

Evaluation of the T-peel Joint Using the Finite Element Method

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ABSTRACT

This report evaluates the effect of environmental conditioning and geometric parameters on the performance of the T-peel test. Finite element analyses were performed to establish the effects of these parameters on joint performance and stress distribution within the adhesive layer. The finite element models presented in this report were constructed and solved using the ABAQUS program with FEMGV as the pre-processor. The analyses were based on experimental data generated within the DTI funded ADH and PAJ programmes.

The effect of environmental conditioning on the joint performance was investigated using a sequentially coupled mechanical-diffusion finite element model, which incorporated continuously varying adhesive material properties. The numerical predictions revealed that the stress distributions become more uniform along the adhesive layer when the adhesive contains increased amounts of moisture. Peel stresses at the edge of the adhesive fillet decrease with increasing moisture content.

Parametric studies on the specimen geometry revealed that stress distributions are sensitive to adherend material properties, adherend thickness and flange radius, the flange radius is the least significant. In general, stresses were reduced when changes in the T-peel geometry resulted in smaller joint displacements for the same load.

The report was prepared as part of the research undertaken at NPL for the Department of Trade and Industry funded project on "Performance of Adhesive Joints - Combined Loading and Hostile Environments".

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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1. INTRODUCTION

Applications of adhesive joints can be found in industries ranging from the construction industry to the aerospace industry. They are used as an alternative to conventional mechanical joints, primarily, due to their light weight and vast design opportunities for joining dissimilar materials and simplifying components. Among the plethora of test methods, the T-peel test has been an integral part of adhesive performance specifications. It has been adopted by most standard organisations and has played an important role in the development of high peel strength adhesives and in rating the environmental resistance of adhesive systems.

The ever increasing need for more reliable and cost efficient joints has extended the demand for suitable peel tests. Test procedures are currently limited to thin flexible adherends with no allowance for large deformations. Consequently, they have been unsuitable for generating design data. This document provides recommendations on the use of the T-peel test method to compare different material systems and to assess the performance of new designs. For this purpose, the finite element method has been employed to perform a series of stress and deformation analyses of the T-peel joint geometry.

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 the three technical projects forming the programme on “Performance of Adhesive Joints - A Programme in Support of Test Methods”.

2. BACKGROUND

The primary purpose of the T-peel test is to determine the relative peel resistance of adhesive bonds between flexible adherends by means of a T-type specimen, depicted in Figure 1. This test geometry has been adopted by most standard bodies and is widely used in the industry to evaluate environmental durability of adhesively bonded systems [1-3]. The popularity of this method can be attributed to the ease of use and the physical resemblance to actual in-service debonding problems.

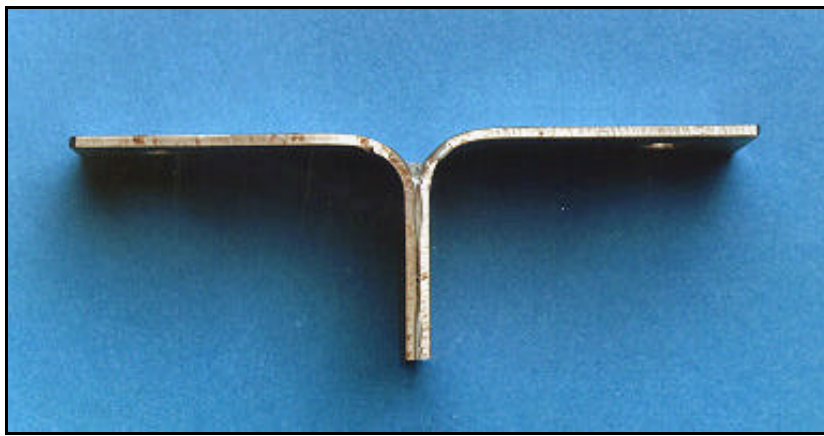


Figure 1 - T-peel joint specimen

Specimen preparation, testing and data reduction are relatively straightforward. The specimen can be readily loaded using standard mechanical test equipment. Peel resistance is defined as the average force per unit test specimen width, measured along the bond line that is required to separate progressively the two adherend members of the bonded joint. The T-peel test has been shown to discriminate between various combinations of pre-treatment and adhesives, although coefficients of variation are typically 20 to 30%, or higher [4].

A major disadvantage of T-peel tests is that excessive extension of flexible adherends contributes to failure at the adhesive/adherend interface. No account has been taken for the possibility of adherend deformation in present procedures and unstable behaviour has caused difficulties in the interpretation and use of test data. Table 1 summarises the advantages and disadvantages of the T-peel test [5].

Table 1 - *Advantages and disadvantages of the T-peel test*

<i>Advantages</i>	<i>Disadvantages</i>
Yields peel strength	Limited to thin flexible adherends
Straightforward/economic	Not suitable for generating design data
- specimen preparation	Large uncertainties in measurements
- testing	No allowance for large adherend deformation
- data reduction	
Discriminates between pretreatments and adhesives	
ISO/ATM standards	
Suitable for in-situ environmental testing (QA only)	
Suitable for fatigue testing	

3. SCOPE

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

- (i) environmental conditions (water immersion for up to 12 days);
- (ii) adherend material (steel, aluminium, titanium and tufnol);
- (iii) adhesive fillet (full or half fillet);
- (iv) adherend thickness (1.4, 2.5 and 5 mm);
- (v) flange radius (6.5, 12.5 and 25 mm).

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.

The report is divided into eight sections - including the Introduction, Background and Scope (Sections 1-3). Section 4 covers the numerical modelling of the T-peel test using the finite element method and includes a comparison between the predicted and measured response of the joint. Section 5 covers the effect of environmental degradation on the joint performance. Sections 6 and 7 cover the effect of adherend properties and joint dimensions on the joint performance, respectively. Conclusions are given in Section 8. Detailed finite element results for different material systems and joint configurations are provided in Appendices A to F.

4. NUMERICAL MODELLING

This section discusses the finite element model of the T-peel joint geometry and provides a number of recommendations on the modelling approach. The finite element models presented in this report were constructed and solved using the ABAQUS [6] program while mesh generation was performed using the FEMGV [7] pre-processor.

4.1. THREE-DIMENSIONAL JOINT DEFORMATIONS

A three-dimensional geometrically linear finite element analysis of the T-peel joint was initially performed to assess the validity of the assumption of plane stress or plane strain to an arbitrary section of the joint. The reduced geometry of the joint is shown in Figure 2(a), which illustrates the symmetric boundary conditions and mesh. The deformed shape of the joint under a tensile load is shown in Figure 2(b).

Four second-order solid elements (C3D20 by the ABAQUS convention) were used through the thickness of the adherend and two elements through the thickness of the adhesive layer. Due to the large computational cost involved in running the model no attempts were made to obtain a converged solution or capture fully the singular solution in the bimaterial region. However, the mesh provided the global three-dimensional deformation fields. Increasing the mesh density would give rise to higher values of stresses at the end of the overlap, but would not change the trends.

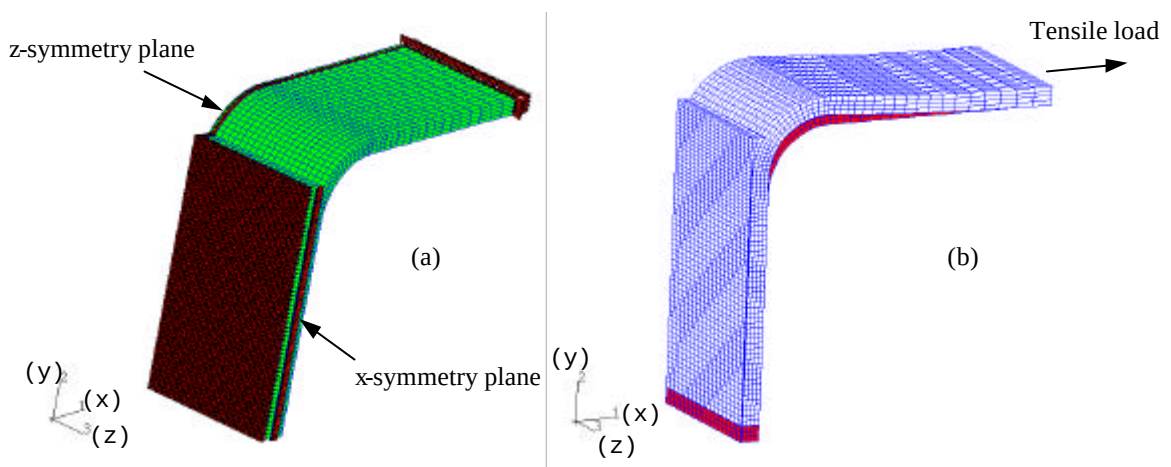


Figure 2 - Three-dimensional finite element joint model

(a) Symmetric boundary conditions and mesh; (b) Deformed shape

The variation of the direct strain in the width direction of the joint was investigated. Figure 3(a) shows the z-strain distribution across the adhesive and the adherend at the end of the overlap. Resultant strains are compressive because of the contraction due to the Poisson effect under tensile loading. This is graphically illustrated in Figure 3(b). The joint is in plane stress at the edge and tends towards plane strain in the interior. The transition from plane stress to plane strain occurs approximately over the same distance from the edges of the adhesive and the adherend, although the former undergoes higher deformations.

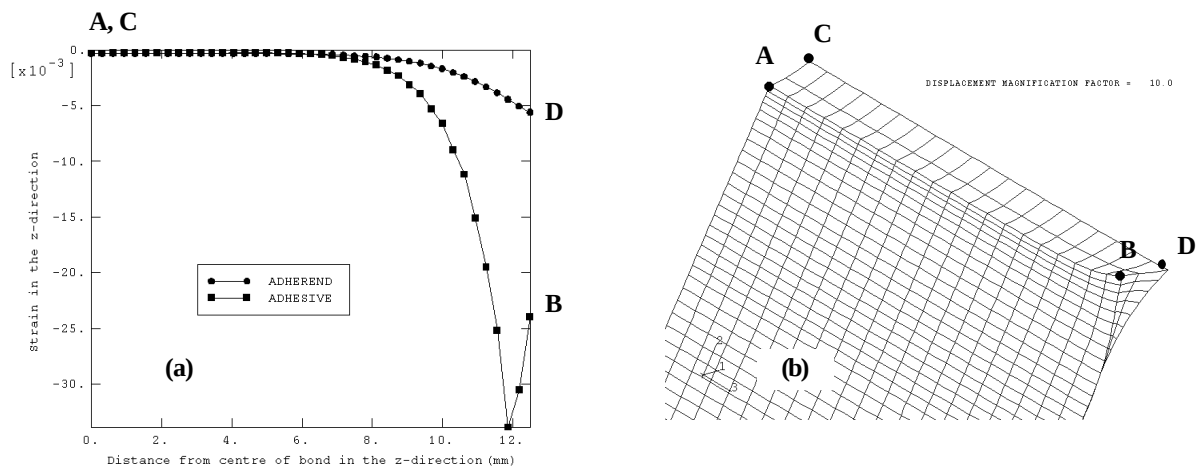


Figure 3 - Deformation fields across the width of the 3-D model

(a) Adhesive and adherend z-strain distribution; (b) Detail of the deformed adhesive layer

Strain results at locations in the adhesive away from the fillet edge showed that the strain distribution differs considerably. As the distance along the y-axis away from the overlap edge increases, the adhesive tends more towards plane strain conditions. This is due to the constraint imposed by the more rigid adherend preventing the adhesive from contracting. Suppressing this contraction effectively holds the adhesive in plane strain.

4.2. TWO-DIMENSIONAL JOINT MODEL

A converged three-dimensional analysis will give a more accurate solution to the problem of the structural assessment of adhesive joints than a two-dimensional analysis. However, the use of three-dimensional solid elements in complex structural analysis research problems has a number of drawbacks. Considerable increases in computer processing time, mesh generation and results processing time make three-dimensional analyses still rather rare. 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 building 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 voids. It has been argued that failure initiation takes place in a plane strain region of the adhesive when the adherend is in plane stress [8, 9]. This is due to cracks propagating more easily in plane strain as the plastic zone is smaller and thus less energy is absorbed. Consequently, the adhesive was represented by plane strain, while the adherends were represented by plane stress isoparametric elements.

Due to symmetry, only half the joint needed to be modelled. 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. Symmetry conditions were imposed by constraining the nodes at the symmetry plane against movement along the x -axis. The boundary conditions are illustrated in Figure 4.

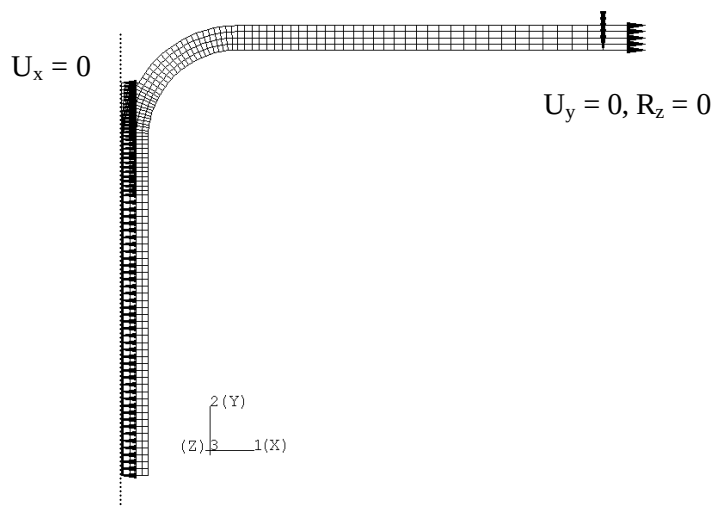


Figure 4 - Boundary conditions applied to the 2-D model

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 to ISO 527:2 [10] specifications. This is shown in Figure 5(a). 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 based on the stress-strain curve in Figure 5(b). The elastic modulus and Poisson's ratio of the epoxy adhesive and the steel adherend were 3.1 MPa and 0.38, 200 GPa and 0.38, respectively.

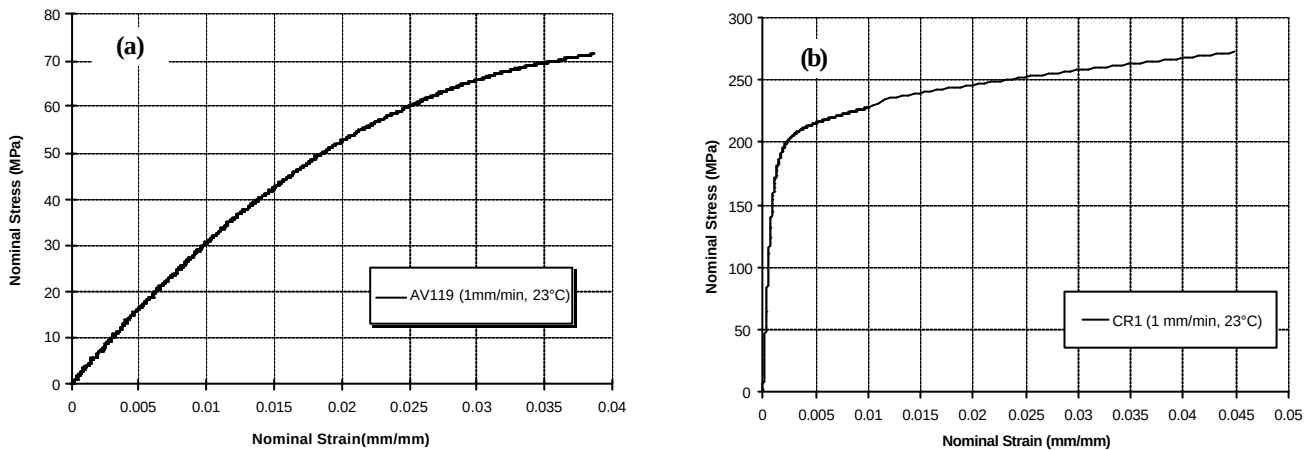


Figure 5 - Tension curves for calibration of elastic-plastic material model

(a) AV119 epoxy adhesive; (b) CR1 mild steel adherend

4.3. MESH DESIGN AND ELEMENT PERFORMANCE

The large thickness differences between the adhesive and the adherend and the very different mechanical properties of these materials lead 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. Multi-point constraints were also utilised to achieve abrupt changes in the mesh density, outside the region of interest, in order to further reduce the size of the problem.

The models used in the mesh convergence study are presented in Appendix A. The coarser mesh comprises 364 quadrilateral elements and the finer 1960 elements of the same type. Elements of linear and quadratic displacement with full or reduced integration were examined. Figure 6 shows the force-displacement curve for different mesh sizes. A mesh of 1013 linear elements provides a converged solution with the least computational cost. Stress results within the adhesive layer also showed convergence for the given mesh density.

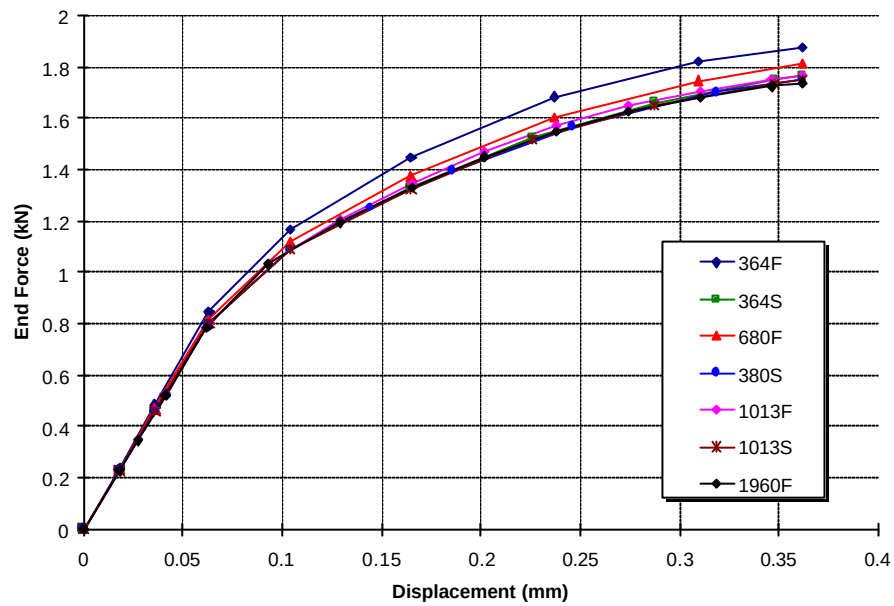


Figure 6 - Mesh convergence graph for first- and second-order quadrilateral elements

4.4. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

The numerical predictions for the joint displacements under tensile loading conditions were validated by making comparisons with experimental results. A series of tensile tests were conducted on T-peel joints bonded with Araldite® 2007 (also known as AV119), a single-part epoxy paste supplied by Ciba Speciality Chemicals. The adherend material was CR1 mild steel, supplied by British Steel. Prior to bonding, the adherends were decreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina. The bondline thickness (0.25mm) was controlled using 250µm 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 and then heated to 120°C for 90 minutes to cure the adhesive. Figure 7 shows the dimensions of the finished specimens.

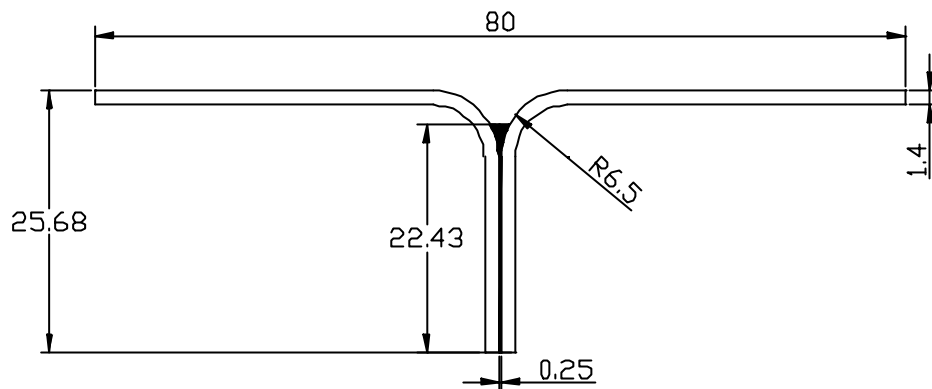


Figure 7 - Dimensions of T-peel specimens

The tests were carried out on an Instron testing machine under standard laboratory conditions (23C/50% relative humidity) to BS 5350 [11] specifications. Instron Series IX software was used to control the machine and to collect the test data. Failure was fully cohesive and centre of bond, as shown in Figure 8.

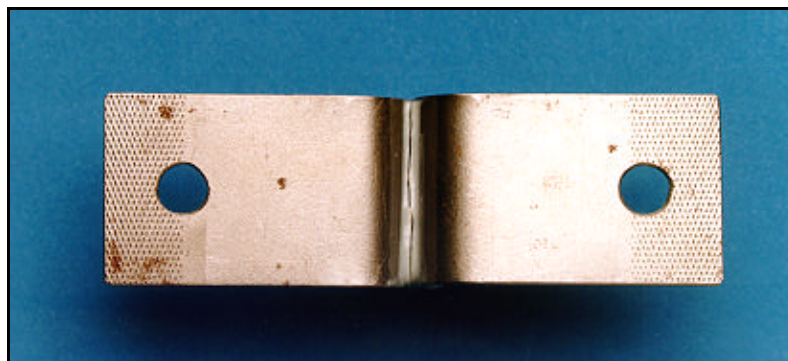


Figure 8 - Failed T-peel joint specimen

The numerical solution is compared with the experimental measurements in Figure 9. There was good agreement between the predicted and the measured force-displacement curve when plastic yielding of the adhesive and adherend materials was taken into account. The linear-elastic finite element model, however, over-predicted the stiffness of the joint at high loads by more than 100%. Moreover, linear-elastic analysis of the joint resulted in adhesive equivalent stresses reaching 211 MPa at the overlap end. This is far in excess of the maximum sustainable stress, which is a clear indication of the need of a non-linear analysis.

An important observation is that experimental results were lower than the non-linear finite element model predictions. This was consistent with results for other joint geometries analysed within the PAJ programme. Lower stiffness values in test results have also been reported in the literature [12]. This may be attributed to a combination of reasons. Possible manufacturing inaccuracies in the fillet formation or slight defects in the bond line would give stiffness values on the low side. Manufacturing errors are critical in the T-peel joint, which has a high proportion of Mode I loading. It has also been shown that for epoxy adhesives the ratio of compression yield stress to tension yield stress is approximately 1.3 [13]. This may suggest the use of a Drucker-Prager material model with a yield surface of either linear, hyperbolic or exponent form.

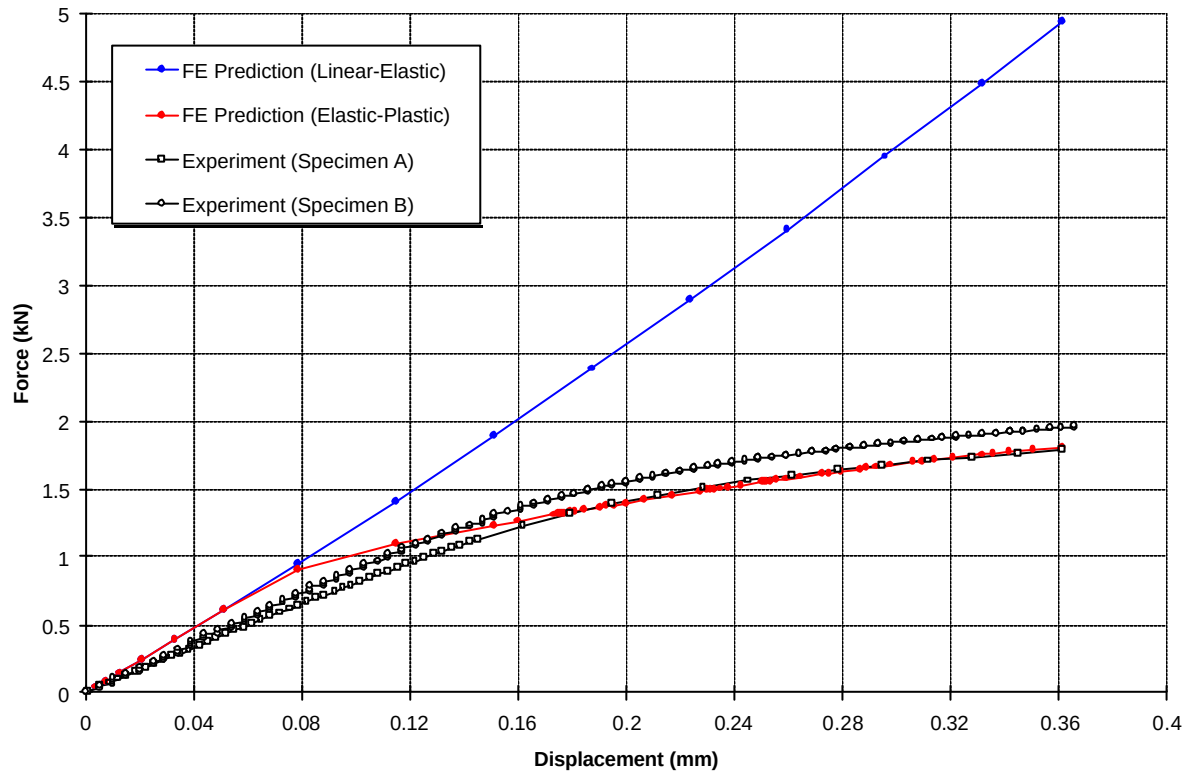


Figure 9 - Comparison of measured and predicted force-displacement response

5. EVALUATION OF THE EFFECT OF ENVIRONMENTAL DEGRADATION

Environmental degradation is the greatest limitation on the widespread use of adhesively bonded assemblies in practical applications. Service conditions can often involve exposure to elevated temperatures and moist environments that have a direct effect on the properties of epoxy adhesives and 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 study is concerned with the weakening of the bulk adhesive. 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. The subject is a very complicated one, primarily due to the coupled mechanical-diffusion response that influences the joint behaviour. 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 [14]. The problem is pictured in Figure 10, 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 reach instantaneously the equilibrium moisture concentration c_a which remains constant.

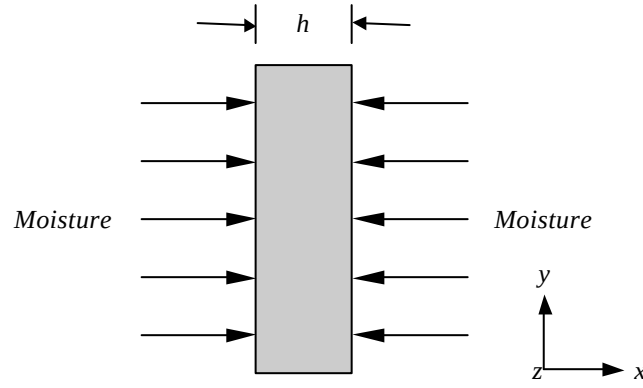


Figure 10 - Graphical representation of one-dimensional diffusion problem

The moisture uptake is described by Fick's law [15]:

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

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 [16] that the diffusivity changes very little with moisture content and thus the solution to equations (1) and (2) is given by [17]:

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

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 T-peel joint, assuming the only concentration gradient is along the bond length and $c_i = 0$. Figure 11 shows the moisture distribution for different time periods up to 12 days, 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 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 [18]. 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 [19]. There are

significant differences between bulk and joint behaviour, which are attributed mainly to interfacial or capillary diffusion effects.

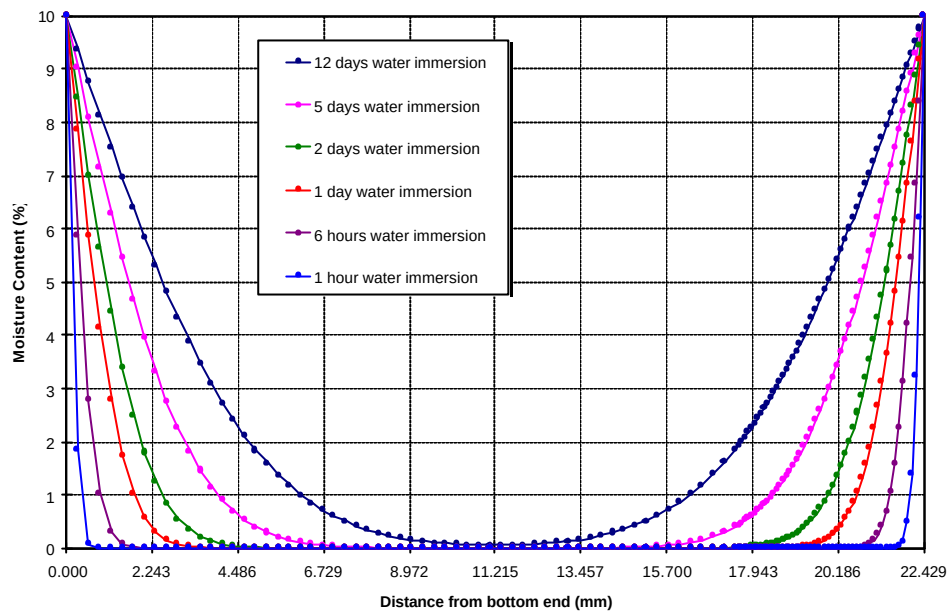


Figure 11 - Predicted moisture concentration distributions along the adhesive layer

The resulting moisture distribution along the overlap, shown in Figure 11, 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 10% at the overlap ends to a dry state at the centre of the overlap. However, the one-dimensional diffusion theory is expected to underestimate the moisture concentration at the wider end of the overlap. This is because one-dimensional expressions cannot take into account changes in bond line thickness.

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 [20]. 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, 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 [10] specifications, were tested for each conditioning time period. The resulted tensile stress-strain data are shown in Figure 12. 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.

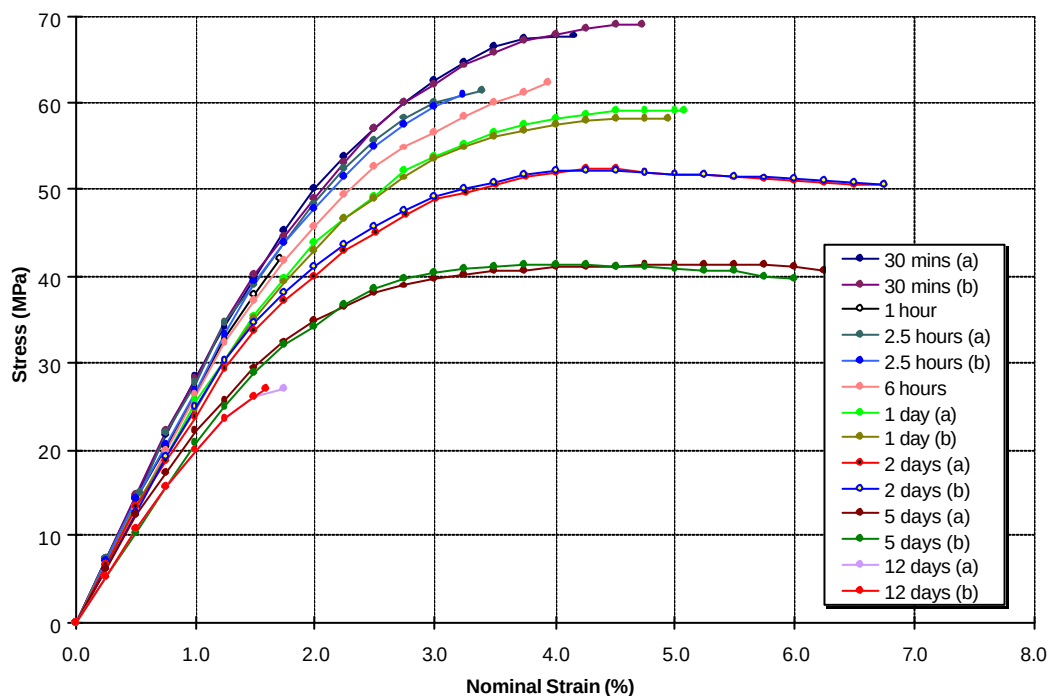


Figure 12 - Stress-strain curves for different water immersion periods

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 weight 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:

$$M = \frac{(W_i - W_0)}{W_i} \times 100\% \quad (4)$$

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 13(a). The effect of increased moisture content on the properties of the adhesive is shown in Figure 13(b). The elastic modulus and Poisson's ratio were reduced by 89% and 20%, respectively, over a time period of 12 days.

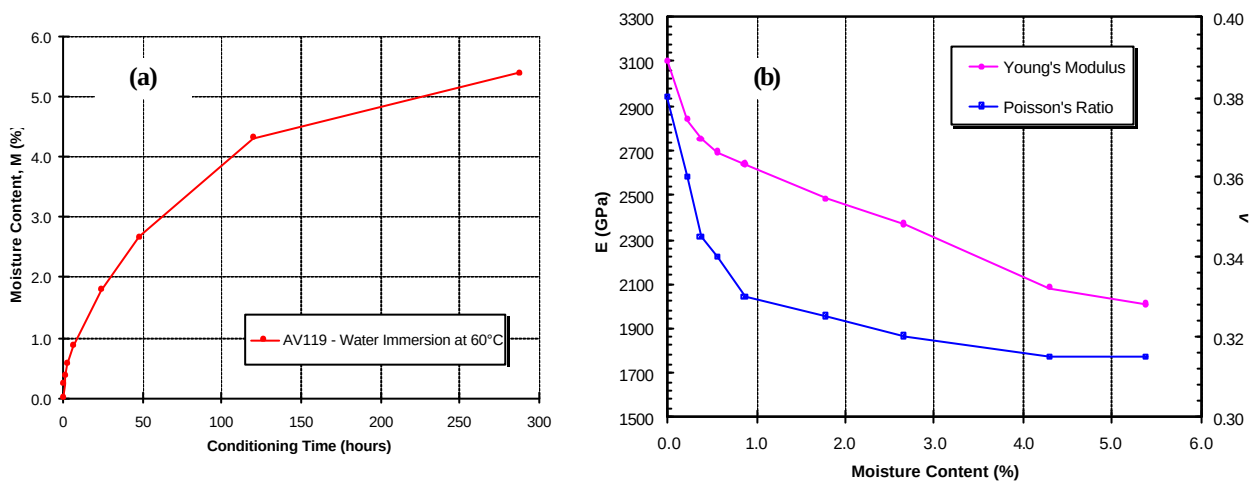


Figure 13 - Water immersion of AV119 adhesive samples. (a) Moisture uptake as a function of time; (b) Effect of moisture content on Young's modulus and Poisson's ratio

The moisture-dependent stress-strain data, shown in Figure 12, 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

Full non-linear elastic-plastic analyses were undertaken for the dry and conditioned steel joints. A prescribed displacement was applied at the nodes of the adherend end. Figure 14 shows the undeformed and deformed mesh for the dry joint configuration.

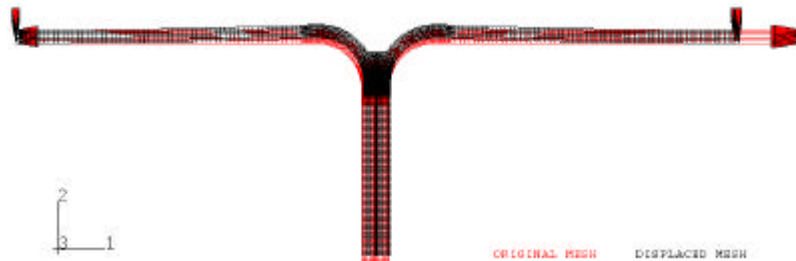


Figure 14 - Deformed and undeformed mesh of dry T-peel joint

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 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, more than three times lower than the stress in the dry joint. This behaviour was due to the wetter adhesive at the overlap end being able to sustain much lower levels of stress and thus transfer less load. Redistribution of plasticity zones was also observed, shown in Figure 15. Significant increase of the adhesive equivalent plastic strain was observed after 12 days of water immersion. The variation of adhesive equivalent and peel stress along the centreline of the adhesive is shown in Figures 16 and 17. Contours of equivalent stresses in both the adherend and adhesive are presented in Appendix B. Figures B.1 to B.7 (Appendix B) illustrate the transition of the maximum stress region towards the centre of the overlap with increased moisture content. Finite element results indicated that moisture absorption had little effect on the stiffness of the joint, typically 10% reduction after 12 days of water immersion.

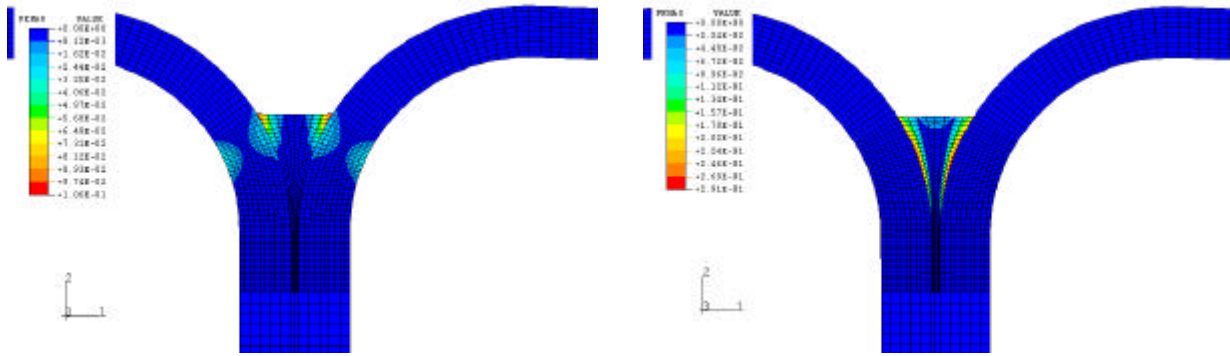


Figure 15 - Equivalent plastic strain: (a) Dry joint; (b) 12 days of water immersion

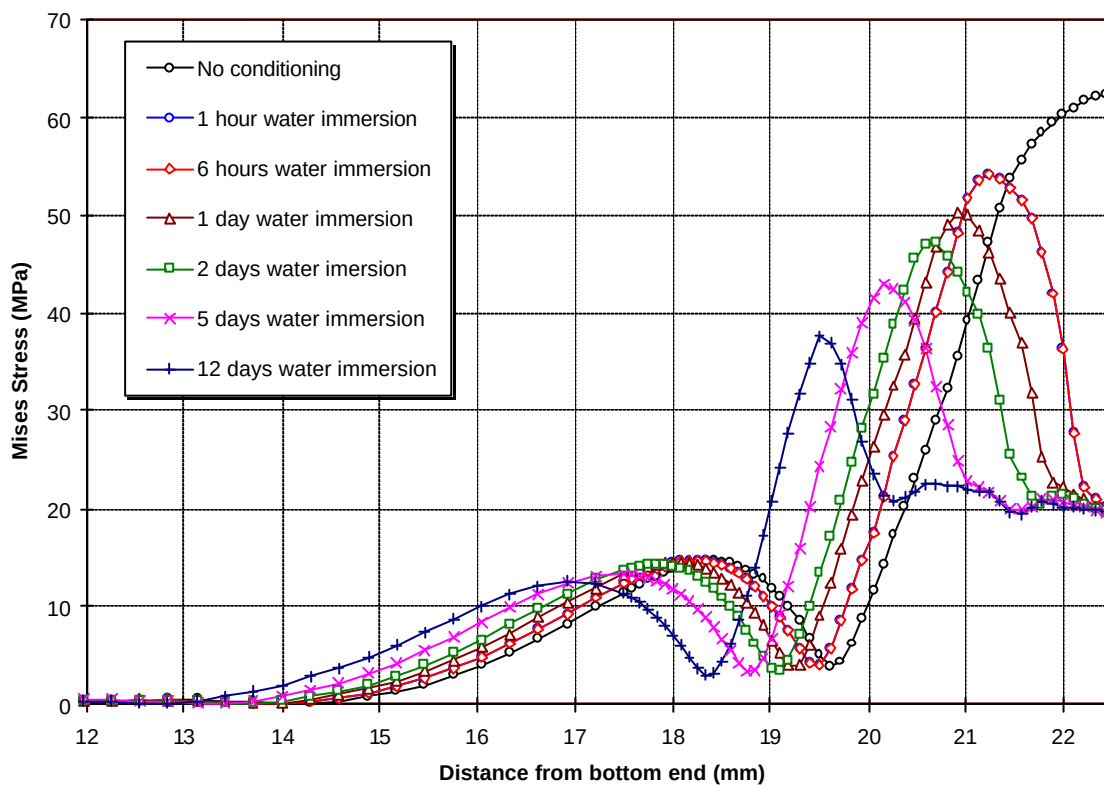


Figure 16 - Mises equivalent stress distribution along the centreline of the adhesive layer

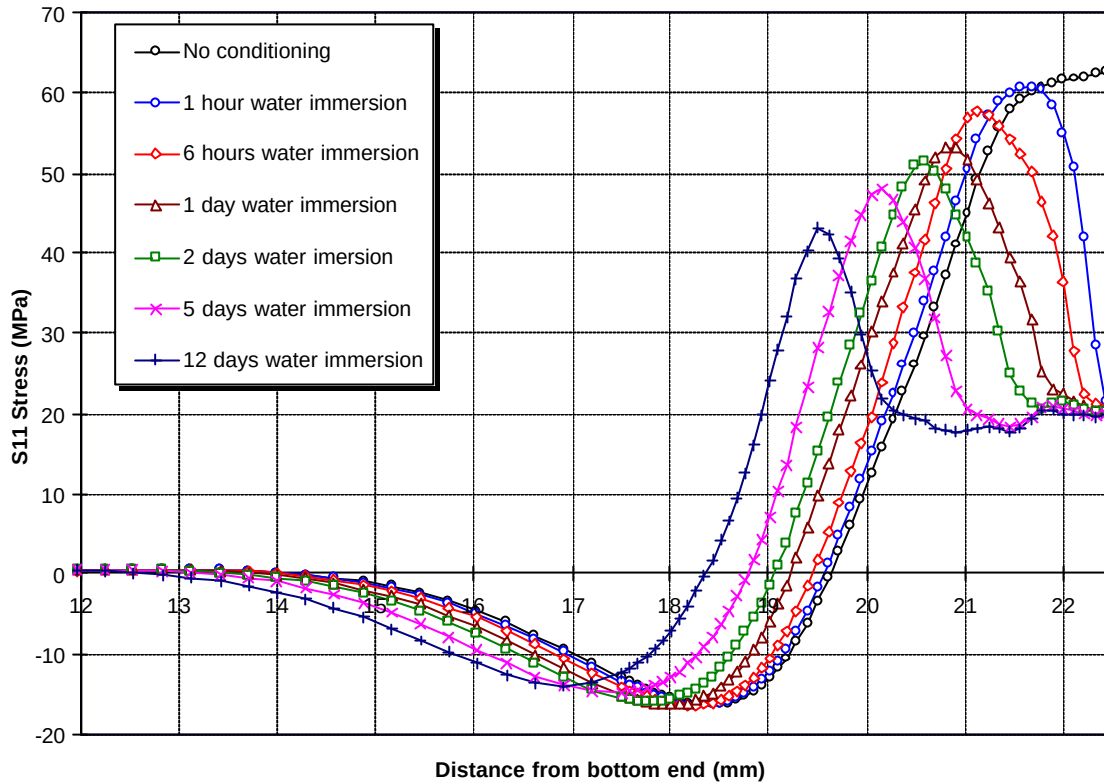


Figure 17 - Peel stress distribution along the centreline of the adhesive layer

6. EVALUATION OF THE EFFECT OF ADHEREND PROPERTIES

In this study, the effect of adherend properties on the joint behaviour was investigated. The materials were CR1 mild steel, 6Al-4V Titanium, 5251 Aluminium and Tufnol 10G/40 plain woven glass-fibre reinforced epoxy laminate, the elastic constants of which are listed in Table 2. 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 are shown in Figure 18. The orthotropic properties of the plain woven fabric composite were measured in-house utilising a series of standardised test methods.

Table 2 - Elastic materials properties of adherends

Property	CR1 Mild Steel	6Al-4V Titanium	5251 Aluminium	Tufnol
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

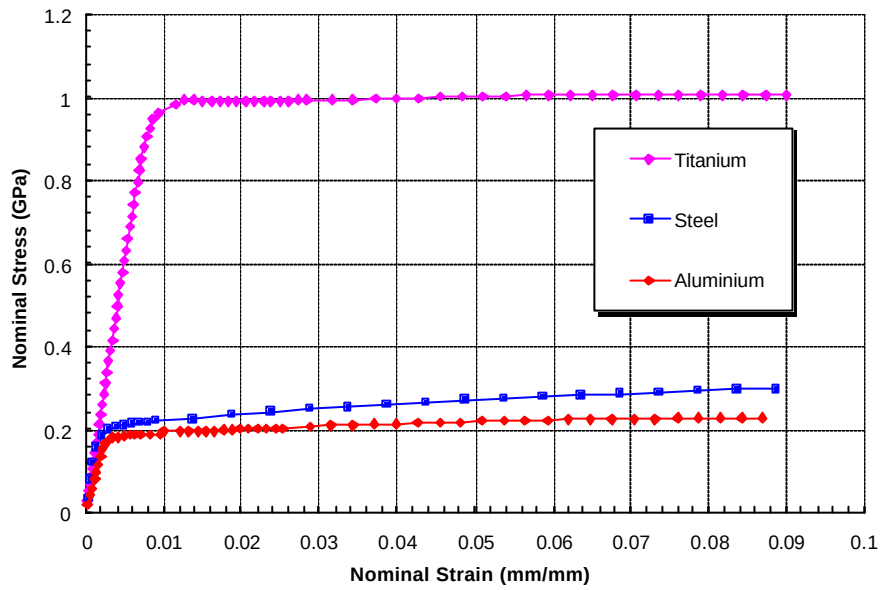


Figure 18 - Stress-strain curves of the metallic adherends

The same finite element mesh and boundary conditions were used in all cases. A non-linear solution algorithm was used. The deformed shape of the joints is shown in Figure 19. Detailed analysis results are presented in Appendix C.

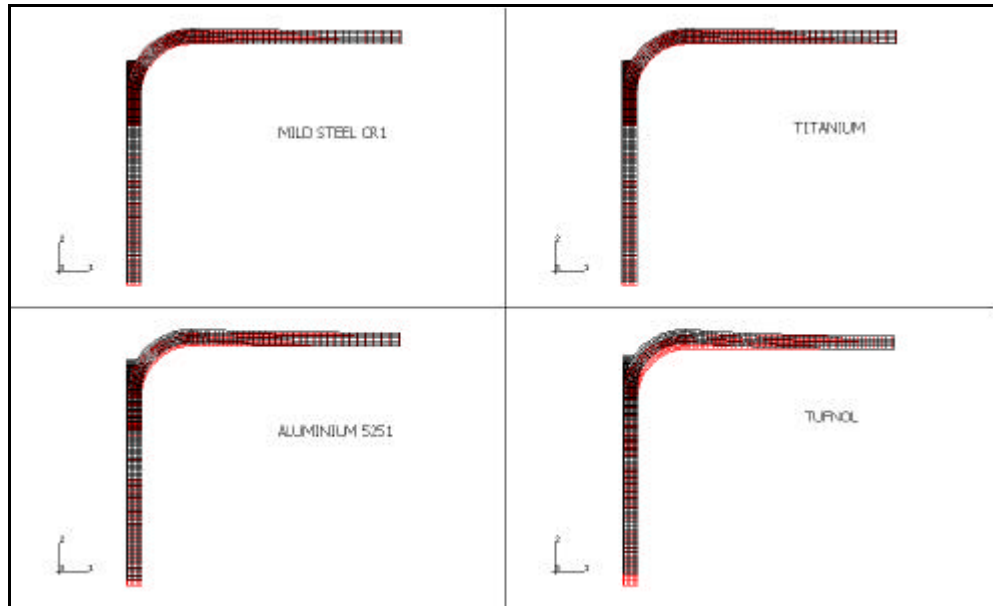


Figure 19 - Deformed and undeformed mesh of joints with different adherend material

The composite joint exhibited significantly higher deformations than the metal joints due to the difference in the elastic constants of the adherends. As a result, higher stresses were developed within the adhesive and finite element results revealed that the equivalent stress at the end of the overlap edge was 37% higher than in the steel joint for the same load. Extensive plastic deformation was present within the adhesive layer in the composite joint, as shown in Figures C.4 and C.8 (Appendix C).

Equivalent and peel stress distributions along the centreline of the adhesive layer are shown in Figures 20 and 21. Stresses increased rapidly as the overlap end was reached and a large stress concentration occurred at the adhesive edge. Stress and strain components away from the edge exhibited a flat distribution. The maximum stress within the adhesive layer decreased with increasing adherend stiffness. However, this effect was less pronounced between steel and titanium joints.

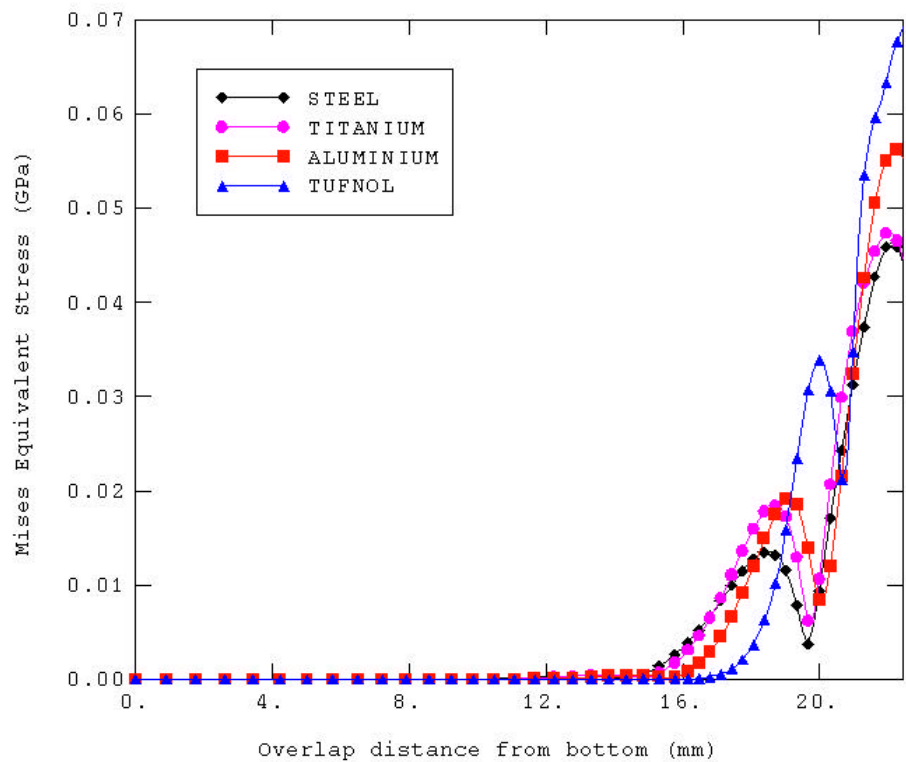


Figure 20 - Mises equivalent stress distributions for different adherend material

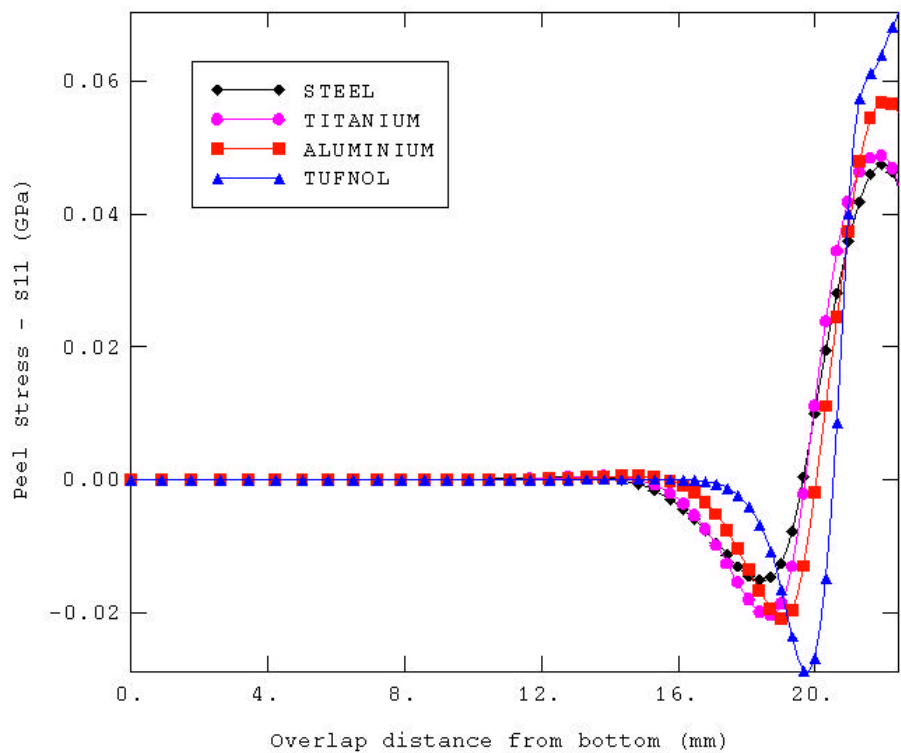


Figure 21 - Peel stress distributions for different adherend material

7. EVALUATION OF THE EFFECT OF JOINT DIMENSIONS

A series of finite element analyses were conducted in order to evaluate the effect of changing the geometric characteristics of the T-peel joint. Parametric studies for the adhesive fillet, adherend thickness and flange radius are presented below.

7.1. ADHESIVE FILLET

In this study, the adhesive fillet occupied either half or all of the space between the steel substrates, as depicted in Figure 22. Full non-linear material properties were used for both the adhesive and the steel adherends. Boundary conditions were consistent with previous finite element models.

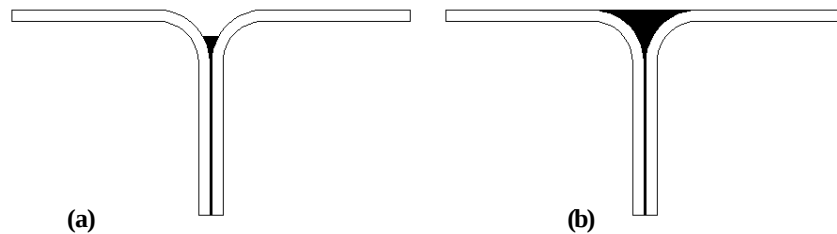


Figure 22 - Schematic of the T-peel joint with (a) 50% and (b) 100% resin fillet

The mesh in the full-fillet joint was locally refined in regions of high stress gradients, using progressively biased elements and kinematic constraints, as depicted in Figure 23(a). Mesh convergence studies were performed to examine the effect of mesh size on the stress distribution within the adhesive. This is shown in Figure 23(b).

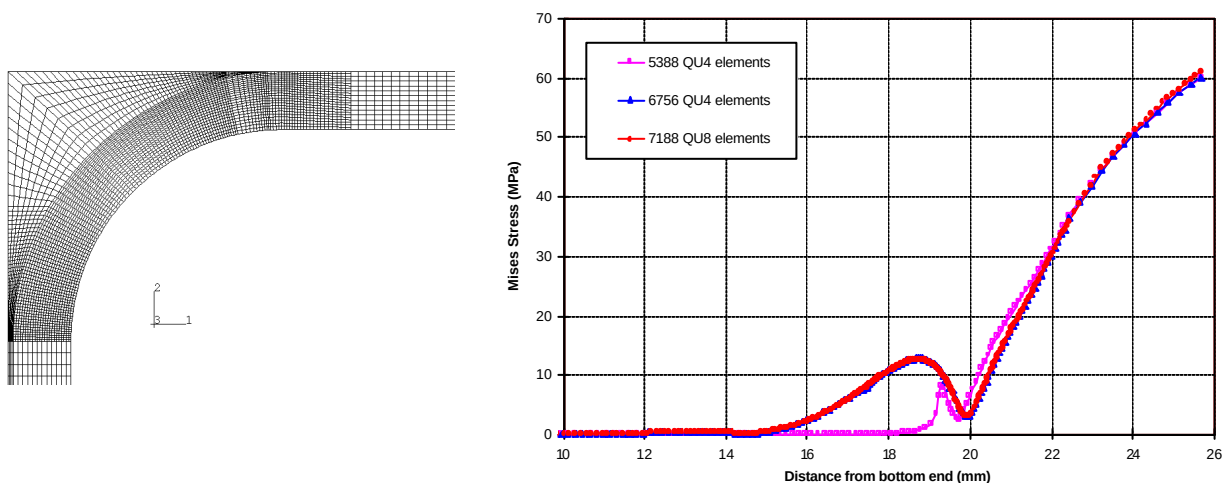


Figure 23 - Finite element model of full-fillet joint: (a) Mesh detail; (b) mesh convergence graph

It was found that the joint with the 50% adhesive fillet deformed substantially more than the joint with the 100% fillet, under the same tensile load. This is shown in Figure 24. As a result, all stress components were significantly reduced when the whole space between the steel substrates was occupied by the adhesive. The equivalent stress at the end of the overlap was reduced by approximately 200%, as shown in Figure 25. Detailed finite element results are presented in Appendix D.

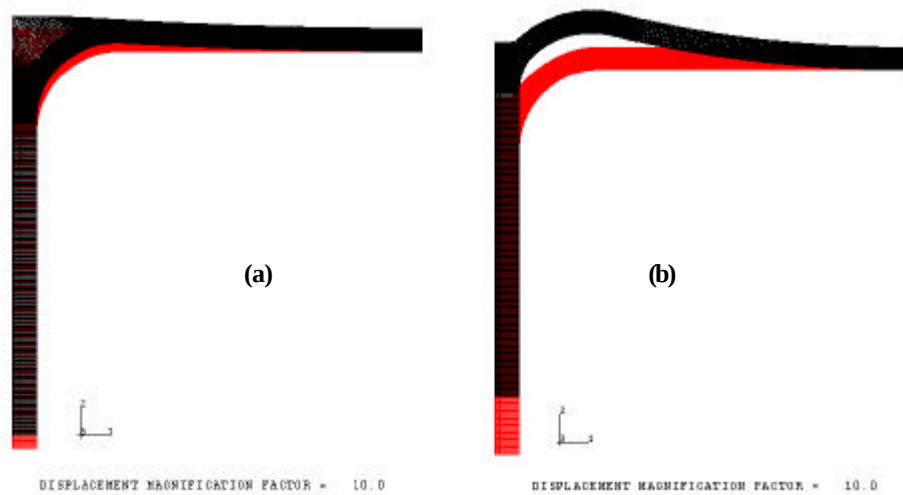


Figure 24 - Undeformed and deformed mesh for joints with different resin fillet;
(a) 100% resin fillet; (b) 50% resin fillet

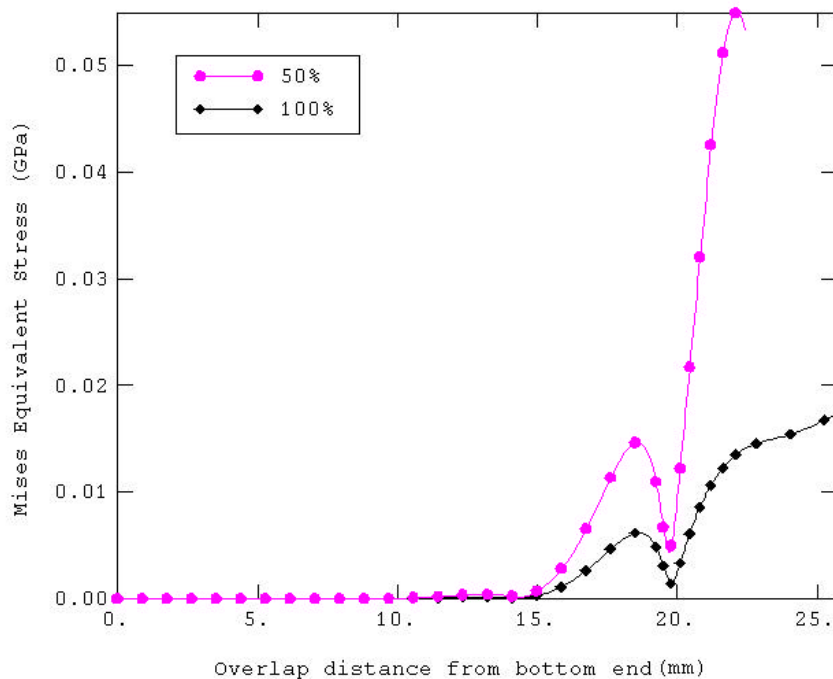


Figure 25 - Mises equivalent stress distribution along the centreline of the adhesive layer

7.2. ADHEREND THICKNESS

In this study, the effect of adherend thickness on the stress distributions of steel T-peel joints was evaluated. Cases with 1.4mm, 2.5mm and 5mm adherend thickness were considered, as depicted in Figure 26. Full non-linear material properties were used for both adhesive and adherend materials. Boundary conditions were consistent with previous finite element models.

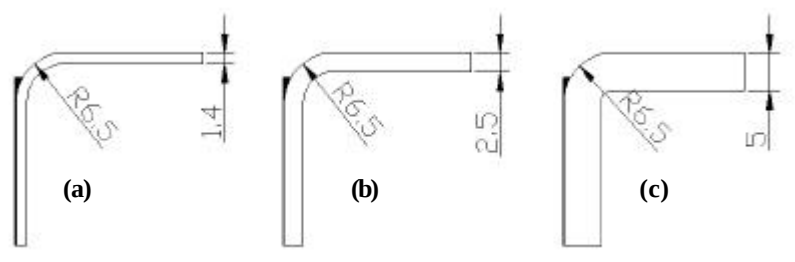


Figure 26 - Joint dimensions for (a) 1.4mm, (b) 2.5mm and (c) 5mm adherend thickness

Comparison of the finite element results revealed that, as expected, the overall displacement of the joint decreased with increasing adherend thickness, under the same tensile load. This is illustrated in Figure 27. Increases in the adherend thickness resulted in reductions in stress magnitudes, as well as, reductions in adhesive plastic deformation. Adherend and adhesive strains were essentially elastic when the adherend thickness was set to 5mm. The maximum equivalent stress within the adhesive layer was reduced by approximately 113% and 215% when the adherend thickness was 2.5mm and 5.0mm, respectively. Equivalent stress distributions for the later configurations revealed that the maximum stresses exhibited an inboard peak, as shown in Figure 25. Detailed finite element results are presented in Appendix E.

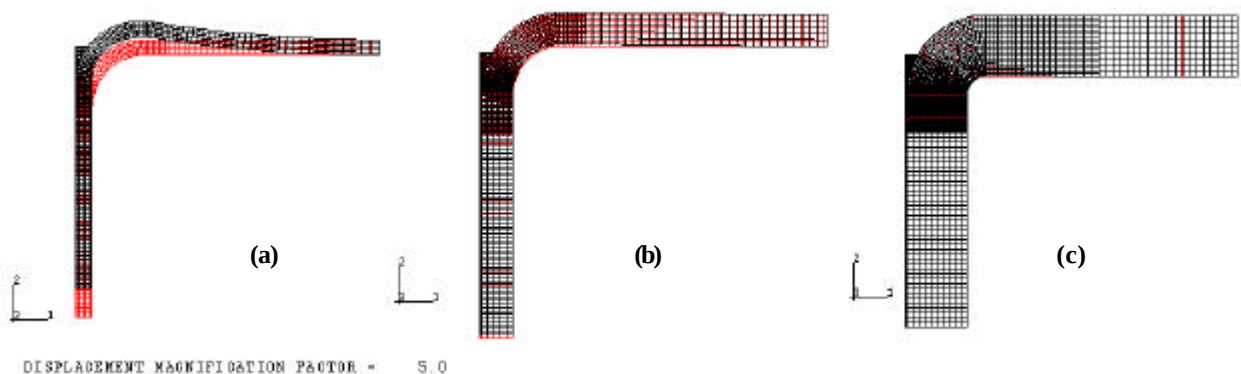


Figure 27 - Undeformed and deformed mesh of joints with different adherend thickness;
(a) 1.4mm, (b) 2.5mm and (c) 5mm adherend thickness

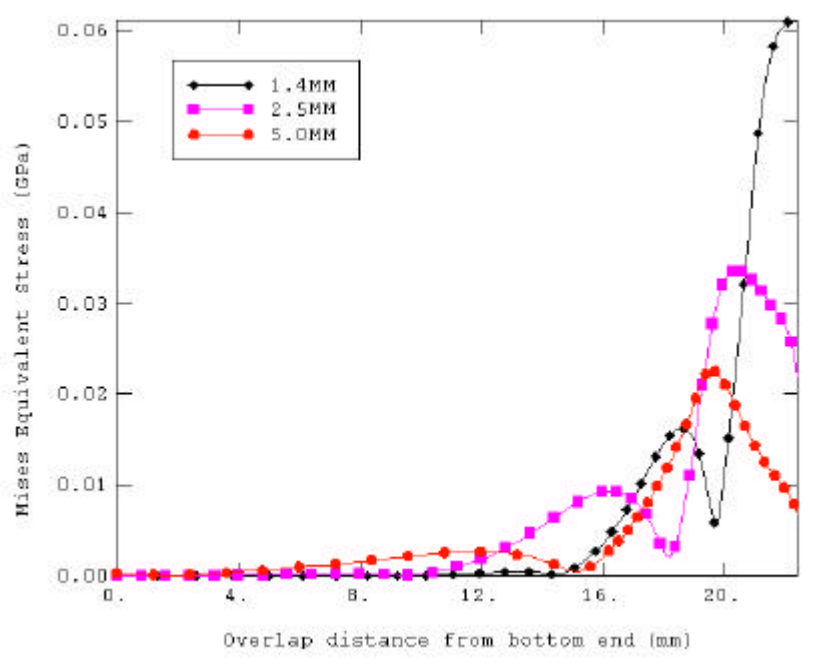


Figure 28 - Mises equivalent stress distribution along the centreline of the adhesive layer

7.3. FLANGE RADIUS

In this study, the flange radius of the joint was varied, as illustrated in Figure 29. Cases with 6.5 mm, 12.5 mm and 25 mm flange radius were considered. Full non-linear material properties were used for both adhesive and adherend materials. Boundary conditions were consistent with previous finite element models.

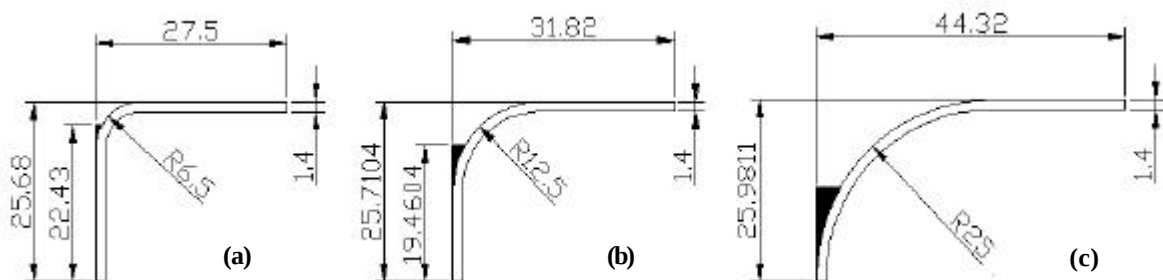


Figure 29 - Joint dimensions for (a) 6.5mm, (b) 12.5mm and (c) 25mm fillet radius

Figure 30 shows the undeformed and deformed mesh of the various configurations. The overall displacement of the joint increased with increasing flange radius, under the same tensile load. However, stress analyses revealed that the equivalent and peel stresses were not significantly influenced by the flange radius. The effect was more pronounced for the axial and shear stress components. This is

shown in Figure 31. Detailed finite element results are presented in Appendix F. For all joint configurations a stress concentration occurred at the end of the overlap. However, the joint with a flange radius of 25mm did not exhibit a flat distribution away from the adhesive edge, as observed in other cases, due to the shorter overlap length.



Figure 30 - Undeformed and deformed shape of joints with different flange radius;
(a) 6.5mm, (b) 12.5mm and (c) 25mm flange radius

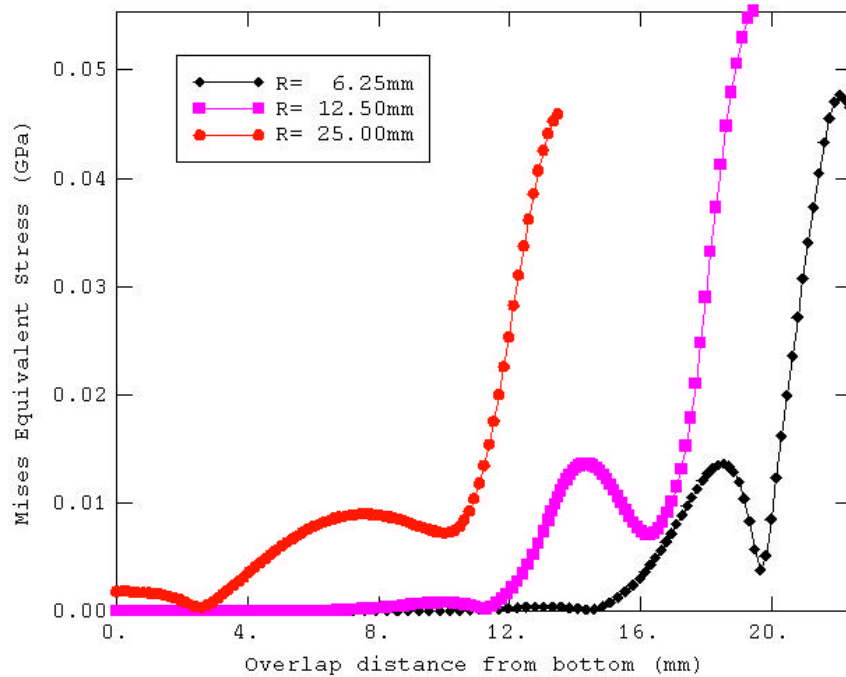


Figure 31 - Mises equivalent stress distribution along the centreline of the adhesive layer for different flange radius

8. CONCLUSIONS

The finite element method has been employed to perform a series of non-linear stress and deformation analyses of multiple T-peel joints under tensile loading. Three-dimensional finite element analyses provided out-of-plane deformation patterns and demonstrated that the adhesive stress and strain distribution varied across the width of the joint (z -direction). However, three-dimensional analyses were far more computer intensive than two-dimensional ones. The work presented in this report demonstrated that an accurate prediction of joint stiffness can be achieved by using a two-dimensional finite element model, provided that plasticity of the adhesive and adherends is taken into account.

Extensive mechanical testing revealed that considerable degradation of the AV119 adhesive occurs with environmental conditioning. The effect of moisture was more pronounced for the ultimate strength than the initial stiffness. The implications of this observation is that changes in the adhesive modulus arising from environmental exposure should not have a major effect on the behaviour of the bonded joint. Testing also revealed that the strain to failure increased with increasing moisture content. However, the adhesive exhibited brittle fracture after extensive environmental conditioning, primarily attributed to chemical degradation. The experimental data were utilised to develop a sequentially coupled mechanical-diffusion finite element model, which incorporated continuously varying adhesive material properties. The numerical predictions revealed that the distributions of stresses become more uniform along the adhesive layer when the adhesive contains increased amounts of moisture.

Parametric studies revealed that stresses distributions are sensitive to adherend material properties, adherend thickness and flange radius, the effect of which is less pronounced for changes in flange radius. In general, stresses were reduced when changes in the T-peel geometry resulted in smaller joint displacements for the same load.

The key findings of the work presented in this report are summarised in Table 3, which shows how the stiffness of the T-peel joint and the stresses and strains exhibited by the adhesive are affected by increasing individual parameters. Further information on the use of the T-peel test method can be found in the literature [21].

Table 3 - Summary of parametric studies*

Property	Moisture Content	Adherend Stiffness	Adhesive Fillet	Adherend Thickness	Flange Radius
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.

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