FAILURE MECHANISMS

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St. Louis, Missouri

<u>LONGITUDINAL TENSION</u>

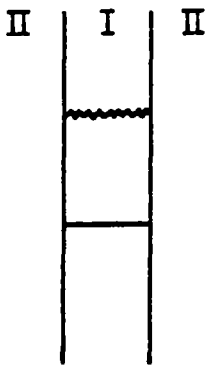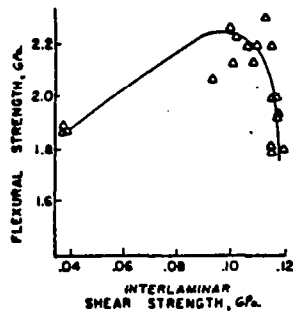• FAILURE MODES

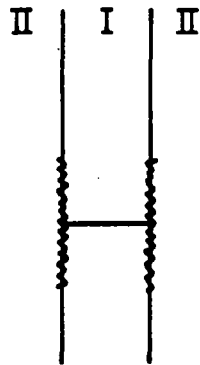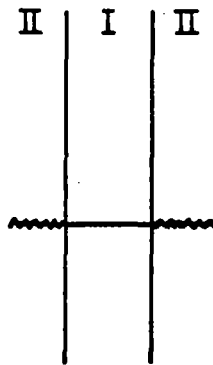WEAK MATRIX   OPTIMUM   STRONG MATRIX

WEAK INTERFACE   STRONG INTERFACE
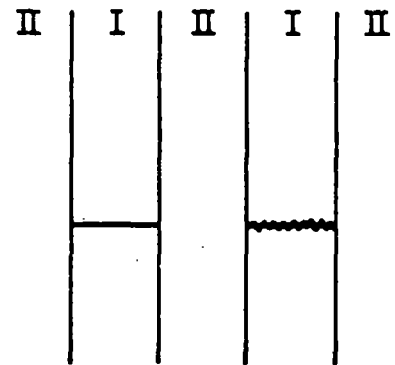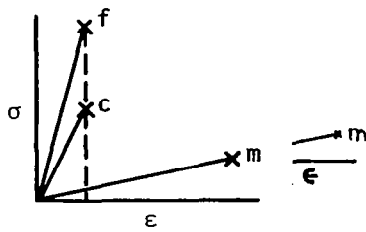
CRACK GROWTH MODES IN UNIDIRECTIONAL COMPOSITES

- PREDICTION OF STRENGTH

  RULE OF MIXTURES

  BRITTLE MATRIX

  $$X_L = (v_f + v_m E_m/E_f)X_f$$

  MINIMUM FIBER VOLUME FRACTION

  $$v_f = \frac{E_f}{E_f - E_m} \left(\frac{X_m}{X_f} - \frac{E_m}{E_f} \right)$$

  DUCTILE MATRIX

  $$X_L = v_f X_f + v_m X_m$$

- BUNDLE STRENGTH

  FIBER STRENGTH DISTRIBUTION

  $$R(X_f) = \exp\left[-L(X_f/X_{fo})^{\alpha}\right]$$

  $$R(Y_f) = \exp\left[-L(Y_f/Y_{fo})^{\alpha}\right]$$

  $$X_{fo} = E_f Y_{fo}$$
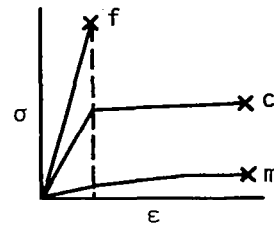
  AVERAGE FIBER STRENGTH

  $$\overline{X}_f = X_{fo}\, L^{-1/\alpha}\, \Gamma(1 + 1/\alpha)$$

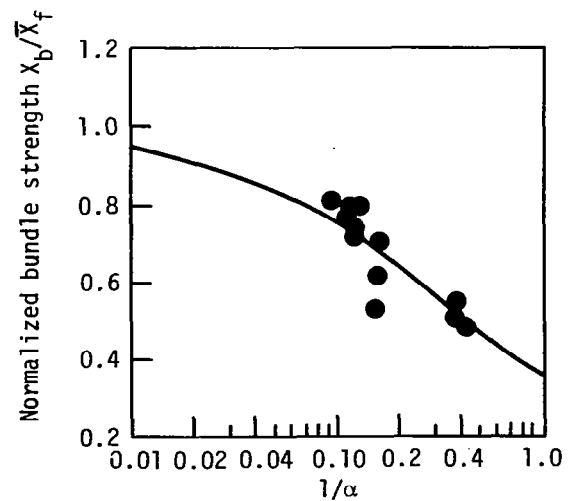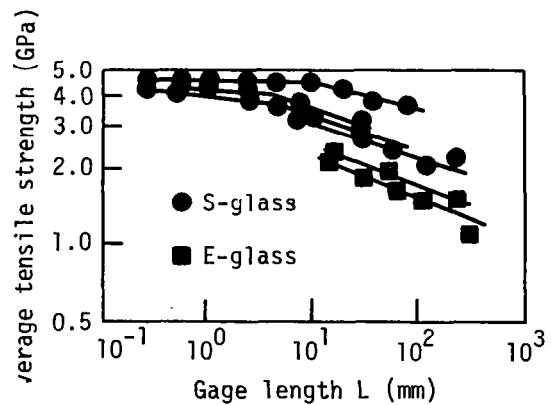 BUNDLE STRENGTH

  $$X_b = X_{fo}\,(L\alpha e)^{-1/\alpha}$$

  BUNDLE-TO-FIBER STRENGTH RATIO

  $$\frac{X_b}{\overline{X}_f} = \frac{1}{(\alpha e)^{1/\alpha}\,\Gamma(1 + 1/\alpha)}$$

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• OPTIMUM STRENGTH

$$X_L = v_f X_b(\delta) + v_m \bar{\sigma}_m^*$$

$$\frac{X_b(\delta)}{\bar{X}_f(L)} = \frac{1}{(\alpha e)^{1/\alpha} \Gamma(1 + 1/\alpha)} \left(\frac{L}{\delta}\right)^{1/\alpha}$$
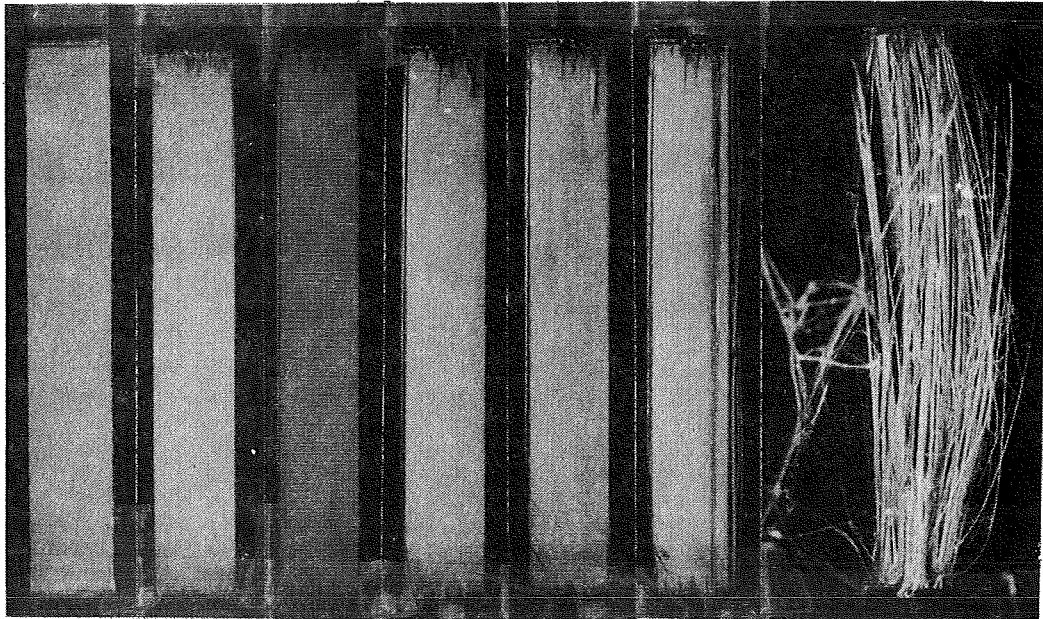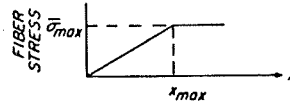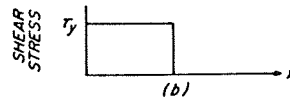
INEFFECTIVE LENGTH OR
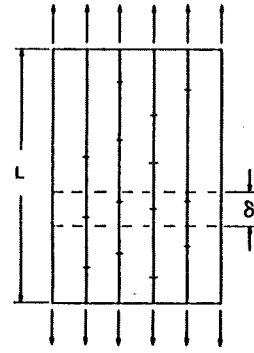LENGTH OF FAILURE INTERACTION ZONE

$$\frac{\delta}{d} = 2 \left(\frac{\bar{X}_f}{4\tau_y}\right)^{\alpha/(\alpha+1)} [(\alpha+1)L/d]^{1/(\alpha+1)}$$

IF $\alpha \gg 1$, RULE OF MIXTURES

$$\frac{\delta}{d} = \frac{\bar{X}_f}{2\tau_y}$$

$$X_L = (v_f + v_m E_m/E_f) \bar{X}_f$$

Stress, %UTS 0   45   72   86   94   99   100

Static failure sequence for Kevlar 49/epoxy

LONGITUDINAL COMPRESSION

- ## MICROBUCKLING OF FIBERS

INITIAL DEFLECTION

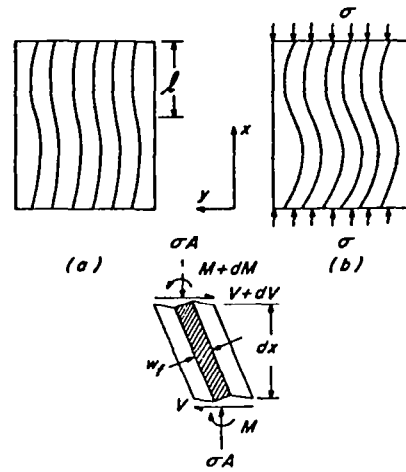$$v_0 = f_0 \sin \frac{\pi X}{\ell}$$

FINAL DEFLECTION

$$v = f \sin \frac{\pi X}{\ell}$$

COMPRESSIVE STRESS

$$\sigma = \left[G_L + \frac{\pi^2}{12} v_f E_f \left(\frac{w_f}{\ell} \right)^2 \right] \left(1 - \frac{f_0}{f} \right)$$

$$\approx G_L \left(1 - \frac{f_0}{f} \right)$$

- COMPRESSIVE STRENGTH

$$X'_L = G_L \left(1 - \frac{f_0}{f_c} \right)$$

LOCAL SHEAR FAILURE

$$f_c = f_0 + \frac{\ell}{\pi} \frac{X_S}{G_L}$$

FLEXURAL FAILURE OF FIBER

$$f_c = f_0 + \frac{2\ell}{w_f} \frac{\ell}{\pi^2} \frac{X_f}{E_f}$$

FINAL STRENGTH

$$X'_L = G_L \frac{1}{1 + (\pi f_0 / \ell)/(X_S / G_L)}$$

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Shear type   Buckling type

Compression failure mode for Gl/Ep

TRANSVERSE TENSION

- ELASTIC PREDICTION

$$(\sigma_m)_{max} = (SCF)\ \bar{\sigma}_2$$

$$X_m = (SCF)\ X_T$$

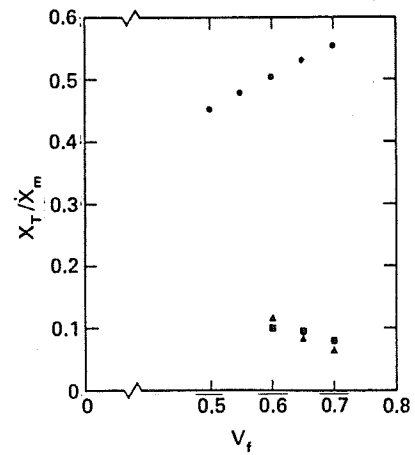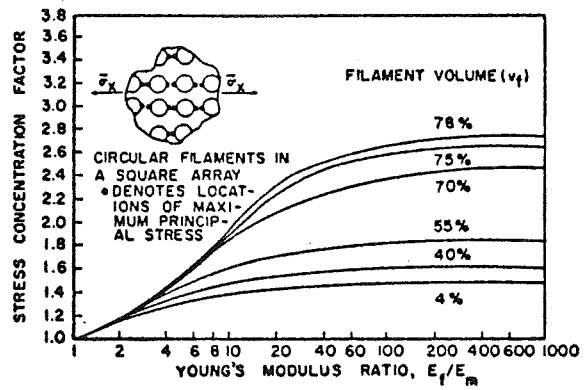$$\frac{X_T}{X_m} = \frac{1}{SCF}$$

$$SCF \uparrow AS\ \frac{E_f}{E_m} \uparrow$$

$$SCF \uparrow AS\ X_m \downarrow$$

$$\frac{X_T}{X_m} \downarrow AS\ X_m \downarrow$$

USE X_{int} IF INTERFACIAL FAILURE

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MATRIX DUCTILITY

$$X_T = v_f \bar{\sigma}_{f2}^* + v_m \bar{\sigma}_{m2}^*$$
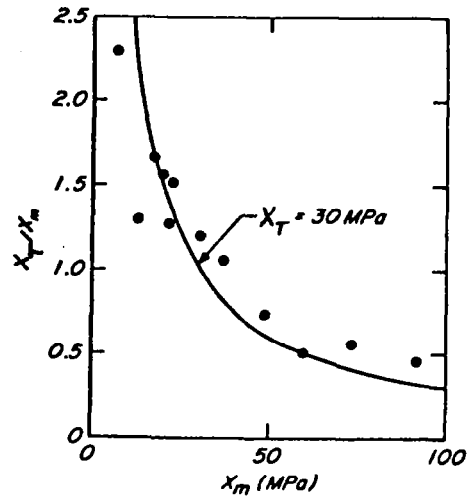
$$= (v_f/\eta_2 + v_m)\, \bar{\sigma}_{m2}^*$$

$$K_{m2} = (\sigma_m)_{max}/\bar{\sigma}_{m2}^*$$

$$\frac{X_T}{X_m} = \frac{1 + v_f\,(1/\eta_2 - 1)}{K_{m2}}$$

$$K_{m2} \uparrow \text{ AS } X_m \uparrow$$

$$\frac{X_T}{X_m} \downarrow \text{ AS } X_m \uparrow$$
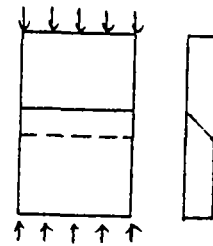

TRANSVERSE COMPRESSION

FAILURE PLANE

~ 45° INCLINED
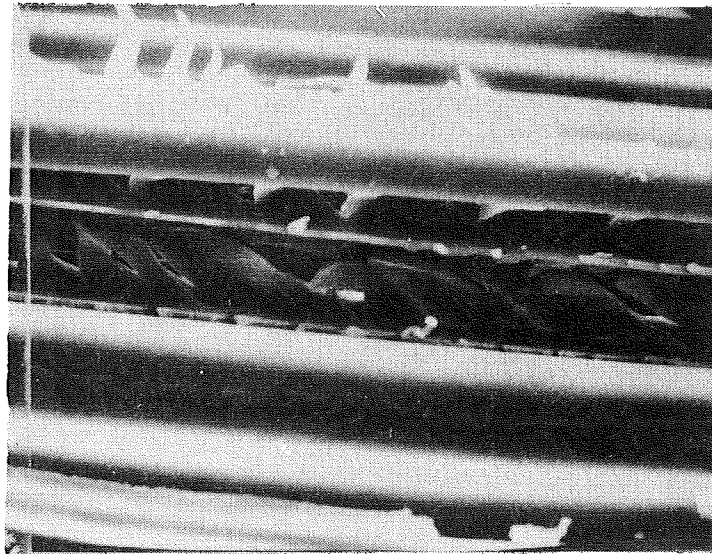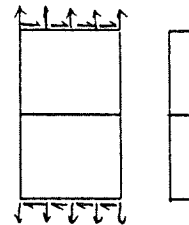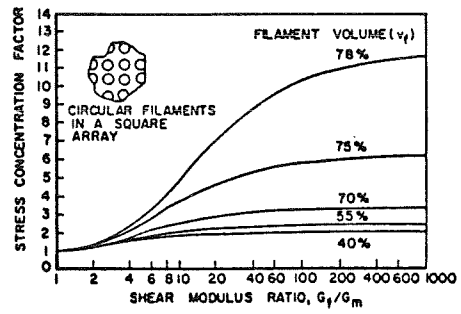
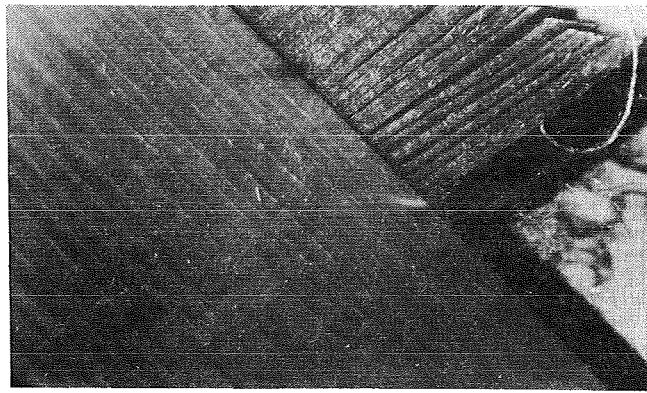$$X'_T/X_T$$

4 ~ 7

~ X'_m

ELASTIC PREDICTION

  SAME AS X_T

  $$\frac{X_S}{S_m} = \frac{1}{SCF}$$

MATRIX DUCTILITY

  $$\frac{X_S}{S_m} = \frac{1 + v_f(1/n_6 - 1)}{K_{m6}}$$

macroscopic

Shear failure for Kevlar 49/Ep

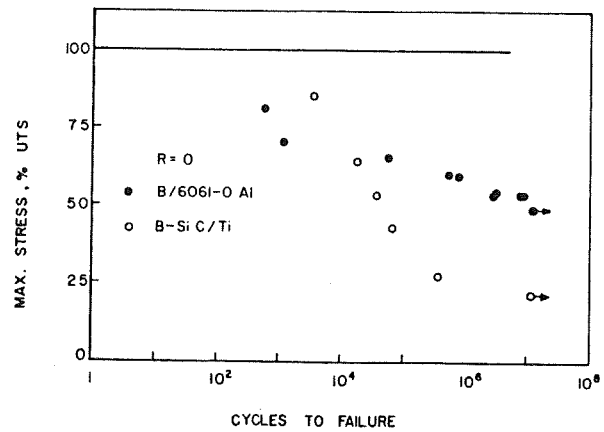## LAMINA FATIGUE

LONGITUDINAL TENSION

MATRIX-CONTROLLED FAILURE LIKELY

FATIGUE LIMIT STRAIN OF MATRIX $\approx$
FATIGUE LIMIT STRAIN OF COMPOSITE

FATIGUE LIMIT STRESS

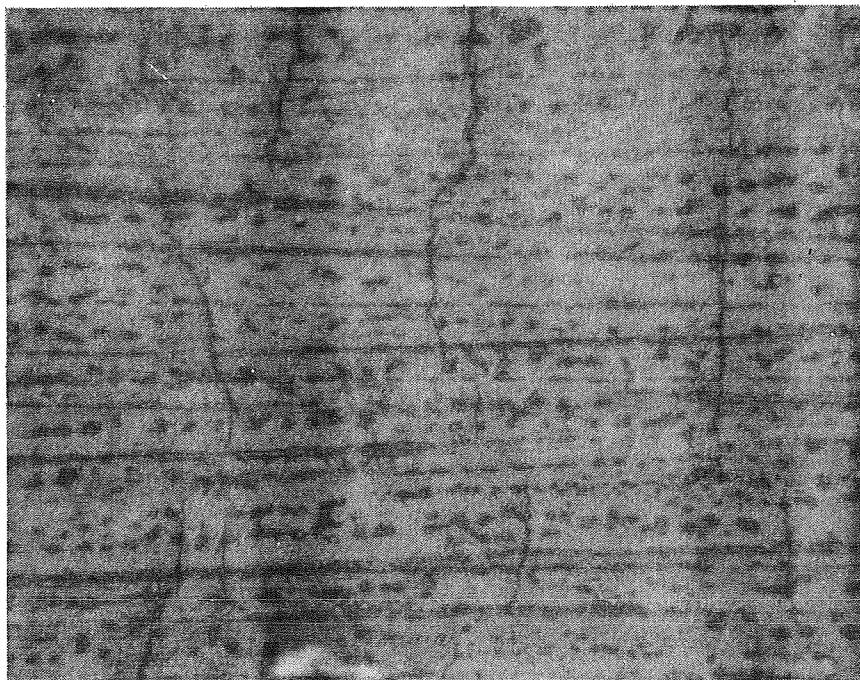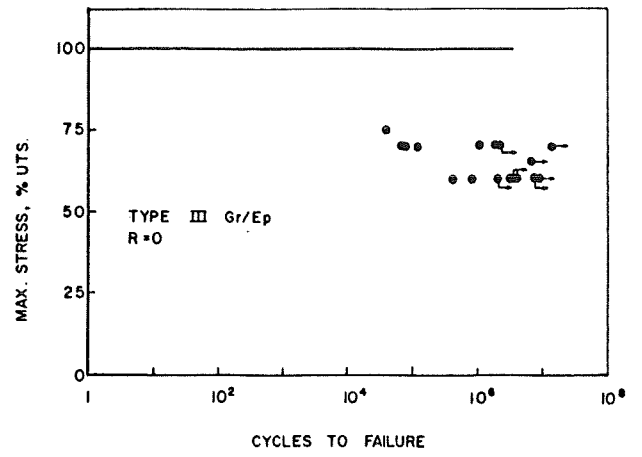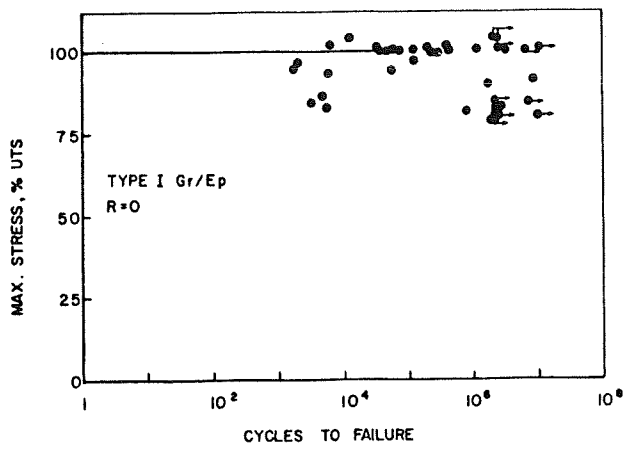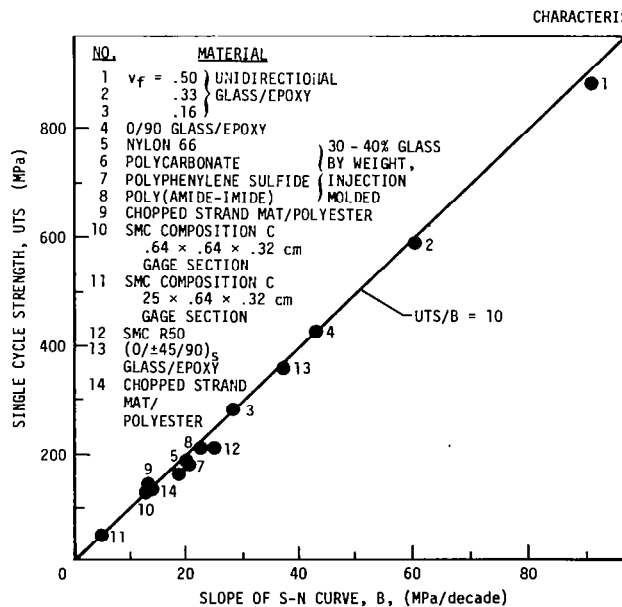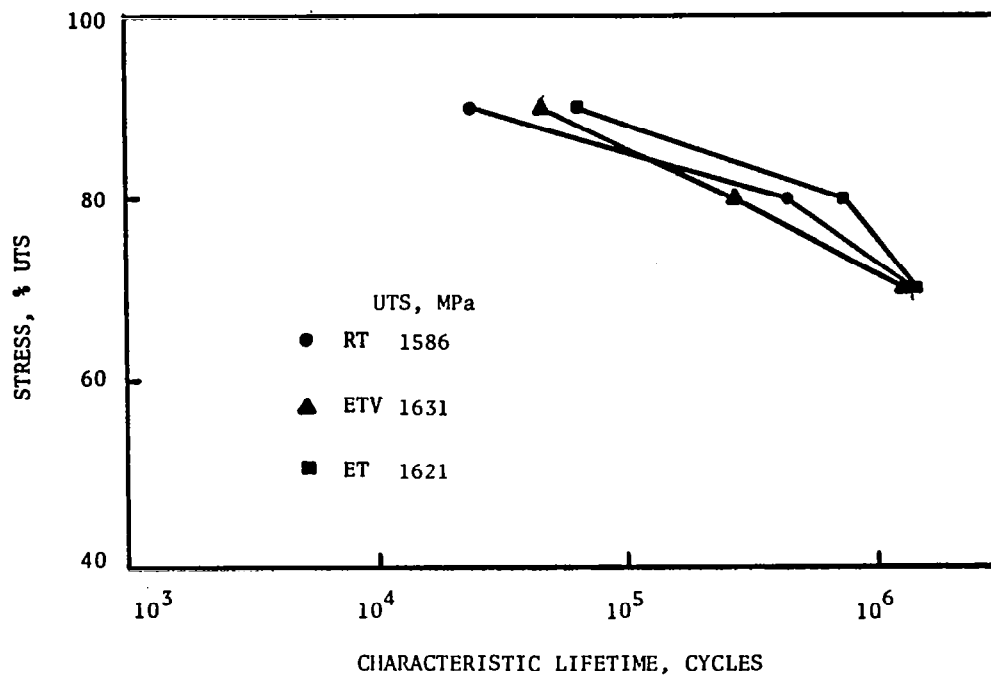$$S_{FL} = S_{mFL} + v_f(E_f/E_m - 1) E_m \varepsilon_{FL}$$

LOW FATIGUE SENSITIVITY IF FATIGUE
LIMIT STRAIN > STATIC FAILURE STRAIN
OF FIBER

Longitudinal S-N data for B/Al and B-SiC/Ti
(Ultimate tensile strength – 1698 MPa for B/Al
and 1296 MPa for B-SiC/Ti)

Figure with two graphs (TYPE I Gr/Ep, R=0 and TYPE III Gr/Ep, R=0) showing MAX. STRESS, % UTS versus CYCLES TO FAILURE, above a micrograph.

Top graph:

STRESS, % UTS (y-axis, 40 to 100)

CHARACTERISTIC LIFETIME, CYCLES (x-axis, 10^3 to 10^6)

UTS, MPa
● RT 1586
▲ ETV 1631
■ ET 1621

Bottom left graph:

SINGLE CYCLE STRENGTH, UTS (MPa) (y-axis)

SLOPE OF S-N CURVE, B, (MPa/decade) (x-axis)

UTS/B = 10

NO.	MATERIAL
1	V_f = .50 } UNIDIRECTIONAL
2	.33 } GLASS/EPOXY
3	.16 }
4	0/90 GLASS/EPOXY
5	NYLON 66 } 30 - 40% GLASS
6	POLYCARBONATE } BY WEIGHT,
7	POLYPHENYLENE SULFIDE { INJECTION
8	POLY(AMIDE-IMIDE) } MOLDED
9	CHOPPED STRAND MAT/POLYESTER
10	SMC COMPOSITION C .64 × .64 × .32 cm GAGE SECTION
11	SMC COMPOSITION C 25 × .64 × .32 cm GAGE SECTION
12	SMC R50
13	$(0/\pm45/90)_S$ GLASS/EPOXY
14	CHOPPED STRAND MAT/ POLYESTER

Bottom right graph:

MAXIMUM CYCLIC STRESS/SINGLE CYCLE STRENGTH (y-axis)

LOG (CYCLES TO FAIL, N) (x-axis)

(a) UNIMPREGNATED STRAND
UTS = 1530 MPa (222 ksi)
$\frac{S}{UTS}$ = 1.00 - .091 log N

(b) POLYESTER IMPREGNATED STRAND
$V_f \approx$ .23
UTS = 455 MPa (66 ksi)
UTS/V_f = 1980 MPa (287 ksi)
$\frac{S}{UTS}$ = 1.00 - .10 log N

(c) EPOXY IMPREGNATED STRAND
V_f = .45
UTS = 971 MPa (141 ksi)
UTS/V_f = 2160 MPa (313 ksi)
$\frac{S}{UTS}$ = 1.00 - .091 log N

(d) RUBBER MODIFIED EPOXY IMPREGNATED STRAND
V_f = .49
UTS = 1102 MPa (160 ksi)
UTS/V_f = 2250 MPa (327 ksi)
$\frac{S}{UTS}$ = 1.00 - .096 log N

Single cycle strength versus slope of S-N curve, nonwoven glass fiber composites, tension-tension fatigue at R = 0 to 0.1
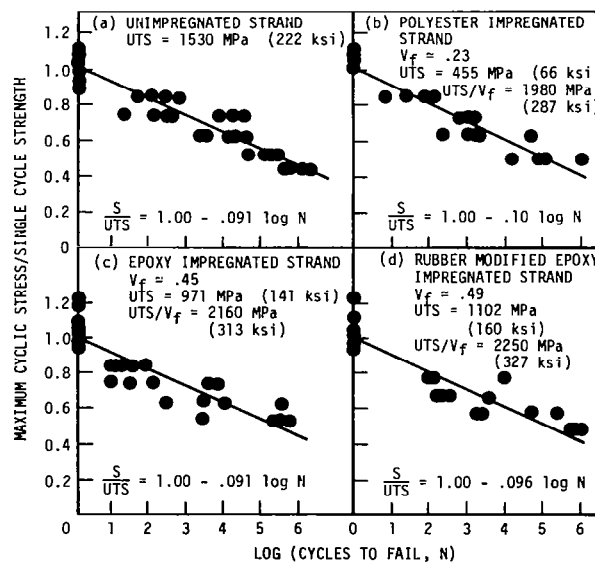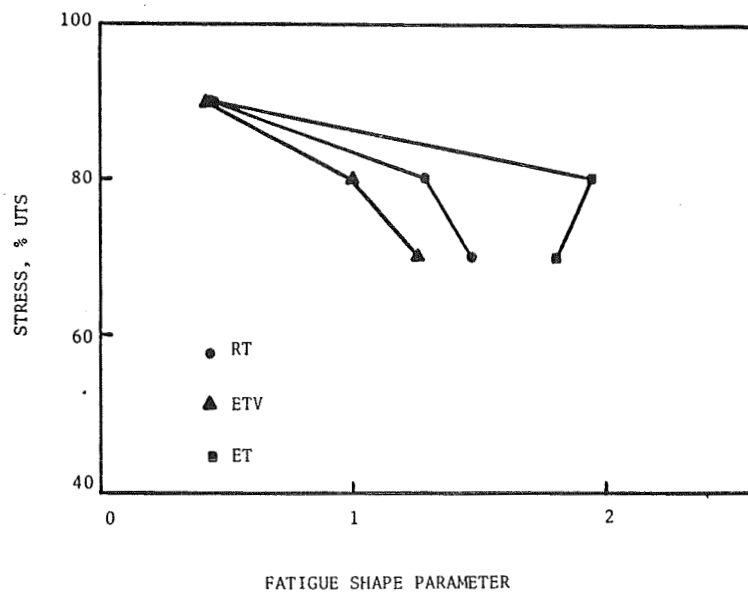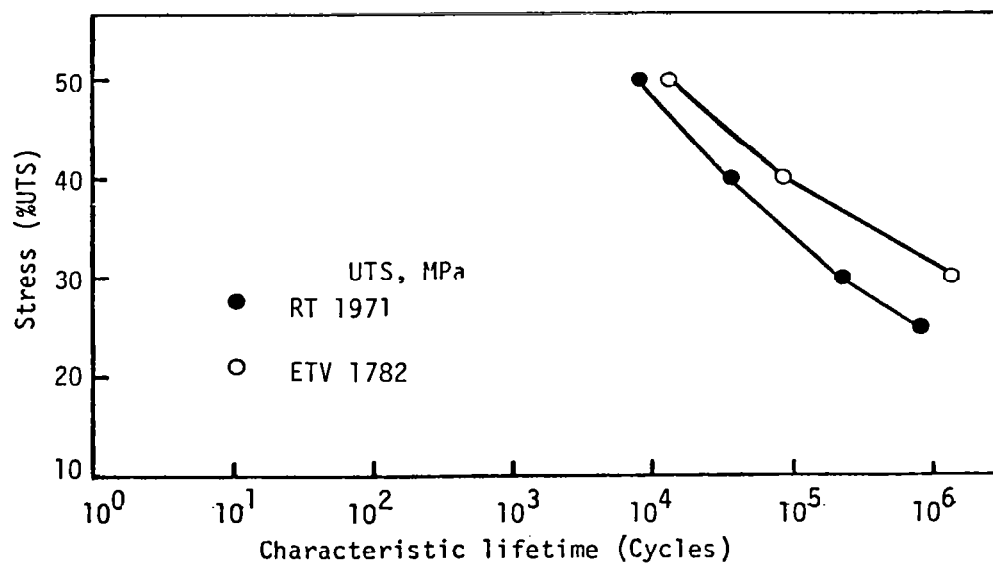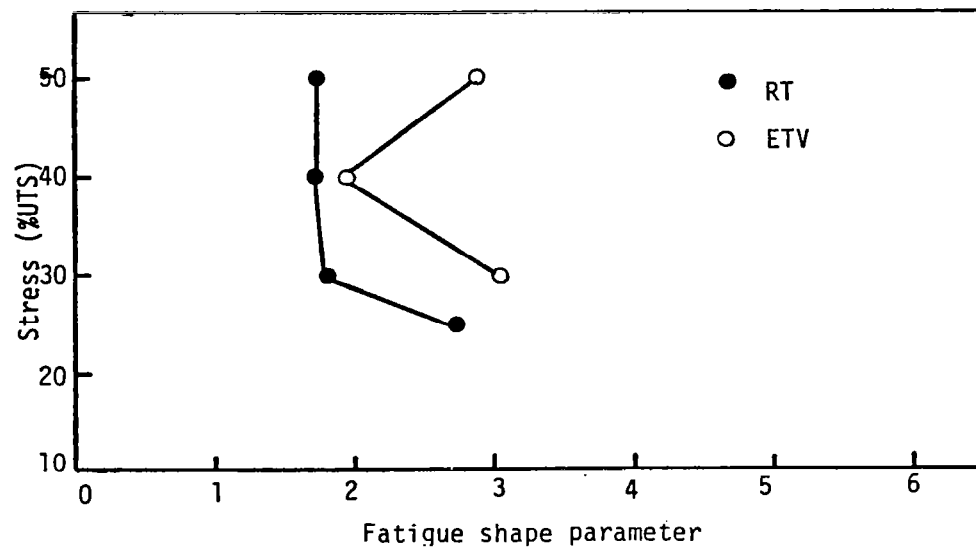
Normalized tensile fatigue life curves for E-glass strand without matrix and with several matrices (5 Hz, R = 0.10).

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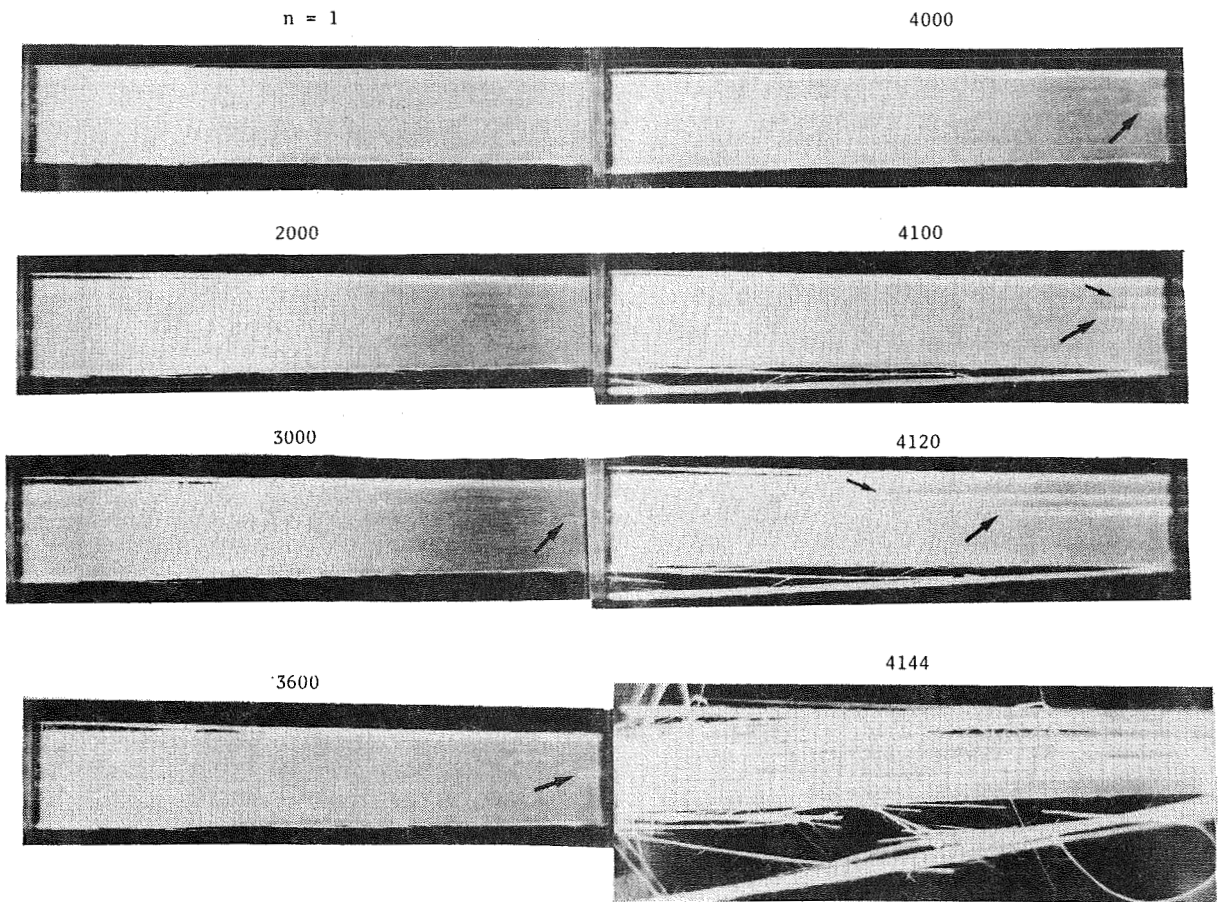
Fatigue failure process at 60 percent UTS, RT, Gl/Ep

FATIGUE SHAPE PARAMETER

Fatigue shape parameters

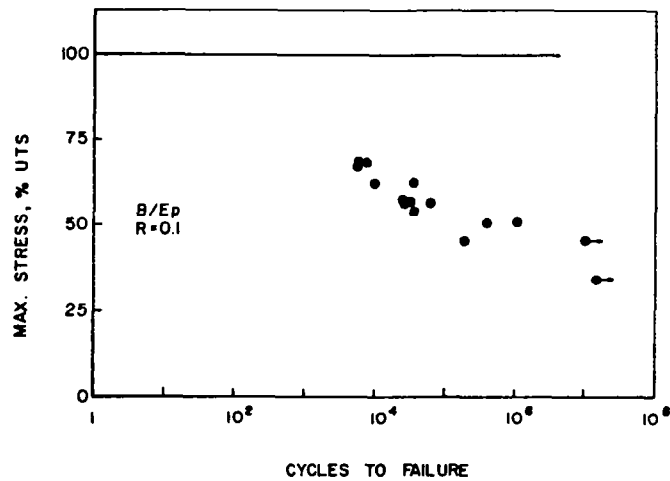Weibull parameters for fatigue life distributions

- TRANSVERSE TENSION AND LONGITUDINAL SHEAR

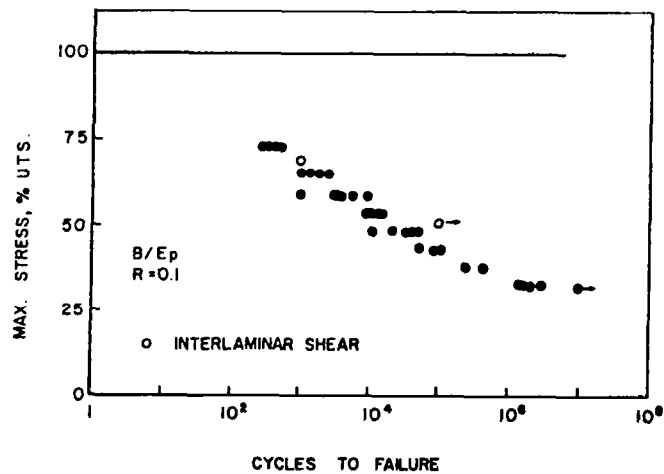 HIGHLY FATIGUE SENSITIVE

  MORE THAN 60% REDUCTION IN STRENGTH
  AT 10^6 CYCLES

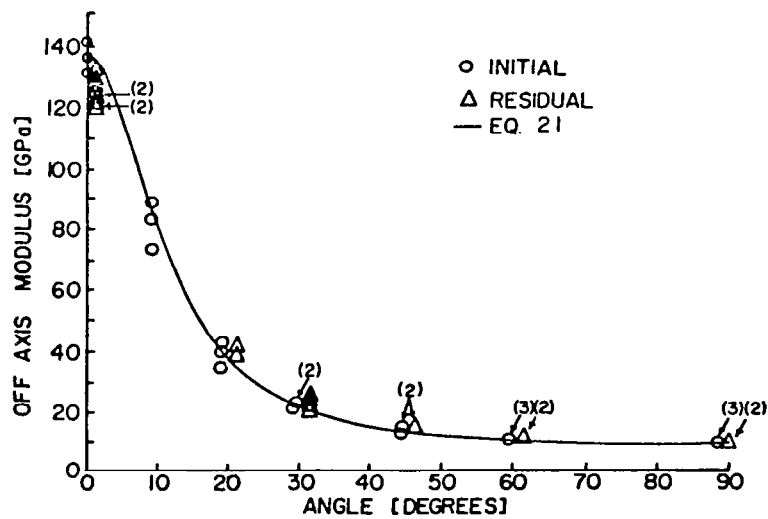 FAILURE RESULTING FROM FAST CRACK
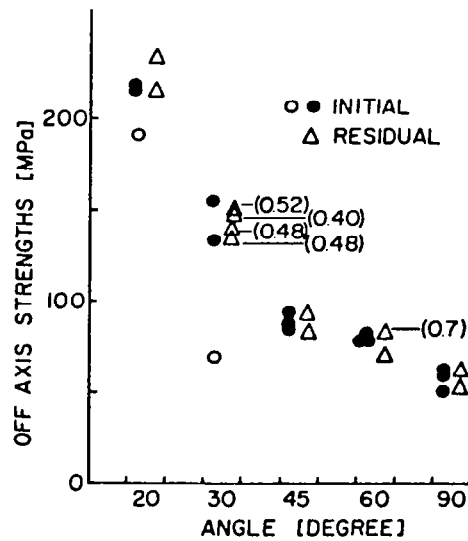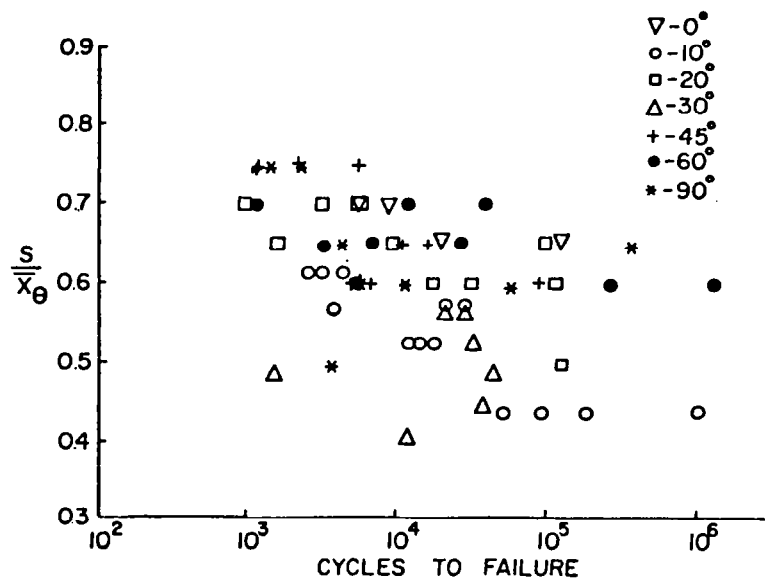 PROPAGATION

  NO INDICATION OF GRADUAL CHANGES IN
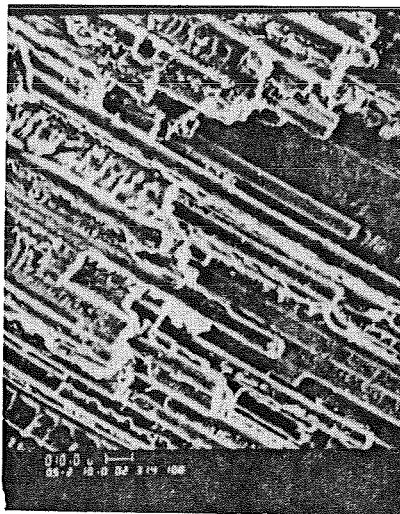 MODULUS AND STRENGTH

Transverse S-N data for B/Ep   (Ultimate tensile
strength = 60.9 MPa)

Shear S-N data for B/Ep.   (Longitudinal shear strength
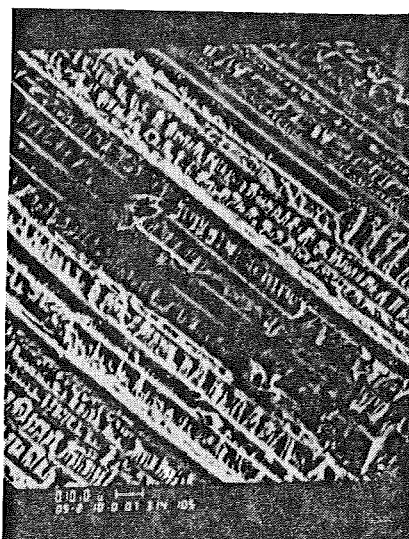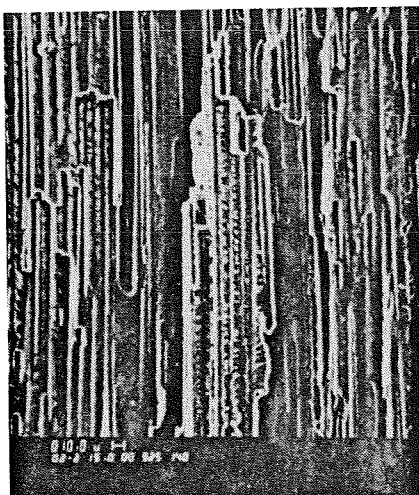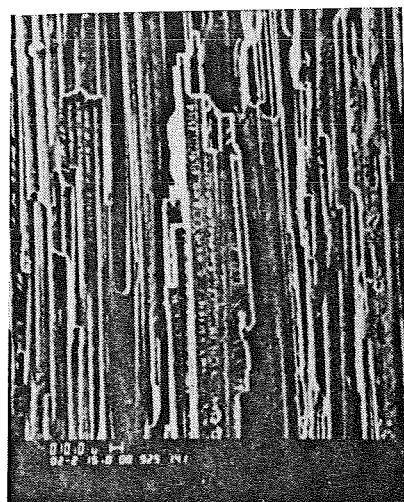= 66.7 MPa, interlaminar shear strength = 81.4 MPa)

Legend (top chart):
∇ – 0°
○ – 10°
□ – 20°
△ – 30°
+ – 45°
● – 60°
* – 90°

$\dfrac{S}{X_\theta}$

CYCLES TO FAILURE

OFF AXIS STRENGTHS [MPa]

○ ● INITIAL
△ RESIDUAL

—(0.52) (0.40)
—(0.48) (0.48)
—(0.7)

ANGLE [DEGREE]

OFF AXIS MODULUS [GPa]

○ INITIAL
△ RESIDUAL
— EQ. 21

(2)
(2)
(2)
(2)
(3X2)
(3X2)

ANGLE [DEGREES]

LEFT

RIGHT

30°

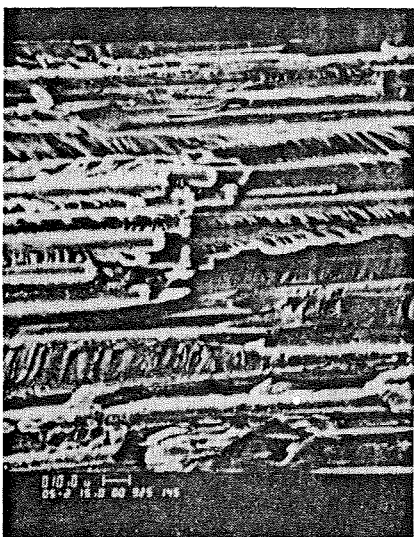LEFT

RIGHT

LEFT

RIGHT

90°

LEFT

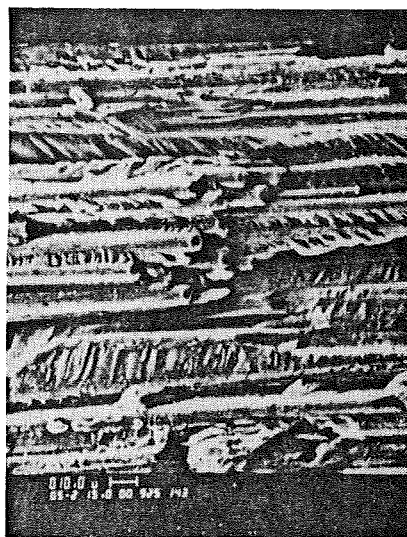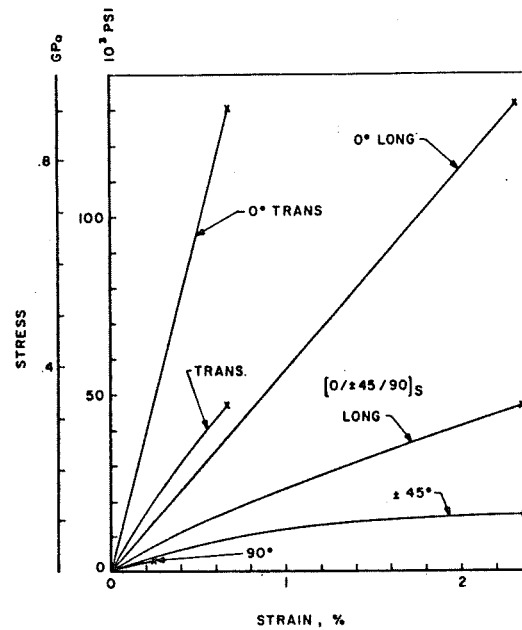**RIGHT**

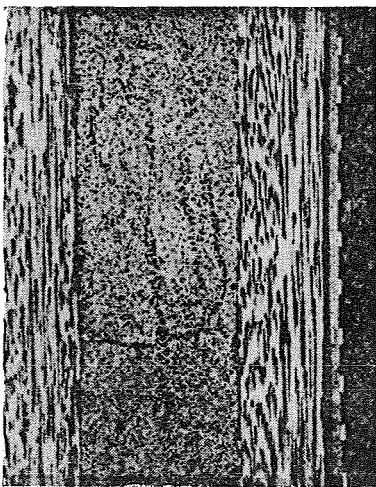# LAMINATE FATIGUE

FAILURE PROCESSES

FIRST PLY-FAILURE
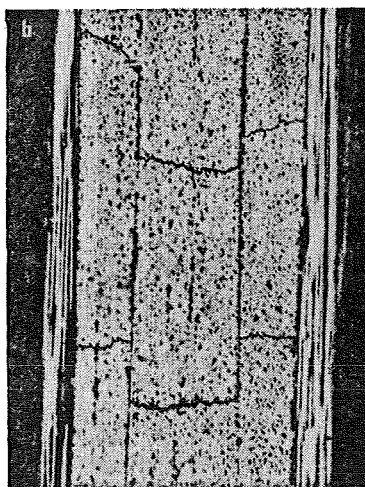ASYMPTOTIC INCREASE IN CRACK DENSITY IN PLIES

DELAMINATION

LAMINATE FRACTURE

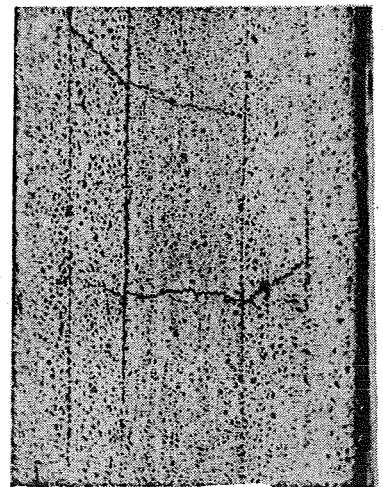Stress-strain relations of $[0/\pm45/90]_S$ Gl/Ep and of constituent plies
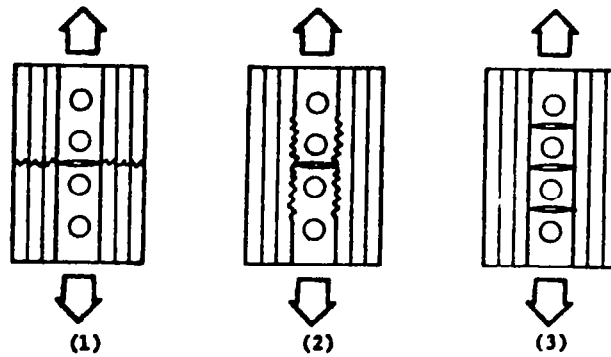

$[0/90]_S$ $[0/\pm45]_S$ $[0/\pm45/90]_S$

Failure modes at free edge

Graphite/Epoxy T300/5208 [0/90/±45]ₛ

Symbol	Maximum Stress ksi	Life N
▣	50	793, 340
☉	50	704, 870
●	60·	37,560
■	60	52, 360
▲	60	23, 090
◆	60	24, 570
✕	40	

(1)   (2)   (3)

Typical failure mechanisms of composite laminates –
Mode (1) is the most catastrophic and mode (3) the
most desirable

Crack Density(No. of cracks/inch)

Fraction of Life(n/N)