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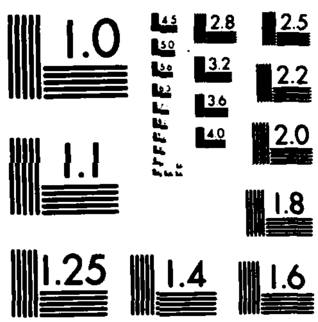

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ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

REPORT 11/83

The Basic Ply Properties of a Kevlar 49/Epoxy Resin Composite System

M L C Jones

Summary

The stress/strain behaviour of a unidirectional Kevlar/epoxy resin composite system under each of five uniaxial stress states has been determined experimentally. The responses of the unreinforced epoxy resin to three uniaxial stress states have also been determined.

The excellent longitudinal tensile properties, combined with the low density of this composite system allow the design of structures which are significantly more weight efficient than similar structures made from an 'E' glass/epoxy system. However, the relatively poor compressive and transverse tensile properties make Kevlar/epoxy composites unsuitable for applications where significant compressive or bending loads are expected.

Approved for issue:

P J Deas
Head of Explosives, Pyrotechnics and Materials Department

CONTENTS

1 INTRODUCTION

A relatively new addition to the family of composite reinforcing materials is the high strength organic aramid fibre currently manufactured by DuPont under the trade name Kevlar. Kevlar 49 is the optimum filament winding grade of this fibre having the highest strength and modulus. Because of its high strength and particularly low density, Kevlar 49 has the highest specific strength of any existing reinforcement. Although Kevlar 49 is expensive in comparison with glass fibre, its use at $50/kg may be justified in applications where weight saving is essential, as in the aerospace and defence fields.

Kevlar fibres are textile in nature, being composed of many fibrils aligned parallel to the fibre axis. Unlike glass, Kevlar fibres are non-brittle and highly anisotropic. A brief review of the properties of Kevlar 49 fibres and Kevlar composites has recently been published (Ref 1). DuPont has prepared a comprehensive data manual for Kevlar 49 which covers most of the mechanical and chemical properties of Kevlar 49 fibres and composites (Ref 2).

The aim of this work was to characterize the properties of a Kevlar 49/epoxy resin system. To complement previous work carried out on glass/epoxy composites, the resin system chosen was the standard filament winding grade epoxy in use at RARDE. The resin response under three uniaxial stress conditions and the mechanical properties of the unidirectional Kevlar composite under the five major uniaxial stress states have been determined. This has enabled a direct comparison to be made between Kevlar 49 and 'E' glass as composite reinforcements. This work has also provided a standard which will form the basis for evaluation of other candidate resin systems and a database for use in existing computer models (Ref 3).

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 Resin

The standard resin system used throughout this work was Ciba-Geigy MY750 epoxy resin with HY917 anhydride hardener and DY063 accelerator in the ratio 100:85:2 parts by weight. The cure schedule was 2 h at 90°C, 1 h at 130°C and 1½ h at 150°C.

2.1.1 Tensile Properties

Heated resin at 50°C was cast between glass plates separated by 2.5mm spacers and sealed with rubber tubing. After cure, standard 'dog-bone' tensile specimens, ASTM D-638 type 1, were cut from the sheet using a 'Tensilcut' routing machine. After measurement and equilibration at 23°C/50% RH the specimens were tested at a strain rate of 0.017 min^{-1}. Strains were monitored using demountable extensometers and foil resistance strain gauges. The specimen geometry is shown in Figure 1.

2.1.2 Compressive Properties

Heated resin was poured into 20mm boiling tubes and cured. On removal from the tubes the samples were cut into 60mm lengths and the ends were squared on a lathe. Two pairs of foil resistance strain gauges were bonded diametrically opposite each other in the centre of the gauge length at 0°-90° to the specimen axis. Compression was carried out between parallel plates at a rate of $0.017 min^{-1}$. The specimen geometry is illustrated in Figure 1.

2.1.3 Shear Properties

Solid 20mm diameter resin blanks were prepared as described in Section 2.1.2. Shear test specimens were machined to the dimensions shown in Figure 1. Brass end collars were fixed to the specimens and a pair of 0°-90° strain gauge rosettes were bonded diametrically opposite each other in the centre of the gauge length at ±45° to the specimen axis. Angular rotation was applied to give a torsional deformation rate of $0.64° min^{-1}$.

2.2 Fibre

The fibre type used throughout this work was DuPont Kevlar 49, type 969 'finish free', 5070 d tex. Unless otherwise stated, the fibres were dried at 105°C for a minimum of 16 h before fabrication of the composite specimens.

2.3 Composite

2.3.1 Longitudinal Tensile Properties

2.3.1.1 Impregnated Strands

One metre lengths of Kevlar roving were manually impregnated with resin and suspended in an oven with 30g weights attached to them to ensure straightness. After cure the strands were cut into 355mm lengths and 50 x 25mm cardboard tabs were glued to the ends as required by ASTM D-2343. Axial strain was applied at a rate of $0.01 min^{-1}$ and was measured using a demountable extensometer. The fibre cross-sectional area and thence the fibre failure stress were calculated from a knowledge of the fibre density and the roving tex.

Tests were carried out on both pre-dried fibres and undried fibres [ie fibres taken directly from the Kevlar creels which had been stored in a normal (uncontrolled) workshop environment].

2.3.1.2 Pultruded Rods

The specimens were prepared by pulling three lengths of uncured resin impregnated Kevlar roving into 1.6mm i.d. PTFE tubing, thereby achieving a known fibre fraction of 52% and a uniform circular cross-section. Specimen preparation, end tabs and testing were as described in Section 2.3.1.1.

2.3.1.3 NOL Rings

NOL rings (Ref 4) of 95mm i.d. were wet wound to a nominal 2.5mm thickness. After curing, removal from the mould and measurement, the split disc gripping technique was used to load the rings to failure in a tensile testing machine at a cross-head speed of 5.0mm min^{-1}. Again, tests were carried out on rings fabricated from both pre-dried and undried fibres.

2.3.1.4 Unidirectional (UD) Coupons

Fibres were wet wound at an angle of 85° around an open rectangular plate mould. After sufficient composite build up had been achieved, the lay-up was partially cured at 90°C. One flat sheet was cut from each side of the formed composite, placed in an open rectangular mould and compressed to the required thickness before completion of the cure cycle. Straight sided specimens, 12mm wide by 250mm long were cut parallel to the fibre direction using a water-cooled diamond cutting wheel. Before testing, aluminium end tabs 12 x 25mm were attached to the specimens. Axial strain was applied to the specimens at a rate of $0.01min^{-1}$ using a tensile testing machine. Strains were monitored by means of a pair of strain gauges at the centre of the gauge length at 0°-90° to the tensile axis.

2.3.2 Longitudinal Compressive Properties

Pultruded rods 10mm in diameter were prepared by pulling 134 strands of resin impregnated Kevlar into a 10mm i.d. PTFE mould. After curing, the rods were cut into 50mm lengths and two 0°-90° strain gauge rosettes were attached diametrically opposite each other in the centre of the gauge length. The rod ends fitted into stainless steel collars (Fig 2) which in turn were fitted into a compression cage attached to an Instron testing machine. The applied compressive strain rate was $0.01min^{-1}$.

2.3.3 Transverse Tensile Properties

2.3.3.1 UD Coupons

UD sheets were wound as described in Section 2.3.1.4. Parallel sided lengths 25mm wide by 200mm long were cut transverse to the fibre direction. Tabs and strain gauges were fixed as before. The applied strain rate was $0.005min^{-1}$.

2.3.3.2 Hoop Wound Tubes

Tubes were wet wound to a nominal 90° angle and 1.5mm wall thickness on 51mm o.d. mandrels. After cure, the uncut tubes had solid aluminium inserts bonded into each end. The ends were reinforced with resin impregnated glass cloth tape, which served to define a 400mm gauge length, as shown in Figure 2. Coupling to the tensile testing machine was via the aluminium inserts. Strain gauges were used to monitor hoop and axial strains. The applied strain rate was $0.0025min^{-1}$.

2.3.4 Transverse Compressive Properties

Hoop wound tubes to a wall thickness of 2.2mm were prepared as in Section 2.3.3.2. Reinforcement was added to the tubes in the regions where the tubes were to be cut to length. Square end cuts were made through the reinforcement and tube wall using a lathe mounted tool. This gave a specimen length of 250mm with a 150mm gauge length (Fig 2). Strains were measured at 0°-90° to the tube axis using foil strain gauges. The applied strain rate was $0.017 min^{-1}$.

2.3.5 In-Plane Shear Properties

Hoop wound tubes of 1.2mm wall thickness were cut into 250mm lengths after having been reinforced around the region of the cuts as in Section 2.3.4. Solid inserts were bonded into the ends to allow coupling to a torsional testing machine. Strains were monitored by means of two 0°-90° strain gauge rosettes fixed at ±45° to the tube axis. The strain rate of approximately $0.025 min^{-1}$ was controlled manually.

2.3.6 Inter-Lamina Shear Properties

Two specimen moulding techniques were used to determine the inter-lamina shear strength (ILSS), a single cavity 6 x 12 x 200mm leaky mould and a 6 x 6mm square cross section pultrusion mould. Both as-moulded specimen types were cut into lengths of 30mm and tested in three point bend with a span of 9.5mm. The low span/depth ratio was necessary to ensure inter-lamina shear failure. Shear displacement was applied to the specimen through the mid point loading nose at a rate of $1.0 mm\ min^{-1}$. To investigate the effect of absorbed moisture in the fibres on the inter-lamina shear strength, both undried and dried fibres were used in fabrication, and tested immediately and after three days storage at 23°C/50% RH. Dry fibre specimens were also aged at 23°C/50% RH for three and ten weeks before testing.

2.3.7 Volume Fraction Determination

There are several analytical methods available for determining the fibre volume fraction in organic fibre composites. These include:

a. the chemical analysis of Kevlar composites to determine a hydrogen to nitrogen ratio from which the fibre content may be calculated (Ref 5),

b. long term exposure of the composite to temperatures of approximately 400°C to give complete resin degradation but controlled fibre degradation (Ref 6),

and c. nitric acid/hydrogen peroxide resin digestion - a technique developed at the Royal Aircraft Establishment for volume fraction determinations of carbon fibre composites. This method should be suitable for Kevlar composites, although specialist chemistry techniques are required.

The standard burn-off technique for volume fraction determination of glass/epoxy composites (BS2782 Method 107K) is unsuitable for use with Kevlar composites because of fibre decomposition at 400°C. In most cases it was possible to estimate the Kevlar fibre fraction from the weight of the fibre creels before and after fabrication and from the weight of the composite.

3 RESULTS

3.1 Resin Properties

TABLE 1 Resin Tensile Properties (Strains Measured Using Extensometers)

Specimen No	Failure Stress (MPa)	Failure Strain (%)	Young's Modulus (GPa)
1	88.7	6.45	2.99
2	84.3	5.90	3.12
3	85.9	6.20	3.30
4	79.0	5.45	3.05
5	87.1	6.20	2.85
6	88.7	4.65	3.17
Mean	85.6	5.80	3.08
CV%	4	12	5

The stress-strain data are given in Figure 3 together with a calculated polynomial best fit curve.

TABLE 2 Resin Tensile Properties (Strains Measured Using Strain Gauges)

Specimen No	Failure Stress (MPa)	Failure Strain (%)	Young's Modulus (GPa)	Poisson's Ratio
1	61.5	2.20	3.16	0.32
2	80.9	3.60	3.10	0.36
3	88.3	4.20	3.08	0.33
4	69.7	2.45	3.40	0.32
5	38.8	1.20	3.26	0.36
Mean	67.8	2.75	3.20	0.34
CV%	28	45	4	6

TABLE 3 Resin Compressive Properties

Specimen No	Failure Stress (MPa)	Yield Strain (%)	Young's Modulus (GPa)	Poisson's Ratio
1	124.9	4.55	3.90	0.29
2	123.7	3.75	4.20	0.30
3	130.2	4.75	3.89	0.28
4	129.4	4.75	3.90	0.29
5	129.4	4.70	3.94	0.28
6	128.6	4.90	3.20	0.28
Mean	127.7	4.60	3.84	0.29
CV%	2	9	9	2

The stress-strain data are given in Figure 4 together with a calculated polynomial best fit curve. A strain corrected average Instron load-deflection curve has been included to show behaviour after strain gauge failure.

TABLE 4 Resin Shear Properties

Specimen No	Failure Stress (MPa)	Yield Strain* (%)	Shear Modulus (GPa)
1	92.1	3.15	1.76
2	94.1	3.05	1.80
3	93.3	3.55	1.79
4	96.1	3.35	1.74
5	92.1	3.80	1.88
Mean	93.5	3.40	1.79
CV%	2	9	3

* Strain at 0.2% offset from linear portion of curve.

The stress-strain data are given in Figure 5 together with a calculated polynomial best fit curve. A strain corrected Instron load-deflection curve has been included to show the resin shear response beyond the limit of the strain gauges.

3.2 Composite Properties

TABLE 5 Longitudinal Tensile Properties (Impregnated Strands, Pre-Dried and Undried Fibres)

Specimen No	Pre-Dried Fibres Failure Load (kN)	Pre-Dried Fibres Fibre Strength (GPa)	Undried Fibres Failure Load (kN)	Undried Fibres Fibre Strength (GPa)
1	1.06	3.03	1.01	2.88
2	0.98	2.80	1.19	3.40
3	0.94	2.68	1.10	3.14
4	1.16	3.31	0.89	2.54
5	1.24	3.54	0.85	2.43
6	0.92	2.63	0.98	2.80
7	0.86	2.46	1.03	2.94
8	1.04	2.97	0.84	2.40
9	0.82	2.34		
Mean	1.00	2.86	0.99	2.82
CV%	14	14	12	12

The stress-strain data for 10 impregnated strands are given in Figure 6 together with a linear best fit plot. A histogram plot of the overall strand strength distribution from 80 strand tests is given in Figure 7.

TABLE 6 Longitudinal Tensile Properties (Pultruded Rods, $V_F = 0.53$)

Specimen No	Composite Failure Stress (GPa)	Fibre Failure Stress (GPa)	Composite Failure Strain (%)	Composite Young's Modulus (GPa)	Fibre Young's Modulus (GPa)
1	1.88	3.58	2.85	60.5	115.2
2	1.73	3.29	3.10	59.0	112.4
3	1.80	3.43	2.90	63.8	121.5
4	1.72	3.24	2.40	73.4	139.8
5	1.85	3.43	2.85	67.0	127.6
Mean	1.79	3.39	2.80	64.7	123.3
CV%	4	4	9	6	11

The stress-strain data are given in Figure 8 together with a calculated polynomial best fit curve.

TABLE 7 Longitudinal Tensile Properties (NOL Rings, Pre-Dried and Undried Fibres)

Specimen No	Pre-Dried Fibres, $V_F = 0.53$ Composite Failure Stress (GPa)	Fibre Failure Stress (GPa)	Undried Fibres, $V_F = 0.48$ Composite Failure Stress (GPa)	Fibre Failure Stress (GPa)
1	1.22	2.30	1.13	2.35
2	0.73	1.38	1.00	2.08
3	0.91	1.73	1.27	2.64
4	0.81	1.54	1.30	2.71
5	0.88	1.66	1.13	2.35
6	1.29	2.43	1.15	2.40
7	1.31	2.47	1.20	2.50
8	1.16	2.18	1.16	2.42
9	-	-	1.21	2.52
Mean	1.04	1.96	1.17	2.44
CV%	22	22	7	7

TABLE 8 Longitudinal Tensile Properties (UD Coupons, $V_F = 0.46$)

Specimen No	Composite Young's Modulus (GPa)	Fibre Young's Modulus (GPa)	Composite Poisson's Ratio
1	57.8	125.6	0.44
2	58.8	127.8	0.46
3	61.7	134.1	0.44
4	66.8	145.2	0.42
Mean	61.3	133.2	0.44
CV%	6	6	3

Failure stresses are not given for this experiment since failure was by in-plane shear and debonding from the tabs, rather than by fibre fracture.

TABLE 9 Longitudinal Compressive Properties (Pultruded Rods, $V_F = 0.60$)

Specimen No	Composite Yield Stress (MPa)	Composite Young's Modulus (GPa)	Composite Poisson's Ratio
1	234.3	65.0	0.44
2	220.3	69.4	0.49
3	216.2	71.3	0.47
4	239.4	66.4	0.38
5	236.8	73.9	0.54
Mean	229.4	69.2	0.46
CV%	4	5	13

The linear portions of the stress-strain data obtained using strain gauges are given in Figure 9. The curves for two of the specimens, obtained using extensometers and corrected to lie within the strain gauge curves, have also been plotted to show the linear limits of the specimen responses. A polynomial best fit curve has been calculated for the data; it is also shown in Figure 9.

TABLE 10 Transverse Tensile Properties (UD Coupons, $V_F = 0.41$)

Specimen No	Composite Failure Stress (MPa)	Composite Failure Strain (%)	Initial Composite Young's Modulus (GPa)	Composite Poisson's Ratio
1	13.0	0.30	4.30	0.042
2	17.3	0.39	4.49	0.038
3	14.8	0.33	4.47	0.039
4	14.4	0.32	4.51	0.046
5	18.5	0.40	4.56	0.036
6	12.3	0.27	4.59	0.048
Mean	15.1	0.33	4.48	0.042
CV%	16	15	2	11

TABLE 11 Transverse Tensile Properties (Hoop Wound Tubes, $V_F = 0.62$)

Specimen No	Composite Failure Stress (MPa)	Composite Failure Strain (%)	Initial Composite Young's Modulus (GPa)	Composite Poisson's Ratio
1	21.2	0.40	5.35	0.062
2	22.6	0.45	4.98	0.058
3	23.4	0.44	5.69	0.050
4	16.7	0.33	4.78	0.051
Mean	20.9	0.41	5.20	0.055
CV%	14	13	7	10

The stress-strain data are given in Figure 10 together with a calculated linear best fit curve.

TABLE 12 Transverse Compressive Properties (Hoop Wound Tubes, $V_F = 0.48$)

Specimen No	Composite Failure Stress (MPa)	Composite Failure Strain (%)	Initial Composite Young's Modulus (GPa)	Composite Poisson's Ratio
1	136.1	3.70	5.51	0.056
2	132.4	3.75	5.23	0.066
3	133.3	3.60	5.28	0.066
4	136.2	3.65	5.46	0.056
5	144.1	3.50	5.94	0.068
6	141.6	3.70	5.74	-
Mean	137.3	3.65	5.53	0.062
CV%	3	2	5	9

The stress-strain data are given in Figure 11 together with a calculated polynomial best fit curve.

TABLE 13 In-Plane Shear Properties (Hoop Wound Tubes, V_F = 0.48)

Specimen No	Composite Failure Stress (MPa)	Composite Failure Strain (%)	Initial Composite Shear Modulus (GPa)
1	76.7	3.90	2.66
2	69.0	3.30	2.55
3	76.7	3.35	2.84
4	66.5	2.45	2.40
5	76.0	3.90	2.53
6	73.1	3.60	2.43
Mean	73.0	3.43	2.57
CV%	6	16	7

The stress-strain data are given in Figure 12 together with a calculated polynomial best fit curve.

TABLE 14 Inter-Lamina Shear Strength (Pre-Dried and Undried Fibres, Specimens Unaged and Aged 72 h at 23°C/50% RH, Leaky Mould, V_F = 0.45)

	Pre-Dried Fibres	Undried Fibres	
	Unaged ILSS, (MPa)	Unaged ILSS, (MPa)	Aged ILSS, (MPa)
	59.0	54.2	57.7
	55.7	59.8	57.1
	61.6	60.7	55.1
Mean	58.8	58.2	56.7
CV%	5	6	2

TABLE 15 Inter-Lamina Shear Strength (Pre-Dried Fibres, Specimens Unaged and Aged at 23°C/50% RH, Pultruded Bars, $V_F = 0.50$)

	Unaged ILSS (MPa)	3 Weeks Ageing ILSS (MPa)	10 Weeks Ageing ILSS (MPa)
	49.6	43.2	51.6
	47.4	43.5	63.6
	52.8	41.9	55.1
	48.2	46.8	70.7
	49.2	39.7	60.8
Mean	49.4	43.0	60.4
CV%	4	6	12

4 DISCUSSION

4.1 Resin System

It may be seen from Figures 3-5 that the standard epoxy resin system used in this work, when fully cured, may be classed as a non-brittle solid of relatively high initial modulus, but also with an ability to sustain large strains before failure. This was particularly evident both in compression where no catastrophic failure occurred and in shear where the resin showed almost elastomeric-like extension.

Differences between tensile and compressive moduli (Tabs 1,2&3) have been observed previously with epoxy resins (Ref 7) but not with polyester resins (Ref 8). For a homogeneous isotropic material the test mode should not affect the apparent Young's modulus. However, the different specimen geometries and preparation methods could give rise to different internal stress states within the specimens, and this could affect the measured modulus.

By utilising the well known formula relating Young's modulus E, Poisson's ratio ν and shear modulus G:

$$G = E/2(1+\nu) \qquad (1)$$

it is possible to correlate the tensile, compressive and shear properties:

Tensile: $E = 3.20\text{GPa}$ $\nu = 0.34$
gives $G = 1.20\text{GPa}$

Compressive: $E = 3.84\text{GPa}$ $\nu = 0.29$
gives $G = 1.49\text{GPa}$

Shear $G = 1.79GPa$

$\nu = 0.34$ gives $E_{tens} = 4.78GPa$

$\nu = 0.29$ gives $E_{comp} = 4.60GPa$

It may be seen that the compression and the shear tests gave the better moduli correlation with respect to each other. It should be noted that the compression and shear test specimens were both cylindrically cast resin blanks, while the tensile specimens were cut from flat cast plates.

4.2 Composite System

Kevlar fibres are able to retain 3-4% moisture under normal laboratory conditions (Ref 2). As this moisture may combine with anhydride groups found in certain epoxy resin hardeners to give deleterious results, DuPont recommends that the fibres should be dried before composite fabrication, and that less moisture sensitive amine curing agents should be used. The anhydride-hardened MY750/HY917/DY063 system used in this investigation was chosen for consistency with previous work using 'E' glass fibre, and there is no suggestion that it is the optimum system for use with Kevlar fibres. Even so, from Tables 5 and 7, it appears that there was no short term loss of fibre strength, in comparison with the results for predried fibre components, for undried fibres impregnated and cured with this resin.

The NOL rings which were wound using pre-dried fibres were fabricated on mandrels which had been used in an earlier experiment with glass fibres. Rings proved difficult to remove from these moulds and may have been damaged in the process. The rings wound with undried fibres were fabricated on clean mandrels and the cured rings were removed with less difficulty. This could account for the apparent anomaly between the pre-dried and undried fibre strengths, the undried fibre having a higher strength than the predried fibre.

There was no evidence of a decrease in ILSS over a period of 10 weeks at 23°C/50% RH with dried fibres (Tab 15). The apparent increase in ILSS after 10 weeks was probably due to fibre misalignment during fabrication which led to scatter in the results, though any deterioration of bond strength would be evident in such a test. There was no significant difference in ILSS between specimens fabricated from pre-dried and undried fibres (Tabs 14 and 15). This should not be taken as an indication that fibre pre-drying is unnecessary. Recent work has shown that it is impossible to filament wind with this resin and undried fibres.

The fibres used throughout this work had a quoted tensile strength of 3.45GPa and a Young's modulus of 124GPa (Ref 2). This strength was rarely realized in the impregnated strand tests (Tab 5), though the specified values were obtained in the pultruded rod test (Tab 6). This difference may be attributable to the more uniform cross section of the rods and to their lesser susceptibility to damage compared with the thin strands. The fibre strength distribution from over 80 strand tests is given in Figure 7, the average failure strength being 2.96GPa. However, some creels gave consistently higher fibre strengths than others. In all the strand tests the fibre's Young's modulus was found to be greater than that specified, varying between 133 and 140GPa, with an average value of 135GPa (Fig 6). NOL rings rarely achieve full fibre efficiency owing to the uneven stress distribution around the circumference and to bending effects, and this is thought to account for the low fibre strength values measured.

Although they have excellent longitudinal tensile strength, Kevlar composites realize only a fraction of this strength in longitudinal compression (Tab 9). Poor bonding transverse to the chain lengths within the fibres themselves is inherent in very highly orientated polymeric fibres. This poor transverse bonding renders the fibres prone to shear buckling at low stresses, a common mechanism in composite rods. From Table 9 it would appear that the fibres have a lower modulus in compression than in tension. This difference is not as great as that recently reported (Ref 9); it may be a true effect or may be due simply to fibre misalignment which would give rise to a decrease in axial modulus of the composite rods.

As with all unidirectional composites, the properties at 90° to the fibre axis of Kevlar composites were very poor (Tabs 10 and 11); transverse tensile failure occurred at 1% of the composite tensile strength, and the modulus was only slightly greater than that of the unreinforced resin. This transverse modulus is significantly lower than that of a glass fibre composite with the same matrix (17.5GPa - 5 times that of the unreinforced resin). The low Kevlar composite transverse modulus may again be attributed to poor transverse bonding of the fibre polymer chains. Using Puck's empirical formulae (Ref 10) for relating constituent properties to those of the composite, a transverse fibre modulus of 6.6GPa is predicted (Ref 1). The low transverse fibre modulus should serve to reduce the microscopic stress concentration effects found around fibres in composites since it is of approximately the same value as that of the matrix. It is not known whether transverse failure was by a fibre-resin debonding mechanism or by transverse fibre splitting; only the former mechanism would be affected by reduced stress concentrations. Similarly, in transverse compression Kevlar composites show a very low Young's modulus and Poisson's ratio (Tab 12). The overall stress/strain response reflected the resin compressive behaviour.

If the fibres may be thought of as long stiff molecular chains, held together by weak transverse bonds which are themselves poorly bonded to a weak matrix, then it would be expected that Kevlar composites would exhibit poor parallel shear properties. This was indeed so; the in-plane shear modulus was found to be approximately equal to that of the resin, the fibres apparently giving no shear stiffness to the composite structure. The large non-linear strain to failure (Fig 11) reflects the non-linear shear response of the resin (Fig 5) and possibly some intra-fibre shear deformation. It is not known if failure was by cohesive resin fibre failure or by adhesive failure of the interface. Bearing in mind the non-linear nature of Kevlar composites in the 3 point bend test, which is due to compressive buckling of the fibres, it must be considered that the transverse tensile and in-plane shear tests are more likely to show differences in interfacial bonding than the 3 point bend ILSS test.

5 CONCLUDING SUMMARY

The properties of a unidirectional Kevlar/epoxy resin composite system under the five major uniaxial stress states and the response of the epoxy matrix to three uniaxial stress states have been determined experimentally. The matrix type chosen was the standard filament winding grade epoxy resin currently in use at RARDE. Despite its relatively high initial Young's modulus this resin was able to exhibit large scale non-linear deformation in both compression and shear.

Although an anhydride curing agent was used with this resin (which is said to react with absorbed moisture in the fibre), the short term mechanical properties of this fibre-resin system were mostly consistent with published results. An average fibre strength of 2.96GPa and modulus of 135GPa were realized in longitudinal tension. In axial compression and transverse tension the composite strengths were very poor. This may be attributed to poor transverse bonding within the fibres themselves and/or to poor fibre-resin bonding.

The stress-strain responses of the unidirectional Kevlar/epoxy resin composite under the five major uniaxial stress states are presented in Figure 13. A summary of the major mechanical properties together with those of an equivalent 'E' glass/epoxy resin, is given in Table 16 below. The figures in brackets refer to the specimen fibre volume fraction.

TABLE 16 Summary of Kevlar 49 and 'E' Glass/Epoxy Resin Composite Properties

TENSILE PROPERTIES	'E' Glass/ Epoxy Resin	Kevlar 49/ Epoxy Resin	
Longitudinal			
Failure Stress (MPa)	1300(60%)	1800(53%)	
" Strain (%)	3(")	2.8(")	
Young's Modulus (GPa)	46(")	65(")	
NOL Ring Strength (MPa)	1100(70%)	1200(48%)	
Major Poisson's Ratio	0.30(60%)	0.45(46%)	
Transverse			
Failure Stress (MPa)	61(70%)	15(41%)	21(62%)
" Strain (%)	0.3(")	0.3(")	0.4(")
Young's Modulus (GPa)	21(")	4.5(")	5.0(")
Minor Poisson's Ratio	0.1(")	0.05(")	0.05(")
COMPRESSIVE PROPERTIES			
Longitudinal			
Failure Stress (MPa)	520(62%)	230(60%)	
" Strain (%)	-	0.3(")	
Young's Modulus (GPa)	-	69(")	
Transverse			
Failure Stress (MPa)	150(63%)	140(48%)	
" Strain (%)	1(")	3.5(")	
Young's Modulus (GPa)	15(")	5.5(")	
SHEAR PROPERTIES			
In-Plane			
Failure Stress (MPa)	73(60%)	73(48%)	
" Strain (%)	4(")	3.4(")	
Shear Modulus (GPa)	6.9(")	2.6(")	

The above table shows that a unidirectional Kevlar/epoxy resin composite has superior longitudinal tensile mechanical properties to those of an 'E' glass/ epoxy resin composite. When the specific gravities of these composites are considered, typically 1.4 for Kevlar and 2.0 for glass, Kevlar composites offer great weight saving potential. However, the poor compressive strength of Kevlar composites renders them unsuitable for any applications where significant compressive or bending stresses exist. This, together with the high material cost and the need for careful resin selection and fibre treatment, are the main restraints on a more widespread introduction of Kevlar composites.

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Reports quoted are not necessarily available to members of the public or to commercial organisations.

7 NOTATION

Symbols

E	Young's Modulus
G	Shear Modulus
ν	Poisson's Ratio
ILSS	Inter Laminar Shear Strength
V_F	Fibre Volume Fraction
CV	Coefficient of Variation

Subscripts

tens	Tension
comp	Compression

FIG. 1

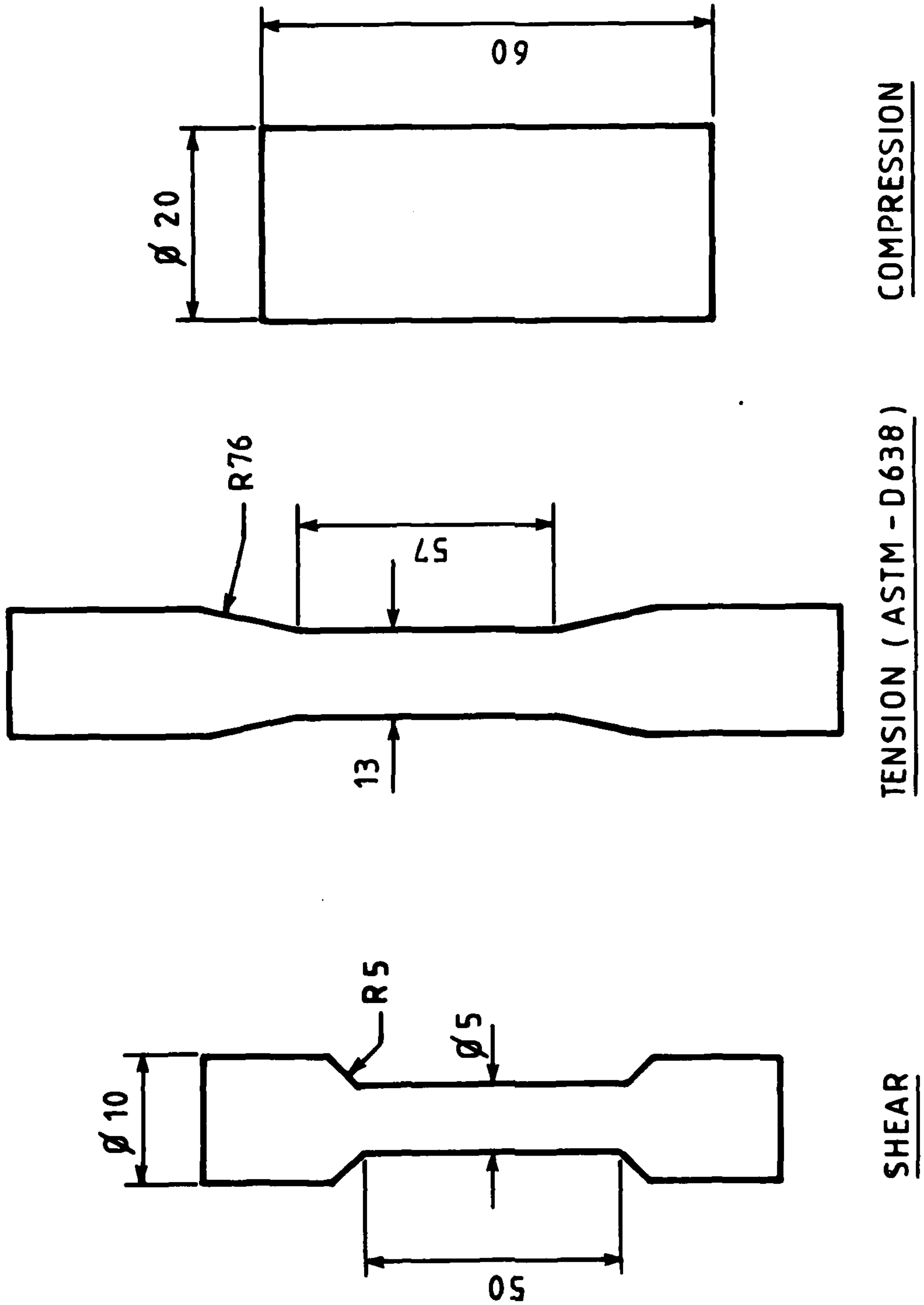

FIG. 1 THE RESIN TEST SPECIMEN GEOMETRIES

ALL DIMS IN mm

FIG. 2

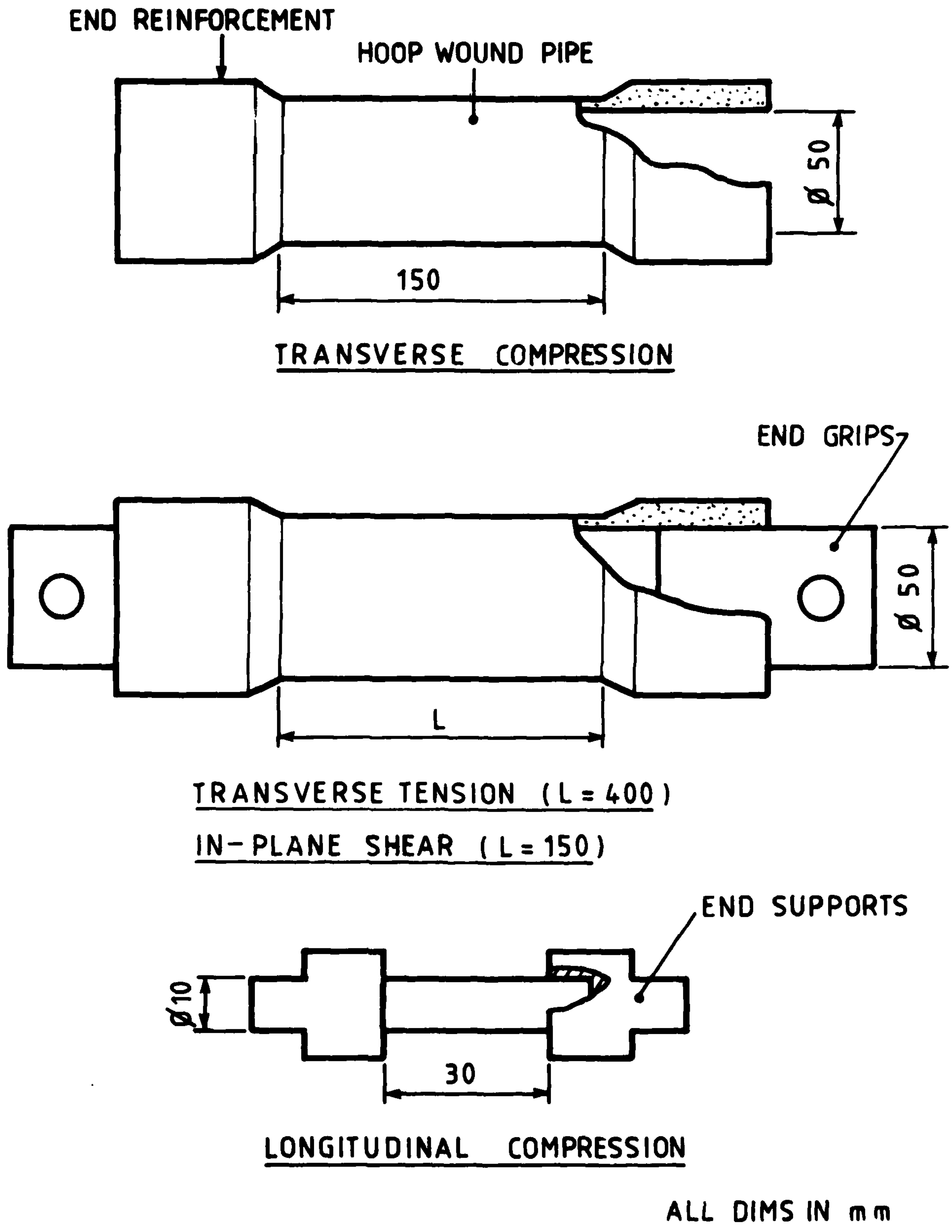

FIG.2 UNIDIRECTIONAL COMPOSITE TEST SPECIMEN GEOMETRIES

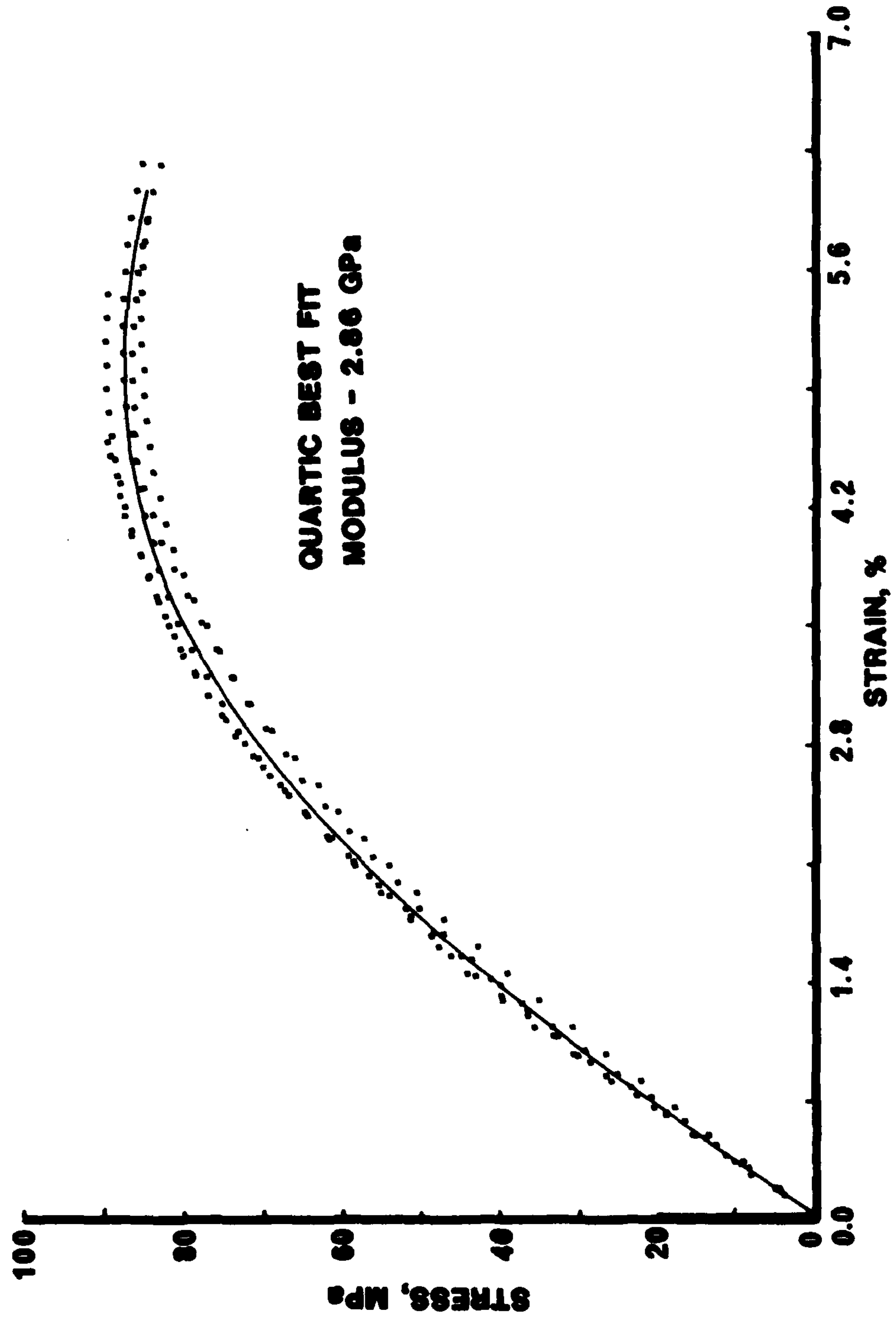

FIG.3 RESIN TENSILE STRESS-STRAIN RESPONSE

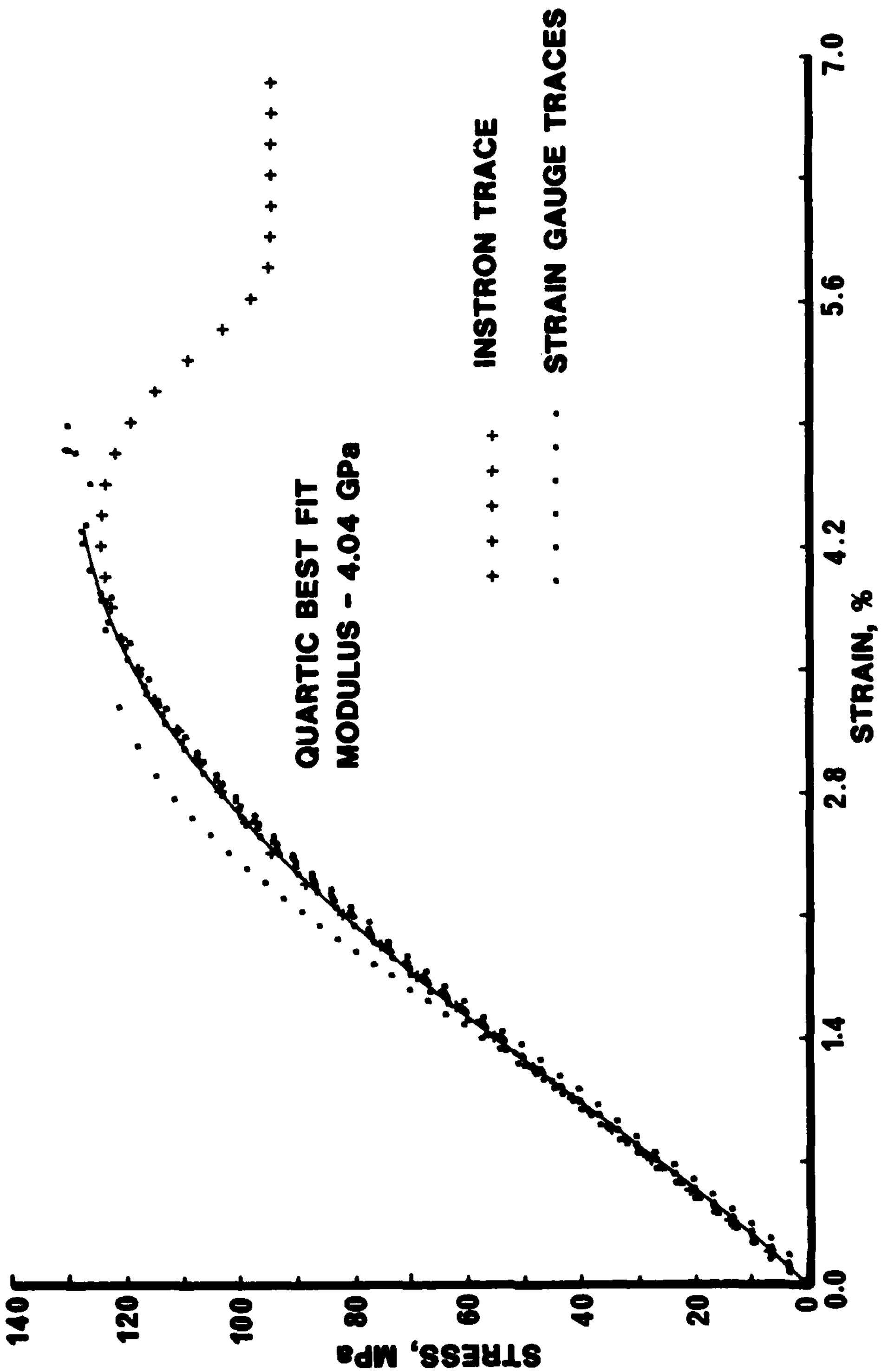

FIG.4 RESIN COMPRESSIVE STRESS-STRAIN RESPONSE

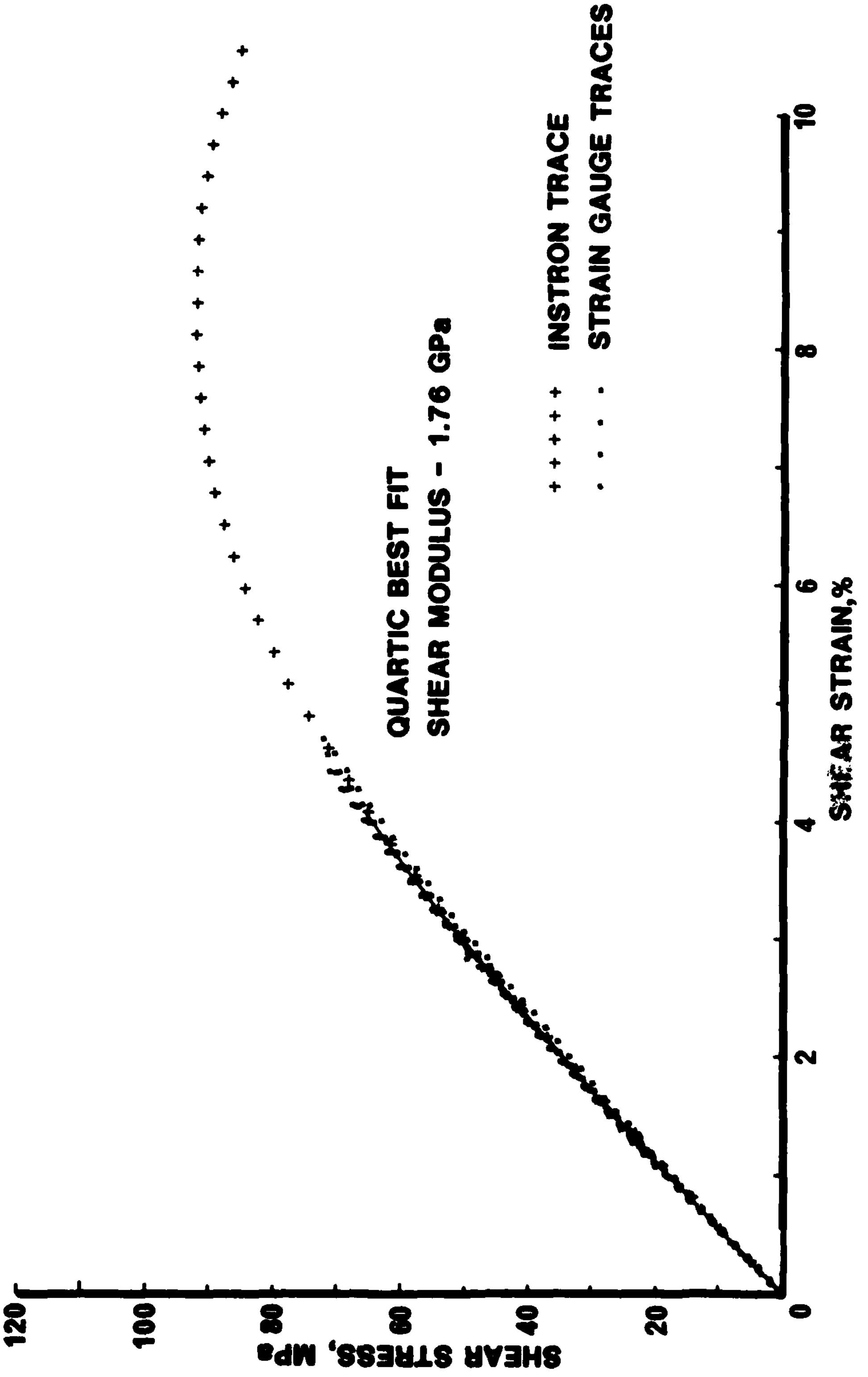

FIG.5 RESIN SHEAR STRESS-STRAIN RESPONSE

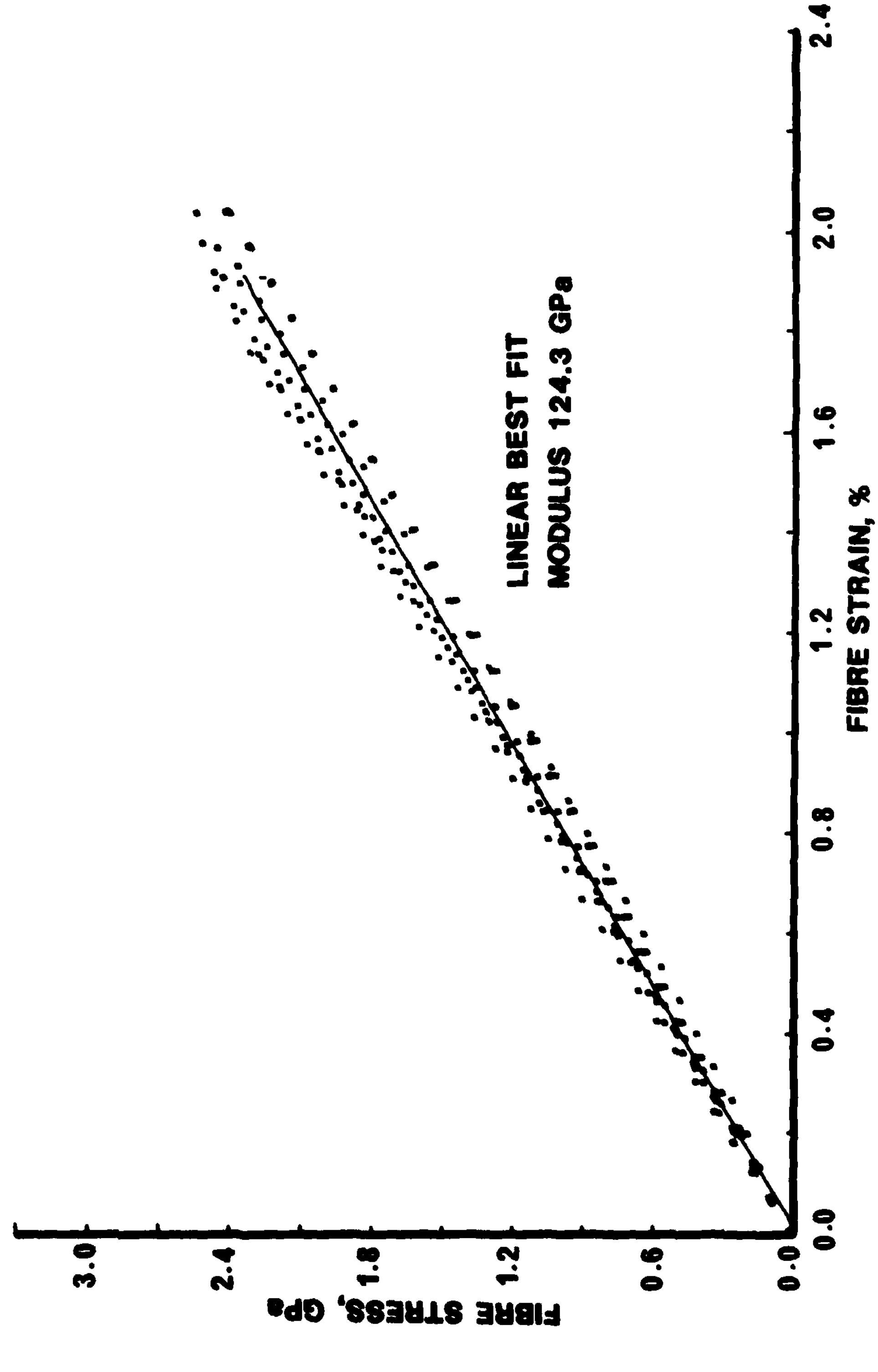

FIG.6 IMPREGNATED FIBRE STRESS-STRAIN RESPONSE

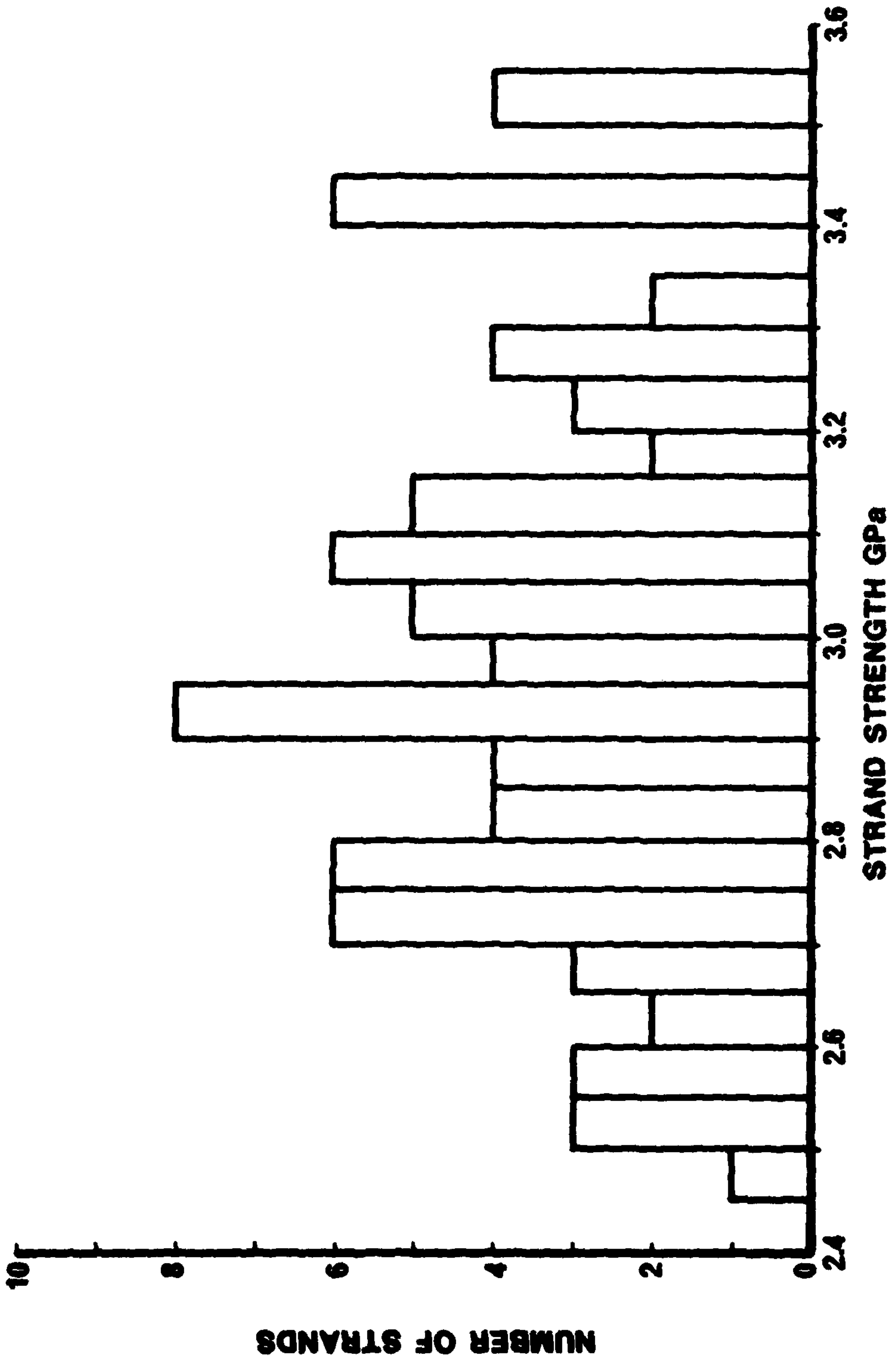

FIG.7 IMPREGNATED FIBRE STRAND STRENGTH DISTRIBUTION

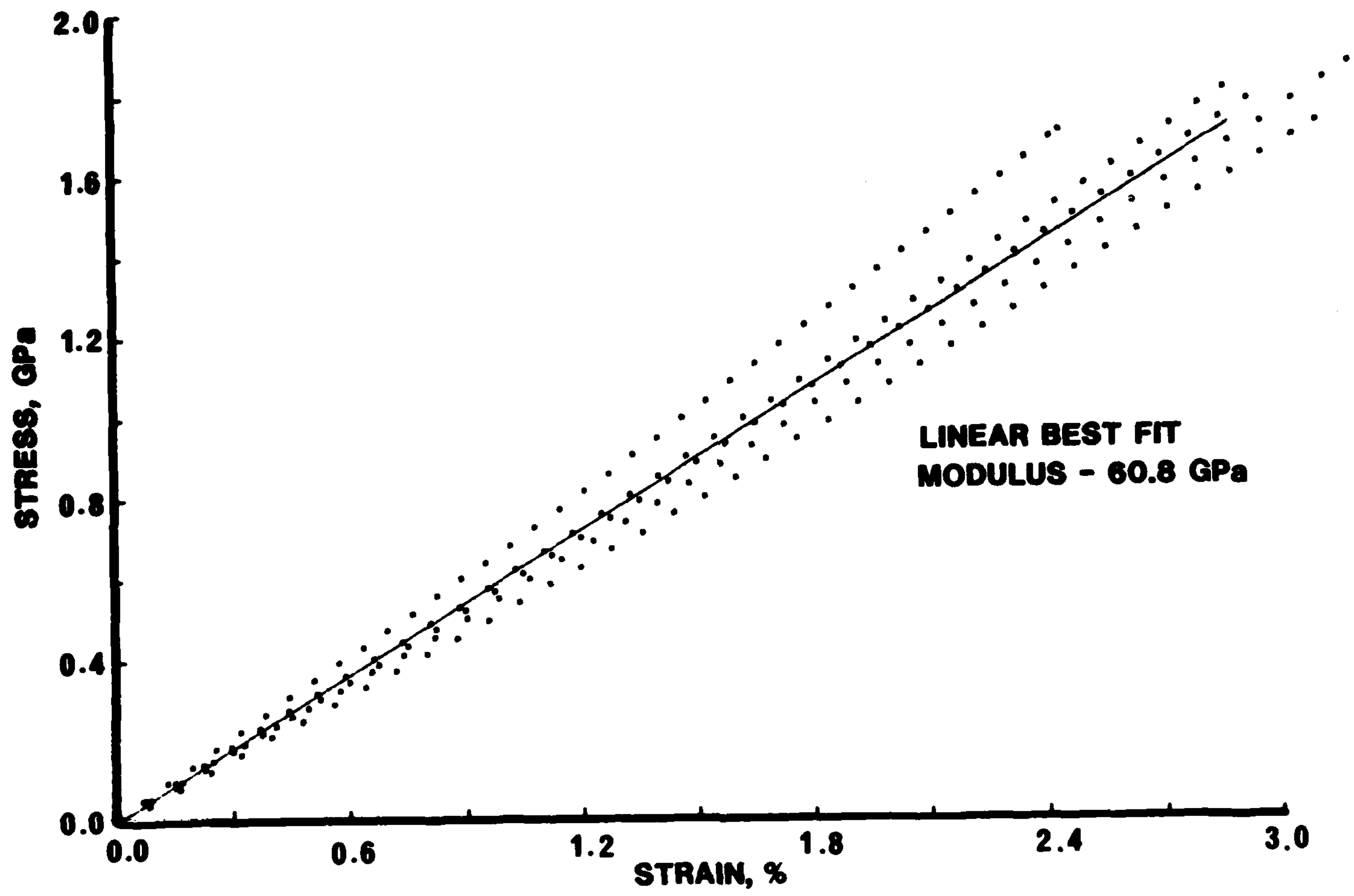

FIG.8 COMPOSITE LONGITUDINAL TENSILE STRESS-STRAIN RESPONSE
(PULTRUDED RODS, Vf 0.53)

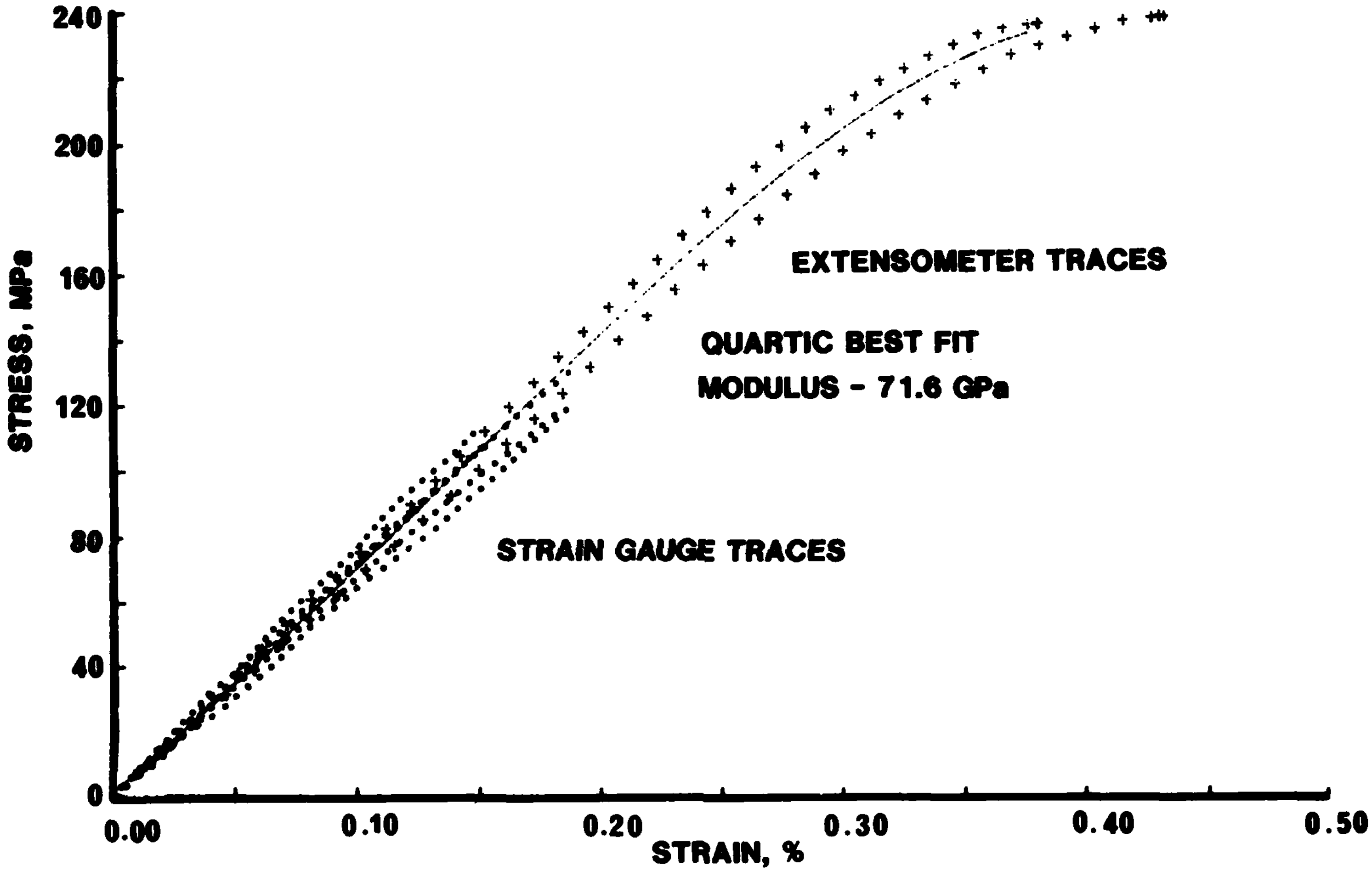

FIG.9 COMPOSITE LONGITUDINAL COMPRESSIVE STRESS-STRAIN RESPONSE
(PULTRUDED RODS, Vf 0.60)

FIG. 10

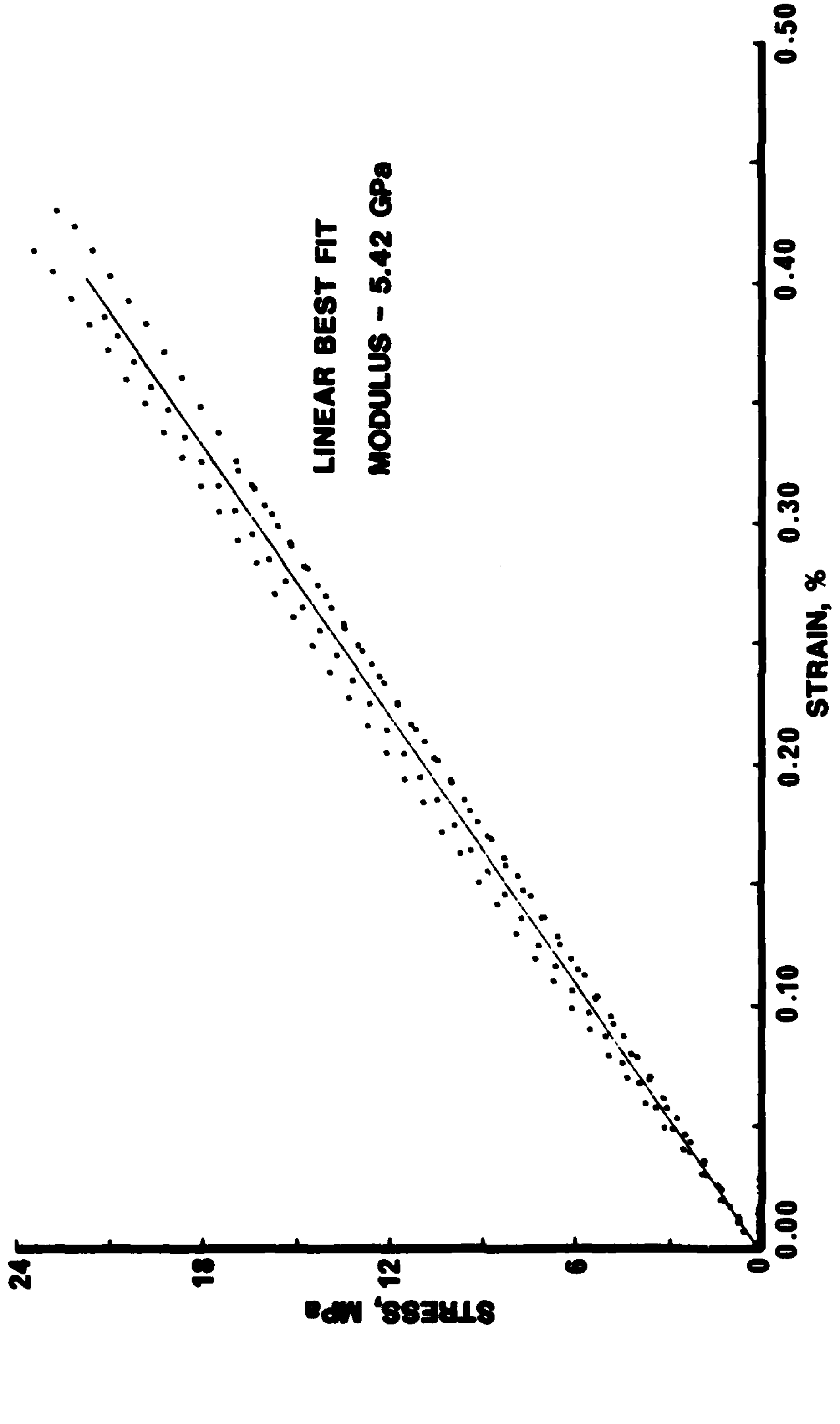

FIG.10 COMPOSITE TRANSVERSE TENSILE STRESS–STRAIN RESPONSE

(HOOP WOUND TUBES, Vf 0.62)

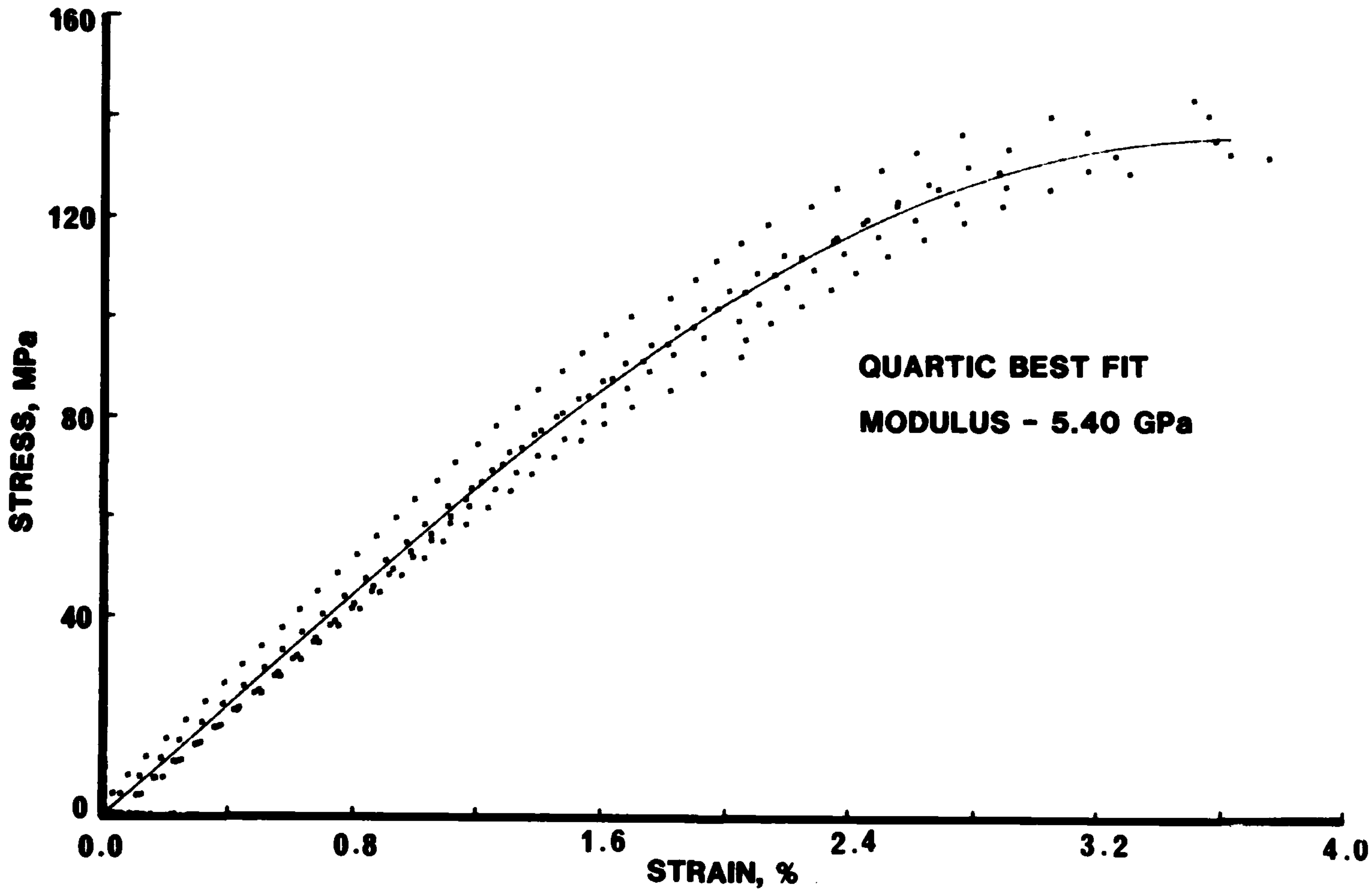

FIG.11 COMPOSITE TRANSVERSE COMPRESSIVE STRESS-STRAIN RESPONSE (HOOP WOUND TUBES, Vf 0.48)

FIG. 12

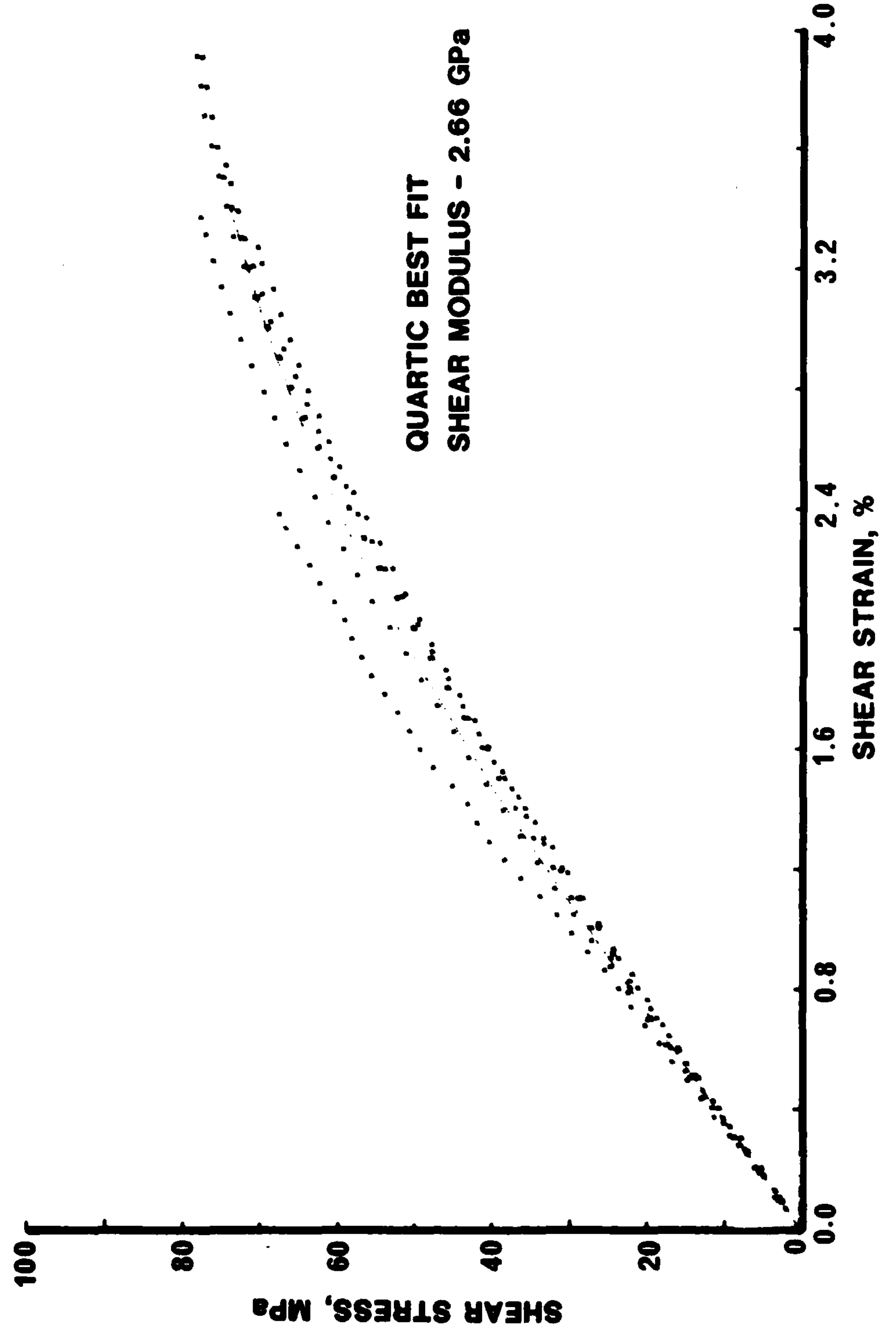

FIG. 12 COMPOSITE IN-PLANE SHEAR STRESS-STRAIN RESPONSE (HOOP WOUND TUBES, Vf 0.48)

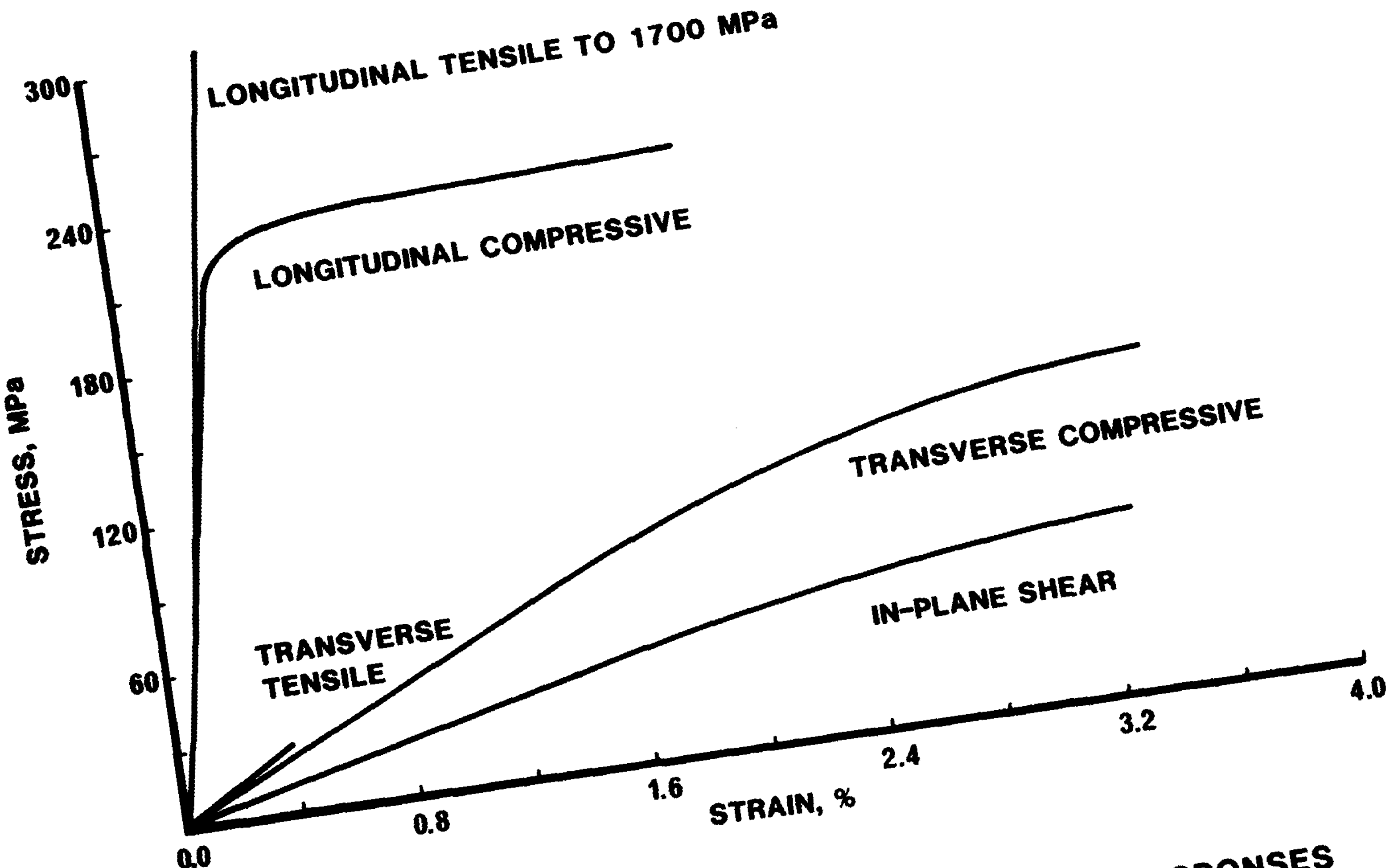

FIG. 13 A COMPARISON OF THE BASIC PLY STRESS-STRAIN RESPONSES

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7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers). Title, place and date of conference

8. Author 1, Surname, initials	9a Author 2	9b Authors 3, 4...	10. Date	pp.	ref
Jones M L C			November '83	33	10

11. Contract Number	12. Period	13. Project	14. Other References

15. Distribution statement

No limitations

Descriptors (or keywords)

Kevlar (fibre)
Epoxy resins
Fibre composites
Strain tests
Tensile stress
Tensile properties

continue on separate piece of paper if necessary

Abstract The stress/strain behaviour of a unidirectional Kevlar/epoxy resin composite system under each of five uniaxial stress states has been determined experimentally. The responses of the unreinforced epoxy resin to three uniaxial stress states have also been determined.

The excellent longitudinal tensile properties, combined with the low density of this composite system allow the design of structures which are significantly more weight efficient than similar structures made from an 'E' glass/epoxy system. However, the relatively poor compressive and transverse tensile properties make Kevlar/epoxy composites unsuitable for applications where significant compressive or bending loads are expected.

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