

B.1.5 PREDICTIVE ULTIMATE TENSILE STRENGTH

B.1.5.1 VOLUME RATIOS

Density of fibres = 1.8 g/cm^3

$$\text{Density of matrix} = \frac{1.17}{100} \times 100 + \frac{0.94}{100} \times 38 = 1.21 \text{ g/cm}^3$$

Volume fraction of fibres

$$V_f = \frac{\frac{0.55}{1.8}}{\frac{0.55}{1.8} + \frac{0.45}{1.21}} = 0.45$$

$$V_m = \frac{\frac{0.45}{1.21}}{\frac{0.45}{1.21} + \frac{0.55}{1.8}} = 0.55$$

$V_m + V_f = 1$ (Note: In this case V_v is ignored).

B1.5.2 LAMINATE STRENGTH

One model for the strength of composites is given by:

$$S_k = S_f V_f + S_m V_m$$

S_k = composite strength

$$S_f = 2.4 \text{ KN/nm}^2$$

S_f = fibre strength

$$S_m = 65 - 68 \text{ N/mm}^2$$

S_m = matrix strength

(Cured 7 days at room temperature)

$$S_k = 1116 - 1127 \text{ MPa}$$

The materials used here are unidirectional carbon tape and epoxy resin with the above mentioned tensile strengths.

This model assumes, however, that the matrix and fibres fail simultaneously. A better approximation would be to assume that the composite fails on the shortest strain of its constituents. The elongation of the matrix at failure is 2.4 - 4.0% and for the fibre it is 1%. Therefore the fibre strain is limited.

Let e = strain

E = Young's modulus = 220 kN/mm^2

= $3200 - 3500 \text{ N/mm}^2$ for matrix

$S_f = E_f e$

$S_m = E_m e$

$S_k = E_f e V_f + E_m e V_m$

taking $e = 1.1 \times 10^{-2}$

$S_k = 1108 \text{ to } 1110 \text{ MPa}$

predicted UTS = $1108 \text{ to } 1110 \text{ MPa}$

Another way is to follow Tsai's suggestion using the following stiffness equation:

$$E_L = K[E_m + (E_f - E_m)V_f]$$

K = misalignment factor

E_L = composite tension modulus

E_f = filament modulus

V_f = fibre volume fraction

For straight filaments $K = 1.0$. However, the carbon yarns are twisted resulting in an effective K of 0.92

In order to find the strength of the laminate the formula below is being used:

$S_L = e E_L$ where S_L is the UTS predicted.

$E_f = 220 \text{ kN/mm}^2$ $e = 1.1 \times 10^{-2}$

$E_m = 3.2 \text{ kN/mm}^2$

$K = 0.92$

$V_f = 0.45$

$E_L = 0.92 [3.2 + (220 - 3.2) 0.45] = 92.6992 \text{ kN/mm}^2$

$S_L = 1.1 \times 92.6992 \times 10^{-2} = 1.01 \text{ GPa or } 1001 \text{ MPa}$

Hence it can be seen that there is approximately an agreement between different assumptions. The values obtained here tend to be made higher than the experimental ones. Poor quality of lamination and specimens mainly attributes to the low ultimate tensile strength values of the various batches.

B.1.5.3 PREDICTION OF LAMINATE THICKNESS OF CARBON/EPOXY

The laminate is a unidirectional tape with the following properties:

Weight = 60 g/m

width = 16 cm

The weight per m^2 is 375 g/m^2

Density $1.8 \text{ g/cm}^3 = 1.8 \text{ Mg/m}^3$

Therefore thickness constant* = $1/1.8 = 0.556$ for carbon.

The matrix to carbon ratio is 45:55 by mass and equals to = 0.82:1

Density = 1.1 Mg/m^3

thickness control = 0.909

'Thickness' of carbon = $0.556 \times 0.375 = 0.2085 \text{ mm}$

'Thickness' of matrix = $0.82 \times 0.375 \times 0.909 = 0.280 \text{ mm}$

Total thickness of a single ply = 0.4885 mm

For the eight ply laminate = 3.904 mm

* Thickness in mm attributable to kg/m^2 of the material.

B.2 FATIGUE PROPERTIES

B.2.1 FATIGUE SPECIMENS

The shape of the fatigue specimens (double notched along the width) is as indicated in Fig 15.

Two 5 mm radius holes were drilled into each side of the sanded C/E blank specimens. The holes were further sanded to remove excess chaff.

B.2.1.1 CRITERIA FOR SELECTION OF DOUBLE EDGE NOTCHED SPECIMENS

The original fatigue specimens had a single edge notch, as indicated in Fig 16.

It was noted during initial testing that a large bending moment was induced in this type of sample. It seems that stress due to bending is far greater than the stress due to normal load. This was thought to modify the loading in an unacceptable fashion and therefore double edge notched specimens were chosen.

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B.2.2 CRITERIA FOR SELECTION OF NOTCHED FATIGUE SPECIMEN WAISTED ALONG ITS THICKNESS

The essence of good materials testing is to use specimens which give unambiguous results. The conventional reinforced plastics dumb-bell type of specimen has not fulfilled this criterion when used with carbon fibre reinforced plastics (CFRP) and new types have been developed which behave well for short-term tests.

It has been found that the fatigue strength is very high but the material variability revealed by UTS measurements is reflected in fatigue.

At loadings at different percentages of UTS some specimens failed quite quickly whilst others continued to sustain the loads for many millions of cycles without loss of tensile strength. Considerable shear damage was

evident in all fatigues specimens. An important requirement of any specimen design is that it provides a means of simple, unambiguous interpretation of the test for which it is used.

The conventional dumb-bell specimen fails outside the narrowest waisted section when used to measure the ultimate tensile strength (UTS) of unidirectional CFRP in the fibre direction. Obviously the results from a specimen which fails outside the narrowest section must be regarded with some suspicion.

To illustrate the problem ³⁶ typical strength values for unidirectional CFRP are of the following orders:

HIGH STRENGTH surface treated fibres in an epoxy resin matrix have the following mechanical properties

$$\begin{aligned}\text{UTS} &= 1600 \text{ MN/m}^2 \\ \text{ILSS} &= 100 \text{ MN/m}^2\end{aligned}$$

It can be seen that the ratio is approximately 16:1 of UTS to ILSS and in some cases (as in the case of untreated fibres) can go up to 36:1.

An analysis shows that if a specimen is to fail at the narrowest section the equation for the slope of the waist at any section Z, a distance X from the narrowest section, is given by

$$\frac{dz}{dx} = \frac{\tau}{\sigma} \frac{Z}{Z_0}$$

where Z_0 is half the thickness of the neck, σ the material UTS and τ the interlaminar shear strength.

This gives a curve of the specimen surface as

$$Z = Z_0 \exp\left(\frac{\tau}{\sigma} \frac{x}{Z_0}\right) \text{ and the maximum allowable taper at the narrow section}$$

$$\left(\frac{dz}{dx}\right)_{Z_0} = \frac{\tau}{\sigma}$$

The most economical use of composites for testing is achieved by waisting through the specimen thickness and not the width. In doing so the overall

length is considerably reduced whilst maintaining an adequately large test section. In addition the specimen has the merit that results are width independent.

CFRP is brittle and unwanted bending of a specimen can produce high local stress which cannot be relieved. A specimen waisted in the thickness is less susceptible to out of plane misalignment in test machine wedge grips than one waisted in the width.

Figures of a section of a waisted specimen and a sketch of the parallel waisted tensile fatigue specimen are given in Figs 17 and 18. It must be borne in mind, however, that the fibre efficiency of that particular type is only 50 percent for hand lay-up compared with 76 percent for autoclave moulded material. Consequently the fatigue strengths represent quite modest fibre stresses.

B.2.3 APPARATUS FOR FATIGUE TESTING

A detailed discussion of equipment operation is included in Appendix D. Equipment used : ESH Serial number 1583.

The samples were tested at each cyclic amplitude as specified by BS 2782 part 3. The exception was that a couple of tests were carried out at 30 percent of UTS. The above tests were carried out in connection with batches [A], [B], [C], [D]. In case of batch E results were slightly different since the specimen were waisted along the thickness.

Due to the primary mode of failure being matrix cracking for the face notched specimens the ESH machine was tripped out when macroscopic longitudinal cracking occurred.

This was done by bonding 1.5 mm coated copper wire to the specimen in such a way that it would break if a crack occurred. The position of this wire is shown in Fig 19.

This wire was bonded completely along the lateral section of the specimen using a 'superglue'. It was necessary to bond it entirely along these lengths to prevent the wire elongating rather than breaking when a crack passed it. The wire was then used to energise the coil of a relay.

When the wire broke a voltage was applied to the socket trip on the ESH machine which would terminate the test.

It is not feasible to use the extension trip on the machine with the type of sample being tested. This is because longitudinal cracking occur, but no lateral cracking. The crosshead can therefore only extend once the specimen pulls loose from the grips.

B.2.4 FATIGUE RESULTS

There are quite a number of points obtained from fatigue results. Five of them are at stress amplitude of 60 percent of the UTS and a cyclic frequency of 50 Hz in order to prove whether the life is frequency dependent or not. All the remaining results are at a cyclic frequency of 15 Hz. Here the tension-tension is examined.

It is worth noticing that batch E is treated as a special case.

The stress amplitude (S) is quoted in percentage of the UTS due to the scatter in UTS results between panels. Expressing S as a percentage therefore non-dimensionalises this quantity.

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TABLE 1

BATCH	MEAN UTS (MPa)
A	878,59
B	552,92
C	448,8
D	416,5

These results are presented graphically in graph 1.

STATISTICAL ANALYSIS OF UTS VALUES

The standard deviations for each batch were calculated and presented in Table 2.

$$S = \frac{\sum x^2 - \frac{(\sum x)^2}{n}}{n-1}$$

TABLE 2

BATCH	MEAN UTS (MPa)	STANDARD DEVIATION
A	878,59	147,19
B	552,92	84,17
C	448,8	67,02
D	416,5	100,16

$$\text{Mean UTS } \bar{X} = \frac{\sum x}{n} = 574,2 \text{ MPa}$$

Standard Deviation S.D = 211,1 MPa

TABLE 3

S (% UTS)

CYCLES TO FAILURE (n)

LOG (n)

90	20	1,30
90	20	1,30
90	400	2,6
90	0	0
90	0	0
90	870	2,94
90	200	1,0
85	50	1,70
85	20	1,30
85	7730	3,89
85	3100	3,49
85	760	2,88
80	70	1,85
80	4230	3,63
80	0	0
80	0	0
80	50	1,7
80	2300	3,36
80	4470	3,65
80	51	1,7
75	650	2,81
75	640	2,81
75	1250	3,10
75	1250	3,10
75	1230	3,10
75	7530	3,88
75	270	2,43
70	80	1,9
70	296	2,46
70	0	0
70	0	0
70	120	2,08
70	9400	3,97
60	4780	3,68
60	75530	4,88
60	11250	4,05
60	2130	3,33

60	49320	4,69
60	0	0
50	92820	4,97
50	2690	3,43
50	165300	5,22
50	189600	5,28
50	0	0
50	2685	3,4
30	1260400	6,10
30	1200001	6,07
30	1560032	6,19
30	1103256	6,04
30	1062574	6,02

TABLE 4

50 Hz

S (% UTS)	(n)	LOG (n)
60	10600	4,03
60	24300	4,39
60	2200	3,34
60	2500	3,40
60	5100	3,71

The above results were plotted in graph 16.

STATISTICAL ANALYSIS OF FATIGUE RESULTS.

For each value of S the following results are presented:

- mean life
- standard deviation (SD) of mean life
- mean of Log n
- standard deviation (SD) of Log n

These results are shown in Table 5.

TABLE 5

CYCLIC AMPLITUDE	CYCLIC FREQUENCY	MEAN LIFE	SD OF n	MEAN LOG n	SD of LOG n
90	15	262	379	1,63	1,18
85	15	2332	3269	2,65	1,12
80	15	1853	2124	2,37	1,45
75	15	2068	3073	3,01	0,54
70	15	1978	4150	2,08	1,42
60	15	28602	32407	4,13	0,66
50	15	104182	75139	4,75	0,76
60	50	3940	9224	3,77	0,44

TABLE 6.0
C FATIGUE LIFE AT 15 HERTZ CYCLIC FREQUENCY

Cyclic Amplitude (% uts)	Specimen No	Notched Area (mm ²)	Load (kN)	Cycles to Failure (n)	log (n)
90	C7	39,71	16,04	20	1,30
90	C8	37,27	15,05	20	1,30
90	C9	38,87	15,7	400	2,6
90	C10	37,37	15,09	0	0
90	C11	37,82	15,28	070	2,94
85	C12	39,95	15,24	50	1,7
85	C13	40,01	15,26	20	1,3
85	C14	41,04	15,66	7730	3,89
85	C15	38,02	14,50	3100	3,49
85	C16	35,87	13,68	760	2,88
80	B18	31,40	13,84	70	1,85
80	B19	38,46	21,27	4230	3,63
80	B20	37,27	16,49	0	0
80	B21	35,33	15,63	50	1,70
80	B22	32,08	14,19	2300	3,36
80	B23	31,56	13,96	4470	3,65
75	D6	44,02	13,75	650	2,81
75	D7	43,08	13,46	640	2,81
75	D8	45,97	14,36	1250	3,10
75	D9	46,04	14,38	270	2,43
75	D10	41,31	12,90	7530	3,88
70	A9	32,88	20,22	80	1,9
70	A10	33,64	20,69	2190	2,46
70	A11	32,95	20,27	0	0
70	A12	33,54	20,63	120	2,08
70	A13	35,53	21,85	9400	3,97
60	B6	38,19	12,67	4780	3,68
60	B8	36,06	11,96	75530	4,88
60	B10	33,87	11,24	11250	4,05
60	E13	31,76	10,54	2130	3,33
60	B14	34,60	11,48	49320	4,69
50	B11	36,42	10,07	92820	4,97
50	B15	31,99	8,84	2690	3,43
50	B16	38,1	10,53	165300	5,22
50	B17	33,75	9,33	189600	5,28
50	C6	36,63	8,22	70500	4,85
30	A14	34,24	9,02	1260400	6,10
30	A17	34,21	9,06	1541256	6,18
30	B18	35,11	9,34	756234	5,87
30	C20	36,42	9,11	1113400	6,04
30	D17	34,11	9,54	287322	5,45

Specimens B7, B9, B12 were reserved due to possible damage during testing.

TABLE 7.0
FATIGUE LIFE AT 50 HERTZ CYCLIC FREQUENCY

LOAD 60% UTS

Specimen	Notched Area (mm ²)	Load (kN)	Cycles to Failure (n)	Log (n)
D11	46,27	11,56	10600	4,03
D12	39,94	9,98	24300	4,34
D13	39,85	9,96	2200	3,34
D14	43,95	10,98	2500	3,40
D15	45,75	11,43	5100	3,71

SUMMARY OF EXPERIMENTAL RESULTS

Test samples were from several panels.

Each panel is designated with a batch letter. That is batch A, B, C, D, A' or E.

These letters are used to prefix the number of each specimen to show which batch it was derived from (eg A2 indicates the second specimen cut from panel A).

ULTIMATE TENSILE STRENGTH DIMENSIONS

The width and thickness of each specimen was measured in three places and the area then averaged out. This is to compensate for any small fluctuations in these dimensions.

TABLE 8.0
BATCH A

No	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
A ₁	154,1	11,46	3,4
		11,28	3,4
		11,3	3,4
A ₂	155,1	11,4	3,52
		11,2	3,5
		11,4	3,54
A ₃	155,3	11,4	3,62
		11,0	3,54
		11,4	3,58
A ₄	156,8	11,4	3,7
		11,4	3,6
		11,5	3,68
A ₅	155,6	11,4	3,2
		11,34	3,28
		11,4	3,16
A ₆	158,8	11,34	3,1
		11,28	3,2
		11,6	3,0
A ₇	156,3	11,48	3,16
		11,4	3,2
		11,56	3,1
A ₈	153,6	11,52	3,32
		11,24	3,3
		11,4	3,3

BATCH B

No	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
B ₁	150	11,12	3,10
		11,32	3,3
		11,10	3,3
B ₂	149,5	11,12	3,16
		11,38	3,36
		11,28	3,28
B ₄	145,3	10,92	3,20
		11,30	3,20
		11,14	2,16
B ₅	143,2	11,32	3,18
		11,48	3,18
		11,28	3,20

BATCH C

No	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
C ₁	140,00	11,00	3,28
		11,36	3,28
		11,28	3,24
C ₂	140,92	11,36	3,08
		11,36	3,18
		11,08	3,06
C ₃	140,12	11,20	3,12
		11,26	3,08
		11,16	3,18
C ₄	140,00	11,04	3,14
		11,28	3,06
		11,24	3,12
C ₅	139,4	11,14	3,28
		11,24	3,26
		11,18	3,34

BATCH D

No	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
D ₁	140,2	11,34	3,64
		11,48	3,60
		11,26	3,62
D ₂	138,6	11,14	3,50
		11,10	3,56
		11,20	3,40
D ₃	139,6	11,12	3,60
		11,44	3,64
		11,16	3,54
D ₄	139,8	11,24	3,50
		11,36	3,5
		11,18	3,48
D ₅	140,7	11,08	3,64
		11,40	3,64
		11,20	3,58

TABLE 9.0

**TEST RESULTS
BATCH A**

No	Load (kN)	Mean Area (mm ²)	UTS (MPa)
A1	28	38,58	725,76
A2	28,4	39,89	711,96
A3	36	40,34	892,41
A4	29	41,85	692,45*
A5	35,5	36,57	970,74
A6	26,5	34,75	762,59
A7	36,5	36,2	1008,29
A8	40,6	37,65	1078,35

* This value was discounted because of a suspect zero setting on the machine for this test.

MEAN UTS = 878,59 MPa

TABLE 10.0

BATCH B

No	Load (kN)	Mean Area (mm ²)	UTS (MPa)
B1	17,5	36,15	484,09
B2	22,25	36,87	603,47
B3	21	35,71	588,07
B4	15,8	35,48	445,32
B5	23,3	36,20	643,65

MEAN UTS = 552,92 MPa

TABLE 11.0

BATCH C

No	Load (kN)	Mean Area (mm ²)	UTS (MPa)
C1	13,5	36,63	368,55
C2	16,5	35,01	471,29
C3	17,75	35,04	506,56
C4	17,75	34,75	510,79
C5	14,25	36,84	386,81

MEAN UTS = 448,8 MPa

TABLE 12.0

BATCH D

No	Load (kN)	Mean Area (mm ²)	UTS (MPa)
D1	21,75	41,12	528,91
D2	16,5	39,22	420,73
D3	20,05	40,39	496,37
D4	13,5	39,56	341,23
D5	12	40,64	292,27

MEAN UTS = 416,5 MPa

FATIGUE RESULTS OF UNNOTCHED SPECIMENS

The results included in previous paragraphs do not include independent tests carried out on unnotched specimens in order for a comparison to be made between notched and unnotched specimens.

Their geometry resembles one of the specimens used for UTS so that extra modification was avoided. Batch No A' is given for this particular type of specimen.

BATCH	MEAN UTS (MPa)
A'	389,4

Frequency was kept also at 15 Hz.

TABLE 13.0

	MN/m ²	% of static strength	Endurance X10 ⁴	Log n
A'1	137.7	35.4	3.3	4.5
A'2	137.7	35.4	1.7	3.2
A'3	137.7	35.4	4.4	4.64
A'4	137.7	35.4	2.3	4.36
A'5	110.1	28.3	13.0	5.11
A'6	110.1	28.3	13.0	5.11
A'7	110.1	28.3	10.0	4
A'8	82.6	21.2	140.0	6.14
A'9	82.6	21.2	38.0	5.57
A'10	55.1	14.1	840	6.92
A'11	55.1	14.1	270.0	6.43
A'12	46.7	12	15.0	5.17
A'13	46.7	12	19	5.27
A'14	46.7	12	69.0	5.83
A'15	38.9	10	53.0	5.72
A'16	31.1	8	230.0	6.36
A'17	31.1	8	55.0	5.7
A'18	23.4	6	56.0	5.74
A'19	15.6	4	2400.0	7.3

TABLE 14.0

EFFECT OF FREQUENCY ON FATIGUE ENDURANCE

	% UTS	Frequency	Endurance X10 ⁴
A'20	30%	100	240.0
A'21	30%	100	0
A'22	30%	100	31.0
A'23	30%	100	34.0
A'24	30%	100	9.0
A'26	30%	50	28.0
A'29	30%	50	2
A'30	30%	50	0.1
A'31	30%	50	26.0
A'32	30%	5	29.0
A'33	30%	5	42.0
A'35	30%	5	47.0
A'36	30%	0.5	0.037
A'37	30%	0.5	0.064
A'38	30%	0.5	0.11
A'40	30%	0.5	0.042

As can be seen here by increasing the test frequency from 0.5 Hz to 100 Hz an increase in endurance of about 2000:1 was obtained for the same conditions of fatigue loading. By contrast, it is usually found that metal specimens show an increase of about 2:1 in endurance for similar change in frequency.

FATIGUE RESULTS FROM BATCH 'E' SPECIMENS

The specimens from batch E are all waisted through the thickness.

CFRP is brittle and unwanted bending of a specimen can produce high local stresses which cannot be relieved. A specimen waisted in the thickness is less susceptible to out of plane misalignment in test machine wedge grips than one waisted in the width.

The profile seems to have performed well for fatigue testing.

AVERAGE UTS: 622,1 MPa

TABLE 15.0

	% UTS	Frequency	No of Cycles	Log n
E2	27.19	15 Hz	1 858 900	6.26
E4	27.19	15 Hz	2 110 200	6.32
E6	29.1	15 Hz	7 118 200	6.85
E8	34.9	15 Hz	0	0
E9	34.9	15 Hz	2 150 000	6.33
E14	34.9	15 Hz	6 100	3.78
E15	34.99	15 Hz	37 000	4.56
E16	36.0	15 Hz	5 500	3.74
E3	36.0	15 Hz	675	2.86
E7	35.2	15 Hz	0	0
E1	35.2	15 Hz	3 475	3.54
E12	37.9	15 Hz	13 300	4.12
E11	37.9	15 Hz	14 200	4.15
E13	36.2	15 Hz	251 600	5.4
E26	36.2	15 Hz	0	0
E19	36.2	15 Hz	6	0.77
E24	36.2	15 Hz	3 300	3.51
E25	32.5	15 Hz	45 300	4.65
E31	32.5	15 Hz	434 600	5.63
E29	32.5	15 Hz	2 450	3.38
E27	29.2	15 Hz	434 252	5.6
E36	29.2	15 Hz	692 000	5.8
E22	29.2	15 Hz	1 252 000	5.09
E34	32.5	15 Hz	74 600	4.87
E32	31.5	15 Hz	497 000	5.6
E33	31.5	15 Hz	78 750	4.8
E21	31.5	15 Hz	106 500	5.02
E28	31.5	15 Hz	117 253	5.06
E39	30.3	15 Hz	156 300	5.19
E40	30.3	15 Hz	260 803	5.41
E42	30.3	15 Hz	788 000	5.89
E46	30.3	15 Hz	309 400	5.4
E43	30.3	15 Hz	819 356	5.91
E45	29.8	15 Hz	659 154	5.81
E49	29.8	15 Hz	1 251 000	6.09
E51	29.8	15 Hz	0	0
E52	29.8	15 Hz	157	2.19
E54	29.8	15 Hz	127 523	5.10

* Specimens missing were destroyed during machining. Specimens here tested until catastrophic failure not until matrix cracking occurred such as it was in the previous case of double notched specimens where a coil was attached.

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Name of thesis Tensile Fatigue Of Notched Carbon/epoxy. 1986

PUBLISHER:

University of the Witwatersrand, Johannesburg

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