

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

Report No 15

**Evaluation of the Single-Lap Joint
Using Finite Element Analysis**

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December 1999

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ABSTRACT

This report evaluates the effect of moisture, specimen geometry and adherend properties on the behaviour of the single-lap joint. Finite element analyses was used to establish the effects of these parameters on the joint stiffness and stress distribution within the adhesive layer. The report also includes an evaluation of the perforated single-lap joint, assumed to promote accelerated ageing by shortening the diffusion path of moisture. A series of stress and deformation analyses using finite element analysis (FEA) has been conducted on the single-lap configuration for this purpose. The analyses were based on experimental data obtained from data generated within the DTI funded ADH and PAJ programmes.

The effect of moisture on the joint performance was investigated using a sequentially coupled mechanical-diffusion finite element model that incorporated continuously varying adhesive material properties. The numerical predictions revealed that the stress distributions become more uniform along the adhesive layer with increasing moisture content. Peel stresses at the ends of the bonded area also decrease with increasing moisture content. The introduction of holes decreases the time taken for the moisture content in the adhesive layer to reach saturation, although increasing the size of the holes and reducing the bonded area only has a marginal effect on the joint performance.

The parametric studies on the specimen geometry revealed that stress distributions are sensitive to changes in adherend material properties, adherend and adhesive thickness and the applied load. In general, stresses were reduced when changes to the joint resulted in smaller joint displacement or an increase in the ability of the adhesive layer to plastically deform.

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ISSN 1361 - 4061

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Head of Centre for Materials Measurement and Technology.

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1. INTRODUCTION

Stress analysis of adhesive joints requires an database of basic engineering properties of the adhesive, substrates and joint geometry. This information is required for both ambient conditions and hostile environment exposure, often in combinations with mechanical loading. Numerous test methods exist for characterising adhesives and bonded joints which may be used to determine fatigue resistance, creep rupture and environmental durability. Adhesive tests can be divided into those methods that provide engineering properties and those methods which can be used to determine the quality of adhesively bonded structures.

Although, an extensive range of test methods is available as national and international standards, most of the test methods can only be used for qualitative measurements, providing a means of checking the effectiveness of different surface treatments and comparing mechanical properties of different adhesive systems (i.e. ranking adhesive formulations) [1]. The single-lap shear test [2-3] is an example of a method that is widely used to measure the relative performance of adhesive/adherend/surface treatment combinations under a wide range of test conditions, but is incapable of providing reliable engineering data. The main problem with the single-lap shear test is that the average strength determined using this method does not correspond to a unique material property of the adhesive, and therefore cannot be used as a design parameter. In fact, this quantity is strongly dependent on the joint geometry and material properties of the constituents. (NB. Ideally, the material properties data from a test method should be relatively insensitive to changes in specimen dimensions).

Altering the standard test geometry [2] in order to accommodate thicker substrates or different substrate materials, or for the purpose of accelerating testing (e.g. introduction of holes in the overlap) inevitably alters the stress and strain distributions within the adhesive layer. These differences have a profound affect on the stress concentrations and consequently the load-capacity of the joint. It is therefore important to appreciate the consequences of changing geometric and material parameters. Although, the technique may only be used for ranking purposes, careful consideration should be given to ensuring that the stress and strain distributions for different systems are similar.

This report evaluates the effect of moisture, specimen geometry and adherend properties on the behaviour of the single-lap joint. Finite element analyses was used to establish the effects of these parameters on the joint stiffness and stress distribution within the adhesive layer. The report also includes an evaluation of the perforated single-lap joint, assumed to promote accelerated ageing by shortening the diffusion path of moisture. A series of stress and deformation analyses using finite element analysis (FEA) has been conducted on the single-lap configuration for this purpose. The analyses was based on experimental data obtained from data generated within the DTI funded ADH and PAJ programmes.

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”.

Throughout this report, statements of particular importance or relevance are highlighted in bold type.

2. SCOPE

The main objective of this report is to assess the single-lap shear method in terms of material compatibility, data generation, environmental conditioning and practicality of using the test method in an industrial environment. FEA has been employed for the purpose of investigating the effect of the following parameters on the joint performance.

- (i) Adherend material (steel, aluminium, titanium and plain weave glass fibre-reinforced composite);
- (ii) Adherend thickness (0.8 to 3.2 mm);
- (iii) Static load (1 to 10 kN);
- (iv) Adhesive thickness (0.25 to 1.0 mm);
- (v) Moisture; and
- (vi) Perforations (3 mm and 4 mm diameter holes).

Particular consideration is given to the formulation of the finite element model and its validation against experimental results. Several additional issues have been considered, including the degree of stress uniformity in the adhesive layer, adherend plastic deformation and non-linear behaviour. Cyclic fatigue and creep performance are also considered.

The report is divided into seven sections; including the Introduction (Section 1) and Scope (Section 2). Section 3 covers the numerical modelling of the single-lap test using the finite element method. The effect of geometric and material parameters on joint performance are considered in Section 4. Sections 5 and 6 cover the effect of environmental degradation on the performance of single-lap joints with and without perforations. Conclusions and discussion are given in Section 7. Detailed finite element results for two adhesive systems and two joint configurations for the perforated single-lap joint are provided in Appendix 1.

3. NUMERICAL MODELLING

This section discusses the finite element model of the single-lap joint and provides a number of recommendations on the modelling approach. The finite element models presented in this report were constructed and solved using ABAQUS [4] program while mesh generation was performed using either PATRAN pre-processor for initial studies and FEMGV [5] pre-processor for the later studies on the effects moisture distribution.

3.1 TWO-DIMENSIONAL JOINT MODEL

Although, a converged three-dimensional analysis may provide a more accurate solution to the problem of structural assessment of adhesive joints than two-dimensional analysis, the time and effort required for mesh generation and analysis of results is substantially increased. A two-dimensional analysis is generally preferred for comparative studies where a series of finite element models are required. **However, the assumptions of plane stress or plane strain will not be valid at all locations within the joint.** Stiffness changes in the width direction cannot be modelled. The state of stress that should be assumed when constructing a two-dimensional model depends on the section through the joint being considered.

A two-dimensional finite element model was constructed to determine the stress fields in the joint and perform parametric studies. The bond between the adherend and the adhesive was assumed to be perfect. The adhesive and the interface were assumed to be free of defects (i.e. voids). Both the adhesive and adherend were represented by plane strain isoparametric elements.

The constraints and loads were applied so as to mimic the tensile loading conditions on the specimen while it was secured in non-rotating clamps. The load was applied along the x-axis as a distributed load acting away from the adherend end. All nodes of the adherend end were coupled in their first degree of freedom so that they move by the same amount in the x-direction. These nodes were constrained against movement perpendicular to the load and against rotation around the z-axis. The boundary conditions are illustrated in Figure 1. The finite element mesh was locally refined at the ends of the overlap.

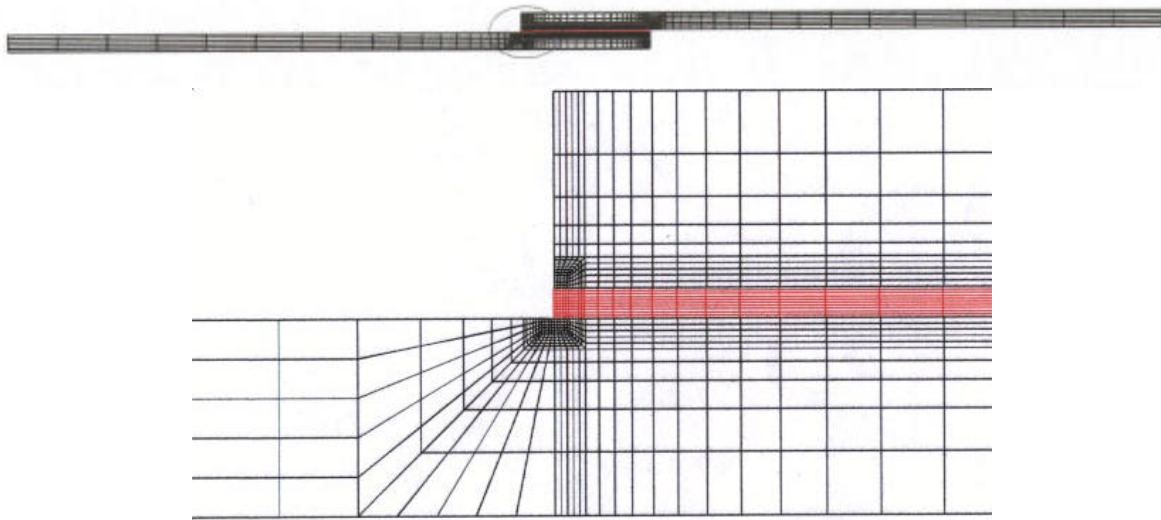


Figure 1 - Boundary conditions applied to the two-dimensional model.

The large stress concentrations at the ends of the adhesive required the use of a non-linear material model. The Mises yield criterion was adopted, which corresponds to identical behaviour in tension and compression. In view of the tension component in the test specimen, the yield criterion was based on the tension stress-strain curve obtained from bulk test specimens, prepared and tested to ISO 527:2 [6] specifications. Figure 2(a) shows a typical stress-strain response for AV119 (also known as Araldite® 2007) supplied by Ciba Speciality Polymers. The yield surface was defined by giving the value of the true uniaxial yield stress as a function of true uniaxial equivalent plastic strain. The metal adherend was also represented by the Mises plasticity model using the stress-strain curves obtained from tensile tests on dumbbell specimens manufactured from the substrate materials. Figure 2(b) shows a typical stress-strain response for CR1 mild steel (supplied by British Steel Plc).

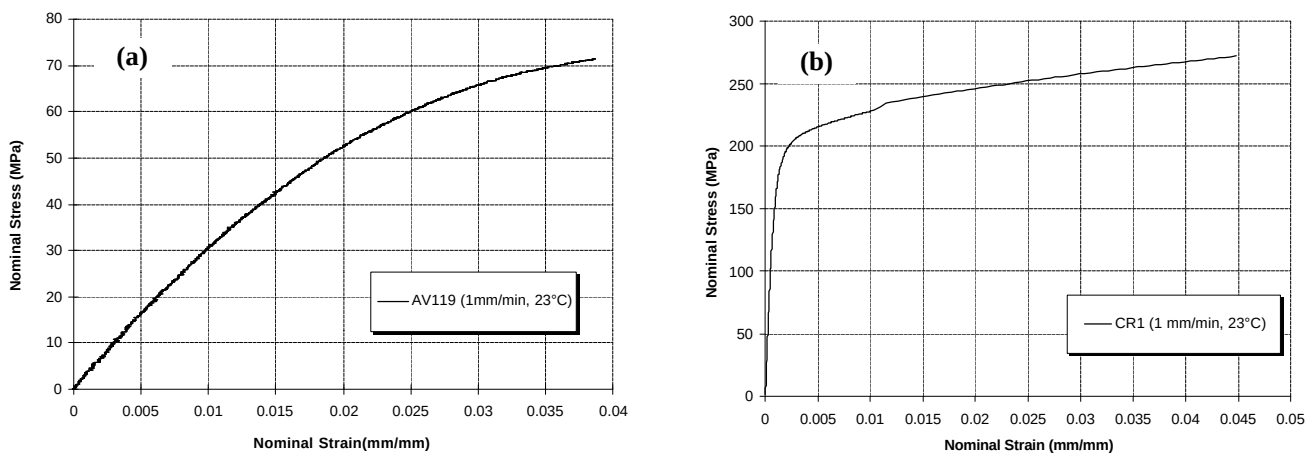


Figure 2 - Tension curves for calibration of elastic-plastic material model.
(a) AV119 epoxy adhesive; and (b) CR1 mild steel adherend.

3.2 MESH DESIGN AND ELEMENT PERFORMANCE

The large thickness differences between the adhesive and the adherend and the large differences in mechanical properties of these materials leads to an ill-conditioned numerical problem. A series of models were analysed examining different mesh densities and element types in order to eliminate any numerical errors. The mesh was refined at the regions of high stress gradients by progressively biasing the elements, keeping their shape as close as possible to the unmapped shape.

4 GEOMETRIC AND MATERIAL PARAMETER EFFECTS

In this study, the effects of geometric and material properties on the joint behaviour were investigated. The materials were CR1 Mild Steel, 6Al-4V Titanium alloy, 5251 Aluminium alloy and Tufnol 10G/40 plain woven glass-fibre reinforced epoxy laminate (see Figure 3). The elastic constants for the four materials are listed in Table 1. The adhesive was AV119 a single part epoxy adhesive supplied by Ciba Speciality Chemicals.

Table 1 – Elastic Properties of Adherends

Property	CR1 Mild Steel	6Al-4V Titanium	5251 Aluminium	Tufnol 10G/40
E_{11} (GPa)	206.0	120.0	72.0	25.2
E_{22} (GPa)	206.0	120.0	72.0	10.7
E_{33} (GPa)	206.0	120.0	72.0	25.2
n_{12}	0.38	0.38	0.35	0.40
n_{13}	0.38	0.38	0.35	0.14
n_{23}	0.38	0.38	0.35	0.40
G_{12} (GPa)	74.6	43.5	26.7	3.25
G_{13} (GPa)	74.6	43.5	26.7	4.41
G_{23} (GPa)	74.6	43.5	26.7	3.25

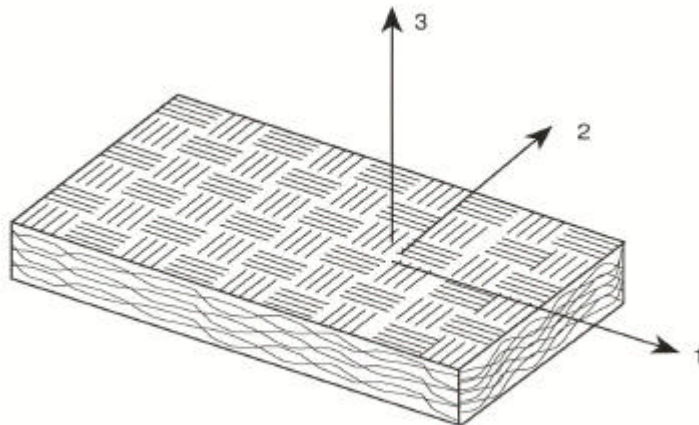


Figure 3 - Principal materials axis for a three-dimensional system.

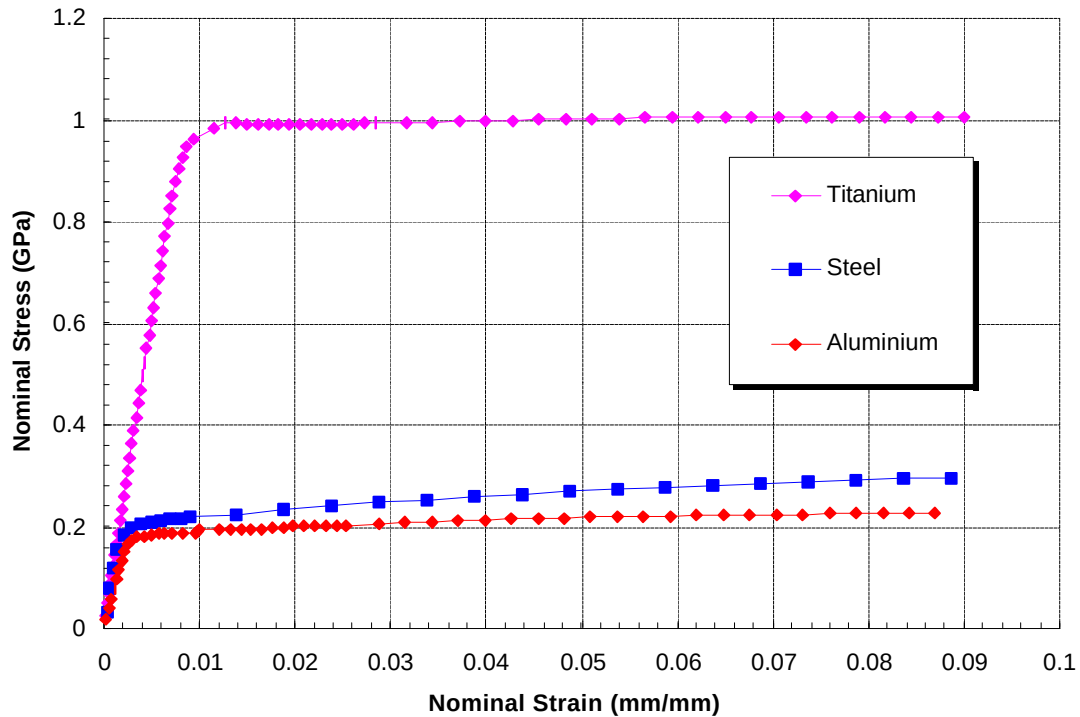


Figure 4 - Stress-strain curves of the metallic adherends.

4.1 ADHEREND MATERIALS

To assess the effect of the adherend plasticity, the metal adherends were modelled as an elastic-plastic material for which the Mises yield criterion was used. Test results from strain-gauged bulk tensile specimens is shown in Figure 4. The orthotropic properties of the plain woven fabric composite were measured in-house utilising a series of test methods specifically designed for testing polymer matrix composites (PMCs).

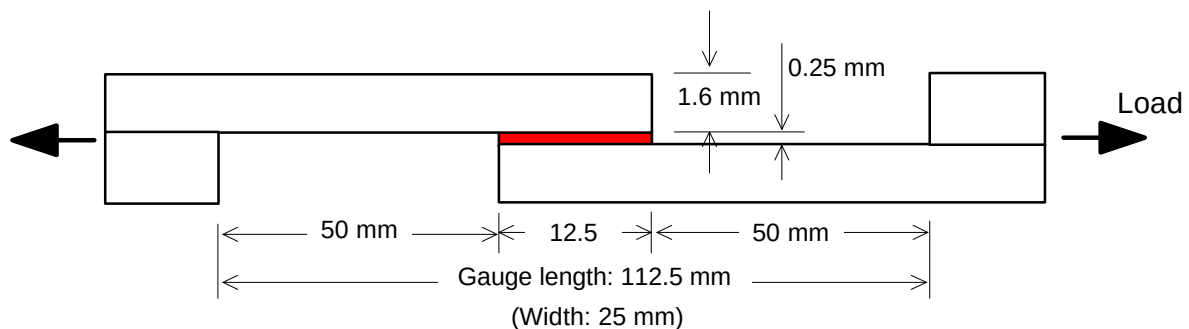


Figure 5 - Single-lap joint geometry.

The basic specimen configuration used in the analyses is shown in Figure 5. The same finite element mesh and boundary conditions were used in all cases. A non-linear solution algorithm was used. Load-displacement (extension) plots for each substrate material is shown in Figure 6. It is worth noting, that the maximum applied load shown in Figure 6 would exceed the ultimate load capacity of the single-lap joint for any of the materials considered in the study. A maximum load of 11.4 kN was measured for 6Al-4V-Titanium alloy joints. The deformed shape (exaggerated) of the joint for each of the four adherend materials is shown in Figure 7.

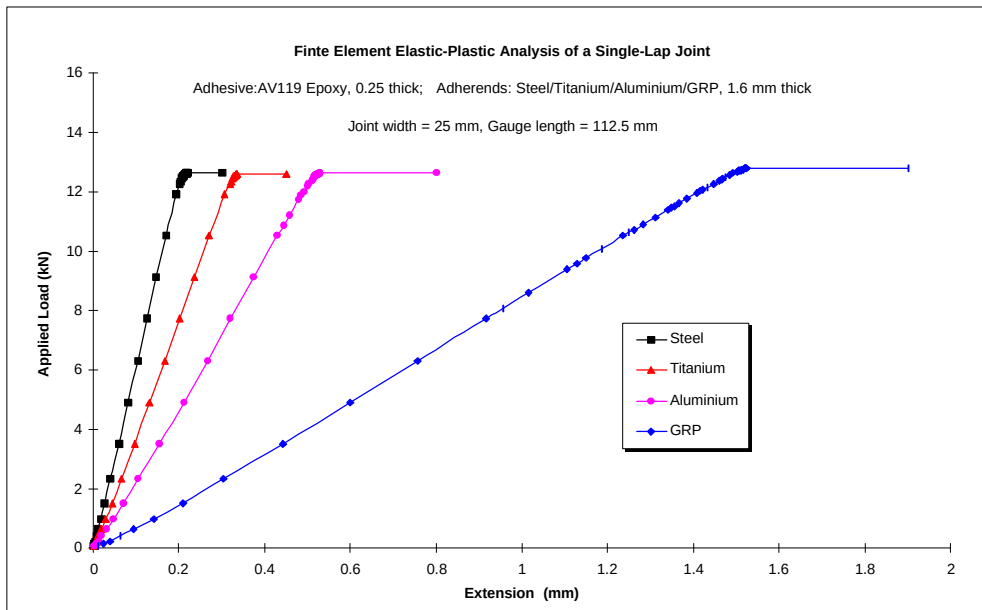


Figure 6 - Predicted load-displacement response for the different substrate materials.

The composite joint exhibited significantly higher deformation than the metal joints due to the differences in the elastic constants of the adherends. As a result, higher stresses were developed within the adhesive. The finite element results revealed that the peel and shear stresses and strains at the ends of the overlap are significantly higher for the low stiffness material (Figures 8 and 9). Mises stress distribution along the bondline is shown in Figure 9.

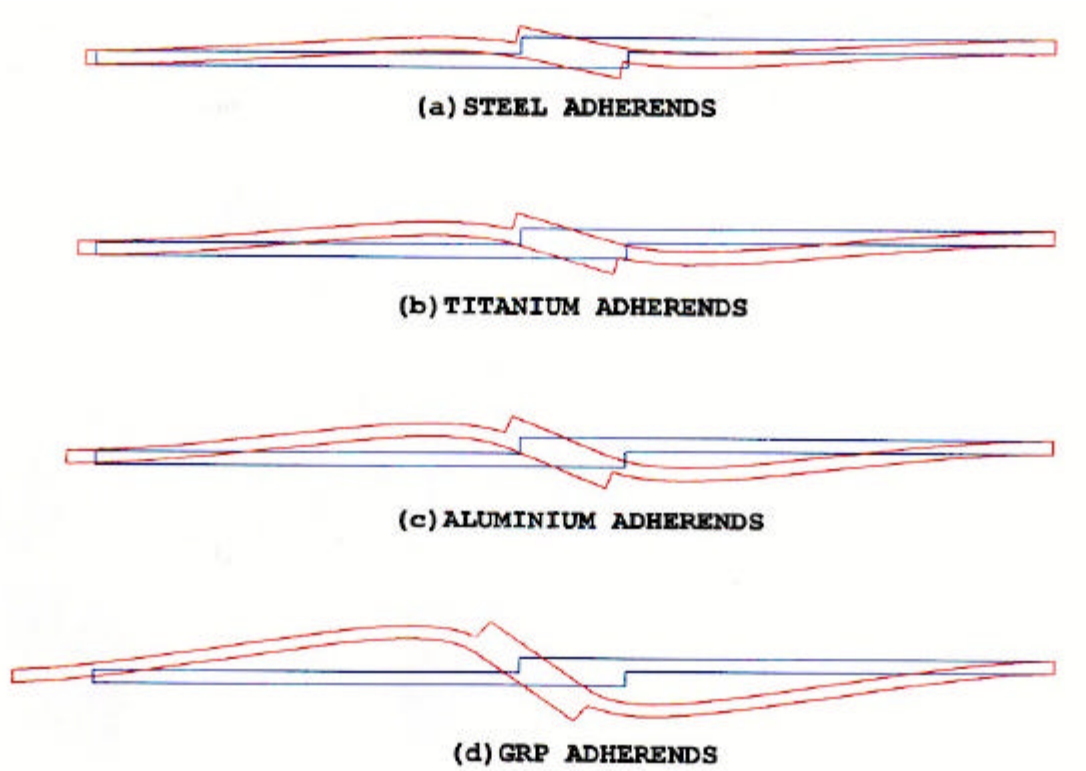


Figure 7 - Relative deformation of the single-lap joint for different substrate materials.

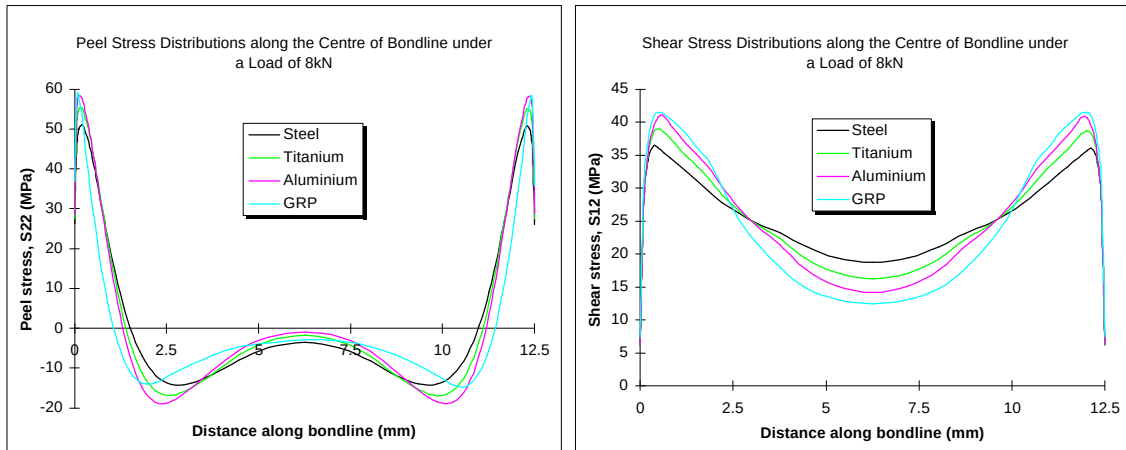


Figure 8 - Peel and shear stress distributions along bondline for different substrate materials.

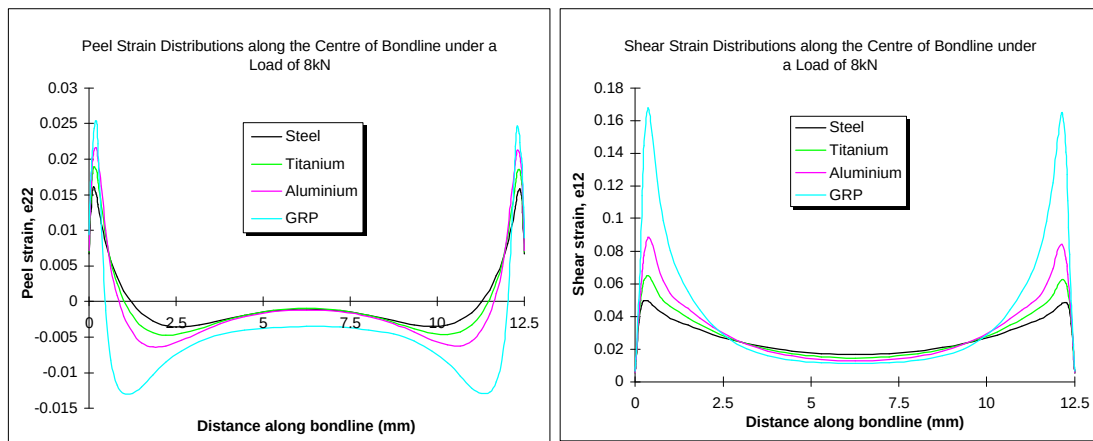


Figure 9 - Peel and shear strain distributions along bondline for different substrate materials.

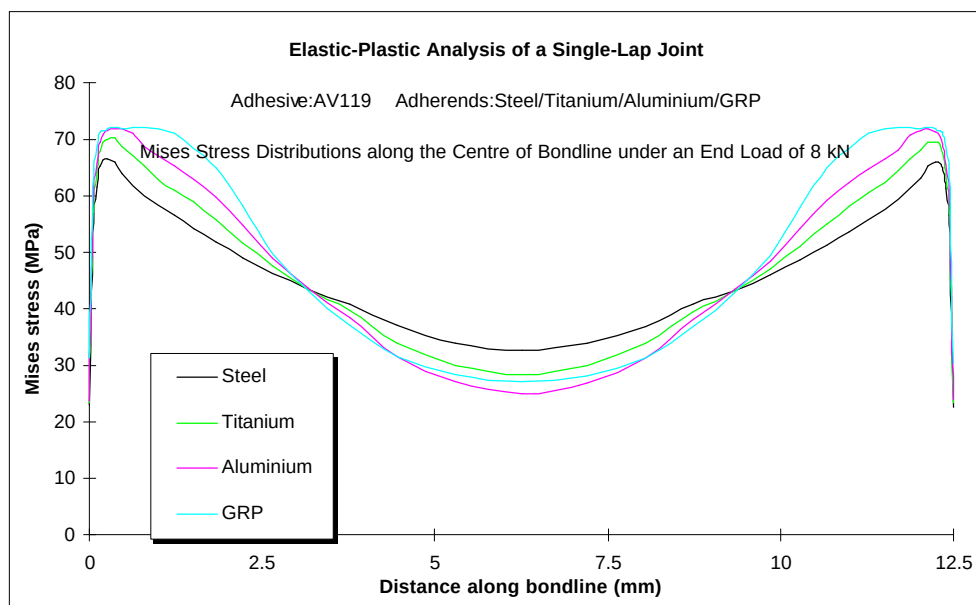


Figure 10 - Mises stress distribution along bondline for different substrate materials.

Maximum peel stress is similar in magnitude to that of the maximum shear stress, but whereas the shear stress gradually decreases to a minimum value at the centre of the overlap length, peel stress rapidly decreases within 1.5 mm from the ends of the overlap. The corresponding strain distributions follow a similar pattern, but with two noticeable differences. The maximum shear strain is at least three times as large as the maximum peel strain and the shear strain distribution along the centre of the bondline is far less uniform than the corresponding shear stress distribution. The Mises equivalent stress distributions (Figure 10) show that a large change in joint stiffness induces a relatively small change in the maximum equivalent stress. An eight fold increase in tensile modulus produced a 7% reduction in the maximum equivalent stress.

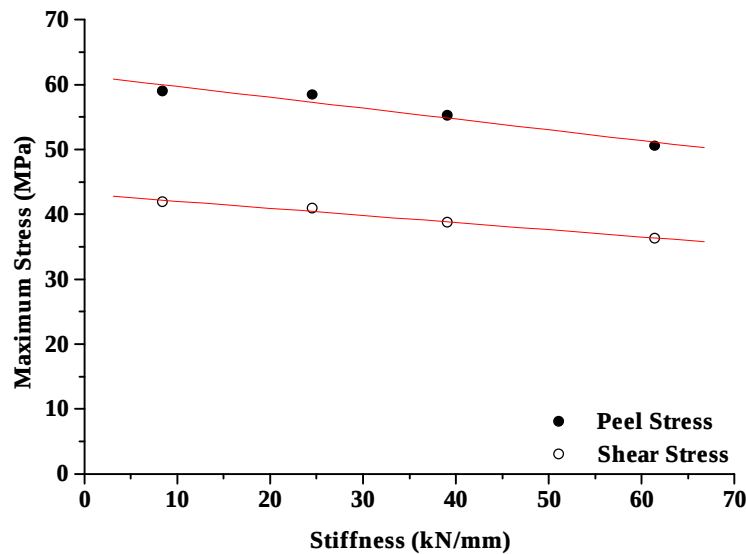


Figure 11 - Maximum peel and shear stresses as a function of joint stiffness.

Figure 11 shows the effect of joint stiffness on both the maximum peel and maximum shear stresses at the ends of the overlap for the different substrate materials. The results are based on the elastic-plastic analysis for a joint subjected to an applied load of 8 kN. Both the maximum shear stress t_{MAX} and maximum peel stress s_{MAX} tend to decrease linearly with increasing joint stiffness.

4.2 ADHEREND THICKNESS

A series of finite element analyses were conducted in order to evaluate the effect of changing the adherend thickness from 0.8 mm to 3.2 mm on the stress and strain distributions within the adhesive layer of the single-lap joint. The basic configuration used in the analyses is shown in Figure 5. The materials used in the study were 5251 aluminium and AV119 epoxy adhesive.

The results of the analyses show that as the adherend thickness increases, the peel and shear stresses and strains decrease (Figures 12 and 13). An applied load of 8 kN was used in the analyses. Increasing the adherend thickness results in an increase in joint stiffness and a reduction in out-of-plane deformation, thus lowering the maximum shear and peel stresses and strains present at the ends of the overlaps. The maximum equivalent stress (Figure 14) is relatively insensitive to changes in adherend thickness; as expected.

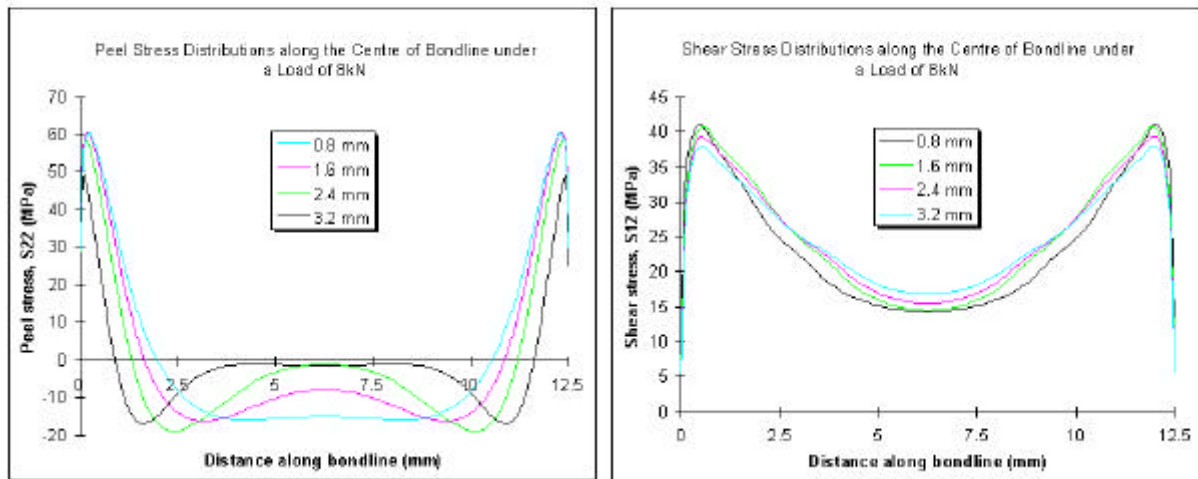


Figure 12 - Peel and shear stress distributions for different substrate thickness.

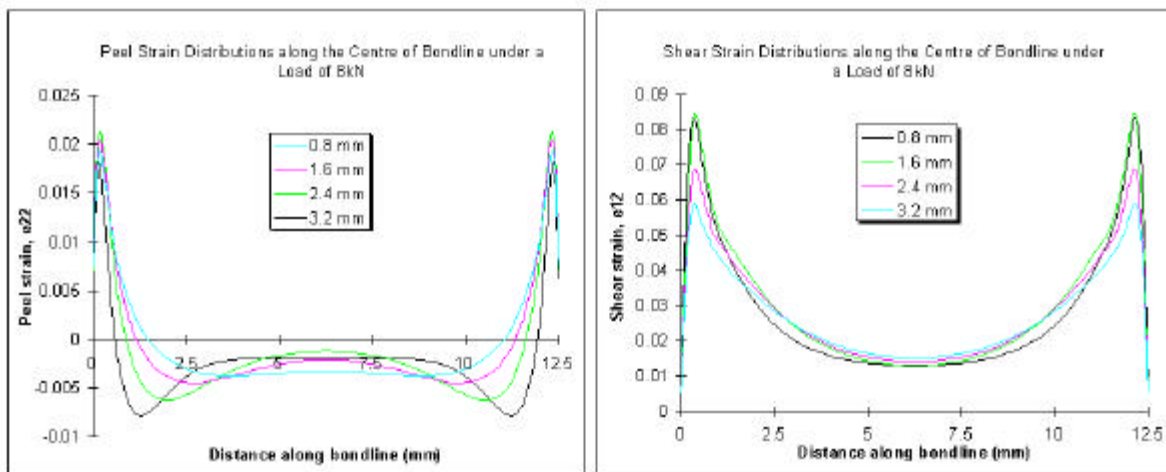


Figure 13 - Peel and shear strain distributions for different substrate thickness.

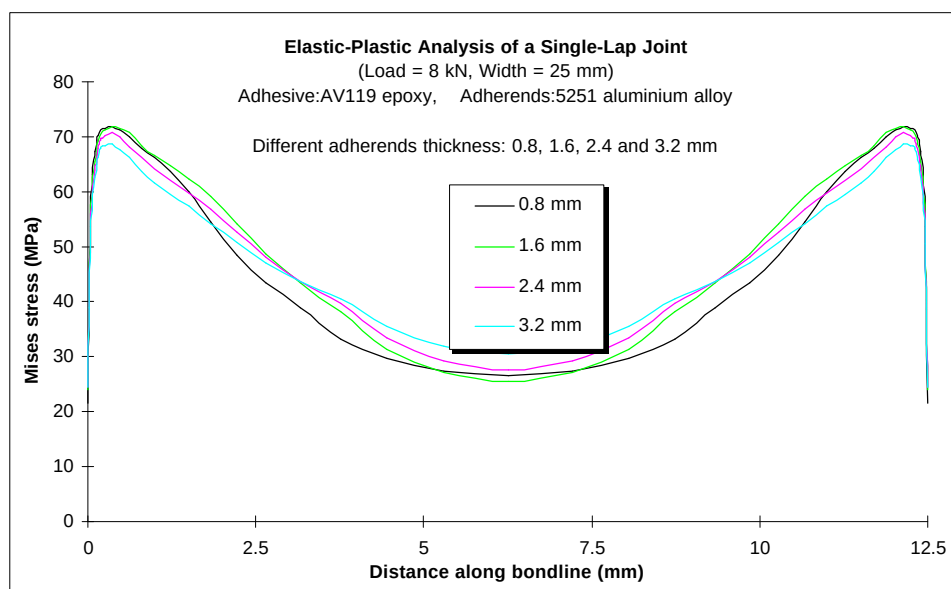


Figure 14 - Mises stress distribution along bondline for different substrate thickness.

Figure 15 shows the effect of adherend thickness on both the maximum peel and maximum shear stresses at the ends of the overlap for the different substrate materials. The results are based on the elastic-plastic analysis results shown in Figures 12 and 13.

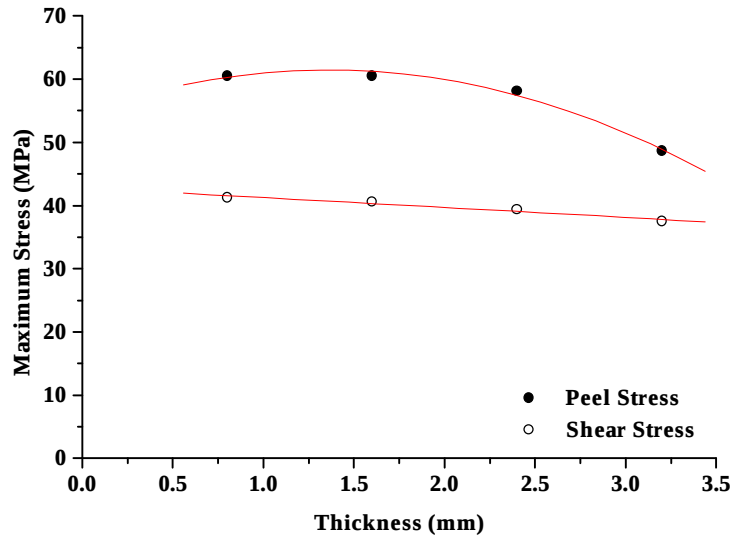


Figure 15 - Maximum peel and shear stresses as a function of substrate thickness. (lines added simply to aid the eye)

4.3 LOAD

Elastic-plastic analysis conducted on the basic single-lap joint configuration (Figure 5) shows that as the applied load on the single-lap joint increases, the maximum shear and peel stresses and strains decrease, and the shear, peel and Mises stress distributions along the centre of the bondline become more uniform (Figures 16 to 21). The change in stress profiles with increasing load can be attributed to plastic deformation of the constituents at high stress levels. In practice, however, the joint would have failed before reaching an applied load of 12.62 kN.

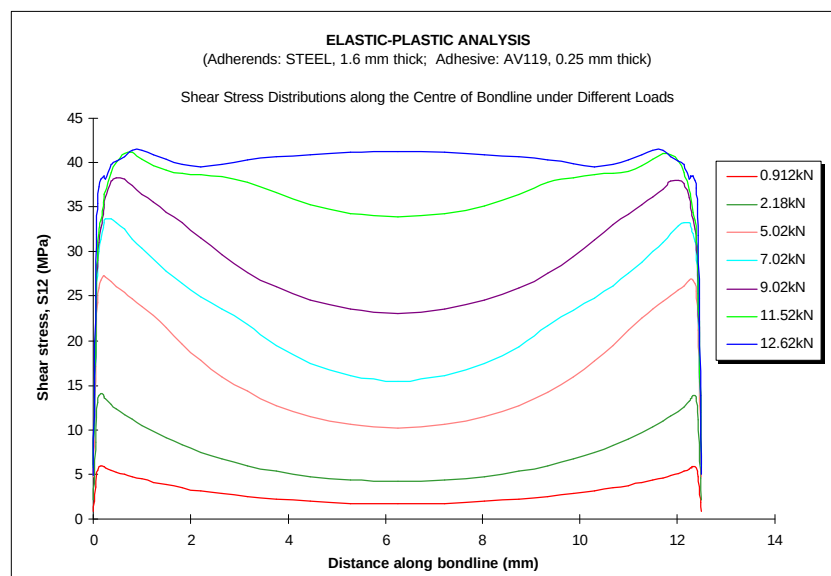


Figure 16 - Shear stress distributions under different loads. (CR1 mild steel/AV119 epoxy joints)

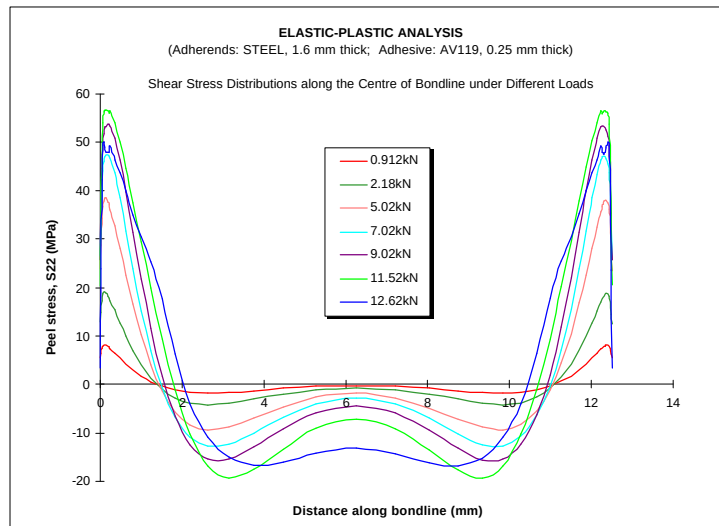


Figure 17 - Peel stress distributions under different loads.
(CR1 mild steel/AV119 epoxy joints)

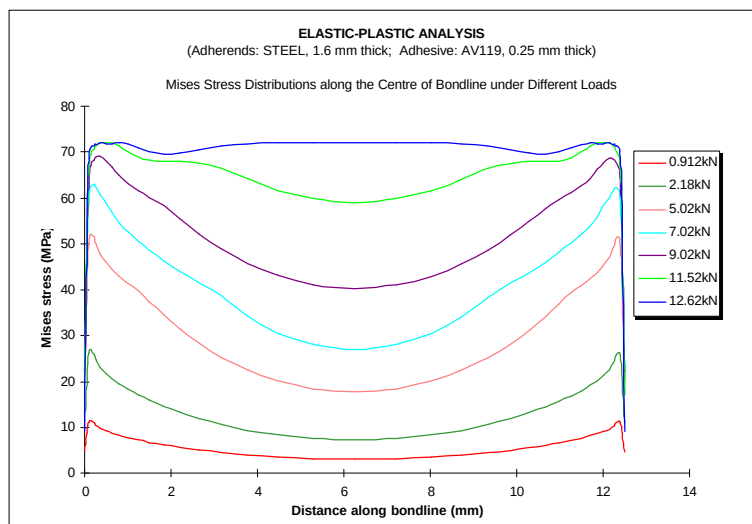


Figure 18 - Mises stress distributions under different loads.
(CR1 mild steel/AV119 epoxy joints)

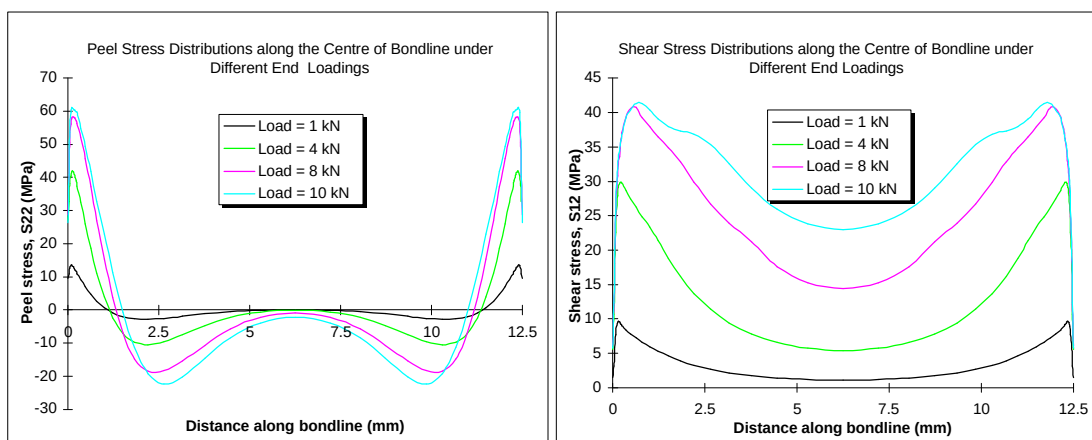


Figure 19 - Peel and shear stress distributions under different loads.
(5251 aluminium alloy/AV119 epoxy joints)

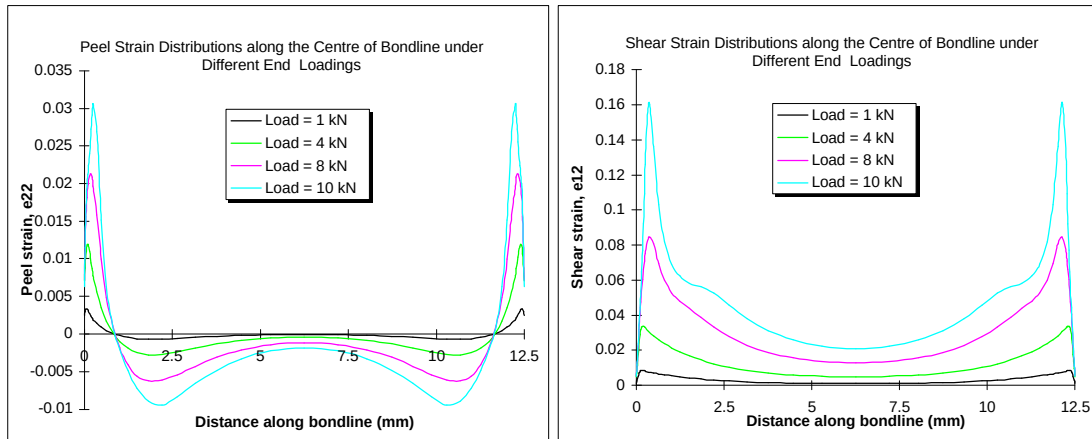


Figure 20 - Peel and shear strain distributions under different loads.
(5251 aluminium alloy/AV119 epoxy joints)

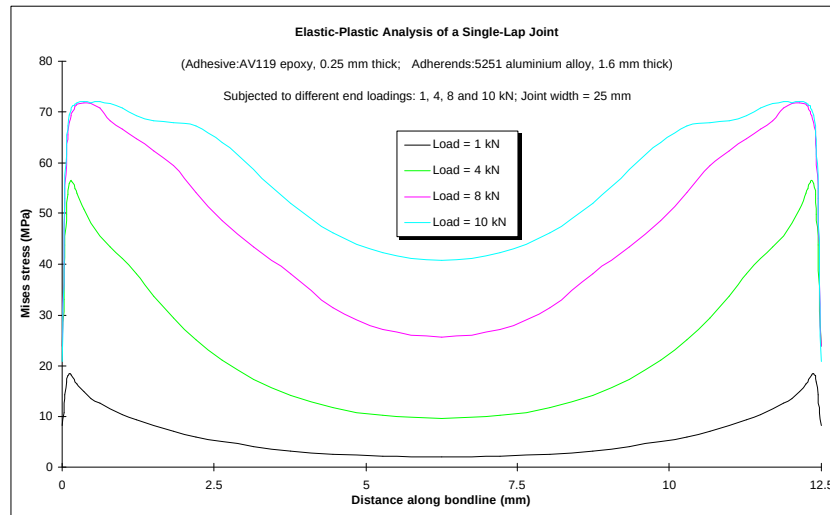


Figure 21 - Mises stress distribution under different loads.
(5251 aluminium alloy/AV119 epoxy joints)

Similar trends were observed for the other two substrate materials. It is interesting to note that as the tensile load increases, the ratio of maximum shear to maximum peel stress (t_{MAX}/s_{MAX}) increases and thus the peel stresses become less dominant. Mises equivalent stress distribution follows a similar trend to that observed for shear.

4.4 ADHESIVE THICKNESS

In this study the effect of adhesive thickness on the stress and strain distributions in the single-lap joint was evaluated. Again, the basic joint configuration shown in Figure 5 was used for the analyses. The substrate material was 5251 aluminium bonded with AV119 epoxy. Four adhesive thickness values (0.25, 0.5, 0.75 and 1.00 mm) were considered. Applied load to the ends of the joint was kept constant at 8 kN. Increasing the adhesive thickness resulted in a marked decrease in the maximum peel and maximum shear stresses and strains at the ends of the overlap (Figures 22 and 23). This reduction stress magnitude is accompanied by a reduction in adhesive plastic deformation. As expected, the corresponding Mises stress distributions along the centre bondline (Figure 24) closely follow the shear distribution. Increasing adhesive thickness from 0.25 mm to 1.00 mm resulted in a 12-13% reduction in the equivalent maximum stress.

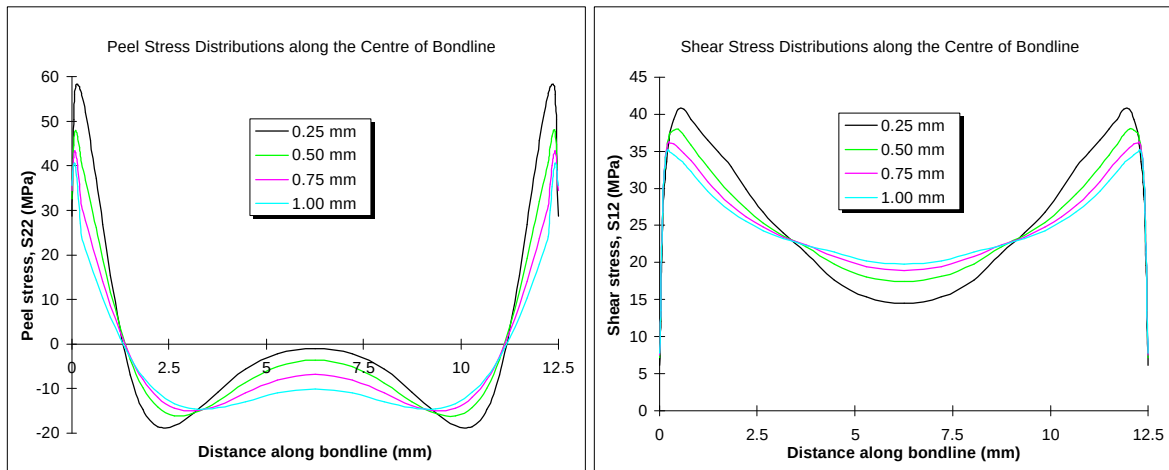


Figure 22 - Shear and peel stress distributions for different adhesive thickness.

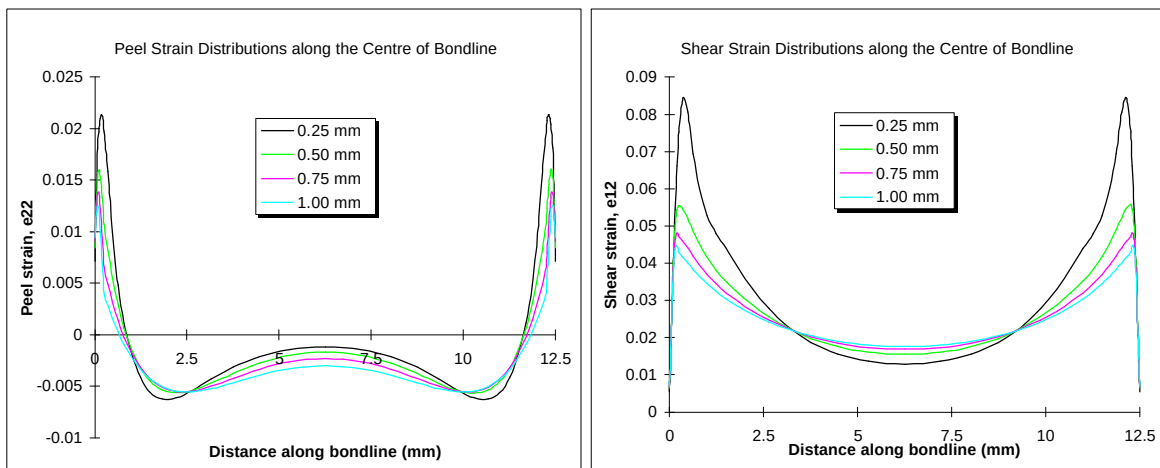


Figure 23 - Shear and peel stress distributions for different adhesive thickness.

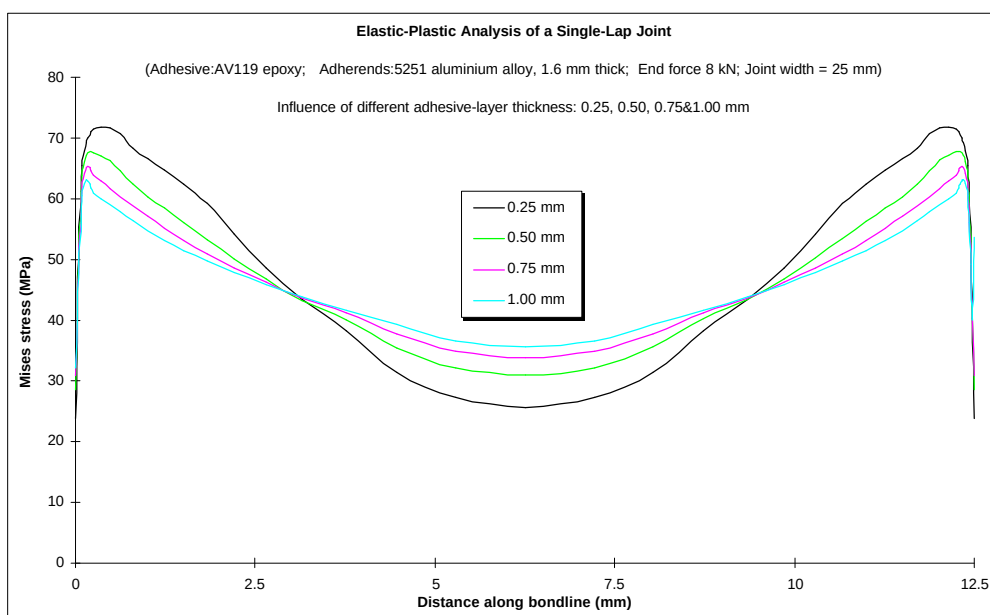


Figure 24 - Mises stress distribution for different adhesive thickness.

The maximum shear stress t_{MAX} tends to decrease linearly with increasing adhesive thickness, whereas the maximum peel stress s_{MAX} appears to asymptote to a minimum value.

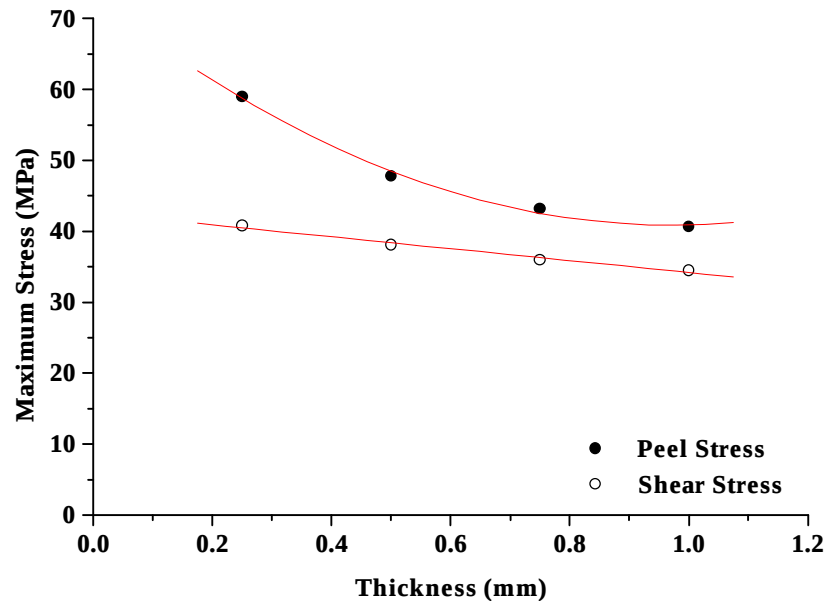


Figure 25 - Maximum peel and shear stresses as a function of adhesive thickness.
(lines added simply to aid the eye)

5. EVALUATION OF THE EFFECT OF ENVIRONMENTAL DEGRADATION

Moisture (water) degradation is often the cause of in-service failure in bonded structures. The ubiquitous nature of water combined with the ability to penetrate into the adhesive structure poses considerable problems. This problem is further exacerbated at elevated temperatures. Hot and humid environments can often cause rapid loss of strength in metal/epoxy adhesive joints within a short duration (i.e. 2 years) with catastrophic consequences. Failure invariably occurring at the adhesive/adherend interface. Even in applications where there are low levels of moisture, water absorption and its effects on mechanical integrity can present problems to the designers. It is therefore essential that the end user and adhesive manufacturer possess the necessary tools for selecting and characterising an adhesive system.

The work presented in this section is concerned with the consequences of moisture degradation of adhesive properties on the performance of adhesive joints. Mass diffusion is considered to be the primary transport process. Consequently, weakening of the joint due to moisture absorption is assumed to occur through plasticisation of the adhesive and failure is assumed to be cohesive in nature. Although in-service failures invariably occur at the adhesive/adherend interface, the joint behaviour is primarily controlled by the coupled mechanical-diffusion response of the adhesive and adherend (e.g. polymer matrix composites). A scheme is presented below that enables the redistribution of stresses in bonded joints due to moisture ingress to be assessed. The modelling procedure consists of two phases:

- (i) Modelling of the moisture absorption in the adhesive layer, and
- (ii) Modelling of the mechanical-diffusion interaction.

5.1 MODELLING OF MOISTURE ABSORPTION

The first step in assessing the environmentally degraded response of bonded joints is finding the temporal and spatial distribution of moisture within the adhesive layer. Analytical expressions for the moisture distribution as a function of time of homogenous materials exposed on one or both sides to water were presented by Shen and Springer [7]. The problem is pictured in Figure 26, where the plate is taken to be infinitely long in the y - and z -directions. The moisture content inside the plate varies only in the x -direction (i.e. the problem is one-dimensional). Initially the moisture concentration c_i inside the plate is uniform. The plate is suddenly exposed to a moist environment and the exposed faces instantaneously reach the equilibrium moisture concentration c_a which remains constant.

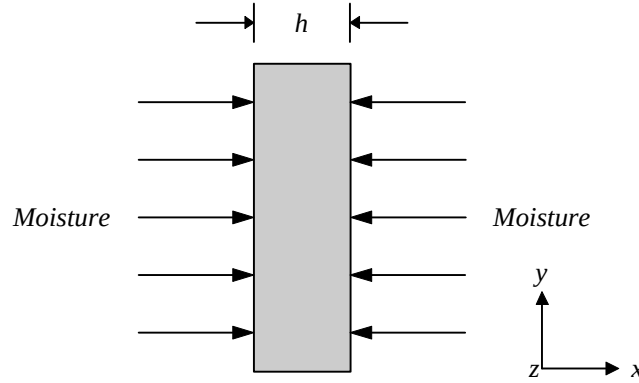


Figure 26 - Graphical representation of one-dimensional diffusion problem.

The moisture uptake is described by Fick's law [8]:

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} \quad (1)$$

where D_x is the diffusivity of the material and the boundary conditions are:

$$c = c_i \quad 0 < x < h \quad t \leq 0 \quad (2a)$$

$$c = c_a \quad x = 0; x = h \quad t > 0 \quad (2b)$$

It has been observed [9] that the diffusivity changes very little with moisture content and thus the solution to Equations (1) and (2) is given by [10]:

$$\frac{c(t) - c_i}{c_a - c_i} = 1 - \frac{4}{p} \sum_{j=0}^N \frac{1}{(2j+1)} \sin \frac{(2j+1)px}{h} \exp \left[-\frac{(2j+1)^2 p^2 D_x t}{h^2} \right] \quad (3)$$

where N is the number of summation terms and $c(t)$ is the instantaneous concentration.

Equation (3) was used to compute the moisture distribution at the nodal co-ordinates within the adhesive in the single-lap joint, assuming the only concentration gradient is along the bond length and $c_i = 0$. Figure 27 shows the moisture distribution for different time periods up to 12 days for CR1 mild steel/AV119 epoxy single-lap joints, using a diffusion coefficient of $6.7 \times 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$. Whilst this value is significantly higher than the diffusion coefficient generated from bulk AV119 samples ($6.4 \times 10^{-13} \text{ m}^2 \cdot \text{s}^{-1}$), it agrees favourably with the diffusion

coefficient calculated from equivalent types of joint samples [11]. Comparative studies between the bulk and joint diffusion process indicate that care needs to be taken if the calculated value of the diffusion coefficient of bulk adhesives is used to predict the extent of water penetration in an adhesive joint [12]. There are significant differences between bulk and joint behaviour, which are attributed mainly to interfacial or capillary diffusion effects.

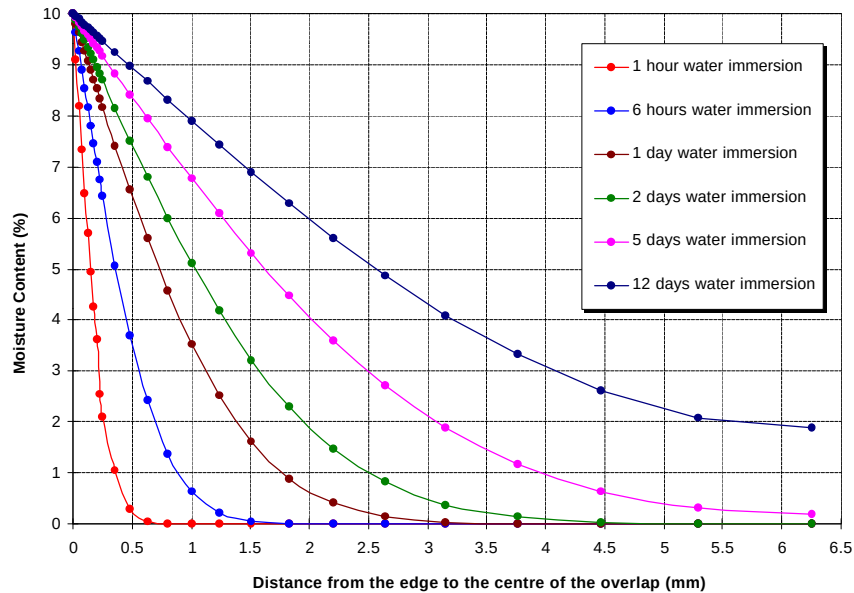


Figure 27 - Predicted moisture concentration distributions along the adhesive layer.

The resulting moisture distribution along the overlap, shown in Figure 27, indicates that the joint is far from the equilibrium moisture content after 12 days of water immersion. The moisture profile is symmetric and decreases steadily from saturation level of 10% at the overlap ends to a dry state at the centre of the overlap.

In cases where the geometry is irregular and/or the problem is no longer one-dimensional, a simple analytical solution is not available. An improved scheme, utilising a transient finite element technique, has been recently developed to enable the assessment of three-dimensional moisture uptake [13]. This approach yields more accurate representations of the moisture concentration field and it can be sequentially coupled with a mechanical analysis.

5.2 MODELLING THE MECHANICAL DIFFUSION INTERACTION

Modelling the mechanical-diffusion interaction requires the moisture-dependent mechanical properties of the adhesive to be determined experimentally. These were obtained from bulk tests performed on the specimens that have been exposed to hot/wet conditions at varying periods of time. The specimens were immersed in distilled/deionised water at 60°C. Batches of conditioned specimens were withdrawn at selected intervals over a 12 day period. Testing was performed under ambient conditions (23 °C and 50% relative humidity) at a constant displacement rate of 1 mm/min using an Instron test frame. Two test specimens, prepared to ISO 527:2 [6] specifications, were tested for each conditioning time period. The resulted tensile stress-strain data are shown in Figure 28. It can be seen, that the result of increased exposure time was to reduce the elastic modulus and the yield stress of the adhesive. The strain-to-failure steadily increased with conditioning time and noticeable plasticisation and necking was observed in specimens that were conditioned for up to 5 days. Test samples tested after 12 days of water immersion failed at low strain levels. This brittle failure mode was attributed to the chemical degradation of the epoxy resin due to the extended period of environmental conditioning.

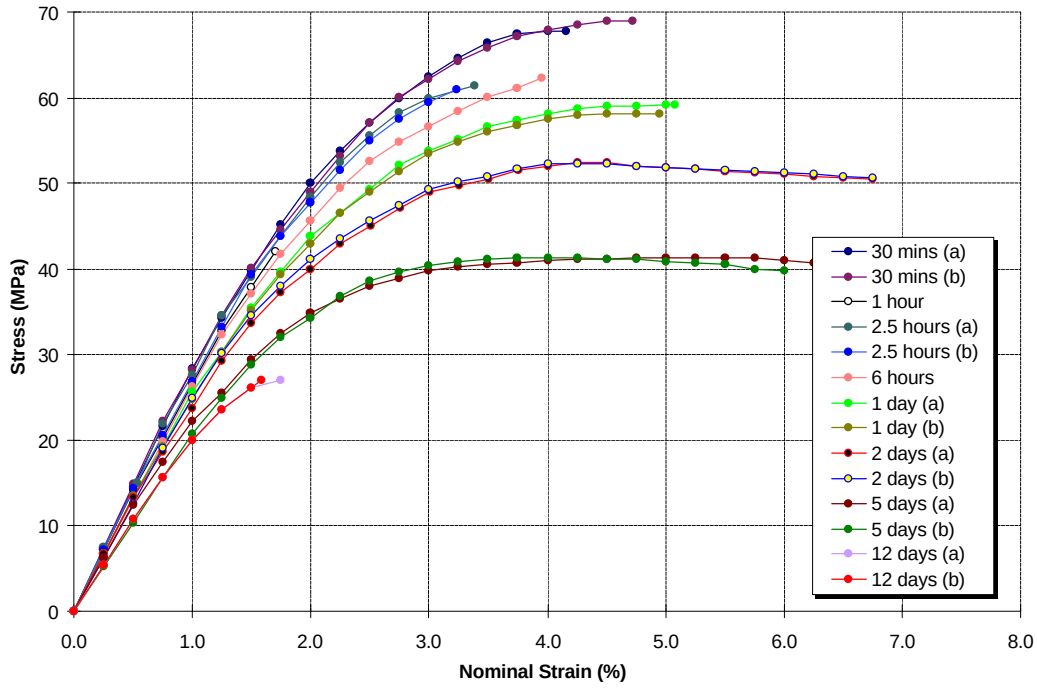


Figure 28 - Stress-strain curves for different water immersion periods.

Weight uptake measurements were carried out for each bulk test specimen, as well as, for one additional specimen for each conditioning time. All specimens were dried and weighed prior to being immersed in water. Specimen weight was recorded as a function of time and the percentage moisture content, M , was calculated using the expression:

$$M = \frac{(W_i - W_0)}{W_i} \times 100\% \quad (8)$$

where W_i and W_0 are the initial and final weight of the specimen, respectively. The moisture uptake is plotted as a function of exposure time in Figure 29(a). The effect of increased moisture content on the properties of the adhesive is shown in Figure 29(b). The elastic modulus and Poisson's ratio were reduced by 35% and 20%, respectively, over a time period of 12 days.

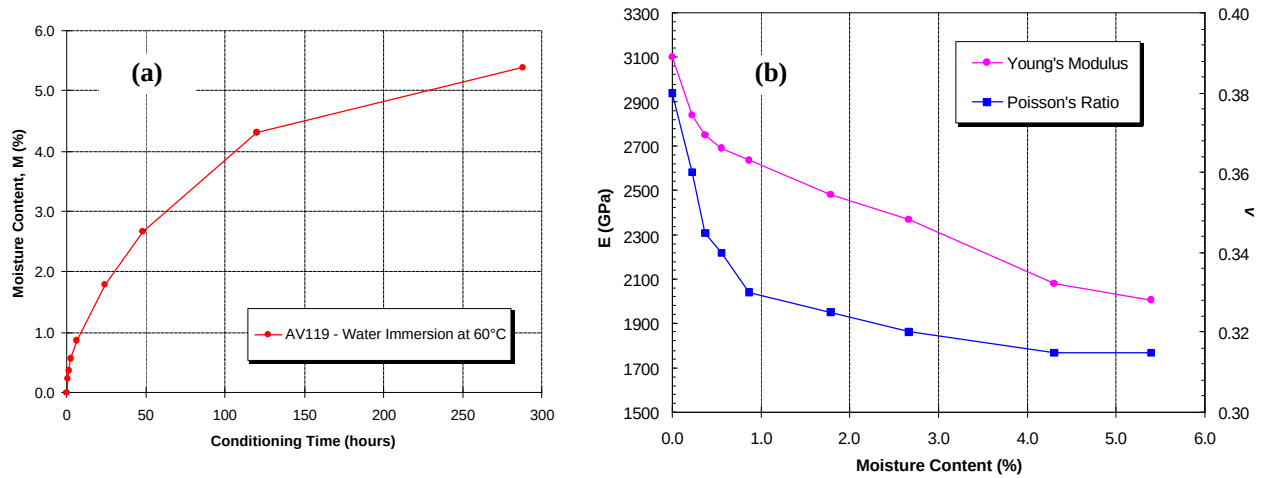


Figure 29 - Water immersion of AV119 adhesive. (a) Moisture uptake as a function of time; and (b) Effect of moisture content on Young's modulus and Poisson's ratio.

The moisture-dependent stress-strain data, shown in Figure 29, enabled the full non-linear description of the bulk adhesive properties for use in the finite element model. Using the analytical solution for the moisture profile along the overlap, a different material curve was used for each element in the adhesive layer. The material properties corresponding to any mass uptake of water were determined by interpolation between the two adjacent curves. However, experimental data for the fully saturated state were not available. Therefore, the mechanical properties of the adhesive for the equilibrium moisture content were determined by extrapolation. For the purposes of analysis, the equivalent plastic strain for each conditioning time was extended to 5%.

5.3 CONDITIONED JOINT ANALYSIS RESULTS AND DISCUSSION

Full non-linear elastic-plastic analyses were undertaken for the dry and conditioned CR1 mild steel joints bonded with AV119 epoxy adhesive. The joint geometry was similar to that shown in Figure 5. The adhesive and adherend thickness were 1.4 mm and 0.25 mm, respectively. The effect of moisture absorption on the stress distribution within the adhesive layer was investigated.

The results of the finite element analysis of the conditioned joints were markedly different from those of the dry joint. In the dry joint the maximum equivalent, shear and peel stresses occurred at the end of the overlap. In the conditioned joint, however, the load transfer was no longer concentrated at the end of the overlap and the maximum stresses in the adhesive exhibited inboard peaks in the interior of the adhesive bondline. The Mises equivalent stress at the end of the overlap of the conditioned joints was reduced to 20 MPa, a 50% reduction in stress compared with the dry joint (Figure 30). This behaviour was due to the wetter adhesive at the ends of the overlap being able to sustain much lower levels of stress and thus transfer less load. Redistribution and enlargement of the plasticity zones was also observed (Figure 31). Significant increase of the adhesive equivalent plastic strain was observed after 12 days of water immersion. The variation of shear and peel stress along the centre bondline of the adhesive is shown in Figures 32 and 33. Finite element results indicated that moisture absorption had little effect on the stiffness of the joint, typically 5% reduction after 12 days of water immersion.

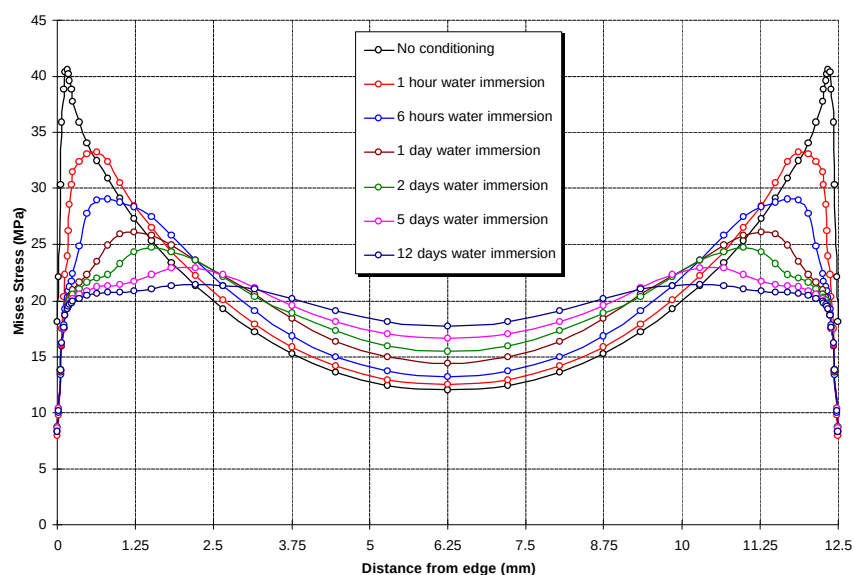


Figure 30 - Mises Stress Distribution Along the Centre of Bondline Using Elastic-Plastic Material Properties (Single Lap Joint, CR1/AV119, Water Immersion at 60°C)

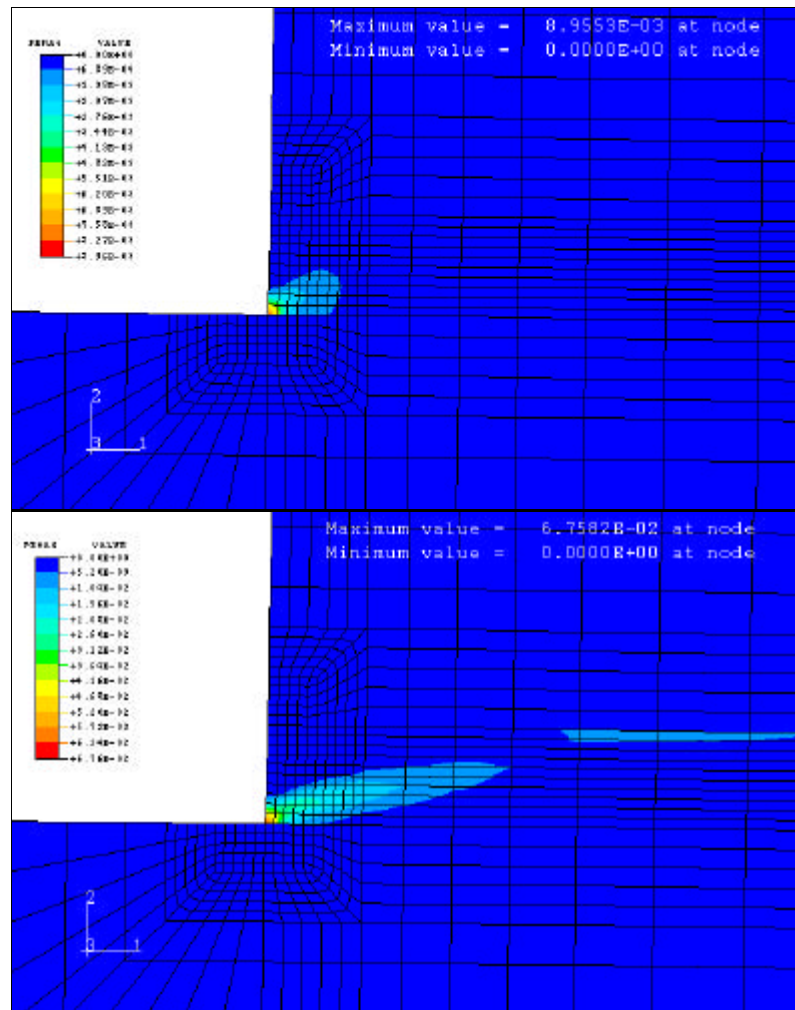


Figure 31 - Plastic strain magnitude.
(Top) unconditioned; and (Bottom) 12 days immersion at 60°C.

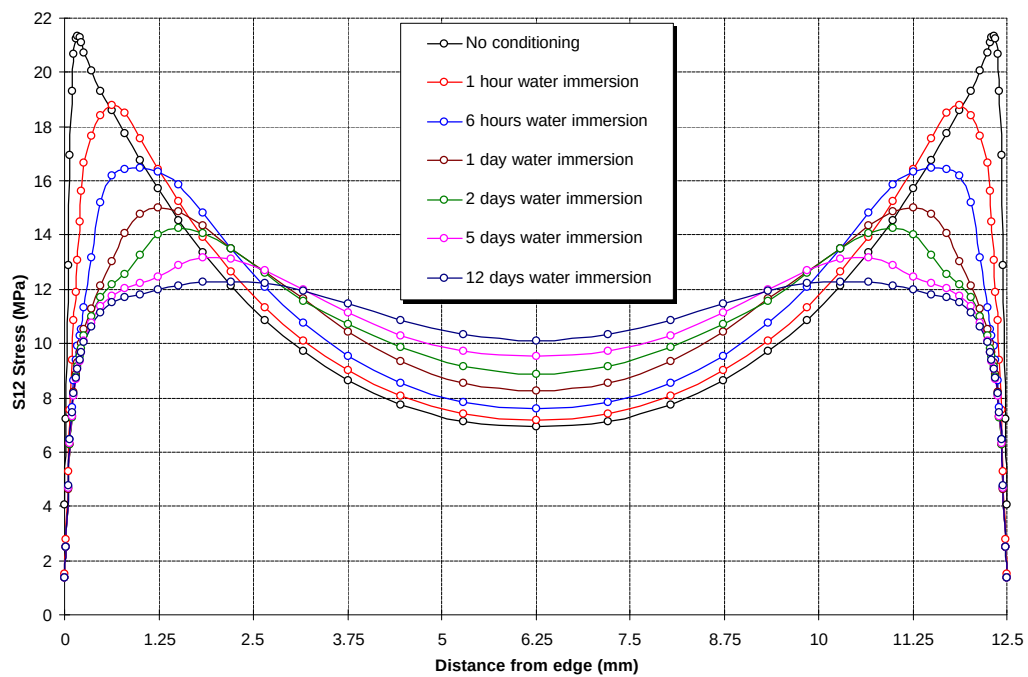


Figure 32 - Shear Stress Distribution Along the Centre of Bondline with exposure time.

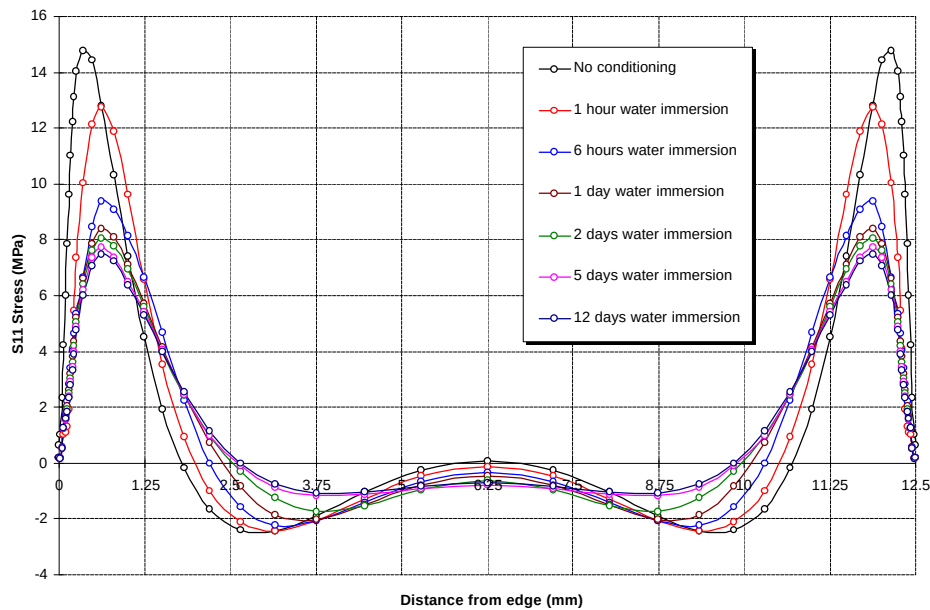


Figure 33 - Peel Stress Distribution Along the Centre of Bondline with exposure time.

The loss of stiffness and strength of AV119 epoxy adhesive (Figure 29) due to the presence of moisture can be expected to have a major effect on the behaviour of the bonded joint. The FEA shows that the peel and shear stresses present at the ends of the overlap should decrease rapidly with moisture uptake. Within 12 days immersion in water at 60 °C the shear stress concentration present at the ends of the overlap should virtually disappear. Consequently, a uniform distribution of Mises equivalent stress should occur along the bondline. If no interfacial degradation were to occur, then the joint strength should increase with increasing exposure time due to the lowering of the peel and shear stresses.

In practice, the strength initially decreased with increasing exposure time due to interfacial degradation and then began to increase between 14 and 21 days (Figure 34). After 42 days exposure, the “apparent” shear strength was almost the same as for the unconditioned specimens. The results shown in Figure 34 was for a series of tests conducted on single-lap joint specimens immersed in distilled/deionised water for up to 42 days at five different temperatures ranging from 23 °C to 70 °C [14].

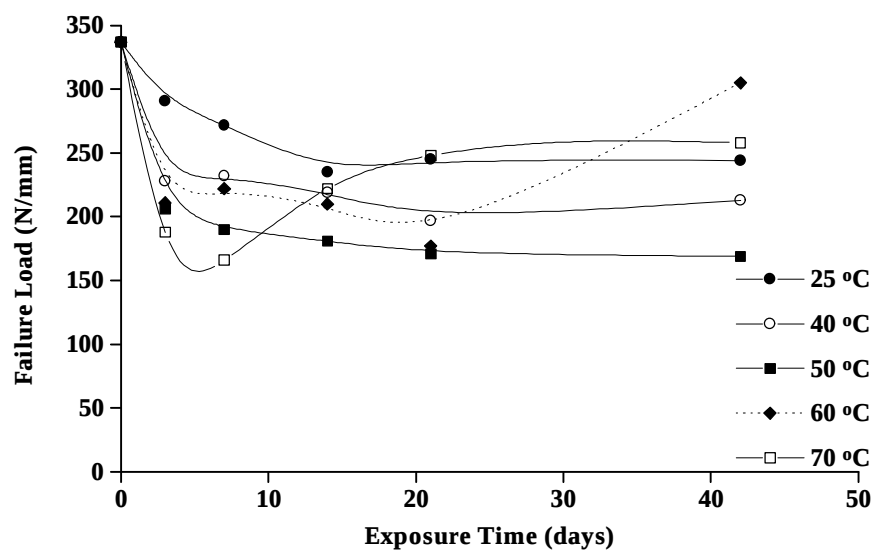


Figure 34 - Temperature and time dependence for the single-lap joint [14].

6. PERFORATED SINGLE-LAP JOINT

The introduction of holes within the bonded area is expected to increase the rate of moisture uptake and therefore the rate of degradation. In principle, the presence of drilled holes in the bonded area accelerates ageing by shortening the diffusion path and increasing the exposed bondline. Care needs to be taken to ensure structural integrity is not compromised through the introduction of the holes. The small diameter of the holes (i.e. 3 mm) is to prevent the possibility of yielding and fracture of the material between the holes. Tests conducted at the National Physical Laboratory on specimens with three 4 mm holes showed noticeable material yielding between the holes in the system studied.

This section evaluates the perforated single-lap geometry using FEA. The assessment examines the effect of changing the overlap dimensions and size of the holes. The effect of adhesive stiffness on the stress and strain distributions is also considered. A 20 node quadratic three-dimensional element was used for this exercise.

6.1 MOISTURE EFFECTS

FEA has been carried out on two test geometries (Figure 35 and Appendix 1) described below:

- (i) Standard geometry (Figure 5) with a bond length of 12.5 mm and a width of 25 mm containing three holes, 3 mm in diameter, located at the specimen centre, a low stress region within the joint overlap. The holes are equally spaced across the width of the specimen.
- (ii) Reduced geometry with a bond length of 10 mm and a width of 20 mm containing three holes, 4 mm in diameter, located at the specimen centre. Again, the holes are equally spaced across the width of the specimen.

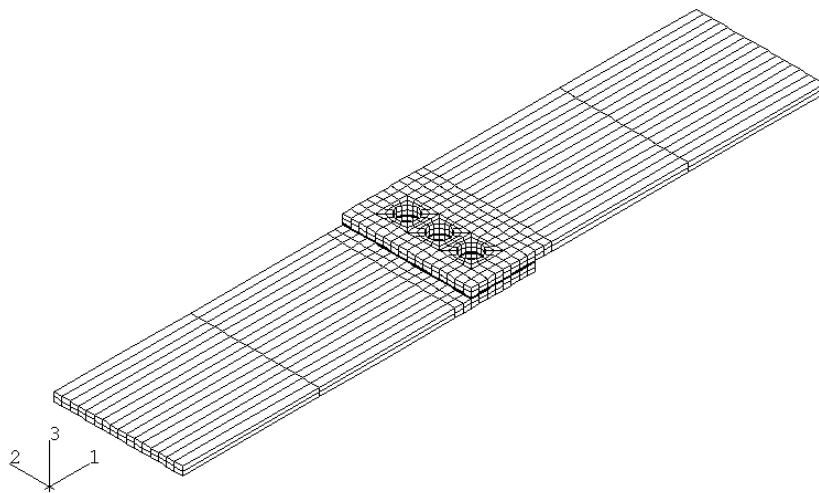


Figure 35 - Finite element mesh for the standard single-lap geometry.

The FEA has shown that the presence of holes accelerates moisture uptake and the normalised moisture concentration is only marginally different for the two perforated joint configurations after 12 days (see Appendix 1). Implying, the differences in bond area dimensions and hole size had only marginal influence on the time taken for the adhesive layer to reach saturation. The standard geometry could be used without having to resort to the smaller non-standard test geometry.

The question arises as to the cause of possible differences, in some cases large, that have been observed by other researchers when comparing the strength data from specimens with and without holes. Differences may reside with specimen fabrication rather than geometric factors. Unless the specimen is fully clamped and supported then thin sheet material can be expected to locally deform around the holes during the drilling process. Drilling may also damage any surface coatings used to promote adhesion or prevent corrosion. It is important that the adherend surfaces are perfectly flat and parallel. Poor contact could result in rapid degradation of the joint. Work at the National Physical Laboratory has shown that joints fabricated from pre-drilled adherends were slightly (5 to 10%) weaker in the unconditioned state than joints that were drilled after bonding.

6.2 INFLUENCE OF ADHESIVE PROPERTIES

A comparative FEA study was carried out on AV119 and XD4600 (Ciba Speciality Chemicals) to determine the effect of adhesive elastic properties on the stress and strain distributions within the adhesive layer of perforated single-lap joints manufactured from CR1 mild steel and 5251 aluminium alloy. The objective was to evaluate any changes that might occur in the vicinity of the holes due to changes in the elastic properties of the adhesive. Typical tensile and shear properties of AV119 and XD4600 are shown in Table 2.

The linear-elastic analysis results in Appendix 1 show that both Mises equivalent stresses and peel stresses at the ends of the overlap are higher than those present in the vicinity of the holes. The stress state away from the ends of the overlap is relatively uniform, although the stresses in the adhesive layer near the holes are higher than the surrounding material. An increase in the stiffness of the adherend or adhesive results in a more uniform stress state within the adhesive layer and lower shear and peel stress concentrations at the ends of the overlap and around the holes. Joints fabricated from CR1 mild steel should in principle require higher loads to failure than joints fabricated with 5251 aluminium alloy. Experimental results show that for single-lap joints (without holes) bonded with AV119, the steel joints are slightly stronger than the aluminium joints.

Table 2 – Typical Tensile and Shear properties for AV119 and XD4600

Property	Adhesive	
	AV119	XD4600
<u>Tension</u>		
Modulus (GPa)	3.05	1.71
Strength (MPa)	70	57.9
Poisson's Ratio	0.34	0.33
<u>Shear</u>		
Modulus (GPa)	1.10	0.64
Strength (MPa)	47	-

7. CONCLUSIONS AND DISCUSSION

Finite element analysis has been employed to perform a series of non-linear stress analyses of the single-lap shear joint under tensile load. The analysis involved two-dimensional modelling of parametric effects on the stress and strain distributions within the adhesive layer. Parametric studies revealed the stress and strain distributions are sensitive to adherend material properties, adherend thickness, adhesive thickness and applied load. The analyses also showed that peel stresses tend to be higher than shear stresses for most practical test geometries. In general, maximum stresses at the ends of the overlap were reduced by increasing the joint stiffness (i.e. increasing tensile modulus of the adherend or

increasing the adherend thickness) or by increasing the adhesive thickness. Subsequently, the “apparent” shear strength should increase. Although, titanium alloy joints have a lower stiffness than an equivalent joint fabricated from mild steel, the joints proved stronger because titanium has a far higher yield strength than the mild steel (see Figure 4).

Extensive mechanical testing revealed that the mechanical properties (i.e. stiffness and strength) of AV119 epoxy adhesive degrade due to the presence of moisture. The effect of stiffness loss with moisture can be expected to have a major effect on the behaviour of the bonded joint. FEA has shown that the peel and shear stresses and strains present at the ends of the overlap should decrease rapidly with moisture uptake and within 12 days immersion in water at 60 °C the shear stress concentration present at the ends of the overlap should disappear. Consequently, a uniform distribution of Mises equivalent stress should occur along the bondline. If no interfacial degradation occurs then the failure load in the initial stages of conditioning should increase with increasing exposure time due to the lowering of the peel and shear stresses at the ends of the overlap. As the moisture level at the centre of the joint approaches saturation, the ability of the joint to carry load can be expected to decrease. This is because the yield stress of the adhesive decreases with moisture content. In practice, the strength initially decreased with increasing exposure time due to interfacial degradation and then began to increase between 14 and 21 days. After 42 days exposure, the “apparent” shear strength was almost the same as for the unconditioned specimens. Longer term tests [15] have shown that the failure load decreases after 36 weeks.

The introduction of holes at the mid-length of the overlap was in principle expected to reduce the path length for moisture, thus accelerating the ageing process. The FEA supports the hypothesis (Appendix 1) that the presence of the holes accelerates moisture uptake. However, the critical region for failure to initiate is at the ends of the overlap. Therefore, the effect of moisture on the stress state at the ends of the overlap plays a major role in joint behaviour and can overshadow the effect of the holes. Statistical analysis has shown that the presence of the holes has minimal effect on joint strength where the adhesive is moisture sensitive (i.e. loss of stiffness and strength with increasing moisture content). The FEA shows that decreasing the dimensions of the overlap and increasing the diameter of the holes had only a marginal effect on the time taken for the joint to reach saturation and that the use of the non-standard geometry gives no advantage over the standard test.

The key observations from the work presented in this report are summarised in Table 3, which shows the effect of material and geometric parameters, and moisture content on joint stiffness, and the stresses and strains at the ends of the overlap. NPL Report CMMT(A) 198 [16] provides detailed analysis on the effect of overlap length, adhesive fillet and adherend corner radius on behaviour of the single-lap joint.

Table 3 – Summary of Parametric Studies

Property	Moisture content	Adherend Stiffness	Adherend Thickness	Adhesive Thickness
Joint stiffness	↓	↑	↑	↓
Equivalent Stress	↓	↓	↓	↓
Peel Stress	↓	↓	↓	↓
Axial Stress	↓	↓	↓	↓
Shear Stress	↓	↓	↓	↓
Plastic Strain	↑	↑	↑	↓

* Symbols ↑, ↓ and –, denote increase, decrease and no significant change in the joint properties, respectively.

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 Fangzhong Hu, Mr Richard Mera, Mr Richard Shaw 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.

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APPENDIX 1

FINITE ELEMENT ANALYSIS
PERFORATED SINGLE-LAP JOINT

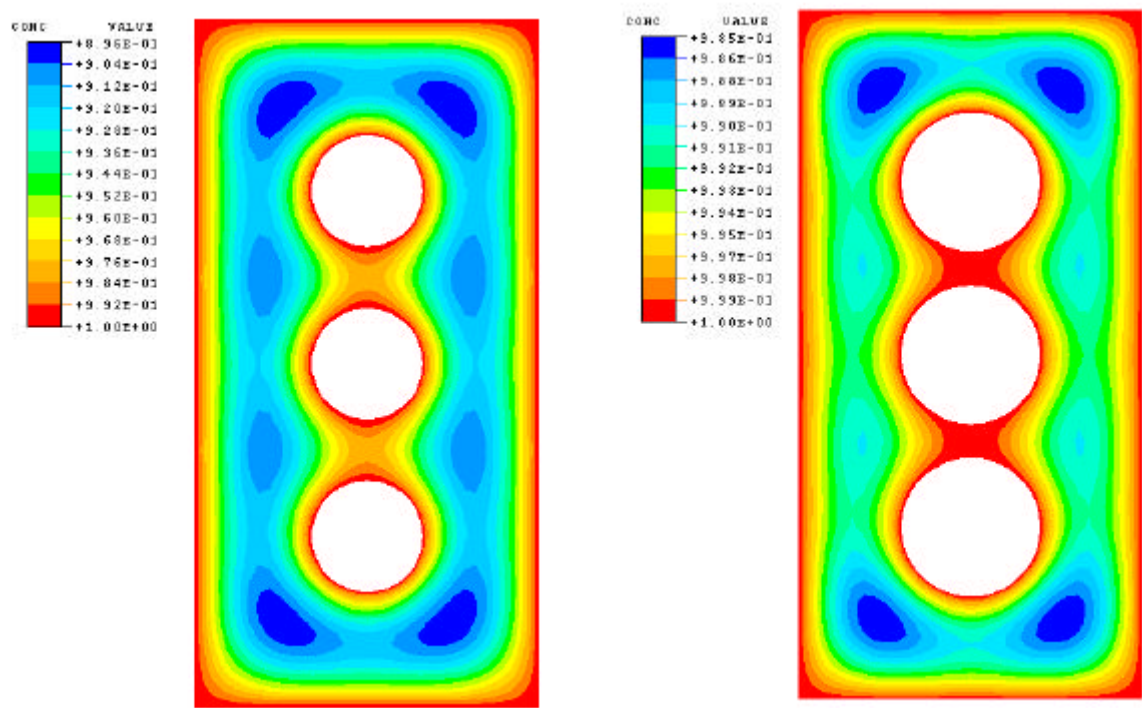


Figure A1 - Moisture contours for standard and miniature perforated single-lap joints.

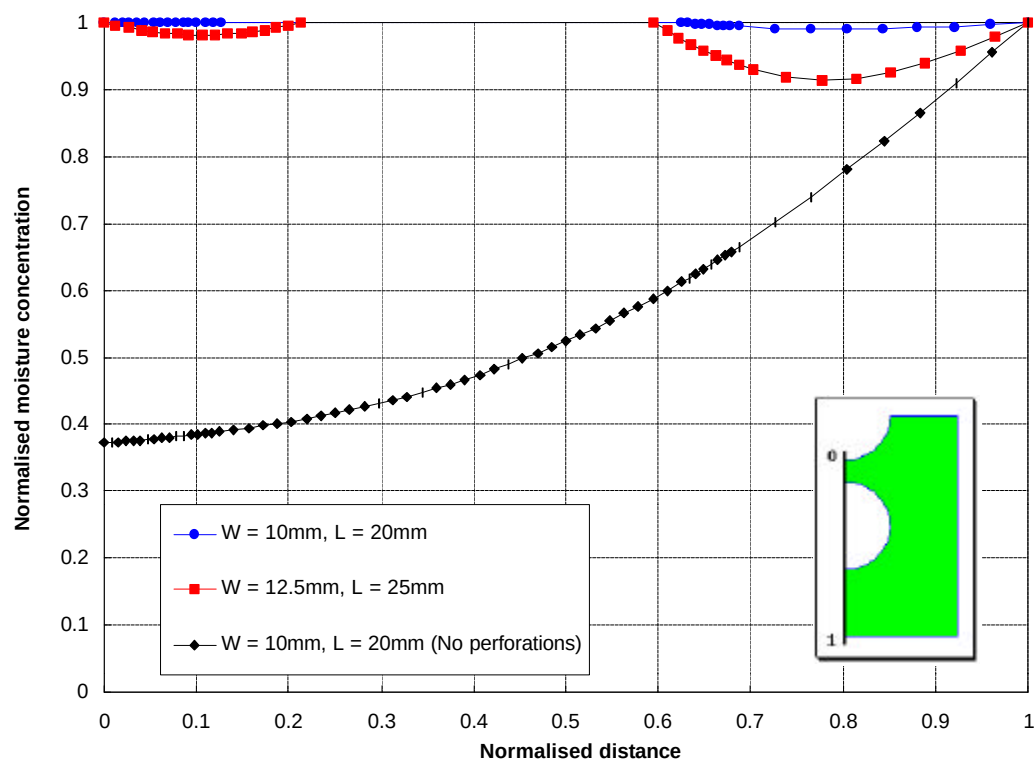


Figure A2 - Normalised moisture concentration across width.

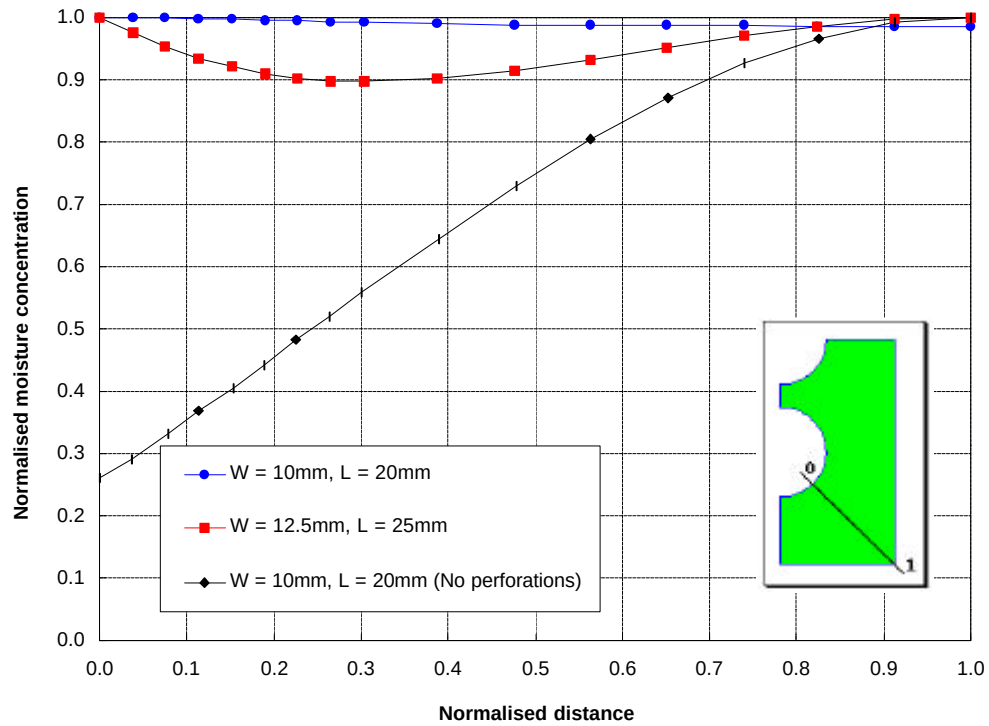


Figure A3 - Normalised moisture concentration - diagonal orientation.

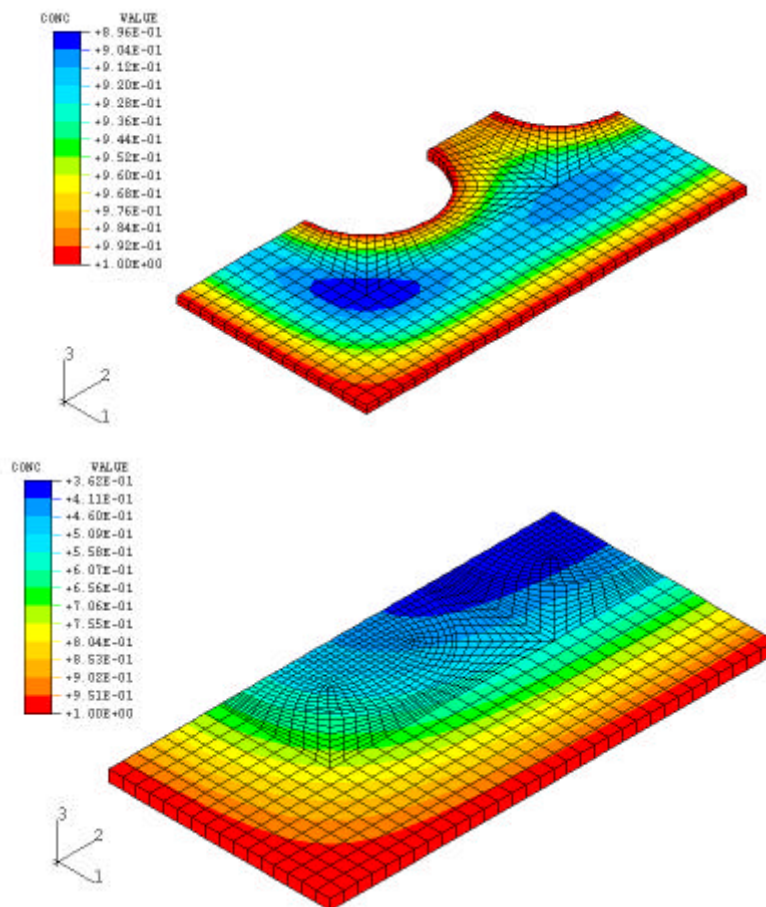


Figure A4 - Moisture contour maps for perforated (top) and unperforated (bottom) joints.

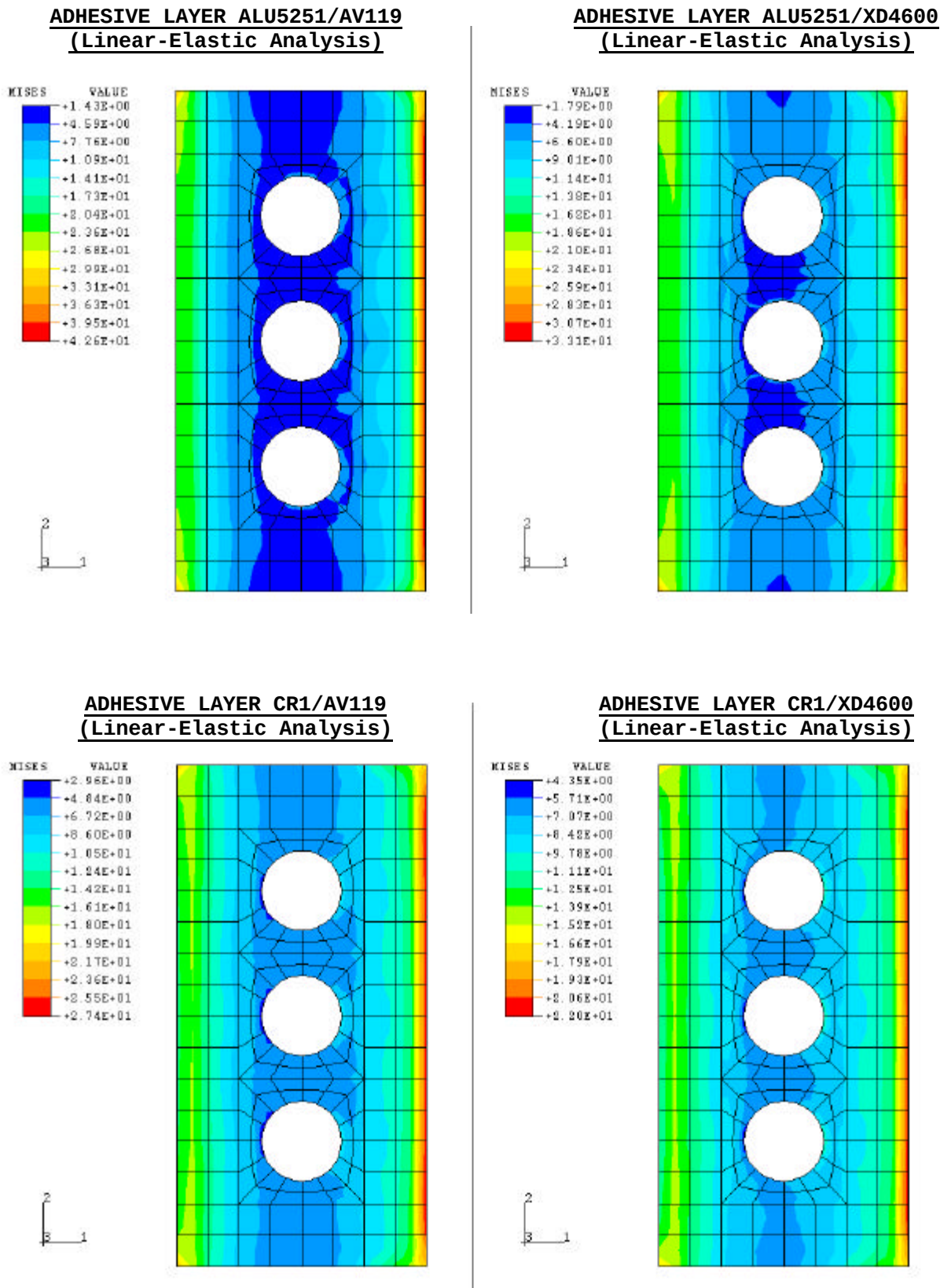
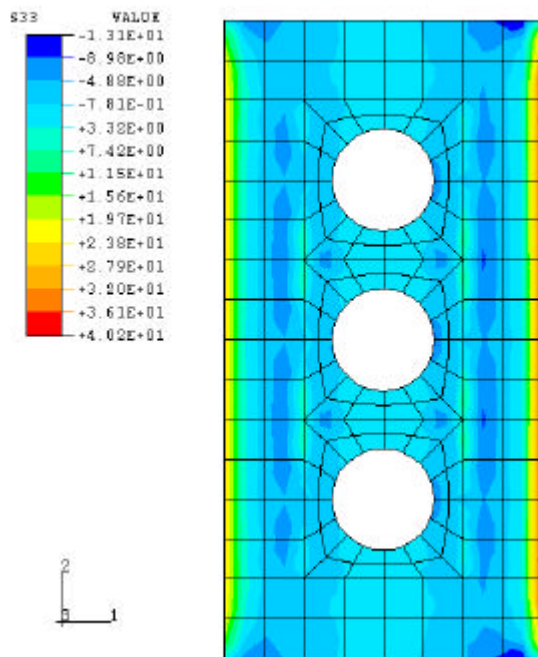
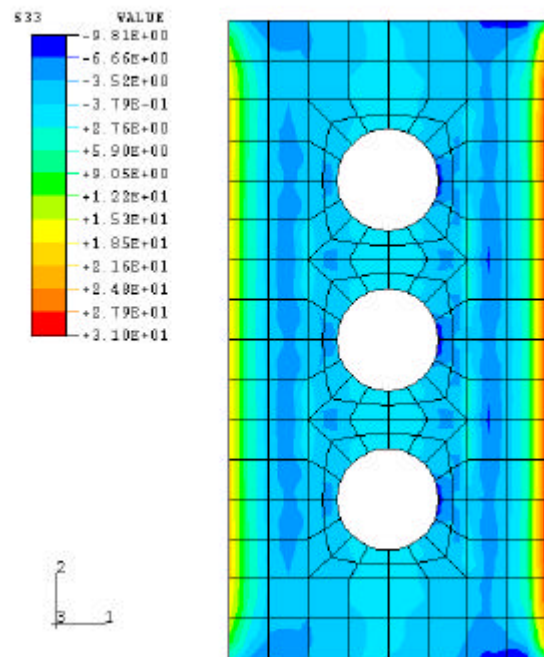


Figure A5 - Mises equivalent stresses at the adhesive layer.

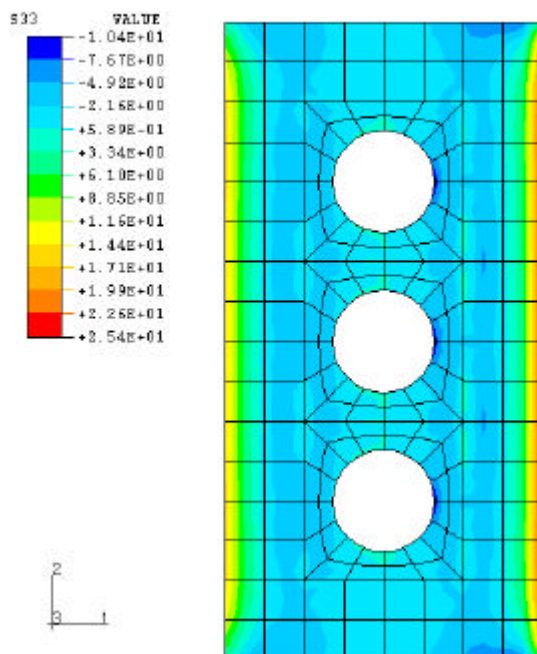
**PEEL STRESS AT THE ADHESIVE LAYER -
ALU5251/AV119 (Linear-Elastic Analysis)**



**PEEL STRESS AT THE ADHESIVE LAYER -
ALU5251/XD4600 (Linear-Elastic Analysis)**



**PEEL STRESS AT THE ADHESIVE LAYER -
CR1/AV119 (Linear-Elastic Analysis)**



**PEEL STRESS AT THE ADHESIVE LAYER -
CR1/XD4600 (Linear-Elastic Analysis)**

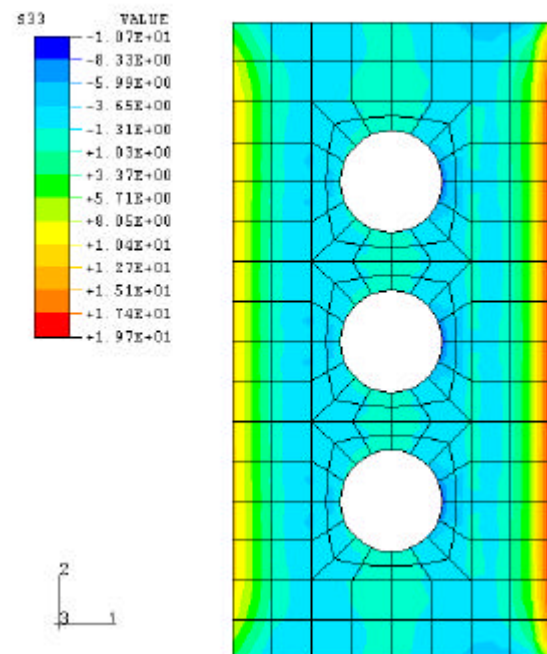


Figure A6 - Peel stresses at the adhesive layer.