Shear Fatigue Testing and Life Prediction of Fibre Composites

Interim Report

R.J. Butler, C.H. Edge & P.M. Barnard

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"The views expressed herein are those of the authors alone and do not necessarily represent those of the Institute."
SUMMARY

This report aims to review and investigate methods of providing shear fatigue test results using flat coupons.

A review of existing literature was carried out which yielded two suitable options; the Rail shear test and the Slotted Tension test.

The Rail shear test was examined using finite element techniques in a static loading environment and, an exhaustive series of test work. This work finally culminated in the construction of an S.N. curve for a +/-45° 'E'-glass/epoxy laminate.

Problems encountered during these tests has prompted the design of a modified Rail shear rig and a Slotted Tension rig.
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Chapter 1

INTRODUCTION

Extensive research and development in the field of fibre reinforced composites has led to significant advances in material properties and production techniques. This newly acquired information and confidence, as well as an increasing requirement to reduce weight, has led to rapidly increasing use of such materials in aerospace and other applications, and a general reduction in metallic material use.

However, there has been reluctance on the part of some industries to consider the option of composite materials due to the lack of well defined material properties.

In general, standard test methods for composite materials have been developed, but there is still doubt when it comes to shear testing. Although considerable work has been carried out on static shear testing, there has been little in the field of shear fatigue.

The problem with shear fatigue testing as in static shear work has been the problem of comparing the results from different research teams. Despite similar composite materials and layups being used, variations in testing techniques and the like, have significantly affected the results hence precise comparisons become difficult.

In view of these problems this report tries to correlate the more important static test methods that are applicable to fatigue testing and to carry our further experimental work in the general area of shear fatigue.

The main objectives of this work are to develop a standard test method for shear fatigue by careful selection of present day test procedures and suggest improvements where necessary based on experimental data and theoretical studies. Consideration will be given to factors that affect fatigue results and how to reduce any adverse problems.

Finally, an S.N. curve will be constructed for a specific material/laminate configuration to highlight the particular advantages of the chosen test method(s).
Chapter 2

CHARACTERISATION OF SHEAR PROPERTIES

**Types of Shear**

Due to the existence of three different shear properties along the orthogonal axis of a composite material there have been misinterpretations of composite material shear data.

To clarify the situation, the three principle types of shear are shown overleaf in Fig.1. The notation is generally used for engineering and should not be confused with the more rigorous tensor notation.

1) **In-Plane Shear**

The in-plane shear modulus and strength are the most useful of all the composite shear properties. By varying the volume of fibres and orientation optimum use can be made of the material and the shear properties adjusted to suit any given load condition. However for most structural applications the presence of associated axial load means that non-optimum layups have to be used reducing the weight advantage over the structural metals.

2) **Inter-Laminar Shear**

Inter-laminar shear properties are not significantly affected by variations in the fibre layup. This is due to the fact that composite materials are typically layered structures and the properties through these layers depend mainly on the matrix properties, the matrix to fibre bond and the manufacturing procedure. The specific inter-laminar shear strength and modulus are much lower than structural metals and this effects such properties as the stability of a compressive surface or the load-transfer at a joint.

3) **Short Transverse Shear**

For most practical purposes shear forces rarely occur in this direction and hence little work has been carried out to define the short transverse properties of composite materials. They are the least important of the three orthogonal shear properties and can be ignored except for structures subjected to significant multi-direction loading.
FIG. 1

PRINCIPLE TYPES OF SHEAR

IN-PLANE SHEAR

INTERLAMINAR SHEAR

SHORT TRANSVERSE SHEAR
2. FACTORS AFFECTING SHEAR PROPERTIES

After the initial choice of the fibre, resin and the manufacturing process have been made there are many factors that will have an influence on the final shear properties of a composite material. Some of the more important variables are discussed below.

1) Fibre Volume Fraction

An increase in the fibre volume fraction will normally result in a higher overall strength and modulus. However due to stress concentrations present during shear loading it is possible that although the shear modulus will increase there may be a drop in shear strength. Variations in shear properties may also occur depending on whether the fibre volume fraction is increased by closing the in-plane spacing between fibres or closing the inter-laminar spacing.

2) Percentage Void Content

Voids in the form of air or gas bubbles present in the resin matrix can seriously affect the shear properties of a composite material. This has been shown by Jones (1) who suggests that a 4% void content can reduce the inter-laminar shear strength by as much as 40%. Such a large void content is unlikely using good prepreg material and a good manufacturing procedure. This problem usually only occurs with wet lay-up coupons produced in a poor manner.

3) Testing Frequency

For fatigue work the frequency of testing may affect the shear properties due to viscoelastic frictional heating. If necessary cooling may be provided.
Chapter 3

SHEAR TEST METHODS FOR COMPOSITES

INTRODUCTION

Shear test methods basically fall into two groups, those using flat laminates and those using tubular cross sections. The various test methods will now be compared critically to establish the most appropriate for this work.

1) **Plate Twist**

This test consists of loading a square specimen at one edge while reacting the load at the other three, (See Fig.2). It has been shown that the deflection $x$ due to a load $P$ is given by:

$$G = \frac{3P\lambda^2}{t^3x}$$

where: $G$ is the shear modulus

$\lambda$ is the side length

$t$ is the plate thickness.

Using classical laminated plate theory Whitney (2,3) has shown that the method is only valid for truly homogeneous orthotropic materials and that any measurements for $\pm 45$ angle ply plates can be in error. It has also been shown that not only is the above relationship developed from linear small deflection theory but when the deflection exceeds several plate thicknesses a point of instability occurs (4).

This instability will be strongly influenced by an initial curvature of the plate. An additional problem is that the shear modulus is a function of the plate thickness to the power three and hence the thickness must be uniform and accurately known. It should also be noted that the shear stress mode is of a 'rotational transverse' nature. An alternative plate twist rig has been developed by Konstantinov and Stretyaev (5) which can be used between the compression platens of a universal test machine.
FIG. 2

PLATE TWIST TEST
2) Rail Shear

This method again uses a square test specimen originally developed by Hennessey (6) as shown in Fig.3. Application of an axial load \( P \) between the two ends induces a shear stress into the specimen. If the angle \( \theta \) is made small the shear stress is simply given by:

\[
\tau = \frac{P}{lt}
\]

where: \( l \) is the plate length
\( t \) is the plate thickness.

Despite the fact that this test method has been widely used (7-13) it has been criticised due to the existence of free edges creating non-uniformity in the stress distribution. Whitney (8) has shown that in specimens of high aspect ratio (1/1 > 10) a uniform stress distribution is found over the majority of the specimen except for + 45° angle ply laminates.

His analysis has also shown that in such a specimen, considerable forces perpendicular to the rails occur at the corners of the test area. For the 0° case, with the fibres aligned at 0° to the side supports, the transverse tensile forces are quite likely to exceed the strength of the material before the ultimate shear strength of the material is reached. With the fibres aligned at 90° the stress is more uniform over the whole area and the stresses perpendicular to the rails are of little importance compared to the longitudinal strength of the composite. Duggan (14) noted that the bolts clamping the two sets of rails required frequent re-tightening throughout the test even in the case of low strength unidirectional materials and with a high friction grating between the specimen and the rails. He also noted that in the case of the higher stiffness laminates it proved impossible to fail the specimens without the grips slipping. Sims (11) has described a 'balanced' rail shear test in which two identical laminate areas are tested in parallel.

In most cases it has been considered that the extra complexity involved in this technique is not justified for flat laminates. Modified versions (15) have used small cubes of unidirectional CFRP to determine the relative shear moduli in the three principle planes.
FIG. 3

RAIL SHEAR TEST
3) **Short Beams**

This method is well known \((16,17)\) and is shown in Fig.4. The testing is based on the fact that in some cases a beam loaded in three point flexure may be induced to fail in 'inter-laminar' shear at the neutral plane before the outer fibres break in tension or compression, however it is not possible to measure shear modulus using this method. A series of investigations \((18-22)\) of the effect of specimen geometry on the measured strength have been made and for CFRP the recommended span/thickness ratio is four to five, but even at this ratio composites of low fibres strength or high inter-laminar shear strength may fail prematurely in flexure \((23,24)\).

Although this test is economical of material and is simple to perform, there are a number of drawbacks. The principle ones are concerned with the non-uniformity of the stresses even in the plane of the laminate, that states of combined stress exist and that severe stress concentrations arise at the points of load application \((18-20,23)\).

Classical beam theory gives the relationship for shear stress as:

\[
\tau = \frac{3P}{4bt}
\]

where: \(P\) is the applied load
\(b\) is the width
\(t\) is the thickness

However is has been shown \((18,20)\) that the assumptions on which this theory is based do not relate to the short beam test. A finite element analysis by Berg \((18)\) has shown that due to stress concentrations in the region of the loading points, the maximum shear stress does not occur at the centre of the beam and that the method may significantly underestimate the true maximum shear strength. Similar conclusions have been reached by Sattar and Kellog \((20)\), using a distorted energy failure criterion and an exact theory of elasticity solution, although the predicted reduction in measured strength may be small. However, this theory is inaccurate \((25)\) as it assumes there are no edge effects and also the above equation assumes a linear elastic stress/strain relationship which in general is not true. In fact the stress distribution will be parabolic in each layer but with a discontinuity in slope at the ply interfaces. As a result the maximum shear stress will not necessarily occur at the centre of the beam. It is also the case that the measured shear properties are dependent on the rate of loading \((26)\).
FIG. 4

SHORT BEAM TEST
It has been shown that measured strength drops with very rapid loading and it has been suggested (27,28) that this is due to the fact that the stress concentrations discussed do not have time to dissipate plastically.

Despite these drawbacks it is a simple and reproducible test useful for qualitative evaluation and it is likely to provide a satisfactory measurement of 'inter-laminar' shear strength for comparative purposes.

4) Transverse Compression

Rosen and Dow (29) suggested that a block compression test of undirectional material transverse to the filaments would yield more representative quantitative values for shear strengths than short beam tests. The presence of transverse compressive forces has been shown (30) to significantly increase the measured composite shear strength in the (31, 32) plane. However, since the test is so simple and economical of material it has been investigated further (15) but only usually to give an upper bound to the value of shear strength in the 'transverse mode'.

5) Thin Walled Tubes

It has been generally accepted that the use of thin walled tubes provides not only the most satisfactory method of determining the 'in plane' shear properties but also a specimen configuration suitable for general composite materials characterisation, (See Fig.5).

If the ratio of tube radius to wall thickness is significantly large and one end of the tube if free to move in the direction of the tube axis as well as rotate, a reasonably pure state of shear has been shown to exist (33-36).

The shear stress can be shown to be:

\[ \tau = \frac{16d_e \times \text{Torque}}{\pi(d_e^4 - d_i^4)} \]

where \( d_e \) and \( d_i \) are the external and internal diameters respectively.

One disadvantage is that the modulus is a function of the internal and external diameters to the power four so that considerable care in tube manufacture is important. Many workers have used filament wound tubes since the constraining end attachment effects on strength do not arise, but such a method of manufacture is unlikely to produce results that are representative of the properties of a flat lamiantes
FIG. 5

THIN WALLED TUBE TEST

Torque
fabricated from resin pre-impregnated sheet. It has therefore been proposed (15) to always use tubes with the fibres aligned parallel to their tube axis. Tube thickness to radius ratios of the order of 1:12.5 have been shown to be adequate. With rigid end fixings Rizzo and Vicario (37) have shown theoretically that serious stress concentrations may arise in the regions of the end attachments.

Purslow (15) tried to alleviate this problem by the use of epoxy end fittings to allow some deformation to occur within the gripped length. This allowed sufficient shear transfer area to distribute the load uniformly from the attachment bolts.

His results showed a reduction between surface and embedded strain gauges to some 15% of the external value, hence some shear strain was able to occur within the embedded region and that this rose to the test section value without significant stress concentrations. As a result Purslow was able to use a tube length considerably shorter than was suggested by Pagano and Whitney (36).

6) **Solid Tubes**

This method utilizes a solid rod laminated from unidirectional material fabricated by either laying up the material in a cylindrical mould or machining the specimen from a solid rectangular bar. This test method is not widely used however, as other methods have an advantage. In particular, a solid rod under torsion yields a shear stress distribution which is linear with respect to the radial distance from the centre of the rod. Hence the calculations for stress is accurate only for linear portions of the load/deformation curve. With the large non-linear response often observed for many unidirectional stress-strain curves, the usefulness of the test is highly reduced. In addition, the solid rod specimens are difficult to fabricate.

7) **+-45° Tensile**

This simple method uses a specimen with a laminate of (45°/-45°/45°/-45°). It has been noted (38) however that the test can be employed to establish shear stress-strain relationships well into the region of non-linear material response. Caution must be exercised in interpretation of the ultimate stress and strain results due to the fact that the lamina state of stress is not pure shear but rather biaxial in nature. Therefore is should be expected that the presence of the
normal stress components would have a deleterious effect on the ultimate shear strength. In particular the transverse normal stress can be expected to significantly alter the apparent shear strength. Duggan (14) has shown other effects in the test procedure by loading specimens in compression instead of tension. His results showed that the values for the mean failure stress were substantially different.

8) Off Axis Tensile

This method is simple to perform but is somewhat prone to shear coupling effects, however these problems can be resolved by careful design of the specimen. The inplane shear stress-strain relationship as determined by this test are consistent for any angle \( \theta \), however, the ultimate shear strength is a function of the fibre orientation of the off axis specimen.

Some analysis predicts that the 45° off axis specimen is attractive but some workers (38) indicate that the ultimate shear strength may be in error by as much as 30-40%. Chamis and Sinclair recommend the 10° off axis test to minimise the effects of longitudinal and transverse tension components on the shear response. Results for a 15° off axis test indicate that the ultimate shear strength determined by the 15° and (+-45°)\(_s\) tensile test compare well (38). Comparisons between the 10° off axis test and the (+-45°)\(_s\) laminate method show that the 10° off axis test gives a higher initial modulus while the (+-45°)\(_s\) laminate test gives a higher strength. The (+-45°)\(_s\) laminate test gives considerably more of the stress-strain curve than the 10° off axis test.

9) Cruciform

In this case the specimen material is bonded to both sides of a light honeycomb core to form a laminated cross beam. The loads are applied to the ends of the beams and for special orientations of the fibres the centre section will be in a state of pure shear at 45° to the cross beam axis. (See Fig.6).

Knowing the specimen dimensions and assuming that the honeycomb has no bending stiffness, it is fairly easy to calculate the shear stress. The main disadvantages of this method are the high cost of specimen production and the fact that the stress concentrations in the corners will almost certainly influence the results.
FIG. 6

CRUCIFORM TEST
As a result it is rarely used for material characterisation, Pascoe (39) has used a similar method for shear fatigue work with little success.

10) **Slotted Laminate**

This test can take two forms, namely in-plane and inter-laminar shear. Both methods use the same basic specimen geometry as shown in Fig.7. This test is perhaps the least expensive of the in-plane shear tests due to the use of a flat specimen and the requirement of simple tensile loading. Values for in-plane shear strength are somewhat dubious because of the severe stress concentrations around the holes. A finite element analysis has been carried out by Elkins (40) who suggested stress concentrations of 1.57 at the edge of the holes and hence from this fact alone it would be expected that the shear strengths obtained are conservative.

For the inter-laminar test the specimen is loaded as in a lap shear test and as such suffers from a non-linear stress distribution across the test area. Material shear strengths are easily measured as the failure mode is well controlled, however as the material physical properties affect the stress distributions in the test area, these strengths should be used for qualitative purposes only.

11) **Bi-axial Loading**

The off-axis tensile test can be used as a means of measuring bi-axial stress strain behaviour relative to the fibre direction. This could be extended to include orthotropic laminates in an off-axis test. The method has however, a number of drawbacks, the most significant being the inability to independently control the bi-axial stress components.

The University of Delaware (38) suggested a bi-axial testing method should meet the following requirements:

a) A significant volume of material must be under a homogeneous state of stress (uniform $\sigma_x, \sigma_y, \sigma_{xy}$).

b) Primary failure must occur in the test section.

c) The state of stress must be known without secondary measurements or analysis.

d) It must be possible to vary the stress components independently.
FIG. 7

SLOTTED LAMINATE TEST
The same report suggested the use of thin walled tubes under combined axial load, torsion and internal pressure but the method has problems concerned with fabrication to required tolerances and difficulties associated with the introduction of loads.

12) Slotted Tension (Duggan)

This slotted laminate specimen is somewhat different from that described, (in 10), as can be seen in Fig.8. The method is based on the well known principle that \( \frac{1}{\sqrt{2}} \) in-plane bi-axial stress is equivalent to pure shear stress on planes orientated 45° relative to the orthogonal axes of applied load. This stress state can be closely achieved with a conventionally sized tensile specimen by loading it along its major axis in tension and simultaneously in compression along a portion of its length in the transverse direction. The axially orientated slots in the specimen insure that the compressive force is transmitted only through the rectangular test section so that the shear stress will be statically determinate to a first approximation. An unslotted test specimen would be statically indeterminate with regard to the transverse stress distribution. This occurs because the transverse load tends to diffuse into regions outside the test zone, and the slots are designed to reduce this effect.

Duggan also performed a finite element analysis for several isotropic and orthotropic materials to evaluate the stress distribution throughout the test area (14). The analysis predicted that the shear stress in the centre of the test zone is within 2% of the stress concentration factor at the slots is some 10%.
FIG. 8

SLOTTED TENSION TEST
Chapter 4

SELECTION OF TEST RIG AND MATERIAL

1) Selection of Test Rig

   It is quite clear from available data that the most accurate method for measuring shear properties is the use of thin-walled tubes. It is also envisaged that fatigue data could also be gained from such a test method as the equipment required to carry out such tests is readily available with present technology. However it is clear that to construct thin-walled tubes accurately and in the desired numbers for S.N. curve determination would be financially prohibitive and extremely time consuming.

   An ideal test method should use flat coupons with the facility to be easily set up in a test machine preferably without constraining guides, (5).

   From these aspects it soon became clear that the Slotted Tension (Duggan) method held the best promise for accurate results from a flat coupon. The test method is made further attractive by the knowledge that it uses a standard sized tension/compression coupon albeit with a small amount of machining required in the form of two slots.

   It should also be noted that the rigs capability to accept shear and unidirectional loading together make it especially promising for modelling of 'actual' loading cases.

   The main problem with this test method is that the loading apparatus consists of both tensile and compressive loading frames which are not readily available and hence considerable time would be required to construct one. For this reason the Duggan method was only considered from a theoretical aspect with design work carried out on its future feasibility as a test method.

   The most obvious contender then became the rail shear rig. It's geometry has now become well defined and its limitations realised. It was therefore decided to use the rail shear rig in the subsequent test work.

   The final rig geometry was based on the work of Garcia et al (41) and it was fortunate that such a rig and its associated coupon drilling jig was available from R.A.E., Farnborough. The only modifications
required were the application of 240 grade Silicon Carbide paper to the rails to provide gripping force to the coupon, and the machining of two new end fittings suitable for use in an Instron 8031 static/fatigue test machine.

2) Selection of Test Material

To validate the selected test procedure to its fullest it seemed logical to use a laminate layup that gave the worst stress diffusion within the test area of the coupon. From the available literature it was clear that a \([±45°]\) layup gave the worst problems with regard to shear testing. It is also true that such a layup resisted shear to a greater degree than any other and hence its shear stress at failure and its shear modulus; for a given material and thickness; would also be the highest. Hence future testing with the particular rig chosen would be possible without any problems assuming that this test work proved successful.

Theoretical analysis suggested that static failure of the coupons would occur below 50 kN which was within the load capacity of the test machine. This material/layup configuration was therefore adopted for the test programme.
Chapter 5

SUMMARY OF RESULTS

Static Results

The more important results from the material characterisation test on \(\pm 45^\circ\) 'E'-glass/epoxy panels are given below.

<table>
<thead>
<tr>
<th>Test</th>
<th>No. of Coupons</th>
<th>Failure Stress (N/mm(^2))</th>
<th>Modulus (N/mm(^2)x10(^6))</th>
<th>Characteristic Stress (N/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>6</td>
<td>288.960</td>
<td>25.571</td>
<td>301.240</td>
</tr>
<tr>
<td>Compression</td>
<td>8</td>
<td>211.790</td>
<td>22.399</td>
<td>217.870</td>
</tr>
<tr>
<td>Shear</td>
<td>11</td>
<td>283.808</td>
<td>10.500</td>
<td>287.870</td>
</tr>
</tbody>
</table>

Poisson's Ratio = 0.57

Fatigue Results

The results from the fatigue tests are similarly given below:

<table>
<thead>
<tr>
<th>% Ultimate Shear Stress</th>
<th>No. of Coupons</th>
<th>Mean Cycles to Failure</th>
<th>Characteristic Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>8</td>
<td>3.25</td>
<td>3.90</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>754.40</td>
<td>851.73</td>
</tr>
<tr>
<td>70</td>
<td>10</td>
<td>7824.20</td>
<td>9011.58</td>
</tr>
<tr>
<td>65</td>
<td>9</td>
<td>70904.66</td>
<td>76456.83</td>
</tr>
<tr>
<td>60</td>
<td>6</td>
<td>115308.00</td>
<td>89728.52</td>
</tr>
<tr>
<td>55</td>
<td>1</td>
<td>676360.00</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>&gt;10(^6)</td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>&gt;10(^6)</td>
<td>-</td>
</tr>
</tbody>
</table>
Chapter 6

DISCUSSION

Static Testing

In general there was little problem in the material characterisation as provided by the static tests once the rigs were modified to accommodate the special problems associated with a $\pm 45^\circ$ laminate.

The compression properties proved the hardest to measure due entirely to the large Poisson's ratio of the material. As will be discussed in Appendix B the modulus values were considered accurate, however the failure stress are specific to this test rig, therefore comparisons can only be made with results from the same or similar rigs.

The static shear testing did not prove too difficult once the problem of coupon bearing failure had been solved.

The results were shown to be very consistent by the value of the Weibull slope, despite the presence of longitudinal and transverse strains in the centre of the coupon and the buckling of the coupon.

This latter problem is easily solved by increasing the thickness of the coupon but at the expense of increasing the failure load.

It has been suggested that carbon specimens should be tested with much fewer problems than glass ones. This is due to carbons greater stiffness, hence its greater buckling resistance. This has advantages in that thinner coupons could be used reducing the failure load to that of a similar glass coupon. A theoretical analysis suggests that a 1.83 mm thick coupon would be appropriate.

As would be expected, tensile tests provided no problems.

In general it was unfortunate that strains to failure for the three static tests could not be measured due to the large strains involved. This would not be such a problem for uni-directional and other symmetric layups if suitable strain gauges and extensometers were used.
Fatigue Testing

As expected the testing of materials under shear loads in fatigue proved to be difficult. The work already reported on this subject does not include the use of the rail shear rig and so the usual problems when experimenting in new areas were found. The main problem; above those already described for static testing; as described in the appendicies was that of bending of the rails and their subsequent failure bringing to an end the test work earlier than expected.

The rail shear rig has been re-designed as described in Appendix F, but due to time limitations construction and testing of such a rig has not yet been done. Hence any improvements have not been quantified, however it is possible to obtain some idea from the finite element calculations as described in Appendix E. The general conclusions were that although the fatigue problems may be overcome the bending of the rails must still occur, though to a lesser extent, the shear iso-stress plots confirm that the stress distribution is still poor.

In general the use of this particular test rig for shear fatigue work is not recommended although it is admitted that the laminate chosen does tend to exaggerate the limitations of the tests. Whatever geometry and stiffness of the rails is used there will always be unwanted stresses induced into the test area.

It was found that the viscoelastic induced heating, a function of test frequency, had no significant effect on the test results. Any temperature rise being well below the glass transition temperature. The temperature of the coupon increased towards the end of the test providing a method of failure determination.

As described in Chapter 4, the best method of shear testing was considered to be the slotted tension coupon. This was supported by finite element analysis (14) which suggested that the experimental results for shear stress would be 2% in error. This figure compared with greater than 10% for the rail shear rig.

This method should remove all unwanted loads in the coupon as long as the control system is accurate enough. This is not true of other test methods as they rely on some form of loading jig. The Duggan rig overcomes this problem as the loading is bi-axial in nature.
The problem area as highlighted by Duggan (14) is ensuring that the compressive loads are introduced into the coupon evenly. It should also be noted that the presence of compressive loads may cause buckling of the coupon. This point will require further work beyond the scope of this report.
Chapter 7

CONCLUSIONS

1) Although an inexpensive test to perform, the Rail shear method of shear fatigue testing is inaccurate due to a non-uniform strain field in the test area, due to bending and buckling effects superimposed on shear.

2) Theoretical studies in the literature suggest the Slotted Tension test to be a much more reliable and accurate method for shear fatigue work.

3) Material characterisation work can only be compared if identical test rigs are used.

4) An S-N curve for +45° 'E'-Glass-913 in rail shear has been produced.

5) The temperature of the coupon rises over the last few per cent of its life. This is considered a possible method of prior failure determination.
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APPENDIX A

LAMINATE AND SAMPLE PREPARATION

Laminate Preparation

All laminates used in the experimental work were produced at R.A.E. Farnborough. In all cases the material used was unidirectional 'E'-Glass fibre with a Fibredux 913 resin system as produced by Ciba Geigy. The curing cycle used was that for a standard autoclave cure (42) consisting of the following:

1) Apply vacuum (560 mm Hg minimum)
2) Heat to 90°C at 2-5°C/minute
3) Dwell for 30 minutes at 90°C
4) Apply 700 kN/m pressure
5) Vent vacuum when pressure reaches 140 kN/m
6) Heat to 120°C at 2-5°C/minute
7) Cure for 60 minutes at 120°C
8) Cool and remove components when temperature falls below 90°C

All panels were the ultrasonically scanned using the 'C' scan process and defects marked so as to be removable at a later date. The final dimensions and layup of the panels was 1000 mm long by 300 mm wide with a nominal thickness of 2.25 mm and layup of \([\pm45^\circ]\)s.

Sample Preparation

Two different sizes of coupons were required:

1) 250 mm x 20 mm for tensile and compressive tests
2) 76 mm x 50 mm for rail shear tests.

Coupon preparation was done according to the College of Aeronautics recommendations and is as follows:

Cutting

Coupons were cut from the laminate sheet using either a fine edged diamond saw or a standard workshop milling machine fitted with a fine diamond tipped disc. In the latter case the blade is rotated at the maximum possible speed and the feed rate set to a minimum. Water based lubricants should be used.
Preparation

Coupons cut on a milling machine should be washed in soapy water to remove traces of lubricant. Light abrasion of the end surface of tensile/compression coupons and the edges of the shear coupons (if required) was achieved using Silicon Carbide paper of 240 grade. This removes the surface texture left by the laminate release cloth in the moulding process without exposing the fibres. Surface dust was removed using a clean towel.

Aluminium tags were cut from sheets of 18 swg (1.22 mm) L71 half hard and etched as follows:

1) Chamfer edge of tags for a distance of 5 mm (tensile/compression coupons only)
2) Degrease in acetone using ultrasonic cleaner
3) Put 100-150 ml of clear water in 1 litre beaker and add 75 ml of concentrated sulphuric acid slowly stirring continuously
4) Still stirring add 37.5 g of sodium dichromate (or 25 g of chromic acid). Fill to 500 ml mark with clean cool water
5) Immerse tags for 30 mins. at 60° to 65°C
6) Remove tags and wash in clean running water and dry on paper towels. Once etched tags were not handled with bare fingers.

Adhesives

To minimise thermal stresses all tags were bonded with cold setting epoxy adhesives. For good fatigue and shear strength, Ciba Geigy BSL 403 two part adhesive was used without exception. The adhesive thickness was minimised and light pressure applied using clamps until the adhesive was set. A cure of 16 hours at 55°C was used.

In the case of the tensile/compressive coupons the end tags were applied to both faces and ends of the coupon and aligned by eye.

For the case of the rail shear coupons the central test area has to be accurately known hence a simple jig was made to ensure constant width of this test area and its parallelism. Tags 250 mm by 20 mm were placed on a steel base between two vertical 7.6 mm diameter rollers. Three coupons were then glued to these tags ensuring a small gap between each coupon and one edge parallel to one of the tags. The second set of tags were then applied to the top face of the coupons. A number of layers of coupons and tags were then constructed in this manner. Finally the coupons
and tags were clamped to the base plate, the rollers removed and the whole assembly placed in an oven for curing. When cured the tags were sawn up between each coupon and all edges filed.

The coupons were then drilled using a jig supplied, with the rail shear jig, from R.A.E. Farnborough. It should be noted that the rollers used in the adhesive jig were also used in final assembly of the rail shear jig to achieve accurate rail spacing.

This method proved very quick and accurate in production of large numbers of tagged coupons.
APPENDIX B

STATIC MATERIAL TESTING

Introduction

For the purpose of constructing finite element models of the various test rigs considered, a complete mechanical property characterisation of the particular laminate was attempted.

For a unidirectional lamina the significant mechanical properties are $E_x$ and $E_y$; the stiffness parallel and perpendicular to the fibre direction respectively, $\nu_1$ and $\nu_2$; Poisson's ratio when strained in the 1 and 2 directions respectively, and finally $G_{xy}$; the in-plane shear modulus. As the laminate chosen for the test work is orthotropic along the 1 and 2 (x and y) directions $E_x = E_y$ and hence $\nu_1 = \nu_2$. As a result only simple tensile and shear tests need to be undertaken and, with the appropriate use of strain gauges, Poisson's ratio can also be calculated. In order to obtain a 'feel' for the material and also provide further data, compressive tests were also conducted.

In all cases moduli and failure stresses are presented but due to the large extensions of this particular laminate, failure strains could not be measured.

Tension

For the tension tests, coupons were cut from the laminate sheets to a size of 250 mm x 20 mm. To reduce the possibility of failure where the machine jaws clamp the coupon, aluminium tags were bonded to the coupon. Specimen preparation is given in Appendix 1.

All coupons were tests on an Instron 1195 static test machine. The general layout of the machine is shown in Fig.9. The loading rate was 0.5 mm/min. Using an extensometer measuring longitudinal strain and the machines load cell measuring load, an x-y plot of stress against strain could be produced if the coupon dimensions were accurately known, and from the initial slope, the $E_x/E_y$ modulus calculated. A typical graph is shown in Fig.10. By applying a $0^\circ/90^\circ$ strain gauge rosette in the centre of the coupon and logging the strains at specific load increments, Poisson's ratio could also be calculated. This latter value was determined to be 0.57.
After failure of the coupon the tensile stress to failure was calculated and a statistical analysis carried out. In total six tensile coupons were tested. Typical failures can be seen in Fig.11, whilst a table of results can be seen in Table 1.

Table 1
Results for Static Tensile Tests

<table>
<thead>
<tr>
<th>Load to Failure (kN)</th>
<th>Coupon Area (mm²)</th>
<th>Tensile Stress (N/mm²)</th>
<th>Modulus (N/mm²x10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.79</td>
<td>44.79</td>
<td>263.228</td>
<td>27.048</td>
</tr>
<tr>
<td>11.90</td>
<td>44.83</td>
<td>265.447</td>
<td>30.444</td>
</tr>
<tr>
<td>13.37</td>
<td>44.96</td>
<td>297.375</td>
<td>25.419</td>
</tr>
<tr>
<td>12.46</td>
<td>44.95</td>
<td>277.197</td>
<td>24.269</td>
</tr>
<tr>
<td>14.01</td>
<td>45.03</td>
<td>311.156</td>
<td>24.785</td>
</tr>
<tr>
<td>14.46</td>
<td>45.27</td>
<td>319.412</td>
<td>25.515</td>
</tr>
</tbody>
</table>

Mean Tensile Stress = 288.960 N/mm²
Median = 287.268 N/mm²
Variance = 568.610
Standard Deviation = 22.140 N/mm²

Weibull Slope = 12.19

Characteristic Stress = 301.240 N/mm²

Mean Modulus of Elasticity = 25.57x10⁶ N/mm²
FIG. 9

INSTRON 1195 TEST MACHINE. GENERAL LAYOUT
FIG. 10

LOAD/DISPLACEMENT PLOT FOR STATIC TENSION TEST
FIG. 11

TYPICAL STATIC TENSION FAILURES
Compression

The compression test coupons are in all respects identical to those used in the tensile tests, however in this case a Dartec 7509 static/fatigue servohydraulic test machine was used. The reason for this is due to the requirement to stop out of plane buckling of the coupon during testing. A rig was already available for this purpose that was suitable for the Dartec and rather than construct one specifically for the Instron 1195, this rig was used. The general setup of the machine is shown in Fig.12 whilst the compressive rig is shown in Fig.13.

It soon became clear after initial testing that accurate measurements of compressive modulus and compressive stress to failure would be practically impossible. The problem is due to the large Poisson's ratio of this material. The compression rig is finely tailored to the specimen using lateral and transverse guides to ensure little movement and hence little chance of buckling. However when compressed the coupon was 'squeezed' outwards and fouled the lateral guides at a low load. As a result the whole coupon would lock and compressive failure would occur in that one localised area.

To try and resolve this problem the allowable lateral displacement was increased but this only resulted in 'snaking' of the coupon and failure again where the coupon touched the lateral guides. Such a failure can be seen in Fig.15 along with an 'acceptable' failure. To resolve this problem altogether proved impossible hence the lateral spacing was chosen to give a failure between the two extremes yet this is considered far from ideal. As a result the modulus and compressive strength value can only be applied to this particular rig set-up and not related to any other test rigs. A total of ten coupons were tested and the results are given in Table 2. A plot of load against displacement is shown in Fig.14.

Shear

The shear testwork produced results for two purposes. Firstly it gave an ultimate shear strength for the specific laminate layup used from which percentages could subsequently be calculated for use in the fatigue test work. Secondly it gave a value of G for use in material characterisation and subsequent use in finite element models.
FIG. 12

DARTIC 7509 TEST MACHINE. GENERAL LAYOUT
FIG. 13

DETAIL OF COMPRESSION TEST RIG AND COUPONS
All static shear testing was carried out on an Instron 8031 static/fatigue testing machine so as to make all shear results directly comparable. As discussed in Chapter 4, a rail shear rig from R.A.E. Farnborough was used for all the shear test work. The basic layout of the machine and shear rig can be seen in Figs. 16 and 17.

Table 2
Results for Static Compression Tests

<table>
<thead>
<tr>
<th>Load to Failure (kN)</th>
<th>Coupon Area (mm²)</th>
<th>Compressive Stress (N/mm²)</th>
<th>Modulus (N/mm²x10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.15</td>
<td>44.06</td>
<td>207.671</td>
<td>22.696</td>
</tr>
<tr>
<td>8.80</td>
<td>44.24</td>
<td>198.915</td>
<td>22.603</td>
</tr>
<tr>
<td>9.65</td>
<td>45.02</td>
<td>214.349</td>
<td>23.212</td>
</tr>
<tr>
<td>9.45</td>
<td>45.39</td>
<td>208.195</td>
<td>22.534</td>
</tr>
<tr>
<td>9.20</td>
<td>44.39</td>
<td>207.254</td>
<td>21.031</td>
</tr>
<tr>
<td>9.85</td>
<td>44.75</td>
<td>220.118</td>
<td>23.564</td>
</tr>
<tr>
<td>10.30</td>
<td>45.19</td>
<td>227.927</td>
<td>22.527</td>
</tr>
<tr>
<td>8.85</td>
<td>45.51</td>
<td>194.428</td>
<td>23.129</td>
</tr>
<tr>
<td>9.25</td>
<td>44.42</td>
<td>208.239</td>
<td>21.973</td>
</tr>
<tr>
<td>10.05</td>
<td>43.54</td>
<td>230.822</td>
<td>22.967</td>
</tr>
</tbody>
</table>

Mean Compressive Stress = 211.790 N/mm²
Median = 208.218 N/mm²
Variance = 136.370
Standard Deviation = 11.670 N/mm²
Weibull Slope = 19.37
Characteristic Stress = 217.300 N/mm²
Mean Modulus of Elasticity = 22.399x10⁶ N/mm²
FIG. 14

LOAD/DISPLACEMENT PLOT FOR STATIC COMPRESSION TEST
FIG. 15

TYPICAL STATIC COMPRESSION FAILURES
FIG. 16

INSTRON 8031 TEST MACHINE. GENERAL LAYOUT
FIG. 17

DETAIL OF RAIL SHEAR RIG AND COUPONS
In all cases the bolt torque applied to the six clamping bolts was kept constant at 16 ft.lbs.(f). This ensured that the clamping pressure remained constant throughout the test programme. The exact figure was chosen as it was just below the plastic limit of the high tensile bolts.

Initial testing used coupons without tags. It soon became apparent however that the coupons were not failing in the test area but were failing due to bearing failure around the upper and lower bolt holes. Such failures can be seen in Fig.18. A simple experiment using a slotted test coupon showed that the clamping force on the coupon was insufficient to stop slippage of the coupon; and hence bolt bearing problems; over a load of 10 kN. As failure of the coupon ocurred at 33 kN slippage must occur.

To alleviate the problem two choices were possible. Either the bolt diameter could be increased or the coupon reinforced to increase its bearing strength around the bolt holes. Due to the small size of the rails in both width and thickness the bolt diameter could not be increased.

Theoretical studies suggested that a bolt size of 9.35 mm (3/8") would remove the bearing problems but the effective rail width would have reduced from 12.7 mm to 9.7 mm which would cause problems from a fatigue aspect.

Instead it was decided to use aluminium tags bonded to the clamped areas of the coupon. This method solved two problems. Firstly it increased the local bearing strength of the clamped area and it also removes any possibility of failure of the coupon under the clamps due to surface indentation of the rails. The method of applying these tags is outlined in Appendix A.

Subsequently, all test results were based on coupons using such tags. A load/displacement plot for these tests is shown in Fig.19.

Strain Field Determination

Ideally the strain field in the centre of the coupon should consist of pure shear with no transverse or longitudinal strain components. In other areas of the coupon this will not be the case as highlighted by Whitney (8) and Garcia et al (9), however, these areas have a low stress concentration compared with the coupon centre resulting in failure occurring in the coupon centre.
FIG. 18

TYPICAL STATIC SHEAR FAILURES (WITHOUT TAGS)
To determine the accuracy of the strain field for this particular rail shear rig, a $0^\circ/45^\circ/90^\circ$ strain gauge rosette was positioned in the centre of both sides of the test area. All six gauges were logged individually at specific increments of load to see if there were any load effects on the strain field.

A total of two coupons in this manner with strain field plots of both sides of the coupon showed in Figs. 20 and 21.

As can be seen, there is a sudden change in the strain gauge readings at approximately 40% ultimate shear stress. There are discontinuities shown in both the $0^\circ$ and $90^\circ$ gauges whilst the $45^\circ$ gauge tends towards infinite strain. (In fact, the strain is not infinite, the gauge actually is broken from the surface of the coupon and the Wheatstone bridge network becomes unbalanced).

This information leads to the conclusion that the coupon is buckling.

To confirm this concept the theoretical buckling shear stress for this coupon was calculated using ESDU sheet 80023.

Taking the worst case, the buckling stress was calculated as 0.35 of that actually recorded. This is usual as the ESDU sheets are usually unconservative in their estimates of shear buckling stress.

Some work was carried out to try and alleviate this buckling problem but it was found that either the coupon aspect ratio had to be reduced or its thickness increased. If the former method were to be adopted, it would effectively invalidate the shear test as it is generally accepted that the coupon aspect ratio must be equal to or greater than 10.0. Alteration of the coupon size would also require construction of a new rig and drilling jig which would have a significant amount of testing time. In its present form the coupons aspect ratio is 10.02.

The latter method would require construction of more laminate sheets and would mean a greater load to failure the specimen. As will be seen in Appendix C this would have caused a significant impact on the machine used for fatigue testing.

For these reasons it was decided to continue using the rig and coupon combination and accept the buckling problem.

A total of ten coupons were tested for static ultimate shear stress (U.S.S.) determination. Typical failures of these coupons can be seen in Fig. 22.
FIG. 19

LOAD/DISPLACEMENT PLOT FOR STATIC RAIL SHEAR TESTS
FIG. 20

RAIL SHEAR COUPON STRAIN FIELD SIDE A
FIG. 21

RAIL SHEAR COUPON STRAIN FIELD SIDE B
From deflection against load plots, the laminate shear modulus was calculated and the failure stress determined. A statistical analysis was carried out on the results which are shown in Table 3.

From these results the mean U.S.S. for use in subsequent fatigue work was determined to be 283.808 N/mm².

### Table 3

**Results for Static Shear Tests**

<table>
<thead>
<tr>
<th>Load to Failure (kN)</th>
<th>Coupon Area (mm²)</th>
<th>Shear Stress (N/mm²)</th>
<th>Modulus (N/mm² x 10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.75</td>
<td>172.66</td>
<td>288.132</td>
<td>12.851</td>
</tr>
<tr>
<td>51.25</td>
<td>190.65</td>
<td>268.819</td>
<td>9.096</td>
</tr>
<tr>
<td>53.00</td>
<td>174.49</td>
<td>303.745</td>
<td>10.576</td>
</tr>
<tr>
<td>51.50</td>
<td>170.17</td>
<td>302.636</td>
<td>10.760</td>
</tr>
<tr>
<td>50.75</td>
<td>177.69</td>
<td>285.617</td>
<td>9.918</td>
</tr>
<tr>
<td>51.50</td>
<td>180.33</td>
<td>285.591</td>
<td>9.998</td>
</tr>
<tr>
<td>49.75</td>
<td>170.42</td>
<td>291.932</td>
<td>10.743</td>
</tr>
<tr>
<td>48.75</td>
<td>174.84</td>
<td>278.823</td>
<td>10.391</td>
</tr>
<tr>
<td>46.00</td>
<td>174.03</td>
<td>264.319</td>
<td>10.348</td>
</tr>
<tr>
<td>46.00</td>
<td>172.91</td>
<td>266.041</td>
<td>10.590</td>
</tr>
<tr>
<td>44.75</td>
<td>173.29</td>
<td>258.235</td>
<td>10.404</td>
</tr>
</tbody>
</table>

Mean Shear Stress = 283.808 N/mm²
Median = 280.029 N/mm²
Variance = 231.880
Standard Deviation = 45.510 N/mm²
Weibull Slope = 20.02
Characteristic Stress = 287.870 N/mm²
Mean Modulus of Elasticity = 10.500 x 10⁶ N/mm²
FIG. 22

TYPICAL STATIC SHEAR FAILURES (WITH TAGS)
APPENDIX C

FATIGUE MATERIAL TESTING

Introduction

The main purpose of the fatigue testing was firstly to determine the suitability of the rail shear rig to fatigue work and secondly construct an S.N. curve for the laminate material chosen. In addition effects such as testing frequency were examined to see if they significantly affected the final results.

The coupon and rig particulars were identical to those of the static shear tests. The coupons were tested on an Instron 8031 static/fatigue test machine with a dynamic capacity of 50 kN. Due to this load limitation, any thickening of the coupon as required to prevent buckling would have exceeded this limitation on high percentage U.S.S. tests.

The frequency at which the different stresses could be tested depend primarily on the deflection of the coupon at maximum load. For example at 90% U.S.S. the deflection is over 1 mm and the machine can be run no faster than a few Hertz, however at 60% U.S.S. frequencies of 15 Hz, are possible.

In general as high a frequency as possible was chosen in order to speed up the test programme.

Frequency - Temperature Effects

To determine if the frequency of testing would induce high temperatures into the coupon, a series of tests were conducted at different frequencies and shear stresses. In total three tests were performed at the following points:

1) 80% U.S.S. at 4 Hz.
2) 70% U.S.S. at 10 Hz.
3) 65% U.S.S. at 14 Hz.

A thermocouple was bonded to the centre of one side of the coupon and the temperature measured against cycles (time) on an X-Y plotter. Plots for all three stress levels are shown in Fig.23.
FIG. 23

TEMPERATURE/CYCLES PLOTS FOR THREE SHEAR STRESS LEVELS
As can be seen especially on the 80% stress level plot, there is a tendency for the temperature to increase from a steady state value to a higher one over the last few percent of its life. It is suggested that if further work is carried out in this area it could lead to a method of determining failure points of components in service, however this is beyond the scope of this work.

As can be seen this effect only occurs on long life coupons as in the short life coupons the temperature doesn't stabilise before the point of failure.

What these plots show is that the maximum temperature of testing is never more than 30°C above ambient even at the highest frequency of the machine.

It is intended to do further work using lower frequency tests.

**Construction of S.N. Curve**

The initial part of the fatigue test programme for S.N. curve determination was to find the endurance stress of the laminate. The endurance limit is defined as the stress at which the coupon will not fail. In effect this is defined as failure, is more than $10^6$ cycles by convention and this criteria was therefore applied to these tests.

Coupons were tested at 40%, 45% and 50% U.S.S. and all failed at greater than $10^6$ cycles. At 55% U.S.S. the coupon lasted some $7 \times 10^5$ cycles and hence the endurance limit occurred between 50% and 55% U.S.S.. This value of stress is significant as it is above the static buckling stress of some 42%. If the endurance limit had occurred below the buckling stress, this would not have involved two modes of behaviour across the S.N. curve.

In total five stress levels were required to construct an adequate S.N. curve. These were 90%, 80%, 70%, 65% and 60% U.S.S..

The testing was based around ten coupons at each stress level if required with a reduced number if results were very consistent.

A statistical analysis was carried out on the results which are given in Tables 4 to 5.
Results marked thus * were not included in the statistical analysis due to bearing failure of the coupon and hence unrepresentative lives.

The S.N. curve produced from these results is shown in Fig.24.

Typical failure modes at the different stress levels are shown in Fig.25.

In all cases the outer fibres were in compression. This was only for consistancy and in fact coupons were tested with their outer fibre in tension but there was no difference in the number of cycles to failure.
Table 4a

Results for High Shear Stress Fatigue Tests

<table>
<thead>
<tr>
<th>Nominal U.S.S. (%)</th>
<th>Actual U.S.S. (%)</th>
<th>Frequency (Hz)</th>
<th>Cycle to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.0</td>
<td>90.50</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>90.0</td>
<td>90.40</td>
<td>0.1</td>
<td>8</td>
</tr>
<tr>
<td>90.0</td>
<td>90.15</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>90.0</td>
<td>88.85</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>90.0</td>
<td>90.08</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>90.0</td>
<td>90.18</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>90.0</td>
<td>90.11</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>90.0</td>
<td>90.10</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>80.0</td>
<td>80.94</td>
<td>4.0</td>
<td>2046</td>
</tr>
<tr>
<td>80.0</td>
<td>80.34</td>
<td>4.0</td>
<td>251</td>
</tr>
<tr>
<td>80.0</td>
<td>79.98</td>
<td>4.0</td>
<td>448</td>
</tr>
<tr>
<td>80.0</td>
<td>79.95</td>
<td>4.0</td>
<td>117</td>
</tr>
<tr>
<td>80.0</td>
<td>80.10</td>
<td>4.0</td>
<td>518</td>
</tr>
<tr>
<td>80.0</td>
<td>80.19</td>
<td>4.0</td>
<td>* 99</td>
</tr>
<tr>
<td>80.0</td>
<td>80.17</td>
<td>4.0</td>
<td>862</td>
</tr>
<tr>
<td>80.0</td>
<td>79.71</td>
<td>4.0</td>
<td>143</td>
</tr>
<tr>
<td>80.0</td>
<td>80.26</td>
<td>4.0</td>
<td>340</td>
</tr>
<tr>
<td>80.0</td>
<td>80.02</td>
<td>4.0</td>
<td>* 76</td>
</tr>
<tr>
<td>80.0</td>
<td>80.36</td>
<td>2.0</td>
<td>* 86</td>
</tr>
<tr>
<td>80.0</td>
<td>80.03</td>
<td>2.0</td>
<td>874</td>
</tr>
<tr>
<td>80.0</td>
<td>79.96</td>
<td>2.0</td>
<td>1945</td>
</tr>
</tbody>
</table>
Table 4b

Results for High shear Stress Fatigue Tests

<table>
<thead>
<tr>
<th>Nominal U.S.S. (%)</th>
<th>Actual U.S.S. (%)</th>
<th>Frequency (Hz)</th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>70.0</td>
<td>70.02</td>
<td>10.0</td>
<td>3360</td>
</tr>
<tr>
<td>70.0</td>
<td>69.58</td>
<td>10.0</td>
<td>7510</td>
</tr>
<tr>
<td>70.0</td>
<td>69.96</td>
<td>10.0</td>
<td>8176</td>
</tr>
<tr>
<td>70.0</td>
<td>69.98</td>
<td>10.0</td>
<td>9808</td>
</tr>
<tr>
<td>70.0</td>
<td>71.87</td>
<td>10.0</td>
<td>8804</td>
</tr>
<tr>
<td>70.0</td>
<td>70.06</td>
<td>10.0</td>
<td>10700</td>
</tr>
<tr>
<td>70.0</td>
<td>69.63</td>
<td>10.0</td>
<td>6710</td>
</tr>
<tr>
<td>70.0</td>
<td>69.83</td>
<td>10.0</td>
<td>4737</td>
</tr>
<tr>
<td>70.0</td>
<td>69.93</td>
<td>10.0</td>
<td>5374</td>
</tr>
<tr>
<td>70.0</td>
<td>69.73</td>
<td>10.0</td>
<td>13063</td>
</tr>
<tr>
<td>65.0</td>
<td>65.19</td>
<td>10.0</td>
<td>17549</td>
</tr>
<tr>
<td>65.0</td>
<td>64.82</td>
<td>10.0</td>
<td>3224</td>
</tr>
<tr>
<td>65.0</td>
<td>64.76</td>
<td>10.0</td>
<td>14545</td>
</tr>
<tr>
<td>65.0</td>
<td>64.75</td>
<td>10.0</td>
<td>99755</td>
</tr>
<tr>
<td>65.0</td>
<td>65.04</td>
<td>10.0</td>
<td>6768</td>
</tr>
<tr>
<td>65.0</td>
<td>64.94</td>
<td>10.0</td>
<td>167129</td>
</tr>
<tr>
<td>65.0</td>
<td>64.95</td>
<td>10.0</td>
<td>128172</td>
</tr>
<tr>
<td>65.0</td>
<td>67.08</td>
<td>10.0</td>
<td>190963</td>
</tr>
<tr>
<td>65.0</td>
<td>65.28</td>
<td>10.0</td>
<td>10037</td>
</tr>
</tbody>
</table>
Table 4c

Results for Low Shear Stress Fatigue Tests

<table>
<thead>
<tr>
<th>Nominal U.S.S. (%)</th>
<th>Actual U.S.S. (%)</th>
<th>Frequency (Hz)</th>
<th>Cycles to Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.0</td>
<td>59.83</td>
<td>15.0</td>
<td>397558</td>
</tr>
<tr>
<td>60.0</td>
<td>59.56</td>
<td>15.0</td>
<td>26124</td>
</tr>
<tr>
<td>60.0</td>
<td>58.53</td>
<td>14.0</td>
<td>16486</td>
</tr>
<tr>
<td>60.0</td>
<td>61.09</td>
<td>14.0</td>
<td>2256</td>
</tr>
<tr>
<td>60.0</td>
<td>59.61</td>
<td>14.0</td>
<td>22371</td>
</tr>
<tr>
<td>60.0</td>
<td>59.36</td>
<td>14.0</td>
<td>227053</td>
</tr>
<tr>
<td>55.0</td>
<td>55.13</td>
<td>15.0</td>
<td>676360</td>
</tr>
<tr>
<td>50.0</td>
<td>50.01</td>
<td>15.0</td>
<td>$&gt; 10^6$</td>
</tr>
<tr>
<td>45.0</td>
<td>44.51</td>
<td>18.0</td>
<td>$&gt; 10^6$</td>
</tr>
</tbody>
</table>
### Table 5a

#### Statistical Results for Shear Fatigue Tests

<table>
<thead>
<tr>
<th>90% Ultimate Shear Stress</th>
<th>Mean</th>
<th>Median</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Weibull Slope</th>
<th>Characteristic Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.25 cycles</td>
<td>2.00 cycles</td>
<td>4.78</td>
<td>2.18 cycles</td>
<td>1.56</td>
<td>3.90 cycles</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>80% Ultimate Shear Stress</th>
<th>Mean</th>
<th>Median</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Weibull Slope</th>
<th>Characteristic Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>754.4 cycles</td>
<td>480.0 cycles</td>
<td>496292.7</td>
<td>704.5 cycles</td>
<td>1.09</td>
<td>851.7 cycles</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>70% Ultimate Shear Stress</th>
<th>Mean</th>
<th>Median</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Weibull Slope</th>
<th>Characteristic Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>7824.2 cycles</td>
<td>7843.0 cycles</td>
<td>8615334.8</td>
<td>2935.2 cycles</td>
<td>2.71</td>
<td>9011.58 cycles</td>
<td></td>
</tr>
</tbody>
</table>
Table 5b

Statistical Results for Shear Fatigue Tests

<table>
<thead>
<tr>
<th></th>
<th>65% Ultimate Shear Stress</th>
<th>60% Ultimate Shear Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>70904.7 cycles</td>
<td>115308.0 cycles</td>
</tr>
<tr>
<td>Median</td>
<td>17549.0 cycles</td>
<td>24247.5 cycles</td>
</tr>
<tr>
<td>Variance</td>
<td>5.7759x10^9</td>
<td>2.6258x10^10</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>75999.2 cycles</td>
<td>162042.0 cycles</td>
</tr>
<tr>
<td>Weibull Slope</td>
<td>0.67</td>
<td>0.54</td>
</tr>
<tr>
<td>Characteristic Life</td>
<td>76456.83 cycles</td>
<td>89728.5 cycles</td>
</tr>
</tbody>
</table>
SN CURVE FOR ±45° E-GLASS/EPOXY UNDER SHEAR LOADING

- DATA POINTS
- CHARACTERISTIC LIFES

\( \% \text{ M.T.S} = 105.445 - 3.812 \times 10^2 \) (CHARACTERISTIC LIFE)
Statistical Results for Shear Fatigue Tests

<table>
<thead>
<tr>
<th>% U.S.S.</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>65%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Mean</td>
<td>3.25</td>
<td>754.4</td>
<td>7824.2</td>
<td>70904.7</td>
<td>115308</td>
</tr>
<tr>
<td>Normal S.D.</td>
<td>2.18</td>
<td>704.5</td>
<td>2935.2</td>
<td>75999.2</td>
<td>162042</td>
</tr>
<tr>
<td>Weibull Slope</td>
<td>1.56</td>
<td>1.09</td>
<td>2.71</td>
<td>0.67</td>
<td>0.54</td>
</tr>
<tr>
<td>Characteristic Life</td>
<td>3.90</td>
<td>851.7</td>
<td>9011.6</td>
<td>76456.8</td>
<td>89728</td>
</tr>
<tr>
<td>Weibull Mean</td>
<td>0.90</td>
<td>0.97</td>
<td>0.89</td>
<td>1.32</td>
<td>1.77</td>
</tr>
<tr>
<td>Weibull S.D.</td>
<td>0.59</td>
<td>0.89</td>
<td>0.13</td>
<td>2.06</td>
<td>12.30</td>
</tr>
</tbody>
</table>

It can be seen from the tabulated statistics and S-N curve that there is a severe degradation of the results below 70% M.T.S. This is particularly evident at 60% where 3 separate failure regions appear to occur. It has been shown that the Rail Shear rig develops a tri-modal stress field on the specimen, namely shear, bending and buckling. Therefore the use of the Rail Shear rig characterise shear properties must be suspect.
FIG. 25

TYPICAL FATIGUE FAILURES
Failure of Rail Shear Rig

During the test programme, which consisted of some 80 static and fatigue coupons, the rail shear rig failed a number of times.

In all cases the failure consisted of a fatigue breakage of a loaded rail due to bending. The loaded rail does exhibit the maximum bending as shown in Fig.28. As the presence of the bolt holes causes a stress concentration factor of 3.0 to be developed, failure in this area is to be expected. A total of three fatigue failures occurred all during low stress/high cycle fatigue testing.

The rig was remade each time using similar steel to the original rails so as to have a constant strain field for direct comparison of results. If the rig had been modified at this stage, the results could not have been directly compared.

Subsequently the rig was modified as discussed in Appendix F.
APPENDIX D

EVALUATION OF MATERIAL FIBRE VOLUME FRACTION

Introduction

A detailed knowledge of the material composition is especially important when dealing with composites as certain physical characteristics can seriously affect their mechanical properties.

Such characteristics include the volume fraction and the percentage void content.

The fibre volume fraction $V_f$ is defined as the fraction of fibre to total composite by volume and is a measure of the amount of reinforcing material present in the resin matrix.

The percentage void content is the percentage by volume of voids present in the composite. Voids in the form of air or gas bubbles can be present in fibre laminates and depend on the moulding pressure, the pot life of the resin and the laminating procedure. As there is no satisfactory method available for determining this property an indication of the void content is obtained by comparing the predicted specific gravity of the composite with that obtained by experiment.

Determination of Fibre Volume Fraction $V_f$

The fibre volume fraction is determined by burning off the resin from a known sample weight of composite and then weighing the remaining fibres. Knowing the relative weight and density of fibre and resin the fibre volume fraction can be calculated.

The composite samples used in the tests were cut from unused test coupons. Sufficient material was used to fill the available crucibles and give sufficient accuracy upon weighing.

Test Procedure

1) The crucibles to be used in the tests were cleaned, identified and tared on a Santorius electronic balance with a measuring accuracy of 0.1 g. The test samples were placed in the crucibles and the weights noted.

2) The crucibles plus samples were placed on a fume cabinets hotplate set at a temperature of 1200°C and left for four hours to allow the resin to burn off.
3) After the heating time had elapsed the crucibles were allowed to cool and re-weighed.

4) The total crucible/fibre weight was noted. The crucible was then cleaned and its weight noted.

A total of three burn off samples were tested from a total of two laminate panels used in the rail shear tests.

Test Results

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sample weight (grams)</td>
<td>11.0</td>
<td>10.1</td>
<td>9.9</td>
</tr>
<tr>
<td>Crucible &amp; fibre weight after burn off (grams)</td>
<td>25.9</td>
<td>25.0</td>
<td>25.2</td>
</tr>
<tr>
<td>Crucible weight after burn off (grams)</td>
<td>18.2</td>
<td>17.8</td>
<td>18.3</td>
</tr>
<tr>
<td>Fibre weight (grams)</td>
<td>7.7</td>
<td>7.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Fibre content by weight *</td>
<td>70.0%</td>
<td>71.28%</td>
<td>69.69%</td>
</tr>
</tbody>
</table>

* Nominal value from Ciba Geigy for Prepreg is 71.0%.

From Ciba Geigy (42) the fibre and matrix densities are:

'E' Glass   Density $p_f = 2.54$ grams/cc  
Fibredux 913 Density $p_r = 1.23$ grams/cc

The volume fraction $V_f$ is given by:

$$V_f = \frac{W_f/p_f}{[(W_f/p_f)+(W_r/p_r)]}$$

Hence for the three samples:

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_f$</td>
<td>0.5305</td>
<td>0.5459</td>
</tr>
</tbody>
</table>

Due to the accuracy of the balance these results are only accurate to +/-1%.
Determination of Specific Gravity

The method chosen for determination of specific gravity was to weigh a known volume of laminate and from the known density of the constituent parts the laminate density could be found.

The laminate sample chosen was of dimensions 1002 mm x 299 mm x 2.25 mm. This gives a volume of 674095.5 mm$^3$. The weight of the sample was measured as 1301.9 grams hence the specific gravity is calculated as 1.931 grams/cc.

For a fibre volume content of 53% the theoretical specific gravity is 1.924 grams/cc therefore the void content is given by

\[
\text{Void content \% volume} = \frac{(\text{Theoretical S.G.}) - (\text{Actual S.G.})}{(\text{Theoretical S.G.})} \times 100
\]

\[
= \frac{1.924 - 1.931}{1.924} \times 100 = -0.003\%
\]

The -ve value for void content is due to the accuracy of the balance being +-0.1 grams. Therefore the void content is less than 0.1%.
APPENDIX E

FINITE ELEMENT REPRESENTATIONS

Introduction

The finite element representations were constructed using Static Analysis Finite Elements (S.A.F.E.) software on VAX/VMS 11/782 hardware.

Two models were constructed to test the suitability of the test rigs to accurately determine static shear properties and hence their suitability to fatigue work. These were the rail shear rig as supplied by R.A.E. Farnborough and the modified rig as designed to remove fatigue problems of the rails. The element meshes for both of the rail shear rigs were identical consisting of 223 structural nodes and 173 elements. This mesh is shown in Fig.26.

Basic Rail Shear Rig

The object of modelling the whole rig was to verify the failure position of the coupon along with its theoretical stress concentration, if any.

It was also necessary to determine if the bending of the rails as seen in experimental testing was due to anything other than stiffness variations in the test rig.

The model was constructed as close to the actual rig as possible hence the rail/coupon/tag areas; and other areas where two or more materials were clamped together, had material properties based on laminate theory. The model assumed loading at a single point and restraint also at a single point. The loaded pin joint was also restrained so as to allow movement only along its load axis. A static load was applied to give a theoretical shear stress in the centre of the coupon equivalent to the experimentally determined value of 283.808 N/mm. The resulting deflections and shear iso-stress contours are plotted in Figs.28 and 29. The deflections are plotted 25 times the actual size for clarity.

As can be seen there is considerable bending of both sets of rails, but in fact there is a 40% greater deflection in the non-loaded rails and its deflection of 0.19 mm as calculated by S.A.F.E. is comparable with optical measurements of the test rig during experiments.
FIG. 26

FINITE ELEMENT MESH FOR RAIL SHEAR RIG
FIG. 27

FINITE ELEMENT PLOT OF RAIL SHEAR RIG DEFLECTIONS
The end deflection of the loaded joint is within 3% of the experimental values for static shear tests, however, the iso-shear stress contours do show some deviation from previous theoretical and experimental work.

The S.A.F.E. model predicts failure in the bottom left hand corner of the coupon at 20% greater stress than the theoretical shear stress whereas experimental work puts the failure in the centre of the coupon. The reason for this discrepancy can only be explained by the buckling behaviour of the coupon as described in Appendix B. It is suggested that this buckling behaviour puts sufficient damage into the coupon; perhaps through interlaminar failure; to cause premature failure at this point. The non-symmetrical nature of the shear stress isoclines can be directly attributed to the ending of the rails introducing localised shear into the bottom region of the coupon. This bending also introduces local compressive transverse and longitudinal stresses into the coupon as shown in Figs.20 and 21.

**Modified Rail Shear Rig**

As described previously, this rig used thickened rails to remove the fatigue problems associated with low-stress, high-cycle tests. This necessitated increasing the total rail thickness of each rail from 6 mm to 10.7 mm. The geometry of the rig is otherwise unchanged to that of the basic rig. Plots of the iso-shear stress contours and the deflections are shown in Figs.30 and 31. As can be seen the deflections are reduced by 4% overall and 3% in the bending deflections of the rails. The isocline plot of shear stress is however little changed with still a large stress concentration in the bottom corner of the test area. This is similar to the basic rig as would be expected.
ISO SHEAR STRESS PLOT FOR RAIL SHEAR RIG
FIG. 29

ISO SHEAR STRESS PLOT FOR MODIFIED RAIL SHEAR RIG
FIG. 30

FINITE ELEMENT PLOT OF MODIFIED RAIL SHEAR RIG DEFLECTIONS
APPENDIX F

STATISTICAL ANALYSIS

Introduction

The statistical analysis of the static and fatigue results culminating with the construction of the S.N. curve of the material laminate follows the method suggested by Lipton and Sheth (43).

Static Analysis

The analysis of the static test data used two different distributions. Firstly the Normal Distribution as widely used in the analysis of material properties data and the Weibull distribution as originally proposed for interpretation of fatigue data but also suitable for static material data.

The Normal Distribution is defined by the mean value of the population and its standard deviation. In the case of the Weibull Distribution, the distribution is defined much more closely by a Characteristic Life and a Shape Parameter (also known as the Weibull Slope).

The Characteristic Life is defined as the life by which 63.2% of the population will have failed. The Weibull Slope can be defined when the data points are plotted on Weibull graph paper.

This paper will produce a straight line plot and hence the name Weibull slope. The slope effectively defines the 'peakiness' of the distribution. The peakier the data plot, i.e. the more consistant the results, the larger the value of the Weibull distribution is that it is not constrained to a symmetrical distribution as in the case of the Normal Distribution.

Fatigue Analysis

For fatigue work there is a choice in the distribution used to analyse results. This is usually between a Log Normal or a Weibull distribution. For consistancy and the reasons given above a Weibull distribution was again chosen with also results from a Normal distribution given for comparison.

The same variables as described above for the static results also apply for fatigue results.
Construction of S.N. Curve

The construction of the S.N. curve used a best line fit through the Characteristic life value for the various stress levels. This is rather an arbitrary choice as equally the mean value could be used. This line fit is determined by the principle of least squares.
APPENDIX G

TEST RIG DESIGN WORK

Modified Rail Shear Rig

As discussed in Appendix B failure of the steel rails occurred on low stress, high cycles fatigue tests; to be precise at 60% ultimate shear stress. From the finite element analysis in Appendix E it was found that the tensile load at the point of failure was 531.5 N/mm² when a stress concentration of 3.0 was included in the calculations. The stress required for a life greater than $10^9$ cycles in mild steel is 100 N/mm². To enable use of the existing coupon drilling rig it was decided to increase the rail thickness rather than its width. The new thickness is therefore calculated to be at least 10.7 mm compared to the present 6.0 mm. As previously mentioned this thickness increase will require the construction of two new end fittings for use in the Instron 8031 test machine.

Slotted Tension Rig

As described in Chapter 2 the coupon for the Slotted Tension test consists of a standard 250 mm x 20 mm coupon with two machines slots in it. For this design 6.35 mm slots were considered appropriate extending from the test area a distance of 80 mm.

As described in Appendix E a coupon from +-45°s 'E'-glass with a nominal thickness of 2.25 mm will require a tensile load of 12 kN and a compressive load of 24 kN to give failure. To apply the tensile load will require a single tensile ram and an earthing point. To apply the compressive load will require two rams. All the rams will need to be capable of high fatigue rates hence double acting rams will be necessary.

A number of such rams are available in the College of Aeronautics originally made by Keelavide Hydraulics. Two rams have a capacity of 5000 lbs.(f) (22.24 kN) with 6" stroke and load cell attachments. These rams are considered adequate for the compressive loads.

Also available is the central control system that will give a maximum frequency of 50 Hz although a simple oscillator will be required. Power packs are also available to power the rams.
There is however no suitable ram that will give a 12 kN load for the tensile loading. There is a possibility to use some 6000 lbs.(f) rams as used on the tracked hovercraft system but there specification is unknown.
FIG. 31

SKETCH OF PROPOSED SLOTTED TENSION RIG

WELDED STEEL FRAME

'KEELAVIDE' RAMS

LOAD CELL

COUPON

CLAMP

EARTH POINT

SCALE = 1:12