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**Cyclic Fatigue Testing of Adhesive Joints
Test Method Assessment**

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ABSTRACT

This report presents an experimental evaluation of three different test configurations to determine the suitability of the techniques for generating shear data under cyclic fatigue loading conditions. Single-lap, tapered-strap and scarf joint configurations were considered. The test methods were evaluated in terms of fitness for purpose in assessing fatigue performance and provides a guide to specimen geometry, manufacture and testing.

Constant amplitude (sinusoidal waveform) fatigue tests were carried out on all three test configurations in load control with the stress ratio **R** ($s_{\text{MIN}}/s_{\text{MAX}}$) equal to 0.1. Test frequency ranged from 5 to 25 Hz. The fatigue performance for each configuration can be represented by a linear-logarithmic (or by a power law) relationship that is dependent on the localised stress state of the adhesive in the bonded joint. The results indicate that peel stresses present at the ends of the bonded regions tends to govern fatigue resistance of bonded structures. Reducing peel stresses in these regions can be expected to extend the life of the bonded component.

The scarf joint exhibited excellent static performance, particular under compression loading, and cyclic fatigue characteristics, thus demonstrating the effectiveness of this configuration from a design perspective. The enhanced performance was attributed to low peel and shear stresses at the ends of the overlap. The tapered-strap joint, although less resistant to cyclic tension-tension loading, offers the potential for monitoring shear deformation under cyclic loading conditions and is compatible with standard extensometry.

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

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1. INTRODUCTION

Adhesive joints are expected to retain a significant proportion of their load bearing capacity for the entire duration of the service life of the bonded structure. Service conditions can often involve exposure to cyclic fatigue, which is possibly the most destructive form of mechanical loading. Fatigue damage is an irreversible process that can occur at relatively low stress levels due to the presence of high peel and shear stresses at the overlap edges. These stresses reduce both the static strength and fatigue life of bonded structures. Debonds and adhesive cracks in the vicinity of the overlap edges will be subject to mixed-mode loading. Shear and tensile-stress concentrations are controlled by geometric (e.g. adherend thickness, overlap (joint) length, adhesive layer thickness and adhesive fillet geometry) and material (adherend tensile modulus, adherend Poisson's ratio and adhesive shear modulus) parameters [1, 2]. These differences have a profound affect on the stress concentrations and consequently the load-bearing capacity and life expectancy of these structures.

A quick perusal of the ASTM and ISO standards [1], and design codes will reveal a multitude of joint configurations, each with the objective of producing a state of pure uniform shear in the adhesive layer. This report presents an experimental evaluation of three different test configurations to determine the suitability of the techniques for generating shear data under cyclic fatigue loading conditions. Single-lap, tapered-strap and scarf joint configurations were considered. The test methods were evaluated in terms of fitness for purpose in assessing fatigue performance. This report also provides guidance on specimen geometry, manufacture, testing. The assessment is supported with finite element analysis. **Throughout this report, statements of particular importance or relevance are highlighted in bold type.**

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

2. SINGLE-LAP TEST

This section discusses the cyclic fatigue results obtained using the single-lap shear test and provides a number of recommendations based on experimental results and numerical analysis.

2.1 SPECIMEN GEOMETRY, PREPARATION AND TESTING

Quasi-static (or monotonic) tests and cyclic fatigue tests were conducted on single-lap specimens (Figure 1) manufactured from CR1 cold rolled mild steel (supplied by British Steel Plc) sections and bonded with AV119 (also known as Araldite® 2007). AV119, a one part epoxy adhesive, was supplied by Ciba Speciality Chemicals. Prior to bonding, the adherends were degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina. A pressure of 85 psi was used to grit-blast the bonded areas. The surfaces to be bonded were then degreased again with 1,1,1-trichloroethane. The bondline thickness (0.25 mm) was controlled using 250 µm ballontini glass spheres. A small quantity of the glass spheres, 1% by weight, was mixed into the adhesive. Specimens were clamped in a special bonding jig [2] and then heated to 140°C for 75 minutes to cure the adhesive.

The specimens consisted of two rectangular sections, typically 25 mm wide, 100 mm long and 1.4 mm thick, bonded together, with an overlap length of 12.5 mm (Figure 1). End tabs, cut from the same material as the adherend sections, were adhesively bonded to the specimen. The end tabs were 37.5 mm in length. **The end tabs have been introduced to reduce (not eliminate) the eccentricity of the load path that causes out-of-plane bending moments, resulting in high peel stresses and non-uniform shear stresses in the adhesive layer.** No attempt was made to control the spew fillet radius. Adherend surfaces were prepared according to ISO 4588 [3]. Checks were made to ensure that there was no mechanical damage due to machining or handling (i.e. adherend bending).

Tests were conducted in accordance with BS EN 1465 [4]. This standard does not specify the use of end tabs, but specifies that the long axis of the specimen coincides with the direction of the applied force through the **centre line** of the grip assembly (see also NPL Report CMMT(A) 196 [2]). Five test specimens per condition were tested. Specimens were stored at 23 °C in a dessicator and tested within 1 to 2 weeks of manufacture. **The “apparent” shear strength measured is given in terms of load per unit width (N/mm) rather than load per unit area.**

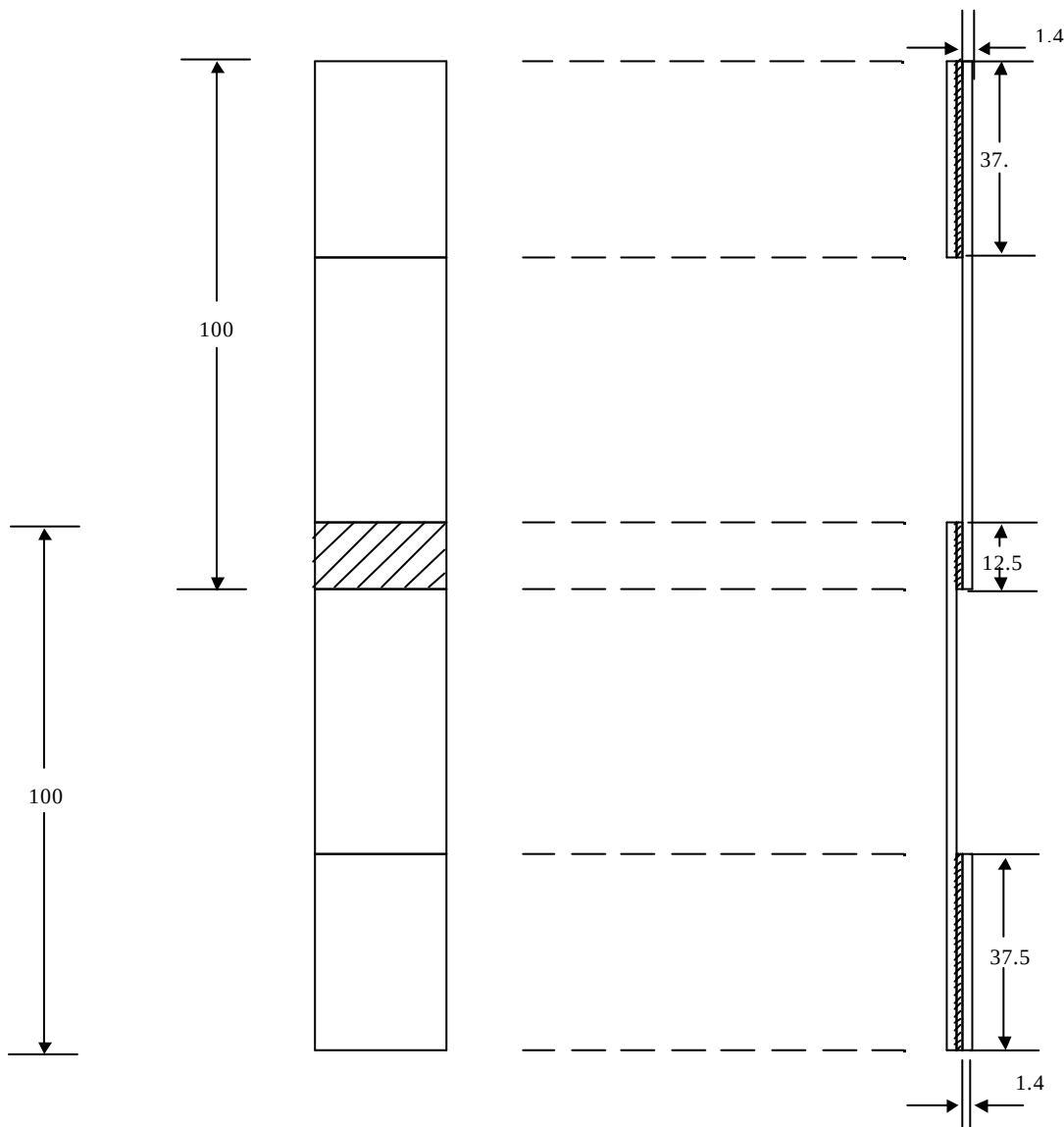


Figure 1 Schematic of single-lap joint (dimensions in mm).

2.2 QUASI-STATIC TESTS

The failure stress was determined for a range of displacement rates (1 to 18,000 mm / min). Displacement was determined directly from the cross-head movement. Tests were conducted in accordance with BS EN 1465 [4] specifications at 23 °C and 50% relative humidity (RH) (i.e. standard laboratory conditions). An Instron 8501 servo-hydraulic test frame was used to load the specimens. The specimens were held by a pair of well aligned manually operated wedge-action grips. Instron Series IX software was used to control the test machine and to collect the test data. The test results (Table 1 and Figure 2) show that AV119 epoxy is relatively rate insensitive with joint strength increasing by approximately 27% over the displacement range considered.

Table 1 Shear Strength Rate Dependence for AV119/CR1 Single-Lap Joint.

Displacement Rate (mm/min)	Load/Width (N/mm)
1	334 ± 11
300	305 ± 10
1,020	317 ± 5
4,800	376 ± 4
13,800	410 ± 8
18,000	423 ± 8

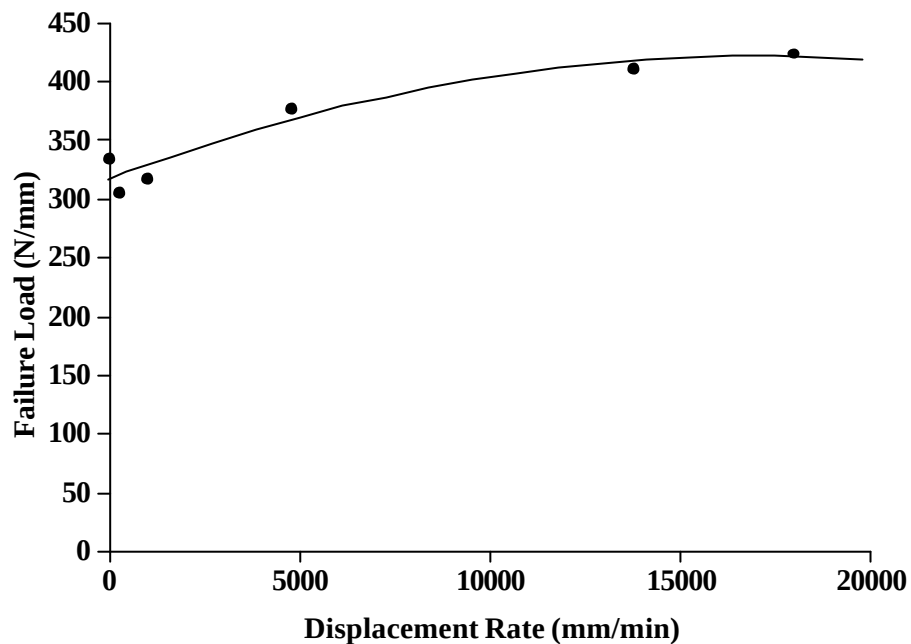


Figure 2 Failure load versus displacement rate for CR1/ AV119 single-lap joint.

Catastrophic failure occurred at the interface between adhesive and adherend. There was no visible sign of crack growth prior to failure. The steel sections permanently deformed under tensile loading. The load-displacement response for all test conditions was essentially linear-elastic up to failure. Consistency of data can be considered excellent (see Table 1). Joint strength could be expected to increase if a chamfer was included or the spew fillet radius was large.

2.3 CYCLIC FATIGUE TESTS

This section presents the results of tensile fatigue tests conducted on single-lap joint specimens, examining the fatigue life (i.e. applied stress, S , against number, N_f , of cycles to failure).

2.3.1 S-N Data

Single-lap specimens were subjected to constant amplitude (sinusoidal waveform) tension-tension cyclic fatigue loading. Constant amplitude fatigue tests were carried out in load control using an Instron 8501 servo-hydraulic test machine. The stress ratio R (P_{MIN}/P_{MAX}) was equal to 0.1. P_{MAX} is the maximum load and P_{MIN} is the minimum load reached at regular intervals by the sinusoidal load. Two test frequencies were considered (i.e. 5 Hz and 25 Hz). All tests were carried out under standard laboratory conditions to BS EN ISO 9664 [5]. Instron MAX software was used to control the servo-hydraulic test machine and to collect the test data.

Five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% of quasi-static strength) on the specimens. In order to limit the duration of tests, the number of cycles was limited to a maximum number of 10^7 cycles (equivalent to 23 days at 5 Hz). The **S-N curve** and associated fatigue data for the these tests are shown in Figure 3. **For inter-comparative purposes, fatigue strength data (Figure 3) are normalised with respect to the ultimate static strength P_0 of identically conditioned specimens measured at the fatigue test loading rate. The scatter associated with fatigue testing is generally large.**

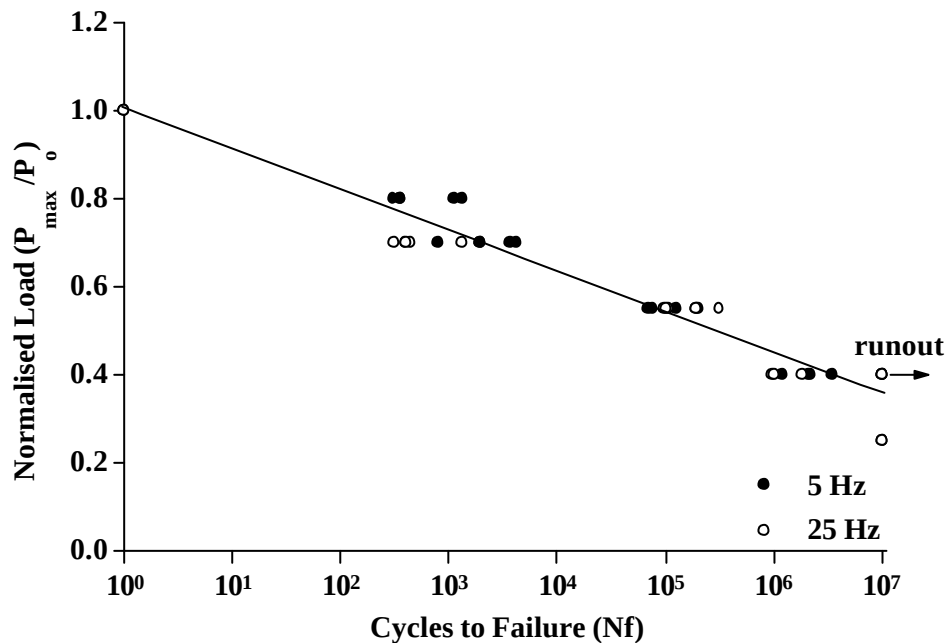


Figure 3 Normalised **S-N** curve for CR1 mild steel / AV119 single-lap joints.

The normalised **S-N** curve (Figure 3) can be approximated by a straight line fit as follows:

$$P_{\text{MAX}} / P_0 = 1 - k \log Nf \quad (1)$$

where **k** is the slope and **P_{MAX}** is the maximum load applied to the specimen. For these tests, **k** is approximately equal to 0.093.

The fatigue limit, which was set at 10^7 cycles, occurs at approximately 25% **P₀** (**N = 1**). At this stress level, there was no visually detectable damage (or changes in stiffness) in the single-lap joints following 10^7 cycles. At higher applied stresses (i.e. 40% **P₀** or greater), specimens failed catastrophically with failure occurring invariably at the edges of the overlap due to high peel and shear stresses. The fatigue response of AV119 is essentially independent of frequency over the range 5 to 25 Hz.

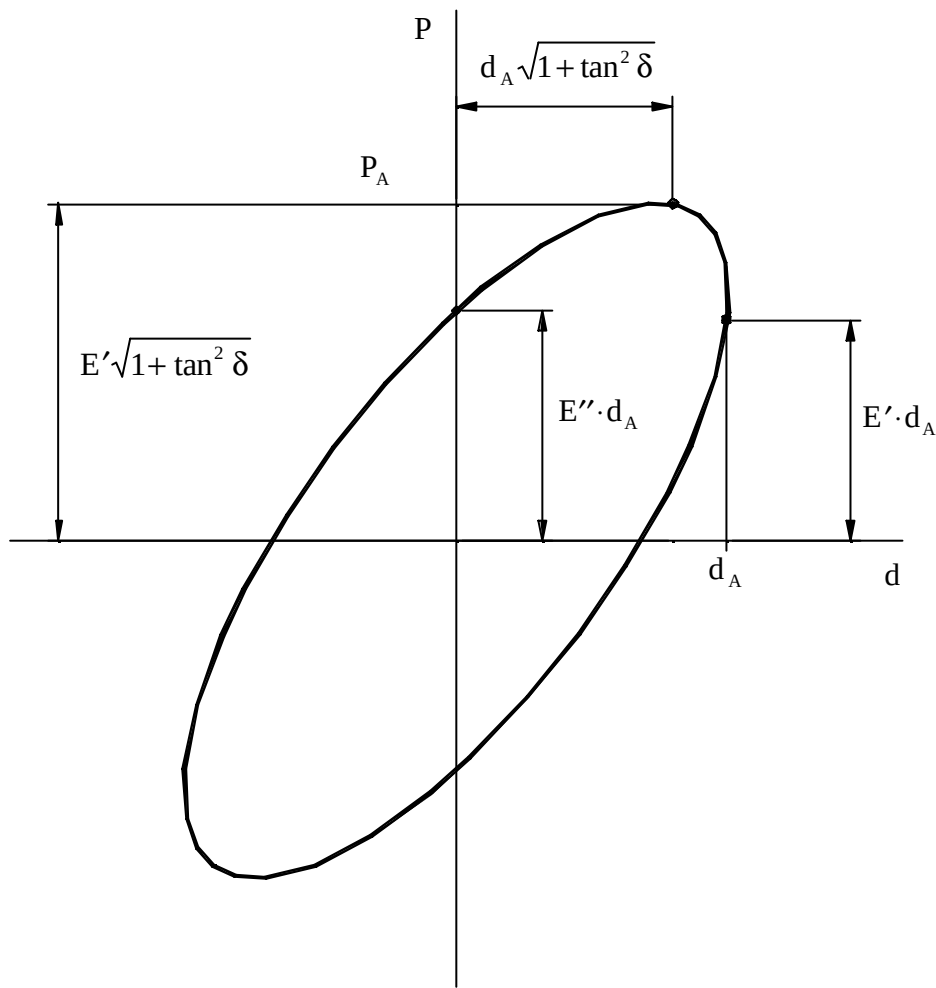


Figure 4 Schematic of load-displacement hysteresis loop.

As a result of cyclic fatigue, damage builds up in the adhesive joint in the vicinity of the overlap edges (i.e. adhesive fillet). This damage consists of interfacial debonding and to a lesser extent yielding and micro-cracking of the adhesive. Visual inspection of the joint reveals whitening in the adhesive fillet. Damage is not evident until late in the fatigue life

of the joint. Final fracture consists of rapid crack growth along the loaded substrate interface. The steel sections were permanently deformed at high stress levels.

2.3.2 Stiffness Reduction

The joint stiffness (i.e. dynamic compliance) remains constant throughout almost the entire life-time of the joint (Appendix 1) with the onset of failure marked by a rapid reduction in joint stiffness and an increase in the loss or damping factor ($\tan \delta$).

The loss factor $\tan \delta$ is the ratio between the tensile storage modulus E' and the tensile loss modulus E'' (i.e. $\tan \delta = E'/E''$) where δ is the phase angle between dynamic load and the dynamic displacement [6]. The storage modulus is proportional to the maximum energy stored during a loading cycle and represents the stiffness of the joint. The loss modulus is proportional to the energy dissipated (lost) during one loading cycle. Figure 4 shows a schematic diagram of a load-displacement (P - d) hysteresis loop in which the subscript A denotes the amplitude of the load and displacement. As damage accumulates the slope of the ellipse will decrease and the area within the ellipse will increase. Appendix 1 shows variations in stiffness and $\tan \delta$ for single-lap joints that have been loaded at 80%, 55% and 40% P_0 (i.e. quasi-static strength) at a test frequency of 5 Hz.

2.3.3 Concluding Remarks

Simple endurance testing of adhesives can be undertaken using the single-lap shear specimen, but for reasons discussed previously in NPL Report CMMT(A) 196 [2] the test can provide only comparative data.

3. TAPERED-STRAP JOINT

A number of design modifications have been recommended to reduce/remove peel stresses associated with single-lap and double-lap joints, and thus increase the strength of the bonded joint [1, 7-8]. An example is the tapered-strap joint (Figures 5 and 6) with external tapered (bevelled) straps. This configuration without tapered straps is also known as the double overlap or double butt-strap joint. Tapering the adherends, minimises peel stresses, increases bond efficiency (i.e. strength) and alters the failure mode from peel to shear. It has been purported that the peel stresses virtually disappear when using 30° fillets [7, 8]. The tapered-strap joint shown in Figures 5 and 6 is potentially suitable for determining shear behaviour under monotonic and cyclic loading conditions. This section evaluates this test method to determine the suitability of the technique for measuring shear modulus and shear strength under monotonic and cyclic loading.

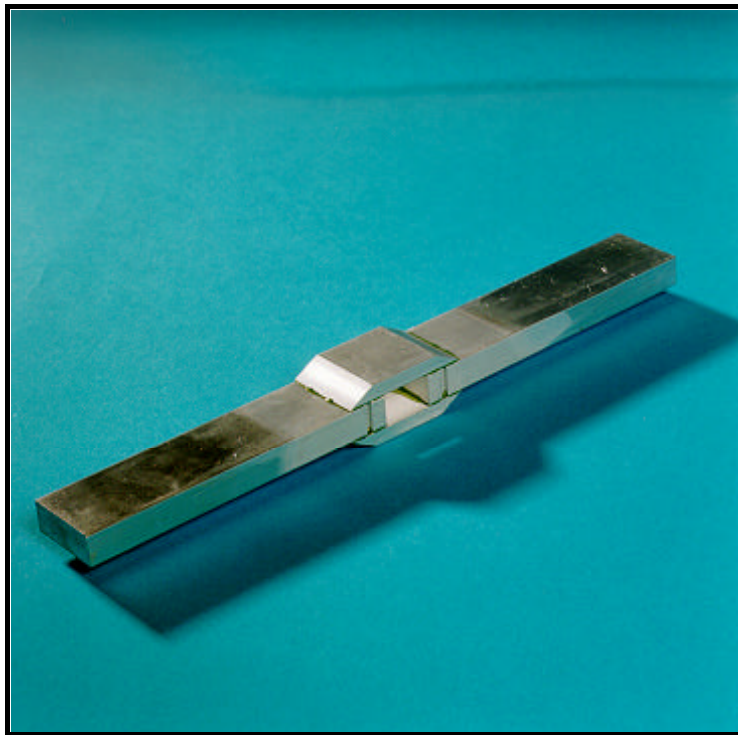


Figure 5 A 5251 aluminium alloy / AF126-2 tapered-strap joint.

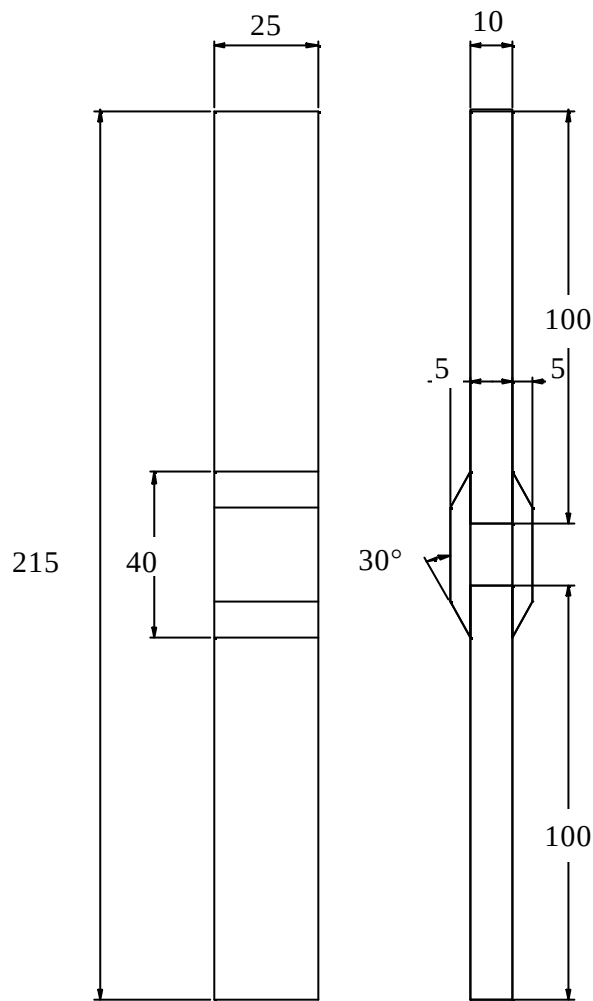


Figure 6 Schematic of tapered-strap joint (dimensions in mm).

3.1 SPECIMEN GEOMETRY AND PREPARATION

Quasi-static and cyclic fatigue tests were conducted on 5251 aluminium alloy tapered-strap joints bonded with AV119 and AF126-2 epoxy film adhesive (supplied by 3M, UK). Prior to bonding, the surfaces of the aluminium alloy sections to be bonded were chromic acid etched. A description of the technique is described below.

Stage 1 - Grit Blast + Degrease: The adherends were first degreased with 1,1,1-trichloroethane and then grit blasted using 80/120 alumina to produce an uniform matt finish. A pressure of 85 psi was used for grit-blasting the areas to be bonded. Any dust remaining after grit blasting was removed with clean compressed air. The surfaces to be bonded were then degreased again with 1,1,1-trichloroethane and dried.

Stage 2 - Chromic Acid Etch: The grit blasted / degreased specimens were then immersed for 30 minutes in a chromic acid etch solution at a temperature of 60-70 °C. The

specimens were removed from the etch solution and washed in cold tap water and then hot tap water. Finally, the specimens were rinsed with acetone and allowed to dry in a fan oven for a few minutes at 120 °C. Specimens were inverted to enable the water to drain from the areas to be bonded. The etch solution consisted of 500 ml of distilled water with 75 ml of sulphuric acid (H₂SO₄) and 37.5 gm of sodium dichromate (Na₂Cr₂O₇·2H₂O).

The cure cycle and a brief description of the two adhesives is given below.

Araldite 2007Ò (AV119): A one part epoxy adhesive (Ciba Speciality Chemicals). The cure schedule was 140 °C for 75 minutes.

AF126-2: A modified epoxy film adhesive (3M, UK). The adhesive contains a carrier fabric for bondline thickness control. The cure cycle was 120 °C for 90 minutes.

The adherends were machined to the required dimensions and surface treated and then adhesively bonded in accordance with the adhesive manufacturer's instructions. Horizontal notches (1.5 mm wide and 1.5 mm deep) were machined in the central adherends, 5 mm either side of the central gap, to allow the insertion of 25 mm gauge-length extensometers for measuring shear deformation (see Figure 5). The gap, which is not essential, was introduced to allow for the possible insertion of clip gauges, which can be difficult to attach to the specimen. Finite element analysis (FEA), carried out at the National Physical Laboratory (NPL), has shown that changing the central gap has a marginal influence on the stress and strain distributions along the bondline (see Section 3.4).

The adherends were bonded whilst held securely in a clamping fixture to ensure accurate alignment of the adherends. **A 15 mm thick strip of polytetrafluoroethylene (PTFE) was inserted in the gap between the adherends after the application of the adhesive and prior to curing.** These spacers were removed after the adhesive was cured.

3.2 ANALYTICAL ANALYSIS

This section lists the main relationships for determining shear deformation, shear modulus and shear strength for the tapered-strap joint (based on one-dimensional analysis) [9].

Shear deformation (i.e. gap displacement between the inner adherends D) is measured using two extensometers located on either side of the specimen. The shear deformation measurements obtained from the two extensometers are averaged to minimise any misalignment effects.

The shear strain in the adhesive γ_A can be related to the relative displacement d (in the adhesive) by:

$$\gamma_A = \frac{\delta}{2t_A} \quad (2)$$

where t_A is the thickness of the adhesive. The value of d is related to the gap displacement D and peak strain in the outer substrate (i.e. strap) ϵ_R by the following relationship:

$$\delta = h e_R - \Delta \quad (3)$$

where **h** is the initial gap length.

Peak strain **e_R** is given by:

$$e_R = \frac{P}{2bE_R t_R} \quad (4)$$

where **b** is the joint width, **P** is the applied load, **E_R** is the Young's modulus of the straps and **t_R** is the thickness of the straps.

The shear strength **t** is given by:

$$\tau = \frac{P_{MAX}}{2bL} \quad (5)$$

where **P_{MAX}** is the maximum load, **b** is the joint width and **L** is the joint overlap length.

3.3 STRESS ANALYSIS

Finite element analysis (FEA) has been carried out on a tapered-strap shear configuration to assess the effect of: (i) taper angle of the outer (bridging) adherends; and (ii) central gap on stress and strain distributions within the adhesive joint (see Appendix 2). The commercial FE code ABAQUS with MSc/Patran pre-processor was used to model peel and shear stresses and strains along the bondline of a mild steel tapered-strap joint bonded with AV119. The results of the modelling using two dimensional symmetric linear-elastic analysis (see Appendix 2) are summarised below:

- Reducing the taper angle from 90° (square ends) to 30° effectively reduces the peel stresses and shear stresses by approximately 10%.
- Reducing the internal gap had minimal effect on stress distributions within the tapered-strap joint.
- High peel and shear stresses are present at the tapered edges of the straps.

The high peel and shear stresses and strains present at the end of the bondline can be expected to be significantly reduced for thicker sections than those used in the example presented in Appendix 2. Ideally, the taper angle should be less than 30° in order to reduce stress concentrations at the overlap ends.

3.4 QUASI-STATIC TESTS

Testing was carried out under ambient conditions (23°C, 50% RH) at a constant displacement rate of 1 mm/min using an Instron 8501 servo-hydraulic test frame. Instron Series IX software was used to control the test machine and to collect the test data. Five specimens were tested. The shear strength and shear modulus measurements are presented in Table 2 (**Note:** TAST denotes thick adherend shear test). Figure 7 shows a typical shear stress-strain curve obtained for a 5251 aluminium alloy / AV119 epoxy joint.

Table 2 Measured Shear Properties for Tapered-Strap Joints

Property	AV119	AF126-2
Shear Modulus (GPa)		
Tapered-Strap Joint	1.06 ± 0.01	0.72 ± 0.11
TAST	1.07 ± 0.04	0.63 ± 0.05
Shear Strength (MPa)		
Tapered-Strap Joint	32.4 ± 3.0	28.8 ± 1.1
TAST	47.6 ± 2.9	43.5 ± 2.3

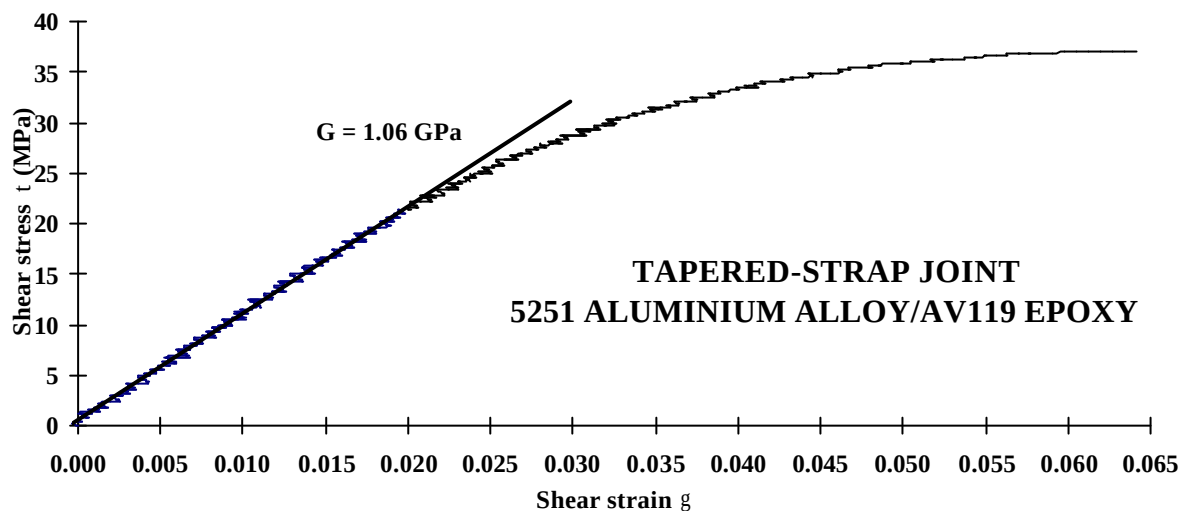


Figure 7 Typical shear stress-strain curve for tapered-strap joint.

Key Observations

- Tapered-strap joint geometry is suitable for measuring shear modulus. Standard type extensometers or clip gauges can be used to measure the shear deformation. **Care needs to be taken to ensure that the extensometers are well aligned and fully supported. Calculating the shear strain from the cross-head movement of the test machine is not a satisfactory method, since the cross-head movement represents the global response of the specimen and loading chain.**
- Failure is strongly influenced by peel stresses at the taper ends. Shear strength data was lower than that measured for bulk adhesives or TAST.

Tapering of the adhesive fillets at the ends of the straps and using inverted tapers on the straps will reduce the peel stresses significantly, although the additional features will add to the overall costs of specimen preparation. Shaped PTFE spacers should be employed for the interior fillets. The use of standard extensometers is relatively straightforward in comparison to the special extensometers (e.g. KGR-1) that are required for measuring shear strain for the TAST [10].

3.5 CYCLIC FATIGUE TESTS

This section evaluates the fatigue performance of the tapered-strap joint under constant amplitude tension-tension cyclic loading.

3.5.1 S-N Data

Constant amplitude fatigue tests were carried out under load control at a frequency of 5 Hz using an Instron 8501 servo-hydraulic test machine. The stress ratio **R** was equal to 0.1. Specimens were held in wedge-action servo-hydraulic grips. The grips asserted a lateral a pressure of 100 psi. All tests were carried out under standard laboratory conditions to BS EN ISO 9664 [6]. Instron MAX software was used to control the servo-hydraulic test machine and to collect the test data.

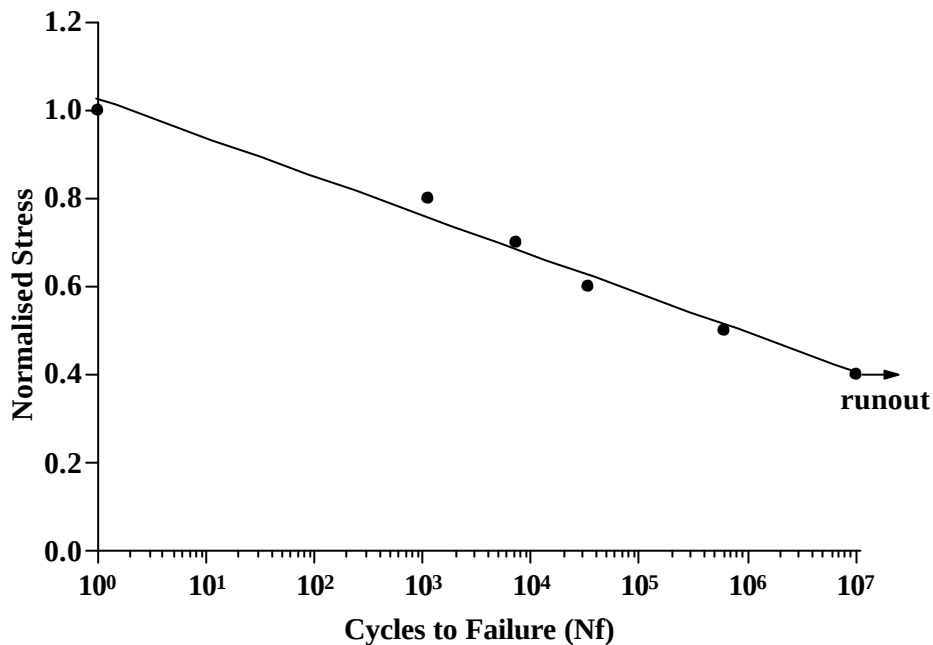


Figure 8 Normalised **S-N** curve for 5251 aluminium alloy / AF126-2 tapered-strap joints.

A limited number of tests were carried out at five stress levels (i.e. 80%, 70%, 60%, 50% and 40% of quasi-static strength) on the specimens. As with the fatigue tests on the single-lap joints, the number of cycles was limited to a maximum number of 10^7 cycles. The **S-N** curve and associated fatigue data for the these tests are shown in Figure 8. The fatigue strength data (Figure 6) are normalised with respect to the ultimate tensile strength, **P₀**, of identically conditioned specimens measured at the fatigue test loading rate.

The normalised **S-N** curve (Figure 8) can be approximated by a straight line fit as given by Equation (1). For these tests, **k** is again approximately 0.088. The fatigue limit (i.e. 10^7 cycles) occurs at approximately 40% **P₀**. At this stress level, there was no detectable damage in the tapered-strap joints following 10^7 cycles. Specimens tested at higher applied stresses (i.e. 50% **P₀** or greater) failed catastrophically with failure occurring at the bevelled edges of the overlaps due to high peel and shear stresses.

As a result of cyclic fatigue, damage builds up in the adhesive joint in the vicinity of the bevelled ends. This damage consists of plastic deformation and micro-cracking of the adhesive. Visual inspection of the joint reveals whitening in the adhesive fillet. Damage is not evident until late in the fatigue life of the joint. Final fracture consists of rapid crack growth through the adhesive (i.e. cohesive failure of the adhesive). The aluminium straps were permanently deformed, whereas the thicker inner sections remained unaffected.

3.5.2 Shear Strain Measurements

A limited number of tests were conducted to determine changes in shear strain during cyclic loading. The shear stiffness can be calculated using Equations (2) to (4) from the shear deformation measurements. Figure 9 shows the shear strain with loading cycles for a specimen loaded at 50% ultimate strength for 100,000 cycles. Following the initial bedding in period, the shear strain level relatively constant for the remainder of the test. Tests were stopped before failure in order to measure residual strength. There was a reduction in residual strength without any apparent reduction in shear stiffness of the joint.

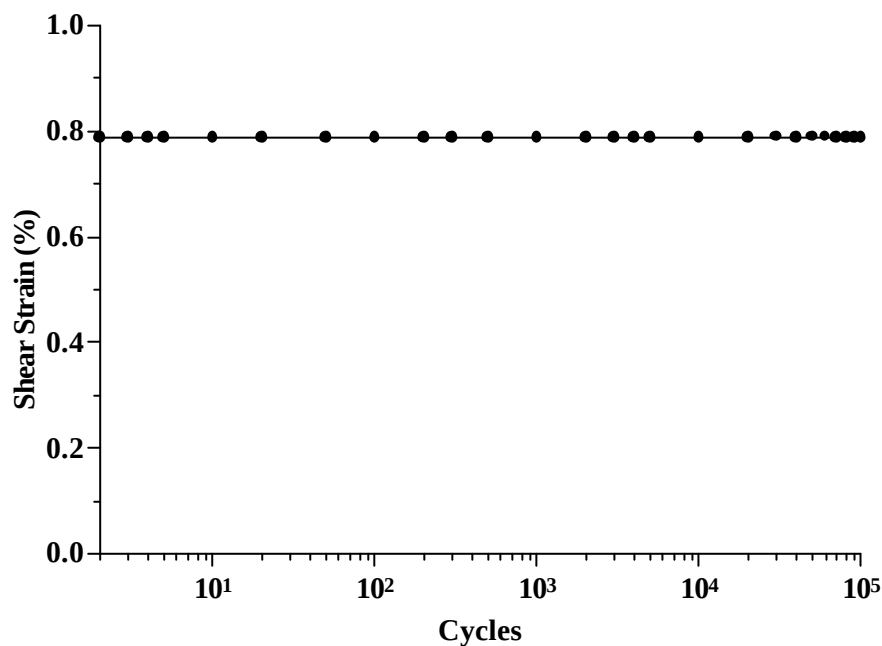


Figure 9 Strain measurements during cyclic loading of tapered-strap joint.

Key Observations

- **Tapered-strap joints exhibit similar fatigue behaviour to the single-lap joints with the reduction in fatigue life being almost identical.**
- **Peel stresses at the overlap ends compromise fatigue performance.**
- **Tapered-strap joints are suitable for measuring dynamic shear deformation.**

4. SCARF JOINT

Scarf joints will develop negligible peel stresses if correctly designed and therefore in principle are suitable for joining thick sections (greater than 6.35 mm thick). The simple scarf joint (Figure 10) is potentially suitable for measuring variations in shear strength for a wide range of environmental and mechanical loading conditions. This section evaluates a simple scarf joint with a 30° angle.

Quasi-static and cyclic fatigue tests have been conducted on the test joint (Figure 10) under standard laboratory conditions in order to assess the reliability of the technique for measuring static and dynamic shear strength. Finite element analysis (FEA) has also been carried out on the test geometry to ascertain the degree of shear stress uniformity along the bondline and to determine the relative magnitude of axial and transverse tensile stresses.

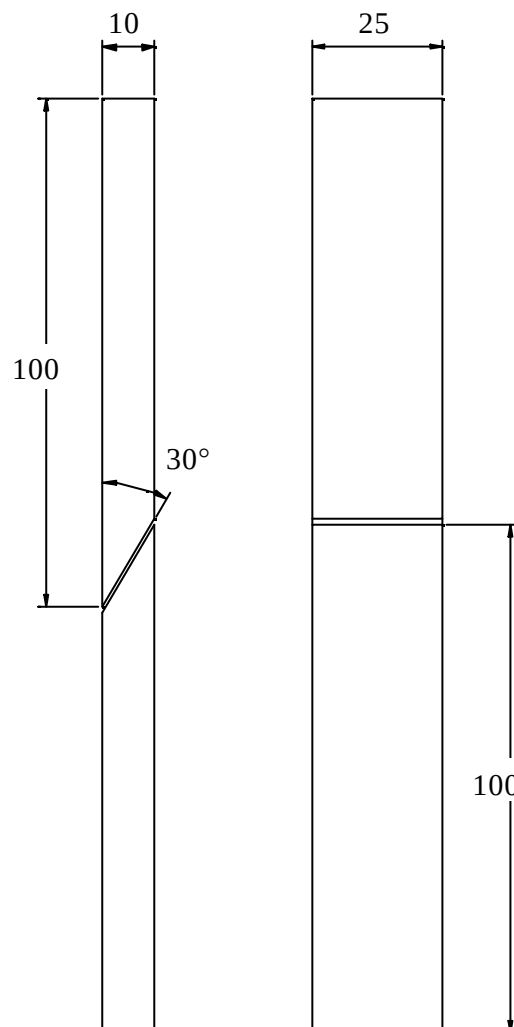


Figure 10 Schematic of scarf joint with taper angle of 30° .

4.1 STRESS ANALYSIS

4.1.1 Analytical Solution

A simple strength-of-materials analysis approach [11], resolving stresses and areas, can be used to determine shear stress τ and normal stress s_T in a simple scarf joint. The analysis predicts a uniform shear stress in the adhesive layer given by [11]:

$$\tau = P \sin \theta \cos \theta / t \quad (6)$$

and a uniform normal stress in the adhesive given by:

$$\sigma_T = P \sin^2 \theta / t \quad (7)$$

where P is the applied (end) load per unit width, t is the adherend thickness and θ is the taper angle.

The ratio of normal stress to shear stress is given by [10]:

$$\sigma_T / \tau = \tan \theta \quad (8)$$

For a taper angle $\theta = 30^\circ$, s_T/t is equal to 0.57. Ideally, the taper angle should be as small as possible. For repair applications, θ is required to be less than 3° (i.e. $s_T/t = 0.05$).

In principle, the load bearing capacity increases in proportion with the thickness of the adherends and is not limited by local stress concentrations at the overlap ends. The above analysis assumes that as the shear stress distribution is uniform and that there is no elastic trough in the stress distribution along the bondline to alleviate continuous strains (deformations) under prolonged loading (e.g. creep or low frequency cyclic fatigue loads). FEA was carried out to verify if these assumptions were valid (see Section 4.1.2).

4.1.2 Finite Element Analysis

FEA was carried out on a simple scarf joint (Figure 10) manufactured from 5251 aluminium and bonded with AV119. The analysis, presented in Appendix 3, shows the shear and normal stress distributions in the adhesive are relatively uniform, thus confirming that the assumptions on which the analytical analysis is based are generally sound. Peel stresses are relatively low in comparison with single-lap joints loaded in tension. Predicted and measured load-displacement responses were in good agreement. The tendency is to overestimate joint stiffness by approximately 5% using FEA. This difference is attributed to a number of factors: (i) plastic deformation within the adhesive joint; and (ii) test machine compliance. **The uniform shear stress distribution and low axial and transverse stresses promotes high bond strengths.** The use of extensometers for measuring displacement rather than the cross-head movement would reduce the difference between predicted and measured joint stiffness.

4.2 QUASI-STATIC TESTS

Quasi-static tests were conducted on 5251 aluminium alloy scarf joints bonded with AF126-2 and AV119 epoxy adhesives. Specimen preparation and tensile testing was essentially identical to that employed for the tapered-strap joints. Compression tests were also conducted on joints bonded with AF126-2. Displacement was measured directly from the cross-head movement of the test machine. The results from the scarf joints (Table 3) show a distinct difference in failure loads for the two adhesive systems tested in tension. The failure stress corresponds to the maximum applied load divided by the cross-sectional area (i.e. width x thickness) of the specimen. Typical tensile and shear properties for the two adhesive systems are presented in Table 4.

Table 3 Failure Stress (MPa) Measurements for Scarf Joints

Adhesive	Failure Stress	Stress Components	
		Shear Stress	Normal Stress
AV119	98.3 ± 3.7	42.6 ± 1.6	24.6 ± 0.9
AF126-2			
Tension	46.3 ± 1.4	20.0 ± 0.4	11.6 ± 0.3
Compression	76.4 ± 1.8	33.1 ± 0.8	19.1 ± 0.6

Table 4 Tensile and Shear Properties for AV119 and AF126-2

Property	Adhesive	
	AV119	AF126-2
Tension		
Modulus (GPa)	3.05	2.03
Strength (MPa)	70	47
Poisson's Ratio	0.34	0.42
Shear		
Modulus (GPa)	1.07 ± 0.04	0.63 ± 0.05
Strength (MPa)	47.6 ± 2.9	43.5 ± 2.3

The results of the quasi-static tests can be summarised as follows:

- Von Mises failure criterion (i.e. s_T (tensile strength) $\approx \sqrt{3}t_Y$ (shear yield strength)) can be used to estimate failure loads for joints bonded with low yielding adhesive systems, such as AV119.
- Predicting the static strength of joints bonded with hydrostatic stress sensitive adhesives, such as AF126-2 is far more difficult.
- Loading scarf joints in compression suppresses tensile peel stresses, resulting in a substantial increase in joint strength.

4.3 CYCLIC FATIGUE TESTS

Constant amplitude fatigue tests were carried out under load control at a frequency of 5 Hz using an Instron 8501 servo-hydraulic test machine. The stress ratio **R** was equal to 0.1. Testing and data analysis were identical to that used for the tapered-strap joints.

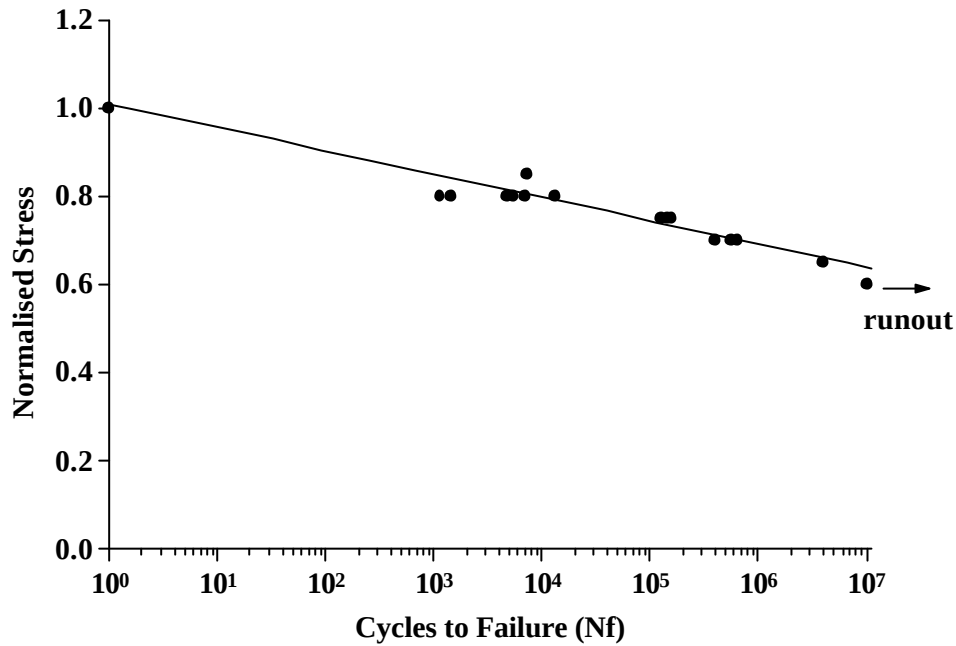


Figure 11 Normalised **S-N** curve for 5251 aluminium alloy / AF126-2 scarf joints. Five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% of quasi-static strength) on the specimens. The number of cycles was limited to a maximum number of 10^7 cycles. The Normalised **S-N** curve and associated fatigue data for the these tests are shown in Figure 11.

The normalised **S-N** curve (Figure 11) can be approximated by a straight line fit as given by Equation (1). For these tests, **k** is again approximately 0.055. The fatigue limit (i.e. 10^7 cycles) occurs at approximately 60% **P₀**. There was no detectable damage in the scarf joints following 10^7 cycles at this stress level. At higher applied stresses, specimens failed catastrophically as a result of cohesive failure of the adhesive. Minimal deformation was observable for the failed specimens. The improved fatigue performance observed for scarf joints compared with the other two joint configurations may be attributed to a reduction in peel and shear stress concentrations at the ends of the overlap.

5. CONCLUDING REMARKS AND DISCUSSION

A number of conclusions can be made in respect to the results obtained from cyclic loading of adhesive joints under ambient conditions.

- Fatigue resistance is dependent on joint geometry with **high shear and peel stress concentrations at the overlap ends severely compromising the fatigue performance of bonded structures. High peel stresses are probably the governing factor.**
- **Joint stiffness remains constant throughout almost the entire life-time of the joint with the onset of failure marked by a rapid reduction in joint stiffness and an increase in the loss or damping factor ($\tan \delta$).**
- Normalised **S-N** curve can be approximated by a straight line fit as follows:

$$P_{\text{MAX}} / P_0 = 1 - k \log Nf$$

where **k** is the slope, **Nf** is the number of cycles to failure, **Pmax** is the maximum load applied to the specimen, **P₀** is the ultimate strength of identically conditioned specimens measured at the fatigue test loading rate.

Single-lap and tapered-strap joints with similar overlap lengths (i.e. 12.5 mm) were less resistant (**k** $\approx$ 0.09) to fatigue loading than the scarf joint (**k** $\approx$ 0.06) configuration. The endurance limit (i.e. 10^7 cycles) occurs at far lower load values for the single-lap and tapered-strap joints in comparison with the scarf joint. **The value of k will increase as the ratio of peel stress to shear stress increases.** Published single-lap and T-peel joint test results [12] indicate a **k** value of between 0.11 and 0.13.

- The fatigue response of the AV119 epoxy adhesive is essentially independent of frequency of the applied load over the range 5 to 25 Hz; as expected since the static strength of single-lap joints remained relatively unaffected by changes in strain rate.
- **Tapered-strap joint geometry is suitable for measuring shear modulus under monotonic and cyclic loading conditions.** Standard type extensometers or clip gauges can be used to measure the shear deformation. Test geometry can be improved by introducing inverted taper angles.
- Loading scarf joints in compression suppresses tensile peel stresses, resulting in a substantial increase in joint strength.

Repeated cyclic loading to high plastic strains can result in creep failure occurring within a relatively short number of cycles due to the cumulative effect of cyclic shear strains. From a design perspective, a sufficiently long overlap length will ensure that the most of adhesive remains elastic. The elastic region acts as an elastic reservoir during unloading, enabling the bond layer to recover (i.e. stress relief) and thereby preventing damage strain accumulating. Provided the minimum shear stress at the middle of the overlap remains within the elastic limit of the adhesive and the maximum shear strain at the ends of the

overlap is limited to a value below the adhesive yield strain, then the joint should be suitable for use under cyclic loading conditions. Creep within the low stress region of the bonded region should be kept to a minimum.

ACKNOWLEDGEMENTS

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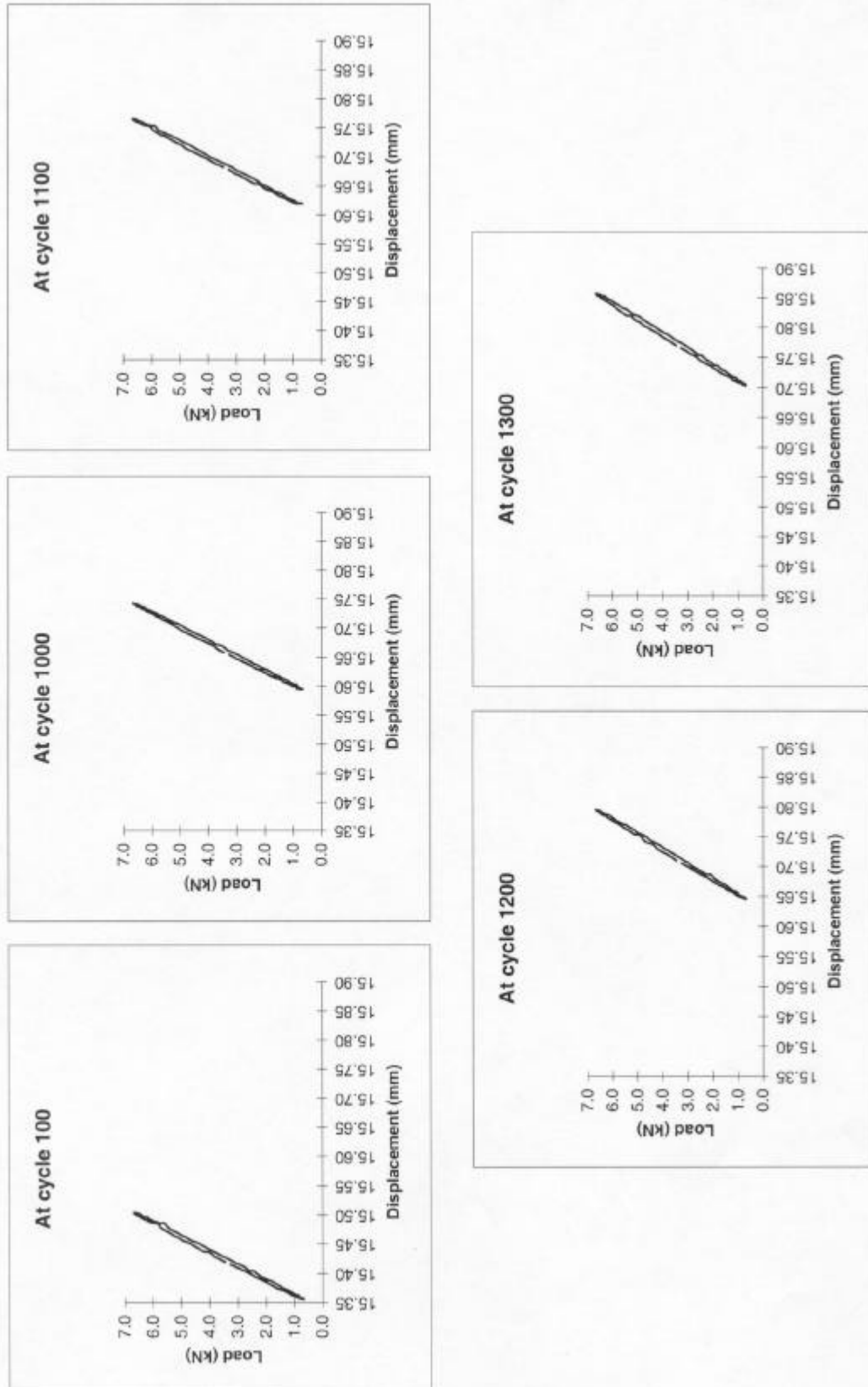
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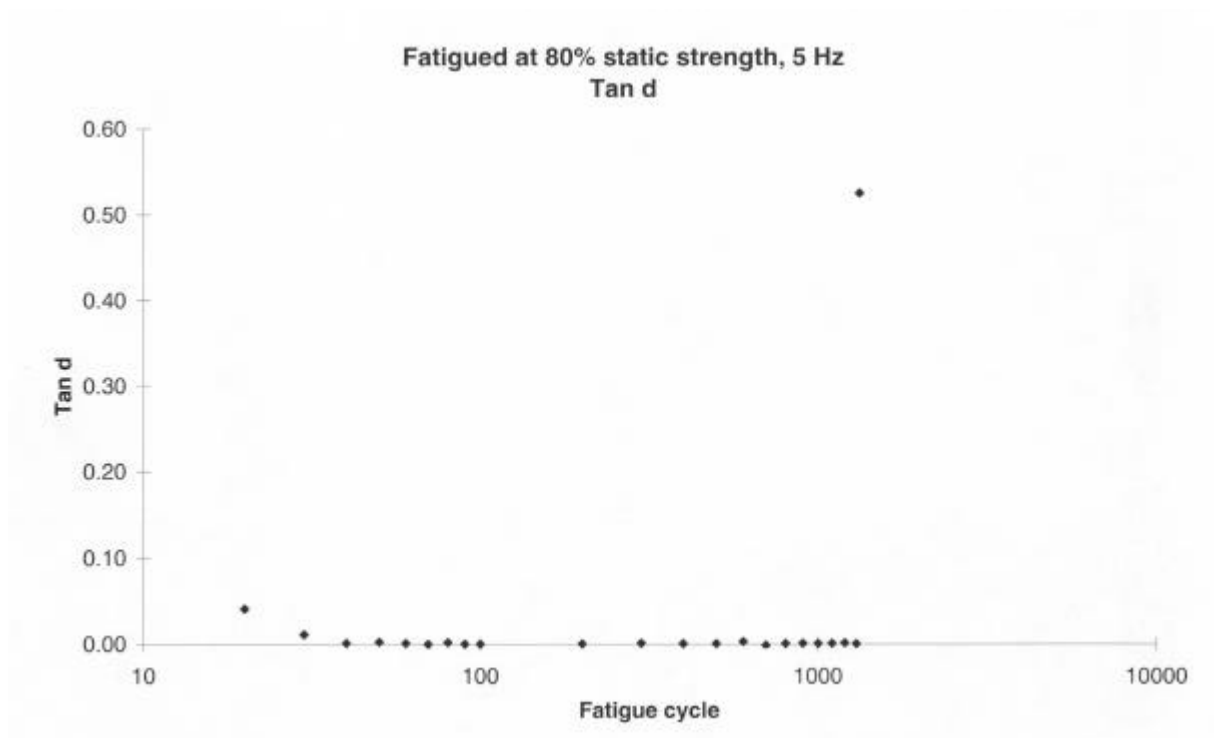
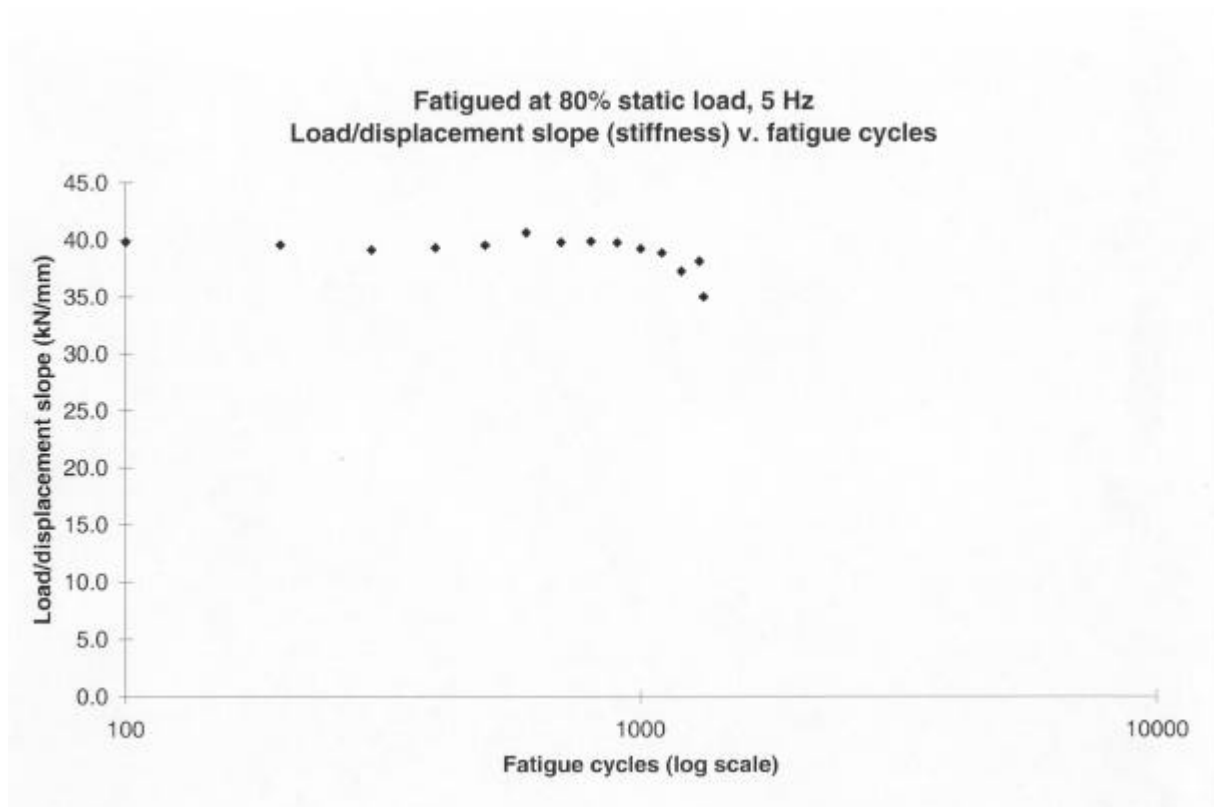
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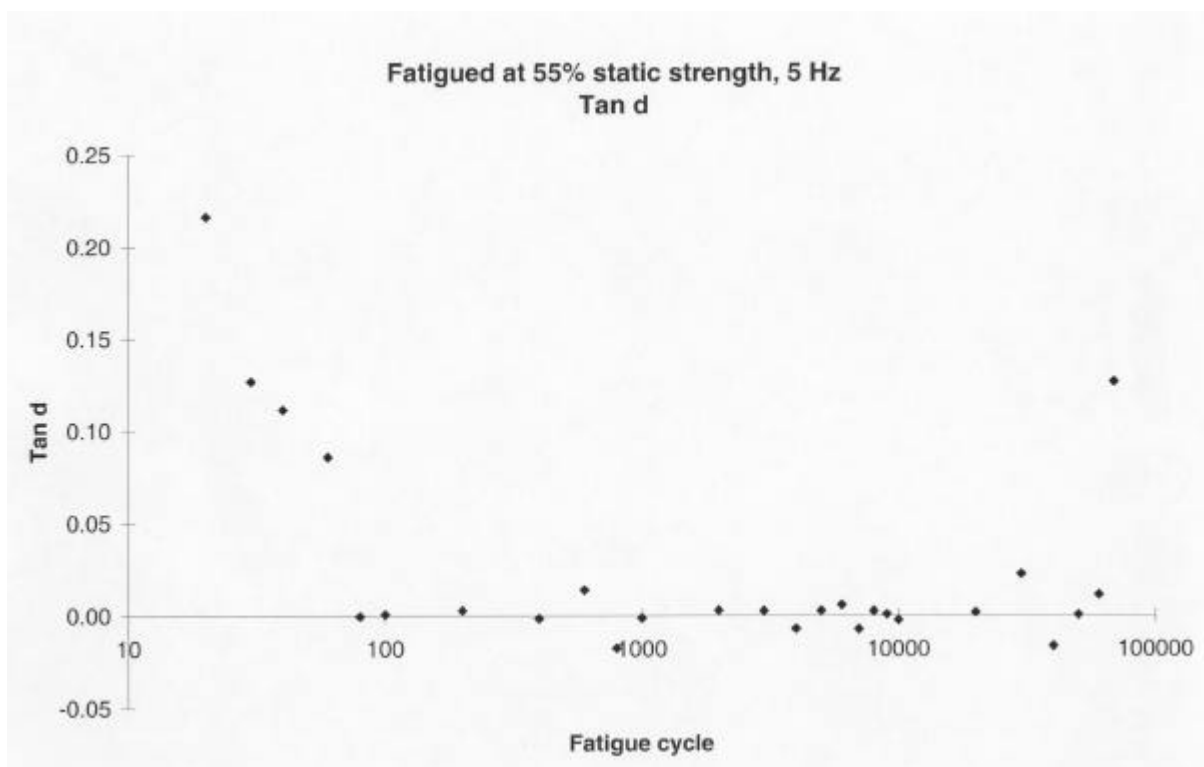
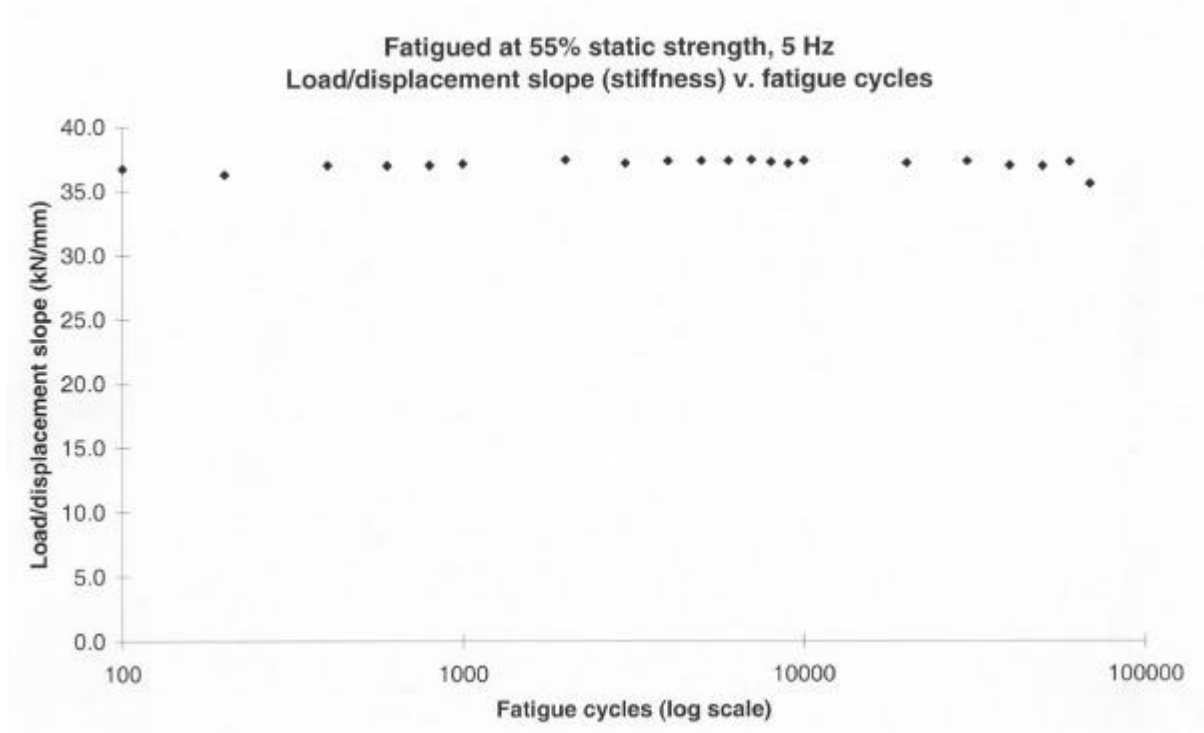
APPENDIX 1

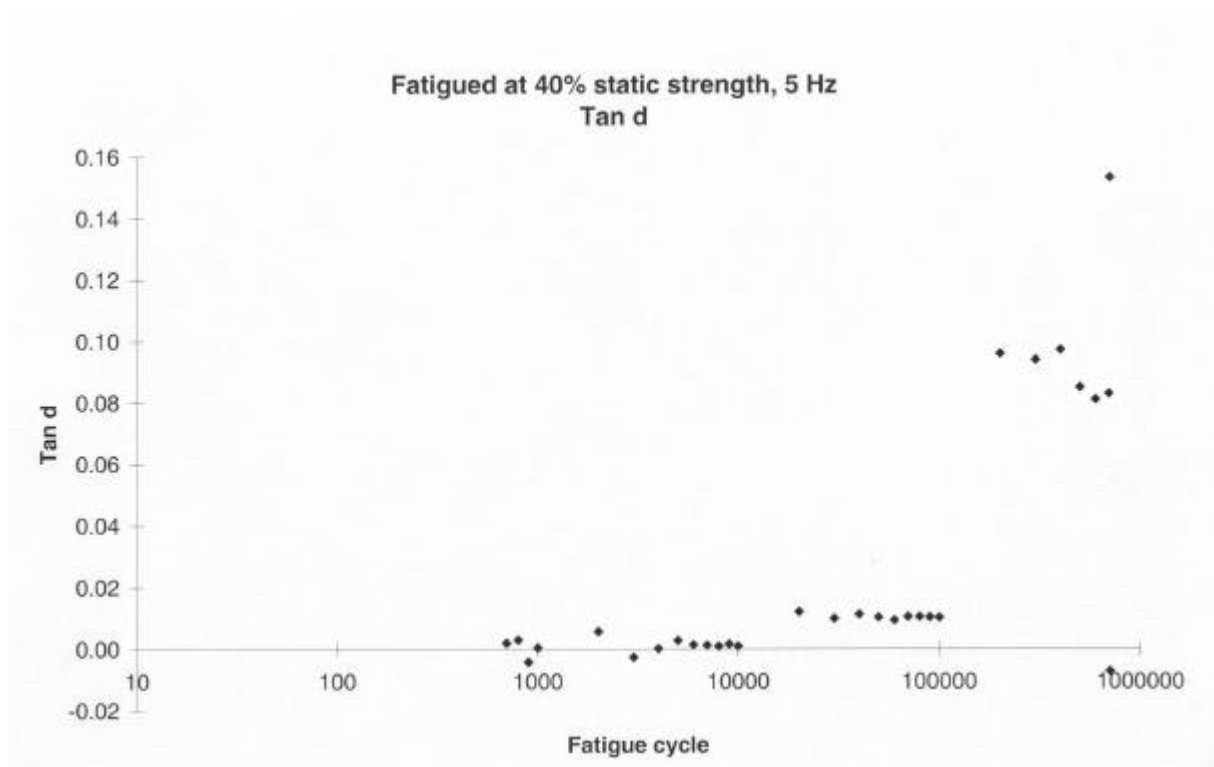
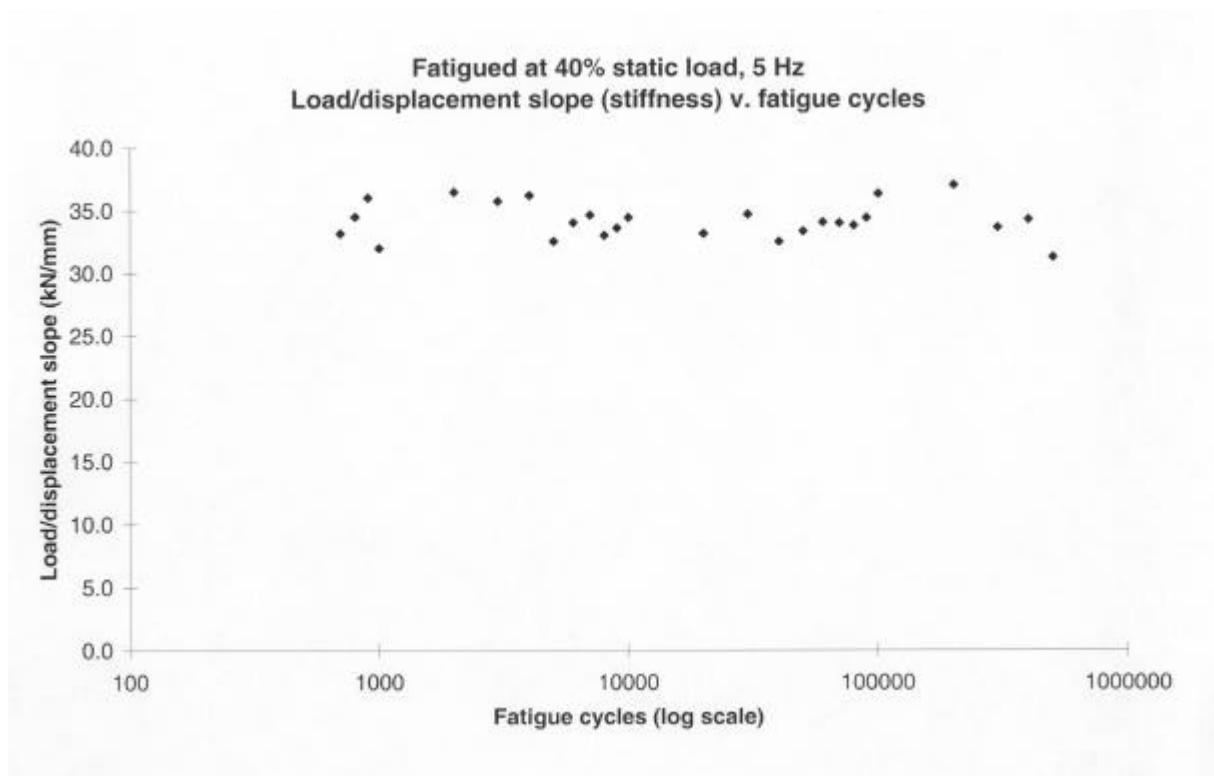
SINGLE-LAP JOINT STIFFNESS AND TAN δ MEASUREMENTS

Fatigued at 80% static strength, 5 Hz
Change of position of load/displacement loop with time



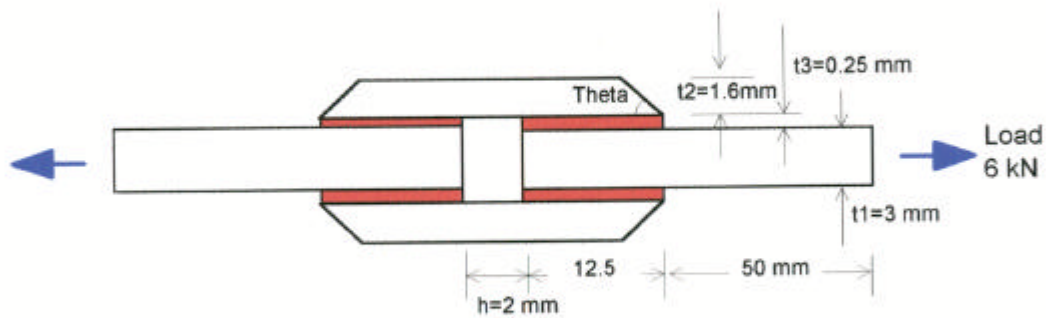






APPENDIX 2 ELASTIC-PLASTIC FEA OF TAPERED-STRAP JOINT

FEA OF DOUBLE-LAP JOINT

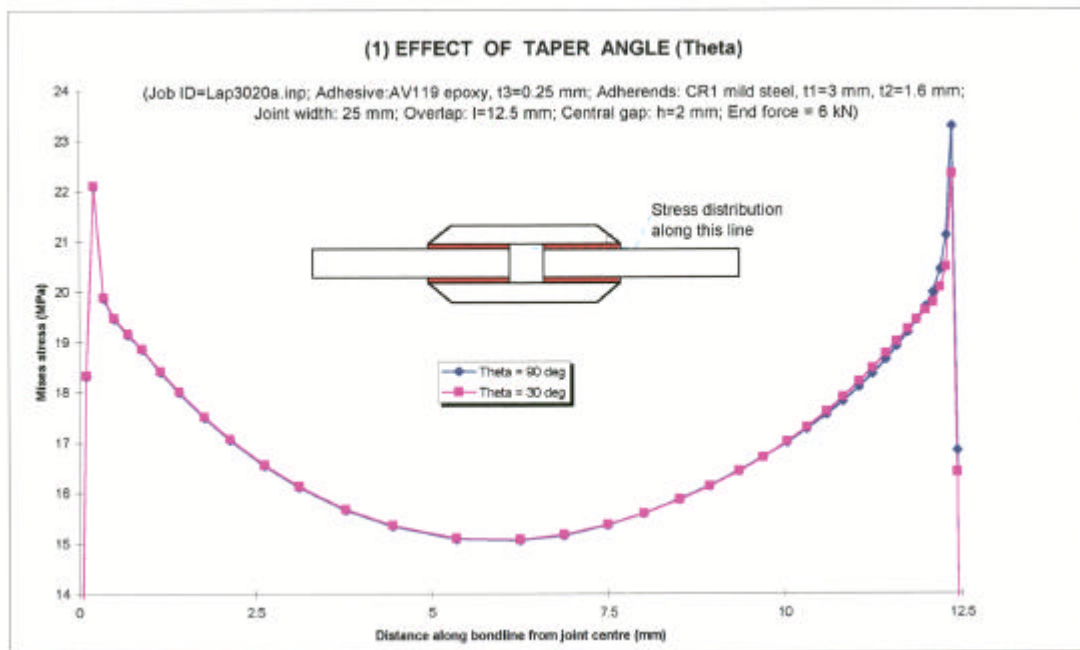


Adhesive Materials: AV119 Epoxy

Adherends Materials: CR1 Mild Rolled Steel

Joint Width: 25 mm

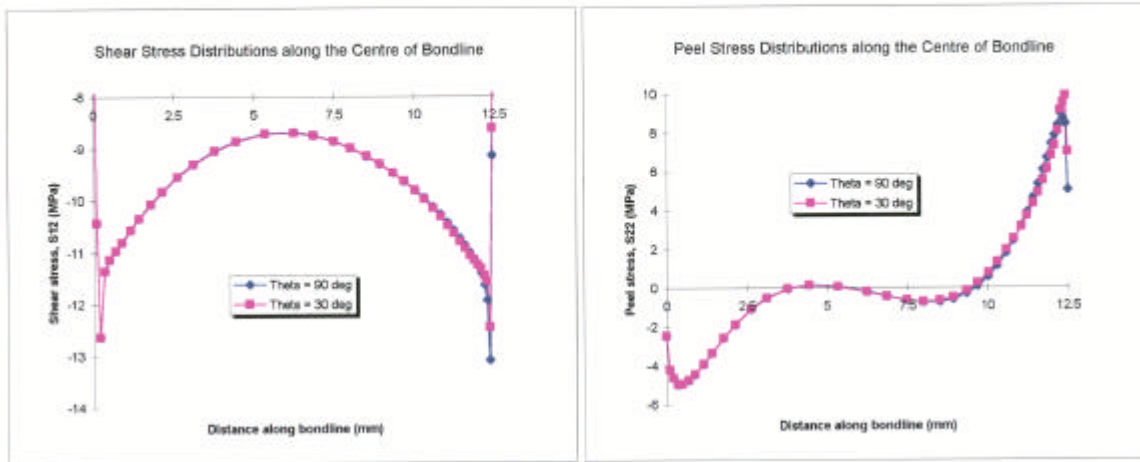
1 - Specimen Geometry.



2 - Effect of Taper Angle on Mises Stress Distributions.

Elastic-Plastic FE Analysis of a Double-Lap Joint

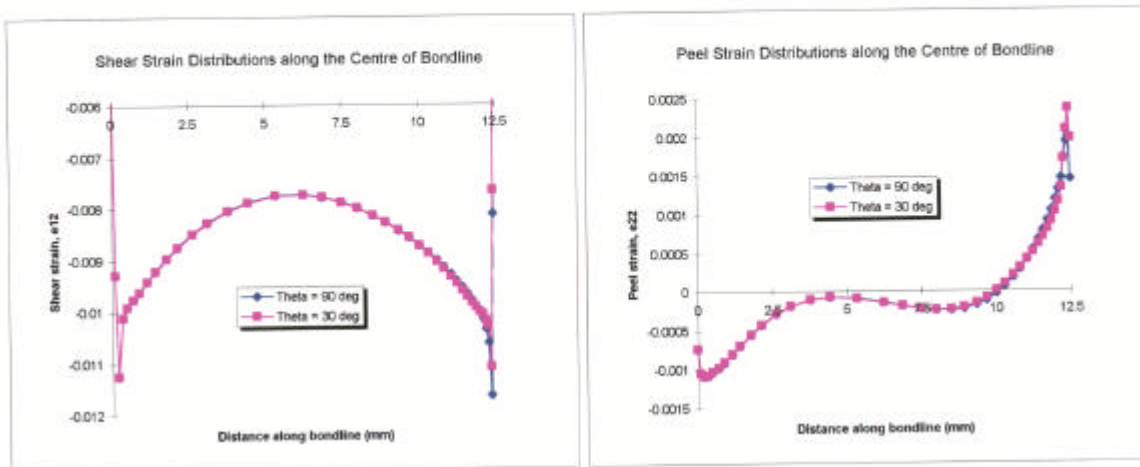
(Job ID=Lap3020a.inp; Adhesive:AV119 epoxy, $t_3=0.25$ mm; Adherends: CR1 mild steel, $t_1=3$ mm, $t_2=1.6$ mm;
Joint width: 25 mm; Overlap: $l=12.5$ mm; Central gap: $h=2$ mm; End force = 6 kN)



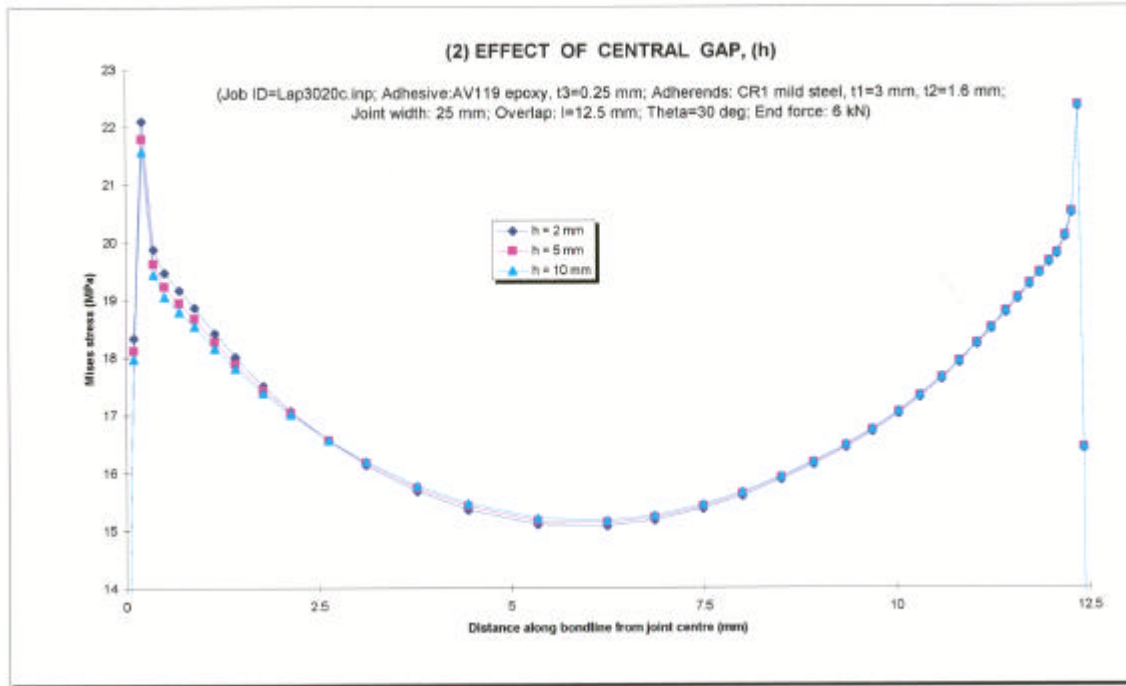
3 - Effect of Taper Angle on Shear and Peel Stress Distributions.

Elastic-Plastic FE Analysis of a Double-Lap Joint

(Job ID=Lap3020a.inp; Adhesive:AV119 epoxy, $t_3=0.25$ mm; Adherends: CR1 mild steel, $t_1=3$ mm, $t_2=1.6$ mm;
Joint width: 25 mm; Overlap: $l=12.5$ mm; Central gap: $h=2$ mm; End force = 6 kN)



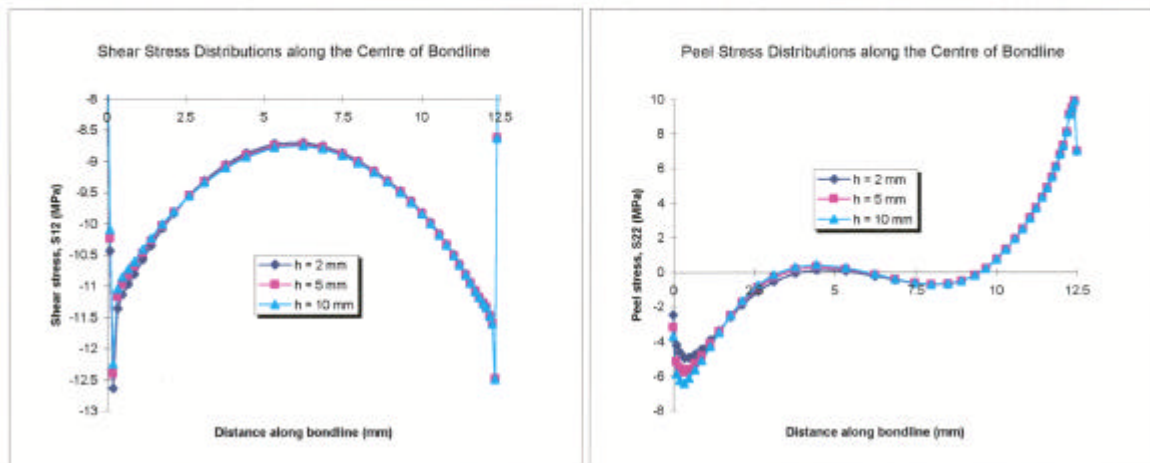
4 - Effect of Taper Angle on Shear and Peel Strain Distributions.



5 - Effect of Central Gap on Mises Stress Distributions.

Elastic-Plastic FE Analysis of a Double-Lap Joint

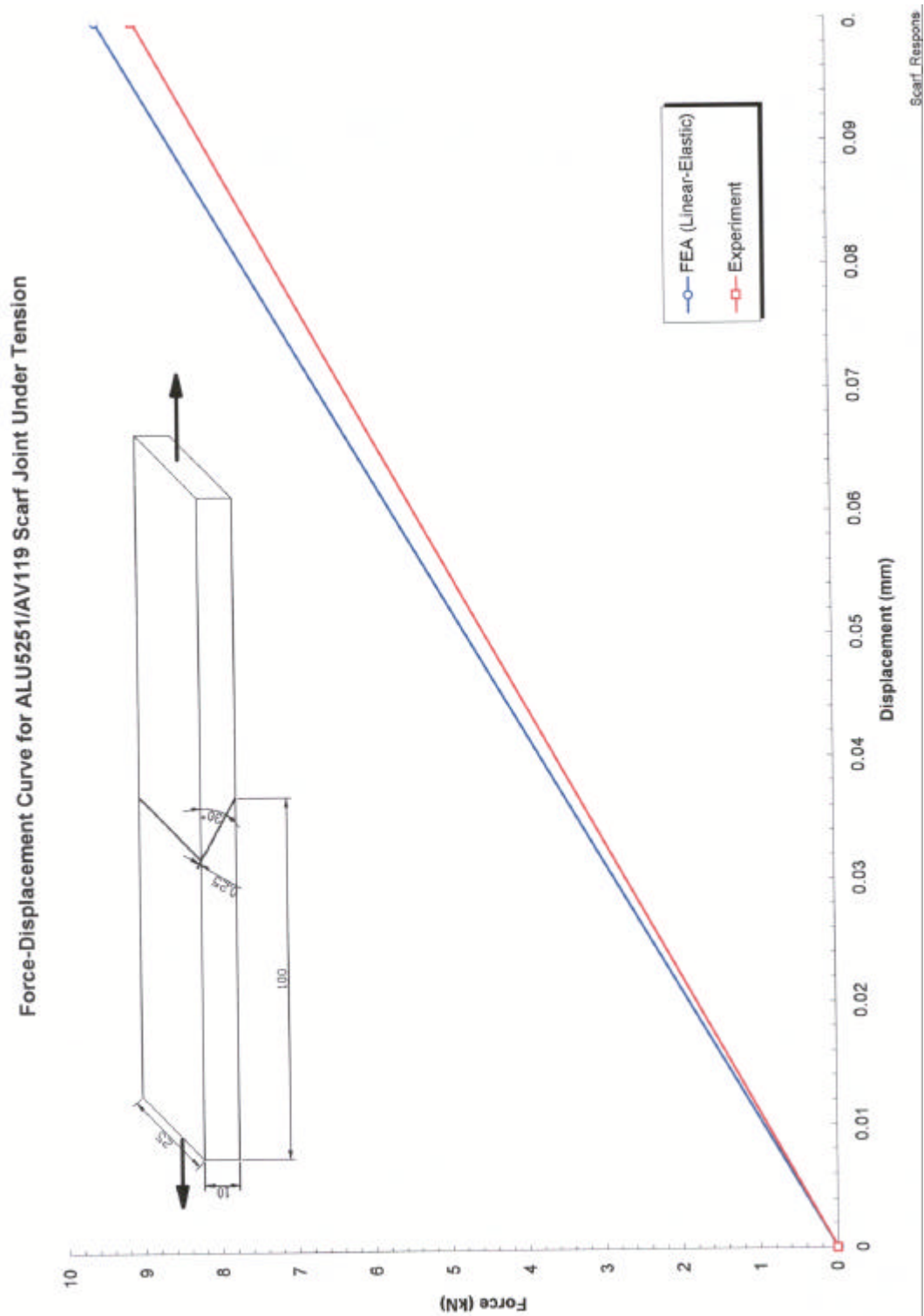
(Job ID=Lap3020c.inp; Adhesive:AV119 epoxy, $t_3=0.25$ mm; Adherends: CR1 mild steel, $t_1=3$ mm, $t_2=1.6$ mm;
Joint width: 25 mm; Overlap: $l=12.5$ mm; Theta=30 deg; End force: 6 kN)



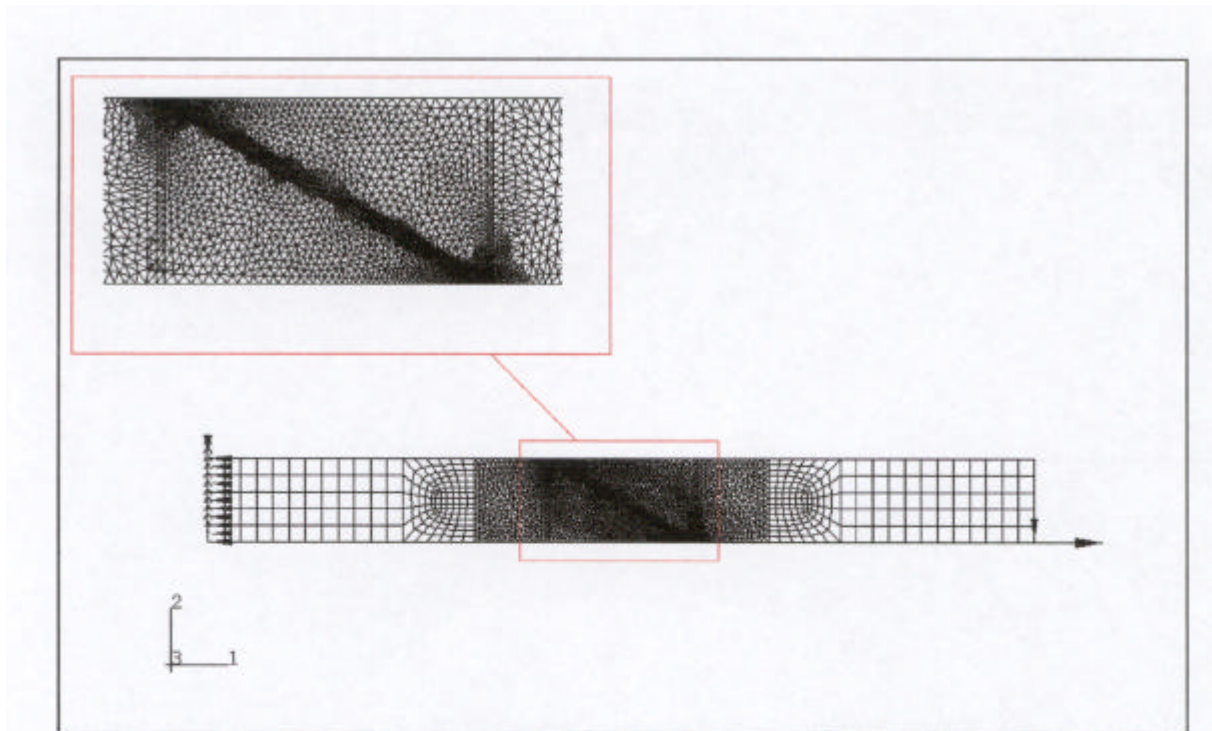
6 - Effect of Central Gap on Shear and Peel Stress Distributions.

APPENDIX 3

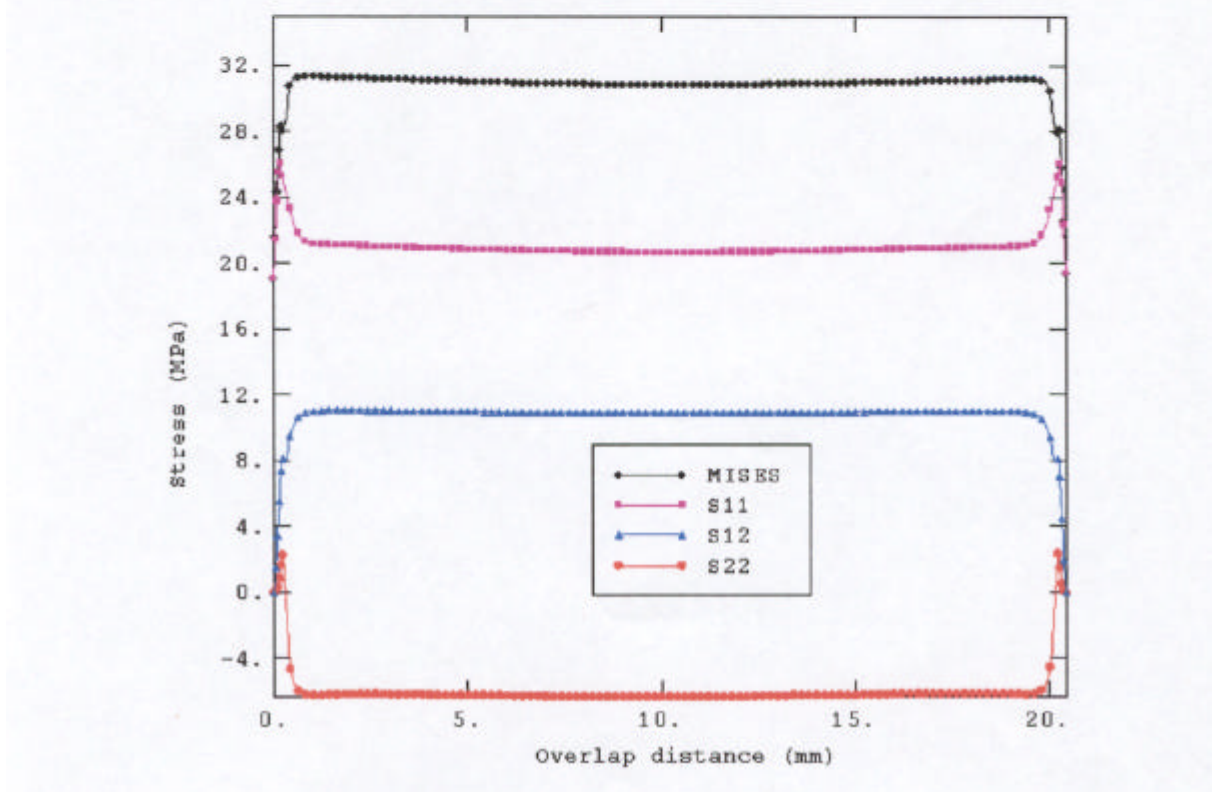
FEA OF SIMPLE SCARF JOINT (5251 ALUMINIUM/AV119 EPOXY ADHESIVE)



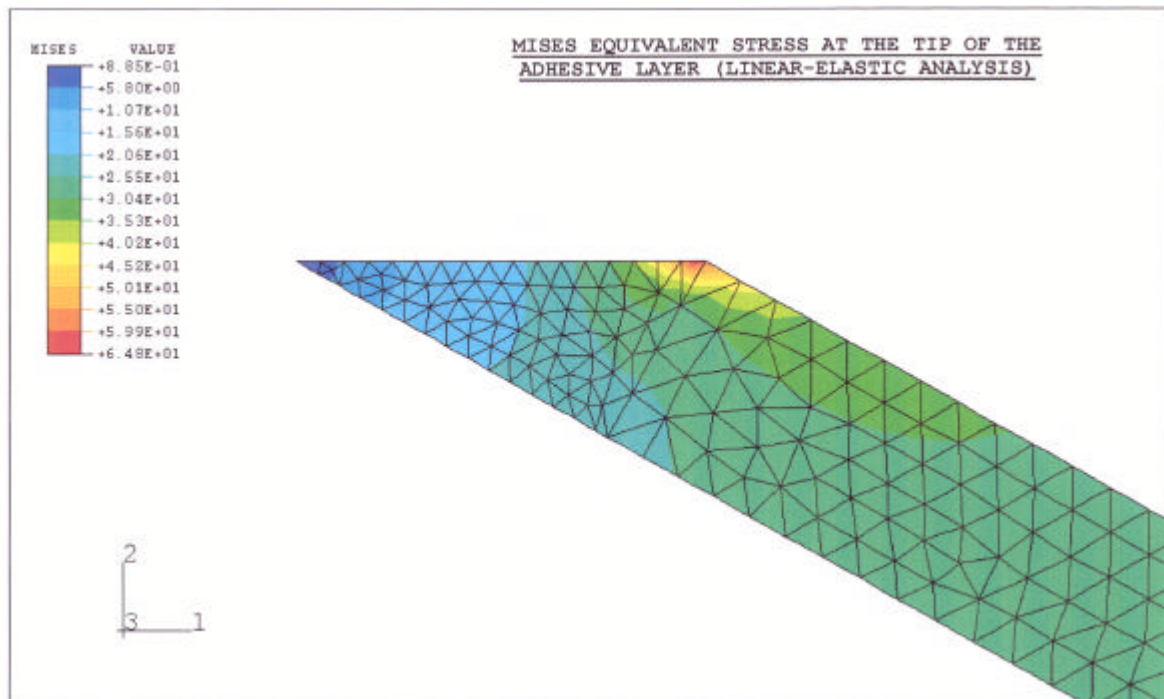
1 - Specimen Geometry and force-displacement curve.



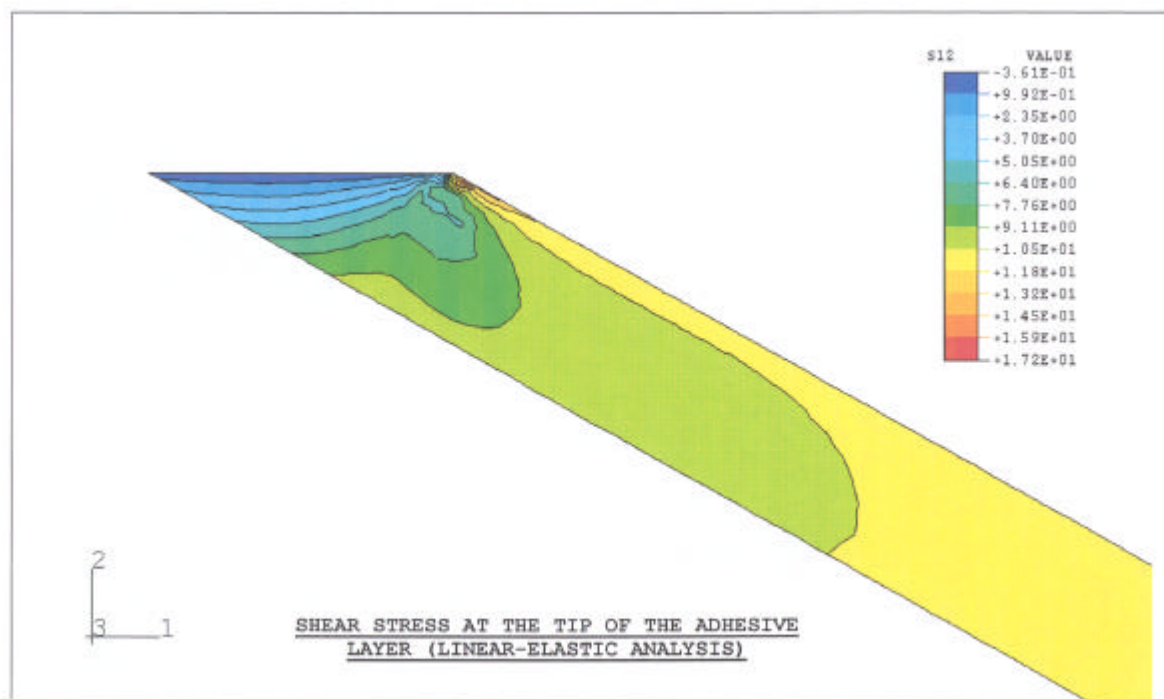
2 - Finite Element Mesh Diagram.



3 - Stress Distributions along Overlap Distance.



4 - Mises Equivalent Stress at the Tip of the Adhesive Layer.



5 - Shear Stress Contours at the Tip of the Adhesive Layer.