THE SPRING RESEARCH ASSOCIATION

THE PRODUCTION, PROPERTIES AND POTENTIAL OF FIBRE REINFORCED PLASTICS FOR USE IN THE SPRING INDUSTRY

by

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SUMMARY

The methods of manufacturing glass fibre reinforced plastics (GRP) and carbon fibre reinforced plastics (CFRP) have been briefly described. The static and dynamic properties of GRP and CFRP have been compared to those of hardened and tempered En 45 steel. It has been shown that if the specific stored energy coefficient (SEC) is used as a design criterion for leaf springs, then CFRP and GRP both show an advantage over En 45 steel. CFRP and GRP and hybrids may all be economically viable in some applications. The choice of material for leaf springs depends on both engineering design requirements and the economics of the application.

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1. INTRODUCTION

Of the several types of fibre reinforcements available, which include boron-coated tungsten wire(1), silicon carbide(1) and high strength steel wires(1), the most commonly employed are glass fibres(2) and carbon fibres(3). Glass fibre reinforced plastics (GRP) are more commonplace in structural design than the more expensive carbon fibre reinforced plastics(4) (CFRP). The application of these reinforcements in the spring industry will probably lie in the production of leaf springs rather than helical springs. Stress distribution is more complex in helical springs and may create difficult design problems in view of the highly anisotropic(1) properties of CFRP and GRP.

The attraction of CFRP and GRP lies in their high specific energy(5) storage capability and their low density,(3) compared to steels. These factors may prove CFRP and GRP valuable new materials for use in the spring industry.

2. MANUFACTURE OF FIBRES

2.1 Carbon Fibres

Carbon fibres are produced by the carbonisation and subsequent graphitisation of polyacrylonitrile(5). Carbonisation under tensile loading creates conditions for the production of a non-shrunken, correctly orientated fibre.

The graphitisation treatment produces the carbon fibre. Graphitisation is carried out at different temperatures depending on whether a high strength or a high modulus fibre is required, as shown in Fig. 1. The final structure of the fibre is of a fibrillar nature, i.e. 'string-like' - a remnant of the structure of polyacrylonitrile. A surface treatment of the fibre is sometimes carried out, which is an oxidation heat treatment and is claimed to improve the fibre strength and the bonding between the carbon fibre and the plastic matrix(6).

2.2 Glass Fibres

The engineering glass fibres such as 'E' glass and 'S' glass are produced by drawing solidifying glass through platinum dies and sizing the resulting fibre before coiling it onto a reel(2).

3. MANUFACTURE OF LAYERED COMPOSITES

Layered composites of CFRP and GRP are individually made up by suitably aligning a given volume fraction of carbon or glass fibres into liquid resins and allowing the whole system to cure at a given temperature(3). Fibres are also produced which are pre-impregnated with resin (pre-pregs) and these can also be used in the production of layered strip(3).

Shapes suitable for leaf springs and other simple sections are generally manufactured by pultrusion(3). In this process, the fibre is pulled continuously through resin, or multi-layer pre-preg is used, both being cured by passing them continuously through heated dies. For additional transverse strength, filament winding(3) is employed. Here a continuous resin-coated strand is wound around the article, rather like winding cotton onto a bobbin. Torsion bars have been made by this technique in CFRP, the windings being at ±45° to the longitudinal axis(7, 24).

4. FIBRE STRENGTH AND COMPOSITE STRENGTH

The strength and modulus values of carbon fibres are largely a function of the graphitisation treatment, as Fig. 1 indicates. Typically, the high modulus carbon fibres are designated Type I or HM which may be followed by the suffix '-S' to indicate surface treatment; high strength fibres are designated Type II or HT; and the intermediate ones Types A, III and IV, depending on the particular manufacturer. Typical strengths and moduli for the various carbon fibres, and for 'E' glass are given in Table I.

Resins are generally used for the 'plastic' matrix. Typical resins used are Shell Epikote 828, CIBA MY753 HY956, BP Cellobond A2784 and Union Carbide ER-LA 4617/DDM. The matrix is designed to protect the surface of individual fibres, to separate the individual fibres, to provide a medium by which load is transferred to the fibre and to restrict crack propagation(3).

Some mechanical properties of unidirectional and cross-plied composite systems are given in Table II; for comparison purposes the mechanical properties of hardened and tempered En 45 steel are also included.

Comparison of the data in Tables I and II indicates a marked decrease in strength and moduli once the fibres have been incorporated into a resin matrix. This arises because the slope of the tensile stress-strain curve of the matrix material must be lower than that of the fibre, in order to allow greater displacement of the matrix and permit the fibres to carry the major part of the load. For volume fractions of fibre up to about 65%, the rule of mixtures(1) gives the composite strength:

$$\sigma_c = \sigma_f V_f + \sigma_p (1 - V_f)$$

and $$E_c = E_f V_f + E_p (1 - V_f)$$

where σ_c = composite strength

E_c = composite modulus

σ_f = fibre strength

E_f = fibre modulus

V_f = fibre volume fraction

σ_p = matrix strength at failure strain of composite

E_p = matrix modulus at failure strain of composite

If a comparison is made between the mechanical properties of composites and En 45 steel, there is no obvious advantage in the strength of composites over the strength of En 45 steel. An advantage does become apparent, however, when the respective specific gravities are considered. The S.G. of En 45 is 7.7; that of 'E' glass Scotchply 1002 is 1.8; that of 'S' glass Scotchply is 2.0; and that of CFRP is 1.7(7). Thus, if the specific strength, given by(1) $\frac{\text{Tensile Strength}}{\text{Specific Gravity}}$ or specific modulus, given by(1) $\frac{\text{Modulus}}{\text{Specific Gravity}}$ are considered, then the values for the composites, particularly CFRP, are considerably higher than those for En 45. In other words, great savings in weight can be obtained by the use of composites, particularly CFRP.

5. COMPOSITE FATIGUE BEHAVIOUR

For leaf spring applications, the fatigue behaviour in bending is probably the most important characteristic, although some consideration may be given to the interlaminar shear fatigue behaviour.

For GRP, the data available(8) show a fatigue strength in reversed plane bending of 250 N/mm^2 at 10^7 cycles. These data were obtained for unidirectionally aligned 'E' glass fibres in an epoxy matrix. Fig. 2 shows the S/N curve.

Plane bending fatigue data, having a zero initial stress, are not available for En 45 but values can be estimated by extrapolating the unidirectional data produced by the SRA(21). This technique gives a stress range of 400 N/mm^2 at a life of 10^7 cycles and a stress range of 680 N/mm^2 at a life of 2×10^5 cycles for En 45 black bar in the unpeened condition.

Probably the most comprehensive studies of the fatigue behaviour of CFRP to date have been undertaken by Morris(10), and Owen and Morris(11, 12). The behaviour of unidirectional HM fibre wet lay-ups in axial fatigue was most satisfactory. Plane bending fatigue behaviour one side of zero(22) of unidirectional lay-ups and $0^o - 90^o - 0^o$ cross plies was less satisfactory(10, 11). These fatigue data are shown in Figs. 3 - 5. Discontinued tests (run-outs) are shown as solid circles with arrows attached. In an attempt to define a stress level below which specimens do not fail, a broken line is shown in each S/N curve through the lowest failures. The solid line in each case is the 'best fit' through the results. The vertical line on the left represents the static properties with the customary high scatter(10,11). The bending strength values are low because a failure initiated in the compressive layers of the specimens(22). For comparison purposes, the bending fatigue strength, i.e. stress range, for unidirectionally aligned fibres is taken as 400 N/mm^2 at 10^7 cycles. This stress level approaches $\sim$70% of the static values. A similar trend was observed when these workers and others(13,14) investigated the interlaminar-shear static and fatigue behaviour of CFRP. These results, together with comparative data for GRP, are shown in Fig. 6. In general, both types of reinforcement give poor shear stress values; the whole range being from $\sim$10 N/mm^2 to $\sim$ 70 N/mm^2.

The static and fatigue properties of GRP and CFRP are adversely affected by the presence of water, but the effect is very slight(7,8,11).

No evidence of experimental work on the fatigue behaviour in bending one side of zero of GRP has been found at the time of writing.

6. DISCUSSION

The data given in Tables I and II show that the properties of GRP and particularly CFRP are very attractive compared with those of En 45, when specific strength values are considered. Mass can thus be regarded as the best criterion for comparing the potential of these materials for spring applications. Since the usual basic function of a spring is to store energy, the design criterion therefore becomes the specific stored energy coefficient(5), $\frac{\sigma^2}{E\rho}$, which is a measure of the strain energy/unit weight stored in a beam element of specific gravity, ρ , and tensile modulus, E, when subjected to a bending moment which produces a maximum flexural stress, σ, in the material.

Table III, based on the published fatigue data(8,10,11,21), indicates that the values of the specific stored energy coefficients (SEC) are highest for Scotchply 1002, the values ranging from 1.0 to 2.0. The SEC values for

En 45 steel are between 0.3 and 0.1 and for Type I CFRP(10,11), 0.5. Thus, GRP appears to be the most suitable material from the viewpoint of SEC, in concurrence with the findings of others(4). However, some reservations must be made about the validity of the data used in calculating the SEC for Type I CFRP. These data are from the work carried out by Owen and Morris(11) and Morris(10). The striking feature of the data, presented in Figs. 3 - 5, is that the static bending strength is only half the static tensile strength. Most other data on CFRP systems, such as those shown in Table II, indicate that these two values are approximately equal. Morris, and Owen and Morris(10,11) have shown that the fatigue strength of Type I CFRP approaches 70% of the static tensile strength. Accordingly, using the data given in Table II, the SEC values have been calculated for various CFRP systems, based on the 70% strength and a more conservative 50% strength criterion. These estimated bending fatigue and SEC data are presented in Table IV. The most promising performances are predicted for Type A-S, Type A, Type II and Type II-S CFRP systems. The highest predicted SEC value of 6.2 was for a Type A-S CFRP system. Thus, the data of Table IV generally predict that the most satisfactory performance can be expected from CFRP, rather than GRP.

GRP is, however, seven times cheaper than CFRP(23) and the fatigue strength of GRP must be considered as adequate for some applications; GRP springs are already used, for example, in light aircraft landing gear(5). However, Henney(5) has pointed out that a leaf spring consisting of a layer of CFRP sandwiched by approximately equal thicknesses of GRP has, for the same stiffness, a weight of about 15% less than an identical spring entirely in GRP, which in turn, as already indicated, stands well above the conventional spring material, steel. As illustrated in Fig. 7, this principle can be extended to the use of a compound sandwich or hybrid(5) which exploits the spectrum of strengths and stiffnesses exhibited by different grades of both glass fibre and carbon fibre. The lay-up shown in Fig. 7 gives a weight saving of 20%(3,5) compared to a GRP spring having the same section thickness.

The cost-effectiveness of CFRP and GRP may be considered, initially, for applications in aviation(16). If one begins with an average fare of, say, £10 per hour, per passenger, an annual utilisation of 2,500 hours per aircraft, and a useful service life of ten years, the revenue value of one passenger seat is £250,000. Taking an average weight of 90 kg per passenger with luggage, the revenue value of one kilo saved is £$\frac{250,000}{90}$ or £2,800 in the life of the aircraft. In other forms of transport the value will be less, though still viable, since the life of rolling stock, for example, is much longer than that of an aircraft.

Clearly, the profit margin depends upon the type of spring material used, i.e. whether it is CFRP or GRP. The choice of material also depends upon the design requirements. Presumably in an attempt to achieve the optimum conditions of engineering design and profit, one large manufacturer(15) of carbon fibres is presently working on the use of hybrids for leaf spring applications.

7. CONCLUSIONS

1. Both GRP and CFRP offer large savings in weight over conventional En 45 leaf spring steel if the specific strength and modulus values are compared.

2. If the SEC is employed as the design criterion, some types of CFRP are far superior to GRP which, in turn, is superior to En 45 steel.

3. CFRP, GRP and hybrid composites are economically viable, particularly in aircraft applications.

8. FUTURE WORK

The fatigue in bending one side of zero of CFRP, GRP and hybrids should be further examined and compared with the existing fatigue data.

The technology of fibres appears to have exceeded that of the 'plastic' matrices, and attempts should be made to improve the properties of the matrix and hence those of the composites.

The joining of CFRP and GRP leaf springs to shackles has been considered to a limited extent(3), but further work should be carried out to improve joint design.

9. ACKNOWLEDGEMENTS

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10. REFERENCES

1. KELLY A. "Strong Solids". Oxford, 1966.

2. DE DANI A. "Glass Fibre Reinforced Plastics". Newnes, 1963.

3. LANGLEY M. (Editor). "Carbon Fibres in Engineering". McGraw-Hill, 1973.

4. VINSON J.R. and CHOU T.W. (Editors). "Composite Materials and their Use in Structures". Applied Science Publishers, 1975.

5. HENNEY A.S. "Preliminary Design of Structural Components in Carbon Fibre Reinforced Plastics and Metals". Aircraft Engineering, November 1970, pp. 18-24.

6. WRONSKI A.S. Private Communication. University of Bradford, April 1975.

7. ANON. "Designing with Carboform Carbon Fibre Reinforced Plastics". Fothergill and Harvey Ltd., 1971.

8. 3M Company Data Sheet, Type 1002, 1st May 1969.

9. WOOLMAN J. and MOTTRAM R.A. "The Mechanical and Physical Properties of the British Standard En Steels". 3, Pergamon Press, 1966.

10. MORRIS S. Ph.D. Thesis, University of Nottingham, 1970.

11. OWEN M.J. and MORRIS S. International Conference on Carbon Fibres. The Plastics Institute, London, 1971, Paper 51.

12. OWEN M.J. and MORRIS S. "Some Interlaminar-Shear Fatigue Properties of Carbon Fibre Reinforced Plastics". Plastics and Polymers, August 1972, pp. 209-216.

13. BEAUMONT P.W.R. and HARRIS S. International Conference on Carbon Fibres. The Plastics Institute, London, 1971, Paper 49.

14. SIMON R.A. and BARNET F.R. ibid., Paper 26.

15. LOVELL D.R. Private Communication. Morganite Modmor Limited, April 1975.

16. SMITH E.A. (Editor). "Carbon Fibres". Design Engineering Series. Morgan-Grampian (Publishers) Ltd., Books Division, 1970.

17. Courtaulds Carbon Fibres Unit Data Sheets G 15 and FC 10. April 1975.

18. Morganite Modmor Data Sheet P101, April 1973.

19. HAYNES R. "The Effect of Shot Peening on the Fatigue Behaviour of Silicon-Manganese Spring Steel". SRA Report No. 161, September 1966.

20. REYNOLDS VALERIE R. and TIMMINS P.F. "The Influence of Decarburisation Depth on the Fatigue Strength of a Si-Mn Spring Steel - A Laboratory Investigation and Production Recommendations". SRA Report No. 244, May 1975.

21. EDWARDS A.J. "Fatigue Data for Black Bar Leaf Springs". SRA Report No. L1009, June 1972.

22. OWEN M.J. Private Communication. University of Nottingham, June 1975.

23. MORRIS R. Private Communication, 3M Company, June 1975.

24. BRAIDEN P.M. Private Communication, A.E.R.E., Harwell, August 1975.

TABLE I SOME AVAILABLE PROPERTY DATA ON FIBRES

1. Carbon Fibre (18)

Type	I - S	II or II - S	III or III - S
Specific Gravity	1.7	1.7	1.7
Tensile Strength N/mm^2	2,000	2,500	2,400
Tensile Modulus N/mm^2	375,000	245,000	200,000

2. 'E' Glass Fibre(2)

Specific Gravity	2.5
Tensile Strength N/mm^2	3,400
Tensile Modulus N/mm^2	70,000

- No data available on 'S' glass fibres

TABLE II PROPERTIES OF COMPOSITES AND En 45 STEEL

1. Scotchply 1002(8) - Unidirectional 'E' Glass in Epoxy. Vf = 62% Glass

Specific Gravity	1.8
Tensile Strength N/mm^2	1100
Tensile Modulus N/mm^2	35,800
Bending Strength N/mm^2	1140
Bending Modulus N/mm^2	35,200
Interlaminar Shear Strength N/mm^2	30

2. 'S' Glass Scotchply(4) - Unidirectional 'S' glass in Epoxy. Vf = 72% Glass

Specific Gravity	2.0
Tensile Strength N/mm^2	1910
Tensile Modulus N/mm^2	10,100

TABLE II (Cont.)

3. Unidirectionally Aligned Carbon Fibres in Various Matrices

Note: Specific Gravity of all CFRP's given is taken as 1.7(7)

a. Vf = 65% fibres in ERLA 4617 DDM epoxy(7)

Carbon Fibre Type	Type I	Type II
Tensile Strength N/mm2	703	1450
Tensile Modulus N/mm2	206,800	131,000
Bending Strength N/mm2	827	1580
Bending Modulus N/mm2	200,000	124,100
Interlaminar Shear Strength N/mm2	55	10

b. Vf = 60% fibres in Shell Epikote 828 epoxy(18)

Carbon Fibre Type	I - S	III or 'A'
Tensile Strength N/mm2	1200	1400
Tensile Modulus N/mm2	208,000	100,000
Interlaminar Shear Strength N/mm2	62	62

TABLE II (Cont.)

c. Vf = 60% fibres in Shell Epikote 828 epoxy(17)

Carbon Fibre Type	A - S	HT - S	HM - S
Tensile Strength N/mm^2	1500	1560	1330
Tensile Modulus N/mm^2	105,000	128,000	187,000
Bending Strength N/mm^2	1480	1470	990
Bending Modulus N/mm^2	103,000	122,000	182,000
Interlaminar Shear Strength N/mm^2	80	80	60

d. Wf = weight fraction fibres = 73% in Shell Epikote 828 epoxy(10,11)

Carbon Fibre Type	I
Tensile Strength N/mm^2	800 - 1100 ≠

≠ Scatter band in experimental results

TABLE II (Cont.)

4. Cross Plied Lay-ups of Type I Unidirectionally Aligned Carbon Fibres(10,11)

Fibres in Shell Epikote 828 epoxy

Lay-up: 0°, 90°, 0°, 90° etc.

Lay-up	Tensile Strength N/mm^2
7 ply (80% weight fraction)	400 - 650 ≠
11 ply (67% weight fraction)	400 - 600 ≠

≠ scatter band in experimental results

5. En 45 steel(9,19,20,21) (OQ 920°C T.475-500°C)

Specific Gravity	7.7
Tensile Strength N/mm^2	1550
Tensile Modulus N/mm^2	208,000
Shear Modulus N/mm^2	79,000
Fatigue Stress ranges, N/mm^2	
Rotating Bending (10^7 cycles)	1000*
Torsional (10^7 cycles)	770
Estimated Reversed Plane Bending	
2×10^5 cycles (un-peened)	680
2×10^5 cycles (shot peened)	850
10^7 cycles (un-peened)	400

* 0.2 mm decarburisation

TABLE III COMPARATIVE FATIGUE DATA AND SPECIFIC STORED ENERGY COEFFICIENTS FOR En 45 STEEL AND VARIOUS UNIDIRECTIONAL CFRP AND GRP COMPOSITES

Material and number of cycles	Plane Bending Fatigue Strength at stress range σ N/mm2	Tensile Modulus E N/mm^2	Specific Gravity ρ	Stored Energy Coefficient $\frac{\sigma^2}{E\rho}$ N/mm^2
En 45 (un-peened) 2 x 10^5 cycles	680	208,000	7.7	0.3
En 45 (shot peened) 2 x 10^5 cycles	850	208,000	7.7	0.4
En 45 (un-peened) 10^7 cycles	400	208,000	7.7	0.1
Scotchply 1002 62% Vf 'E' glass 10^7 cycles	250	35,800	1.8	1.0
2 x 10^5 cycles	375	35,800	1.8	2.2
73% Wf Type I carbon fibres in Epikote 828 10^7 cycles	400	208,000	1.7	0.5

Data from Table I

TABLE IV **ESTIMATED BENDING FATIGUE STRENGTHS OF UNIDIRECTIONAL CFRP SYSTEMS AND RESULTANT STORED ENERGY COEFFICIENTS**

Note: The stored energy coefficients are calculated on the assumption that the bending fatigue strengths are 50% to 70% of the static tensile strengths

Material	Tensile Strength N/mm^2	Estimated Plane Bending Fatigue Strength, σ N/mm^2		Tensile Modulus, E N/mm^2	Stored Energy Coefficient $\frac{\sigma^2}{1.7\ E}$ N/mm^2	
		= 70% Tensile	= 50% Tensile		= 70% Tensile	= 50% Tensile
65% Vf Type I fibres in ERLA 4617DDM	703	490	350	206,800	0.7	0.4
65% Vf Type II fibres in ERLA 4617DDM	1450	1000	725	131,000	4.5	2.4
60% Vf Type I - S fibres in Epikote 828	1200	840	600	208,000	2.0	1.0
60% Vf Type II - S fibres in Epikote 828	1560	1100	780	128,000	5.6	2.8
60% Vf Type A fibres in Epikote 828	1400	980	700	100,000	5.7	2.9
60% Vf Type A - S fibres in Epikote 828	1500	1050	750	105,000	6.2	3.2

Data from Table I

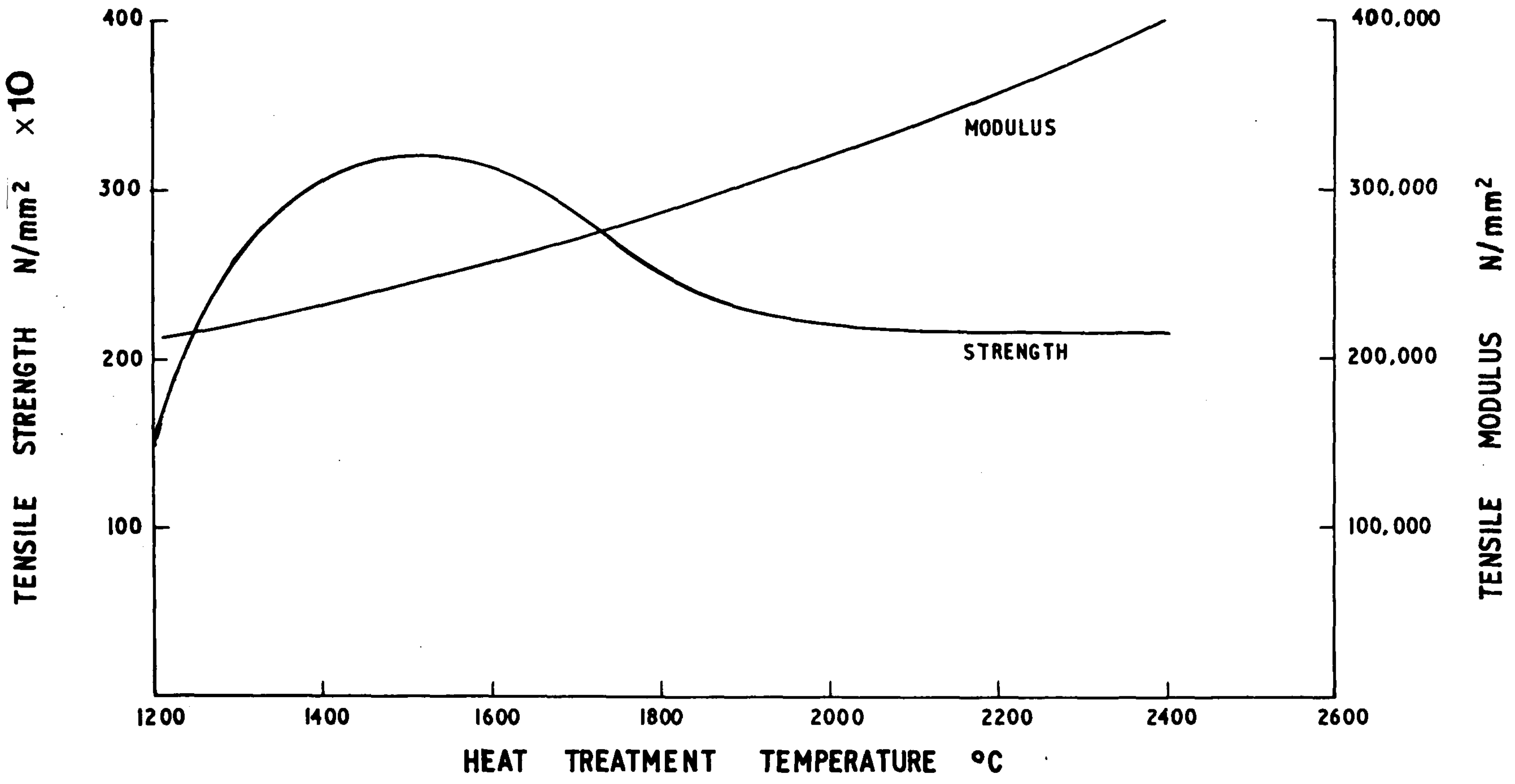

FIG. I VARIATION OF CARBON FIBRE STRENGTH AND MODULUS WITH GRAPHITISATION TEMPERATURE. (FROM REF. 5.)

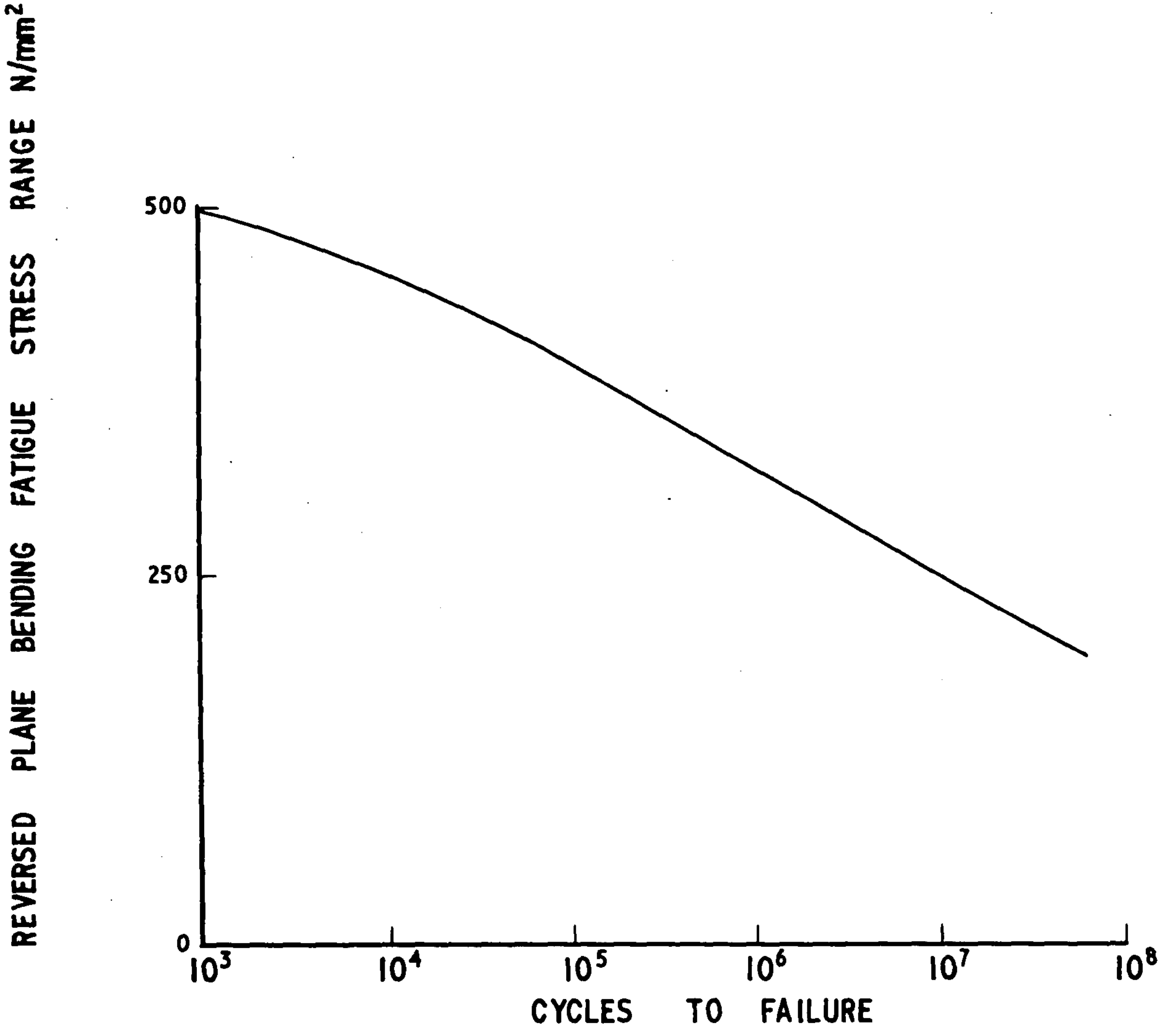

FIG. 2 S/N CURVE FOR UNIDIRECTIONALLY ALIGNED E GLASS FIBRES IN AN EPOXY MATRIX. (FROM REF. 8.)

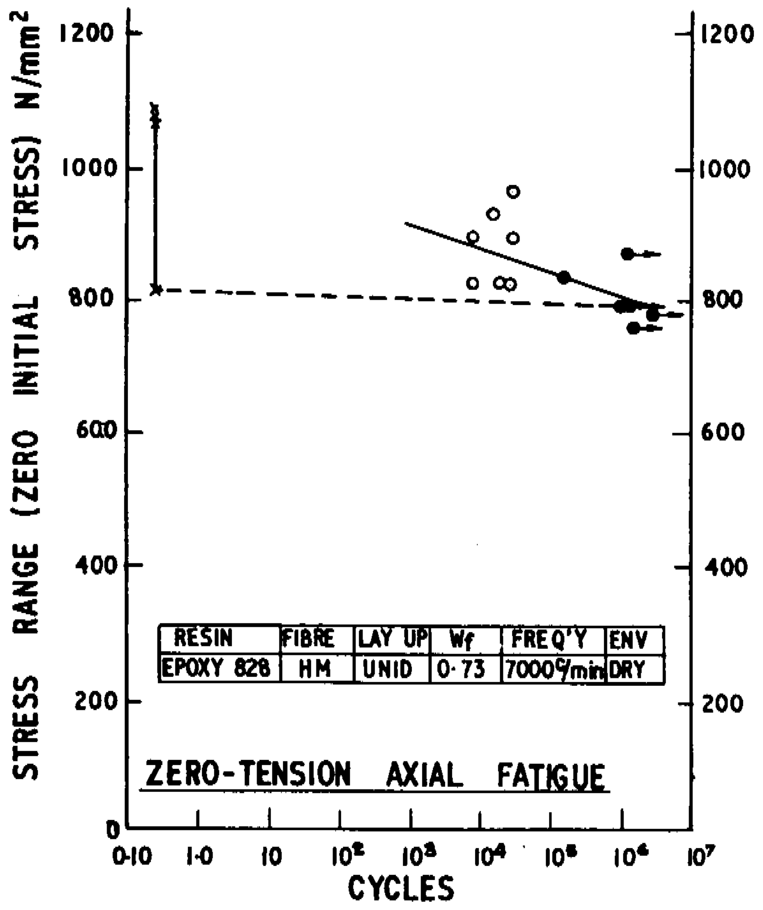

FIG. 3 S/N CURVE FOR CFRP: AXIAL LOADING (FROM REFS 10 AND 11)

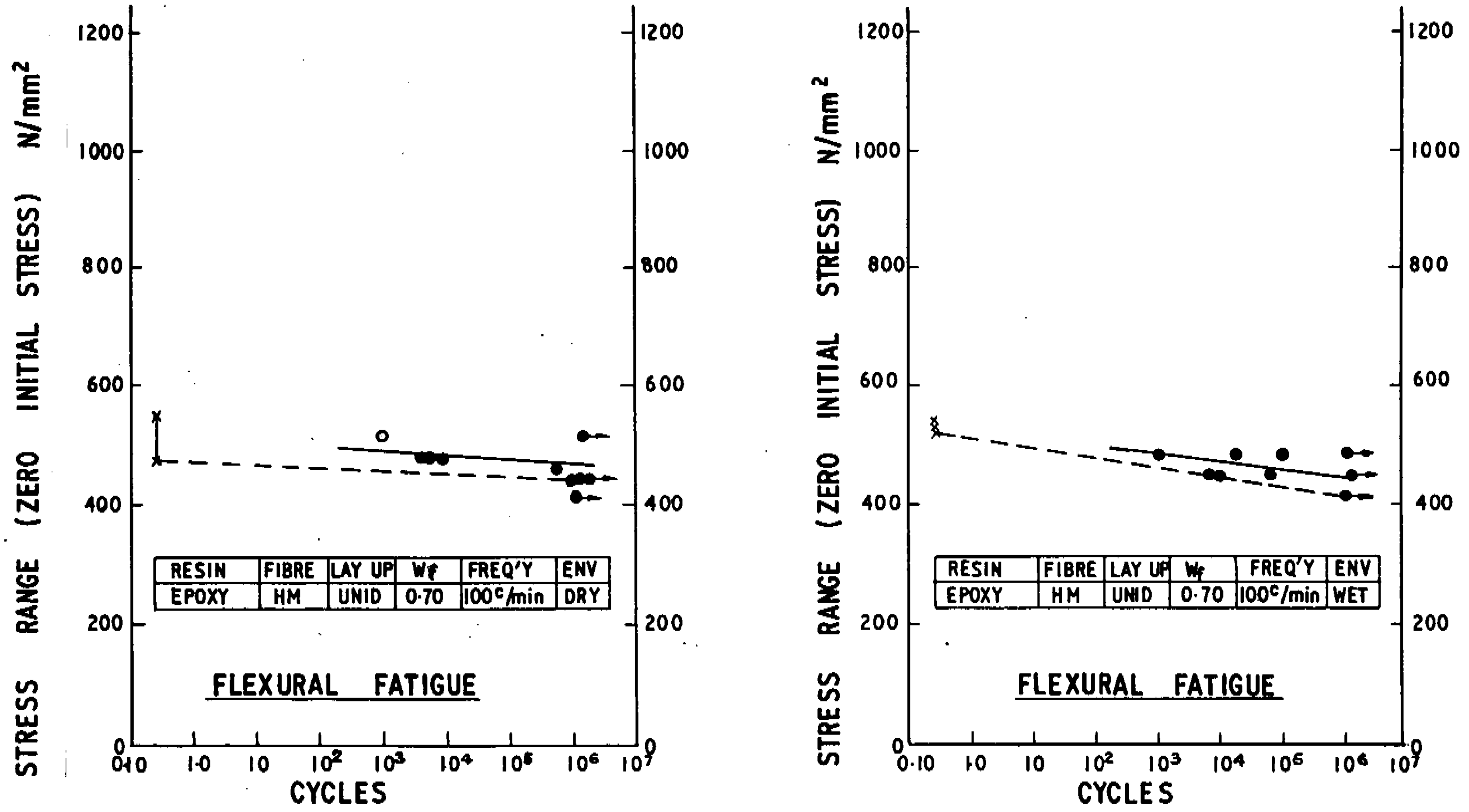

FIG. 4 S/N CURVES FOR CFRP: FLEXURAL (PLANE BENDING) LOADING. (FROM REFS. 10 AND 11)

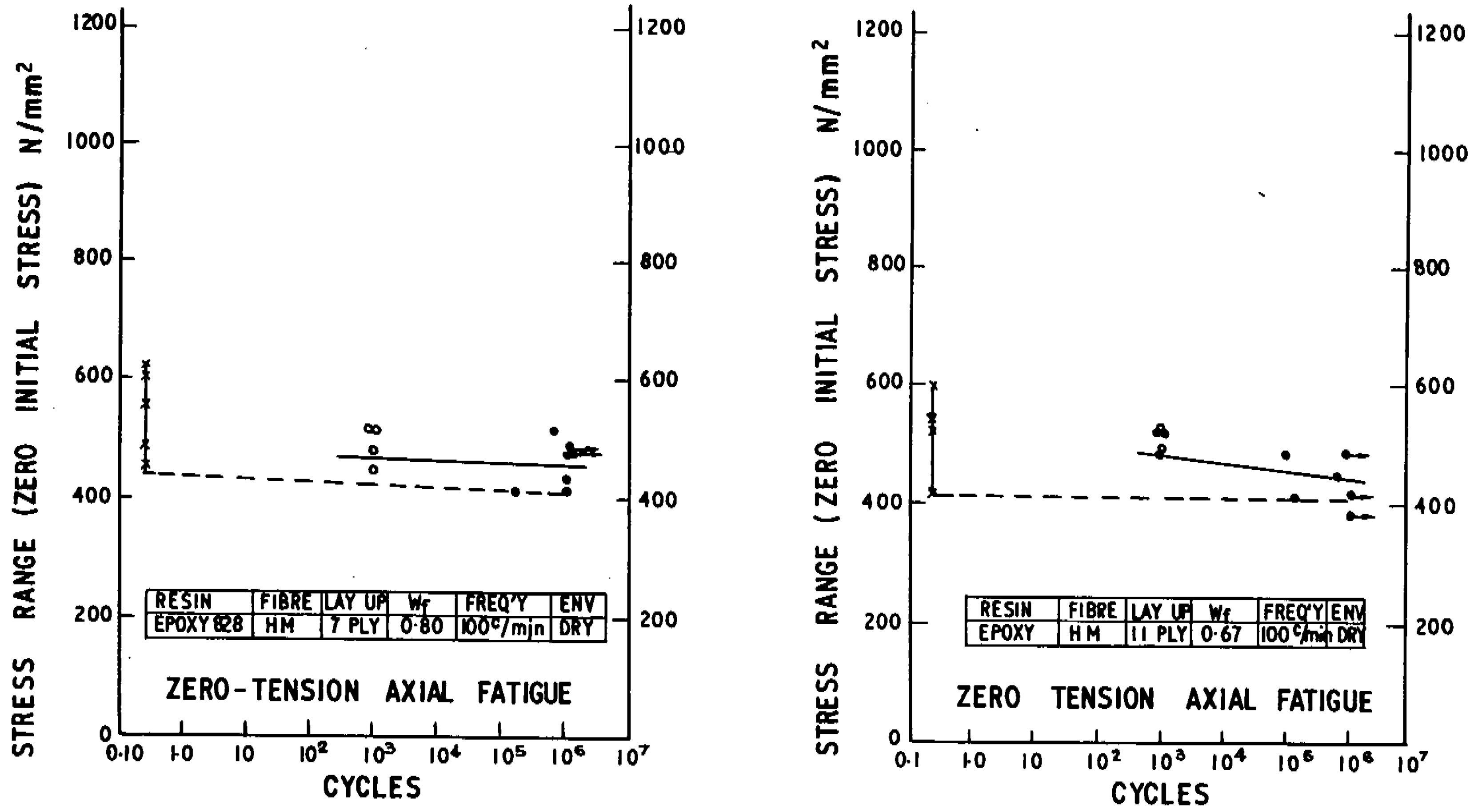

FIG. 5 S/N CURVES FOR CROSS PLIED CFRP: AXIAL LOADING (FROM REFS 10 AND 11)

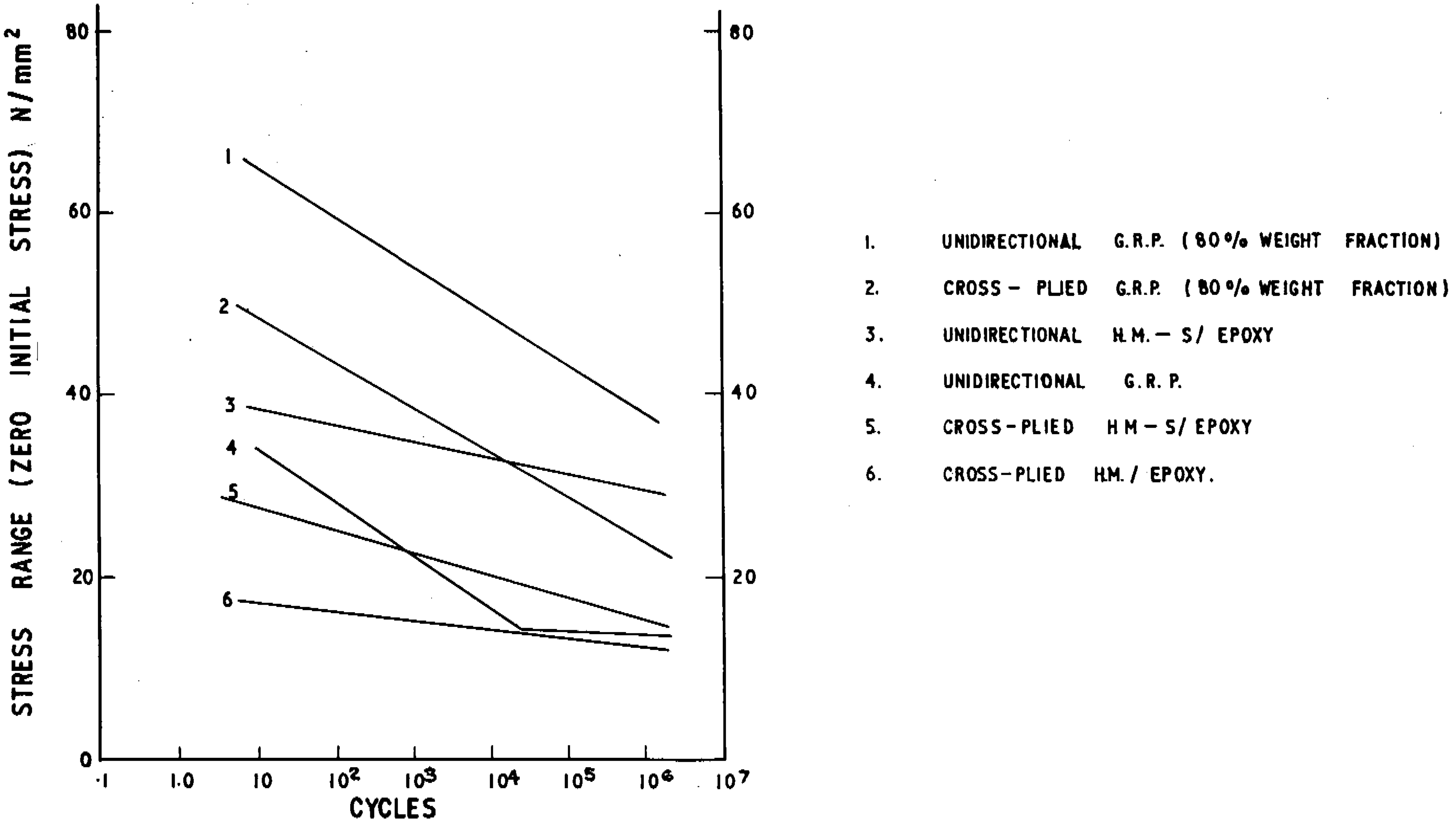

FIG. 6 COMPARISON OF SHEAR FATIGUE PROPERTIES OF G.R.P. AND C.F.R.P. (FROM REFS. 10 AND 12)

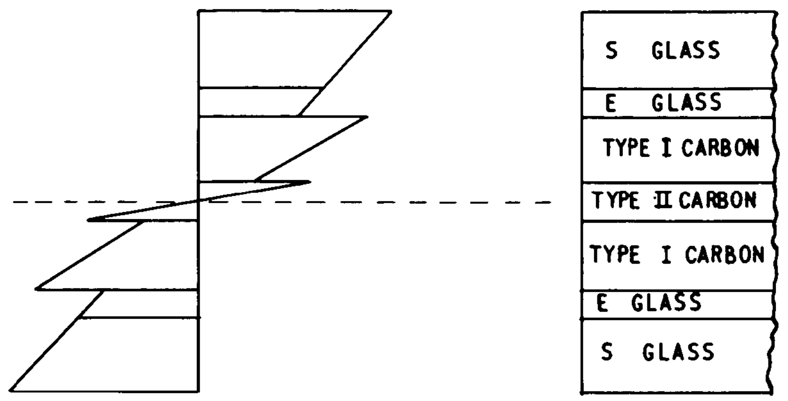

FIG. 7. STRESS DISTRIBUTION IN A HYBRID GLASS / CARBON REINFORCED PLASTIC LEAF SPRING. (FROM REF. 5.)