Normalized Standard Error (NSE) = 0,72

The NSE is very high, indicating that the mean line may not be significant. Upon inspection of the points, it was decided to plot the best fit parabola through these points, as is shown in graph 14. The formula and error for this curve are:

$S = 2.14 \log n^2 + 5.49 \log n + 79{,}57$

NSE = 0,59

The parabola is therefore a far better representation of the points than a straight line due to its far lower error. This seems to be a contradiction to previous assumptions that the best fit line for the fatigue life of notched carbon/epoxy specimens is of the form

$S = UTS - B \log n$

Instead by looking at the limits plotted on graph 9 these are of the form:

$S = A \log^2 n + B \log n + C$

where (A,B,C) = (-2,89, 8,34, 88,02) for the upper limit and (A,B,C) = (-3,35, 6,85, 69,89) for the lower limit. The experimental results tend to be more closely followed by these limits.

Many more tests should be carried out and more points should be found before a prediction of the equations of these curves is established. These curves are only representative in the regions tested, the extrapolated areas were not verified.

4.7.2 Effect of frequency

A number of workers (Smith and Pascoe, 1979[33], Stinchcomb, Reifsnider, Williams, 1975, O'Brien[34] 1977) have reported a frequency effect. Smith and Pascoe, using very thick, GFRP specimens, reported that, in general, a hysteritic heating effect shortened lives at **higher** frequencies, whilst Reifsnider and co-workers generally reported a more rapid damage development in carbon/epoxy specimens at lower frequencies. They further showed that specimens cycled under identical loads, but at frequencies 0.5 and 5.0 Hz respectively, behaved in exactly the same manner. Similar tests at 5.0 Hz and 10.0 Hz also showed no significant difference in behaviour.

During the testing under laboratory conditions the following were co-observed:

Five points were measured at a cyclic amplitude of 60 percent of the UTS and at a cyclic frequency of 50 Hz. These results have already been tabulated. The results are plotted on graph 16, along with the S = 60 percent at 15 Hz. Testing was started at 100 Hz, but due to irregularities from the testing machine results were rejected. However from the limited results it appeared that the fatigue life at 100 Hz may be better than that at 50 Hz. It was concluded that of varying the frequency did not have such a great effect on these particular specimens. However, insufficient tests were done to predict accurately what the effect will be. See graph 14.

4.7.3 **Temperature Effects**

Mandel suggested that for investigation of temperature rise the frequency lies in the range 5-20 Hz. After a small temperature rise of the order of two degrees, the temperature at 15 Hz remained stable thereafter. This seems to validate the decision to test at as low frequency as 15 Hz to avoid hysteretis heating especially as a temperature rise above 10 Hz. The temperature rise of 2°C was noted at 20,000 cycles.

Further tests were carried out at 30, 40, 60, 80 and 90 percent UTS at frequencies of 10 Hz and 40 Hz. The majority of them did not seem to be affected at the lower load and frequency limits till catastrophic failure occurs. The remainder seem to behave like the ones mentioned above with a slight initial increase of two degrees and them remaining stable till total failure occured.

The results generally show that carbon/epoxy specimens are heat absorbent and their fatigue properties are not temperature dependent. It should be mentioned that environmental factors such as room humidity were not taken into account.

4.7.4 **Face Notched specimens**

Part of the investigation is the fatigue behaviour of notched specimens with notches on the thickness of the specimen and not along the width. From the tests carried out the behaviour of long lifetimes at high stress levels was observed. During each test shear cracking was noted, usually running back into the area between the grips, similar to the one shown in Fig 6.
S-N data fit a line of the equation form S = UTS-Bologn. See graphs 15 and

16. B in this case is equal to 0.99. A lower scatter bond is also observed indicating that the specimens are not influenced by the notch to the extent like the specimens with the notch along the width.

4.7.5 Unnotched specimens

These unnotched specimens from batch E showed slightly lower UTS than the previous batches but their fatigue life was much higher than the notched ones as table 13 and graph 15 indicate. According to graph 16 the best fit line is a straight line of the equation form S = UTS-Blogn.

It is rather difficult to assess the behaviour of the fatigue life at higher stress loadings but work carried out by Reifsnider and co-workers indicate that the best fit line is still of the form S = UTS-Blogn but of a higher slope.

The increase in residual tensile strength over the UTS, for those specimens which did not fail in fatigue, is particularly interesting. It would normally be expected that about half of the specimens would break in the full fatigue loading of a stress amplitude equivalent to the material UTS. This was not observed in all specimens.

It appears that the fatigue loading causes some strengthening mechanism to operate in the composite. According to Sturgeon 1973[36], there is no conclusive evidence that the longer exposure is detrimental to the specimen. The fatigue failure surface of some of the specimens has been photographed and it appears that they failed statically. The surface appearance is similar to the surface of statically failed specimen but the major difference is that the fatigue specimen has a more jagged appearance. See Fig 6. Frequency effects were further examined. Increased frequency expected to cause an increase in the internal heating, however a small temperature rise was recorded, similar to the previous specimens.

The temperature of specimens was monitored for a final run to failure. See table 17. The specimens temperature shows sharp changes where there was sudden cracking and break up of specimens. A most interesting point is that there was a rise in temperature at the end of the specimen lifetime and this being particularly sharp in the last few thousand cycles. This seems to suggest that relatively minor failures occur throughout the lifetime of the specimen but the major fractures leading to failure only take place in the last few cycles.

4.8 Adhesive Failure

Another important observation was the failure of the aluminium tabs attached to the grips of the specimens. Misalignment of the load axis and improper surface treatment together with a shearing effect between adherent surfaces and adhesive were the main reason for failure.

After a lengthly treatment of the surface of the adherent shearing failure occurred again at the grips. The case of a double lap joint where a load is applied to the adhesive surface can be characterized. The stress in this case is complex. A bending moment exists and therefore the joint will rotate.

Clearly the adhesive layer will no longer be solely in shear but will have tearing stresses at the ends of the joint. Further, the adherents are no longer in simple tension but are bent.

4.9 Microscopic analysis

The useage of the microscope is described in the appendix D. A number of specimens were brought forward for inspection. In order to make full use of specimens it is necessary to be able to assess the quality of the material simply and quickly.

One such parameter required is the void content. Acid digestion techniques give reliable measurements of the void content of fibre/resin only if expertly carried out. However, the technique is not applicable to all types of fibres and in our case of carbon/epoxy specimens the results could be questionable.

A quick and reliable technique was established by RAE[36] (1983) so that the void content could be established using the cross section of the specimen under the microscope. The specimens under inspection showed a variation in void content. The average value obtained was approximately 4 --5 percent. See fig 7.

The specimens brought forward for inspection after UTS testing, showed a clear tensile failure. Fibre debonding accompanied by fibre breakage and fibre pull out was evident. In the case of notched specimens it was desirable to photograph and carefully examine the entire notch area. The notch area for the specimens with a semicircular notch along the width is shown in Fig 8.

The maximum possible magnification of this area on a 35 mm film frame is at the most 200 x. Because of the small size of the individual graphite fibres it would be advantageous to increase this magnification, but the resolution becomes poor. In the early stages high contrast film was used which proved to be unsatisfactory for the carbon/epoxy specimens.

The difference in contrast between the matrix material and void was not sufficiently large under vertical illumination for the film to discriminate between them. A special liquid supplied by 'Olympus' was spread on the surface of the specimens in order to obtain a clearer image.

Examination of the fracture surfaces of the semicircular configuration indicates that the drilled area appears to be damaged, thus helping crack initiation. On the initial cycles, during which high loads were applied the specimen failed before the programmed maximum load was attained, careful examination of the fractured surface shows a fibre-matrix debonding and a crack spreading from the root of the notch closest to the centre line of the specimens. There is also a degree of fibre breakage at the origin of the crack.

The visual observation of extremely localized damage within the gauge length seems to be the result of some of the secondary damage zones coalescing into one large and continuous 'macro-crack'.

Finally examining the surface of the specimens with face notches, resin rich areas could be seen clearly, see Fig 9. Some fibres also have been cut and destroyed during machining indicating a initiation zone. There is a marked difference in the fracture surface of fatigued and static specimens. The fracture surface of the fatigued specimens shows a relatively clean, longitudinal splitting of the unidirectional plies. The failure of a fatigued specimen is a low energy failure compared to the explosive disintegration of the static specimen.

The 'toothbrush' appearance of the unidirectional plies fracture surface is similar to the fatigue crack surface of notched GFRP laminates tested by that reported by Wells (1982)[38] who studied a crack growing from a notch into unidirectional material.

4.10 CONCLUSIONS

Some of the conclusions reached are mentioned briefly at the beginning of the discussion section. They can be summarised together with the following:

A large scatter was obtained in the ultimate tensile strengths due to the irregularities occuring during manufacturing and testing.
The scatter in the fatigue test results is comparable with that of metals.
The normalised standard error for a linear fit through the experimental data varied considerably.
The normalised standard error for a parabolic fit through the experimental data was 0.59.
Graphs (3) and (4) refer to specimens with a semi-circular notches along their width. High concentration factors of up to 7,5 seem to be one of the reasons for this form of fitting.
The results obtained from the double waisted specimens along the thickness appear to show less scatter on an logorithmic scale.They appear to agree with the predicted empirical equation of the form S=UTS-Blogn.
Unnotched specimens tested agree with the empirical model employed. See graphs 17 and 18.
It has been demonstrated that the short-term tensile specimen recommended with the thickness being waisted can be successfully adopted for the fatigue testing.
The fatigue properties suffered great variability due to the characteristics of the materials employed.
The undesirable break-up of the specimens could be attributed to stress distribution around the notch of the specimen.
No conclusive results could be drawn from the temperature and frequency effects.
The dominant mode of failure in specimens from batch [E] was tensile breaking fracture.
The successful use of notched carbon/epoxy composite structures will depend on minimising shear effects when fatigue is considered.
It is assumed in this case that the various irregularities and defects which were observed in the surface micrographs are representative of

that reported by Wells (1982)[38] who studied a crack growing from a notch into unidirectional material.

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It is assumed in this case that the various irregularities and defects which were observed in the surface micrographs are representative of conditions in the interior of the composite specimens.

It is also likely from the limited evidence available that in any one specimen the manufacturing defects and irregularities are non-uniformly distributed and the mechanical properties of the material have random spatial variation.

If the notches are located in the region with few defects, the static strength of the specimen will be high. If there are many defects and material irregularties in the notch region, lower static strength is expected. Hence in a group of notched specimens with random defects tested under similar conditions one should expect considerably more scatter in failure data than would be the case for uniform specimens, therefore, there would be a large scatter in the fatigue lives. Although only a small number of specimens were tested, the results of the tests suggest that the material as manufactured was a poor candidate for structural applications.

In addition to stress redistribution, material degradation and localisation of damage are critical aspects of long-term damage development and consequent failure. Even under uniaxial uniform stress states, unnotched coupons eventually fail under load levels which may be only 60 to 70 percent of the static ultimate tensile strength.

As a result a very complex, widely distributed and dense array of micro damage develops with a distinct localisation process that precedes the final failure event.

Finally the effect of matrix plasticity on stress concentration in a notched specimen together with the effect of the crack blunting on the change of stress and consequently on the strength should be investigated since an analytical expression for the elasto-plastic boundary is unknown.

4.11 SUGGESTIONS FOR FURTHER WORK

* Predict the initiation of the crack by employing finite element techniques.
* Develop more accurate mathematical models to simulate the fatigue behaviour of carbon reinforced plastics.
* More extensive testing requires to verify the proposed parabolic limits.

* Testing with different ply orientations.
* Conduct further frequency and temperature dependency tests.
* Fatigue damage detection using Moire interferometry. It can be used to detect the delaminated region around the edge of the hole.
* NDI testing such as ultrasonics, acoustic etc, require skilled operators while the method described if fully utilised is inexpensive and faster.
* The behaviour at low stresses and long lifetimes requires further investigation.
* Environmental effects (eg humidity, heat) affecting the bond of CFRP
* Effect of moisture on the notch sensitivity of carbon fibre composites.
* Environmental degradation of notched CFRP in either tension or compression.

APPENDIX A **Page**

A.1 LAY-UP OF PANELS

The hand lay-up technique was used. The materials used were as follows:

CARBON : SIGRATEX KDU-1006 UNIDIRECTIONAL TAPE

SUPPLIER: SIGRI-GERMANY

EPOXY : ARALDITE - SUPPLIER CIBA-GEIGY

A1.1 SP[illegible]

Carbon Tape Type of Sigrafil rovings	Number of rovings	Tape Width cm	Tape Weight g/m
NF12	75	16,0	60

MATRIX: ARALDITE XB 3052 A (RESIN)
ARALDITE 3052 B (HARDENER)

PROPERTIES OF RESIN AND HARDENER AS SUPPLIED

CIBA GEIGY-ARALDITE		XB3052A (Resin)	XB3052B (Hardener)
Physical number		Liquid	Liquid
Colour number		3	3
Viscosity at 25°C	Pas	1000-1500	40-60
Specific gravity at 25°C	g/cm^3	1.16-1.18	0.93-0,95
Epoxy content	eq/kg	6.6-6.9	-

A.1.2 SAMPLE CALCULATION OF WEIGHTS

Fibre mass ratio = 0.55
Matrix mass ratio = 0.45
Mass of fibres = 380,5 g

$$\text{Mass of matrix} = \frac{380{,}5}{0.55} \times 0.45 = 311.32 \text{ g}$$

Since the matrix consists of 100 parts of resin and 38 parts of hardener by weight,

$$\text{the mass of resin} = \frac{311,32}{138} \times 100 = 225,59 \text{ g}$$

$$\text{Mass of hardener} = \frac{311,32}{} \times 38 = 85,73 \text{ g}$$

CHECK: 225,59 + 85,73 = 311,32 g

A.2 QUALITY CONTROL

A.2.1 ASTM-D2584

There are several non-destructive tests that are used to examine the preparation and the quality of carbon/epoxy specimens. These test methods have not been standardized except in the case of ASTM D2584, although they have been developed to improve quality assurance.

ASTM D2584 suggests that the carbon/epoxy ratio could be established, based on the digestion of the resin matrix by chemicals which will not attack the fibre excessively. The digestive media for epoxy resins is concentrated nitric acid. After the testing, distinct parts of epoxy were still attached to the fibres and it was difficult to establish the carbon/resin ratio.

A.2.2 VISUAL INSPECTION

Instead of ASTM-D2584 other techniques such as microscopy was used. Existing methods tend to prove the dynamic use of the microscope with great accuracy [36] of calculating void content at a faster rate than using chemicals with great accuracy. The equipment employed was an OLYMPUS PM-10M photomicrographic system. Use of the system is given in Appendix C. The primary areas looked at were modes of failure and void content. Void content was assessed as by Ref[36]. Magnifications available are 50X, 100X and 200X. Fig 10 shows the photomicrographic system.

A.3 MACHINING

A.3.1 SHAPING OF SPECIMENS:

The panels marked off by drawing on the peel ply tape with an overhead marker pen. A waste area must be worked off around the edge of the panel in the area where all tape layers may not be present.

Th specimens are then marked off inside this area. For the tests the specimens were marked off as 25 mm by 150 mm to 160 mm. The individual specimens were then cut on a bandsaw. The bandsaw specifications are:

TYPE	:	DOALL MODEL DBW-15
SERIAL NUMBER	:	290-722 653
BLADE	:	1.2 mm thickness
		8 teeth per inch
BLADE SPEED	:	225 feet per minute.

The following step is to sand the samples down. The sander used was as follows:

TYPE	:	ROCKWELL MANUFACTURING COMPANY 31-630
SERIAL NUMBER	:	CW 5390
BELT	:	WOOD

* Ensure that an extraction fan is used while sanding carbon/epoxy.

The specimens were clamped and sanded together in batches to ensure consistent dimensions. The dimensions were also periodically measured to ensure that the specimens were 'true' ie that they did not taper to one end. Once the specimens had been sanded at the edges they were then shaped.

It is worth noticing that the machining of fibre reinforced plastics implies requirements and conditions essentially different from those of metal cutting.

CFRP are machineable only in a limited range of temperature. Even though the fibres will withstand higher temperatures, the curing temperature should not be exceeded to avoid material disintegration especially of the resins.

Low thermal conductivity favours heat build-up in the cutting zone during machining operations, since there is only little dissipation into the material. The greatest part of the heat has to be carried away through the tool.

The difference in coefficients of thermal expansion between matrix (highly positive) and fibre (slightly negative for carbon) is favourable for the formation of residual stress and making it difficult to attain high dimensional accuracy. Drilled hole, for example, later often show a smaller diameter than the drill used.

Carbon fibres (which are anisotropic) show a brittle fracture as they consist of axially oriented, intertwisted graphite layer tapes, which lack a comparable sliding mechanism. The features of the individual filament are immediately reflected by the problems in machining reinforced material.

The quality of the machined surface is a major parameter for evaluating the cutting process.

The surfaces obtained when cutting parallel to the fibres are of reasonably good quality, but they are rather poor when the specimens are machined perpendicular to the fibres.

By cutting parallel to the fibres a surface with visible fibres is produced. Nearly all the fibres are fractured perpendicular to their longitudinal direction. A few are smashed and there are pieces of raked matrix material between them (see Fig 11).

When the workpiece is machined perpendicular to the fibres, there is no longer visible fibres on the surface. The whole surface is covered with a thin layer of matrix material.

Fig 12 shows a macrograph of two quick-stop specimens, one machined perpendicular to the fibre direction and the other parallel. When the machining is perpendicular to the fibre direction, a rather sharp notch is formed and there are no cracks in front of the notch. During machining the CFRP perpendicular to the fibres, two separated effects occur near the tool tip. As the tool moves forward it presses the composite in front of it, causing the composite to fracture and create a chip.

An improvement in drilling by using di. ond coated edge surfaces can be obtained. Fig 13 shows a drill prototype made by Klenk of Balzheim in West Germany and the increase in quality at the tool entry compared to a conventional tool.

APPENDIX B

Determination of Mechanical Properties **Page**

APPENDIX B

Determination of Mechanical Properties

B.1 TENSILE PROPERTIES

B.1.1 Definitions

According to British Standards (BS2782) the following apply:

i) Tensile stress: The tensile force carried by the test piece per unit area of the original cross-sectional area between the reference lines.

ii) Tensile strength: The maximum tensile stress which the test piece is capable of supporting.

iii) Yield stress: The tensile stress at which occurs the first marked inflection of the stress-strain curve. Where any increase in strain occurs without any increase in stress, this point is taken as the yield stress.

B.1.2 TENSILE TESTING MACHINE REQUIREMENTS

BS 5214: Part 1: 1975 requirements of the tensile testing machine-grade A, specifies that the machine shall be power driven and capable of maintaining the appropriate rate of grip separation corresponding to an appropriate test procedure ie the test piece shall be held in such a manner that slip relative to the grips is prevented, and the clamping system should not produce premature failure at the grips.

The above assures that the grips total elastic longitudinal strain is not greater than 1% of the longitudinal strain, shown simultaneously in the gauge length of the specimen. These requirements will be satisfied for any force less than or equal to the rated capacity of the testing machine.

B.1.3 Tensile testing of specimens

Measure: width, b, to the nearest 0.1 mm and the thickness, h, to the nearest 0.02 mm at the midpoint of the specimen and within 5 mm of each end of the gauge length. Calculate arithmetic means.

Determination of material properties. Mount the test pieces in the testing machine in axial alignment with the direction of pull.

Adjust rate of transverse to:

2 mm/min (or 5kN/min):

- when measuring elongations
- when determining the moduli of elasticity in tension
- when determining the fracture load.

Record: deformations to corresponding forces.

Returning the shape of the ultimate tensile strength of the specimen, the following shape was selected. See Fig 14.

To form this, the blank samples are first clamped into a template (or former). While clamped in the former, the excess material was removed on a router to obtain the desired shape.

ROUTER TYPE : TENSILKUT B22144
SPEED : 2500 rpm

B.1.4 **APPARATUS**

INSTRON TESTING MACHINE, MODEL TT-CM
SERIAL NUMBER A0144
LOAD CELL FULL SCALE RANGES, 100, 200, 500, 1000, 2000, 5000 Kg
LOAD CELL SERIAL NUMBER UKFM042
CROSS HEAD SPEED = 5 mm/min
OPERATIONS OF EQUIPMENT IS DESCRIBED IN APPENDIX D.