/mm)
CR1 Mild Rolled Steel 1.4 mm thick / 12.5 mm overlap	334 ± 11
<u>2.5 mm thick</u> • 12.5 mm overlap	354 ± 10
• 25.0 mm overlap	428 ± 38
• 50.0 mm overlap	633 ± 63
5251 Aluminium Alloy 1.6 mm thick / 12.5 mm overlap	191 ± 14
3.0 mm thick / 12.5 mm overlap	325 ± 28
6Al-4V-Titanium Alloy 2.0 mm thick / 12.5 mm overlap	457 ± 52
Unidirectional T300/924 Carbon/Epoxy 2.0 mm thick / 12.5 mm overlap	369 ± 41
Plain Woven Fabric (Tufnol 10G/40) <u>2.5 mm thick</u> • 12.5 mm overlap	275 ± 28
• 25.0 mm overlap	454 ± 27
• 50.0 mm overlap	511 ± 32
5.1 mm thick / 12.5 mm overlap	327 ± 27

NB. CR1 - cold-rolled mild steel sheet (supplied by British Steel Plc)

A number of observations can be made in relation to the results presented in Table 1.

- Increasing either the adherend stiffness (i.e. elastic modulus) or adherend thickness results in an increase in load-bearing capacity of the single-lap joint.
- Increasing the lap length increases the load-bearing capacity of the joint.
- All the results are well below the average shear strength measured for the bulk adhesive (46 MPa). The titanium alloy specimens out performed the other materials of equivalent dimensions with an average applied stress at failure of 37 MPa.
- Low failure stresses for the mild steel specimens was due to interfacial failure.
- **The average shear strength does not correspond to a unique material property of the adhesive, and therefore cannot be used as a design parameter.**

For a single-lap joint, the maximum adhesive shear stress, $\tau_{o, \max}$ and peel stress, $\sigma_{o, \max}$ can be calculated using the following equations [7]:

$$\tau_{o, \max} = \frac{\sigma}{8} (1 + 3k) \sqrt{\frac{8G_a t}{E t_a}} \quad (2)$$

$$\frac{\sigma_{o, \max}}{\sigma} \left(\frac{c}{t} \right)^2 = \lambda^2 \frac{k}{2} \frac{\sinh(2\lambda) - \sin(2\lambda)}{\sinh(2\lambda) + \sin(2\lambda)} - \lambda k' \frac{\cosh(2\lambda) + \cos(2\lambda)}{\sinh(2\lambda) + \sin(2\lambda)} \quad (3)$$

where:

$$\sigma = \frac{P}{t} \quad (4)$$

$$c = \frac{L}{2} \quad (5)$$

$$k = \frac{\cosh(u_2 c) \sinh(u_1 L)}{\sinh(u_1 L) \cosh(u_2 c) + 2\sqrt{2} \cosh(u_1 L) \sinh(u_2 c)} \quad (6)$$

$$u_1 = 2\sqrt{2} u_2 \quad (7)$$

$$u_2 = \sqrt{\frac{3\sigma(1-\nu^2)}{2Et^2}} \quad (8)$$

$$k' = k c \sqrt{\frac{3\sigma(1-\nu^2)}{Et^2}} \quad (9)$$

$$\lambda = \frac{c}{t} \left(\frac{6E_a t}{Et_a} \right)^{1/4} \quad (10)$$

and

P = load per unit width

L = length of overlap (bond length)

t = adherend thickness

E = adherend modulus

G_a = adhesive shear modulus (initial)

t_a = adhesive layer thickness

E_a = adhesive tensile modulus

n = adherend Poisson's ratio

Table 2 shows maximum adhesive shear stress, $\tau_{0, \max}$, and peel stress, $\sigma_{0, \max}$, determined for a range of materials, adherend thicknesses and overlap lengths using the above analytical analysis. These results are for unconditioned (i.e. dry) adhesive joints bonded with AV119 epoxy adhesive. The stresses correspond to an applied load per unit width of 250 N/mm.

Table 2 Maximum Shear and Peel Stresses for Single-Lap Joint Configurations

Adherend Thickness/Overlap Length	Maximum Shear Stress (MPa)	Maximum Peel Stress (MPa)
CR1 Mild Rolled Steel		
1.4 mm thick / 12.5 mm overlap	31.28	34.68
<u>2.5 mm thick</u>		
12.5 mm overlap	24.30	29.68
25.0 mm overlap	23.71	27.71
50.0 mm overlap	21.95	24.56
5251 Aluminium Alloy		
1.4 mm thick / 12.5 mm overlap	49.42	50.72
1.6 mm thick / 12.5 mm overlap	47.70	50.66
3.0 mm thick / 12.5 mm overlap	37.29	43.98
6Al-4V-Titanium Alloy		
1.4 mm thick / 12.5 mm overlap	39.85	42.78
2.0 mm thick / 12.5 mm overlap	34.91	39.65
Unidirectional Carbon/Epoxy		
1.4 mm thick / 12.5 mm overlap	39.24	42.15
2.0 mm thick / 12.5 mm overlap	34.35	39.07
Plain Woven Fabric		
1.4 mm thick / 12.5 mm overlap	73.39	64.60
2.0 mm thick / 12.5 mm overlap	69.33	70.16
5.1 mm thick / 12.5 mm overlap	48.59	59.16

The results presented in Table 2, and Appendix 2 clearly indicate that both shear and tensile-stress concentrations are controlled by geometric (e.g. adherend thickness, overlap (joint) length and adhesive layer thickness) and material (adherend tensile modulus, adherend Poisson's ratio and adhesive shear modulus) parameters. These differences have a profound affect on the stress concentrations and consequently the load-bearing capacity of the joint. Linear-elastic predictive analysis indicates that shear and peel stresses exceed the bulk adhesive shear strength because it does not account for the plastic-elastic behaviour of the adhesive in the bonded joint. **The single-lap joint provides the user with an “apparent” shear strength value. The apparent shear strength measured with a single-lap specimen cannot be assumed to predict the strength of joints of differing geometry.** A finite element analysis evaluation has been conducted on the single-lap joint in which a number of factors were considered. These include the affect of adherend properties and dimensions, and moisture ingress on joint behaviour. This work will be presented in a future report.

Ideally, the data from a test method should be relatively insensitive to changes in specimen dimensions. In the case of the single-lap joint, which is used frequently for comparative studies, **careful consideration should be given to ensuring that the stress/strain distributions for different systems are at least similar.** For example, a direct comparison could possibly be made between 6Al-4V-Ti alloy and unidirectional carbon/epoxy specimens with an adherend thickness of 1.4 mm and an overlap length of 12.5 mm (see Table 3). Maximum peel and shear stresses are almost identical. An equivalent single-lap joint manufactured from 5251 aluminium alloy would need to be fabricated from 3.5 mm thick sections. An algorithm based on the analytical approach presented in this section could be used to back calculate the equivalent specimen dimensions (e.g. adherend

thickness) that would produce similar peel and shear stresses for different adhesive/adherend systems. A numerical approach would be more reliable.

As a first approximation:

$$E_1 t_1 = E_2 t_2 \quad (11)$$

where subscripts 1 and 2 refer to materials 1 and 2. Peel and shear stresses should be minimised through the use of: (i) tapered or bevelled external scarf and radius fillets at the bondline ends; and (ii) thicker adherends than specified in BS EN 1465 ($E t \approx 200 \text{ MNm}^{-1}$).

3. ACCELERATED TESTING

A number of industrial concerns within the United Kingdom use the perforated single-lap joint to accelerate ageing. Testing can involve significant numbers of specimens, rack mounted and instrumented, often transported overland by heavy duty vehicles through a range of climatic zones (including arid and tropical environments) or exposed to marine environments for several years. The introduction of holes within the bonded area to increase the rate of moisture uptake and therefore the rate of degradation seems a logical approach. The presence of drilled holes in the bonded area accelerates ageing by shortening the diffusion path and increasing the exposed bondline. The initial concern would be ensuring structural integrity was not compromised through the introduction of the holes. In a previous NPL Report (CMMT(A) 98 [8]), Design of Experiments (DOE) techniques were used to assess durability data obtained from perforated single-lap adhesive joints that had been immersed in water at ambient or elevated temperatures for up to 42 days. This period was considered representative for the development of an accelerated ageing test programme.

This section evaluates the test method and data from an experimental perspective. The assessment is based on a comprehensive test programme carried out on standard and perforated single-lap joint mild steel specimens bonded with a moisture sensitive adhesive.

3.1 EXPERIMENTAL PROGRAMME

Tensile tests were conducted on standard and perforated single-lap joints. The single-lap joint specimens, schematically shown in Figure 1, were made from CR1 cold-rolled mild steel sheet and AV119. The basic specimen geometry, surface preparation and testing was the same as that employed in Section 2.3. Perforated specimens contained either one, two or three, 3 mm diameter holes, drilled at the specimen centre, a low stress region within the joint overlap (Figure 2). The holes were equally spaced across the width of the specimen. The small diameter of the holes was to prevent the possibility of yielding and fracture of the material between the holes. Tests conducted on specimens with three 4 mm holes showed noticeable material yielding between the holes. Specimens were drilled after the curing process. **Drilling the adherends before assembling leads to lower strength values; as the thin steel sheet is locally deformed, thus preventing good surface contact. Specimens should be fully clamped and supported during the drilling operation. Sacrificial material and pilot holes (e.g. 15 mm diameter) should be used to prevent burring and minimise debonding around the circumference of the holes.**

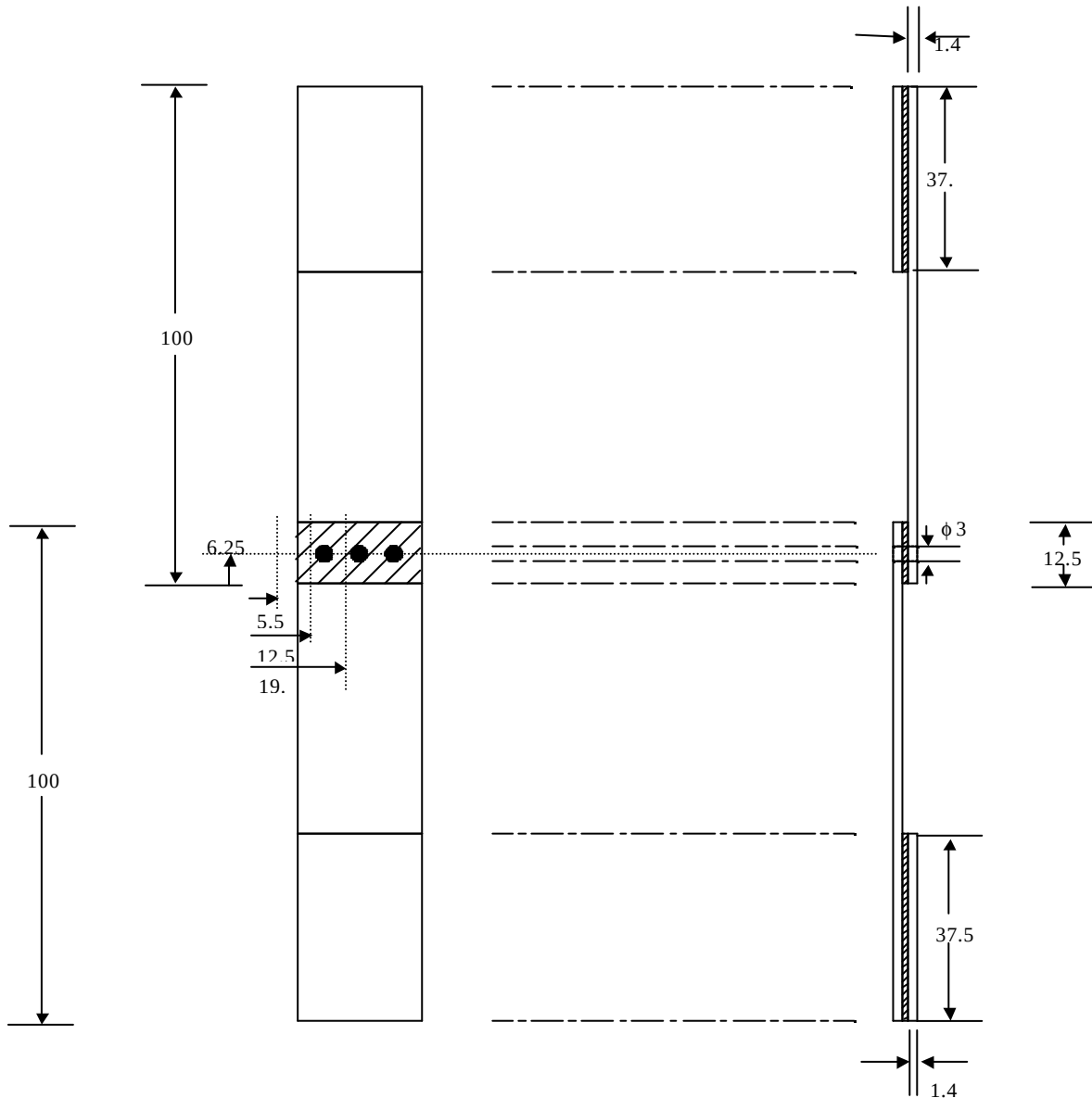


Figure 2 Schematic of perforated single-lap joint (dimensions in mm).

The specimens were immersed in distilled / deionised water at either 25°C, 40°C or 60°C. A limited number of tests were conducted on specimens that been immersed in water at 50 °C and 70 °C. Batches of conditioned specimens (five specimens per batch) were withdrawn at selected intervals over a 6 week period. Testing was carried out under ambient conditions (23°C, 50% relative humidity) at a constant displacement rate of 1 mm/min using an Instron 1196 screw-driven test frame. Instron Series IX software was used to control the test machine and to collect the test data.

3.2 TEST RESULTS

The strength (N/mm) data from the tests carried out moisture conditioned specimens are summarised in Tables 3 to 5 (see also reference [8]). The results for perforated specimens with 4 mm diameter holes are also shown in Table 5.

Table 3 Strength Data for Moisture Conditioned CR1/AV119 Single-Lap Joints - 25 °C

Exposure Time (days)	Unperforated	Single Hole	Double Hole	Triple Hole
0	334 ± 11	301 ± 16	300 ± 21	304 ± 21
3	291 ± 9	263 ± 12	264 ± 2	295 ± 11
7	272 ± 5	258 ± 11	259 ± 7	260 ± 12
14	235 ± 6	232 ± 6	217 ± 3	222 ± 5
21	248 ± 8	260 ± 12	265 ± 8	247 ± 10
42	244 ± 7	235 ± 7	245 ± 16	266 ± 12

Table 4 Strength Data for Moisture Conditioned CR1/AV119 Single-Lap Joints - 40 °C

Exposure Time (days)	Unperforated	Single Hole	Double Hole	Triple Hole
0	334 ± 11	301 ± 16	300 ± 21	304 ± 21
3	228 ± 9	272 ± 7	260 ± 19	243 ± 9
7	232 ± 7	229 ± 5	223 ± 8	230 ± 8
14	219 ± 8	198 ± 6	243 ± 11	204 ± 7
21	197 ± 7	208 ± 4	204 ± 14	204 ± 3
42	213 ± 7	216 ± 13	210 ± 10	191 ± 6

Table 5 Strength Data for Moisture Conditioned CR1/AV119 Single-Lap Joints - 60 °C

Exposure Time (days)	Unperforated	Single Hole	Double Hole	Triple Hole 3 mm/4 mm
0	334 ± 11	301 ± 16	301 ± 21	304 ± 21 / 292 ± 19
3	211 ± 9	216 ± 9	208 ± 10	207 ± 4 / 194 ± 11
7	222 ± 7	216 ± 6	213 ± 6	212 ± 7 / 195 ± 6
14	211 ± 5	183 ± 14	189 ± 14	181 ± 9 / 145 ± 22
21	177 ± 8	151 ± 6	174 ± 15	167 ± 6 / 175 ± 25
42	305 ± 7	283 ± 12	256 ± 9	243 ± 6 / 222 ± 20

For the particular adhesive system under investigation, the introduction of additional holes after the initial hole had no major effect on failure (Figure 3). Temperature and exposure time have a far greater influence on strength retention (Figures 4 and 5). **The results presented in Figures 3 to 5 are based on the statistical average of all the results in Tables 2 to 5 (with the exception of the 4 mm hole data).**

Confirmation of a satisfactory accelerated test regime would have been realised from a series of well separated parallel curves, which in this case was not observed. FEA showed that moisture ingress at the ends of the lap joints plasticised the adhesive, thus reducing peel and shear stress concentrations at these locations (Appendix 3). This seemed to have a far more influential effect on joint performance than the presence of the holes. **The larger holes (i.e. 4 mm diameter) reduced the intrinsic strength of the joint without significantly contributing to the accelerated ageing process.**

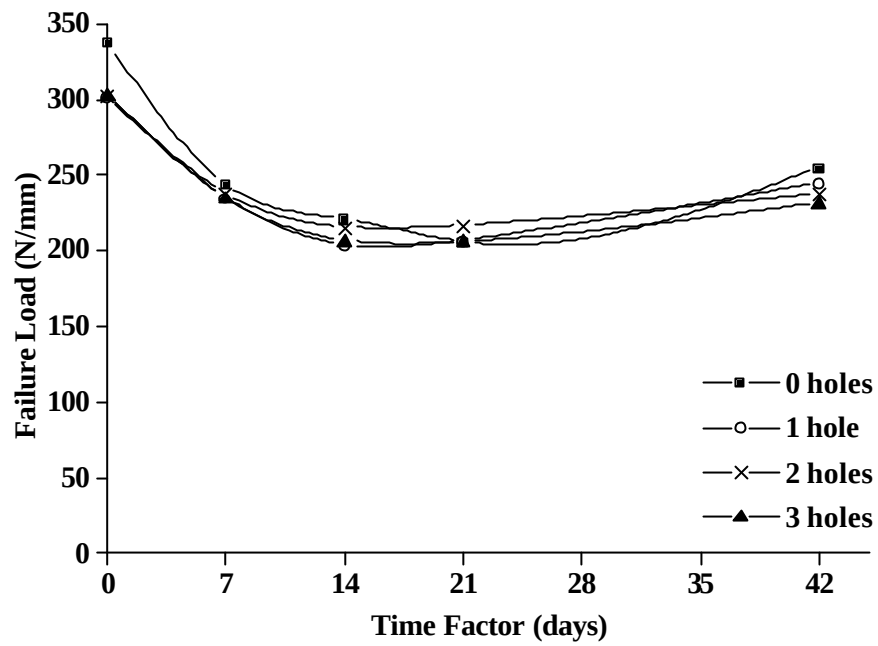


Figure 3 Interaction between the number of holes and time [8].

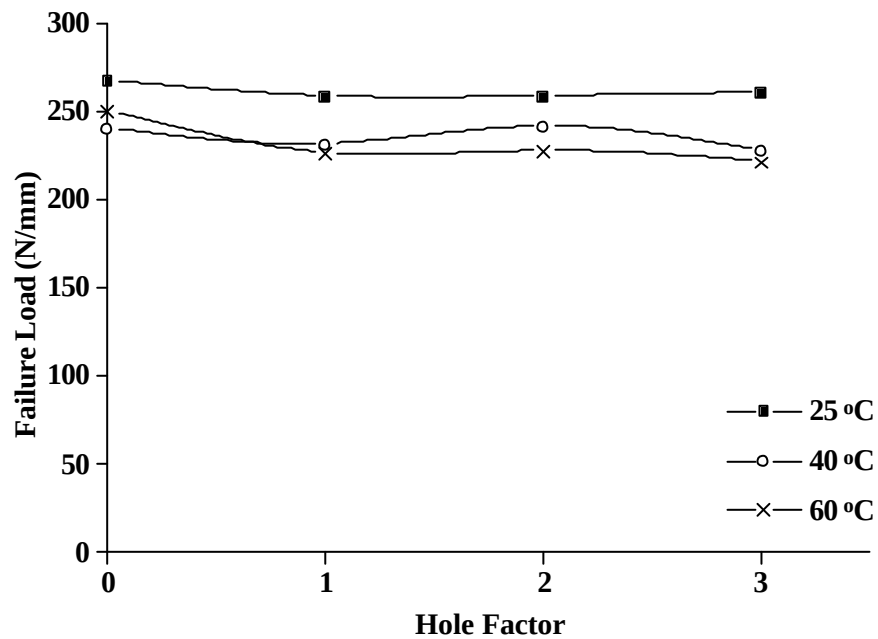


Figure 4 Interaction between temperature and number of holes [8].

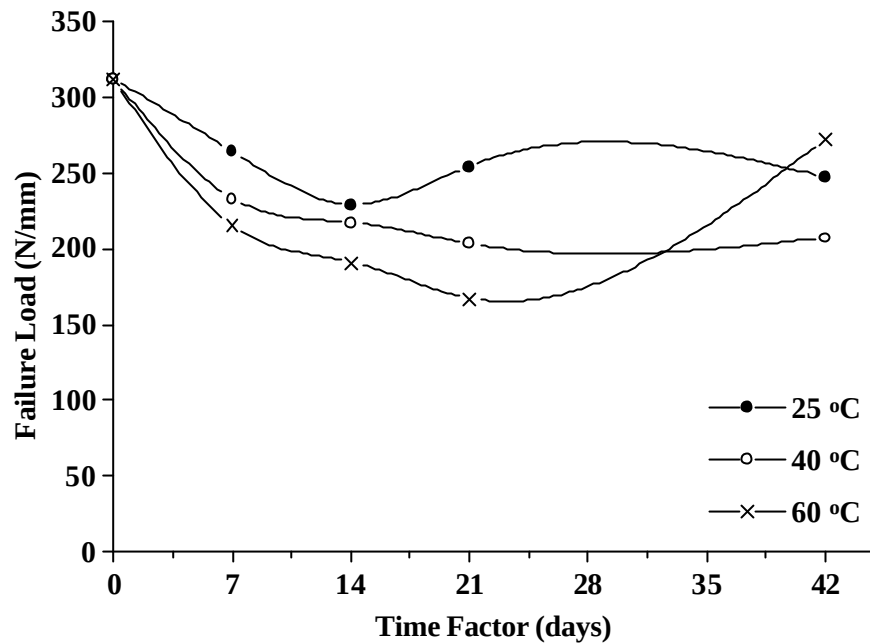


Figure 5 Interaction between temperature and time [8].

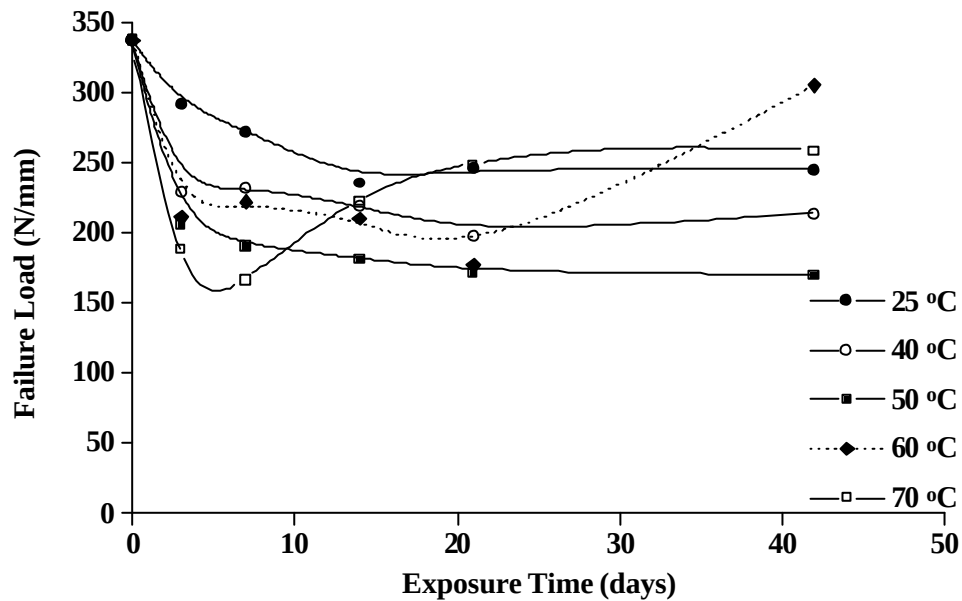


Figure 6 Temperature and time dependence for unperforated single-lap joint configuration.

Increasing the water temperature increases the rate of strength loss, Figure 6. The rapid loss of strength for short exposure times is typical for adhesive joints with poor environmental resistance. The loss of strength was attributed to interfacial failure between the adhesive and substrate. A marked gain in joint strength can be observed after 21 days for those specimens that have been conditioned at 60°C. The increase in “apparent” strength, also observed by AEA Technology [9], is attributed to plasticisation of the

adhesive. This results in a reduction in peel and shear stresses at the joint ends to a level lower than experienced by drier specimens, thereby masking interfacial effects. This effect may be also occurring at lower immersion temperatures, albeit to a much lesser extent. Increasing the water temperature to 70 °C increases both the rate of moisture uptake and interfacial degradation with the rate of stress relief at the joint ends having a far more influential effect on joint strength (Figure 6). Moisture ingress in the vicinity of the holes had minimal effect on joint performance; as the holes are located in a low stress region. A reduction in localised stresses in these regions has minimal effect on strength retention. As previously mentioned, FEA has been carried out on both conditioned and unconditioned single-lap joints with and without holes (to be presented in a future report).

3.3 DYNAMIC MECHANICAL THERMAL ANALYSIS (DMTA)

Dynamic mechanical thermal analysis (DMTA) measurements were carried out on moisture conditioned bulk AV119 resin specimens (25 °C, 40 °C and 60 °C) to determine the change in glass-transition temperature **T_g** as a function of moisture content (Figure 7). Measurements were carried out in accordance with ISO 6721-1 [10]. The results form a master curve which asymptotes to approximately 48 °C. The saturation level for this adhesive was estimated to be 10 wt%. The results in Figures 6 and 7 indicate that for AV119, **the maximum operating temperature dry is 102 °C and wet 48 °C.**

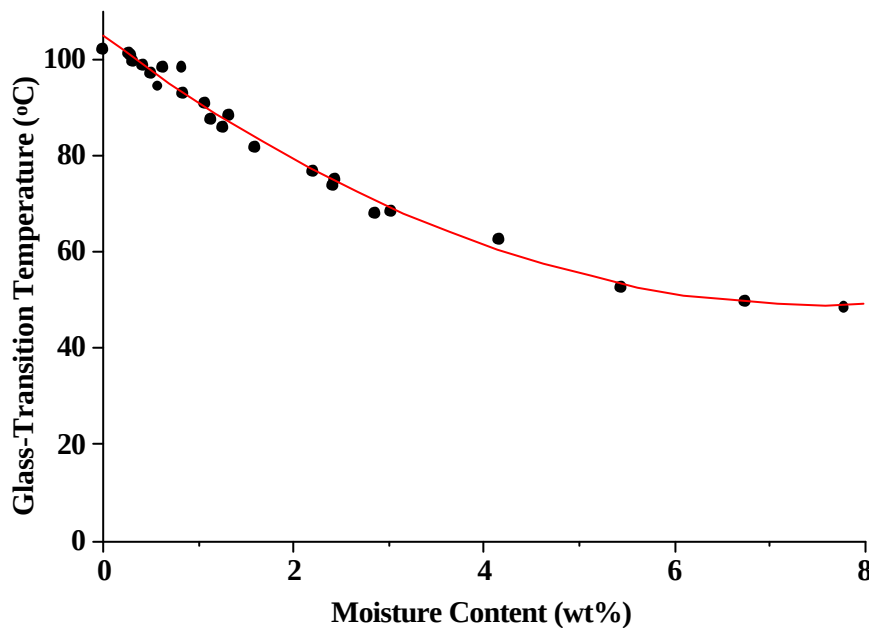


Figure 7 Glass-transition temperature of AV119 as a function of moisture content.

3.4 DISCUSSION

Although the results of the investigation bring into question the indiscriminate use of the perforated single-lap joint for accelerated ageing, they do not necessarily invalidate the procedure. Material properties of the AV119 adhesive were observed to be highly sensitive to moisture. This highlights the need for a full understanding of key factors that influence the results obtained from the test method. **Comparing the results from unconditioned**

and conditioned specimens may not always be appropriate, considering the changes in the stress state within specimens that can result from environmental exposure. It is recommended that the use of a perforated specimen be restricted to conditions where the adhesive properties remain relatively unaffected.

In the case of AV119, which is a moisture sensitive adhesive, the tensile strength and tensile modulus of the bulk adhesive rapidly decrease with moisture content. Figures 8 and 9 show the relationship between the two properties (measured at room-temperature) and **T_g** is essentially linear. These changes in mechanical properties of the adhesive have been shown to have a marked effect on the stress and strain distributions within the single-lap joints (see Appendix 3).

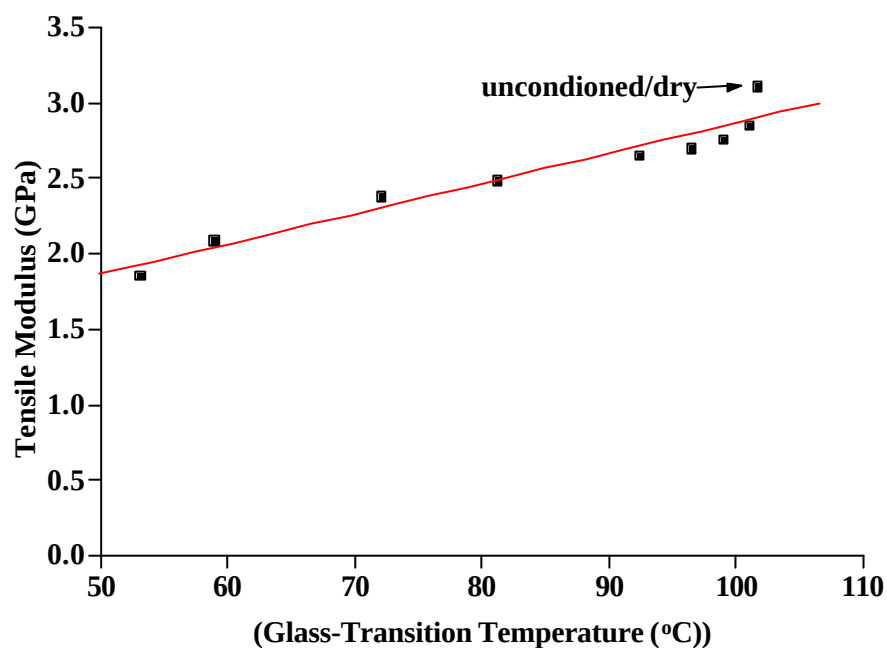


Figure 8 Tensile modulus of AV119 as a function of glass-transition temperature.

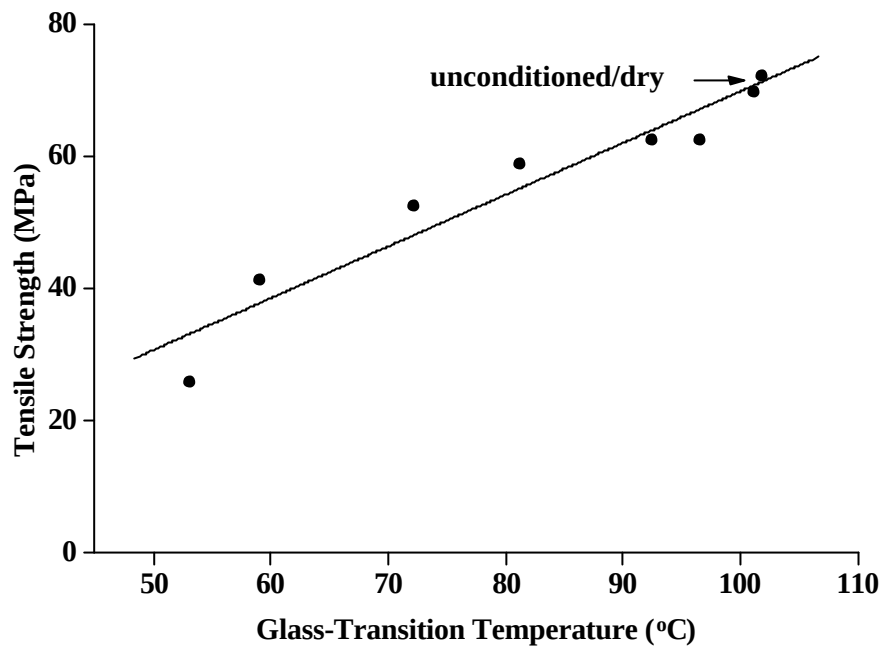


Figure 9 Tensile strength of AV119 as a function of glass-transition temperature.

4. ELEVATED TEMPERATURE TESTS

Tests were also carried out at ambient and elevated temperatures (40 °C, 60 °C and 80 °C) on unperforated single-lap specimens that had been immersed in water at 60 °C for 2 weeks. The results, presented in Table 6 and Figure 9, show a linear reduction in strength with increasing test temperature for both dry and conditioned specimens. The presence of moisture within the single-lap joint results in a systematic strength reduction of approximately 120 N/mm. It was not possible to directly relate the reduction in joint strength with moisture induced changes in the tensile properties of the adhesive. Although, knock down factors to account for moisture and temperature can be determined.

Table 6 Failure Load (N/mm) of CR1 mild steel/AV119 Adhesive Joint with Temperature

Condition	Test Temperature (°C)			
	23	40	60	80
Dry	334 ± 11	272 ± 7	282 ± 9	263 ± 3
Wet	211 ± 5	172 ± 3	184 ± 11	129 ± 8

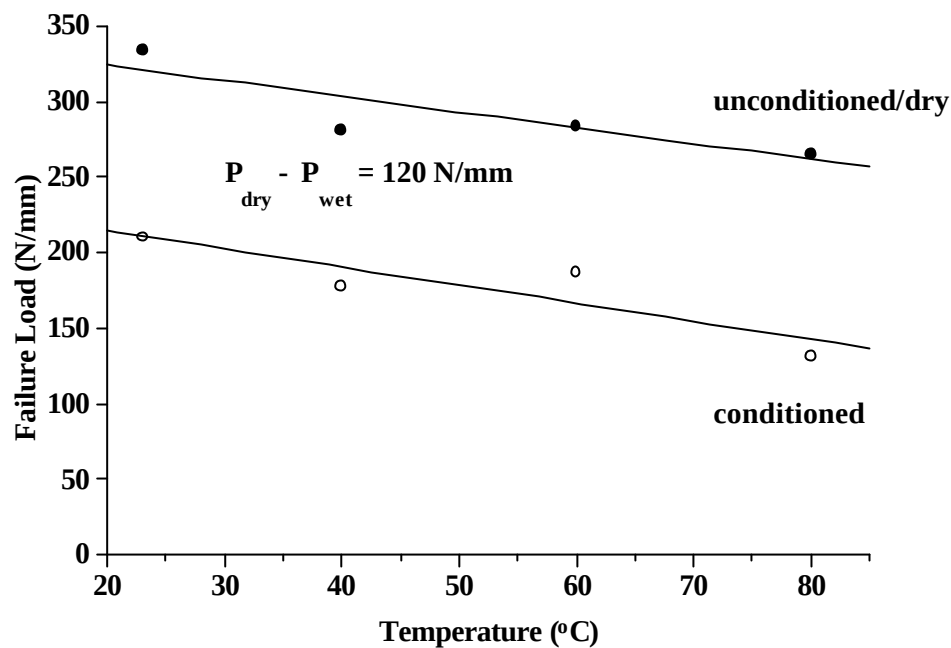


Figure 9 Shear Strength of CR1 mild steel / AV119 adhesive joint with test temperature.

5. CONCLUDING REMARKS

The results clearly show that due care needs to be taken when using either the standard or perforated single-lap geometry for assessing the durability of an adhesive/adherend system or surface pretreatment. Failure of bonded joints is dependent upon interfacial effects and chemical degradation of the adhesive and the adherends. A comprehensive understanding of the specimen is essential before comparing the relative durability of adhesives and surface treatments. Extrapolation of short-term accelerated test data, obtained using the single-lap test, to actual in-service performance of structural joints needs to be approached with caution. **It is recommended from a design perspective that the thick adherend shear test (TAST) be used for measuring environmental resistance in preference to single-lap or double-lap joint configurations.**

The results in this report demonstrate that for moisture sensitive adhesives (i.e. material properties decrease with moisture content), the introduction of holes in an attempt to accelerate ageing has little or no effect on strength retention. Temperature and time have a far more influential effect on joint performance than the presence of holes. Chemical and physical changes that occur within the adhesive, adherends and interface at the ends of the overlap will dominate joint failure.

ACKNOWLEDGEMENTS

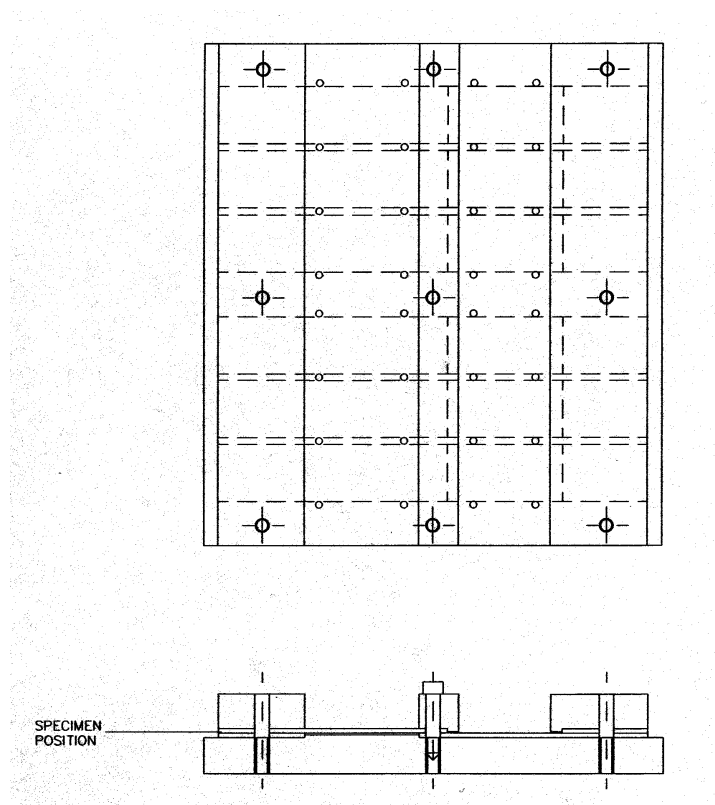
This work forms part of the programme on adhesives measurement technology funded by the Engineering Industries Directorate of the UK Department of Trade and Industry, as part of its support of the technological competitiveness of UK industry. The authors would like to express their gratitude to Dr A Olusanya, Dr Fangzhong Hu, Dr S Maudgal, Mr M Gower and Mr S Gnaniah, and to all members of the Industrial Advisory Group

(IAG) and to the members of UK industry outside the IAG, whose contributions and advice have made the work possible. Other DTI funded programmes on materials are also conducted by the Centre for Materials Measurement and Technology, NPL as prime contractor. For further details please contact Mrs G Tellet, NPL.

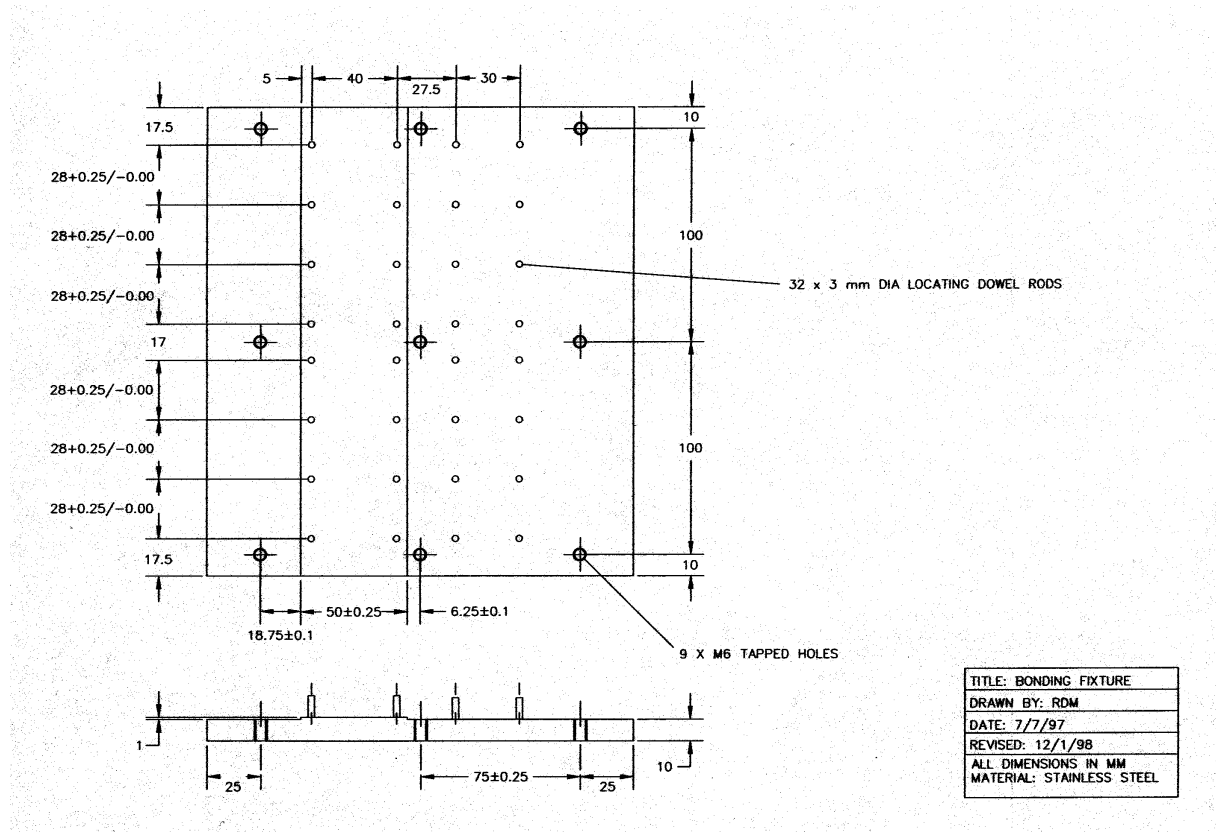
REFERENCES

1. Broughton, W.R. and Mera R.D., "Review of Durability Test Methods and Standards for Assessing Long Term Performance of Adhesive Joints", NPL Report CMMT (A) 61, 1997.
2. BS EN 1465:1995, "Adhesives - Determination of Tensile Lap-shear Strength of Rigid-to-Rigid Bonded Assemblies".
3. ASTM D 1062, "Standard Test Method for Apparent Shear Strength of Single-Lap Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)", Volume 15.06, ASTM Standards, 1995, pp 44-47.
4. BS 5350 - Part C5: 1990, "Adhesives - Determination of Bond Strength in Longitudinal Shear".
5. ISO 4588, "Adhesives - Preparation of Metal Surfaces for Adhesive Bonding".
6. ISO 2818: 1991, "Plastics - Preparation of Test Specimens by Machining".
7. "Structural Design of Polymer Composites, EROCOMP Design Code and Handbook, Clarke, J.L., Editor, E and F.N. Spon, 1996.
8. Olusanya, A, Tully, K, Mera, R, Broughton, W R "A Comparison of Commercial Design of Experiment Software Programs for the Analysis of Durability Data", NPL Report CMMT(A) 98, 1998.
9. "Experimental Assessment of Durability of Test Methods", MTS Adhesives Programme, Project 3: Environmental Durability of Adhesive Joints, Report No 8, AEA Technology, Harwell, United Kingdom, January 1995.
10. ISO 6721:1996, "Plastics - Determination of Dynamic Mechanical Properties. Part 1. General Principles".

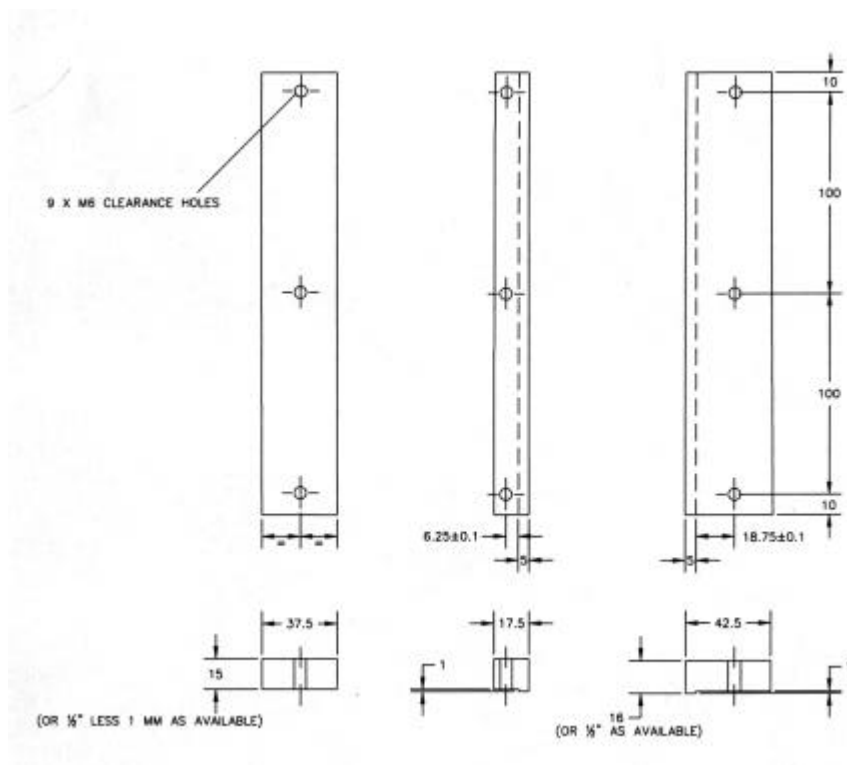
APPENDIX 1 BONDING FIXTURE



Bonding Fixture Assembly (specimen positions indicated by dashed lines)



Bonding Fixture Alignment Pin Locations)



Bonding Fixture Clamps

APPENDIX 2

FEA OF SINGLE-LAP JOINT - INFLUENCE OF ADHERENDS (RESULTS CORRESPOND TO AN END LOAD OF 8 kN)

CONTENTS

Figure 1 - Specimen Geometry.

Figure 2 - Predicted Linear Elastic Load-Displacement Response.

Figure 3 - Influence of Adherend Materials on Joint Deformation (exaggerated).

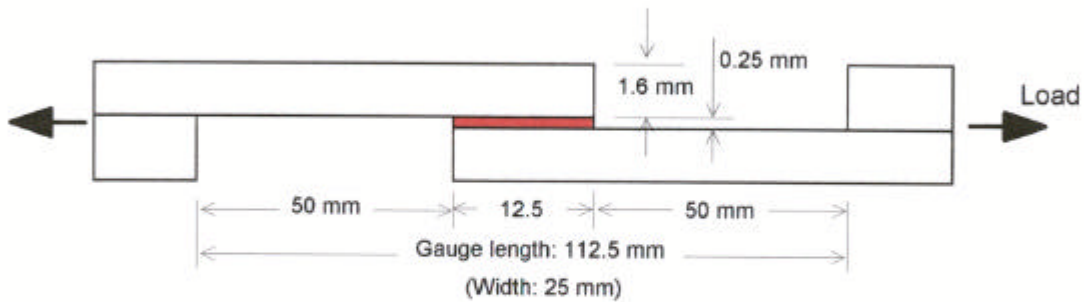
Figure 4 - Peel and Shear Stress Distributions Along the Centre of Bondline.

Figure 5 - Peel and Shear Strain Distributions Along the Centre of Bondline.

Figure 6 - Mises Stress Distributions Along the Centre of Bondline.

Elastic-Plastic Analysis of a Single-Lap Joint

(I) Influence of Adherends Materials



MATERIALS

Adhesive: AV119 Epoxy

Adherends : (a) CRI Mild Rolled Steel
(b) 6Al-4V-Titanium Alloy
(c) 5251 Aluminium Alloy
(d) Tufnol 10G/40 Plain Weave GRP

Figure 1 - Specimen Geometry

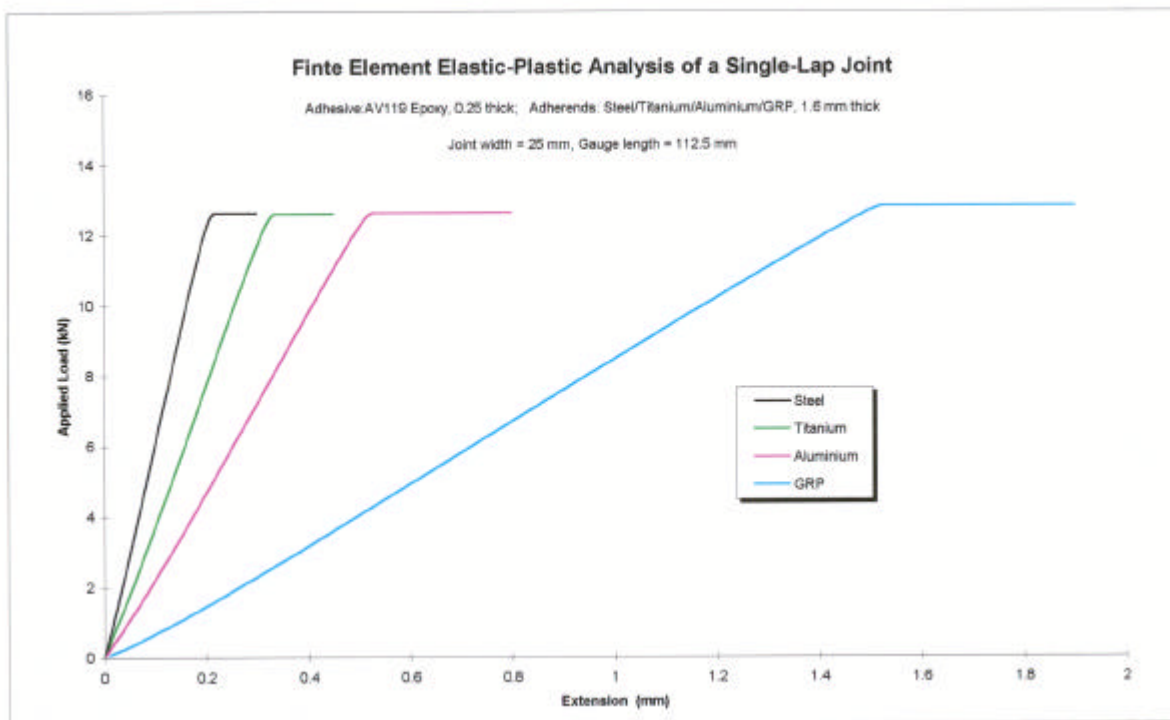


Figure 2 - Predicted Linear Elastic Load-Displacement Response

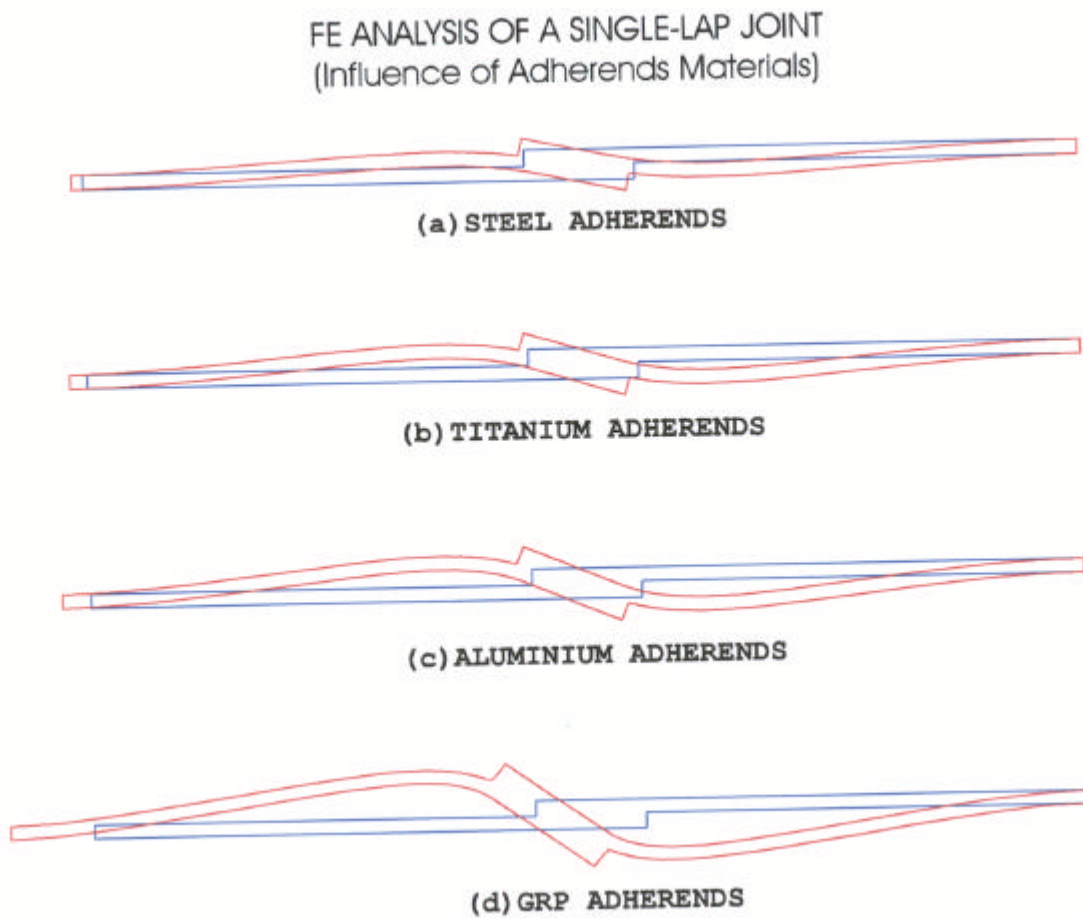


Figure 3 - Influence of Adherend Materials on Joint Deformation (exaggerated)

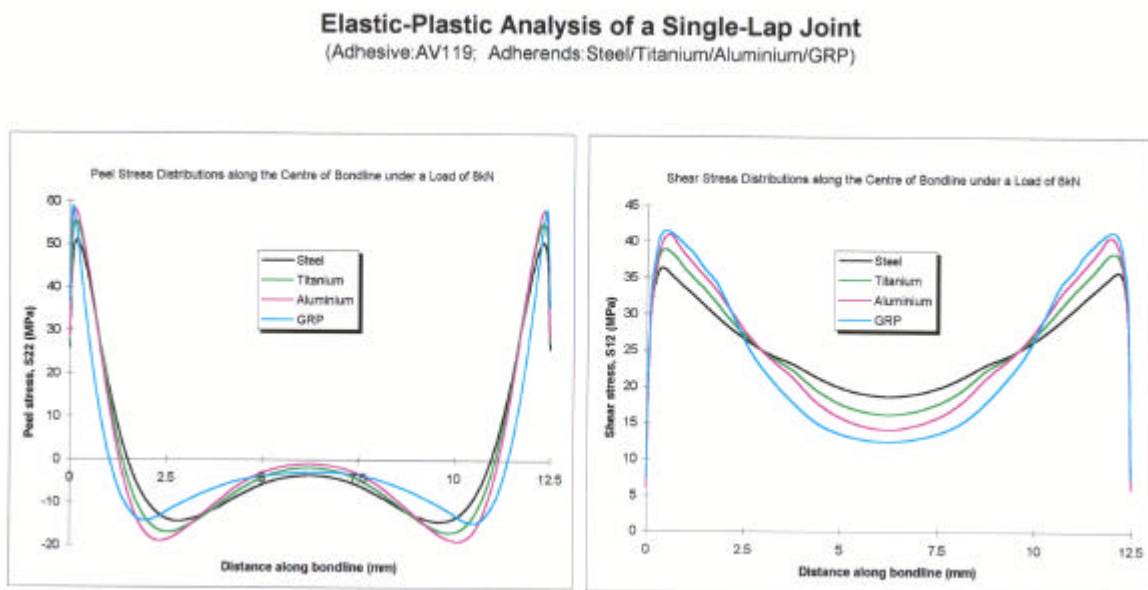


Figure 4 - Peel and Shear Stress Distributions Along the Centre of Bondline

Elastic-Plastic Analysis of a Single-Lap Joint (Adhesive:AV119; Adherends:Steel/Titanium/Aluminium/GRP)

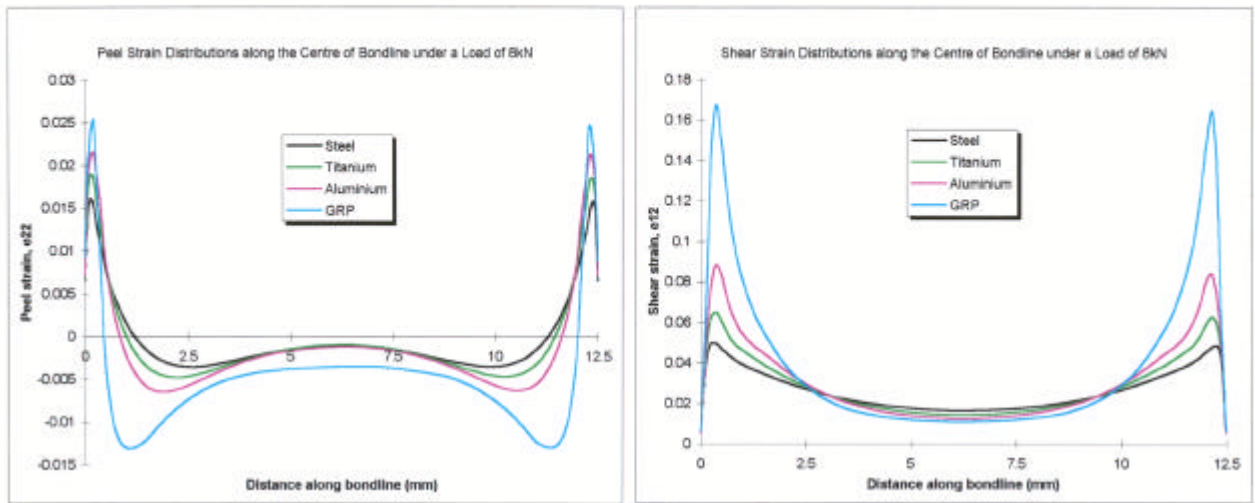


Figure 5 - Peel and Shear Strain Distributions Along the Centre of Bondline

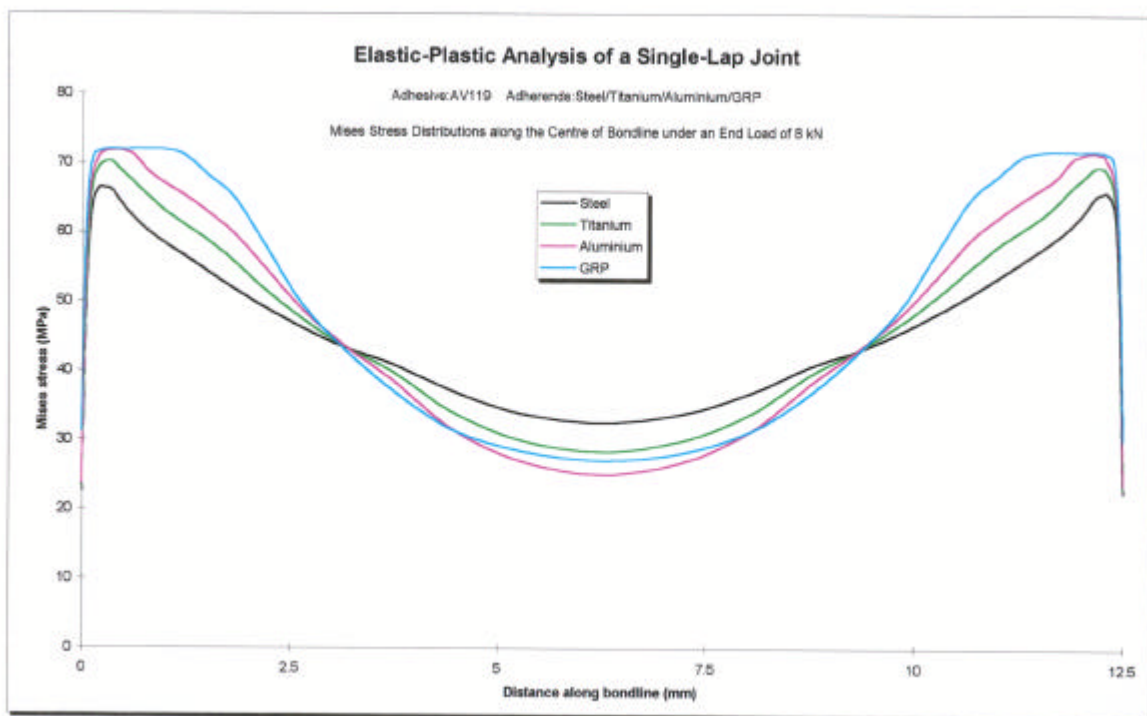


Figure 6 - Mises Stress Distributions Along the Centre of Bondline

APPENDIX 3

FEA OF SINGLE-LAP JOINT - INFLUENCE OF MOISTURE (RESULTS CORRESPOND TO AN END LOAD OF 3.5 KN)

